Renewable Energy Systems

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A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions

Second Edition

Henrik Lund

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Henrik Lund
September 2013

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Willett Kempton is trained as a cognitive anthropologist and electrical engineer. He serves as Director of the Center for Carbon-Free Power Integration and Professor in the College of Earth, Ocean, and Environment at the University of Delaware. With co-authors, Kempton published the first proposal for what is now called Vehicle-to-Grid (V2G) power in 1997, and the fundamental equations for V2G power and V2G markets in 2005. Kempton and industry partners have created the Mid-Atlantic Grid-Interactive Cars Consortium (MAGICC), seeking to establish commercial-scale V2G implementation. In addition to his articles and reports on V2G, Dr. Kempton has published research on offshore wind power, the beliefs and values that citizens and policy makers apply to environmental issues, cognitive and behavioral aspects of energy efficiency, and factors that move citizens to environmental action.

Frede Hvelplund is a Professor in Energy Planning at Aalborg University, Denmark. He has a background in Economics and Social Anthropology. Hvelplund has written a comprehensive series of books and articles on the transition to renewable energy systems; among others, *Alternative Energy Plans*, which was written in interdisciplinary groups together with engineers. Hvelplund is a "concrete institutional economist" and understands the market as a social construction that for decades has been conditioned to support a fossil fuel-based economy. Hence, Hvelplund believes that a transition to a "renewable energy" economy requires fundamental changes of an array of concrete institutional rules, laws, and market conditions. In 2005, Hvelplund obtained the Danish Dr. Techn. Degree, and in December 2008, he received the EUROSOLAR European Solar Prize.

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Woodrow W. Clark II, MA^3, Ph.D., is a qualitative economist. He is one of the co-recipients of the 2007 Nobel Peace Prize for his work as a member of the United Nations Intergovernmental Panel on Climate Change. Clark was the Renewable Energy Advisor to the Governor of California from 2000 to 2003 and is a frequent keynote speaker and lecturer in California, Europe, and Asia. Furthermore, Clark is the founder of the company Clark Strategic Partners, which creates sustainable communities to use smart green infrastructures, grids, technologies, public policies (plans), and economics (finance and investment). Clark has written over 50 peer-reviewed papers and 6 books related to the topic of renewable energy and sustainable communities, among others, the recent book *The Next Economics* and the forthcoming books *The Green Industrial Revolution* and *Global Sustainable Communities Design Handbook* (2014).

Paul Quinlan is Director of Economic Research and Development at the North Carolina Sustainable Energy Association, a nonprofit organization that specializes in the statewide advancement of renewable energy and energy efficiency resources through public policy, education, and economic development. Quinlan's work focuses on leading an innovative economic research program that informs public policy and market development initiatives. He publishes an annual renewable energy and energy efficiency survey that details the dynamics and growth of the emerging industry in North Carolina. His research interest and expertise also include wind energy and workforce development. Quinlan holds a Master's degree in Public Policy and a Master's degree in Environmental Management from Duke University.

Poul Alberg Østergaard is an associate professor in Energy Planning at Aalborg University, Denmark. Østergaard holds a M.Sc. and a Ph.D. in energy planning—the latter with particular focus on integrated resource planning and the organizational structure of the energy sector. He has conducted research and authored publications on energy planning since 1995 and has been project manager, work package leader, or participant in a series of research projects that are mostly centered on the large-scale integration of renewable energy sources and the development of renewable energy scenarios. In addition, Østergaard is the program coordinator of the M.Sc. program in Sustainable Energy Planning and Management at Aalborg University and has been involved in various teaching and training activities, notably energy systems analysis workshops in Denmark, Nicaragua, Jordan, and Malaysia.

Brian Vad Mathiesen is a professor in Energy Planning at Aalborg University. Mathiesen holds a M.Sc. and a Ph.D. focusing on fuel cells in future energy systems (2008). His research covers analyses of short-term, well-known transition technologies and 100% renewable energy systems as well as technical energy system analyses and studies of feasibility, public regulation, and technological change. Since 2005, Mathiesen has been involved in research in renewable energy systems as well as technologies for the large-scale integration of wind power. He was responsible for the technical and socioeconomic analyses that formed the basis for a detailed roadmap toward 100% renewable energy in the IDA Climate Plan 2050 (2009) and in the strategic research project CEESA (2011). In 2008 and 2010, he was involved in creating the Heat Plan Denmark, which analyzed future heat options.

David Connolly is an assistant professor in Energy Planning at Aalborg University, Denmark. In his research, he primarily develops energy models at a national or international level to evaluate the technical, environmental, and financial consequences of energy systems, with specific emphasis on 100% renewable energy systems. Connolly's research to date has focused on the role of electricity storage, district heating, and synthetic fuels in a 100% renewable energy system. He holds a Ph.D. in energy planning from the University of Limerick, Ireland, for which he won the Best Early Career Researcher award at the Globe Forum conference in 2010.

Wen Liu is a lecturer and researcher at Hanze University of Applied Science in the Netherlands. She holds a Ph.D. in Energy Planning from Aalborg University, Denmark, and a Master's degree in Environmental Science completed at Beijing Normal University in China. Liu's work focuses on energy system analysis, modeling, and sustainable transport technologies seen from the perspectives of sustainable transport transition and large-scale renewable energy integration. Liu has published a series of articles proposing the analysis of renewable energy systems and evaluating a sustainable transport transition in China. Liu was also the first researcher to apply the EnergyPLAN computer tool to the Chinese energy system.

Anders N. Andersen is the Head of the Energy Systems Department at EMD International (www.emd.dk). This department is, among others, responsible for the development of the simulation tool energyPRO, which is used worldwide for simulating and optimizing distributed energy plants equipped with energy stores and participating in wholesale and balancing electricity markets. Andersen holds a M.Sc. in Mathematics and Physics and a diploma in Business Administration and Organization.

Abbreviations

Power Plant Technologies

CHP: Combined Heat and Power
PP: Power Plant (condensing unit)
CAES: Compressed Air Energy Storage
CCS: Carbon Capture and Storage
CCR: Carbon Capture and Recycling
COP: Coefficient of Performance (ratio between the output heat and input work/electricity of a heat pump)

Electricity Demand and Production

DSM: Demand Side Management
CEEP: Critical Excess Electricity Production
EEEP: Exportable Excess Electricity Production

Renewable Energy and Fuels

RES: Renewable Energy Sources
PV: Photovoltaic
DME: Dimethyl Ether — first derivative of methanol

Transportation

BEV: Battery Electric Vehicle
HFCV: Hydrogen Fuel Cell Vehicle
V2G: Vehicle to Grid (vehicle supplying power to the public grid)
pkm: Person kilometer (Person transportation)
tkm: Ton kilometer (Freight transportation)

Buildings and Energy Infrastructures

DH: District Heating
4GDH: Fourth Generation District Heating
ZEB: Zero Energy Building/Zero Emissions Building

Policy and Planning

EIA: Environmental Impact Assessment
GIS: Geographical Information Systems

Economy

GDP: Gross Domestic Product
DEC: Danish Economic Council
O&M: Operation and Maintenance
DKK: Danish Kroner
USD: U.S. Dollar
THB: Thai Bath
DM: Deutsche Mark
EUR: Euro

Energy and Power Units

TWh: Terawatt hour (energy unit equal to 1 billion kWh)
GWh: Gigawatt hour (energy unit equal to 1 million kWh)

PJ: Peta Joule (energy unit equal to 1 million billion Joule)
MW: Megawatt (power capacity unit equal to 1 million Watt)
GW: Gigawatt (power capacity unit equal to 1 billion Watt)
MWe: Megawatt electric output
MWth: Megawatt thermal output

Chapter 1

Introduction

How can society convert to 100 percent renewable energy? The answer to that question is the main topic of this book. Two important aspects must be considered. First, from a technical point of view, which technologies can we use to make sure that the resources available meet the demands? To answer this question, this book presents an energy system analysis methodology and a tool for the design of renewable energy systems. This part includes the results of more than 15 comprehensive energy system analysis studies. The large-scale integration of renewable energy into the present system has been analyzed, as well as the implementation of 100 percent renewable energy systems. Moreover, as part of this new edition, a chapter on Smart Energy Systems and Infrastructures has been added (Chapter 6).

Second, in terms of politics and social science, how can society implement such a technological change? To answer that question, this book introduces a theoretical framework approach, which aims at understanding how major technological changes, such as renewable energy, can be implemented at both the national and international levels. This second aspect involves the formulation of the Choice Awareness theory, as well as the analysis of 11 major empirical cases from Denmark and other countries.

Regarding the implementation of the change from fossil fuels to renewable energy, Denmark is an interesting case. Like many other Western countries, Denmark was totally dependent on the import of oil at the time of the first oil crisis in 1973. Almost all transportation and residential heating were based on oil. Furthermore, 85 percent of the electricity supplied in Denmark was produced from oil. Altogether, prior to the oil crisis, more than 90 percent of its primary energy supply was based on oil.

Denmark, like many other countries, was unprepared for the sudden rise in oil prices. Danish energy planning had been based on the principle of supply meeting demand. Power stations were planned and built on a prognosis based on the historical development of needs. Denmark had no minister of energy and no energy department, no action plans in the case of being cut off from oil supplies, and no long-term strategy for the future in case oil resources were depleted.

Nevertheless, now 40 years later, Danish society has proved its ability to implement rather remarkable changes. Figure 1.1 shows the development of the primary energy supply of Denmark since 1972 and illustrates two important

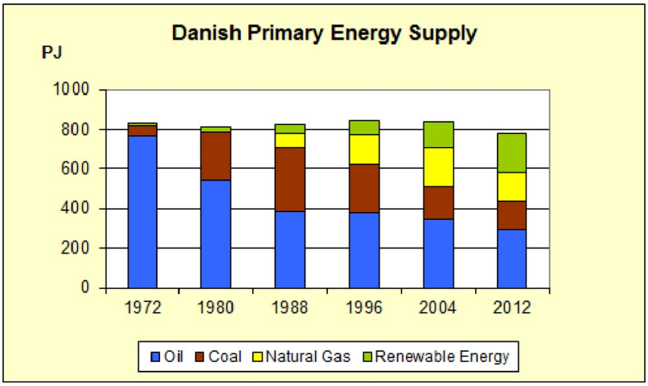

FIGURE 1.1 Danish primary energy supply.

factors: half of the oil consumption has been replaced by other fuels—for example, coal, natural gas, and, to some extent, renewable energy—and Denmark has managed to stabilize the primary energy supply at the same level as in 1972. This stabilization is unique compared to other countries, as it has been achieved simultaneously with a "normal western European" economic growth.

The primary means have been energy conservation and efficiency improvements in the supply. Buildings have been insulated, and combined heat and power (CHP) production has been expanded. Thus, 40 years later, the primary energy supply for heating has been reduced to two-thirds of what was used prior to 1973, even though the heated space area has increased by more than 50 percent in the same period. The renewable energy share of the primary energy supply has increased from around zero in 1972 to more than 20 percent in 2012, and wind power production has grown to more than a 25 percent share of the electricity demand.

Since 2006, the target of the Danish Government has been that Denmark will become completely fossil fuel free. Since the first edition of this book was published, Denmark has defined a target of using 100 percent renewable energy in its energy and transportation sectors by 2050. In March 2012, a new political agreement constituting an important step toward fulfilling the 2050 target was reached by 95 percent of the members of Parliament. By 2020, the agreement will, among other initiatives, increase the share of renewable energy in the final energy consumption to more than 35 percent; increase the share of wind power to approximately 50 percent of the electricity demand; and reduce greenhouse gas emissions by 34 percent compared to 1990 (Danish Energy Agency 2012).

Moreover, Denmark started to produce oil and natural gas from the North Sea in the early 1980s and has, since 1997, been more than self-supplied with energy. However, the Danish oil and gas resources are scarce and are likely to last for only a few decades. Can Denmark convert to 100 percent renewable energy within a few decades, or will it have to return once again to the former dependence on imported fossil fuels? This question is indeed relevant not only to Denmark but to Europe in general as well as the United States, China, and many other nations around the world.

The idea of this book is to unify the results and deduce the learning of a number of separate studies and thereby contribute to a coherent understanding of how society can implement renewable energy systems. The book is based on 25 years of involvement in a number of important and representative political decision-making processes in Denmark and other countries. As we will see, these processes reveal the lack of ability of organizations and institutions linked to existing technologies to produce and promote proposals and alternatives based on radical changes in technology.

On the other hand, the stabilization of the primary energy supply shown in Figure 1.1 proves that the ability to act as a society has been possible, despite conflicts with representatives of the old technologies. In Denmark, during this period, official energy objectives and plans have been developed due to a constant interaction between Parliament and public participation. In this interaction, the description of new technologies and alternative energy plans has played an important role.

The theory of Choice Awareness seeks to understand and explain why the best alternatives are not described and developed per se and what can be done about it. Choice Awareness theory argues that public participation, and thus the awareness of choices, has been an important factor in successful decision-making processes and puts forward four strategies to help along these processes.

1. BOOK CONTENTS AND STRUCTURE

Figure 1.2 shows the structure of this book. The Choice Awareness section (the gray area) includes a theoretical understanding and a framework for the development of renewable energy system analysis tools and methodologies (the white area). This chapter introduces both aspects and provides some important definitions.

Chapter 2 introduces the Choice Awareness theory, which deals with how to implement radical technological changes such as renewable energy systems. This theory argues that the perception of reality and the interests of existing organizations will influence the societal perception of choices. Often these organizations seek to hinder radical institutional changes by which they expect to lose power and influence. Choice Awareness theory states that one key factor in this manifestation is the societal perception of having either a *choice* or *no choice*.

The Choice Awareness theory presents two theses. The first states that when society defines and wishes to implement objectives implying radical technological change, existing organizations will often seek to create the perception that the radical change in technologies is not an option and that society has *no choice* but to implement a solution involving the technologies that will save and constitute existing positions. The second thesis argues that, in such a situation,

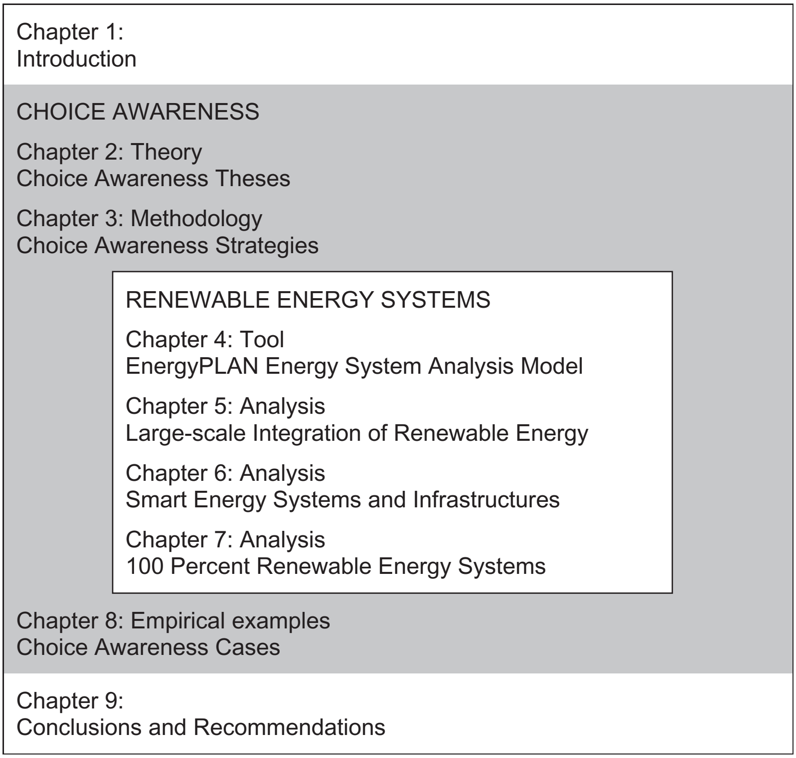

FIGURE 1.2 Contents and overall structure of the book.

society will benefit from focusing on Choice Awareness, that is, raising the awareness that alternatives *do* exist and that it is possible to make a choice. Four key strategies are identified from which society will benefit when seeking to raise Choice Awareness.

Chapter 3 elaborates on the Choice Awareness strategies related to the second thesis: the design of concrete technical alternatives, feasibility studies based on institutional economic thinking, the design of public regulation measures, and the promotion of a democratic infrastructure based on new corporative regulation.

Chapter 4 describes the method of designing concrete technical alternatives based on renewable energy technologies. This method distinguishes between three implementation phases: introduction, large-scale integration, and 100 percent renewable energy systems. The need for simulation tools in the two latter phases is especially emphasized. Both methodology and tool development are discussed in relation to the theoretical framework of Choice Awareness, and the energy system analysis tool, EnergyPLAN, is described. The EnergyPLAN model is a freeware that can be accessed from the home page, www.EnergyPLAN.eu, together with documentation and a training program.

Chapter 5 refers to and deduces the essence of a wide range of studies of the Danish energy system. In these studies, the EnergyPLAN model has been applied to the analysis of large-scale integration of renewable energy. The Danish energy system is characterized by a high share of renewable energy and is therefore a suitable case for the analysis of further large-scale integration. The question in focus is how to design energy systems with a high capability of utilizing intermittent renewable energy sources. This chapter describes important methodology developments and compares the capability of different systems, including how they treat the fact that the fluctuations and intermittence of, for example, wind power differ from one year to another.

Chapter 6 adds to the previous chapter by focusing on infrastructures and introduces the term *Smart Energy Systems*. In recent years, a number of new names and definitions of subsystems have been promoted to define and describe new paradigms in the design of future energy systems, such as *smart grid* and *power to gas*. These infrastructures are essential new components in the design of future renewable energy systems. However, each of them is also a subsystem that cannot be fully understood or analyzed if it is not properly put into the context of the overall energy system. Chapter 6 illustrates how this context can be established by the use of the EnergyPLAN tool and presents the results of a number of recent studies including the role of the smart grid, future district heating technologies and systems, as well as smart transportation and power to gas systems.

Chapter 7 proceeds with the topics of the previous chapters and presents a number of results achieved by applying the EnergyPLAN tool to the design of 100 percent renewable energy systems. The question in focus is how to compose and evaluate these systems. This chapter treats the principal changes in the methods of analysis and evaluation applied to these systems compared to systems based on fossil fuels with or without large-scale integration of renewable energy. In this edition, studies including smart energy systems have been added and the focus has been increased on the application of concrete institutional economics in the current situation of financial crisis. How can countries and regions afford to invest in renewable energy without further increasing public expenditures? And which methodologies should be applied to design such solutions?

Chapter 8 returns to the discussion of the theoretical framework. This chapter refers to a number of cases applying Choice Awareness strategies to specific decision-making processes of energy investments in the period since 1983. Typically, researchers have been involved in these processes through the design and introduction of concrete technical alternatives and/or the application of other Choice Awareness strategies. The cases refer to a large number of publications and documented cases. Chapter 8 seeks to deduce what can be learned from the cases with regard to the Choice Awareness theses and strategies formulated in Chapters 2 and 3.

Chapter 9 returns to the concerted discussions of the two aspects: Choice Awareness and renewable energy systems. This chapter presents reflections and conclusions drawn from this book in terms of the implementation of renewable energy systems at the societal level.

2. DEFINITIONS

Both the issue of Choice Awareness and the case of renewable energy systems involve some basic definitions, which are provided in the following section.

Choice Awareness

The theory of Choice Awareness addresses the societal level. It concerns collective decision making in a process involving many individuals and organizations representing different interests and discourses, as well as different levels of power to influence the decision-making process. The term *choice* obviously plays an important role in the definition of Choice Awareness. The *Oxford English Dictionary* (2008) defines choice as "the act of choosing; preferential determination between things proposed; selection, election". Choice involves the act of thinking and the process of judging the pros and cons of multiple options and selecting one of the options for action. This book distinguishes between a *true* choice and a *false* choice.

A *true* choice is a choice between two or more real options, while a *false* choice refers to a situation in which the choice is some sort of illusion. Some examples of false choices are a Catch-22 and Hobson's Choice—in other words, a free choice in which actually only one option is offered. These two types of false choices will be explained further in Chapter 2. More examples of false choices are blackmail and extortion, both involving the condition to either do what you are told or suffer unpleasant consequences.

The *Oxford English Dictionary* (2008) defines awareness as "the quality or state of being aware; consciousness". In biological psychology, awareness comprises a person's perception and cognitive reaction to a condition or event. In principle, awareness does not necessarily imply understanding; it is just an ability to be conscious of, feel, or perceive. However, here the term is combined with *choice*, which implies the acts of thinking and judging. Thus, Choice Awareness does involve an element of understanding. Choice Awareness is used here to describe the *collective perception* of having a *true choice*. Moreover, this situation involves a cognitive reaction in terms of judging the merits of relevant options and selecting one of them for action.

Collective perception is defined as a general perception in society. It does not include a few individuals who know better or different; the fact that a single person comes up with new ideas or invents new alternatives does not change the collective perception, as long as the person keeps these ideas to him- or herself. Only if individuals raise awareness by convincing or informing the public in general does this knowledge become part of the collective perception. In the same manner, the collective perception may be manipulated by individuals or organizations if they prove successful in convincing society in general that a certain alternative does not exist—meaning that it does not comply with technical requirements or other regulations.

Choice-eliminating mechanisms influence the collective perception in the direction of not having a choice at all or having a false choice, as just described. *Raising Choice Awareness* involves influencing the collective perception in the direction of having a true choice and identifying and understanding the pros and cons of relevant alternatives.

Radical Technological Change

Choice Awareness theory is concerned with the implementation of radical technological change. *Technology* is defined as one of the means by which mankind reproduces and expands its living conditions. The definition of *technology* embraces a combination of four elements—technique, knowledge, organization, and products—and is discussed further in Chapter 2.

Radical technological change is defined as a change of more than one of the four elements of technology. In Choice Awareness, special focus is placed on the change of existing organizations, and a distinction is made between organizations and institutions. *Organization* is defined as a social arrangement that pursues collective goals, controls its own performance, and has a boundary that separates it from its environment. Typical examples of organizations are companies, nongovernmental organizations, businesses, and administrative units. *Institutions* are structures and mechanisms of social order and cooperation. They govern the behavior of more than one individual and/or organization, and they include a formal regime for political rule making and enforcement. Thus, in short, one may say that institutions are organizations including all of the written laws and regulations and all of the unwritten codes of culture regulating them.

Applied and Concrete Economics

Choice Awareness theory involves four strategies in which concrete institutional economics, as opposed to applied neoclassical economics, plays an important role. *Applied neoclassical economics* is defined as neoclassical-based methods, such as cost-benefit analyses and equilibrium models, applied to existing real-life market economies. This is seen as opposed to theoretically correct methods applied to market economies that fulfill the theoretical assumptions of a free market. As discussed further in Chapter 3, the theory of neoclassical market economics is based on a number of assumptions that are not fulfilled in real-life market economies. The critique of neoclassical-based methods of this book is directed toward the real-life applications of the methods, and it is not decisive whether this critique is valid for theoretically correct applications or not.

Concrete institutional economics is defined as economics that deals with the concrete institutional conditions that form the development of a specific society. *Institutional economics* focuses on the understanding of the role of human-made institutions in the shaping of economic behavior. The concrete institutional conditions vary from one society to another, and the method linked to concrete institutional economics therefore deals with defining analytical aims, contexts, and aggregation levels for the analysis of the concrete societal institutions in a specific society (Hvelplund 2005, pp. 91–95).

Renewable Energy

Renewable energy is defined as energy that is produced by natural resources—such as sunlight, wind, rain, waves, tides, and geothermal heat—that are naturally replenished within a time span of a few years. Renewable energy includes the technologies that convert natural resources into useful energy services:

- Wind, wave, tidal, and hydropower (including micro- and river-off hydropower)
- Solar power (including photovoltaic), solar thermal, and geothermal
- Biomass and biofuel technologies (including biogas)
- Renewable fraction of waste (household and industrial waste)

Household and industrial waste is composed of different types of waste. Some parts are considered renewable energy sources—for example, potato peel—whereas other parts, such as plastic products, are not. Only the fraction of waste that is naturally replenished is usually included in the definition. In this book, however, for practical reasons, the whole waste fraction is included as part of the renewable energy sources identified in most analyses.

Renewable Energy Systems

Renewable energy systems are defined as complete energy supply and demand systems based on renewable energy as opposed to nuclear and fossil fuels. They include supply as well as demand. The transition from traditional nuclear and fossil fuel-based systems to renewable energy systems involves coordinated changes in the following:

- Demand technologies related to energy savings and conservation
- Efficiency improvements in the supply system, such as CHP
- Integration of fluctuating renewable energy sources, such as wind power

A distinction can be made between *end use* and *demand*. *Energy end use* is defined as the human call for energy services such as room temperature, light and transportation. *Energy demand* is defined as consumer demands for heat, electricity, and fuel. Consumers include households and industry as well as public and private service sectors. Fuel may be used for heating or transportation. Heat demand may be divided into different temperature levels such as district heating and process heating.

Within end use, one may distinguish further between, on the one hand, basic needs such as food, basic temperatures, and transportation from home to work, and on the other hand, specific requirements such as a certain number of square meters with a certain room temperature and a certain number of kilometers of driving. This distinction can be critical, for example, when analyzing the transportation infrastructure related to food production or to transportation between home and work. However, in the analyses presented in this book, it has not been necessary to make this distinction.

Changes such as insulation and efficiency improvements of electric devices leading to changes in the energy demand for heat, electricity, or fuel are defined as *changes in the demand system*. In addition to the preceding renewable energy technologies, renewable energy systems include both technologies, which can convert from one form of energy into another—for example, electricity into hydrogen—as well as storage technologies that can save energy from one hour to another. Mathiesen (Mathiesen and Lund 2009) and Blarke (Blarke and Lund 2008) comprised these technologies under the designation relocation technologies. However, in the following, the difference between *energy conversion* and *energy storage* technologies is emphasized.

Energy conversion technologies are technologies that can convert from one demand (heat, electricity, or fuel) to another, such as the following:

- Conversion of fuel into heat and/or electricity by the use of power stations, boilers, and CHP (including steam turbines as well as fuel cells)
- Conversion of electricity into heat by the use of electric boilers and heat pumps
- Conversion of solid fuels into gas or liquid fuel by the use of electrolyzers and biogas and biofuel plants

Energy storage technologies are defined as technologies that can store various forms of energy from one hour to another, such as the following:

- Fuel, heat, and electricity storage technologies
- Compressed air energy storage
- Hydrogen storage technologies

The definition of *storage technologies* is broader than the concept of storage itself. For example, in the case of electricity, which is stored by converting it into hydrogen, the storage technology may include conversion technologies such as electrolyzers and fuel cells. The distinction between conversion and storage technologies is defined by the purpose of the technology in question. If the purpose is to convert electricity to hydrogen because a car needs hydrogen, then the electrolyzer is defined as a conversion technology. However, if the purpose is to store electricity, then the combination of electrolyzer, hydrogen storage, and fuel cell is defined as a storage technology.

In complex renewable energy systems, single components may be used for both purposes. For instance, the same electrolyzer may be used to supply cars with hydrogen and, at the same time, produce hydrogen for storage purposes. In this case, the electrolyzer is simply regarded as both a conversion and a storage technology.

The distinction between the two types of technologies is important when designing renewable energy systems, as will be elaborated on in Chapters 4–7. It is important to distinguish between, on the one hand, the need for balancing time, and on the other hand, the need for balancing the annual amounts of different types of energy demands.

Smart Energy Systems

The transformation toward future renewable energy systems poses a challenge as it involves substantial changes in the infrastructures to carry the energy, i.e., the electricity grid, the gas grid, and the district heating and cooling grids. All these grids face the common challenge of facilitating distributed activities that involve the interaction with consumers and bidirectional flows. To meet this challenge, all grids will benefit from the use of modern information and communication technologies as an integrated part of the grids at all levels. On this basis, as elaborated on in Chapter 6, the following smart grid concepts have been defined:

Smart Electricity Grids are defined as electricity infrastructures that can intelligently integrate the actions of all users connected to them—generators, consumers, and those that do both—in order to efficiently deliver sustainable, economic, and secure electricity supplies.

Smart Thermal Grids are defined as a network of pipes connecting the buildings in a neighborhood, town center, or whole city, so that they can be served from centralized plants as well as from a number of distributed heating or cooling production units including individual contributions from the connected buildings.

Smart Gas Grids are defined as gas infrastructures that can intelligently integrate the actions of all users connected to them—suppliers, consumers, and those that do both—in order to efficiently deliver sustainable, economic, and secure gas supplies and storage.

All three types of smart grids are important contributions to future renewable energy systems. However, each individual smart grid should not be seen as separate from the others or separate from the other parts of the overall energy system. First, it does not make much sense to convert one sector to renewable energy if this is not coordinated with a similar conversion of the other parts of the energy system. Second, this coordination makes it possible to identify additional and better solutions to the implementation of smart grid solutions within the individual sector, compared to the solutions identified with a sole focus on the sector in question. Consequently, this book promotes the concept of *Smart Energy Systems*.

Smart Energy Systems are defined as an approach in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them to achieve an optimal solution for each individual sector as well as for the overall energy system.

3. RENEWABLE VERSUS SUSTAINABLE

This book often uses the term *renewable* energy, but why not use *sustainable* energy instead? After all, in many situations, these two terms are used interchangeably. However, significant differences can be found between the two terms. So renewable is used for the following reasons.

Sustainable Energy

Sustainable energy can be defined as energy sources that are not expected to be depleted in a time frame relevant to the human race; therefore they contribute to the sustainability of all species.

This definition of sustainable energy and the preceding definition of renewable energy represent typical definitions of both terms. They match rather closely the definitions given by the Internet encyclopedia Wikipedia. These definitions, however, reveal a difference in the significance of the two terms. Most important, Wikipedia (2008) includes the word *nuclear* in the sources defined as sustainable energy sources. However, as Wikipedia adds, for social and political reasons, there is a controversy as to whether nuclear sources should be regarded as sustainable. Nevertheless, at the present technological stage, nuclear is not sustainable, since it needs uranium, which is a scarce resource within the relevant time frame.

The same discussions seem to apply to carbon capture and storage (CCS) technologies, which have recently been promoted as an important solution in the debate on how to combat climate change. Very often this solution is proposed in relation to the use of fossil fuels, especially coal. Often the question is posed, why not continue to burn coal and even invest in new coal-fired power stations when this technology can be made sustainable by the use of CCS?

On the other hand, even though sustainable energy sources are most often considered to include all renewable sources, some renewable energy sources do not necessarily fulfill the requirements of sustainability. For instance, the production of biofuels such as ethanol from fermentation has in some life cycle analyses proven to be non-sustainable. Again, this is a controversy that has not yet found a consensus.

Nevertheless, the conclusion is that sustainable energy in some definitions *may* include nuclear and fossil fuels in combination with CCS, while these technologies and sources are not included in the definition of renewable energy.

On the other hand, renewable energy may include some biomass resources that *may* prove not to be sustainable.

Political Reasons for Renewable Energy

Besides the preceding difference, another important disparity exists between renewable and sustainable. This has to do with the reasons for wishing for technological change. Why does society *want* to implement renewable energy solutions? And why does society aim at implementing sustainable energy solutions? The reasons for introducing sustainable solutions are mainly, if not solely, related to an environmental motive. However, several reasons can be found for implementing renewable energy.

In the article "Choice Awareness" (Lund 2000) and in Chapter 23 of the book *Tools for Sustainable Development* (Lund 2007b), I described the recent history of Danish energy planning and policy since the first oil crisis in 1973. At least three main reasons can be defined for replacing fossil fuels by technologies related to renewable energy systems, including energy conservation and efficiency measures:

- *Energy security*, with an emphasis on oil dependence (and oil depletion). This reason played an all-important role in Danish society in the 1970s and has, in the beginning of the twenty-first century, experienced a revival caused by increasing oil prices in combination with the relations between the Western world and the governments in power of the remaining oil reserves.
- *Economics*, with an emphasis on job creation, industrial innovation, and the balance of payment. This reason took over and played a major role in Denmark in the 1980s. The main problem changed from being based on the issue of whether we could *get* the oil to whether we could *afford* it. This reason became the driving political force behind the industrial development of, among others, solar thermal and wind power in Denmark in the 1980s and 1990s.
- *Environment and development*, with an emphasis on climate change. This third reason became a key issue in the 1990s after the introduction of the Brundtland report (United Nations 1987) and has since been of increasing social importance along with the rising discussions on global warming.

All three reasons have formed part of the political discussions and have been identified as political goals of the Danish Energy Policy during the entire period. However, the main focus has changed in such a way that each reason has been considered the most important one from one decade to another.

The concerns related to energy security are based on the underlying fact that fossil fuels constitute a limited resource. The United Nations' discussions on environment and development are based on the fact that energy consumptions are indeed not equally distributed between what is considered the rich and the poor countries of the world, respectively. This is described and discussed in relation to the rising global energy consumption in the paper "The Kyoto Mechanisms and Technological Change" (Lund 2006a). In this paper, it is argued that the introduction of the so-called Kyoto mechanisms actually had the opposite effect of what the United Nations intended. The Kyoto mechanisms allow rich countries to implement climate change projects in other countries instead of decreasing their own emissions. Thereby, they increase the differences in energy consumption between rich and poor countries rather than decreasing them. Moreover, the mechanisms may slow down the needed technological development.

With regard to the discussion of the difference between *renewable* and *sustainable* energy, a main point is that if society accepts nuclear power and fossil fuels in combination with CCS as parts of the solution, society may be able to achieve parts of the environmental goals. However, society will not be able to solve the fundamental problems of scarce and limited resources of fossil fuels and uranium. Seen from the point of view of a Western country such as Denmark, society will not be able to meet the goals of energy security, and, with regard to economics, Denmark will still have to import fossil fuels and/or uranium.

Renewable Energy and Democracy

Another difference between renewable and sustainable energy is worth discussing. This difference has democracy as its main focus and is quite relevant to the issue of energy systems and the implementation of technological change such as those addressed by the Choice Awareness theory, as we will see in Chapter 2.

In the 1970s, an energy movement arose in Denmark as in many other Western countries. This movement was comprised of, among others, the antinuclear movement (OOA) and the Danish Organization for Renewable Energy (OVE). When the OOA was created and these energy problems were discussed, the issues of democracy and living conditions in local communities played major roles in the arguments against nuclear and in favor of renewable energy. With regard to nuclear, some were afraid of the consequences of implementing the technology in terms of security and ownership. The question was how to guard the plants and the transportation of radioactive waste without having to hire security staff and erecting fences. Who should own and operate these big power stations? If ownership was assigned to big companies, it would mean that local communities would lose influence. Also, how should space for nuclear power stations be allocated and radioactive waste be disposed of without impacting the quality of life of the communities involved? The antinuclear movement (OOA 1980) discussed all of these concerns, as well as the relations between nuclear power and nuclear weapons.

The issue of local ownership also played an important role in the discussions on renewable energy. To have an influence on these decisions, the citizens in the local communities preferred to have their own renewable sources of energy instead of depending on nuclear or imported fossil fuels (OVE 2000). As we will see in Chapter 2, these beliefs conform to the concept of Choice Awareness, which highlights the benefits of choice in creating a "life worth living" at both the individual and societal levels.

In this view, the difference between renewable and sustainable energy becomes important. If society accepts nuclear power and fossil fuels in combination with CCS as major parts of the solution, the technological change may not meet the local communities' wishes to improve their influence on decisions that are important to their lives. In short, one can say that the implementation of renewable energy systems helps to create what I, in Chapter 3, refer to as a *suitable democratic infrastructure* according to the Choice Awareness theory. This suitable democratic infrastructure may improve the awareness of choices and thereby, in general, create better living conditions. On the other hand, an improved democratic infrastructure will also improve the circumstances of making the choice of implementing renewable energy systems. More important, depending on the specific definition applied, this may not be the case with sustainable energy systems. Based on these considerations, the term *renewable* energy systems is used in this book.

Chapter 2

Theory

Choice Awareness Theses

This chapter introduces the two theses of the Choice Awareness theory. The theory deals with *how* to implement radical technological changes such as renewable energy systems. The step from nuclear and fossil fuel systems to renewable energy systems involves a radical technological change. As we will see, it cannot be implemented by existing organizations within existing institutions, but it will imply organizational and institutional changes. This means that someone will win and someone will lose as a result of these changes.

With a reference to discourse and power theories, the Choice Awareness theory emphasizes that different organizations see things differently. Existing organizational interests will thus seek to keep renewable energy proposals out of the agenda at many levels. The Choice Awareness theory is based on the observation that, in many cases, these conditions lead to a situation of *no choice*. As a society, we are subject to a collective perception that states, for example, that "We have no choice but to build another coal-fired power station". The Choice Awareness theory, however, maintains that this is not true: We *do* have a choice. The theory tells us how to be aware of this choice; thus it enables us to debate our common future and make better decisions.

The theory addresses the societal level. It concerns collective decision making in a process that involves many individuals and organizations representing different interests and discourses, as well as different levels of power to influence the decision-making process. The theory is not comprehensive, but it emphasizes the key factor that existing organizational interests will often seek to eliminate choices from the political decision-making process.

The Choice Awareness theory advocates counterstrategies involving the design of technical alternatives, feasibility studies based on institutional economic thinking, and the design of public regulation measures seen in light of conflicting interests as well as changes in the democratic decision-making infrastructure. Those strategies are examined in more detail in Chapter 3.

1. CHOICE AND CHANGE

The word *choice* obviously plays an important role in the definition of Choice Awareness. In this book, a distinction is made between a *true* choice and a *false* choice. As already defined in Chapter 1, a true choice is a choice between two or more real options, while a false choice refers to a situation in which choice is some sort of illusion. One example of a false choice is the concept referred to as Hobson's Choice, that is, a free choice in which only one option is offered. The "choice" is between deciding on the option or not. The phrase is said to originate from Thomas Hobson (1544–1630), who delivered mail between London and Cambridge by horse. When the horses were not needed for the mail delivery, they were rented out to students and academic staff at the university. Hobson soon discovered that his best (and fastest) horses were the most popular ones and thus overworked. To prevent further exhaustion of his best horses, Hobson devised a strict rotation system, only allowing customers to rent the next horse in line. His policy, "This one or none", has come to be known as Hobson's Choice, when an apparent choice is in fact no choice at all (Smith 1882).

Another example of a false choice is the prototypical Catch-22, as formulated by Joseph Heller in his novel of the same title (Heller 1961). It considers the case of a bombardier who wishes to be excused from combat flight duty. To do so, he must submit an official medical certificate demonstrating that he is unfit because he is insane. However, according to Army regulations, any sane person would naturally not want to fly combat missions because they are so dangerous. By requesting permission not to fly combat missions on the grounds of insanity, the bombardier demonstrates that he is in fact sane and therefore is fit to fly. Conversely, any flyer who wanted to fly combat missions implicitly demonstrated that he was insane and was unfit to fly and should therefore be excused. To be excused, however, the unwilling individual had to submit a request, and, naturally, he never did. If the reluctant flyer did submit a request to be excused, the Catch-22 would assert itself, short circuiting any such attempt to escape from combat duty.

Choice/No Choice at the Individual Level

As mentioned, the theory of Choice Awareness addresses the societal level, but the term itself is inspired by the activities that take place at the individual level. The term *Choice Awareness* is inspired by kinesiology, a method of treating emotional stress at the individual level. In 1984 and 1986, Stokes and Whiteside examined the emotional causes of physical problems, including dyslexia. They described a method of healing certain health problems by working with the emotional state of the individual. By using various psychological tools, Stokes and Whiteside believed that certain individual psychological problems could be cured.

An important tool is the behavioral barometer providing a systematic way of relating different feelings to one another. The idea of the barometer is that a person's feelings relate and respond to one another at the conscious, the subconscious, and the body levels, as defined by Stokes and Whiteside. For example, if a person feels "unappreciated" at the conscious level, according to the barometer, this feeling corresponds to other, related feelings at the subconscious and body levels. By understanding these relations between different feelings at different levels of consciousness and awareness, one can work with individual problems. In combination with various other methods, the behavioral barometer is a powerful tool for helping individual problems.

In kinesiology, the word *choice* plays an essential role. According to Stokes and Whiteside, every human being has from birth the feeling that "we have *no choice*; and without *choice*, we have no power".[1] The feeling of no choice is an emotional condition in which individuals may find themselves. This feeling may manifest itself when a person experiences emotional problems. As expressed by Stokes and Whiteside, when "we buy in to no choice, we check out on our individuality, our self-worth, and the reality of spirit".[2]

According to Stokes and Whiteside, the feeling of no choice is both essential and fatal. If a person enters into a chronic state of feeling that he or she has no choice but to do something that he or she does not want to do, this condition is fatal. The cure is to make the person realize that he or she always has a choice. Even when experiencing the desperate situation of having no real alternative to begin with, one can still choose to say "no". The experience is that when a person accepts that he or she indeed has a choice to make—by saying no—he or she will be able to think of even better and real constructive alternatives. The point of Choice Awareness is that this *feeling*—or *perception*, as I prefer to call it—can also be observed at the collective and societal levels.

Choice/No Choice at the Societal Level

During my participation in various decision-making processes (11 of which are discussed in Chapter 8), I found that the *perception* of no choice appeared many times and in several forms also at the *collective* and societal levels. By the term *collective perception*, I am referring to the general perception in society. It does not include a few individuals who know better or differently. The fact that single persons get new ideas or come up with new alternatives does not change the collective perception, as long as they keep these ideas to themselves. Only if they raise awareness by convincing or informing the public in general does this knowledge become part of the collective perception. In the same manner, the collective perception may be manipulated by individuals or organizations if they prove successful in convincing society in general that a certain alternative does not exist, that is, it does not comply with certain requirements for technical or other reasons.

1. Stokes and Whiteside (1986), Chapter 1, p. 8.
2. Stokes and Whiteside (1986), Chapter 1, p. 9.

As we will see in Chapter 8, examples of the perception of no choice can be observed in the case of deciding for a new power station in my hometown of Aalborg in Denmark in the 1990s. At that time, the power company was owned by the municipality and electricity consumers, and a board of representatives and politicians were to make the decision. When the issue of electricity supply was put on the agenda, only one solution was presented: to build a coal-fired power station. One of the representatives was very frustrated by the decision-making process and really felt that he had no choice, since voting no would mean that, sooner or later, Aalborg would have no electricity supply at all. He wanted to consider an alternative in terms of a combined-cycle natural gas-fired power station, but this alternative was disregarded before the decision was to be made.

Later, the local county of Northern Jutland had to decide whether to approve the plant or not. In the public debate, the argument of job creation from the construction work played an important role. As described in detail in Chapter 8, the coal-fired power station was one of the least local job-creating alternatives one could imagine when seen in relation to the lifetime of the plant. An investment in renewable energy in combination with fuel-saving technologies, such as conservation and distributed combined heat and power (CHP) plants, would save the imports of coal and leave more money for local job creation. However, the power companies' association in Western Denmark argued that if the coal-fired power station was not approved, they would spend the money investing in a power station somewhere else, outside the region of Northern Jutland. This led to a collective perception of no choice in the region. The alternative to the coal-fired power station and the jobs created, even though they were few, was nothing: "This power station or none!" A real Hobson's Choice.

At the regional level, no true choice existed. However, at a higher level, society did in principle have a choice. It would have been possible to implement an institutional change making CHP and renewable energy an option at the regional level.

I have also observed such collective perception of no choice in Eastern Germany, Thailand, and Vietnam. In all cases, the combat between discourses and the execution of power creates a situation in which the community ends up with the perception that "we have *no choice* but to build another coal-fired power station". Even though it is recognized that this solution is not beneficial to the environment, health, energy efficiency, security, job creation, or technological innovation, it seems to be the only option.

The general observation made here is that the construction of the collective perception of no choice plays an important role when making major societal decisions on energy planning. Choice Awareness, however, is crucial to the implementation of political aims and objectives when radical technological changes are needed.

While I was writing the first edition of this book, I saw a new example in the newspaper *Ingeniøren*, which was related to the discussion of climate change.

In his opening speech to the Parliament in October 2006, Danish Prime Minister Anders Fogh Rasmussen announced the government's long-term objective for Danish energy policy: 100 percent independence from fossil fuels. When asked directly, the prime minister answered that nuclear sources will not form part of the solution. In other words, the long-term target is to convert to 100 percent renewable energy. This governmental objective has been repeated several times since then.

It is clear that coal does not form part of this long-term objective. However, the organizations that make a profit from burning coal have involved themselves in the promotion of coal in combination with carbon capture technology. The January 11, 2008, issue of *Ingeniøren* (2008a) dedicated two pages to a new report on how Denmark can decrease its greenhouse gas emissions by up to 80 percent before the year 2050. The article states that the report "is the first mapping of such large-scale reductions in Denmark".[3] It concludes with the statement

Electric vehicles, heat pumps, offshore wind power, and carbon capture and storage (CCS) are some of the technologies which we are simply forced to use.[4]

This information, however, is not correct. Alternatives without coal and CCS do exist. At least three other surveys were conducted before the preceding one, one of them based on the joint effort of the Danish Society of Engineers (see Chapter 8) and all of them describing how 100 percent renewable energy systems without coal and CCS can be reached by the year 2050. However, the message of the article is clear: Denmark has no choice. We simply have to include coal and CCS in the future energy supply.

The following week, the front page of *Ingeniøren* (2008b) reported a statement from the development and research manager of DONG, a company that owns several coal-fired power stations:

The storage of CO_2 is absolutely necessary if we are to achieve a reduction of CO_2 emissions of such a scale as planned for the period after 2020. Europe cannot possibly do without coal. Therefore, we are forced to clean CO_2 from coal-fired power stations.[5]

Again, the message is clear: Denmark and Europe have no choice but to burn coal and introduce CCS.

It is doubtful that the preceding statements deliberately ignored other studies or dismissed the fact that alternatives without coal do exist. Moreover, the

3. Translated from Danish: "Cowirapporten er den første kortlægning af så massive reduktioner i Danmark". *Ingeniøren*, January 11, 2008, p. 14.

4. Translated from Danish: "Elbiler, varmepumper, havvindmøller og CCS er nogle af de teknologier, vi simpelthen bliver nødt til at benytte". *Ingeniøren*, January 11, 2008, p. 14.

5. Translated from Danish: "CO_2-lagring er bydende nødvendigt, hvis vi vil opnå CO_2-reduktioner i den størrelsesorden, der er på tale efter 2020. Europa kan umuligt klare sig uden kul. Derfor er vi nødt til at rense CO_2 fra kulkraftværkerne". *Ingeniøren*, January 18, 2008, p. 1.

individuals cited are very skilled and competent in the field. Nevertheless, the statements are clearly seeking to influence the collective perception of choice. As we will see later, the preceding aspect is general for all of the cases discussed in Chapter 8. The reasons behind the resulting collective perceptions of no choice are much more fundamental. To understand the nature of the mechanisms leading to these perceptions, it is important to understand the term *radical technological change*.

Radical Technological Change

Not all technological changes are equally fundamental in the sense that they involve changes in existing organizations and institutions. Therefore, some technological changes challenge the political decision-making process more than others. Müller, Remmen, and Christensen (1984) defined technology as follows:

Technology embraces a combination of four constituents: Technique, Knowledge, Organization, and Products.[6]

Hvelplund (2005) added *profit* as a fifth dimension of technology, which is considered useful when analyzing changes in the energy sector. The basic assumption of the technology theory of Müller, Remmen, and Christensen is that

a qualitative change in any of the components will eventually result in supplementary, compensatory, and/or retaliatory change in the others.[7]

In other words, if one dimension is substantially changed, at least one of the others will follow. If they do not, the initial change will be abandoned over a period of time. Society cannot make a fundamental change in a technique without changing the knowledge and/or the organization and/or the product related to this technique. If one or more of the other dimensions are not changed, the new technique will not be implemented, and the traditional technique will be used once again.

After this definition of *technology* was introduced, Hvelplund (2005) defined the degree of radical change as increasing with the number of dimensions that must change. Hvelplund defined radical technological change as a change that affects more than one dimension.[8] The transition from nuclear and fossil fuel-based energy systems to renewable energy systems is to be considered a radical technological change. As we will see, this change in technique implies substantial changes in organization.

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6. This definition is cited from *A Conceptual Framework for Technology Analysis* (Müller 2003). The definition was first forwarded by Müller (1973) and was later expanded by Müller, Remmen, and Christensen (1984).
7. Müller (2003), p. 30.
8. Hvelplund (2005), p. 12.

It should be emphasized that technological change must be placed in a historical and institutional context. Hvelplund (2005) pointed out that the existing institutional set-up may favor established technologies at many levels. Consequently, coherent and coordinated changes are needed at different levels in society. However, a technological change such as wind power replacing a coal-fired power station may result in radical changes for those who own and work in the coal mines, while at the same time this does not necessarily imply any change for the electricity consumer.

The technological change from nuclear and fossil fuel-based energy systems to renewable energy systems involves an economic redistribution, as investments in large power stations are replaced by investments in energy conservation and distributed CHP plants. Furthermore, for example, coal mining is replaced by the harvesting of biomass resources and investments in wind turbines and solar thermal power.

The description of the technological change from fossil fuel to renewable energy systems in this section is based on Hvelplund, Lund, and Sukkumnoed (2007). The existing context is characterized by large supply companies on the one hand and many differentiated consumers divided into households and public and private enterprises on the other hand. Typically, the existing supply system is characterized by single-purpose companies, that is, enterprises that have the production and/or sale of energy services as their only purpose. They are often segmented into heat, electricity, or natural gas supply systems. Investments are capital intensive; they have a very long technical lifetime of 20–40 years and are almost 100 percent asset specific. Asset specificity means that the assets, such as district heating systems, supply stations, and power grids, can be used only for their present purposes. The organizations linked to the existing technologies are consolidated from an economic as well as a political point of view.

The existing consumers' system is characterized by many multipurpose organizations, which refers to the fact that households and private or public firms have other main purposes than investing in renewable energy system technologies. These organizations often lack capital for investing in renewable energy system technologies, including energy conservation activities, and they have no common organization of activities related to these technologies.

Unlike nuclear and fossil fuel technologies based on large power stations, renewable energy system technologies will typically benefit from a wide geographical distribution throughout their areas of consumption. The technological solutions differ from one place to another, and sometimes new, not well-proven technologies must be implemented. The maintenance of these new technologies is dependent on ownership and organization. Along with the implementation of new technologies, new types of organizations are therefore likely to develop.

Investments must be made by multipurpose organizations. Thus, electricity savings must be implemented by private households and industries with only a limited awareness of consumption and with main objectives quite unrelated to simply producing or consuming heat or electricity. This has to be compared with the former situation in which investments in supply technologies were carried out by single-purpose organizations, such as utility companies, with energy production as their primary objective.

The technologies must be implemented by many mutually independent organizations. Again, this has to be compared with the former situation with a limited number of companies. The financial capital of these new organizations will often be scarce compared with the financial capital of the existing supply companies. The political capital of these new organizations will also be relatively scarce compared with that of the existing companies.

All in all, this technological change can often be seen as a change from undifferentiated solutions implemented by a few single-purpose organizations to differentiated solutions implemented by many multipurpose organizations. Therefore, the change to renewable energy systems is to be regarded as a radical technological change. The important point is that this entails substantial changes in existing organizations and institutions, and these changes will challenge these organizations. Moreover, it will influence the general perception of choice in society.

2. CHOICE PERCEPTION AND ELIMINATION

Since the radical technological change to renewable energy systems implies substantial challenges and poses a threat to existing organizations, these organizations will not by themselves create and promote the alternatives required to implement this change. Existing organizations can create certain alternatives, whereas other alternatives are out of their perception. Even if they should wish to promote such alternatives, they would often not be able to implement them within the existing institutional set-up.

Choice Perception

The case of the power station Nordkraft (see Chapter 8) is an example from the early 1980s. In this case, the station was considering converting from oil to coal. The initial proposal put forward by the power company was a *one—and only one—alternative* proposal. The power company proposed that an oil boiler should be replaced by a coal boiler, a technology fitting well into the existing organizations of the power companies. No other alternative was presented to the public when the proposal was to be approved. City council members expressed preference for an alternative based on natural gas, but this alternative was not presented and did not form part of the basis for the decision-making process.

The local citizens had to describe and promote a concrete technical alternative representing radical technological change—in this case, the insulation of houses and the expansion of CHP outside the borders of the municipality. This alternative has subsequently proved to be the best solution in terms of economic feasibility when based on actual historical fuel prices. However, the institutional set-up of existing power companies could not identify and implement the best alternative by itself. The alternative entailed a radical technological change; in other words, it could not be implemented without changes in institutions, including the existing organizations.

The discourse of the power companies referred to an optimization of the use of fuels within the existing technical and organizational set-up. The identification of radically and technologically different alternatives was not a part of their interest or perception of reality. And even if it was, the implementation of these alternatives would be out of their reach, since it would involve investments in the insulation of private houses as well as CHP units in district heating companies owned by others.

The main concern of the city council was to maintain low district heating consumer prices. Moreover, they also had to manage urban and environmental concerns in the physical planning. Again, the implementation of insulation and CHP outside the municipality was out of their reach. Natural gas was an option that was within the reach and perception of the city council. However, the city council did not have the power or the resources to ensure a proper analysis and description of this alternative when faced with the risk of substantial rises in district heating prices.

The proposal of technologically and radically different alternatives had to come from citizens outside the power companies and the city council. The existence of an alternative could raise the public awareness of the fact that, from a technoeconomic point of view, a choice did exist, and as a result, 700 citizens made claims for the description and inclusion of alternatives in the debate. However, given the institutional set-up, such technologically and radically different alternatives could not be implemented. Institutional changes were required at a higher level.

Discourse theory can be used to explain why existing organizations will design and promote some alternatives but not others. This theory is inspired by linguistic philosophy and it perceives social reality as a linguistic construction (Thomsen, Frølund, and Andersen 1996). Articulation and discourse are key concepts in this theory. Laclau and Mouffe (1985) defined articulation as "any practice establishing a relation among elements such that their identity is modified as a result of the articulation practice". Discourse is defined as the "structured totality resulting from the articulation practice".[9]

According to discourse theory, different organizations perceive and articulate things differently; they exercise different discourses. In the description and discussion of climate change, some politicians and environmental organizations may have one perception of reality, while other politicians and organizations have another. For example, industrial organizations do not seem to ascribe to

9. Laclau and Mouffe (1985), p. 105.

the problems of climate change to the same extent as environmental organizations do. Moreover, industrial organizations do not draw the same conclusions with regard to the solution of the problems. They typically express the idea that an environmentally safe production should be available on existing markets, that is, managed by existing organizations and institutions (Thomsen, Frølund, and Andersen 1996).

A central element in discourse theory is the belief that reality is established through a combat between competing perceptions and articulations of reality and that these competing perceptions, to some extent, define one another. Mouffe (1993) argued that the collective identification of a "we" always raises the possibility that a "we"/"them" relationship is created and that the notion of "them" plays an important part in the definition of "we". Mouffe argued that, on the eve of the twenty-first century, the processes of redefining collective identities in our societies were "linked to the collapse of Communism and the disappearance of the democracy/totalitarianism opposition".[10]

Seen in relation to discourse theory, the implementation of renewable energy systems becomes a combat between different articulations and perceptions of reality. Choice Awareness theory argues that the perception of choice or no choice, including the collective perception of which alternatives to consider, is a core element. However, one perception cannot claim to be more real or true than the other. Reality is present in all of the different sets of articulations and perceptions. The main point in discourse theory is the idea that different perceptions of reality result in different mind constructions, that is, different ways of approaching the same real problems. Consequently, it is not solely a matter of different interests and views; the linguistic dimension also influences the construction of reality itself. According to Laclau and Mouffe,

Any discourse is constituted as an attempt to dominate the field of discursivity, to arrest the flow of differences, to construct a centre.[11]

Applied to the implementation of renewable energy systems, discourse theory implies the understanding that different organizations represent different perceptions of reality and therefore have different views on what should be done to solve the same problem. According to the theory, one could therefore expect that existing organizations linked to the burning of fossil fuels perceive climate change problems as a less severe threat that can be handled within the existing institutional framework, in other words, by technologies represented by existing organizations. If renewable sources are to be implemented according to this perception, those renewable technologies that fit into the framework of these organizations will be preferred.

One example of the advancement of technologies that fits well into existing organizations is the promotion of CCS, as described previously. Another

10. Mouffe (1993), p. 3.
11. Laclau and Mouffe (1985), p. 112.

example can be seen in the present debate (2005–2015) on how to expand wind power in Denmark. The most cost-effective way is to increase the number of onshore wind turbines. From many years of experience, Danish society knows that this can be done if institutional frameworks are established in which neighbors can own shares of the wind turbines and make a profit. Danish society also knows that if neighbors are not involved, they are likely to protest against this solution. In Christensen and Lund (1998), an analysis is conducted of how society, by applying local ownership, has managed to implement wind power in a socially acceptable as well as environmentally benign way.

However, based on the argument that wind power should adjust to the market, the institutional framework for neighbor-owned wind turbines has been abolished and, instead, the government wishes to expand offshore wind farms. These wind farms are not economically feasible compared to onshore wind turbines, and they increase the need for subsidy. However, offshore wind farms correspond perfectly to the institutional framework of existing power companies. In short, the discourse that wind turbines should adjust to existing market institutions leads to the implementation of renewable technologies that are suitable for these institutions. This is the case even if these technologies are not economically feasible compared to alternatives that require the establishment of new organizations and involve neighbor ownership.

Different existing organizations reflect different perceptions of reality. Therefore, they can design project proposals and alternatives that are relevant to these perceptions, but they cannot be expected to design technologically and radically different alternatives. These alternatives have to come from someone else. To illustrate this point, one may refer to the preceding case of Nordkraft (also discussed further in Chapter 8), in which the local radio station asked Nordkraft's managing director if he could *imagine* that the project, which had met a lot of resistance, would not be implemented. The managing director answered that he could not imagine which other alternative one would suggest instead. Alternatives representing radical technological change simply do not form part of the imagination or perception of existing organizations.

However, the explanation for why and how certain choices do not become part of the collective perception is not only related to the discourses of existing power companies. When local citizens and environmental organizations raise Choice Awareness by introducing alternatives representing radical technological change, the organizations representing existing technologies also may respond by using different choice-eliminating mechanisms and strategies.

Choice-Eliminating Mechanisms

Radical technological changes pose a threat to those existing organizations that depend on the technologies to be replaced or diminished. These organizations respond to the threat. Choice Awareness theory argues that a core element in this response is the elimination of choice in the public debate and collective perception.

The existing organizations will execute power to protect their interests. However, in the investigation of the relationship between rationality and power, Flyvbjerg (1991) argued that the most important execution of power can be found and studied outside the scene of formal direct power. Flyvbjerg combined a theoretical approach with a comprehensive case study:

In many cases, pivotal activities are not to be found in the design of objectives, policies, legislation, and plans nor in public participation and formal political decision making in relevant political assemblies. On the contrary, they take place before *any objectives, policies, legislation, and plans have been formulated, in what one may call the* genesis *of planning and policies, and* after *the formal political decision has been made, during the implementation of plans and policies.*[12]

Flyvbjerg distinguished between, on the one hand, *formal planning* and *formal politics*, and on the other hand, *real planning* and *real politics*. With regard to the relationship between implementation and formal and real politics, he pointed out that when important actors cannot implement their wishes through the *formal* political process, they will often seek to do so in the implementation phase by use of *real* politics, typically hidden from an immediate look. The only way to get access to such real politics is by conducting thorough studies of concrete planning and policy-making processes.

As we will see in Chapter 8, the study of concrete planning and policy-making processes reveals that choice-eliminating strategies and mechanisms executed outside the scene of formal power are manifold and take various forms. One form is the simple exclusion of alternatives from the agenda. The exclusion of a natural gas alternative—as in the case of Nordkraft power station in the early 1980s—has already been presented. Another example is the case of Aalborg heat planning in the mid-1980s, in which the municipality simply disregarded an alternative of small CHP plants. This solution did not fit well with the interests and perceptions of the city council and the municipality-owned district heating company. The solution was simply disregarded in the definition of optional alternatives in the public participation phase, initiated by the municipality in accordance with the legal procedures of heat planning.

Alternatives representing radical technological change had to come from the university and local citizens. The case of Aalborg heat planning revealed some interesting choice-eliminating mechanisms and strategies when these

12. Translated from Danish: "De afgørende aktiviteter findes således mange gange ikke i udformningen af mål, politikker, lovgivning og planer eller i borgerdeltagelse og formel politisk behandling i relevante politiske forsamlinger. De findes derimod **før** der overhovedet er noget, som hedder mål, politikker, love og planer, i det man kunne kalde planlægningens og politikkens **genese**, og **efter** den formelle politiske vedtagelse, i planlægningens og politikkens implementering". Flyvbjerg 1991, p. 19.

alternatives were designed and promoted. When addressing the public discussion phase, as already mentioned, the municipality simply left out certain alternatives. When these alternatives were proposed by the citizens, the municipality disregarded them in the comparative analyses. When comparative analyses could no longer be avoided and showed an inconvenient result, new analyses were made. Only the analyses that showed the most convenient result were put forward by the administration to the city council. And when citizens mailed "inconvenient" results to the city council, the content of the analysis was disregarded. Instead, a discussion of the letterhead used was initiated to incriminate the senders.

As just shown, choice-eliminating activities have been executed at many levels and in various forms. Power theory can be used to identify a systematic way of analyzing the different levels at which these activities are practiced. In their book *Silent Control—About Power and Participation*,[13] Christensen and Jensen (1986) described different levels of power and provided an understanding of how and where power is executed when existing organizations influence the decision-making process. The basic idea of the book is to understand how power is executed for the purpose of developing participation strategies. Consequently, their definition of power is quite broad: "Power is seen as the possibilities of actors to attend to their interests in relation to the allocation of goods and burdens in society (material as well as immaterial)".[14] With references to, among others, Robert A. Dahl (1961), Peter Bachrach and Morton Baratz (1962), Steven Lukes (1974), and James G. March (1966), Christensen and Jensen categorized power into four levels: direct power, indirect power, mind-controlling power, and structural power.[15]

The three latter levels of power are of particular interest to the Choice Awareness theory. The execution of power leading to the collective perception of whether alternatives exist and how they should be evaluated often takes place before the scene is even set for the exercise of direct power.

Direct power is executed in a decision-making process, for example, as items on the agenda of a meeting in a board or a city council or in Parliament. As already mentioned, this execution of power is rare with regard to the elimination of choice. The choice-eliminating strategies and mechanisms are typically executed before the mere existence of alternatives leads to the perception of even having a choice. Thus, in the case of the Environmental Impact Assessment procedures (see Chapter 8) in the mid-1990s, the County Council of Northern Jutland was allowed to choose freely from different alternatives to the construction of a new coal-fired power station. According to the legal procedures, they had only to ensure the proper description (and existence) of alternatives, including those suggested in a public participation phase. They were

13. Translated from Danish.
14. Translated from Danish, p. 12.
15. Translated from Danish, pp. 13–14.

not obligated to choose them. However, in general, the legal procedure failed to ensure a proper description of alternatives representing radical technological change (i.e., changes to the institutional set-up of the power companies and the regional authorities), even when such alternatives were promoted by local citizens in the public participation phase. By executing indirect power, the local county eliminated this choice before the item reached the agenda.

With *indirect power*, focus is placed on the execution of power both before and after the official meetings, for example, the decision of what is and is not put on the agenda. It is recognized that not all matters have equal access to the decision-making process. Consequently, powerful interest groups can seek to exclude certain items, or they can seek to influence the implementation in such a manner that the result has other consequences than expected. The execution of indirect power is indeed relevant to the identification of choice-eliminating mechanisms, and the examples are manifold, as we will see in Chapter 8. The examples involve disregarding alternatives and incriminating senders, as already mentioned, as well as claiming that alternatives are based on incorrect technical data, while withholding the "correct" data by referring to "national security". The latter was the situation in the case of the transmission line described in Chapter 8.

Indirect power also involves power being executed after decisions have been made, in the form of not implementing the decisions or implementing something else. The case of Nordjyllandsværket in the mid-1990s represents such a situation. The Danish Parliament had decided on an energy policy, called Energy 21, according to which no new coal-fired power station was needed. Instead, the Parliament decided to implement electricity savings and expand the number of small CHP plants. Still, the power companies, supported by the minority government, succeeded in implementing another coal-fired power station.

At the *direct* and *indirect power* levels, choices are eliminated when it is decided how many and which alternatives the decision body can choose from. Time and resources are limited, and, consequently, someone must choose which alternatives to analyze and describe and which consequences to identify in which way. Moreover, the elimination of choice is executed when it is decided if matters should be discussed, where, and for how long. However, choices are not only eliminated by disregarding alternatives. Choice elimination also has to do with influencing the perception of those who imagine, design, and promote those alternatives. This phase is out of reach of the organizations that represent the existing technologies. Instead, this power is executed at the next two levels.

Mind-controlling power includes the execution of power in such a way that some actors influence other actors' perception of their interests and how these interests can be promoted in a legitimate way. Mind-controlling power and direct and indirect power have in common the fact that they are executed among actors. This is not the case with level four, *structural power*, which is executed through a collective unconscious acceptance of the societal framework constituted by habits, routines, and norms.

At the *mind-controlling* and *structural* levels, Choice Awareness is influenced, among other factors, by the perception and design of the democratic infrastructure, as explained in Chapter 3—for example, the perception of which and how well interests should be represented in key committee work. Another example of mind-controlling power is the discussion of *sustainable energy*, as explained in Chapter 1. Defining sustainable energy in such a way that it includes nuclear and/or coal in combination with CCS can be considered a way to make people who are in favor of renewable energy support and promote nuclear and coal instead.

Structural power can be seen as executed through the presence of the existing institutional set-up. For example, in the case of the Environmental Impact Assessments procedures of the mid-1990s, the choice-eliminating mechanisms were indeed related to the simple fact that the local county council wanted to stick to alternatives within the borderlines of their jurisdiction. And in the case of Nordkraft, the existing power company and the municipality could not perceive and design alternatives beyond the ownership of the power company or the borders of the municipality. Even if they had been able to do so, the implementation would be out of their hands in the given institutional set-up. In those cases, the structural power of the existing institutional set-up influenced the perception of potential alternatives.

In conclusion, it is important to be aware that choices are not only eliminated in the sense that they are erased from the collective perception, but are also eliminated due to the awareness among certain actors that certain alternatives cannot be implemented without introducing substantial changes to the institutional set-up. Therefore, my colleagues at Aalborg University and I have for many years executed the combined design and promotion of *technical alternatives* as well as *institutional alternatives*. We have used the promotion and public discussion of our technical alternatives to identify institutional barriers to be able to design institutional alternatives. In this way, we have for many years involved ourselves in raising choice awareness with regard to technical as well as institutional changes.

The First Choice Awareness Thesis

The theory of Choice Awareness addresses the societal level. As mentioned, it concerns collective decision making in a process that involves many people and organizations representing different interests and discourses, as well as different levels of power to influence the decision-making process. The theory concerns the implementation of radical technological change in society, that is, changes that imply significant institutional reorganization.

With a reference to discourse and power theory, it is assumed that the perception of reality and the interests of existing organizations will often make them seek to hinder radical institutional changes by which they expect to lose power and influence. Choice Awareness theory advocates that one key factor in this manifestation is the societal perception of having a choice or having no choice.

The first thesis of the Choice Awareness theory states that when society defines and seeks to implement objectives implying radical technological change, the influence and discourse of existing institutions will affect the implementation. This impact will hinder the development of new solutions and eliminate certain alternatives and will seek to create a perception indicating that society has no choice but to implement technologies that will save and constitute existing positions. The results of this influence will take various forms, including the following:

- The exclusion of technical alternatives from the debate and the decision-making arenas
- The technical evaluation of alternatives on the basis of methodologies that assess the radical new technology in question as not being relevant to or not complying with the requirements
- The design of feasibility studies in such a way that radical new technologies are assessed as not being economically feasible to society

These forms of influence will typically be based on the applied neoclassical perception that the existing institutional and technological set-up is defined by the market, which works in such a way that it will, by definition, identify and implement the best solutions.

3. RAISING CHOICE AWARENESS

The first Choice Awareness thesis is based on the observation that the collective perception of no choice is often constructed when major societal decisions on energy planning are discussed. As previously described, the mechanisms applied involve both the elimination of technical alternatives representing radical technological change as well as institutional barriers to the implementation. At the structural power level, this will again influence the collective perception of choice.

The theory argues that Choice Awareness is crucial when radical technological changes are at issue. But what can be done about it? The core element is to raise the awareness of the fact that society *does* have a choice. Radical technological change is possible. And since choice-eliminating mechanisms are executed at many levels, the second Choice Awareness thesis advocates that counterstrategies are introduced at the same variety of levels. Consequently, the rise of choice awareness involves the design and promotion of technical alternatives and the use of evaluation methods as well as the design of institutional alternatives. The latter includes both direct public regulation measures and the promotion of a suitable democratic infrastructure.

As already mentioned, I have observed the elimination of choice in many situations. However, I have also experienced how the introduction and description of concrete alternatives can raise the public awareness of the fact that we, as a society, *do* have a choice. Over a period of time, this awareness can lead to institutional changes in such a way that it actually becomes possible for society to choose among relevant alternatives. The recent history of Danish energy planning during four decades is an important example of such a transformation. Danish energy policy has been formed as a result of a process of conflicts. This process has led to the implementation of radical technological changes, and Denmark has been able to show remarkable results on the international stage. This ability to act as a society has been possible despite conflicts with representatives of the old technologies. Official energy objectives and plans have been developed as a result of constant interaction between Parliament and public participation, in which the description of new technologies and alternative energy plans has played an important role. Public participation, and thus the awareness of choices, has been an important factor in the ultimate decision-making process. The conflict-ridden debates should, therefore, be seen as necessary conditions for further improvements of energy initiatives and programs.

Some examples of the influence of this long-term institutional change are presented in Chapter 8. For example, in the aforementioned case of Aalborg heat planning, the promotion of concrete technical proposals led to the identification of specific institutional barriers in the energy taxation structure. As a follow-up on that case, a colleague and I promoted concrete proposals for how to change the Danish energy taxation system to create a situation in which the socioeconomically best solution would also generate the best consumer heat prices.

In the case of Nordjyllandsværket, the promotion of concrete technical alternatives played a role in the understanding of the contradiction between project proposal and the official parliamentary energy policy. Danish society was not powerful enough to avoid the central power stations, which fitted well into the organizations of existing power companies. However, the Parliament was powerful enough to promote small CHP plants more or less simultaneously with the approval of the central power stations. Such a decision brought substantial changes in the institutional set-up of market conditions for small CHP plants. Hereby, the Parliament opened up for investments in small CHP plants with a capacity of more than 1,000 MW in the mid- and late 1990s.

The second Choice Awareness thesis advocates raising Choice Awareness at many levels. Very often step one is to design concrete technical alternatives. These ideas of the Choice Awareness theory are much in line with the recommendations of Mary O'Brian (2000) on replacing risk assessment with alternatives assessment:

Risk assessment is one of the major methods by which parts (corporations such as Monsanto or Hyundai, "private landowners", industrial nations) can act on their wants at the expenses of wholes (e.g., whole communities and countries, or seventh-generation from now) without appearing to be doing so. Risk assessment lets them appear simply "scientific" or "rational" as they numerically estimate whether or how many deaths or what birth defects will be caused, and ignore other regions of human experiences that also matter to people.[16]

16. O'Brian (2000), p. xviii.

Thus, risk assessment becomes one of the ways to justify "one alternative decision".

O'Brian advocated a replacement of risk assessment with alternatives assessment, defined as the evaluation of the pros and cons of a wide range of options. The goal is to replace the assessment of a narrow range of options with the public assessment of a wider range. O'Brian pointed out that this methodology does not reflect the interests of existing institutions. Alternatives assessment is

a simple and sensible alternative, but it is resisted mightily because the consideration of options is a threat to business as usual and business as planned—and often, to established power arrangements.[17]

Like Choice Awareness, the idea of alternatives assessment has also been inspired by processes at the individual level. O'Brian referred to her sister, a psychiatric social worker, who told her that one sign that a client might be suicidal is when the person is convinced that he or she has only one or two options, and both of them are terrible. O'Brian explained as follows:

Replacing risk assessment with alternatives assessment involves the same simple principle. Instead of allowing ourselves to be limited to one or two options that are terrible, we can insist on public consideration of a range of alternatives that seem good for different reasons. We can evaluate these alternatives and choose the one that seems best.[18]

The ideas of the Choice Awareness theory are also in accordance with Groupthink theory. In his books *Victims of Groupthink* (1972) and *Groupthink* (1982), Janis introduced the term *groupthink*, which is defined as the psychological drive for consensus at any cost that suppresses disagreement and prevents the appraisal of alternatives in cohesive decision-making groups. Janis showed how this phenomenon contributed to some of the major U.S. foreign policy fiascos, such as the Korean War stalemate, the escalation of the Vietnam War, the failure to prepare for the attack on Pearl Harbor, and the Bay of Pigs blunder.

Janis used the term *groupthink* as

a quick and easy way to refer to a mode of thinking that people engage in when they are deeply involved in a cohesive ingroup, when the members' strivings for unanimity override their motivation to realistically appraise alternative courses of action.[19]

He described seven symptoms and consequences of groupthink in which the "incomplete survey of alternatives" comes in as number one on the list.[20] Thus, groupthink is very much in line with Choice Awareness theory in general and, in particular, with the Choice Awareness strategy emphasizing the importance of

17. O'Brian (2000), p. xiii.
18. O'Brian (2000), p. 129.
19. Janis (1982), p. 9.
20. Janis (1982), p. 175.

promoting a new corporative democratic infrastructure, which can produce relevant alternatives for the decision-making process (see Chapter 3).

Janis (1982) recommended a number of strategies to prevent groupthink. One of these is the suggestion that

organizations should routinely follow the administrative practice of setting up several independent policy-planning and evaluation groups to work on the same policy question, each carrying out its deliberations under a different leader.[21]

This recommendation is also very much in line with the recommendations of Choice Awareness to promote a better democratic infrastructure, which is explained further in Chapter 3.

In his thesis “Alternatives, Nature and Farming”, Christensen (1998) discussed the human relationship with nature and the perception of alternatives in agriculture. Christensen engaged in the discussion of what is a “real” alternative. For example, is organic farming a real alternative to conventional agriculture? The environmental and nature protection problems of our time require innovative thinking regarding our perception of nature as well as our agricultural practice. According to Christensen, it is not solely a matter of getting new ideas. Alternative visions have to be combined with level-headed and complex analyses. The key issue is to raise the question of how to inspire to a fruitful change in such a way that alternatives are not isolated or end up being another part of the existing systems.

Christensen related to the term *radical change*, which corresponds well to the concept of radical technological change as used when formulating the two theses of the Choice Awareness theory. Christensen discussed radical change regarding alternatives of organic farming: “The proposals intend to unify two goals: social viability and environmental sustainability”.[22] However, Christensen pointed out, “It seems that a focus on social viability very easily may reduce the extent to which environmental problems are taken into account”.[23] Thus, Christensen emphasized the problem of how to implement radical technological changes without adjusting technology to social viability to such an extent that it is integrated into the existing systems and radical changes are not implemented after all. This issue is a core element in Choice Awareness. The four Choice Awareness strategies elaborated in Chapter 3 address exactly such a challenge.

The Second Choice Awareness Thesis

Choice Awareness theory addresses a situation in which society defines and seeks to implement objectives that will imply radical technological changes.

21. Janis (1982), p. 264.
22. Christensen (1998), p. 446.
23. Christensen (1998), p. 446.

The second thesis of the Choice Awareness theory argues that in this situation, society will benefit from focusing on Choice Awareness, that is, raising the awareness that alternatives *do* exist and that it is possible to make a choice. The awareness can be promoted by various means, including the following:

- Promoting the description of concrete technological alternatives in various debates and decisions on new plans and projects at all levels
- Promoting feasibility study methodologies that include relevant political objectives in the analyses
- Promoting the concrete description of public regulation measures to advance new technologies

The advancement of these three promotions can in general be helped by changes in the democratic decision-making infrastructure, which advance the representatives of new technologies.

The concept of Choice Awareness, including the two theses, emphasizes the words *conflict* and *process*. The decision-making procedures, including the definition of alternatives and how these should be assessed, are to be seen as a *conflict*. This conflict is a fight between different interests, influences, and discourses, in which well-established organizations seek not to lose power and influence. Furthermore, it is a *process* over time. Developing societal procedures that allow the design of alternatives, proper assessment methodologies, and good public regulation measures takes time. It is a process, and in this process, it is not important to win every battle; it is important to win the war.

Chapter 3

Methodology

Choice Awareness Strategies

The basic idea of Choice Awareness is to understand that existing institutional perceptions and organizational interests will often seek to eliminate certain choices from the political decision-making process when the introduction of radical technological change is discussed. The counterstrategy is to raise public awareness of the fact that alternatives do exist and that it is possible to make a choice. Becoming aware of choice-eliminating mechanisms is in itself an important part of raising this awareness. Furthermore, Choice Awareness can be promoted by the strategies mentioned in Chapter 2 and illustrated in Figure 3.1. Each of the strategies is elaborated on in this chapter.

1. TECHNICAL ALTERNATIVES

The description and promotion of concrete alternatives is a core strategy in Choice Awareness. It is the essential first step that must be taken to change the focus of a public discussion. Typically, "the one and only" solution presented, such as another coal-fired power station without combined heat and power (CHP) production, is reckoned to have a negative impact on pollution and energy efficiencies. However, the general perception seems to be "If this is the only alternative, so what?" Society has no choice but to choose it. However, if someone succeeds in putting forward and promoting a concrete alternative, two changes take place in this process. First, it becomes obvious that society indeed does have a choice. Second, the focus of the discussion changes from "Yes, it is bad, but so what?" to "Which of the alternatives is the best solution?"

When a second alternative is presented, the risk arises that even though this alternative is considered the best solution, it cannot be implemented for various institutional reasons, such as organizational and economic barriers. In this case, the concrete identification of specific barriers becomes important in relation to further discussions. Again, one should remember that the implementation of renewable energy systems is a long-term process. It is not important to win every battle, but it *is* important to win the war.

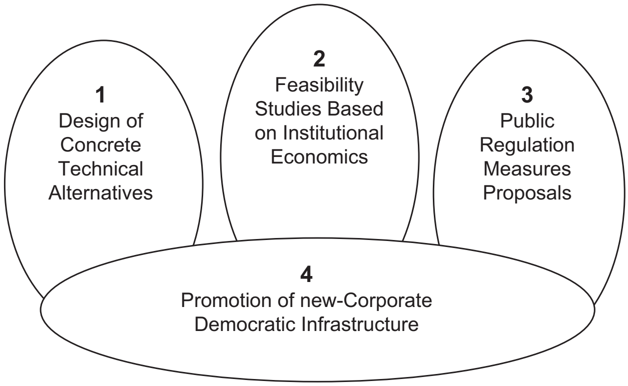


FIGURE 3.1 Choice Awareness strategies.

But how should good, concrete renewable energy system alternatives be designed? And which counterarguments should be considered? In the book *Public Regulation and Technological Change,*[1] Lund and Hvelplund (1994) described some of the arguments that the introduction of an alternative may face. Our analysis is based on the cases of Nordjyllandsværket and the transmission line (see Chapter 8), and these descriptions are called "the anatomy of *half-true* statements".

Half-true statements can be grouped into the following categories:

The half-true statement of an incorrect context: This is a statement concerning one element put into a context that is not in accordance with the context assumed by the addressee. One example from the Nordjyllandsværket case is when the chairman of the board of the power company ELSAM informed a number of local politicians that the planned power station would be feasible and would improve the environment. This statement was half-true because it did not make clear that it was valid for only certain special cases, which were not in accordance with the implementation of the governmental energy policy. This type of statement will typically be seen as a comparison of the present solution and the new alternative but without mentioning other possible—and better—alternatives. For example, it might be reported that a new coal-fired power station is better for the environment than an old one, but other alternatives that may be even better for the environment are not mentioned.

The half-true statement of the incorrect time dimension: This statement disregards dynamics in economic cost structures and technological innovation. For example, in the Nordjyllandsværket case, the power companies wanted to build two power stations instead of one to achieve discount advantage in relation to the investment costs. In this case, the energy authorities informed the politicians that surplus capacity would have no influence on the

1. *Offentlig Regulering og Teknologisk Kursændring. Sagen om Nordjyllandsværket.*

electricity demand without considering the change in cost structure that was likely to be produced by such overcapacity.

The half-true statement of non-equalized evaluation: This statement promotes only advantages and disregards disadvantages. The Nordjyllandsværket case contained several examples of this. For example, the discount of 300 million DKK achieved by buying two power stations was intensively promoted, while the disadvantage of losing technological innovation (better efficiencies) by building the second plant now instead of later was disregarded. We calculated this disadvantage to correspond to approximately 700 million DKK (see Chapter 8).

A half-true statement may be used by "manipulators" to promote a solution. From their point of view, a good half-true statement is characterized as a "part" of the truth that can be communicated and understood easier than a comprehensive view of the truth itself.

It is easy to understand that a new power station is better than an old one, so the environment will benefit from a replacement of the old plant. It is much more complex to explain that, for example, a new power station was not even necessary in the case of Nordjyllandsværket. This explanation involves detailed discussions on the forecasting of demands and small CHP plants and the technological advantages of waiting until the need arises. It is also easy to understand that surplus capacity does not influence the electricity demand. It is much more complex to explain that the dynamics of politics and economics in a situation of surplus capacity typically result in economic barriers to the implementation of new conservation and electricity-saving technologies. It seems to be a good idea to get a discount by buying two power stations. It is much more complicated to explain that, some years into the future, this technology will be old compared to the ones accessible when the need really arises.

The construction of a good half-true statement is to some extent built into the institutional and organizational set-up of existing interests. Typically, one can observe a certain division of labor between the administrative and the managerial and political levels. For example, in the case of Nordjyllandsværket, the planning department of the power company produced technical analyses that were correct on the given premises. Thus, the department made an assessment of the economic feasibility of replacing old power stations with new ones compared to prolonging the lifetime of the old ones. These analyses led to the statement that based on certain assumptions, it would be a good idea to invest in two new power stations. Subsequently, the communication department and the chairman of the board generalized the statement in such a way that the public understood that the investment in two power stations was good for the environment in all situations and was implemented in line with the governmental energy policy. Politicians then used the same argument in favor of the power station. The energy authorities and the power company's planning department remained passive and let this generalization pass without reacting.

The preceding story forms a good introduction to why and how good alternatives should be designed. A major purpose is to avoid the dominance of half-true statements. By introducing a concrete alternative, a statement such as "new coal-fired power stations are better than old ones" will have to argue against even better alternatives. By introducing concrete alternatives, focus shifts from accepting bad solutions, because society has no choice, to discussing various options, for example, which choice to make. However, the introduction of alternatives should expect resistance from existing organizational interests. Consequently, the specific design of alternatives does matter.

Based on the experience from the many cases discussed in Chapter 8, the following guidelines can be defined:

1. *Alternatives must be designed in such a way that they are equally comparable in terms of the central parameters, such as capacity and energy production*. Otherwise, they can easily be disregarded. Energy savings may be included if saved capacity is calculated. If the main proposal may lead to overcapacity, which is actually often the case regarding large power stations, the alternative should still be designed with the same capacity. However, the costs of creating overcapacity in the main proposal should be illustrated by distributing the investment in capacity over a period of time in the alternative. The calculation of investment should also include the benefit achieved by cost reduction and maybe even the benefit achieved by expected technological innovation in terms of better efficiencies or lower costs.
2. *Elements from all three aspects of renewable energy systems should be involved*. This includes savings in demand, efficiency improvements in supply such as CHP, and renewable energy sources. Thereby, the alternative is typically not an option that exists only once. By including all aspects, it becomes a generalized example of the radical technological change represented by the transition to renewable energy systems. If the alternative was only to replace coal by biomass, one could easily argue that this is not a long-term solution. The resources of biomass are not sufficient, and soon society would have to build a new coal-fired plant anyway. However, by combining all of the elements of renewable energy systems, the alternative will, in principle, be able to replace all future coal-fired plants.
3. *The alternative should be designed in such a way that the direct costs correspond to those of the main proposal*. This aspect actually complies very well with the idea of including all three elements of renewable energy systems, since savings in demand are typically very cost-effective. Moreover, cost reduction may be achieved by postponing some of the investments instead of establishing overcapacity.

By designing the alternative in such a way that the capacity and energy production (including savings) and the direct costs of the two solutions are the same, it may be possible to focus on a discussion of the issues in which the main proposal and the alternative differ. This involves comparing the alternatives with the main proposal in terms of all the central parameters: environment, local jobs, balance of payment, rural development, technological innovation, and industrial development. How to design feasibility studies regarding such parameters is discussed in the next section.

Typical examples of the design of alternatives are cases like Nordjyllandsværket (Denmark), Lausitz (Germany), or Prachuap Khiri Khan (Thailand). In all of these cases, the main proposal was to build a new or to expand an existing coal-fired power station without considering the benefits that could be achieved by increasing CHP production. Moreover, the proposed power stations were typically very large, and overcapacity was a general result.

As long as the main proposal is the only alternative presented, the problem of not integrating CHP is unclear. However, in all three examples, substantial heat production was left to heat-alone boilers. When designing an alternative of small CHP plants, the heat-alone boilers were included in the discussion and the fuel efficiency improvements of CHP were shown. Consequently, in all cases, it was possible to design better alternatives that were still comparable in terms of direct costs if fuel efficiency improvements were included.

2. ECONOMIC FEASIBILITY STUDIES

Choice Awareness theory is based on the basic assumption that in societal decision-making processes involving radical technological change, existing institutional interests will try to influence the process in the direction of no choice. This influence involves the elimination of technical alternatives from the agenda, as well as the use of feasibility studies based on methodologies and assumptions supporting existing organizational interests. Consequently, Choice Awareness includes the awareness of how feasibility studies are and should be carried out.

This section is based on the book *Feasibility Studies and Public Regulation in a Market Economy* by Hvelplund and Lund (1998a) and two chapters from the book *Tools for Sustainable Development* (Hvelplund, Lund, and Sukkumnoed 2007). As will be discussed further in the next section, the theory of neoclassical market economics is based on a number of assumptions that are not fulfilled in real-life market economics. However, the critique of neoclassical-based methods of this book is directed toward their real-life application. It is not of decisive importance whether this critique is valid for theoretically correct applications. Consequently, the term *applied neoclassical economics* is used and defined as neoclassical-based methods, such as cost-benefit analyses and equilibrium models, when applied to existing market economies. This is seen as opposed to theoretically correct methods when applied to market economies that fulfill the theoretical assumptions of a free market. Every market economy is formed by a number of market institutions. In applied neoclassical economics, the analysis of those institutions is usually outside the scope of the analytical model, and these institutions are therefore, in practice, treated as static or unchangeable. But, as explained in Chapter 2, in situations of radical technological change, it is very important to address the issue of changes in the institutions in which the market is embedded.

Neoclassical economics are based on the concept of a *free market*. The theoretical *free market* requires a number of institutional preconditions, such as many mutually independent suppliers of a product, many mutually independent buyers of a product, full information regarding quality and prices of available products, agents on the market acting with rational behavior, sellers who maximize profits, and buyers who maximize utility.

When these and other conditions are fulfilled, it can be argued that if all consumers and producers act to optimize their individual profits, the market will define what is best for society. The market becomes a democratic place, where free and rational buyers, who are well informed about their options, buy the goods they want. Therefore, when the previously mentioned institutional preconditions are present, any interference with this free-market process can be regarded as non-democratic.

It is important to emphasize that a *free market* is not a market without public intervention but a market where public regulation in a decisive way acts to establish and maintain the institutional preconditions of the free market. Most market economies are mixed economies consisting of a private and a public sector. In the private sector, an exchange takes place on the market, based on supply and demand, between sellers and buyers of goods, labor, and capital. The public sector redistributes incomes and produces goods and services, mainly outside the market.

In applied neoclassical economics, the market is usually considered a *free market*. Activities on the market are the result of well-informed, free, and rational agents, each optimizing its utility function, and no private regulation influences the allocation process. In neoclassical economics, the relationship between the public sector and the market sector is usually one where the state autonomously constructs the laws and institutional framework of the market via public regulation measures; taxes, goods, and services from the public sector are defined as neutral from an allocation point of view.

Consequently, in applied neoclassical economics, the public sector is defined as neutral with regard to the effects of regulation on the market processes. The combination of the two premises—the private and the public sectors do not distort the allocation process and the market process is governed by free, rational, and well-informed actors—means that the production at any given time can be regarded as optimal. This premise of optimality is a precondition in most econometric models inspired by neoclassical economic thinking when these models are used for planning purposes by macroeconomists.

From the premise "We are living in the best of all worlds", we can deduce that any change away from this optimum represents socioeconomic losses to society. For instance, all costs related to policies of reducing greenhouse gas emissions or increasing the share of renewable energy are considered extra societal costs in all computations. In the case of the IDA Energy Plan 2030 (see Chapter 7), an example is given of the discussion of such computations. In these econometric models, systematic institutional mistakes do not exist in the economic process. Meanwhile, in real life, this premise is not fulfilled. Therefore, it is necessary to see the economy of a country or region as an institutional economy, in which the present situation may very well not be optimal at all.

In the following, some guidelines are presented for performing feasibility studies in a situation of radical technological change. The guidelines refer to issues involving environmental concerns and have technological innovation and institutional change as their main objectives. Therefore, the scope and focus of these feasibility studies are much broader than in the conventional cost-effectiveness and cost-benefit analysis approach.

The feasibility study should include the design of feasible technological alternatives; an evaluation of the social, environmental, and economic costs; an overview of the innovative potential of these alternatives; and an analysis of the institutional conditions that influence the implementation of the alternatives. Since these feasibility studies can be applied to both public and private decision making, one should distinguish between socioeconomic and business economic evaluations. In socioeconomic feasibility studies, the question is whether a project is feasible to society as a whole, whereas in business economic feasibility studies, the goal is only to determine whether a project is feasible from a business perspective. However, companies can also apply the criteria of socioeconomic feasibility studies to achieve a better understanding of the impact of their decisions on society as a whole.

Thus, any feasibility study or public regulation activity should begin with a series of specific analyses of the institutional and political contexts of the given project in the country or region in question. Therefore, feasibility studies should not be conducted on the basis of the neoclassical assumption of a society placed in an economic optimum. It is not an easy task to perform these institutional analyses. It is, however, an interesting task that may result in the identification of projects that have not been implemented under present institutional conditions, despite being both economically and environmentally feasible from a socioeconomic point of view.

In situations of radical technological change, new technologies must be developed, and investments in these technologies must be made while they compete with and are compared to well-established existing technologies. More importantly, these competitions or comparisons never occur in the ideal free-market situation but are mainly embedded in certain political and institutional frameworks. These frameworks are usually created over time and thus favor old technological schemes. The introduction of a new technology is, therefore, far more than an issue of cost-benefit calculations. It requires a thorough examination of the total construction of systems; that these systems are connected to the broader objectives and conditions of society; and, finally, that the idea of just maintaining old technological systems instead of investing in newer and cleaner ones is challenged.

Therefore, in such situations, feasibility studies are not simply cost-benefit calculations that assume that the present institutional conditions will lead to the best of all worlds. When designing feasibility studies, one must understand that society often does not find itself in an economically optimal situation. Furthermore, it is important to recognize that other possibilities may exist that will benefit both the economy and the environment. Feasibility studies should, therefore, be designed to identify such possibilities as well as the institutional policies that will make it possible for visionary politicians to implement them. It should also be understood that because of their significant impacts on the development of different technologies, feasibility studies are mostly subject to influences or pressures from different political and economic interests. It is important to be aware of this and to prepare an integrative, communicative, innovative, and transparent study process to ensure that the study groups and society in question will not be trapped in the dominant technological schemes and interests. In short, feasibility studies aim to serve as an effective social learning tool that can be used for overcoming these institutional and political barriers and pave the way for radical technological change.

The preceding conclusions regarding the present technical and institutional situation lead to the following guidelines on the design of feasibility studies:

- Start by making a systematic analysis of the decision-making context: Who will use the feasibility study and for which purpose? Which relevant political objectives should be included in the study? Make sure to design the concrete study in such a way that it will provide relevant information in relation to the actual context.
- Seek to have an open political process in the discussion of methodologies and parameters. Raise public awareness of the fact that feasibility study methodologies form part of the study itself.
- Perform analyses with a very long time horizon to find the best solutions independent of existing technological systems.
- Analyze the bindings of existing technological systems. This is particularly important in case overcapacity is found in the existing system. For example, a power system with overcapacity tends to either result in energy prices close to the short-term marginal costs or lead to pressure from the energy companies on the political process, urging the politicians to protect these companies from the competition of newer technologies.
- Analyze the links between the economics of a project and future technological changes. For example, if we deal with renewable energy, what happens to the economics of solar heating systems in a system with a high share of nuclear power or a system with a high share of CHP? This may be designated a *technical sensibility analysis*.

- Analyze the links between the economics of the project and the legislation needed to make it feasible. For example, what happens if the rules ensuring the right to sell electricity to the public grid are abolished? What happens if economic policy results in increased interest rates? This may be designated an *institutional sensibility analysis*.
- Analyze the links between the institutional sensibility analysis and the political process. For example, which agents on the energy market have the financial and political motivation to "kill" newcomer technologies? Can any counterforces be defined that can support newcomer technologies? How can the political balance of power in the sector in question be described? Which political scenarios can be developed and what effects will they have on the particular project? This is designated a *political sensibility analysis*.

3. PUBLIC REGULATION

Successful public regulation measures to implement radical technological change cannot be designed on the basis of the aforementioned preconditions of applied neoclassical economic theory. The main problem is that the necessary technical solutions often require new organizations and new institutions. In general, the applied neoclassical model considers the institutional conditions as given and does not consider them to be modifiable via public regulation. It is essential to distinguish between the *free market*, as previously described, and the *real market* with its institutions at a given place and a given time.

The *real market* is the market with its specific institutions as they exist in reality and as they relate to private market power, public regulation, infrastructure, accessibility of information, business structure, and so forth. This market very often has a considerable level of private regulation. In particular, the traditional energy supplies are usually monopolistic or oligopolistic, with one or only a few suppliers of given goods. Even when many suppliers are on the market, they are often interconnected through ownership relations and are therefore not mutually independent. Information is frequently kept secret by referring to commercial interests, despite the fact that full information and openness are preconditions for well-functioning free markets.

All in all, the *real market* does not fulfill the institutional preconditions of the *free market* described in economic textbooks. The interplay between the *real market* and the *free market* is often one of ideology, where the strongest actors on an oligopolistic *real market* use the ideology of the *free market* to argue for no public regulation without removing their own private regulation of the market. In the world of reality, the argument "let the free market decide" is synonymous with the sentence "let us decide". "Us" means the strongest actors on an oligopolistic market with a few dominating companies.

Furthermore, the *free-market* premise of the public sector is neutral in the sense that market allocation processes are not fulfilled. It seems obvious that the use of public funds for education, roads, harbors, defense, and medical care has different effects on the direction of market processes. A high level of infrastructure investments in roads will support the economic sectors linked to the car industry. Military expenses support economic sectors linked to military projects. The examples are infinite and, consequently, the premise that the activity of the public sector does not influence the direction of the market processes is not valid.

Thus, even if the market sector was "free" in the sense described in economics textbooks, the market would still not be free from the interference of the public sector. Therefore, it can be concluded that in the real-market world, some form of either public or private hierarchal regulation will always take place. Regulation is defined as any organized purpose directed to influence the framework of the market and the organization of cooperation on the market.

When designing public regulation measures, it therefore becomes important to distinguish between socioeconomic feasibility studies, where the purpose is to examine whether a given project is feasible from a societal point of view, and business economic feasibility studies, where the purpose is to examine whether a given project is economical from the point of view of a specific company. Figure 3.2 shows the relationship between business economy, socioeconomy, and public regulation on a given market in the case of capital-intensive technologies with a long technical lifetime.

Figure 3.2 shows that in the present situation ("Situation I"), specific market conditions and a specific legislation can be identified ("Market Economy I" and "Public Regulation I"). Typically, under present conditions, existing technologies are favored and will turn up as the most feasible alternative in a business economic evaluation, while the economy of alternatives of radical technological change may be bad from a business economic point of view ("Business Economy I"). Nevertheless, socioeconomic feasibility studies ("Socioeconomy I") may show that the development and investment in new technologies are feasible from a societal point of view.

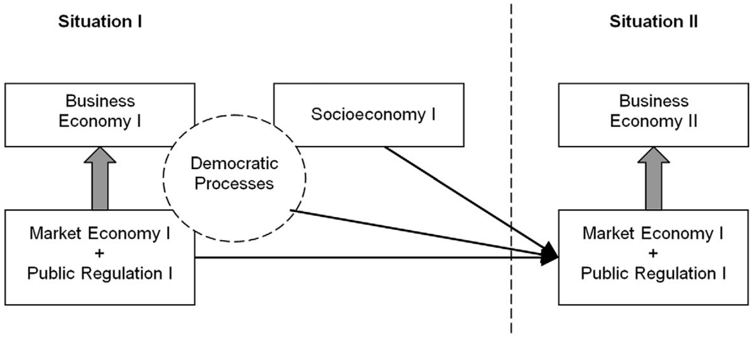


FIGURE 3.2 The relationship between business economy, socioeconomy, and public regulation on a given market. Source: *Hvelplund, Lund, and Sukkumnoed (2007).*

In this case, what is good for society is not good for business, and the situation should then be discussed by the democratic institutions (the dotted circle). Eventually, these discussions may lead to the development and implementation of a new regulation strategy (“Public Regulation II”). This should ensure that the best solution from the point of view of society also becomes best for business, as a new business economic strategy (“Business Economy II”) is established with the same priority as “Socioeconomy I”. Now an ideal situation is identified in which the market companies will act in accordance with what is considered best for society.

In “Situation I”, a company that wants to evaluate alternatives of radical technological change should carry out business economic feasibility studies (“Evaluate Business Economy I”) to estimate the economic consequences under current institutional and technical conditions (“Market Economy I” and “Public Regulation I”). But it is also recommended that the same company should perform socioeconomic feasibility studies (“Analyze Socioeconomy I”) to evaluate the socioeconomic consequences of potential future actions implemented by the government. In this way, a company may be able to identify in advance the types of changes in public regulation (“Public Regulation II”) that the government could introduce.

The government should carry out socioeconomic feasibility studies (“Analyze Socioeconomy I”) to develop an environmental policy that pursues the goals of society. However, it is also recommended that the government should conduct business economic feasibility studies (“Analyze Business Economy I”) to understand the calculations made by companies under the given market conditions. Consequently, both business and socioeconomic feasibility studies are important and should be conducted by both governmental institutions and private organizations. Several successful examples can be reviewed from Hvelplund and Lund (1998a), especially the cases of wind energy development and CHP district heating systems in Denmark. The feasibility studies of these cases clearly show the overall benefits that can be achieved by Danish society. They encourage the Danish government to introduce various public regulation measures that will lead to the emergence and expansion of new technologies and industries and provide several socioeconomic benefits.

Similar studies have been made of the three Baltic countries regarding the replacement of, among others, nuclear and central power stations based on oil shale by CHP generation (Lund, Hvelplund, Kass, Dukalskis, and Blumberga 1999; Lund, Hvelplund, Ingermann, and Kask 2000; Lund, Šiupšinskas, and Martinaitis 2005; Rasburskis, Lund, and Prieskienis 2007). In all cases, it has been shown how the countries, from a socioeconomic point of view including job creation and the influence on the balance of payment, would benefit from CHP, whereas from a business economic point of view, it would not pay for companies to invest in CHP under the present public regulation conditions.

A similar analysis was made in the case of the European Communities as a whole in the article “Energy, Employment and the Environment: Towards an Integrated Approach” (Lund and Hvelplund 1998). The study uses the European Union (EU) figures of supply and demand of the late 1990s as a reference point.

As a result of increasing demands and decreasing reserves in the EU, the imports of fossil fuels from other countries are expected to increase.

Following this, the article proposes an alternative composed by a number of technically feasible measures. The aim is to improve energy efficiency and assist in the realization of the EU's CO_2 emissions reduction target of the late 1990s and to improve energy security. The technically feasible measures include 20 percent savings in demand, a 50 percent increase in CHP, and a 10 percent increase in wind power. If adopted, these measures would result in a 25 percent reduction of CO_2 emissions in the EU, compared with the level of 1990. It would also lead to fossil fuel imports 50 percent lower than those predicted at that time.

Moreover, through these measures, the EU would be able to improve its possibilities of job creation without a significant impact on the EU balance of payments. The application of the proposed measures would create around 1.5 million jobs in Europe from 2000 to 2010, because of the construction work required. The balance of payments would initially be affected by this phase of investment in new energy technologies, although this effect could be minimized by subsidizing EU suppliers of these technologies and associated services. Furthermore, a positive net effect would develop as the imports of fuel would decrease.

This article further points out that the relative labor force in Europe was expected to decrease, so it would be easier to explore these opportunities at that time than in the future. The aim of reducing CO_2 emissions and improving energy security measures, such as those proposed in the article, will have to be explored at some point. The article concludes by posing the question "Why wait until 2010 to solve the problems when the EU at that time is likely to have higher CO_2 emissions, higher fuel imports, and possibly a smaller labor force?"

Another example of what can be gained by public regulation when making both socioeconomic and business economic feasibility studies is the case of electric heating conversion in Denmark, as described in the article "Implementation of Energy-Conservation Policies: The Case of Electric Heating Conversion in Denmark" (Lund 1999a). This article analyzes which kinds of public planning, regulation, and initiatives are suitable for the implementation of energy conservation policies. The case of electric heating conversion in Denmark illustrates a number of general problems and demonstrates which radical technological changes are needed to implement the political objectives of CO_2 reduction. The case also provides an example of how public regulation can deal with those problems.

First, it must be understood that the implementation of CO_2 reduction policies is characterized by a change in technology. This change requires not only minor technological modifications but also large organizational changes that may include the establishment of completely new organizations. Second, the existing institutional set-up is strongly influenced by existing organizations, and these are closely linked to the old technologies that will no longer be needed.

Therefore, the implementation of new technologies represents a challenge to public regulation. On the one hand, it must be expected that it will meet resistance from representatives of the old technologies; on the other hand, it must initiate the establishment of new institutional set-ups. In the case of electric heating conversion in Denmark, these barriers have so far been overcome partly by introducing a mixture of numerous, differentiated, and multipurpose public regulation instruments and partly by changing strategy in terms of implementing the "least-feasible" conversions first, thereby avoiding conflicts with the old technologies. The specific details of this case are described in Lund's (1999a) article.

The design of public regulation measures based on concrete institutional economics is not only relevant when radical technological change is in question. The California energy crisis in the summer of 2000 and spring of 2001, during which the electricity supply was not capable of meeting the demands and electricity prices increased dramatically, raised the question of whether deregulated markets can ensure security of supply (Clark and Lund 2001). California had to confront the basic issue of whether a public good like electricity supply could be left to the *free market* or if the government should play an active role in certain infrastructure sectors, such as the energy sector. Clark and Bradshaw (2004) presented a strategy to avoid such crises in the future, emphasizing the point that both government and industry need clear, concise, long-term-oriented, and consistent market rules, standards, codes, and operating protocols to achieve the goals of sustainable society and business. Also, in the identification and design of market rules, one can benefit from analyzing the concrete institutional market conditions.

4. DEMOCRATIC INFRASTRUCTURE

The three previously mentioned strategies deal with the issues of describing concrete technical alternatives, using suitable feasibility studies, and designing proper public regulation measures. However, *who* should do all this? It is clear that society cannot expect such initiatives to come from existing organizations that depend on existing institutional set-ups. Someone else has to do it, but *who*? The principal answer is the representatives of future societal interests and the representatives of potential new technologies. These representatives must be found among citizens, nongovernmental organizations, small emerging companies, and politicians who are involved in public decision making.

However, it is important to realize that public decision making does not occur in a political vacuum. The decision-making process is shaped by various political and economic interest groups in society who strive to protect their profits or pursue their values. When seeking the implementation of radical technological change, it is therefore important to be aware that, typically, existing technologies are well represented in the democratic decision-making infrastructure, whereas potential future technologies are weakly represented, if represented at all.

In 1995, Hvelplund, Serup, Mæng, and I (1995) described and analyzed the democratic infrastructure of Danish energy planning at that time. Based on these descriptions, we proposed certain changes to achieve a better fulfillment of political renewable energy objectives in a book that defines the terms *old-corporative* and *new-corporative* regulation. *Corporative* indicates that in any mixed-market economy, the authorities typically cooperate with the representatives of different technologies.

The analysis revealed that the Danish regulation was "old-corporative" in the sense that the authorities at all levels favored the old technologies, while the representatives of new technologies experienced difficulties in being heard. This old-corporative regulation was particularly visible in the committees who conducted the technical and economic analyses and provided information to the political decision making. These committees always seemed to include many representatives from power stations and natural gas and district heating companies. None or very few, however, were recruited from the renewable energy industry or from independent environmental and energy efficiency organizations.

Unfortunately, meetings behind closed doors were also characteristic features of the old-corporative regulation. The authorities and the representatives of the old technologies would not allow the public to know what was going on. Indeed, the public was not informed until after the decision was made. As part of the analysis, we asked to see documents from the work of three very important committees of the early 1990s, namely, the Electric Heating Conversion Committee, the Electricity Strategy Committee, and the High Voltage Transmission Line Committee. In all three cases, the result was the same. The doors remained closed until the committees' work was finalized. The public was not allowed to interfere but was informed when the decision had been made.

In accordance with Danish law, the public had the right to be informed of a dialog between different bodies of authorities and private companies, such as utilities. Consequently, the public had a legal right to see documents, which were passed on from one authority to another or to private companies. However, to be able to make this dialog in private, the authorities defined new "autonomous authorities", including representatives from both the authorities and the utility companies and "personal members", who kept their "personal" papers in the archive of these authorities. These "personal" papers, the authorities argued, were not part of the legal act. This practice was approved by the appeal authority: the Danish ombudsman institution. In some cases, the authorities could not manage to distinguish between all of the "autonomous authorities" and "personal members". In these cases, the authorities had to apologize, and their apology was accepted by the ombudsman. However, no measures were taken to hinder such a procedure from ever happening again.

The representation of the committees could be seen in the results. One example is the Combined Heat and Power Committee from 1985, which is described in detail in Hvelplund, Lund, Serup, and Mæng (1995) and Hvelplund (2005). The job of the committee was to identify the potential for small CHP plants in

Denmark. The committee concluded that the potential was so small that it was of no interest or importance, that is, technical potential of 450 MW. However, time has shown that the potential was indeed much larger, since already a few years later more than 2000 MW was implemented. Other important examples are documented in Hvelplund, Lund, Serup, and Mæng.

Old-corporative regulation makes both the authorities and society blind to the potential of new technologies. Practice makes it difficult to implement radical technological changes such as renewable energy systems. As a consequence, we advocated the replacement of old-corporative regulation with new-corporative regulation in Denmark in 1995. Among other suggestions, we proposed that representatives of new technologies should be involved in committee work at all levels.

The preceding example illustrates how important it is to pay attention to the democratic infrastructure when society seeks to implement radical technological change. Consequently, a focus on old-corporative versus new-corporative regulation becomes a very important part of the Choice Awareness strategies. Changes in the democratic infrastructure may be the key to initiating the fulfillment of the three other strategies, namely, to promote the description of alternatives, to conduct suitable feasibility studies, and to present concrete proposals for public regulation measures.

5. RESEARCH METHODOLOGY

According to the Choice Awareness theory, as described in Chapter 2, one cannot expect organizations linked to existing technologies to initiate and promote radical technological changes. It does not form part of their perception and interests. Proposals representing such changes have to come from someone else. Accepting this fact has an impact on the development of strategies to raise Choice Awareness, as described in the previous sections of this chapter, as well as an impact on the research method one has to apply.

As a researcher, one cannot expect to be able to observe all the many facets of choice-eliminating mechanisms if no one puts forward any alternatives representing radical technological change. Furthermore, one cannot expect such alternatives to emerge by themselves. Therefore, the Energy Planning research group at Aalborg University has developed a research method, in which we, on the basis of our expertise in the energy field, design and promote concrete technical alternatives as well as coherent institutional alternatives. For many years, the group has involved researchers with technical as well as socioeconomic expertise. This enables our group to construct, design, and promote alternative energy plans, which are described both technically and in terms of their socioeconomic impacts.

Furthermore, we often contribute to the public debate with suggestions regarding public regulation at the socioeconomic level. Our energy plans and suggestions are published and discussed in public with the public administration at the national and municipal levels as well as with different energy companies.

Members of the group have developed and used this research method since 1975 and have made alternative energy projects and plans for Denmark and its regions, as well as applied the method to other countries.

The aim of this method is twofold. First, we wish to increase the number of technical and societal possibilities in general, which are sometimes blocked by economic and politically vested interests. In this way, we seek to fulfill our "public service" obligation as employees of a public university. Second, this research method can generate new information about the dynamics of society because we have established a socioeconomic experiment by introducing discussions that may otherwise not have taken place.

This research method has been applied to all the cases described in Chapter 8. Without applying this method, we would probably not have been able to do our research. For example, in the case of European Environmental Impact Assessment (EIA) procedures in Denmark, our aim was to examine whether the Danish implementation of EIA would ensure a thorough examination of alternatives representing radical technological change. However, the authorities had no legal power to require it, and the power company had no motivation for proposing such alternatives. The situation made it unlikely that cleaner technology alternatives would even be put on the EIA agenda. Consequently, our research method included a participatory component, by which we introduced renewable energy technology alternatives to the EIA authorities (the county). Furthermore, we filed complaints to the Nature Protection Appeal Board when we felt that our alternatives were not examined properly by the council authorities.

One could describe our method as "questioning" by introducing technical alternatives and institutional alternatives followed by subsequent complaints. In the preceding example, the different EIA authorities reacted and, in this way, provided answers to our "questioning". By this method, society received important information on how EIA authorities in practice react to the proposal of alternatives. Moreover, awareness was raised of the fact that cleaner technology alternatives did exist and it was questioned why they were not implemented.

When applying the research method to our involvement in different cases, we have used the steps shown in Figure 3.3.

Step 1: To identify and design relevant technical alternatives. These alternatives have typically been related to the fulfillment of certain political goals. The identification of relevant goals very often includes a combination of energy policy objectives and economic objectives. Energy policy objectives often comprise energy security, environmental protection, and the promotion of renewable energy, while economic objectives typically comprise economic growth and, depending on the economic situation, job creation, balance of payment, innovation, and industrial development. One may refer to well-defined parliamentary goals or introduce other goals into the discussion.

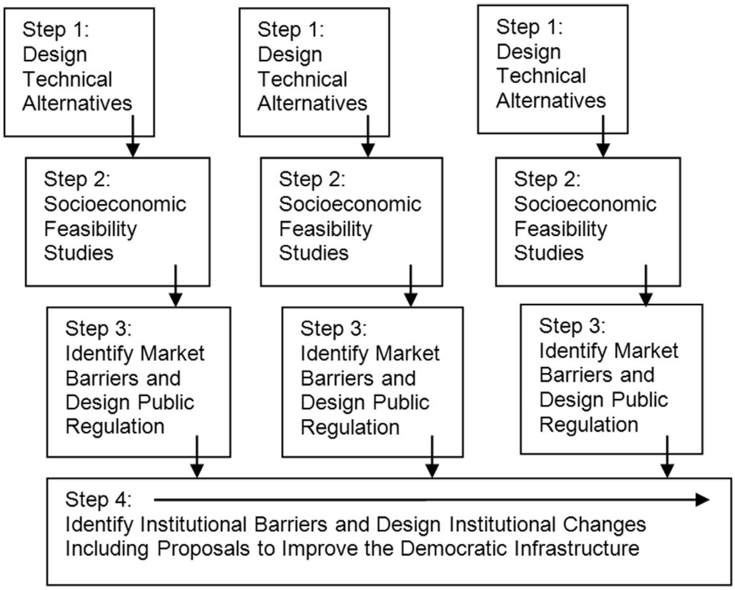


FIGURE 3.3 Step-by-step research method. Technical alternatives and socioeconomic evaluations lead to the identification of, first, market barriers, and second, other institutional barriers.

Step 2: To conduct socioeconomic feasibility studies that can provide relevant information in terms of defining which of the alternatives will be able to fulfill the political goals in the best way. Such information is typically hard to achieve by applying methods such as cost-benefit analyses and macroeconomic equilibrium models based on applied neoclassical economics. Instead, the methods based on what has here been defined as concrete institutional economics are recommended.

Step 3: To identify market economic institutional barriers to the implementation of socioeconomic least-cost solutions (i.e., the alternatives that can best fulfill the political energy policy and economic objectives). These barriers can be distinguished from others by making business economic feasibility studies and comparing the results of these to the results of the socioeconomic studies. Part of this step is also to make concrete proposals for short-term public regulation measures (changes in taxes, subsidies, financing options, energy sales, and connection rules and agreements).

Step 4: To identify further institutional barriers of a more general nature, such as the lack of proper organizations, the lack of knowledge, or the lack of institutions providing relevant information for the decision-making process, and design proposals for the long-term institutional changes in organizations and in the democratic infrastructure. In our case, step 4 has been carried out by using inputs from several cases.

Chapter 4

Tool

The EnergyPLAN Energy System Analysis Model

This chapter deals with the development of energy system analysis tools and methodologies that are suitable for the design and evaluation of renewable energy system alternatives. The specific purpose of this chapter is to present the energy system analysis model EnergyPLAN and describe how to use the model for the design of relevant alternatives. In Chapters 5–7, this model is used for the analysis of renewable energy systems and alternatives.

The EnergyPLAN model is an input/output energy systems analysis model that has been developed and expanded on a continuous basis since 1999. It is deterministic and aims to identify optimal energy system designs and operation strategies using hourly simulations over a 1-year time period. The model analyzes national energy systems on an aggregated basis and emphasizes the evaluation of potential synergies between the different subsectors. Thus, the model involves hourly balances of district heating and cooling as well as electricity and gas grids. It also includes a wide range of cross-sector technologies such as heat pumps, combined heat and power (CHP) plants, electrolyzers, and electric vehicles as well as gasification, hydrogenation, and co-electrolyzer units. The model is a freeware that has been widely used in different countries across the world. In this chapter, EnergyPLAN is described and compared to various other energy system analysis models.

First, this chapter presents some overall considerations for the use and construction of models for the purpose of designing alternative energy systems. The overall understanding of how, when, and why such specific descriptions of alternatives are needed was discussed in Chapters 2 and 3 with regard to Choice Awareness. In this chapter, these issues are examined in the context of the design of energy system analysis models and concrete technical alternatives based on renewable energy technologies. This methodology distinguishes between three implementation phases: introduction, large-scale integration, and 100 percent renewable energy systems.

1. OVERALL CONSIDERATIONS

In accordance with the idea of Choice Awareness, the overall aim of the EnergyPLAN model is to analyze energy systems for the purpose of assisting the design of alternatives based on renewable energy system technologies. Based on the description of Choice Awareness in Chapter 3, the following key considerations can be highlighted.

The model should be able to make a consistent and comparative analysis of all alternatives in question as well as a reference. It is important that all alternatives including the reference are calculated and analyzed equally to create the basis for a consistent comparison. The reference may be an existing proposal that one may want to challenge by introducing alternatives, or it may be an official plan made by authorities that can relate the discussion of the alternatives in question to other proposals.

The model should be able to analyze radical technological changes. Consequently, it should be able to analyze both the existing system as well as other systems that are radically different both technically and institutionally. This means that the model should not be too influenced by the technical design of the existing system. Nor should the model focus solely on the existing institutional set-up, such as the existing electricity market design. A balance must be created so that it can conduct an analysis on the basis of existing technical and institutional set-ups without depending on these conditions to such an extent that the analysis of radical changes cannot be made properly. For example, if the existing version of a specific electricity market such as Nord Pool is an integrated part of the model, it may become impossible to analyze radically different alternatives. Or if the existing power station structure is an integrated part of the model, it may become impossible to analyze radically different technical options.

The model should be able to provide suitable information for feasibility studies and the design of public regulation measures based on concrete institutional economics. Therefore, it should be able to contribute to feasibility studies with an analysis of relevant parameters such as external costs, job creation, and industrial innovation. In the case of station optimization based on market prices, the model should be able to distinguish between business and socioeconomic feasibility studies.

The model should have a transparent and consistent methodology that produces understandable results. This means that it should have a consistent documentation and be publicly available, user friendly, and easily accessed. Moreover, good references or other forms of public acceptance will improve the model.

In addition to the preceding four important criteria, one may add that the model, in some cases, should be able to help identify and design proper alternatives for future systems in which the number of alternative combinations is almost infinite. Therefore, the model should be able to explore a wide range of future options. It should be fast and capable of managing changes in various inputs in a straightforward and systematic way.

Moreover, if used to identify 100 percent renewable energy systems, the model should be able to analyze the two major challenges of these systems as elaborated in the following section.

The Two Major Challenges of 100 Percent Renewable Energy Systems

The implementation of 100 percent renewable energy systems involves several substantial challenges. However, from the viewpoint of energy system analysis models, two may be considered the most important: (1) the amount of biomass resources that can be used for energy is limited and substantially lower than the present level of fossil fuels used and (2) the remaining sources, mostly wind and solar, are fluctuating and intermittent.

To include the first challenge, it becomes essential for the energy system analysis model to include methodologies and technologies that optimize the use of the limited biomass resources, while also building a bridge between the biomass resource and the need for gas or liquid fuels to supplement the direct use of electricity in the transportation sector.

To include the second challenge, it becomes essential to include temporal distributions and the intermittencies of renewable energy sources in the analysis. The time steps may be hourly or similar. As a decisive factor, the model must be able to include the impacts of fluctuations in renewable energy sources in the analysis in a suitable way. This is normally done on an hourly basis as opposed to annual or monthly time steps. However, the need for such accuracy depends on the degree of implementation of renewable energy in the system in question. In the following section, three implementation phases are defined.

Three Implementation Phases

The need for energy systems analysis tools depends on the share of renewable energy in the system. The following three phases of implementing renewable energy technologies can be defined.

The introduction phase: This phase represents a situation in which no or only a small share of renewable energy is present in the existing energy system. The phase is characterized by marginal proposals for the introduction of renewable energy, for example, wind turbines integrated into a system without or with only a small share of wind power. The system will respond in the same way during all hours of the year, and the technical influence of the integration on the system is easy to identify in terms of saved fuel on an annual basis.

The large-scale integration phase: This phase represents a situation in which a large share of renewable energy already exists in the system, for example, when more wind turbines are added to a system that already has a large share of wind power. In this phase, further increases in renewable energy will have an influence on the system, which will vary from one hour to another, depending, for example, on whether a heat storage is full or whether the electricity demand is high or low during the given hour. The influence of wind power integration on the system, and thereby the calculation of the fuel saved on an annual basis, becomes complex and requires a detailed calculation with hourly simulation models.

The 100 percent renewable energy phase: This phase represents a situation in which the energy system has been or is being transformed into a system based 100 percent on renewable energy. The system is characterized by the fact that new investments in renewable energy must be compared not to nuclear or fossil fuels, but to other sorts of renewable energy system technologies. These technologies include conservation, efficiency improvements, and storage and conversion technologies, as well as the use of smart grids (electricity, district heating, and gas). The influence on the system is complex, not only in terms of differences from one hour to another, but also regarding the identification of adequate conversion and storage technologies as well as the smart operation of grid infrastructures.

The definition of these three implementation phases can be used in the selection and design of proper tools for the technical analyses. In the first phase, the technical calculations are rather simple and do not require complex models. Typically, annual fuel savings can be calculated without models or by using simple models based on duration curves or similar data. However, in the next phase, it becomes essential to make hour-by-hour calculations due to the fluctuations in most renewable energy sources. In the third phase, it also becomes essential to include proper analyses of advanced conversion and storage technologies as well as smart grid infrastructures in the system.

Different Types of Energy System Analysis Models

On a global scale, a large number of different computer models exist that can all be called energy system analysis models because they make calculations related to the analysis of energy systems. Based on a list of 68, Connolly, Lund, Mathiesen, and Leahy (2010) provided a detailed description and review of 37 different models. Table 4.1 lists some of the models. In general, all models address the implementation of renewable energy sources or other technologies related to renewable energy systems such as CHP.

Based on discussions with the different tool developers while completing the review in Connolly, Lund, Mathiesen, and Leahy (2010), it became apparent that the developers did not share a common language to classify different types

TABLE 4.1 Energy System Analysis Models

Name	Description
BALMOREL	The purpose of the BALMOREL project is to support modeling and analyses of the energy sector with emphasis on the electricity and combined heat and power sectors. These analyses typically cover a number of countries and include aspects of energy, environment, and economy. The project maintains and develops the BALMOREL model, a tool that can be used by energy system experts, energy companies, authorities, transmission system operators, researchers, and others for the analyses of future developments of a regional energy sector. This model is developed and distributed under open source ideals. Hosted by the BALMOREL project, Denmark. Can be accessed from www.balmorel.com.
COMPOSE	COMPOSE has been developed for externality-oriented technoeconomic energy projects that offer cost-benefit and cost-effectiveness analyses based on a wide range of important inputs, such as energy resources, environment, economic costs, financial costs, employment, balance of payment, and fiscal costs. COMPOSE has a solid institutional user base in Malaysia and is used by a few Danish energy consultancies as a platform for project analysis and capacity building in energy. Hosted by Aalborg University, Denmark.
CHPSizer	A tool for conducting preliminary evaluations of CHP for hospitals and hotels in the UK. The software enables the user to make a preliminary evaluation of CHP for a building. This will guide the user in deciding whether to proceed with a more detailed examination of CHP for the building in question. Rather than being based on theoretical calculations, the software has been developed using actual energy profile data collected from buildings in the UK. Can be accessed from www.chp.bre.co.uk/chpoverview.html.
EnergyBALANCE	This model is a simple energy balance spreadsheet that provides a good comprehensive view of a regional or national energy system. It is part of the Energy Planning Tool. The energy balance methodology is intended to be very simple and very easy to implement. Basically, the energy balance of a country or region can be calculated on one page in a spreadsheet. Hosted by the Danish Organization for Renewable Energy. Can be accessed from www.orgve.dk.
EnergyPLAN	Computer model for hour-by-hour simulations of complete regional or national energy systems, including electricity, individual and district heating, cooling, industry, and transportation. Focuses on the design and evaluation of renewable energy systems with high penetration of fluctuating renewable energy sources, CHP, and different energy storage options. Hosted by Aalborg University, Denmark. Can be accessed from www.EnergyPLAN.eu.

Continued

TABLE 4.1 Energy System Analysis Models—Cont'd

Name	Description
energyPRO	A complete modeling software package for combined technoeconomic design, analysis, and optimization of both fossil- and bio-fueled cogeneration and trigeneration projects, as well as other types of complex energy projects. Simulates and optimizes energy production in fixed and fluctuating electricity tariff systems by active use of thermal and fuel store. Hosted by EMD International A/S, Denmark. Can be accessed from www.emd.dk.
ENPEP	Suite of models for integrated energy/environment analysis. ENPEP was developed by Argonne National Laboratory and is distributed for use in over 70 countries. This model provides state-of-the-art capabilities for use in energy policy evaluation, energy pricing studies, assessing energy efficiency and renewable resource potential, assessing overall energy sector development strategies, and analyzing environmental burdens and greenhouse gas mitigation options. Hosted by Argonne National Laboratory for the International Atomic Energy Agency. Can be accessed from www.adica.com.
H2RES	A model designed for balancing between hourly time series of water, electricity, and hydrogen demand, appropriate storage, and supply (wind, solar, hydro, diesel, or mainland grid). The main purpose is energy planning of islands and isolated regions that operate as stand-alone systems, but it may also serve other purposes. Hosted by Zagreb University.
HOMER	This model is made particularly for small, isolated power systems, although it enables grid connection. Optimization and sensitivity analysis algorithms provide the basis for an evaluation of the economic and technical feasibility of a large number of technologies. Models both conventional and renewable energy technologies. Hosted by National Energy Laboratory, in the United States. Can be accessed from www.nrel.gov/homer.
HYDROGEMS	Library of computer models for simulation of integrated hydrogen systems based on renewable energy. The objective is to provide a set of modeling tools that can be used to optimize the design and control of RE/H2 systems. Hosted by Institute for Energy Technology, Norway. Can be accessed from www.hydrogems.no.
LEAP	Scenario-based energy-environment modeling tool. Its scenarios are based on comprehensive accounting of how energy is consumed, converted, and produced in a given region or economy under a range of alternative assumptions on population, economic development, technology, price, and so on. Scenarios can be built and then compared to assess their energy requirements, social costs and benefits, and environmental impacts. Hosted by Stockholm Environment Institute in Boston. Can be accessed from www.energycommunity.org.

TABLE 4.1 Energy System Analysis Models—Cont'd

Name	Description
MARKAL	Integrated energy/environment analysis. MARKAL is a generic model tailored by the input data to represent the evolution of a specific energy system over a period of usually 40–50 years at the national, regional, state, province, or community level. Hosted by the International Energy Agency's Energy Technology Systems Analysis Program. Can be accessed from www.etsap.org.
MESAP	MESAP is an energy systems toolbox for application-oriented system solutions in many areas: market analysis in electricity trade, database for power plant operation control, data pool for technical reporting, management of control data in grid companies, CO_2 monitoring, emission inventories for air pollutants, and database for energy models, as well as systems for common statistics administration. MESAP is the only software for all of these applications. It is hosted by Seven2one Informationssysteme GmbH, Karlsruhe, Germany. Can be accessed from www.seven2one.de.
PRIMES	Modeling system that simulates a market equilibrium solution for energy supply and demand in the European Union Member States. This model determines the equilibrium by finding the prices of each energy form. Thereby, the quantity producers find the best solution that matches the quantity demanded by consumers. The equilibrium is static (within each time period) but repeated in a time-forward path under dynamic relationships. Hosted by National Technical University of Athens. Can be accessed from www.e3mlab.ntua.gr.
RAMSES	Simulation/planning model for electricity and district heating supply. Semilinear hour simulation of Nordic electricity and district heating system. INPUT: Plant database (existing and new plants), transmission lines, prices and taxes, electricity and district heating demand, and load curve sets. OUTPUT: Electricity price, fuel consumption, emissions, cash flows, loss of load probability, and so on. Hosted by the Danish Energy Agency.
Ready Reckoner	Model to assist users with a "first pass" technical and financial analysis of cogeneration at their site. The program is a Ready Reckoner intended for quick preliminary evaluations. The Ready Reckoner conducts a simple technical and financial analysis of a cogeneration opportunity. Should the cogeneration opportunity appear attractive in this evaluation, then the user is recommended to conduct more detailed analyses or engage suitable advisers to consider the project evaluation to the extent necessary to commit funds. Hosted by Department of Industry Science and Resources and the Australian EcoGeneration Association (Australia). Can be accessed from www.eere.energy.gov.

Continued

TABLE 4.1 Energy System Analysis Models—Cont'd

Name	Description
RETScreen	A model that can be used to evaluate the energy production and savings, life cycle costs, emission reductions, financial viability, and risk of various types of energy-efficient and renewable energy technologies. The software also includes product, cost, and climate databases. Hosted by RETScreen International Clean Energy Decision Support Centre. Can be accessed from www.retscreen.net.
SESAM	SESAM is a generic multiscenario model that may represent a local, regional, or national energy system consisting of several countries. A SESAM model is a physical model. A SESAM database comprises 25 data registers in which the present and the possible future structural and physical properties of the energy system in question as well as data specifying alternative quantitative development factors are registered. The SESAM programs compute the energy flows in the system on a monthly and daily basis. Hosted by Klaus Illum, Denmark. Can be accessed from www.klausillum.dk/sesam.
SIVAEL	SIVAEL is a simulation program for a thermal power system with related CHP areas. The program makes a simulation with start/stop and load distribution on an hourly basis. The simulation period is from 1 day to 1 year. The program can handle condensing plants, CHP plants—both back pressure and extraction—and also wind power, electricity storage (battery or pumping power), and trade with foreign countries. Hosted by the Danish TSO energinet.dk. Can be accessed from www.energinet.dk/en/menu/Planning/Analysis+models/Sivael/SIVAEL.htm.
WASP	Long-term electricity generation planning including environment analysis. This model determines the least cost-generating system expansion plan that adequately meets the demand for electrical power while respecting user-specified constraints on system reliability. WASP uses probabilistic simulation to calculate the production costs of a large number of possible future system configurations and dynamic programming. It also determines the optimal expansion plan for the electric power system considered. Hosted by the International Atomic Energy Agency. Can be accessed from www.adica.com.

of energy tools. Consequently, to ensure that the tools were described correctly, seven general definitions were created and sent to the developers to distinguish between the different types of energy tools. One or more of these definitions can be used to describe an energy tool. The energy tool types include:

1. A *simulation tool* simulates the operation of a given energy system to supply a given set of energy demands. Typically, a simulation tool is operated in hourly time steps over a 1-year time period.

2. A *scenario tool* usually combines a series of years into a long-term scenario. Typically, scenario tools function in time steps of 1 year and combine the annual results into a scenario of typically 20–50 years.
3. An *equilibrium tool* seeks to explain the behavior of supply, demand, and prices in a whole economy or part of an economy (general or partial) with several or many markets. It is often assumed that agents are price takers and that equilibrium can be identified.
4. A *top-down tool* is a macroeconomic tool using general macroeconomic data to determine growth in energy prices and demands. Typically, top-down tools are also equilibrium tools.
5. A *bottom-up tool* identifies and analyzes the specific energy technologies and thereby identifies investment options and alternatives.
6. *Operation optimization tools* optimize the operation of a given energy system. Typically, operation optimization tools are also simulation tools optimizing the operation of a given system.
7. *Investment optimization tools* optimize the investments in an energy system. Typically, optimization tools are also scenario tools optimizing investments in new energy stations and technologies.

Regarding the idea of Choice Awareness and the introduction of the three implementation phases just described, important differences can be found among the models. One important difference is whether the model makes a detailed hour-by-hour simulation or is based on aggregated annual calculations, possibly made by using duration curves or similar data. Another important difference is whether the model addresses the national or regional system level or the project or single station level. In Table 4.2, the chosen models are grouped according to these essential differences.

Not all models are designed in such a way that they fit perfectly into these groupings. Consequently, one model is located in two groups, and other models may have aspects across more than one group. The MESAP model is not shown in Table 4.2 because it is really a database system that combines the use of other models. Moreover, some models are being further developed on a continuous basis. Typically, models based on aggregated annual calculations also contain some hourly simulations in different parts of the calculation process. Nevertheless, Table 4.2 shows two important differences.

As described regarding the three implementation phases, models based on aggregated data are typically suitable for the *introduction phase*. They can provide an adequate level of detail, since in this phase it is not necessary to run detailed hourly simulations, which is often a complicated and data-consuming process. Moreover, models based on aggregated data typically have the advantage of being easy to document and communicate compared to hourly simulation models. However, for the analysis of large-scale integration or 100 percent renewable energy systems, hour-by-hour simulation models are essential.

TABLE 4.2 Grouping of Energy System Analysis Models

	Aggregated Annual Calculations	Detailed Hour-by-Hour Simulations
Regional/National System Level	EnergyBALANCE LEAP MARKAL PRIMES ENPEP	EnergyPLAN LEAP RAMSES BALMOREL SESAM SIVAEL WASP H2RES HOMER
Project/Station System Level	Ready Reckoner CHPSizer RETScreen	energyPRO HYDROGEMS COMPOSE

In the division concerning areas usually considered, the models at the project/station level typically cannot evaluate the influence of, for example, fluctuating renewable energy sources on the overall regional and/or national system. On the other hand, they are typically better equipped for making detailed analyses of the business economic operation and design of single stations. Consequently, in the groupings in Table 4.2, only detailed hour-by-hour simulation models at the regional/national level can fulfill the requirements for energy system analyses of renewable energy systems on the large-scale and 100 percent renewable energy implementation phases.

It should be emphasized, however, that the design of alternatives by use of these models in many cases may benefit from being combined with either models based on aggregated data or models at the project/station level. For example, analyses made with the EnergyPLAN model have, in some cases, been combined with analyses conducted by one of the "sister models": energyPRO and EnergyBALANCE (Lund et al. 2004). The energyPRO model has been used for additional analyses of how single stations will respond to changes in the energy system design defined by use of the EnergyPLAN model. The EnergyBALANCE model has been used to make fast and easy first estimates of different large-scale options, before involving the EnergyPLAN model.

Hourly Simulation Models at the National Level

Historically, energy system analysis models based on hourly simulations at the regional/national level have typically been developed with two purposes in mind. Some models have been developed to optimize the load dispatch between single power stations in utility systems, whereas others have been made for planning purposes, that is, identifying proper investment strategies.

The overall aim of the load dispatch models is to design suitable operation strategies on a day-to-day basis. These models have, prior to the introduction of national and international electricity markets, been used and designed by electricity system operators to plan least-cost production strategies of electricity supply systems with several production units. As these models must be able to calculate exact operational costs and emissions, they are typically very comprehensive and detailed in their description of each individual power station.

The overall aim of planning models is to identify suitable future investment strategies. These models have been used and designed by public planning authorities, utility companies, and different nongovernmental organizations, including universities and research institutions. Sometimes load dispatch models have been used for planning purposes, or planning models have been developed on the basis of load dispatch models. In practice, these models have sometimes proven to be very conservative in the sense that they have mainly been able to analyze small, short-term adjustments to the existing system rather than radical changes in the overall system design and regulation. Moreover, the use of these models is typically very time-consuming because of the need for detailed data.

Both load dispatch models and planning models have been influenced by the introduction of international electricity markets, which has taken place in many countries around the world since the late 1990s. Operation strategies for power production units are now determined by the market, and the models are used to identify optimal market behavior. Planning models have begun to include the modeling of international electricity markets in the analyses. Some models have chosen to convert to solely making simulations of the results of market operations based on the present institutional set-up of the international electricity market, while, for example, the EnergyPLAN model has been equipped with the ability to make both market analyses as well as simulations on the basis of pure technical optimizations.

Consequently, hour-by-hour simulation models at the regional/national level have important differences. One is whether the present electricity market structure forms the only institutional basis for the simulation and/or operational optimization procedure of the model or if this simulation is also based on technical and/or economic optimization. In the latter case, it is also important to define whether this optimization is made on the basis of a business economic market strategy or some sort of socioeconomic least-cost strategy.

Another important difference is whether the model combines all sectors of a regional/national energy system or includes only parts of this system, such as the electricity supply. This difference is important to the analysis of large-scale integration and especially 100 percent renewable energy systems. These

TABLE 4.3 National Level Hour-by-Hour Simulation Models

Detailed Hour-by-Hour Simulation Models at the Regional/National Level	Operational Optimization Based on Technoeconomic Optimization	Operational Optimization Based on Electricity Market Simulations
Include all sectors: electricity, district heating, individual heating, industry transportation	EnergyPLAN SESAM	EnergyPLAN RAMSES (BALMOREL)
Include mainly the electricity sector	H2RES HOMER	BALMOREL SIVAEL WASP

systems will benefit from efficiency measures such as CHP production, which makes an integrated analysis of the electricity and the heating sector relevant. They will also benefit from the use of electricity for transportation purposes, which makes the combined analysis of the electricity and transport sectors essential.

In Table 4.3, the hour-by-hour simulation models applied to the regional/national level have been grouped according to their optimization and their operation levels. Again, this grouping is not 100 percent accurate for all models. The LEAP model is left out, which is characterized as a simulation model rather than an optimization model because other models optimize the operation of the system. In principle, the two models, SIVAEL and BALMOREL, do not include all sectors, as individual heating and transportation are left out. However, they do consider the operation of the electricity grid for technologies such as micro-CHP or electric vehicles.

In Table 4.3, the EnergyPLAN model is placed in both the technoeconomic optimization and the electricity market optimization model groups. This model is designed to calculate the consequences of both types of optimization strategies. Moreover, the calculation of the market-economic strategy is based on a business economic optimization of individual stations in which different taxes and subsidies can be specified. The aim is to be able to provide information for the discussion on suitable public regulation measures.

It must be emphasized that the models have differences other than those presented in Tables 4.2 and 4.3. Models, such as LEAP and RAMSES, emphasize the analyses of scenarios and include the calculation for a series of years. However, these characteristics illustrate the variety of models currently available.

2. THE ENERGYPLAN MODEL

EnergyPLAN is a computer model designed for energy systems analysis. This model has been developed and expanded on a continuous basis since 1999. It is a user-friendly tool designed in a series of tab sheets and programmed in Delphi Pascal. The inputs are defined by the user in a number of technical input tab sheets and a few cost specification input tab sheets (see Figure 4.1).

The following section provides a brief description of the EnergyPLAN model. A full documentation of it can be found on www.EnergyPLAN.eu. Moreover, it is described and compared to other models in Lund and Münster (2003a), Lund and Münster (2003b), Lund, Duić, Krajacić, and Carvalho (2007), and Connolly, Lund, Mathiesen, and Leahy (2010).

Purpose and Application

The main purpose of this model is to assist the design of national or regional energy planning strategies on the basis of technical and economic analyses of the consequences of implementing different energy systems and investments. It encompasses the whole national or regional energy system, including heat, gas, and electricity supplies as well as the transportation and industrial sectors.

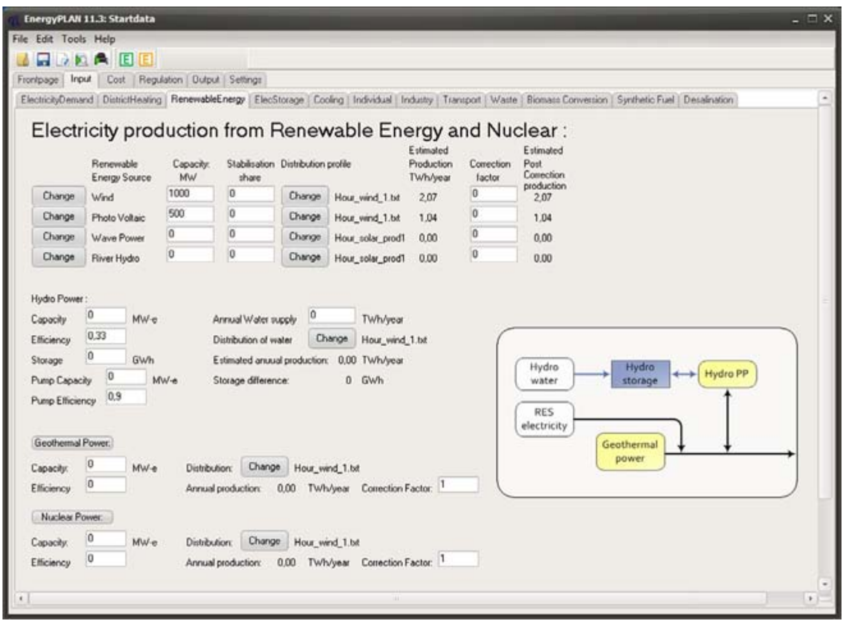


FIGURE 4.1 Example of an Input tab sheet in the EnergyPLAN model.

Regarding electricity supply, this model emphasizes the analysis of different regulation strategies and focuses on the interaction between CHP and fluctuating renewable energy sources. Moreover, it includes various biomass conversion and power-to-gas options.

The EnergyPLAN model is a deterministic input/output model. General inputs are demands, renewable energy sources, energy station capacities, costs, and a number of optional different regulation strategies emphasizing import/export and excess electricity production. Outputs are energy balances and resulting annual production, fuel consumption, import/exports of electricity, and total costs, including income from the exchange of electricity (see Figure 4.2).

Compared to other similar models, the following characteristics of EnergyPLAN can be highlighted:

- EnergyPLAN is a *deterministic* model as opposed to a stochastic model or models using Monte Carlo methods. With the same input, it will always come to the same results. However, as we will see in Chapter 5, it can perform a calculation on the basis of RES data of a stochastic and intermittent nature and still provide system results that are valid for future RES data inputs.
- EnergyPLAN is an *hour-simulation* model as opposed to a model based on aggregated annual demands and production. Consequently, the model can analyze the influence of fluctuating RES on the system as well as weekly and seasonal differences in electricity, gas, and heat demands and water inputs to large hydropower systems.
- EnergyPLAN is *aggregated in its system description* as opposed to models in which each individual station and component is described. For example, in EnergyPLAN, the district heating systems are aggregated and defined as three principal groups.
- EnergyPLAN *optimizes the operation* of a given system as opposed to models that optimize investments in the system. However, by analyzing different systems (investments), this model can be used for identifying feasible investments, as we will see in Chapters 5–7.
- EnergyPLAN provides a choice between *different regulation strategies* for a given system as opposed to models into which a specific institutional framework (such as the Nord Pool electricity market) is incorporated.
- EnergyPLAN *analyzes 1 year* in steps of 1 hour as opposed to scenario models analyzing a series of years. However, several analyses each covering 1 year may be combined into scenarios.
- EnergyPLAN is based on *analytical programming* as opposed to iterations, dynamic programming, or advanced mathematical tools. This makes the calculations direct and the model very fast when performing calculations. In the programming, any procedures that would increase the calculation time have been avoided, and the computation of 1 year requires only a few seconds on a normal computer, even in the case of complicated national energy systems.

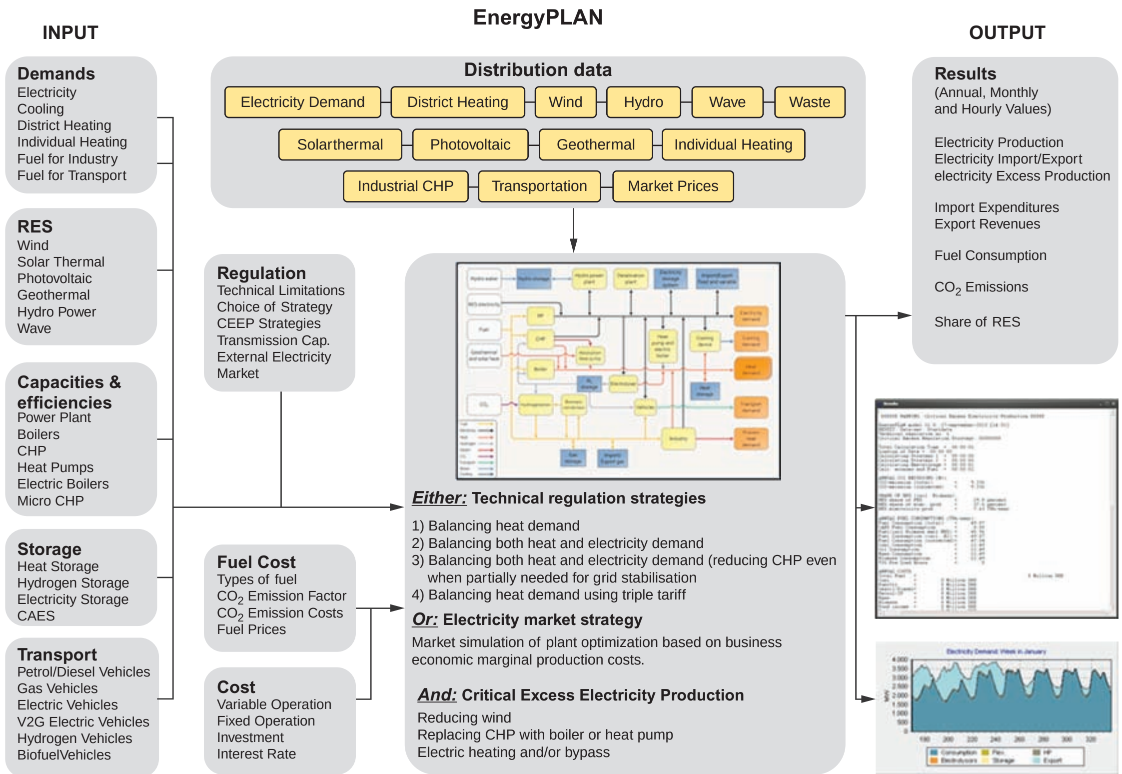


FIGURE 4.2 Input–output structure of the EnergyPLAN model.

- EnergyPLAN includes hourly analyses of the complete *smart energy system*, i.e., district heating and cooling as well as electricity and gas grids and infrastructures, as opposed to models that have a sole focus on, for instance, the electricity sector.

Energy Systems Analysis Structure

The EnergyPLAN model can be used to calculate the consequences of operating a given energy system in such a way that it meets the set of energy demands of a given year. Different operation strategies can be analyzed. Basically, the model distinguishes between technical regulation (i.e., identifying the least fuel-consuming solution) and market-economic regulation (i.e., identifying the consequences of operating each station on the electricity market with the aim of optimizing the business economic profit). In both situations, most technologies can be actively involved in the regulation, and in both situations, the total costs of the systems can be calculated. In the documentation of the model, a list of energy demands is presented as well as an overview of all components of the model. A short description of how they are operated in relation to the two different regulation strategies is also presented together with a list of the main inputs for each component.

The model includes a large number of traditional technologies, such as power stations, CHP, and boilers, as well as energy conversion and technologies used in renewable energy systems, such as heat pumps, electrolyzers, and heat, electricity, and hydrogen storage technologies, including Compressed Air Energy Storage (CAES). It can also include a number of alternative vehicles, such as sophisticated technologies like V2G (vehicle to grid), in which vehicles supply the electric grid, and synthetic fuel vehicles, which use methanol and/or methane. Moreover, the model includes various renewable energy sources, such as solar thermal and photovoltaic (PV), wind, wave, and hydropower.

The EnergyPLAN model is further expanded and improved on an ongoing basis in a dialog with the users of the model. Since the first edition of this book was published, the model has been expanded in terms of hourly analyses of the gas grid, including gas storage and a number of biomass and/or power to gas conversion units such as gasification and hydrogenation. In Chapters 6 and 7, examples are presented showing the use of these facilities to study fuel pathways for transportation and to make hourly analyses of the complete energy system including the use of various smart grids and infrastructures.

Figure 4.3 shows the procedure of the energy system analysis. As a first step, calculations are based on a small computation, which is made simultaneously with the typing of input data in the input and cost tab sheets. The next step consists of a series of initial calculations that do not involve electricity balancing. Then the procedure is divided into *either* a technical *or* a market-economic optimization. The user chooses which one to apply. However, each calculation lasts only a few seconds and, consequently, it is possible to make both calculations,

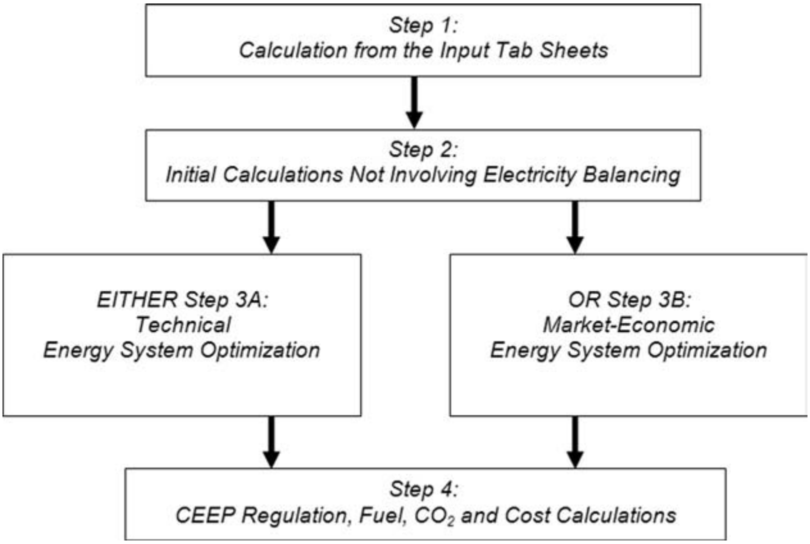


FIGURE 4.3 Overall structure of the energy system analysis procedures.

one after another. The technical optimization minimizes the import/export of electricity and seeks to identify the least fuel-consuming solution. On the other hand, the market-economic optimization identifies the least-cost solution on the basis of the business economic costs for each production unit. In both situations, the model can calculate the socioeconomic consequences that provide important information for the design of different public regulation measures.

The principle of the energy system of the EnergyPLAN model is shown in Figure 4.4. In the EnergyPLAN model, an aggregated analysis is made of the many individual stations that together form a regional or national energy system. Thus, all boilers, CHP stations, and so forth that produce heat for district heating are grouped into three district heating systems. Moreover, the EnergyPLAN model includes a series of optional renewable energy sources as well as a large number of conversion and storage technologies. In this way, the model can make comprehensive analyses of rather complex 100 percent renewable energy systems without the need for an enormous quantity of detailed data.

Validation of Model

In Lund and Mathiesen (2012), the validation of a model like EnergyPLAN is described. The validation of this kind of model is complicated, since the models are typically huge and involve a substantial number of assumptions and formulas of which all cannot easily be described. Kleindorfer, O'Neill, and Ram (1998) argued that the validation of such models may be compared to the validation of miniature scientific theories. The principle of validation is discussed

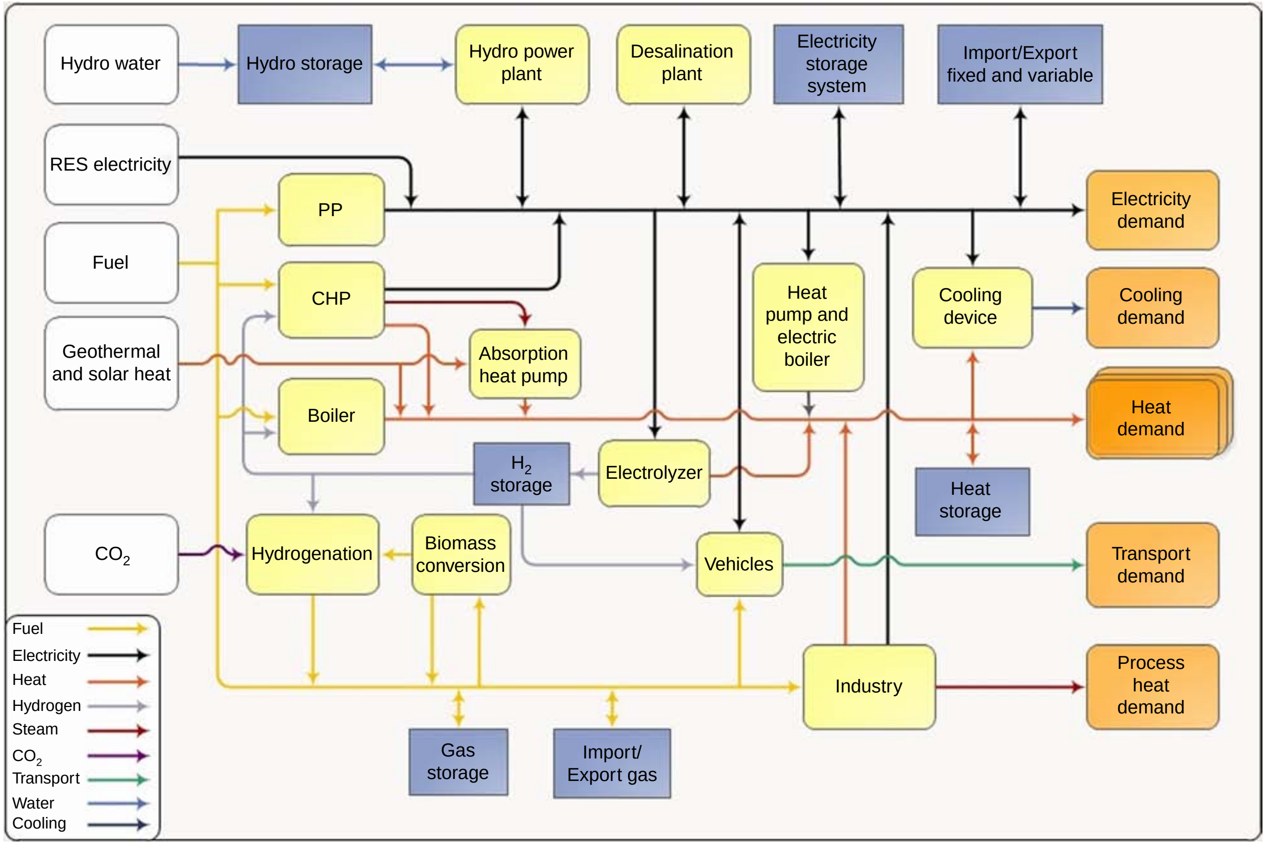


FIGURE 4.4 Overall sketch of the energy system described in the EnergyPLAN model.

in relation to different philosophical positions, including Rationalism, Empiricism, and Positive Economics, emphasizing a discussion of the objectivist approach versus the relativist approach: foundationalism versus anti-foundationalism. On the one side, an extreme objectivist believes that model validation can be separated from the model builder and its context and that validation is an algorithmic process that is not open to interpretation or debate. In contrast, an extreme relativist believes that the model and model builder are inseparable and that validation is a matter of opinion.

Kleindorfer, O'Neill, and Ram (1998) argued that most practitioners have instinctively adopted a middle ground in this debate and they compare the validation of simulation models to the situation in a courthouse. The prosecutor does not have to prove the guilt in any foundationalist sense, but rather "beyond reasonable doubt". Extending the courthouse metaphor, the authors argue that

The model builder would be free to establish and increase the credibility of the model through any reasonable means. This process would also involve other model stakeholders, such as model users and referees of journal articles.

In the process of defining reasonable, one may refer to papers such as Pidd (2010) and Qudrat-Ullah and Seong (2010) in which the purpose of the model is highlighted as essential, i.e., if the model is acceptable for its intended use. Following these guidelines, it should initially be highlighted that the purpose of the EnergyPLAN model is to assist in the design of complete renewable energy systems seen in the light of a wish to transform the present energy system into a future sustainable energy system, which from a Choice Awareness perspective requires a radical technological change.

Seen in this light, the following items are highlighted in relation to the validation of the EnergyPLAN model. First, the EnergyPLAN energy system analysis model has a complete documentation of which an updated version can always be downloaded from www.EnergyPLAN.eu. Next, EnergyPLAN has proven its ability to form the basis for the modeling of complete national energy systems in various studies. Thus, the EnergyPLAN model has been used in a number of recent studies in different countries including Denmark, Romania, China, and Ireland. These studies typically involve the analysis of a reference that has been compared to official statistics or similar. Furthermore, the model has been used to analyze the role of a number of different technologies in future sustainable energy systems including wind, wave and PV, CHP, heat pumps, waste to energy, CAES, and electricity and biofuels for transportation including V2G. All these studies have been published in refereed journal papers and a list of most of them can be found on www.EnergyPLAN.eu. Third, the EnergyPLAN model is a freeware that can be downloaded from the home page already mentioned. This means that anyone can access the model and then repeat and/or evaluate the studies completed by others.

Energy System Analysis Methodology

A short outline of how to use the model in the design of energy alternatives at the national level (Lund, Andersen, and Antonoff 2007) is presented here. On the home page of the model, www.EnergyPLAN.eu, a whole set of exercises and assignments can be downloaded, including detailed answers, that together constitute a comprehensive set of guidelines on how to use the model. As already shown in Table 4.3, the model can be used for different kinds of energy systems analyses.

Technical analysis: Design and analysis of complex energy systems at the national or regional level and according to different technical regulation strategies. In this analysis, input is a description of energy demands, production capacities and efficiencies, and energy sources. Output consists of annual energy balances, fuel consumptions, and CO_2 emissions.

Market exchange analysis: Further analysis of trade and exchange on international electricity markets. In this case, the model needs further input to identify market prices and to determine the response of these prices to changes in import and export. Input is also needed to determine marginal production costs of the individual electricity-producing unit. The modeling is based on the fundamental assumption that each station optimizes according to business economic profits, including any taxes and CO_2 emissions costs.

Feasibility studies: Calculation of feasibility in terms of total annual costs of the system according to different designs and regulation strategies. In this case, inputs such as investment costs and fixed operation and maintenance costs must be added together with lifetime periods and an interest rate. The model determines the socioeconomic consequences (taxes and subsidies are not included) for the energy system. The costs are divided into fuel costs, variable operation costs, investment costs, fixed operation costs, electricity exchange costs and benefits, and possible CO_2 payments.

A Step-by-Step Approach to National Energy Systems Analysis

The approach to energy systems analysis used in the EnergyPLAN model can be divided into four steps:

Step 1: Defining reference energy demands
Step 2: Defining a reference energy supply system
Step 3: Defining the regulation of the energy supply system
Step 4: Defining alternatives

Step 1: Defining Reference Energy Demands

The first step is to define a reference energy demand. The electricity demand is simply defined by identifying an annual demand (TWh/year) and choosing an hourly distribution. The distribution data can be picked from the database of the model, or one can create a new distribution (for more information, please consult the model documentation). Energy conservation is included by modifying the energy demands. The model has been designed in such a way that it helps to change the hourly distribution where necessary; for example, the electricity demand is altered when electric heating or cooling demands decrease as a result of energy-saving measures.

Though the annual demand is sufficient, the model also offers the possibility of defining two additional demands with separate distribution datasets. One is meant to be used for adding electricity to transportation and another for fixed import/exports, but they can be used for any purpose; the model simply adds up the three demands.

The model can also include flexible electricity demands: these are demands that are included in the regulation of securing a balance between supply and demand. One must choose among flexibility within 1 day, 1 week, or 1 month (4 weeks). For each group, a flexible demand can be identified by two values: annual demand (TWh/year) and maximum capacity (MW).

District heating demand is defined in the same way as the electricity demand: it uses an annual demand (TWh/year) and a selected distribution dataset. The model divides district heating supply into three groups, and the demand of each group must be defined. The first group comprises traditional district heating stations with boilers, the second group consists of small CHP stations, and the third group includes large CHP stations based on thermal extraction stations.

With regard to the energy systems analysis, the model focuses on electricity demand and district heating demand. However, all sectors are included in the model, and industry as well as individual heating and transportation may be included in the electricity and district heating balancing of demand and supply. If industrial CHP stations produce electricity or district heating, these can be specified for each of the three district heating groups. The production is specified in the same way as the demand, by using an annual production and a selected distribution dataset.

With regard to the transportation and individual heating sectors, various options exist in terms of several different electric, hydrogen, and biofuel vehicles and various solar thermal and micro-CHP systems, including conversion and storage technologies such as electrolyzers. If these technologies involve the district heating or electricity sectors, they are included in the hourly balancing during the computation.

Step 2: Defining a Reference Energy Supply System

Step 2 is to define the reference energy supply system, divided into renewable energy sources, capacities, and efficiencies of energy production units, and the division of fuel based on annual average consumption. Renewable energy sources for electricity production, such as wind power, PV power, and wave power, are defined by an installed capacity and by a selected distribution dataset. Again, the distribution data can be chosen from the existing database, or new distributions can be made. The model offers the possibility of adding a factor (between 0 and 1) to modify the distribution curve. The factor adjusts the distribution curve to higher annual productions if, for instance, new wind power capacities are being built on locations with better wind potentials.

Renewable energy sources for district heating production, such as solar thermal, can be specified for each of the three district heating groups in the same way as heat production from industry: in other words, by an annual production (TWh/year) and a selected distribution dataset. Moreover, heat, electricity, and hydrogen storage and energy conversion technologies, such as electrolyzers, can be specified.

Capacities and efficiencies of the energy production units are defined as average values for each type of station in each of the three district heating groups. For group one (district heating boilers), only the efficiency needs to be stated, since the capacity of the boiler must always be sufficient. For groups two and three (CHP), capacities (MW_e and MW_{th}) and efficiencies are given for CHP units and boilers. Moreover, a heat pump and a heat storage capacity (GWh) can be defined for each of the two groups. The heat pump is defined by the capacity (MW_e) and the coefficient of performance (COP) factor (heat output divided by electric input). Moreover, the maximum share of heat production from the heat pump can be specified to achieve the specified COP.

Finally, the capacity (MW) and the efficiency of a condensing power station are given. The model distinguishes between the CHP stations in group three and the condensing power stations. However, in practice, these stations may be the same units (extraction stations). Consequently, the model makes the calculation assuming that the capacity input of the condensing power stations constitutes the total maximum capacity of both the condensing stations and the CHP stations in group three. Thus, if the CHP capacity at a certain stage of the analysis is not used for CHP production, the same capacity might be used for condensing power production (but with a different efficiency).

The fuel consumption of the stations can be calculated by the model on the basis of efficiencies. To track fuel use and CO_2 emissions, the model needs inputs in terms of the share of fuel types at the different stations. The shares are given by relative numbers, and all types of fuels are increased or decreased accordingly. However, the model enables an adjustment of the amount of one or more types of fuels.

Step 3: Defining the Regulation of the Energy Supply System

The regulation strategy is defined by choosing one of the predefined general strategies and then specifying some limitations and additional options. Basically, the technical analyses distinguish between a technical optimization and an electricity market optimization. In the market-economic optimization, electricity production is determined on the basis of business economic marginal production costs of the different types of electricity-producing units. Moreover, electricity-consuming units, such as heat pumps and electrolyzers, are also included. One can specify various taxes on different fuels and types of production and thereby conduct analyses of the consequences of changing taxes and/or introducing new ones.

With regard to the technical optimization, one must choose one of the two following strategies:

Technical Regulation Strategy 1: Meeting heat demand. In this strategy, all units produce solely according to the heat demand. In district heating systems without CHP, the boiler simply supplies the difference between the district heating demand and the production from solar thermal and industrial CHP. For district heating with CHP, the units are prioritized according to the sequence (1) solar thermal, (2) industrial CHP, (3) CHP units, (4) heat pumps, and (5) peak load boilers. The model offers the option of operating the small CHP units according to a triple tariff, giving an incentive to allocate electricity production during hours of high and peak demand.

Technical Regulation Strategy 2: Meeting both heat and electricity demands. When choosing Strategy 2, the export of electricity is minimized mainly by replacing CHP heat production with boilers or heat pumps. This strategy simultaneously increases electricity consumption and decreases electricity production, as the CHP units must lower their heat production. Similarly, when there is extra capacity available at the CHP stations and space in the heat storage, the production at the condensation stations is replaced with CHP production, thus increasing the overall efficiency of the energy system.

Two additional technical regulation strategies exist that are variants of the preceding two. For detailed explanations, please consult the model documentation.

The model also considers the ancillary services required to secure grid stability in the electricity system. Limitations in identifying optimal operation strategies can be specified in terms of the minimum share of electricity production required from a unit for it to supply ancillary services. The condensing power stations and the CHP stations in group three are always assumed to have these abilities. Any share of small CHP stations and renewable energy sources with ancillary service abilities can be specified as an input value.

As part of the regulation strategy, one can specify system limitations on the export/import of electricity represented by transmission line capacities (MW). Depending on the situation and the chosen regulation strategy, bottlenecks may occur that require higher exports of electricity than the amount allowed by the transmission lines: this is called critical excess electricity production. Consequently, one can specify strategies to avoid this problem. As shown in Chapters 5–7, the description and analysis of the reference system can be used to establish a common point of departure when promoting and discussing alternative strategies.

Step 4: Defining Alternatives

When a reference is described, the analysis of alternatives is relatively easy. The computation of the whole system takes only a few seconds on a normal personal computer. Analyzing different regulation strategies is, in many cases, a simple matter of pressing a button to change regulation and run the computation once again. Changing technologies is a matter of choosing other technologies. Of course, this change depends on a proper definition of inputs in terms of efficiencies and costs, which may be time-consuming to find for new technologies.

Sister Models to EnergyPLAN

The EnergyPLAN computer model has three sister models (sister models in the sense that they originate from Aalborg University and have been made to supplement and support one another): EnergyBALANCE, energyPRO, and COMPOSE. The EnergyBALANCE model is a simple spreadsheet model based on aggregated annual calculations of energy balances. It is designed for an easy integration of typical inputs from national statistics. This model adds different data of efficiencies, and so forth, to make overall analyses of changes in demand and supply technologies. It is now made available from the Danish Organization for Renewable Energy (OVE) via its home page, www.orgve.dk.

The energyPRO model excels in modeling and optimizing the operation of a single station. It has the ability to evaluate many different types of technologies and performance criteria for generating units, particularly CHP stations, and enables the user to add detailed definitions of parameters, such as heat production, electricity production, fuel costs, power curves, and control strategies. It can also conduct a sophisticated economic analysis that considers varying values for revenues (such as heat prices and spot market electricity prices) and costs (such as fuel costs, taxes, and other operational expenses). However, this level of detail may also require a significant amount of research and data input to properly initialize the model, and it implies a high level of understanding of the specific performance characteristics of the station.

The model focuses primarily on production aspects and, apart from a few exceptions such as heat distribution losses, it does not consider how the station fits into the broader energy system. It is an advanced computer tool for the design and operation of CHP stations, and it has been used to design most of the existing small CHP stations in Denmark. The initial version of energyPRO was designed in the late 1980s. Shortly afterward, the program was made commercially available by the software company Energy and environMental Data (EMD). Based on an ongoing dialog with users, EMD has refined and added new facilities and features to the model on a continuous basis. It has become a widely used software package for the analysis of local energy stations based on gas engines, gas turbines, and steam turbines burning both waste and wood chips, as well as stations based on boilers only. EnergyPRO has been used in Lund and Andersen (2005) and Andersen and Lund (2007).

COMPOSE (Compare Options for Sustainable Energy), designed by Morten Blarke, is a technoeconomic energy project assessment model. It enables the evaluation of user-defined sustainable energy projects in user-defined energy systems and includes user-selected methodology options. The mission of COMPOSE is to combine the strength of energy project operational simulation models with the strength of energy system scenario models to create a modeling framework that supports an increasingly realistic and qualified comparative assessment of sustainable energy options.

The current functionality of COMPOSE focuses on the modeling of a framework design. The model currently enables the user to calculate the relocation coefficient of an energy project and an energy system defined by the user. User-defined uncertainties may be specified to enable extensive risk analyses, such as specifying uncertainty ranges for wind production. Special features currently include, among others, Monte Carlo risk assessments, the import of projects from energyPRO, and the import of hourly distributions from EnergyPLAN.

The vision is to establish COMPOSE as a cost-benefit and cost-effectiveness toolbox for private and public decision makers. COMPOSE focuses on assessing to which degree energy projects may support intermittency, while generally offering a realistic evaluation of the distribution of costs and benefits with uncertainty. In coming releases, COMPOSE will increasingly improve the evaluation of energy projects in a project-system hybrid perspective with respect to fossil energy consumption, emissions, economic costs, financial costs, fiscal costs, employment, balance of payment, and distributional aspects of costs and benefits.

3. REFLECTIONS

Based on the formulation of the Choice Awareness theory in Chapter 3, this chapter discussed some overall key issues to consider when designing tools for the analysis and assessment of renewable energy alternatives, representing radical technological change. The following reflections can be made regarding these key considerations and the EnergyPLAN model:

- The EnergyPLAN model can make a consistent and comparative analysis of different energy systems based on fossil fuels, nuclear energy, and renewable energy. When the reference energy system is described, EnergyPLAN makes it possible to conduct a fast and easy analysis of radically different alternatives without losing coherence and consistency in the technical assessment of even complex renewable energy systems.
- The EnergyPLAN model seeks to enable the analysis of radical technological changes. The model describes existing fossil fuel systems in aggregated

technical terms, which can be relatively easily changed into radically different systems, such as systems based on 100 percent renewable energy sources. This model divides the input to market-economic analyses into taxes and fuel costs, making it possible to analyze different institutional frameworks in the form of different taxes. Moreover, if more radical institutional structures are to be analyzed, it can provide purely technical optimizations. This makes it possible to separate the discussion of institutional frameworks, such as specific electricity market designs, from the analysis of fuel and/or CO_2 emissions alternatives. Compared to many other models, EnergyPLAN has not incorporated the institutional set-up of the electricity market of today as the only institutional framework.

- The model can calculate the costs of the total system divided into investments costs, operation costs, and taxes such as CO_2 emissions trading costs. Thereby, the model can create data for further analysis in socioeconomic feasibility studies, including balance of payment, job creation, industrial innovation, and so on.
- The model has a coherent documentation and seeks to provide a user-friendly communication in input/output tab sheets. Moreover, it is very fast. On a normal PC, the complete hour-by-hour simulations of even very complex national energy systems take only a few seconds. Consequently, the model can be used interactively to test different input combinations in the design of references as well as to make several different calculations of many options without taking very much time. This is further helped by the library of distribution data incorporated into the model, which makes it rather fast and easy to implement comprehensive changes in the input.
- Regarding the three different implementation phases, this model includes a very high number of different technologies that are relevant to renewable energy systems. Consequently, it serves as a good tool for making detailed and comprehensive analyses of a very wide spectrum of large-scale integration possibilities, as well as 100 percent renewable energy systems.

Chapter 5

Analysis

Large-Scale Integration of Renewable Energy

With a contribution by Willet Kempton
Associate Professor, College of Marine and Earth Studies, University of Delaware

The large-scale integration of renewable energy sources into existing energy systems must meet the challenge of coordinating fluctuating and intermittent renewable energy production with the rest of the energy system. Meeting this challenge is essential, especially with regard to electricity production, since electricity systems depend on an exact balance between demand and supply at any time. Given the nature of photovoltaic (PV), wind, wave, and tidal power, little can be gained by regulating the renewable source itself. Large hydropower producers are an exception, since these units are typically well suited for electricity balancing. In general, however, the possibilities of achieving a suitable integration are to be found in the surrounding supply system, that is, in power and CHP stations. The regulation in supply may be facilitated by flexible demands, for example, heat pumps, consumers' demand, and electricity for transportation. Moreover, the integration can be helped by different energy storage technologies. However, not all measures are equally efficient and effective.

This chapter examines and deduces the essence from a series of studies in which the EnergyPLAN model has been applied to the analysis of large-scale integration of renewable energy sources (RES) into the Danish energy system. At present, the Danish energy system already has a relatively high share of renewable energy and is therefore suitable for the analysis of further large-scale integration. The studies conducted address the integration of RES into future energy systems and seek to identify the best suitable means. The analyses are based on official projections of the Danish energy system made by the Danish Energy Agency in 2001. The projections are presented in the beginning of this chapter.

In addition to these studies, this chapter presents a method for comparing different energy systems in terms of their ability to integrate RES on a large scale. The question in focus is how to design energy systems with a high capability of utilizing intermittent RES, also considering the problem that the fluctuations and intermittence of, for example, wind power differ from one year to another. This challenge is met by analyzing and illustrating different energy systems in so-called excess electricity diagrams. In these diagrams, a curve represents the system in all of the years, regardless of the fact that the fluctuations of RES differ from one year to another.

A number of studies of large-scale integration of RES are presented and, finally, some reflections and conclusions sum up the chapter with regard to the methodologies and principles as well as the technical measures involved. This leads to a series of recommendations concerning the most feasible technical measures, how to combine the measures, and when to use them considering the share of RES in the system.

1. THE DANISH REFERENCE ENERGY SYSTEM

The different analyses of large-scale integration of renewable energy presented in this chapter are all based on a projection of the future Danish energy supply by the year 2020. In 2001, at the request of the Danish Parliament, the Danish Energy Agency formed an expert group for the purpose of investigating and analyzing possible means and strategies for managing the problem of excess electricity production from combined heat and power (CHP) and RES (Danish Energy Agency 2001). According to the official Danish Energy Policy of that time, as expressed in the government's energy plan, Energy 21 (Danish Ministry of Environment and Energy 1996), the share of CHP and especially the share of wind power were expected to increase.

The expert group defined the two terms *exportable excess electricity production* (EEEP) and *critical excess electricity production* (CEEP).[1] EEEP can be exported, while CEEP refers to a situation in which the electricity produced exceeds both the demand and the export capacity of transmission lines out of the system (Denmark). This situation must be avoided so the electricity system will not collapse. Based on these definitions, the expert group defined a reference scenario showing the resulting development in both CEEP and EEEP if expansions in CHP, wind power, and demand were to be implemented according to the official energy policy. Three years—2005, 2010, and 2020—were chosen for the analysis.

At that time, the Danish electricity system was divided into two separate geographical areas: East Denmark and West Denmark. Excess electricity production can arise in one area without being present in the other. Subsequently, the Danish government decided to connect the two systems by a DC connection, but this decision was not final at the time the projection was done. Consequently, it was decided to analyze each area separately. The reference system is characterized by the following development:

- The Danish electricity demand is expected to rise from 35.3 TWh in 2001 to 41.1 TWh in 2020, equal to an annual rise of approximately 0.8 percent.

1. Translated from Danish: Kritisk og Eksporterbart Eloverløb.

- The installed capacity of wind power is expected to rise from 570 to 1850 MW in East Denmark and from 1870 to 3860 MW in West Denmark from 2001 to 2020. The increase is primarily due to the expected implementation of one 150 MW offshore wind farm each year.
- Existing large coal-fired CHP steam turbines are to be replaced by new natural gas-fired combined cycle CHP units when the lifetime of each of the old CHP stations runs out. Additionally, distributed CHP stations and industrial CHPs are due for a small expansion.

Denmark has quite good transmission line capacities to its neighboring countries. Thus, East Denmark is connected to Sweden (1700 MW AC) and East Germany (600 MW DC), and West Denmark is connected to North Germany (1200 MW AC), Sweden (600 MW DC), and Norway (1000 MW DC). When defining CEEP, the capacities of all the existing transmission lines were included apart from the AC connection to North Germany, as this area has a very high wind power production and has similar excess production problems during the same hours as West Denmark.

Based on the preceding assumptions, the expert group evaluated the magnitude of the expected excess electricity production problem divided into EEEP and CEEP. The result of the analysis is shown in Table 5.1. In the reference scenario, excess electricity production is expected to increase considerably in the period toward the year 2020. The expected excess production of 1680 GWh in East Denmark equals 11 percent of the demand in 2020. In West Denmark, excess production equals 28 percent of the demand in 2020. The expectations of high excess production illustrated in Table 5.1 can be explained mainly by two assumptions. First, in the reference scenario, small- and medium-scale CHP stations were not expected to regulate according to fluctuations in

TABLE 5.1 Expected Excess Electricity Production in the Danish Reference Scenario Defined in 2001

Reference Scenario GWh	2000	2005	2010	2020
East Denmark				
EEEP	2	190	460	1680
CEEP	0	0	0	0
Total	2	190	460	1680
West Denmark				
EEEP	520	3130	3360	5070
CEEP	0	170	290	1330
Total	520	3300	3650	6400

wind power but solely according to heat demands. In Denmark, CHP stations have been paid through a triple-tariff system with high payments in the morning and the afternoon, reflecting a high electricity demand during these periods, and low payments during night hours, weekends, and holidays.

Consequently, Danish CHP has been designed with relatively high CHP capacities and heat storage, making it possible to produce mainly during high-tariff periods. When electricity sales prices are high, the CHP unit operates at full capacity and stores the heat. When prices are low, the CHP unit stops, and heat for district heating is supplied from the storage. By 2001, this regulation ability had not been used to integrate fluctuations in renewable energy. It had only been used to adjust to changes in electricity demand by applying the so-called triple tariff. This means that production is given a low, medium, or high price, depending on production conditions, in other words, whether or not production takes place during peak load.

The second assumption behind the resulting high excess production is that the task of securing grid (voltage and frequency) stability has been managed solely by large power stations. Consequently, distributed production from small CHP units and wind turbines was considered a burden to the fulfillment of this task. As part of the study, the EnergyPLAN model was used to conduct analyses of how to avoid excess production problems (Lund and Münster 2001; 2003b).

Most of the analyses in the coming sections of this chapter apply to West Denmark. However, because it was later decided to connect the two Danish systems, some analyses were based on a joint reference system including all of Denmark. Moreover, the work of the expert group only included analyses of the electricity system. Consequently, data for the remaining sectors, including the transportation sector, have been added on the basis of the official Danish energy plan, Energy 21 (Danish Ministry of Environment and Energy 1996). The main data of the joint reference scenario are given in Table 5.2.

Electrification of Transportation Scenario

Several of the studies presented in this chapter include the conversion of parts of the transportation fleet into electric vehicles in combination with hydrogen fuel cell vehicles. All of the studies are based on a scenario described by Risø National Laboratory, Electric Vehicles and Renewable Energy in the Transport Sector—Energy System Consequences (Nielsen and Jørgensen 2000). This report concludes that the technical performance, particularly the range, of battery cars and hydrogen fuel cell cars will gradually improve in the coming decades, making it feasible to replace a substantial part of the transportation task of passenger cars and small delivery vans below 2 tons by these types of cars. By the year 2030, 80 percent of the Danish vehicles weighing less than 2 tons are to be replaced by a combination of battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs). According to the study, this transformation will lead

TABLE 5.2 Reference Energy System: Denmark 2020

Key Data	TWh/year
Electricity demand	41.1
District heating demand	30.0
Excess electricity production (CEEP + EEEP)	8.4
Primary Energy Supply	
Wind power	17.7
Fuel for CHP and power stations	92.3
Fuel for households	19.7
Fuel for industry	20.2
Fuel for transport	50.7
Fuel for refinery and so forth	17.4
Total	218.0

to a rise in the electricity consumption by 7.3 TWh/year and fuel savings by 20.8 TWh/year. When applied to West Denmark, an alternative system has been defined in which 12.6 TWh of gasoline is replaced by 4.4 TWh of electricity, equal to the share of West Denmark.

2. EXCESS ELECTRICITY DIAGRAMS[2]

This section is based on Lund's (2003a) article "Excess Electricity Diagrams and the Integration of Renewable Energy", which presents a method for demonstrating the ability of a given energy system to use specific RES in the electricity supply. In the article, the method is applied to the large-scale integration of wind, PV, and wave power into a future Danish reference energy system. The RES integration potential is expressed in terms of the ability of the system to avoid excess electricity production. The different energy sources are analyzed according to an electricity production ranging from 0 to 100 percent of the electricity demand. The analyses have taken into account the fact that certain ancillary services are needed to secure the grid stabilization (voltage and frequency) of the electricity supply system. As a conclusion, excess electricity diagrams show the different patterns of each of the RES. As we will see, these diagrams

2. Excerpts reprinted from *International Journal of Sustainable Energy*, 23/4, Henrik Lund, "Excess electricity diagrams and the integration of renewable energy", pp. 149–156 (2003), with permission from Taylor and Francis.

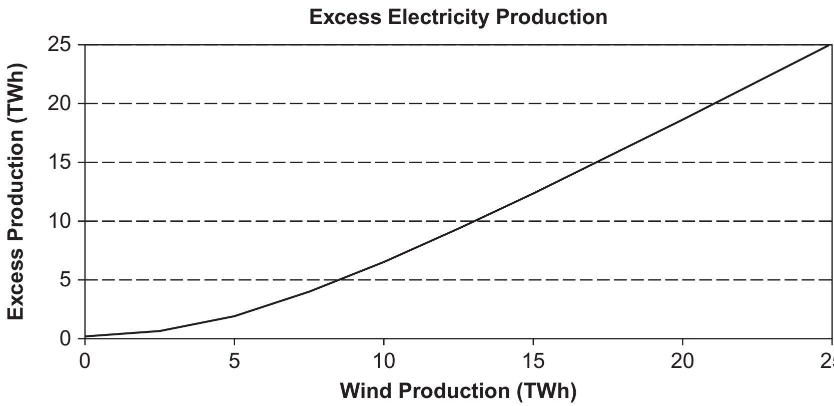


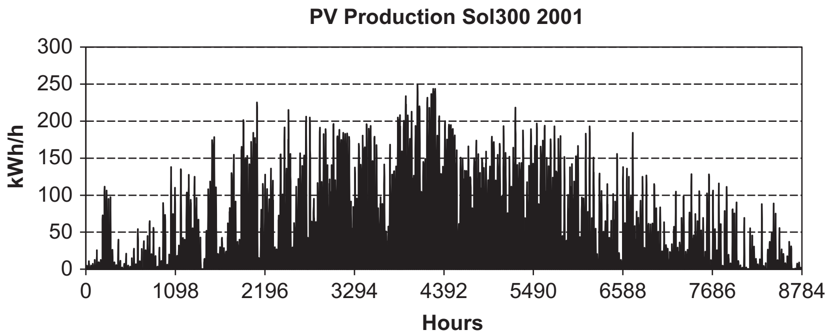
FIGURE 5.1 Excess electricity production diagram for the reference energy system, West Denmark, 2020.

are capable of showing the general characteristics of a given system even though the fluctuations of RES differ from one year to another.

The analyses that follow were made for West Denmark in 2020, as described in the previous section. For such reference energy systems, the ability to integrate a fluctuating RES can be illustrated in diagrams, as shown in Figure 5.1. The diagram shows the resulting annual excess production of the system as a function of the share of wind power, assuming that wind power has the exact same hourly distribution as it did in West Denmark in 2001.

Figure 5.1 is based on a series of 1-year complete energy system analyses of the system made in the EnergyPLAN model. Each analysis includes hour-by-hour calculations of all electricity production and demands given the specified production units and regulation strategies. Based on these calculations, annual electricity production is identified, including excess electricity production defined as the difference between the total electricity production and the demand. In the case of Figure 5.1, the system was first analyzed with a wind power input of 0 TWh/year. Then the input was raised in steps of 5 TWh/year up to 25 TWh/year.

The x-axis shows the wind power production between 0 and 25 TWh, equal to a variation from 0 to 100 percent of the demand (24.87 TWh). In addition, the y-axis shows excess production in TWh. The lower the excess production is, the better the integration of RES. In the article and in Figure 5.1, the analysis has been made with the following restrictions in ancillary services to achieve grid stability (voltage and frequency): At least 30 percent of the power (at any hour) must come from power production units that are capable of supplying ancillary services. At least a 350 MW running capacity of large power stations must be available at any moment. Distributed generation from CHP and RES is not capable of supplying ancillary services. As can be seen, the excess production in such a system is substantial.



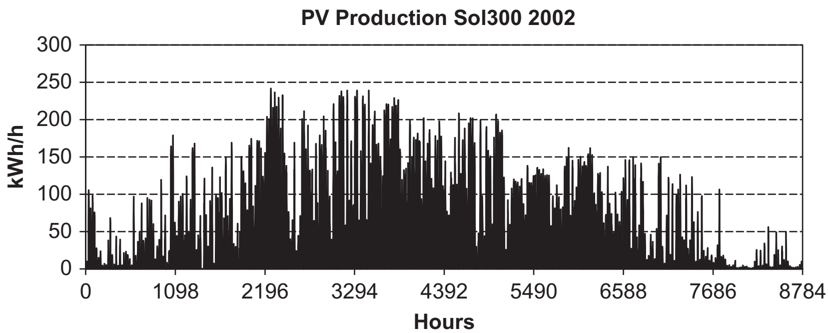


FIGURE 5.2 Hourly distributions of PV electricity production in the Danish Sol300 project.

In Lund's article, it was analyzed how the resulting excess electricity curve varies with the wind power production from one year to another. The same kind of analysis is made for PV and wave power. The hour-by-hour distributions of the different RES have been based on actual measurements whenever possible. In the case of PV, data based on actual measurements have been available. The distribution of electricity production derives from the Danish Sol300 project. The project involves 267 PV systems installed in typical one-family houses at eight locations in Denmark beginning in 2000. Distribution data have been provided for two years, as illustrated in Figure 5.2.

For onshore wind power, which has existed in Denmark for many years, the distribution is based on the actual production of wind turbines located in the reference area: West Denmark. These data have been provided by the transmission system operator (TSO) company of the region. Three years have been analyzed, and the data are shown in Figure 5.3.

Data based on actual measurements are not yet available for Danish wave power. So far, wave power stations in Denmark have existed only as small test facilities. The distribution of wave power is therefore made on the basis of wave measurements in the North Sea off the west coast of Denmark. Distribution data have been provided for two years, as illustrated in Figure 5.4. Lund's article describes in more detail the sources of the data for all three types of RES.

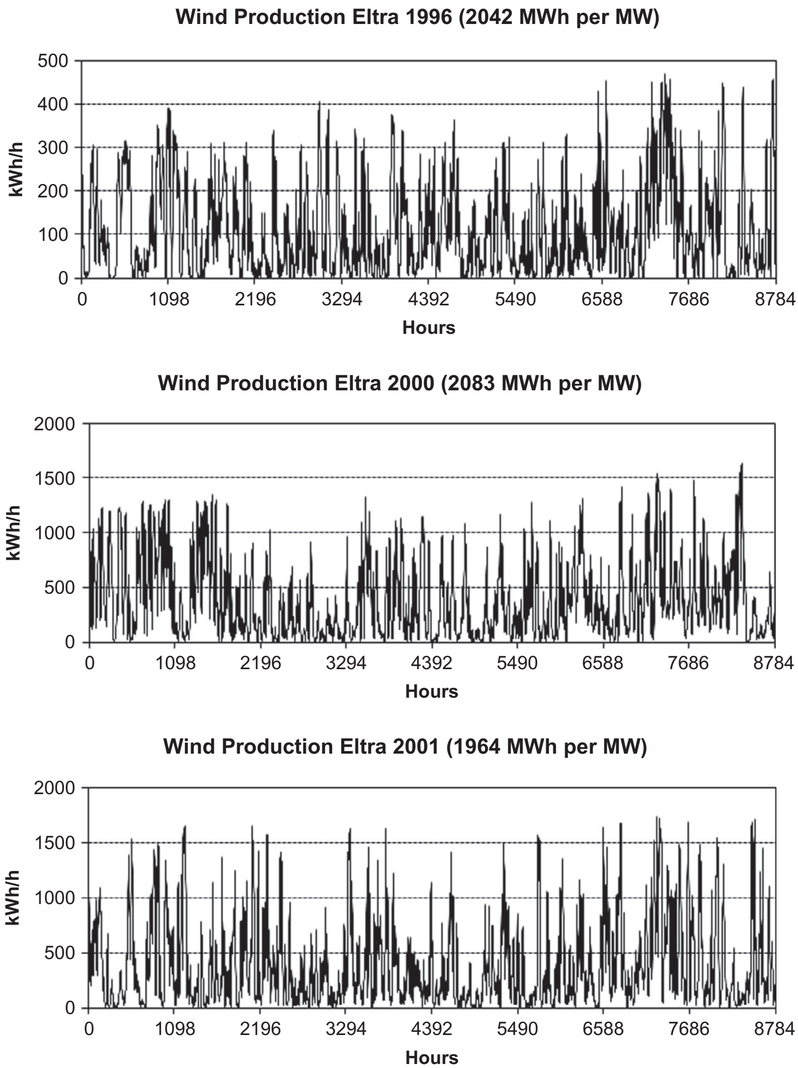


FIGURE 5.3 Hourly distributions of electricity production from onshore wind power in West Denmark (actual measurements of electricity production).

When you look at Figures 5.2–5.4, two obvious observations can be made. First, the electricity production from all three types of fluctuating RES evidently differs from one year to another. When comparing a specific hour on the same specific date of each of the two years, one may find that wind power production is high in 2000 and low in 2001. The same applies to the other two types of sources. However, even though the production differs, some main characteristics can be found and an overall picture can be identified. Thus, looking at these figures, it is quite easy to distinguish between wave and wind power.

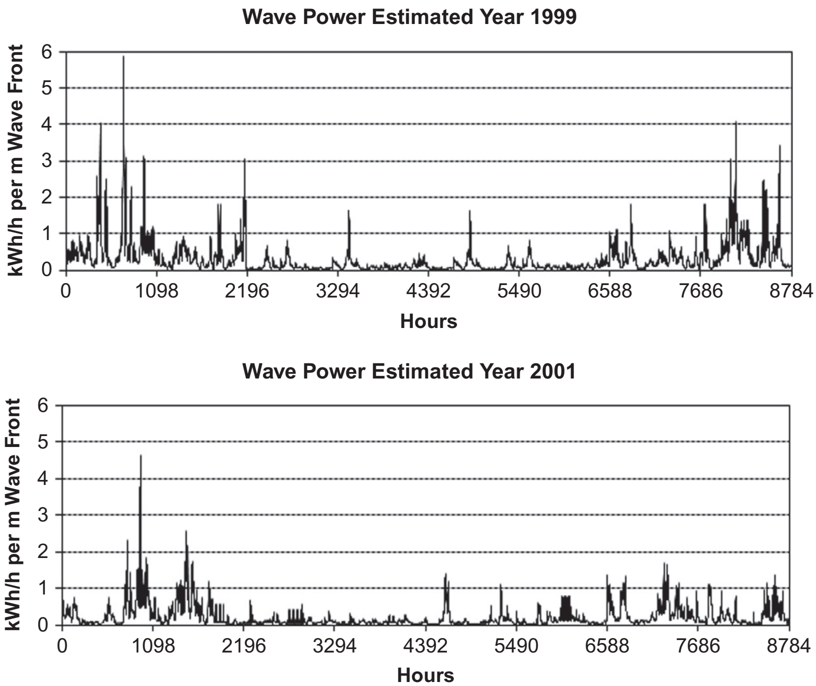


FIGURE 5.4 Estimated hourly distributions of electricity production from wave power based on wave measurements in the Danish North Sea.

Excess electricity production diagrams have been made for the three types of sources and the years shown in Figures 5.2–5.4. Moreover, a "synthetic" PV year is analyzed on the basis of statistically typical numbers and distributions of solar power in Denmark—the so-called Test Reference Year. The results of the different RES are shown in Figure 5.5. In general, PV is the RES that generates the highest excess production, followed by wave power and onshore wind power in the analyzed system.

The analysis revealed one important fact: It was discovered that even though significant variations can be seen from one year to another, the results in terms of excess production curves are almost exactly the same for each of the individual RES. This discovery is important because the excess electricity diagrams may then serve as an illustration of the ability of a system to integrate fluctuating RES, which does not depend on the difference in fluctuations between the different years. Consequently, the distribution of wind power of all years can be shown by the same curve. This makes it possible to compare different energy systems in terms of their ability to integrate RES on a large scale by comparing two curves in the same diagram. Depending on whether a year is good or bad in terms of wind, one may have to go a bit up or down the curve from one year to another, but it is still the same curve.

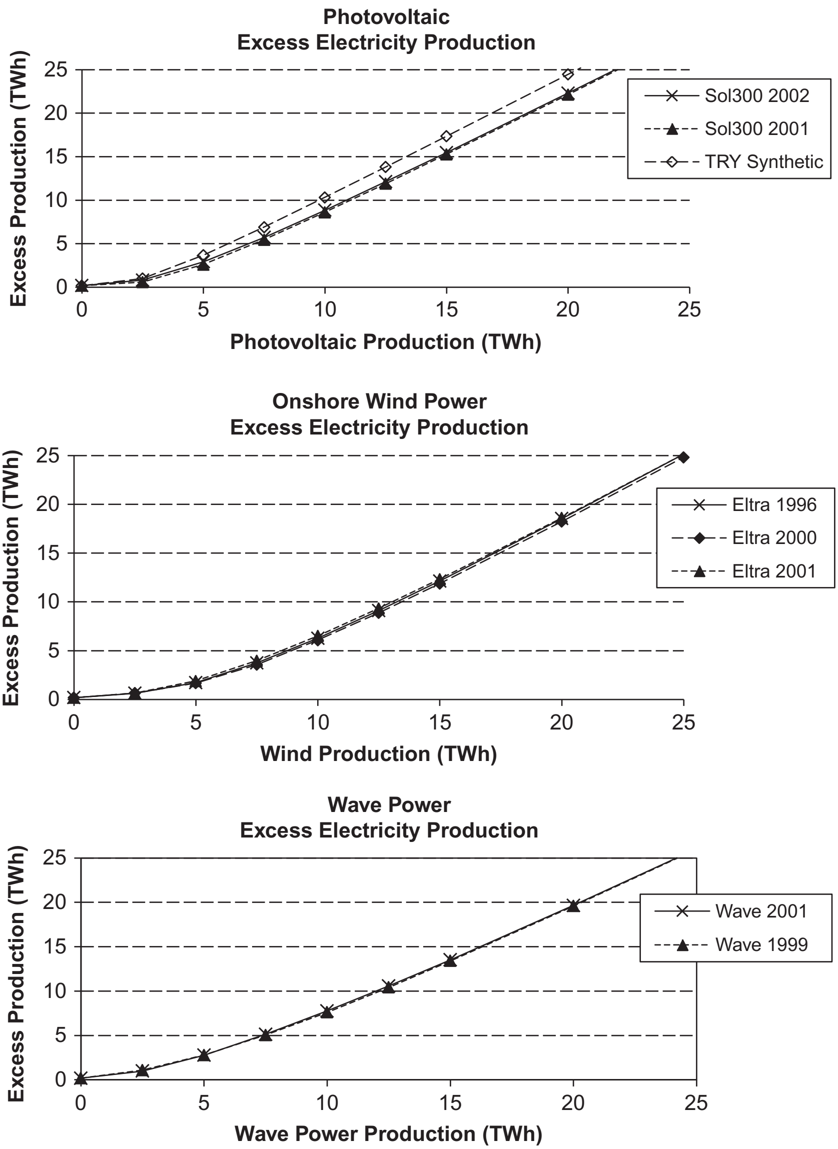


FIGURE 5.5 Excess electricity diagrams for different years, showing hourly distribution of electricity production from wind, wave, and PV power.

The only curve that differs in Figure 5.5 is the curve of the *synthetic* PV, which shows an excess production slightly higher than the two curves based on actual measurements. This is due to the fact that the actual measurements include an element of correlation between the many locations, whereas the synthetically generated distribution, in principle, assumes all installations to be located on the same spot. This emphasizes the importance of using measurements and not synthetic data. Actual data that reflect the dispatched locations of distributed RES are better than both actual measurements of one location and synthetic data. This also indicates that the result of the synthetic wave power data may provide a minor overestimation of the excess production.

In Figure 5.6, a curve representing 2001 is shown for the three different types of RES and compared to one another. As can be seen, the curves representing PV are a little higher than the two others.

The methodology of excess electricity diagrams does not only apply to the preceding reference system but to radically different systems as well. In Figure 5.7, the same diagrams are shown for two systems (which will be elaborated on in Chapter 7): a Danish business-as-usual reference system year 2030

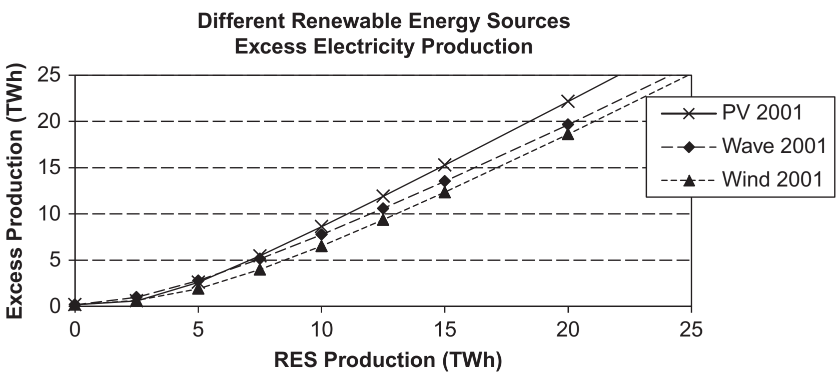


FIGURE 5.6 Excess electricity diagram comparing wind, wave, and PV power fed into the same energy system.

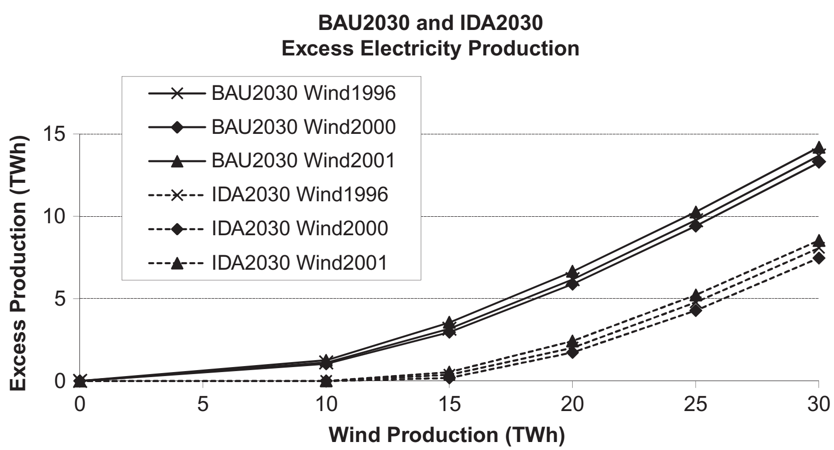


FIGURE 5.7 Excess electricity diagrams for two different energy systems (BAU2030 and IDA2030). The systems have been analyzed for three different years of hourly distributions of electricity production from wind power: Wind 1996, Wind 2000, and Wind 2001.

(BAU2030) and a radical change in design prepared by the Danish Society of Engineers (IDA2030). Both systems have been analyzed in the EnergyPLAN model for three different wind years: Wind 1996, Wind 2000, and Wind 2001. As can be seen, the differences in wind years only result in marginal changes in the excess electricity diagrams compared to the impacts of changing the system from BAU2030 to IDA2030. Thus, Figure 5.7 illustrates how these excess electricity diagrams can compare different energy systems in terms of their ability to use fluctuating sources such as wind. More important, this illustration does not change from one year to another even though the fluctuations in wind production do change.

3. OPTIMAL COMBINATIONS OF RES[3]

This section is based on Lund's (2006b) article "Large-Scale Integration of Optimal Combinations of PV, Wind, and Wave Power into the Electricity Supply", which presents the results of a series of analyses of large-scale integration of wind, PV, and wave power into the Danish energy system. It is based on the same data as already presented in Figures 5.2–5.4, and, again, the reference used is the projection of the future energy system in West Denmark by 2020. The idea is to use the different patterns in the fluctuations of different renewable sources, and the purpose is to identify optimal combinations of RES from a technical point of view.

The analysis is made on the basis of hourly distributions beginning in 2001, since data are available for all three types of RES in that year. By basing the analysis on the same year, any correlation between, for example, wind and waves is included in the study. The results are shown in curves of excess electricity production generated by increasing RES inputs. Results have been generated for each of the different RES and for relevant combinations to identify an optimal mixture. It should be added that electricity production from a single RES that equals 100 percent of the demand is hard to imagine in practice, especially for technologies such as PV and wave power. For example, an annual production of 25 TWh from PV requires approximately 25,000 MWp installed capacity, which is not financially or practically realistic. The same applies to wave power. Moreover, this amount of RES is not likely to be added to the reference system without improving the integration ability of the system and thereby decreasing excess production. Such improved systems are discussed in more detail later in this chapter. The analysis constitutes a valid illustration of the differences among the three different RES and serves as an important basis for the identification of optimal combinations.

3. Excerpts reprinted from *Renewable Energy*, 31/4, Henrik Lund, "Large-Scale Integration of Optimal Combinations of PV, Wind, and Wave Power into the Electricity Supply", pp. 503–515 (2006), with permission from Elsevier.

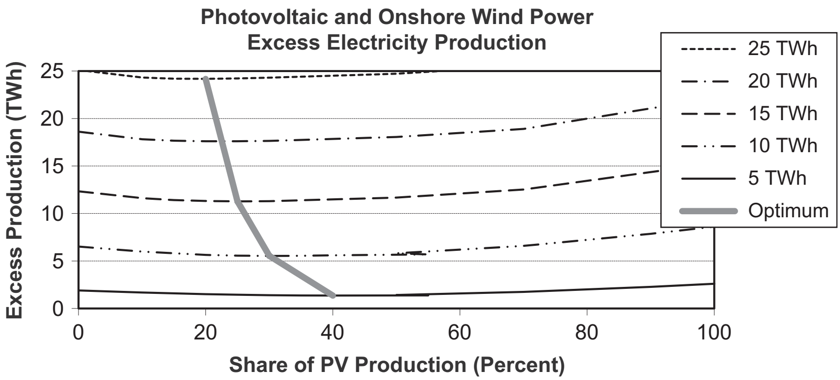


FIGURE 5.8 The analysis identifying optimal combinations of PV and onshore wind power.

The optimal combinations of two types of RES technologies are shown in Figure 5.8, along with the annual excess electricity production for the combination of onshore wind and PV power. The excess production generated has been calculated with different inputs of total electricity from RES. This is illustrated by the curves starting with a total of 5 TWh and rising in steps of 5 TWh to a total of 25 TWh. Each curve shows the resulting excess production of different shares of PV and wind power.

On the left side of Figure 5.8 the share of PV is zero, and on the right side, the share of PV is 100 percent. All curves show an optimal combination in which excess production is minimal. An optimal combination is achieved with a PV share of 20 percent when the total RES electricity production is high, and 40 percent when the total production is low. In the same way, optimal combinations of PV, onshore wind, and wave power have been identified. Figure 5.9 shows the optimal combination of the three RES, that is, the combination that generates minimum excess electricity production.

In Figure 5.10, the excess electricity diagram of the optimal combination (Optimix) is compared to the results of each of the different RES technologies, assuming that the same production is to come from only one type of RES. In general, PV is the RES with the highest excess production, followed by wave power and onshore wind power. The optimal combination of the three types of RES results in less excess production.

Figure 5.10 illustrates how the combination of different sources reduces the integration problem. However, the excess production is still considerable. It should be emphasized that a very high percentage of RES can be integrated into the electricity supply without any excess production if other measures are implemented, such as flexible energy systems (see the following sections). Figure 5.10 shows how a certain combination of RES units will enhance the effect of these implementation strategies.

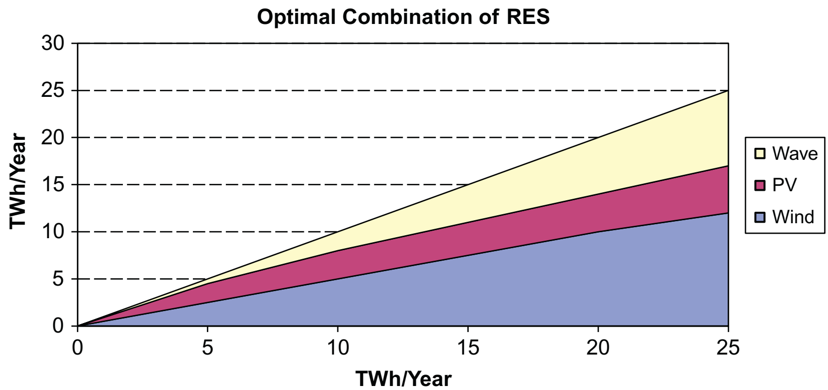


FIGURE 5.9 Optimal combination of the renewable sources, that is, the combination of minimum excess production.

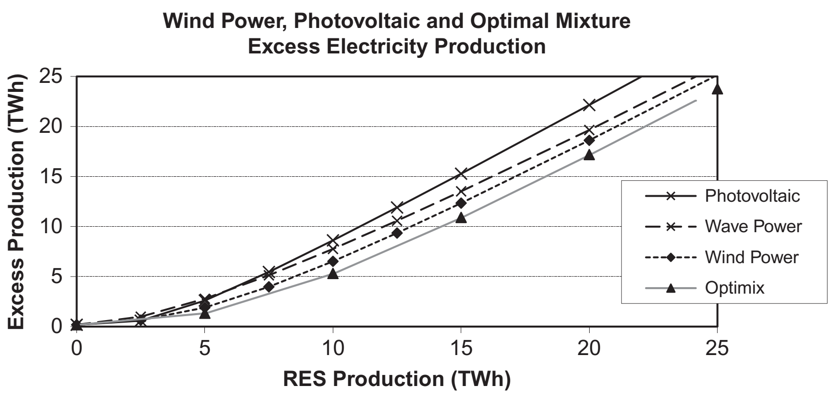


FIGURE 5.10 The integration of individual renewable sources compared to the optimal mixture.

The result illustrates how excess production increases when the RES input in terms of wind, PV, and wave power is raised. Meanwhile, combinations of different RES can slow down the increase in excess production. For example, an optimal combination of 20–40 percent PV and consequently 60–80 percent wind power has been found to generate less excess production than 100 percent of either PV or wind power alone.

As can be seen from Figure 5.9, the optimal mixture seems to be reached by an onshore wind power production of approximately 50 percent of the total renewable electricity production. Meanwhile, the optimal mixture between PV and wave power seems to depend on the total amount of electricity produced by RES. When the total RES input is below 20 percent of the demand, PV should cover 40 percent and wave power only 10 percent. When the total input is above 80 percent of the demand, PV should cover 20 percent and wave power

30 percent. The combination of different RES as the only measure is far from a solution to the RES integration problem. Other measures such as the investment in flexible energy supply and demand systems and the integration of the transportation sector have much more potential for solving the problem.

4. FLEXIBLE ENERGY SYSTEMS[4]

This section is based on Lund's (2003b) article "Flexible Energy Systems: Integration of Electricity Production from CHP and Fluctuating Renewable Energy", which discusses and analyzes different national strategies for large-scale integration of renewable energy. It points out key changes required in the energy system to benefit from a high percentage of wind and CHP without generating excess electricity production. Here, the altered system is referred to as a *flexible energy system*.

This study was made prior to the work of the Energy Agency's expert group mentioned previously. Thus, the study is not based on exactly the same reference scenario. However, the study used the expected development of the official Danish energy policy expressed in the government's energy plan, Energy 21, as a reference, and this reference is very similar to the previous one. According to Energy 21, the rate of wind power is expected to increase to approximately 50 percent in 2030, and excess electricity production is expected to increase accordingly and create serious problems for the regulation of the electricity supply. The magnitude of the problem is illustrated in Figure 5.11.

Even though electricity consumption is expected to decrease slightly, the production has to increase substantially. In 2030, the excess production is expected to constitute 80 percent of the electricity production from wind and

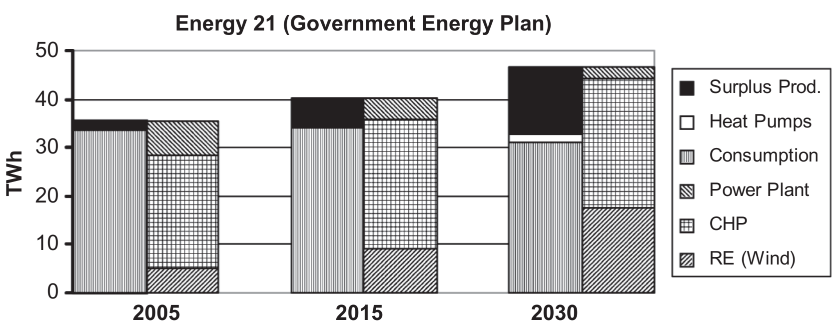


FIGURE 5.11 Electricity balance according to the Danish government's energy plan, Energy 21.

4. Excerpts reprinted from *International Journal of Energy Technology and Policy*, 1/3, Henrik Lund, "Flexible Energy Systems: Integration of Electricity Production from CHP and Fluctuating Renewable Energy", pp. 250–261 (2003), with permission from Inderscience.

other renewable resources. The implementation of the Danish energy policy according to Energy 21 is based on three initiatives: energy conservation resulting in slightly decreasing electricity consumption, the integration of more renewable energy sources, and the efficient use of fuels by CHP. The fluctuations in demand and production resulting in excess production are, in principle, the result of applying these three means at the same time. The fact that a high level of excess electricity production is expected, as illustrated in Figure 5.11, can be specifically explained by the assumptions that (1) the small- and medium-sized CHP stations are not expected to regulate according to fluctuations in wind power but solely according to heat demands and (2) the task of securing grid stability (voltage and frequency) is managed solely by large power stations.

Figure 5.11 illustrates an important condition; namely, that the excess production problem changes radically during the period. In 2005, the excess production was much lower than the production from condensing power stations. This means that, in principle, the problem can be solved solely by moving and/or storing electricity, in other words, by using *energy storage technologies*, as defined in Chapter 1. In 2030, on the other hand, excess production is expected to be much higher than the production from condensing power stations, which means that moving and/or storing the production cannot solve the problem. In that case, other sorts of changes are needed, such as *energy conversion technologies*, as defined in Chapter 1. As will be elaborated further in Chapter 6, one might say that, in the 2005 situation, the problem may be solved solely within the electricity sector, i.e., within the concept of *smart grid*; while in 2030, the problem can only be solved by involving the other sectors, i.e., within the concept of *smart energy systems*.

The reference was modeled in the EnergyPLAN model, and the results are shown in Figure 5.12. The diagrams show the implementation of the Energy 21 reference from Figure 5.11 in four weeks representing winter, spring, summer, and fall. Consumption is shown to the left and production to the right. "Export" represents excess production. Figure 5.12 illustrates how excess electricity production is mainly the result of combinations of wind power and CHP. Meanwhile, the constraints of maintaining grid stability sometimes require that power stations without CHP produce in periods with excess production and thus add to the problem. Figure 5.12 shows that the excess electricity production problem is substantial all year round.

Flexible Energy System

The EnergyPLAN model has analyzed various investment and regulation means to find suitable designs of flexible energy systems. The following initiatives seem to be the most important ones:

Regulation of CHP: The fact that CHP stations are not expected to regulate according to fluctuations in wind power, but solely according to heat

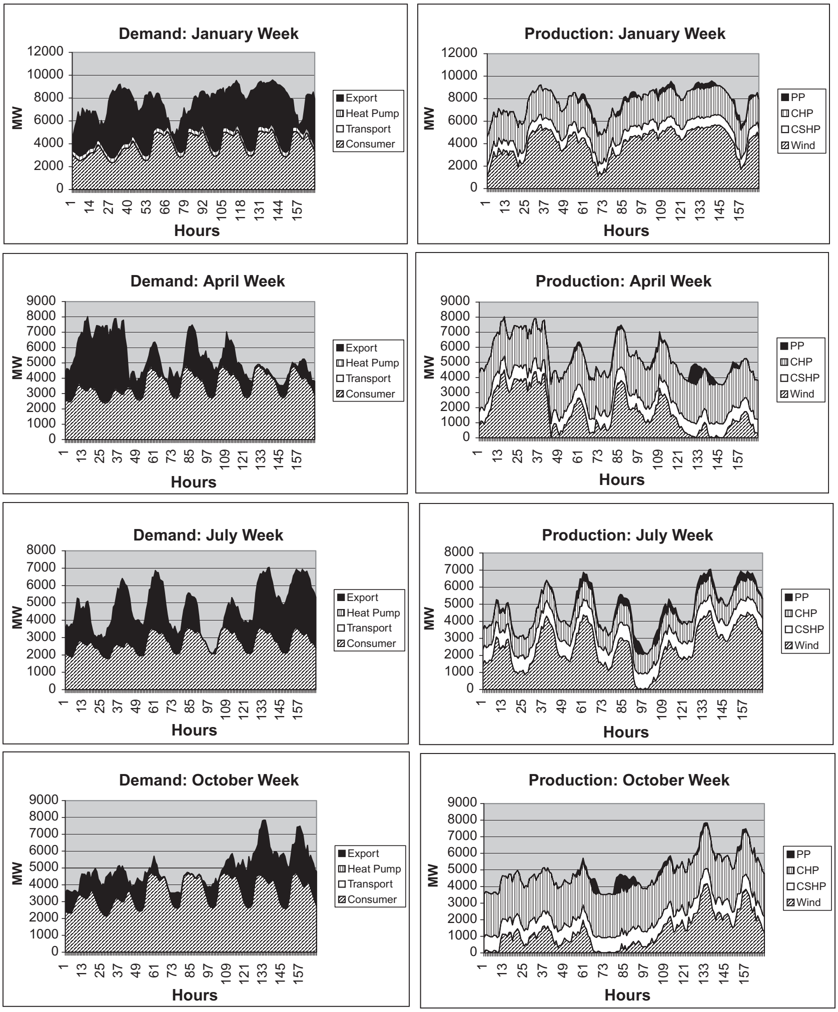


FIGURE 5.12 Excess production (export) in energy plan, Energy 21. PP: power plants; CSHP: industrial combined steam and heat power.

demand, is significant to the size of the excess electricity production problem shown in Figures 5.11 and 5.12. Consequently, an alternative regulation strategy has been analyzed in which CHP stations are partly replaced by heat production from boilers in case of excess electricity production. This change in strategy can solve the problem in the beginning of the period, when the problem is small. Meanwhile, the benefit of using CHP decreases, and the result is lower fuel efficiency (the rate of fuel per unit of heat and electricity produced increases).

Investments in heat pumps and heat storage capacity: Adding heat pumps to the systems means that they can be used instead of boilers to restore fuel efficiency. Additionally, the energy system becomes much more flexible in more than one way. First, using heat pumps can decrease excess electricity production. Second, by replacing CHP heat production by heat pumps, the flexibility of the CHP stations is increased as long as the capacity is maintained. Third, by adding heat storage capacity to the system, the flexibility is further increased. This flexibility can solve most of the excess electricity production problems. Meanwhile, situations in which the production from big power stations is needed to maintain grid stability will arise more often and limit the decrease in excess electricity production.

Grid-stabilizing CHP and wind power: The task of securing grid stability (voltage and frequency) had so far been managed only by large power stations. Consequently, distributed production from small- and medium-sized CHP units and wind power may become a burden and may set a limit to the fulfillment of this task. This limit can be overcome by involving distributed production units in securing grid stability.

The following flexible energy system has been analyzed using the EnergyPLAN model:

- The CHP units in the energy system are supplemented by heat pumps equal to ~1000 MW of electric power in 2030 and heat storage capacity equal to the heat consumption of approximately 1 day.
- CHP units and heat pumps are operated according to a strategy of meeting the difference between demand and wind power production.
- All CHP units and wind turbines built after 2005 are involved in securing grid stability.

The result of implementing this system is shown in Figure 5.13. Fuel efficiency is maintained, while most of the excess electricity production has been avoided.

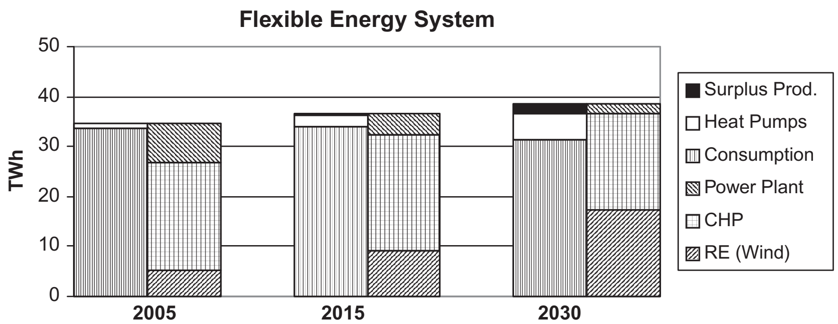


FIGURE 5.13 Electricity balance when implemented by flexible energy systems.

Flexible Energy Systems Including Electricity for Transportation

As the percentage of wind power increases, it becomes more and more difficult for flexible energy systems, based on CHP, heat pumps, and heat storage, to manage excess electricity production. Sooner or later, further initiatives will have to be taken. The electrification of the transportation sector results in better flexibility and, at the same time, improves the fuel efficiency. The analyses used an earlier version of the EnergyPLAN model in which the modeling of transportation was not a specific subject. However, it was possible to do a modeling of the flexible electricity demands arising from the use of electricity for transportation (batteries and/or hydrogen). These demands were assumed to be evenly distributed over the year but could be made flexible within shorter periods of time.

The EnergyPLAN model has evaluated the possibilities of integrating the transportation sector into the energy system. By 2030, 80 percent of the Danish vehicles weighing less than 2 tons will be replaced by a combination of BEVs and HFCVs, leading to a rise in the electricity consumption by 7.30 TWh/year and fuel savings by 20.83 TWh/year.

The electricity transportation scenario has been analyzed along with the preceding flexible energy systems based on CHP, heat pumps, and heat storage. The results of the analysis are shown in Figures 5.14 and 5.15. In the analysis shown, electricity for transportation has been made flexible within a period of 1 day. Figure 5.14 illustrates how excess electricity production is nearly removed, even in 2030. Figure 5.15 shows how consumption and production are balanced by regulating CHP and heat pumps together with the use of electricity for transportation for a period of 4 weeks.

When the official Danish energy plan, Energy 21, was launched in 1995, Denmark's main policy was to export the problem simply by selling future excess production on the European electricity market. However, Europe cannot solve the total problem if every individual country adopts the same policy. Furthermore, Denmark has to face problems of low revenues and high

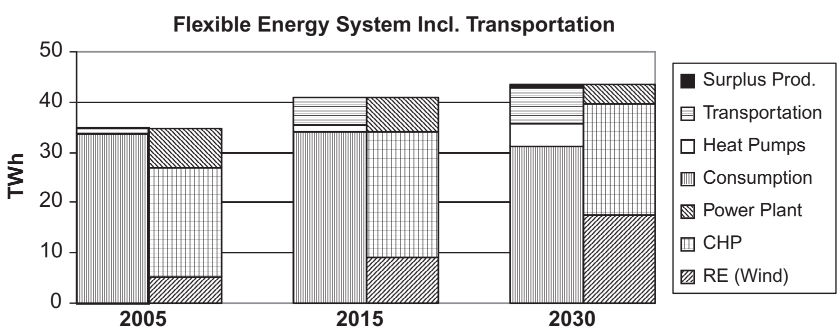


FIGURE 5.14 Electricity balance when implemented by flexible energy systems, including electricity for transportation.

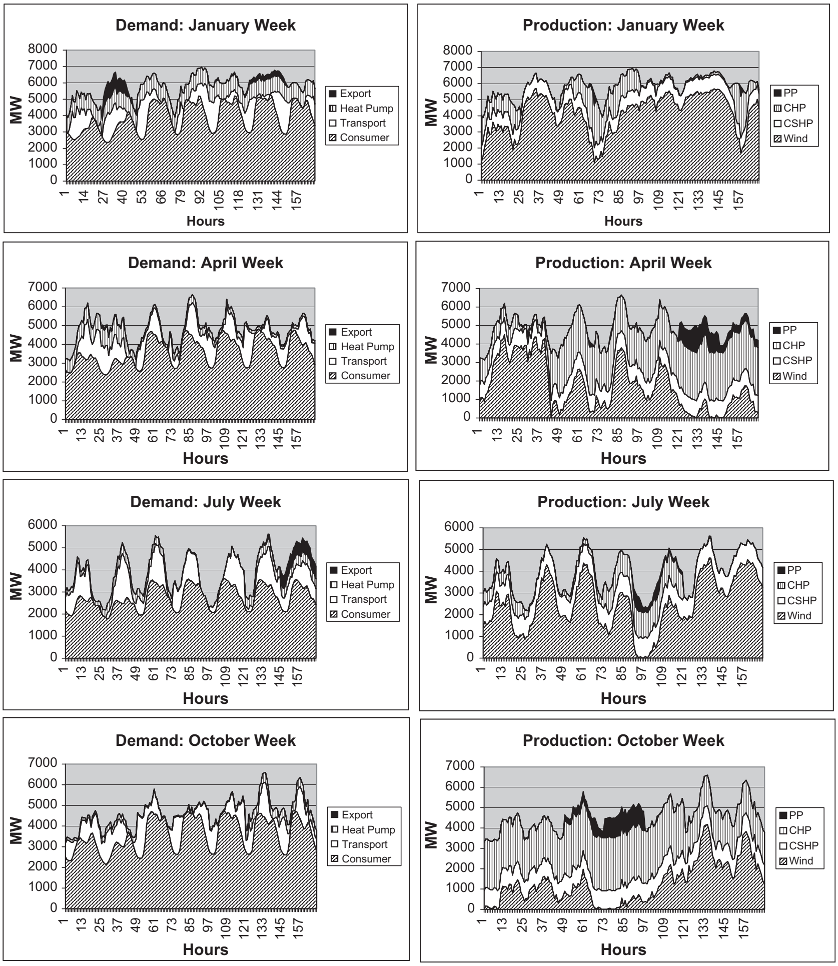


FIGURE 5.15 Excess electricity production (export) when implemented with flexible energy systems, including transportation. PP: power plants; CSHP: industrial combined steam and heat power.

investments in transmission lines and meet agreements of reducing CO_2 emissions. The introduction of flexible energy systems can solve the problem of integrating fluctuations from a high percentage of renewable energy and distributed CHP production. The key factors of this solution seem to be the following:

- Making CHP stations operate according to fluctuations in RES
- Investing in heat pumps and heat storage capacity
- Integrating small CHP stations and wind power when securing grid stability
- Integrating the electricity sector and the transportation sector by introducing electric vehicles (battery and hydrogen)

By introducing such flexible energy systems to reduce the export of excess electricity production, fuel consumption and CO_2 emissions in Denmark are reduced accordingly. In the case of integrating the transportation sector by converting to battery and hydrogen vehicles, the total reduction in fuel consumption is very high because of the low efficiencies of vehicle combustion engines.

5. DIFFERENT ENERGY SYSTEMS[5]

This section is based on Lund's (2005) article "Large-Scale Integration of Wind Power into Different Energy Systems". Earlier in this chapter, excess electricity diagrams were presented for the integration of renewable energy into a reference energy system of West Denmark 2020. Here, the same reference system is compared to other energy systems. Excess electricity diagrams are supplemented by CO_2 emission reduction diagrams, and the impacts of adding flexible technologies are presented. Thus, the article discusses the abilities of different energy systems and regulation strategies to integrate wind power.

In this article, the reference system has been defined as the present regulation adjusted by a number of measures that may be introduced to avoid critical excess production. Thus, the reference regulation can be described as follows:

- All wind turbines produce according to fluctuations in the wind.
- All CHP stations produce according to heat demand (or triple tariff).
- Only large power stations participate in the task of balancing supply and demand and securing grid stability.
- Minimum 300 MW and minimum 30 percent of the production must come from grid-stabilizing power stations.
- CEEP is avoided by applying the following priorities: (1) replacing CHP with boilers; (2) using electric heating; and (3), if necessary, stopping the wind turbines.

This reference system has been compared to the following three alternative energy systems:

50 percent more CHP: In the reference system, 21.21 TWh equaling approximately 50 percent of the total Danish heating demand is produced by CHP. An alternative system has been defined in which the share of CHP is increased by 50 percent to 31.82 TWh.

Fuel cell technology: Improvements of electric efficiencies in CHP units and power stations (as, for example, fuel cells) increase the efficiency and consequently decrease the fuel consumption. An alternative system has been defined by raising CHP electricity efficiencies from the average of 38 to 55 percent and power station efficiencies from 50 to 60 percent.

5. Excerpts reprinted from *Energy*, 30/13, Henrik Lund, "Large-Scale Integration of Wind Power into Different Energy Systems", pp. 2402–2412 (2005), with permission from Elsevier.

Electrification of cars: Based on the study of the electrification of cars (partly BEVs and HFCVs), an alternative system has been defined in which 12.6 TWh of gasoline can be replaced by 4.4 TWh of electricity.

The results of the analyses of the alternative systems are shown in Figure 5.16. The diagram illustrates how improvements in terms of more CHP (50 percent CHP) and better efficiencies (fuel cell) accelerate the excess production problem, while the electrification of cars (transport) decreases this problem. At the starting point, without any wind power, all improvements decrease CO_2 emissions compared to the reference energy system. However, along with the increase of wind input, only the electrification of cars maintains a good CO_2 reduction ability.

If all three alternative improvements in Figure 5.16 are combined, the excess production becomes severe even in the case of no wind power. The ability of such a system to integrate wind power has been compared with a number of alternative regulations. These are based on the principle that small CHP units

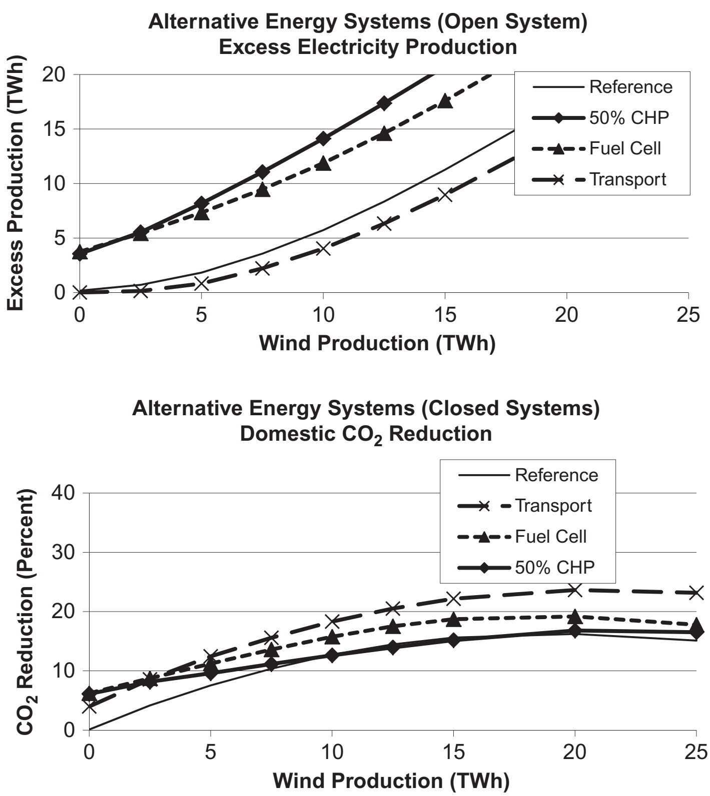


FIGURE 5.16 Excess electricity production and domestic CO_2 reduction in the three alternative energy systems compared to the reference.

are involved in the grid stabilization task and that these CHP units operate to integrate wind power by reducing their electricity production at hours of excess production. Three variants replacing heat production by other devices have been analyzed:

- *CHPregB*: Boilers replace CHP heat production.
- *CHPregEH*: Electric heaters (boilers) replace CHP heat production.
- *CHPregHP*: Heat pumps replace CHP heat production.

Figure 5.17 shows the results of adding alternative regulation systems to the reference system shown in Figure 5.16. Figure 5.17 shows how important it is to involve the CHP units in the regulation. This measure alone decreases excess production radically. Meanwhile, if the CHP units are replaced by boilers (CHPregB), the fuel efficiency is decreased and the potential for reducing CO_2 emissions is not fully exploited. Adding electric heating to the system

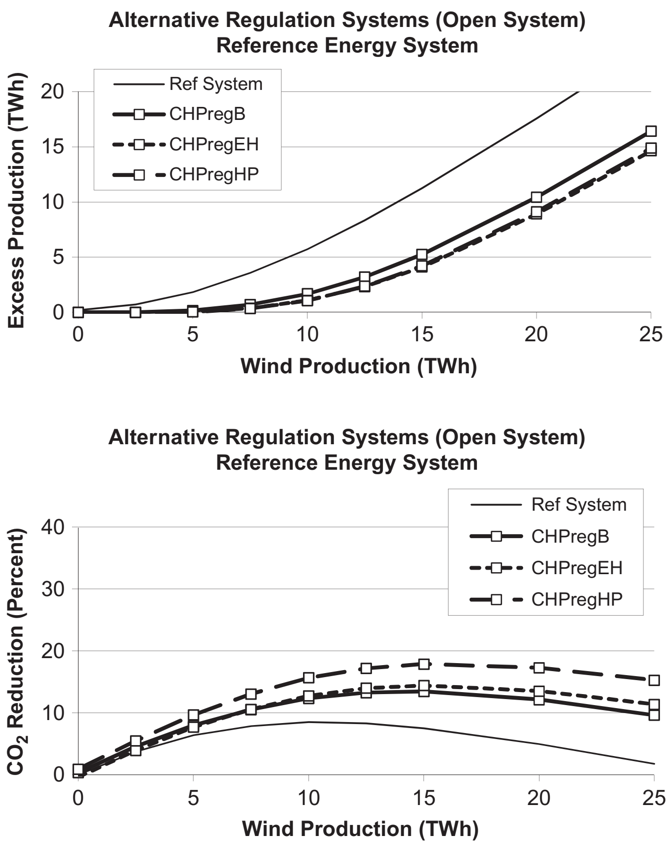


FIGURE 5.17 Excess electricity production and domestic CO_2 reduction of the three alternative regulation systems applied to the reference energy system.

(CHPregEH) does not solve the problem, but the introduction of heat pumps (CHPregHP) makes it possible to decrease the excess production and, at the same time, maintain fuel efficiencies. In the next chapter, an example is given of how the solution of including existing small CHP units in the regulation has been implemented in the Danish system, which is a part of the Nord Pool electricity market.

Figure 5.18 shows the results of adding the previously mentioned alternative regulations to a system in which all three system changes presented in Figure 5.16 are implemented, that is, increasing CHP and introducing fuel cells and electricity for transport. Again, the diagram shows how important it is to involve the CHP units in the regulation.

Together, the results of Figures 5.17 and 5.18 confirm the results of the analysis of flexible energy systems and show that this conclusion is also valid for the three other systems. Moreover, the article illustrates how different energy

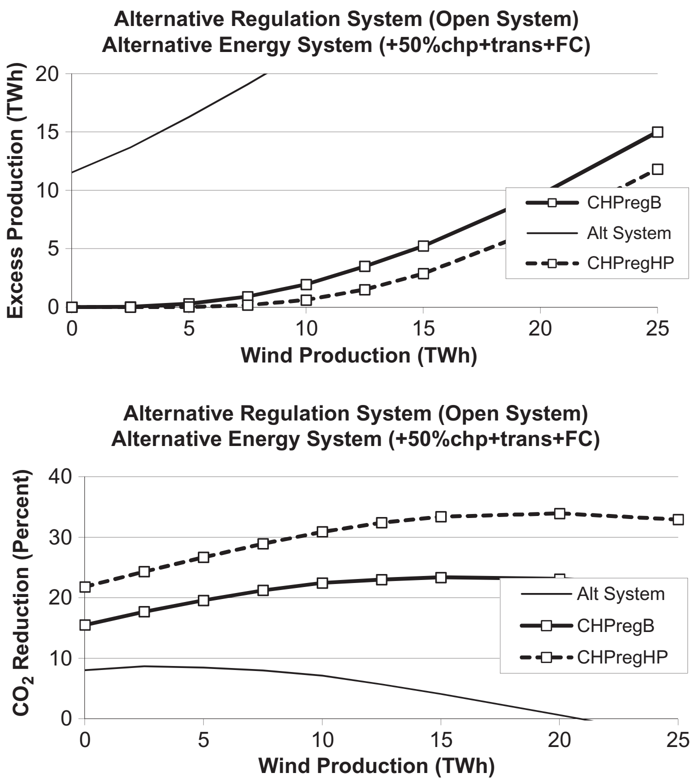


FIGURE 5.18 Excess electricity production and domestic CO_2 reduction of the three alternative regulation systems applied to the alternative energy system including an increase in CHP as well as the introduction of fuel cells and electricity for transportation.

systems can be compared to one another in the same diagram in terms of their ability to integrate RES on a large scale.

6. GRID STABILITY[6]

This section is based on Lund's (2004) article "Electric Grid Stability and the Design of Sustainable Energy Systems", which analyzes the significance of including future distributed CHP and renewable power production units in the task of grid stabilization, that is, securing voltage and frequency stability of the electricity supply. Today, in most countries, electricity is produced either from hydropower or large steam turbines on the basis of fossil fuels or nuclear power. Electricity from distributed generation constitutes only a small part of the production. Until now, the tasks of balancing supply and demand and securing frequency and voltage on the grid are managed only by these large production units.

However, the implementation of cleaner technologies, such as renewable energy, CHP, and energy conservation, is necessary to secure future renewable energy systems. Consequently, such distributed production units sooner or later need to contribute to the task of securing a balance between electricity production and consumer demands. The article presents technical designs of potential future flexible energy systems, which will be able both to balance production and demand and to fulfill voltage and frequency stability requirements to the grid. Again, the analysis is based on the reference scenario for West Denmark by the year 2020, and again, an example is given in Chapter 6 of how the solution of including existing small CHP units in the grid stabilization has been implemented in the Danish system, which is part of the Nord Pool electricity market.

Figure 5.19 shows the starting point of the analysis. The task of securing a balance between electricity production and consumer demand has so far only been managed by large power stations. However, small-scale CHP units have the technical potential for solving some of the balancing problems. When the analysis was made, small- and medium-sized CHP stations did not participate directly in balancing wind power in Denmark. These stations, however, did contribute to the balancing of fluctuations in the demand. CHP stations have been paid through a triple-tariff system, with high payment between morning and late afternoon, reflecting a high electricity demand during this period, and low payment during night hours, weekends, and holidays.

Consequently, the Danish CHP units have been designed with relatively high production and heat storage capacities, making it possible to produce mainly during the high-tariff period. When electricity sales prices are high,

6. Excerpts reprinted from *International Journal of Sustainable Energy*, 24/1, Henrik Lund, "Electric Grid Stability and the Design of Sustainable Energy Systems", pp. 45–54 (2004), with permission from Taylor and Francis.

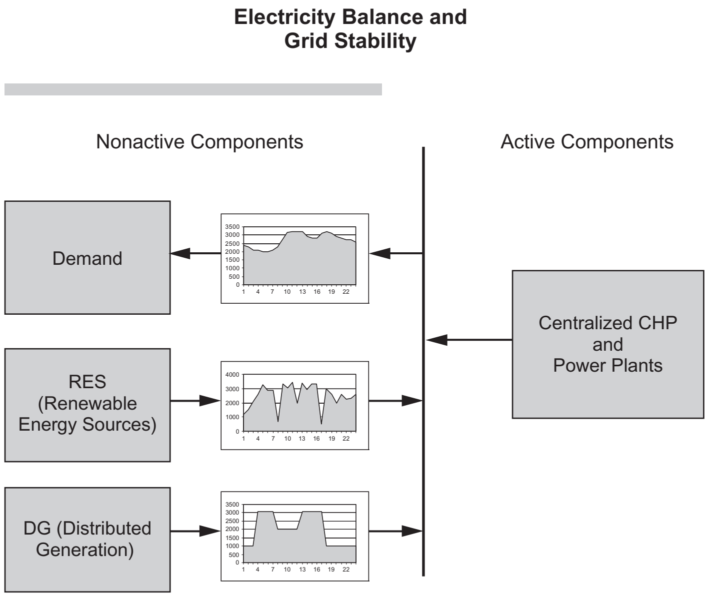


FIGURE 5.19 The current electricity system in Denmark.

the CHP unit operates at full capacity and stores excess heat in the heat storage. When prices are low, the CHP unit stops, and heat for district heating is supplied from the storage. Until 2004, this regulation ability was not used to integrate fluctuations in renewable energy.

Small CHP units can be used to balance the fluctuating output of wind power. The heat storage facilities of the CHP station are important features of this technique. Provided the excess heat production can be stored for future use, the CHP station is able to increase the electricity production when and if required for balancing activities, without any economic penalty.

In the current Danish system, both tasks are solved primarily by large power stations. In some countries, large hydropower stations participate in fulfilling the task as well. When the share of distributed generation is small, balance requirements will not be compromised. However, when the share increases, the balance may be at stake. Consequently, the system design has defined limits to the integration of CHP and RES. In Figure 5.19, small- and medium-sized CHP stations are illustrated as distributed generation components operating in accordance with a fixed triple tariff.

To identify limits and possible solutions to increasing the shares of RES and CHP, three potential future systems have been analyzed and compared with the existing system. Figure 5.20 compares a reference (system 0) with three potential future alternatives:

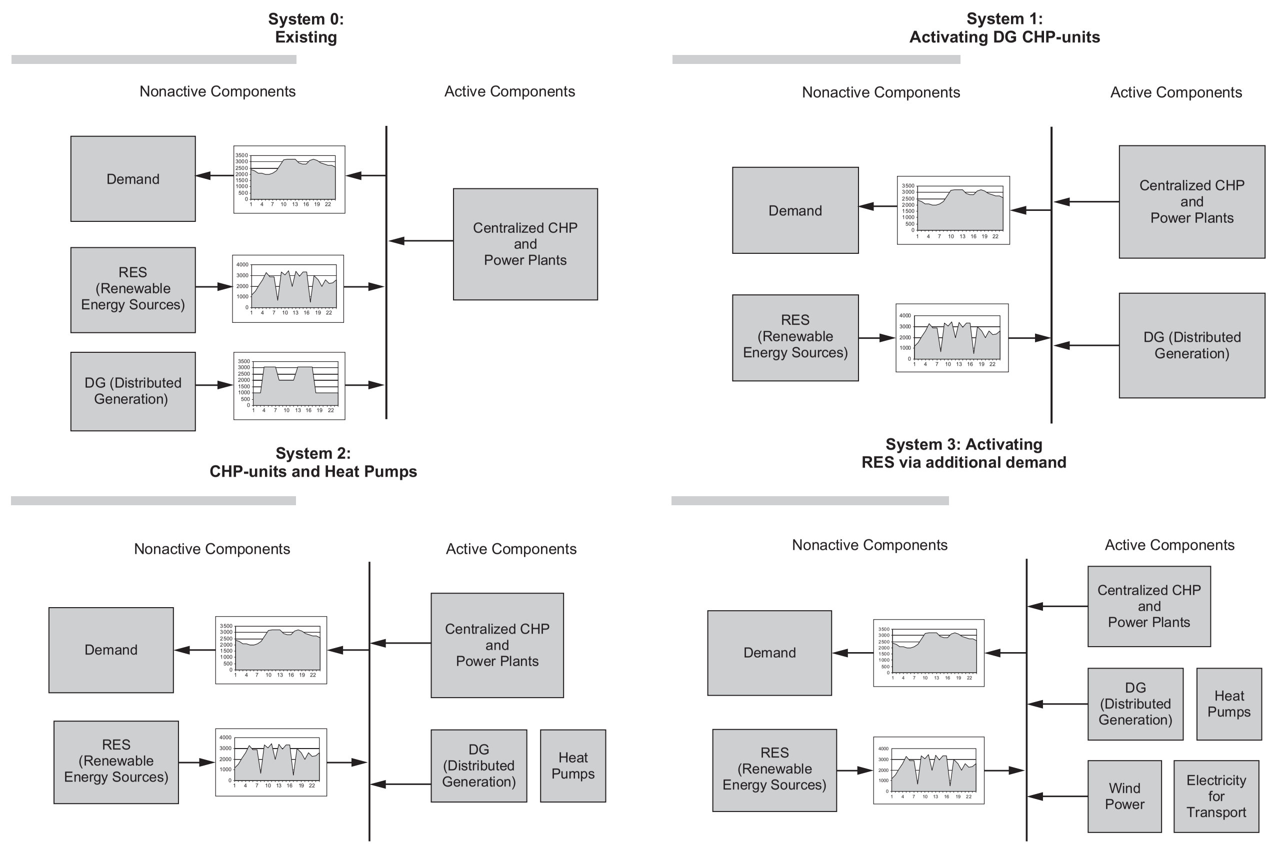


FIGURE 5.20 Different energy system designs with regard to grid stabilization.

System 0 (reference) is characterized by the following:

- Distributed generation units are operating according to fluctuations in heat demand during the season in question and to a fixed triple tariff during the period of 1 week.
- RES (i.e., wind turbines) are operated according to fluctuations in the wind.
- Centralized power stations, including large CHP stations, are operated to secure a balance between electricity demands and production while still meeting seasonal fluctuations in the district heating demand.
- The task of securing frequency and voltage stability is left solely to the centralized units, under the restriction that the production of these units must always correspond to at least 30 percent of the total electricity production, and the production must always be at least 350 MW (in order to have the necessary units operating).

This system represents the present system in Denmark.

System 1 (activating small- and medium-sized CHP stations): The system is the same as the reference apart from the fact that all CHP stations are operated to balance both heat and electricity production. If the electricity production exceeds the demand, parts of the CHP units are replaced by boilers. The heat storage capacities are used to minimize such replacements. The system has been analyzed both in a situation in which small- and medium-sized CHP stations do not participate in the grid-stabilizing task (System 1A) and in a situation in which they do participate (System 1B).
System 2 (adding heat pumps): In System 1, CHP production is replaced by heat production from boilers in periods of excess electricity production, and, consequently, the fuel efficiency is decreased. The idea of System 2 is to compensate for the increase in fuel consumption by adding heat pumps to the system. Furthermore, heat pumps increase the flexibility of the system because they can consume electricity at hours of excess production and, at the same time, replace the heat production of CHP units. Again, the system has been analyzed both in a situation in which the small stations do not participate in the grid-stabilizing task (System 2A) and in a situation in which they do participate (System 2B).
System 3 (including electricity for transport): In System 3, the electricity consumption for transportation is added to the regulation system according to the scenario described earlier in this chapter. Vehicles that weigh less than 2 tons are replaced by BEVs and HFCVs, respectively. In 2030, 20.8 TWh of oil will be replaced by 7.3 TWh of electricity. On the basis of this national scenario, it has been chosen to analyze a scenario for West Denmark in 2020, in which 3.2 TWh of electricity substitutes 9.8 TWh of oil.

In Lund (2004), both the reference and the three alternative regulation systems have been analyzed in terms of their ability to balance supply and demand in the given scenario with different wind power inputs. The results of the three

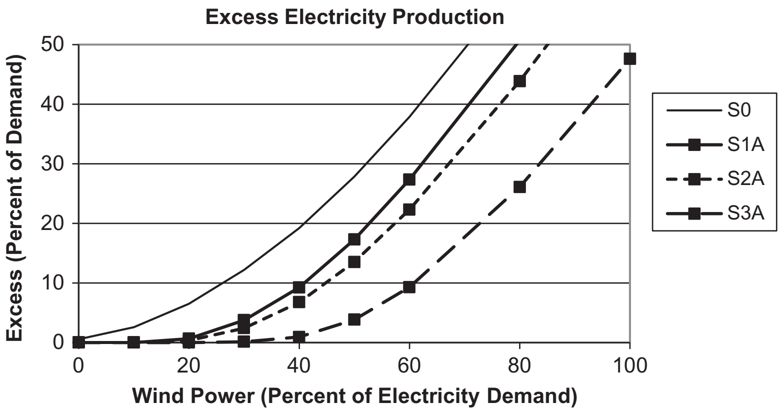


FIGURE 5.21 Excess electricity production in percentage of demand if small CHP units do *not* participate in the task of grid stabilization.

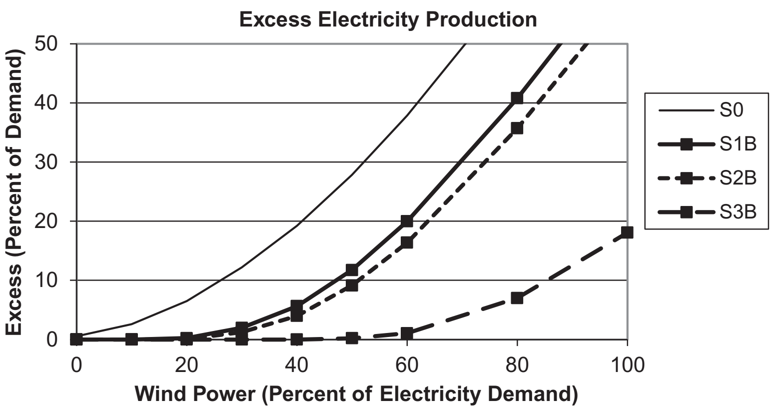


FIGURE 5.22 Excess electricity production in percentage of demand if small CHP units *do* participate in the task of grid stabilization.

regulation systems are shown in Figures 5.21 and 5.22. In System B, small CHP stations are involved in the task of grid stabilization, while in System A, they are not. In both diagrams, the results are compared with the reference (System 0). In Figures 5.21 and 5.22, the regulation ability is illustrated in terms of excess electricity produced as a function of wind power input. Both values are given as percentages of the electricity demand.

The diagram should be read as follows: for a given wind power input of 40 percent, the S0 curve representing the reference shows an excess electricity production of 20 percent. Consequently, only half of the wind power input can be used directly in the system. For the same input, the S3 curve (both S3A and S3B) shows an excess production of approximately zero.

Consequently, all wind power produced can be utilized directly if this regulation system is implemented.

In the West Denmark reference scenario, the wind power input in 2000 was 20 percent. Figures 5.21 and 5.22 illustrate how this wind power input creates a small excess production, which was actually the case in that year. Meanwhile, the excess production problem can easily be avoided by involving small- and medium-sized CHP units in the balancing task. In the Danish case, this step was partly implemented starting from 2004 and did decrease the problem significantly. In the reference scenario, the wind power input was planned to increase to 25 percent in 2005 and 35 percent in 2010. Consequently, further steps, such as involving CHP units in the grid stabilization task and/or investing in heat pumps, should be considered. By 2020, wind power had increased to almost 50 percent in the reference scenario. Thus, the inclusion of electricity for transportation should be considered, if excess electricity production is to be avoided. It might be added that even though the implementation of wind power in Denmark was slowed down in the period after 2004, the implementation is not far behind the plans referred to earlier. As a result, the wind power share in 2012 was nearly 30 percent and an increase to 50 percent by 2020 is being implemented.

7. LOCAL ENERGY MARKETS[7]

This section is based on Lund and Münster's (2006a) article "Integrated Energy Systems and Local Energy Markets", which takes its point of departure in the two research reports "Local Energy Markets" (Lund et al. 2004) and "MOSAIK" (Østergaard et al. 2004). The article adds to the analyses in the previous sections by making an economic feasibility study of flexible energy technologies. Moreover, the analysis includes the modeling of the Nordic electricity market Nord Pool. With the technical analyses of the previous sections of this chapter as the starting point, this analysis focuses on how Denmark can benefit from international electricity trade while integrating RES.

The conclusion is that significant benefits can be achieved by increasing the flexibility of the Danish energy system. On the one hand, the flexible energy system makes it possible to benefit from trading electricity with neighboring countries, and on the other, Denmark will be able to make better use of wind power and other types of renewable energy in the future. The article analyzes different ways of increasing the flexibility in the Danish energy system by using the same flexible technologies as described in the previous sections of this chapter. The strategy is compared with the opposite extreme, that is, trying to solve all balancing problems via electricity trade on the international market. The analysis concludes that it is feasible for Danish society to involve CHP stations

7. Excerpts reprinted from Energy Policy, 34/10, Henrik Lund & Ebbe Münster, "Integrated Energy Systems and Local Energy Markets", pp. 1152–1160 (2006), with permission from Elsevier.

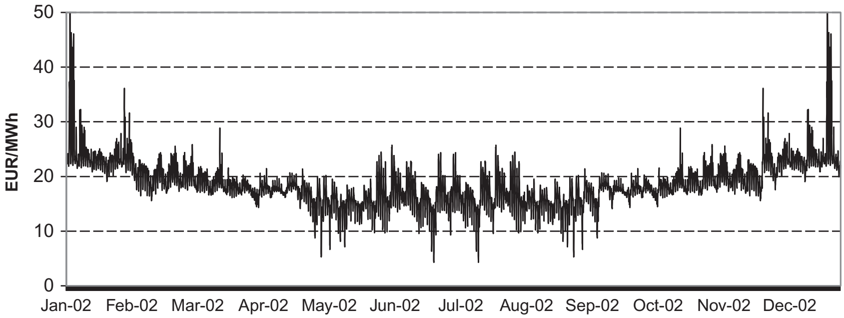


FIGURE 5.23 Typical spot market price fluctuations on the Nordic Nord Pool electricity market used as a basis for the analysis.

in the balancing of fluctuating wind power. Moreover, major advantages can be derived from equipping both small and large CHP stations with heat pumps. By doing so, it will be possible to increase the share of wind power from the 2004 level of 20–40 percent without causing significant problems of imbalance between electricity consumption and production, as already shown in the previous sections. As we will see in the following, this investment is also economically feasible to Danish society. Furthermore, it will have the positive side effect that the feasibility of large-scale wind power production is improved.

This article describes how the Nordic electricity spot market Nord Pool is modeled in the EnergyPLAN model and which data are used to make an economic feasibility study of the integration of wind power into different energy systems. The model is based on typical historical fluctuations in the Nord Pool prices, as shown in Figure 5.23.

Based on this price variation, the model includes a price elasticity function that evaluates the impacts of electricity export and import on the Nord Pool spot market prices. Export comprises excess electricity produced from CHP and wind power, while import covers electricity produced from hydropower in Norway and Sweden. The model includes the influence from a CO_2 emission trading market. Moreover, the model includes a combination of “wet”, “dry”, and “normal” years with regard to differences in the water content in the hydro reservoirs in Norway and Sweden. This analysis is based on a statistical 7-year cycle and includes the average of a 7-year period. The modeling as well as the data behind the analyses are described in detail in the article.

The model just described has been used to analyze the ability of flexible energy systems to integrate RES, as well as the consequences of this integration. The main purpose of the analysis has been to identify the changes required in the energy system to increase the flexibility and thereby the ability to integrate and utilize more wind power in the system. The EnergyPLAN model has been used to calculate the annual costs of the energy supply of West Denmark, including the exchange of electricity on the Nord Pool market and the cost of investing in

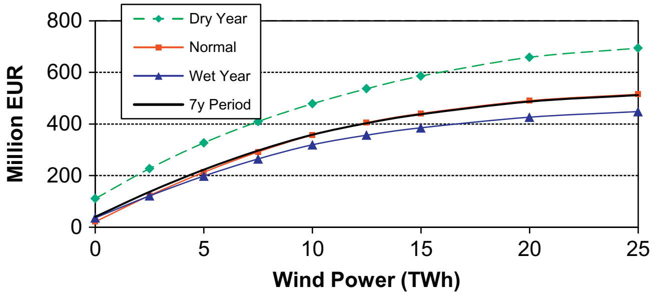


FIGURE 5.24 Annual income (including CO_2 payment) from trading wind power on Nord Pool.

flexibility, if any. The input of wind power has been analyzed in relation to an annual wind electricity production ranging from 0 to 25 TWh, equal to 100 percent of the electricity demand in West Denmark.

First, the value of wind power has been calculated as integrated into the reference energy system with no investments in flexibility. Then the value has been calculated together with different kinds of flexibility investments. In Figure 5.24, the annual income of wind power including CO_2 payment has been calculated for each of the three different years: wet year, normal year, and dry year. Also, the average of a 7-year period is shown in the diagram. The result is the net income of Danish society of different levels of annual wind production assuming that the system seeks to optimize exchange on Nord Pool. The net income is shown as the extra income when compared to the situation with no wind and "no trading", in other words, running the system with as little import/export as possible. No investment costs are included in Figure 5.24. The diagram illustrates how market exchange in combination with wind power is an advantage for Denmark in all situations, but the net profit achieved by a marginal expansion of wind power decreases with the increase of annual wind power production.

In Figure 5.25 (top), the curve of the average of the 7-year period is shown including investment costs of wind power (20-year lifetime, 5 percent net interest rate). The optimal wind power investment is given for the maximum value of the curve. The location of this point is better illustrated in Figure 5.25 (bottom), in which marginal net profit (without investments) is compared with marginal production costs, including investments in wind power expansion. Figure 5.25 is based on the reference assumption of an international CO_2 price of 13 EUR/ton and, as illustrated, a wind power production cost of 29 EUR/MWh.

It has been analyzed whether investments in new large steam turbine power stations are feasible in such a system. The analysis concludes that the possibilities of increasing the profit of trading are very limited, and the additional income is far from sufficient to repay the investment. As illustrated, the value of wind power in the reference energy system decreases rapidly as wind power investment increases. The marginal profit gained will soon be lower than the

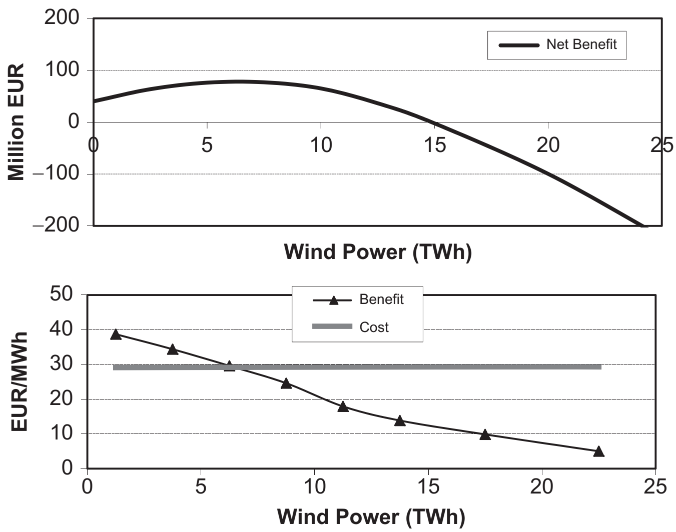


FIGURE 5.25 Net profit (top) and marginal cost benefit (bottom) of wind power (per year).

marginal costs of installing new wind power capacities, even when a CO_2 payment of 13 EUR/ton is included. The rapid decrease illustrates the problems of integrating electricity production from fluctuating renewable sources when the reference energy system is not regulated for the purpose of integration. Consequently, the following alternative systems have been analyzed in which small additional investments have been made to improve the flexibility of the system to which the wind turbines are connected:

- *regCHP*: CHP production is replaced by boilers in situations of excess production and in periods when Nord Pool electricity prices are low.
- *regCHP + HP*: Corresponds to "regCHP" plus 350 MWe of heat pump capacity used in combination with heat storage capacity to replace boilers, whenever feasible due to low Nord Pool electricity prices.

Figure 5.26 shows the results, including both investments in wind power and heat pumps. The investments in flexible energy systems seem to be very profitable. In particular, the alternative including heat pumps raises the net income of the Danish energy supply. Thus, the annual net profit (after investment costs are paid) is raised by approximately 5 million EUR/year for a wind power production of 5 TWh/year and increasing to more than 80 million EUR/year for a wind power production of 15 TWh/year. This rise in profits must be compared with the annual costs of integrating heat pumps into the system of approximately 16 million EUR/year including capital costs. Consequently, the internal rate of return of these measures is as high as several hundred percent for a wide range of wind power capacities.

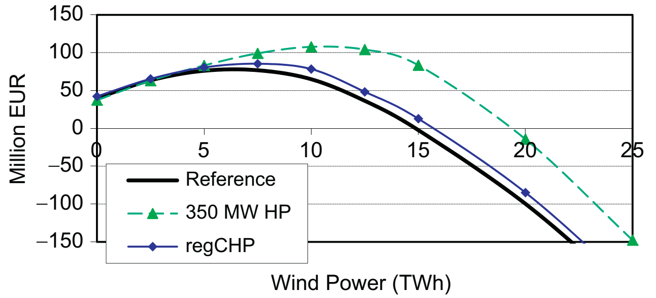


FIGURE 5.26 Annual net earnings of electricity trading for two flexible energy systems compared to a reference. Better regulation of small CHP stations (regCHP) and investments in 350-MWe heat pump capacity (350 MW HP) increase the annual earnings of wind power production.

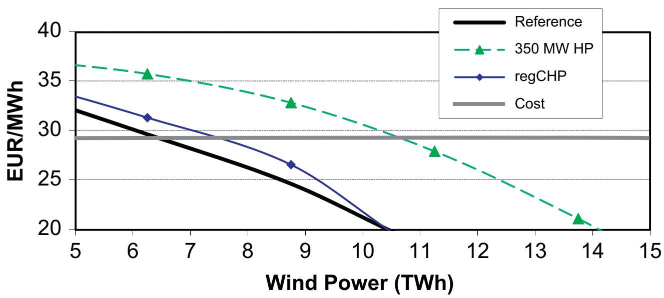


FIGURE 5.27 Feasibility of wind power in flexible versus nonflexible energy systems. The net earnings of increasing wind power are higher for flexible energy systems than in the reference. The optimum in which the marginal net earnings cannot exceed the marginal costs is changed from approximately 6 to more than 10 TWh/year.

As illustrated, investments in flexibility measures, such as adding heat pumps to the energy system, are feasible when wind power production exceeds approximately 20 percent of the demand. Moreover, such investments influence the feasibility of wind power, as shown in Figure 5.27. This figure is comparable to Figure 5.25 (bottom) and identifies the optimal Danish wind power investment when optimizing the exchange on Nord Pool and including CO_2 payment in the income. Figure 5.27 illustrates how the optimal wind power investment is higher for the two flexible energy systems than for the reference.

Given a production price for new wind power capacities of 29 EUR/MWh and a CO_2 payment of 13 EUR/ton, the optimal investment in the reference system is 6–7 TWh, equal to 25 percent of the demand. Meanwhile, the same optimum is 30 percent if CHP units are included in the regulation (regCHP) and above 40 percent if heat pumps are included.

A comprehensive sensitivity analysis of the preceding feasibility study has been conducted including the following parameters:

- A 50 percent increase in the investment costs of heat pumps
- Changes in CO_2 payment (between 0 and 33 EUR/ton)

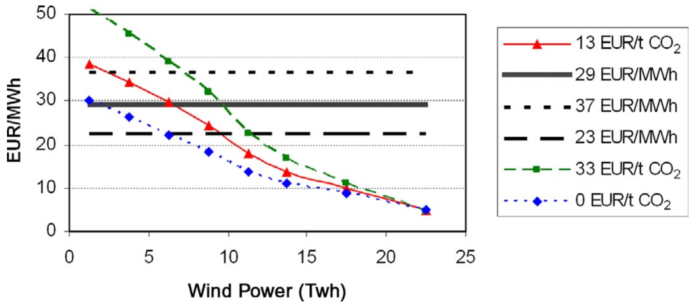


FIGURE 5.28 Sensitivity analysis. The feasibility of wind power in flexible versus nonflexible energy systems depends mainly on CO_2 emission costs and wind power investment costs.

- Changes in wind power production costs (between 23 and 37 EUR/MWh)
- Changes in fuel costs
- Changes in marginal CO_2 savings on the Nord Pool market
- Changes in the influence of CO_2 reductions on Nord Pool spot prices
- Changes in future average price on Nord Pool from 32 to 40 EUR/MWh
- Change in import/export to Germany
- Change in the range of Nord Pool price variations (more volatile prices)

From this sensitivity analysis it can be seen that the feasibility of new wind power investments is very sensitive to, especially, CO_2 payment and wind power production costs, as illustrated in Figure 5.28 for the reference system.

The same influence has been found for the flexible energy systems; however, the feasibility of these systems is better in general. Two factors have proven to be resistant to any changes in the assumptions: the high feasibility of investing in flexible energy systems (such as heat pumps) whenever wind power exceeds 20 percent of annual electricity production and the fact that flexible energy systems also improve the feasibility of wind power.

8. INTEGRATION OF TRANSPORTATION[8]

This section is based on Lund and Münster's (2006b) article "Integrated Transportation and Energy Sector CO_2 Emission Control Strategies", which illustrates and quantifies the mutual benefits of integrating the transportation and energy sectors in the analysis of the Danish energy system. As shown earlier in this chapter, this issue is very relevant in relation to the large-scale integration of renewable energy. In short, the energy sector can help the transportation sector replace oil by

8. Excerpts reprinted from *Transport Policy*, 13/5, Henrik Lund & Ebbe Münster, "Integrated Transportation and Energy Sector CO_2 Emission Control Strategies", pp. 426–433 (2006), with permission from Elsevier.

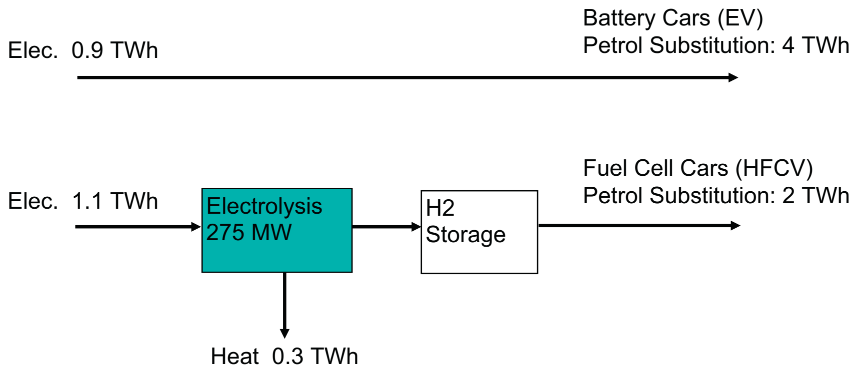


FIGURE 5.29 Transport scenario #1: BEVs in combination with HFCVs.

renewable energy and CHP, while the transportation sector can assist the energy sector in integrating a higher share of intermittent RES and CHP.

Again, the reference energy system applied is the system of West Denmark in the year 2020. To investigate the impact that a potential electrification of part of the transportation system would have on the existing electrical system, two scenarios have been defined for the year 2020. One has already been analyzed in the previous sections: the study that concluded that the technical performance, particularly the range, of BEVs and HFCVs will gradually improve in the coming decades, making it feasible to replace a substantial part of the transportation task of passenger cars and small delivery vans below 2 tons by these types of cars. Fuel cell cars powered by synthetic fuels like methanol were left out because the study expected them to have a poorer overall efficiency.

The scenario shown in Figure 5.29 is scaled down to correspond to West Denmark only. The scenario assumes that by 2020 27 percent of passenger cars and small vans based on an internal combustion engine (ICE) will be replaced by battery cars, while 14 percent will be substituted by HFCVs. The batteries of the cars are assumed to be large enough to level out consumption on a 24-hour basis (loading during the night), while the combined hydrogen storage of the electrolyzer stations and cars is assumed to level out consumption on a 4-week basis. The electrolyzers are dimensioned to operate approximately 4000 hours/year. The heat produced by the electrolyzers is not considered in the model. If the electrolyzers are placed close to CHP stations, the heat produced in periods when the system needs to increase electricity consumption will have a positive effect on the balance of the grid. If the produced heat is used by the district heating network, the CHP station will have a lower heat and thus electricity production. However, this effect was not included in the analysis.

An alternative scenario based on the liquid fuels (biofuels and synthetic fuels) that ICE cars use is presented in Figure 5.30. This scenario is based on

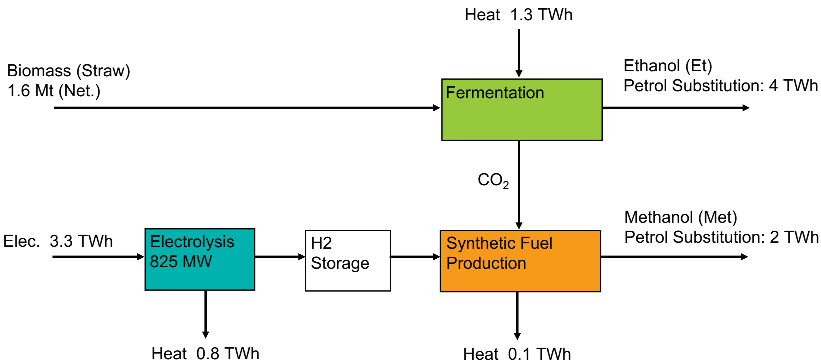


FIGURE 5.30 Transport scenario #2: Ethanol and methanol in vehicles using internal combustion engines.

the REtrol-vision[9] of the Danish power company ELSAM, now DONG Energy (ELSAM 2005). It has been scaled to provide the same gasoline substitution as scenario #1. As can be seen, this scenario has a lower overall efficiency, but it cannot be directly compared to scenario #1 because it assumes the use of ICE-based cars, which are either standard cars (low percentage mix of ethanol or methanol with gasoline) or slightly converted cars (higher percentage mix). Hence, the total costs of the system, including conversion of the fleet, are much lower. In this case, the heat balance is negative because the heat produced by the ICE of the cars is not considered. The consumed heat is provided as waste heat from condensing power stations. An important asset of this scenario is the fact that ethanol fermenters produce the carbon needed for the production of methanol. In this way, the total system, including the cars, can be regarded as CO_2 neutral. Apart from ethanol, the fermenter produces a solid biofuel. This fuel has been subtracted from the biomass input. As in scenario #1, the electricity consumption of the electrolyzers is assumed to be flexible to the extent that it is leveled out on a 4-week basis.

In this article, the different alternatives are first compared in an excess electricity production diagram, as shown in Figure 5.31. The “Ref” curve shows how most of the wind power electricity in 2020 must be exported from West Denmark, if the reference regulation method described in the previous sections is used. Please note that 25 TWh of wind power corresponds to 100 percent of the electricity demand of West Denmark. If 350 MW electric heat pumps are established at the CHP stations and the alternative regulation method is used (HP 350 MW), the situation will improve considerably.

If transportation scenario #1 (EV/HFCV) is introduced instead, it will have more or less the same effect. Transportation scenario #2 (Et/Met) has a larger

9. Translated from Danish: *VEnzin*.

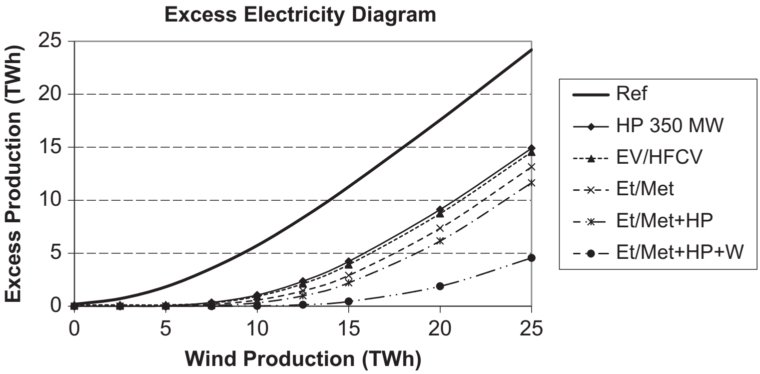


FIGURE 5.31 Excess electricity diagram comparing the two transportation scenarios (EV/HFCV and Et/Met) with and without heat pumps (HP) to the reference system (Ref).

impact because it uses more electricity. A combination of heat pumps and scenario #2 is only marginally better, because the minimum fraction needed by the power stations for stabilizing purposes puts a limit to the regulation possibilities.

If this constraint is eased by assuming that 50 percent of the wind turbines are supplied with advanced high-voltage semiconductor regulation equipment and are thereby able to perform phase and frequency regulation, the situation will again improve considerably (Et/Met + HP + W). This type of equipment is available today and is considered economically feasible for the very big offshore turbines that are to be established in the future. It is particularly relevant to the combination of wind turbine and electrolyzer because this combination can perform both upward and downward regulations when both parts are active (Østergaard et al. 2004). The economic impacts of converting the entire fleet have not been calculated, but the positive effects on the economy of such a conversion of the energy system as a whole have been evaluated.

Figure 5.32 shows the influence of the alternatives on the feasibility of wind power and the marginal benefits of adding extra wind power to the system. In the diagram, it is seen how the optimal share of wind power production increases with the flexibility of the system. Optimal wind power production moves from about the present situation of the reference system to 40 and even 50 percent of the demand when heat pumps and transportation electrification are assumed. Scenario #2 (Et/Met + HP) has the highest optimal value because it uses more electricity than scenario #1 (EV/HFCV + HP).

Thus, we can see how the use of electricity for transportation increases the optimal amount of wind turbines in West Denmark. While the establishment of 350 MWe heat pumps at the CHP stations leads to an increase of this optimum from approximately 25 percent to approximately 40 percent in 2020, the additional electrification of the transportation fleet further increases the optimum to approximately 50 percent.

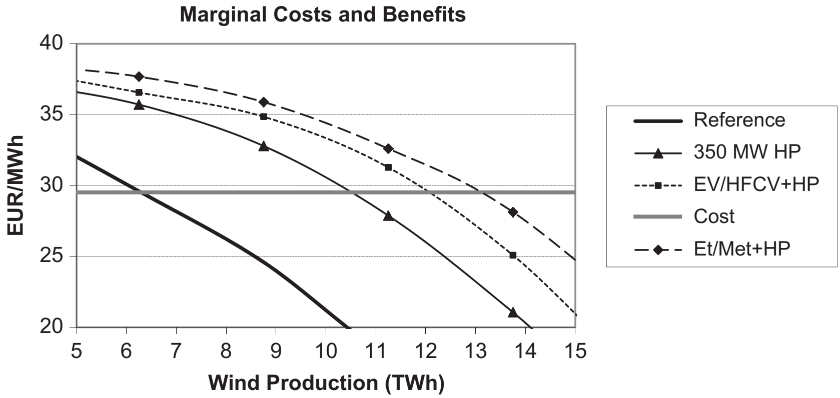


FIGURE 5.32 Marginal costs and benefits of wind power for West Denmark 2020. Compared to the reference, the net earnings of increasing wind power are higher if one of the two transportation scenarios is implemented. The optimum in which the marginal net earnings cannot exceed the marginal costs of wind power is changed from approximately 6 to between 10 and 14 TWh/year.

The article includes calculations of CO_2 balances, which show that the two scenarios result in savings of approximately 1 Mt CO_2 per year for West Denmark. If the indirect CO_2 savings achieved in the neighboring countries by exporting electricity are considered, even larger savings ($\sim$2 Mt) can be gained with the previously mentioned facilitation of an increase in the number of wind turbines.

9. ELECTRIC VEHICLES AND V2G[10]

This Section Is Courtesy of Guest Writer Willet Kempton

This section is based on Lund and Kempton's (2008) article "Integration of Renewable Energy into the Transport and Electricity Sectors through V2G", which adds to the preceding analyses of the transportation sector by including vehicles to grid (V2Gs), that is, vehicles supplying electricity to the grid. Plug-in electric vehicles (EVs) can reduce or eliminate the use of oil for the light vehicle fleet. Adding V2G technology to EVs can provide storage possibilities, matching the generation and loading time.

In this article, two national energy reference systems are selected: the projections of the energy system in West Denmark by the year 2020 and a joint system that includes all of Denmark. The projections used in the previous sections of this chapter included only analyses of the electricity system. Here, for a more integrated energy system view, data for the rest of the energy sectors, including the transportation sector, have been added on the basis of the former Danish governmental energy plan, Energy 21.

10. Excerpts reprinted from Energy Policy, 36/9, Henrik Lund & Willett Kempton, "Integration of Renewable Energy into the Transport and Electricity Sectors through V2G", pp. 3578–3587 (2008), with permission from Elsevier.

The Danish reference case, with its high share of CHP, is not typical for most countries. Therefore, a non-CHP reference has been defined simply by replacing all CHP in the Danish system by heat production from district heating thermal boilers and electricity production from condensing power stations. The second national reference system is set at the same total size as the Danish energy system, for comparison purposes. The modeling of transportation demands is based on Danish statistics from 2001, in which the vehicle fleet consisted of 1.9 million combustion cars driving an average of 20,000 km/year and in total consuming 2700 million liters of gasoline, equal to 25.5 TWh/year. The reference combustion vehicle fleet (REF) is compared to four electric vehicle alternatives:

- BEV: battery electric vehicles, with night charge
- InBEV: intelligent battery electric vehicles
- V2G: vehicle to grid cars
- V2G+: vehicle to grid cars with a battery three times larger than normal

Except for the combustion case, all are referred to as EVs. All EVs, except V2G+ (discussed later), are assumed to have a battery capacity of 30 kWh and a grid connection of 10 kW. The EVs have an efficiency of 6 km/kWh and consume 3333 kWh/year to drive 20,000 km. Based on these statistics and assumptions, the reference fleet and three alternative vehicle fleets have been defined, as shown in Table 5.3.

TABLE 5.3 Input Parameters of Transportation Reference Case and Three Alternatives

	REF Reference	BEV Night Charge	InBEV Intelligent Charge	V2G
Number of vehicles	1.9 million	1.9 million	1.9 million	1.9 million
Average use	20,000 km/year	20,000 km/year	20,000 km/year	20,000 km/year
Vehicle efficiency	14 km/liter	6 km/kWh	6 km/kWh	6 km/kWh
Gasoline consumption	25.5 TWh/year	—	—	—
Electricity consumption	—	6.33 TWh/year	6.33 TWh/year	6.33 TWh/year
Charging capacity	—	19 GW	19 GW	19 GW
Battery storage	—	57 GWh	57 GWh	57 GWh
Discharging capacity	—	0	0	19 GW

The night charge BEV is assumed to charge during the night, starting after 4 P.M., when it is plugged in, and continuing slowly until the battery is fully charged. Unlike the night charge, the InBEV and V2G charging is based on signals from the electric system, as described in detail in Lund and Kempton's (2008) article. The InBEV recharges as much as possible when excess power is available. The V2G also does this, which additionally supplies the grid with power when the production from power stations, wind turbines, or running CHP stations is low. The aggregated national demand for transportation is based on time-specific driving data from the United States.

In both the CHP and the non-CHP system, the impacts of EVs and V2Gs are calculated in the case of wind power ranging from 0 to 45 TWh/year in a national system the size of Denmark. Wind power of 45 TWh/year would be approximately 100 percent of the foreseen Danish national electricity demand in 2020, including the electric vehicles. This is equivalent to an average power output of 5.2 GW. Figures 5.33–5.36 show the results of the modeling for the entire energy system.

At the top of Figure 5.33, the excess electricity production in the CHP system is illustrated. As the fraction of wind power increases beyond 5 TWh, the

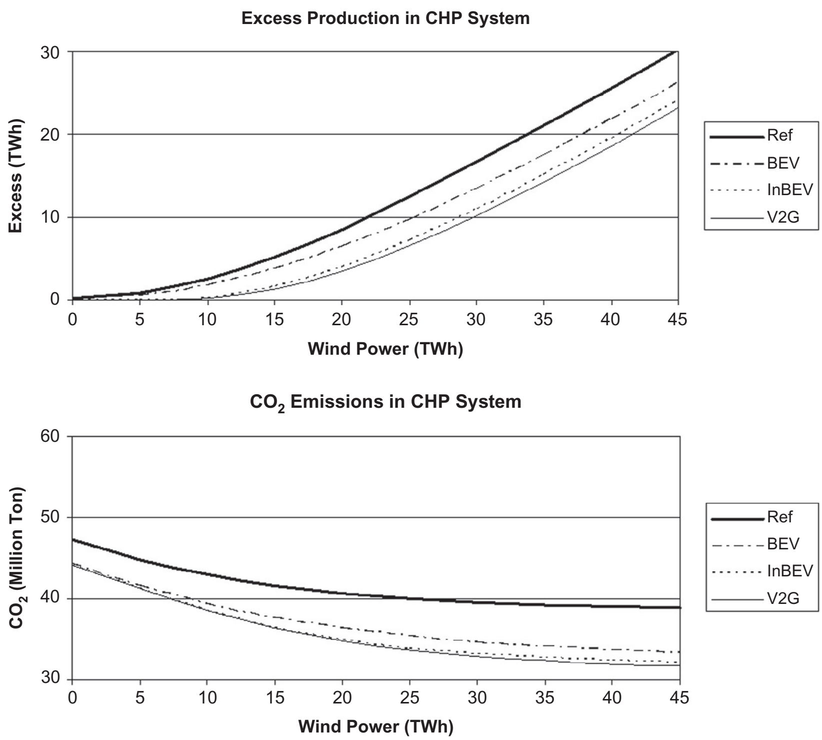


FIGURE 5.33 CHP system, annual excess electricity production (top), and CO_2 emissions (bottom) as electricity from wind power increases.

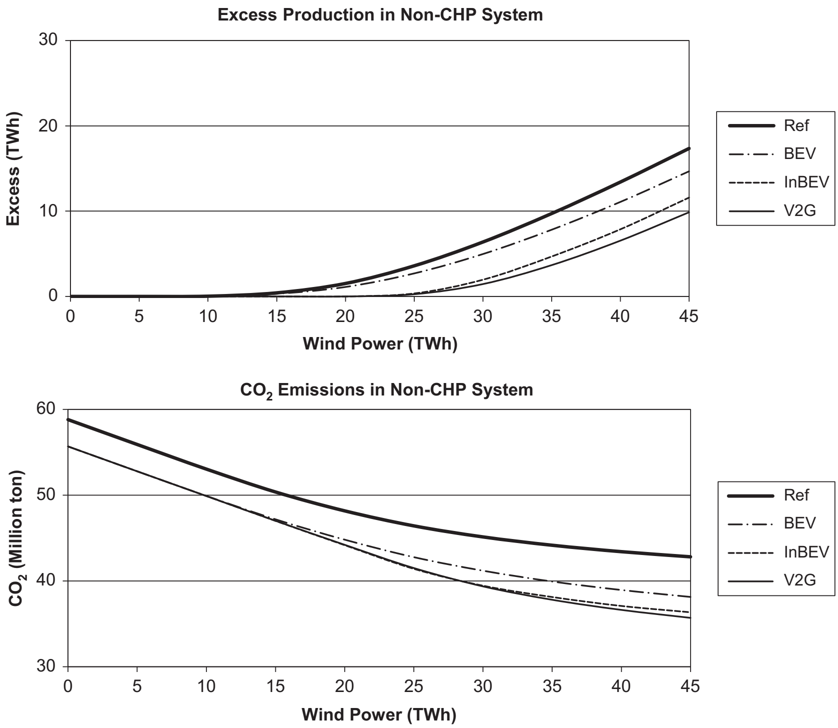


FIGURE 5.34 Non-CHP system, annual excess electricity production (top), and CO_2 emissions (bottom) as electricity from wind power increases.

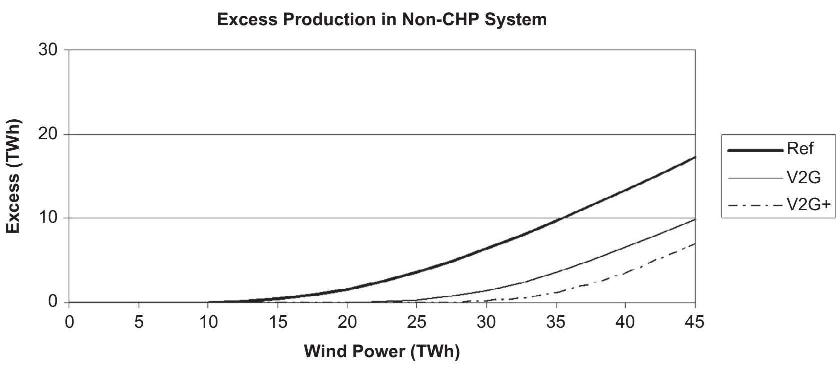


FIGURE 5.35 V2G impact on annual excess electricity production in the non-CHP system compared to a system with three times higher battery storage capacity (V2G+).

excess production of electricity increases. Following the dark line for the REF case, at 10 percent wind power (about 5 TWh), there is a little excess production, whereas at 50 percent (22.5 TWh), a substantial fraction (approximately 50 percent) of the wind power produced is excess production. The other lines

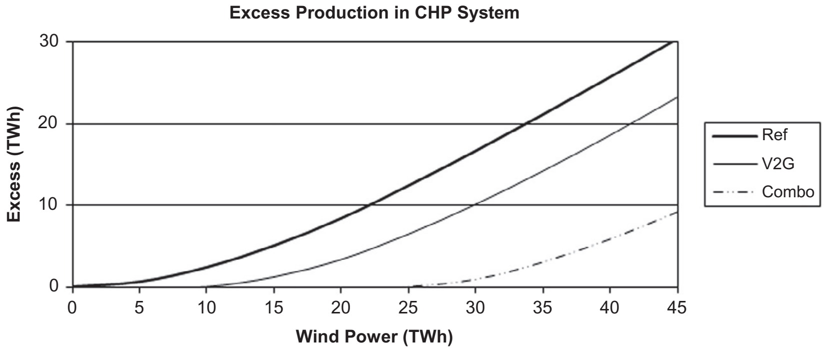


FIGURE 5.36 V2G impact on annual excess electricity production in the CHP system compared to a system in which V2G cars are combined with an active regulation of CHP stations, including heat pumps and heat storage (Combo).

show that the excess production is reduced successively by BEV with night charge, BEV with intelligent charging, and V2G. In short, the excess production decreases partly because cars are added as load, themselves increasing the electricity demand from 41 TWh/year to approximately 47 TWh/year. Additionally, each refinement of the vehicle fleet successively reduces excess production. The combined reductions are significant. For example, in the 50 percent wind scenario, the change from reference combustion fleet to V2G reduces excess electricity production by 50 percent.

The BEV with night charge significantly reduces both excess production and CO_2 emissions (Figure 5.33, bottom). From the BEV night charge line, the incremental benefit to the InBEV intelligent charging and to V2G is small. These results suggest that the ability of EVs to absorb excess power from wind may be at least as important as their ability to return bulk power at times of need. However, the small additional decrement via V2G is also due to the model assumptions at this point. The "night charge" is actually more intelligent than current plug-in vehicles, as the model assumes charging only during the night. Also, the small incremental benefit achieved by using intelligent charging to V2G is partly because the study does not include the ability of V2G to provide regulating power.

The bottom of Figure 5.33 shows the CO_2 emissions of the CHP system. The solid dark line representing the reference (combustion) vehicle shows that with no electrical vehicles, increasing wind generation reduces CO_2 emissions. However, the slope of CO_2 reduction begins to level off at about 10–15 TWh of wind power production and is almost flat at three-quarters of wind power (33 TWh). Again, the addition of night charge BEV and other types of intelligent charging and V2G will substantially reduce CO_2 emissions.

The leftmost edge of Figure 5.33 (bottom), with 0 TWh of wind, depicts the CO_2 impact from the replacement of gasoline-fueled cars by electric cars. The zero shows the reduction of CO_2 emissions achieved by displacing gasoline. The reduction in CO_2 emissions achieved at a level of zero wind power is substantial, even though the power stations are fueled by fossil fuels, due to the much better vehicle efficiencies (one electric vehicle displaces 13,000 kWh of gasoline with 3333 kWh of electricity). This connection between REF and V2G becomes of growing importance as the proportion of wind power increases. As more electricity is produced from wind, an electric fleet will have an increasingly beneficial CO_2 impact.

The right side of Figure 5.33 demonstrates the REF-V2G values if wind power is 45 TWh/year. These values are almost twice the size of the values shown on the left side, where wind power equals zero. This means that the size of the direct CO_2 reduction achieved by completely eliminating motor fuels is smaller than the indirect effect created by reducing CO_2 from electric generators by using EV and V2G.

Figure 5.34 shows the results for the non-CHP system, which represents the system of a typical industrialized country, with heat provided by independent devices (in this case district heating) rather than combined with power stations. CHP is more efficient, which means that when wind power equals zero, the CHP system has considerably lower CO_2 emissions. This effect continues at all wind power levels. On the other hand, excess electricity production begins earlier in the CHP system, before reaching 5 TWh of wind (for combustion cars), and the excess production is considerably higher when wind power production is high. This is because electricity production from CHP adds to the excess wind power production.

The addition of EVs has a larger effect, proportionally, in the non-CHP system. With V2G, even at high wind fractions—for instance, three-quarters of the electricity or 34 TWh produced from wind—the CHP system still has 12 TWh of excess production, while only 4 TWh of excess production is found in the non-CHP system. The introduction of all types of EVs leads to a reduction in both excess production and CO_2 emissions for high shares of wind. However, the influence does not completely erase excess power or CO_2. The lines phasing out toward the right mean that the beneficial effects of the EVs are reduced as the fraction of wind becomes higher.

One important factor is the limitation of the capacity in the battery storage. In Figure 5.35, the impact of a V2G fleet with base characteristics is compared to the impact of a V2G fleet with a storage capacity three times higher (here called V2G+), in other words, 90 kWh/vehicle or 171 GWh altogether. A 90 kWh vehicle would be sensible, since it would have a range of 540 km and would thus more completely substitute a liquid-fuel or plug-in hybrid vehicle. (It would not, however, be practical today due to battery costs and weight, but the technology is improving rapidly.) As seen in Figure 5.35, this increase in the storage capacity significantly reduces excess production (and CO_2 emissions, not shown here).

In the preceding results, CHP stations are not included in the regulation of wind power, and small CHP stations do not contribute to the fulfillment of maintaining grid stability. To examine the effect of including CHP stations, the same analysis has been conducted for alternative scenarios, in which CHP stations participate in the regulation and heat pumps and heat storage capacities have been added to the system. As shown in the previous sections, heat pumps in combination with heat storage and CHP have proven to be a very efficient technology in terms of integrating wind power. Consequently, these investments decrease excess production as well as CO_2 emissions in general. Figure 5.36 shows how the combination of V2G with an active regulation of CHP stations, including heat pumps and heat storage together (here called "Combo"), significantly reduces excess electricity production with even very high shares of wind power.

Altogether, these analyses show that EVs with night charging and, to a larger extent, V2G will improve the efficiency of national energy systems, reduce CO_2 emissions, and improve the ability of the systems to integrate large shares of wind power. Moreover, V2G can be combined with other measures, such as heat pumps and active regulation of CHP stations, in such a way that they together form a coherent solution to the large-scale integration of wind power into renewable energy systems.

It should be noted that the assumptions in this first application of the national energy model to V2G are conservative in the sense that they probably underestimate the value of V2G. First, the most important advantage of V2G over simple EVs is its potential to completely replace regulating power stations and thereby provide grid stability (both voltage and frequency). This benefit was not included in the above analysis. However, as part of the CEESA study (see Chapter 7), Pillai and Bak-Jensen (2011) subsequently showed how V2G could provide a significant contribution in terms of providing grid stabilization. Second, it was assumed that the V2G controllers did not relate to their drivers' operating schedules and were thus required to fully charge the battery each morning. In this way, more power station operation was required during nights with little excess electricity, and less battery capacity was available during the day to absorb this electricity. Refinements will most likely be made to future models and analyses.

10. ELECTRICITY STORAGE OPTIONS[11]

This section is based on Lund and Salgi's (2009) article "The Role of Compressed Air Energy Storage (CAES) in Future Sustainable Energy Systems", which focuses on CAES technologies as one example of introducing electricity storage technologies in the energy system with the aim of improving the large-scale integration of RES. However, the article includes a comparative study of other relevant electricity storage options and thereby serves as a general study on electricity storage technologies.

The primary purpose of the study is to examine the feasibility of CAES stations when applying load level to improve the integration of wind power into regional or national energy systems. Part of this analysis is to compare CAES

11. Excerpts reprinted from *Energy Conversion and Management*, 50/5, Henrik Lund & Georges Salgi, "The Role of Compressed Air Energy Storage (CAES) in Future Sustainable Energy Systems", pp. 1172–1179 (2009), with permission from Elsevier.

stations to other technologies with the same aim. In its nature, this analysis, of course, depends on the energy system in question and especially on the share of wind power and other production units with limitations or restrictions in the system, such as, for example, distributed CHP stations. Here, the starting point for the evaluation is a business-as-usual extension of the present Danish energy system into 2030, as conducted by the Danish Energy Agency. By using the EnergyPLAN model, the system has been analyzed, applying different shares of wind power and leading to low or high amounts of excess electricity production.

First, an infinite CAES station has been added to the system. The analysis showed that when the wind power share was up to 59 percent (wind production compared to electricity demand), the infinite CAES station was able to remove all excess electricity production and use all stored energy to replace the power production of non-CHP power stations. With a wind power share above 59 percent, even the infinite CAES station was not able to use all of its excess production for the simple reason that the power stations did not produce enough power that could be replaced by the wind turbine production. Similarly, the infinite CAES station can replace all non-CHP power production in the system when the wind power share is down to 59 percent. Below 59 percent, the lack of excess electricity production will set the limit on filling the storage. In other words, in systems with low wind power shares, the lack of excess power sets the limitations, and in systems with high wind power shares, the lack of non-CHP power production sets the limitations on a full utilization of CAES stations. In the Danish system as expected for the year 2030, the optimal use of CAES is found to be a wind power share of 59 percent.

In the next analysis, the infinite CAES station was replaced by a 360 MW station described in detail in the article and analyzed in the optimal situation of 59 percent wind power. The results showed that the limited capacity of the specific station significantly reduced the influence of the CAES station. The reason for this is illustrated in Figure 5.37.

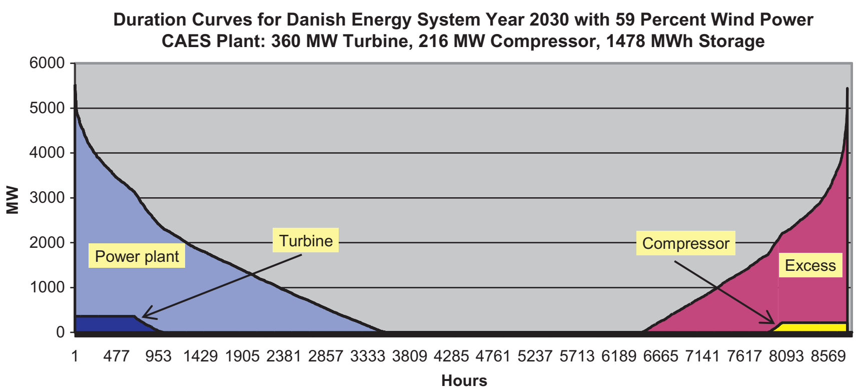


FIGURE 5.37 Duration curves of power station and excess electricity production compared to CAES turbine and compressor contributions.

Figure 5.37 shows the duration curves of excess electricity (to the right) and non-CHP power production (to the left) and compares these to the resulting annual turbine and compressor consumption and production, respectively, when modeled in EnergyPLAN with the aim of reducing excess and power station electricity production. As seen from the diagram, the influence of the CAES station is marginal. The capacity of the share of excess electricity produced is much higher than that of the compressor, and, consequently, most of the excess production cannot be absorbed by the compressor. The problem is the same with regard to power production and turbine capacity. Also, the storage capacity sets a limitation, which can be identified by conducting the same analysis of a CAES station with infinite storage. However, even in this situation, the influence of the CAES station is marginal.

It is important to understand that the reason for this marginal influence from CAES—and for that matter from any other electricity storage technology—is based on the nature of the RES fluctuations. The nature dictates relatively high power outputs from the RES during relatively few hours, as shown by the duration curves in Figure 5.37. Thus, the situation requires high compressor and turbine capacities and, consequently, high investments that can only be utilized in a few hours. Moreover, the combination of the amounts of energy and the time span in which the energy needs to be stored requires a huge storage capacity that again will be filled and emptied relatively few times.

However, even though the influence of CAES with regard to using excess production is marginal, the CAES station itself may be economically feasible for the system. The feasibility has been assessed by identifying the value of the fuel saved in the system. The results are shown in Figure 5.38 in terms of annual net operational income of the CAES station. The net income has been calculated as the difference between, on the one hand, the values of variable operation and excess electricity costs and, on the other, the fuel and variable operation costs saved in the system. Three different sets of fuel prices have been used, as expressed by the three different oil prices of 40, 68, and 96 USD/barrel.

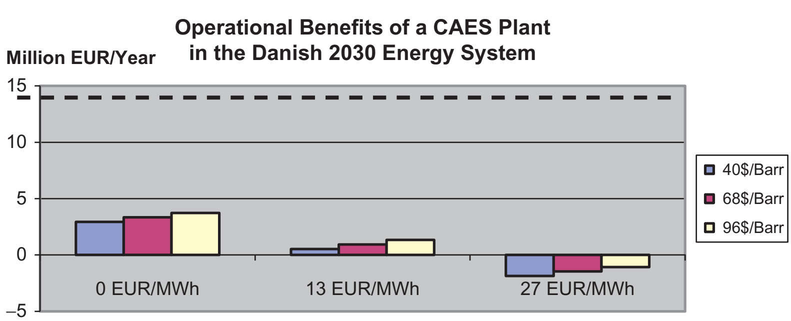


FIGURE 5.38 Net operational income of a CAES station in the Danish year 2030 energy system compared to the annual investment and fixed operation cost of 14 million EUR/year (the dotted line).

If the excess electricity produced is not used in CAES systems, one alternative is to sell it on the Nordic electricity market. In Figure 5.38, three different selling prices have been analyzed: 0, 13, and 27 EUR/MWh, respectively.

In Figure 5.38, the annual net operational income is compared to the investment and fixed operational cost per year of 14 million EUR (marked by a dotted line). As shown, variations in the fuel price mean little to the results because CAES stations burn natural gas, and, consequently, fuel savings at the power stations are counterbalanced by fuel costs at the CAES station. The price of excess electricity production is important. However, even if the excess power produced is free, annual net earnings are far from the level of annual investment and fixed operation costs.

The system economic feasibility of CAES stations has been compared to other technologies that may also use excess electricity production and contribute to a better system integration of wind power. All alternative technologies have been designed in such a way that they all have the same annual investment and fixed operation costs as explained previously, namely, 14 million EUR/year. The cost components are based on Mathiesen and Lund (2009) and explained in Lund and Salgi's (2009) article, and the results are shown in Figure 5.39. The results in Figure 5.39 apply an oil price of 68 USD/barrel and an excess electricity price of 13 EUR/MWh. However, only minor changes are achieved by applying other price levels, apart from the electric boiler, which is especially sensitive to the price of excess electricity.

It can be seen from Figure 5.39 that CAES stations are not feasible, and other options are significantly more attractive. It must, however, be emphasized that this analysis is solely concerned with the benefits of better operation, including the integration of wind power. In one important aspect, the technologies are not comparable; the CAES and the hydrogen/fuel cell technology add production capacities to the system, which the other options do not.

Consequently, CAES may reduce the need for backup capacity and thereby save investment costs in the system. A sensitivity analysis has been made in which the saved investment costs have been included, resulting in up to

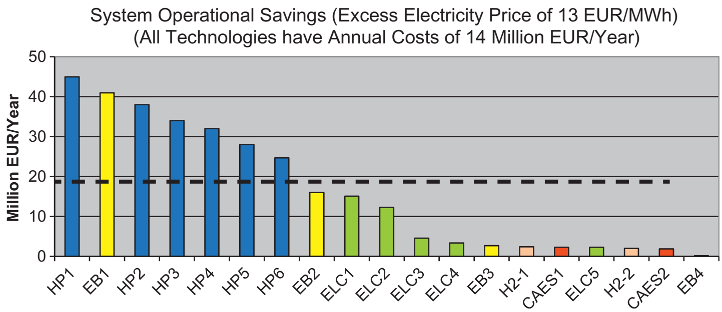


FIGURE 5.39 Savings of CAES compared to other alternative investments, all with the same annual investment and fixed operation costs of 14 million EUR/year (the dotted line).

1 million EUR/MW of steam turbines with a lifetime of 30 years. In this analysis, the CAES station becomes economically feasible, even though it still cannot compete with some of the other technologies.

With regard to the CAES station, it is concluded that these stations cannot alone solve the problems of excess electricity production, and that other options are significantly more attractive. However, if CAES stations can save investments in power station capacities in the system, the CAES technology has economically feasible potential.

With regard to electricity storage technologies in general, it is concluded that these technologies have only a minor influence on the large-scale integration of renewable energy and that the economic feasibility is in general very low. In particular, when compared to conversion technologies, such as heat pumps in combination with heat storage capacities, which have a major impact, electricity storage technologies in general cannot compete. If these technologies are to be competitive, they must provide other benefits such as saving power station capacity and/or supporting grid stability.

11. REFLECTIONS

The reflections and conclusions on the different analyses of large-scale integration of renewable energy presented in this chapter are drawn with regard to principles and methodologies as well as the practical implementation of renewable energy systems in Denmark and in other countries.

Principles and Methodologies

As mentioned at the beginning of this chapter, the discipline of analyzing the large-scale integration of renewable energy into existing systems must address the challenge of redesigning the systems based on the characteristics of the fluctuating renewable sources. The systems must be designed in such a way that they are able to cope with the fluctuating and intermittent nature of renewable energy sources, especially with regard to the electricity supply.

From a methodological point of view, this raises the problem of how to deal with fluctuations of the same installed capacity of RES, such as PV, wind, wave, and tidal power, varying from one year to another. One may be able to design a suitable energy system to cope with the fluctuations of last year, but how can one be sure that such a system will also be able to meet the fluctuations of the present and coming years in the same efficient way? When comparing two alternative investments in flexible energy systems, how can one be sure that the best option considering last year's fluctuations will also be the best way to cope with the fluctuations of coming years?

To deal with these problems, excess electricity production diagrams have proven to be a suitable and workable methodology. In these diagrams, each energy system is represented by only one curve that shows the ability of the system to integrate fluctuating RES representing several years of different hour-by-hour fluctuations. The diagrams have proven usable for PV, wind, and wave power.

Moreover, the analyses show that in the design of systems suitable for the large-scale integration of RES, one should distinguish between two different issues. The first issue is concerned with *annual amounts* of energy, that is, on an annual basis, the supply of each of the amounts of electricity, heating, and fuel must meet the corresponding demands. The other issue is concerned with *time*—that the supply of the same amounts of energy must meet the timely duration of the corresponding demands. The latter is of special importance to the electricity supply.

This distinction between amounts and time is important, since one cannot solve the problem of time if the amounts produced do not match the demand. One cannot use a storage capacity efficiently if the electricity production on an annual basis significantly exceeds the demand. Under this condition, one may be able to fill the storage but not empty it again. Consequently, when designing energy systems that are suitable for the large-scale integration of RES, one should first design the system in such a way that a balance of the annual amounts can be created and *then* look into the time problem; that is, design the system in such a way that the hourly distribution of especially the electricity demands can be met.

As a result, it is important to distinguish between *conversion* technologies and *storage* technologies, as described in the definitions in Chapter 1. With regard to recommendations, a general understanding can be drawn from the analyses. Conversion technologies, such as heat pumps and electric vehicles, may improve the efficiency of the system, and they also entail the possibilities of cost-effective and efficient storage options. On the other hand, "pure" electricity storage technologies, such as CAES and hydrogen/fuel cell systems, only contribute marginally to the integration of fluctuating RES and also have a low feasibility.

Conclusions and Recommendations

The large-scale integration of renewable energy should be considered a way to approach renewable energy systems. The integration of RES must be coordinated with energy conservation and efficiency improvements, including the use of CHP and the introduction of fuel cells. All these measures each improve the fuel efficiency of the system. However, they also add to the electricity balancing problem and contribute to the excess electricity production.

The point is that RES should not be regarded as the only measure when conducting analyses of large-scale integration. The long-term relevant systems are those in which these measures are combined with energy conservation and system efficiency improvements. In that respect, the Danish energy system with a high share of CHP can be regarded a front runner and a system well suited for the analysis of the large-scale integration of renewable energy. In systems with a high share of CHP (in this chapter represented by the Danish energy system), excess electricity production can best be dealt with by giving priority to the following technologies:

1. CHP stations should be operated in such a way that they produce less when the RES input is high and more when the RES input is low. When including

heat storage capacity, these measures are likely to integrate fluctuating RES up to 10–20 percent of the demand without losing fuel efficiency in the overall system. After this point, the system will begin to lose efficiency as heat production from CHP units is replaced by thermal or electric boilers.

2. Heat pumps, and maybe additional heat storage capacity, should be added to the CHP stations and operated in such a way that further RES can be efficiently integrated. These measures will allow the integration of up to 40 percent of fluctuating RES into the electricity supply without losing overall system efficiency. The economic feasibility of the investments in heat pumps proves very high for Danish society. Moreover, the investment in wind power is substantially improved.
3. Electricity should be used in the transportation sector, preferably in electric vehicles. This measure will serve as an efficient improvement of the integration of fluctuating RES.
4. In general, it is not beneficial to include electricity storage capacity in the preceding steps. This storage capacity is both inefficient and expensive compared to the benefits that may be achieved. Moreover, the nature of fluctuating RES dictates the need for high capacities of both conversion units and storage in combination with a low number of full load hours. Thus, the electricity storage technologies call for high investments in combination with low utilization. If these technologies are to be competitive, they should provide further benefits, such as saving power station capacity and/or securing grid stability.
5. It is not necessary to include flexible consumer demands in the regulation. The use of such a measure raises the same problems as for electricity storage technologies. The nature of fluctuating RES calls for high energy amounts and long time spans to such an extent that a realistic flexible consumer demand cannot really do the job.
6. It is much more important to involve the new flexible technologies, such as CHP, heat pumps, and the electrification of transportation (batteries and electrolyzers), in the grid stabilization tasks, in other words, to secure and maintain voltage and frequency in the electricity supply. Such involvement becomes increasingly important along with the acceleration of the share of RES.
7. With regard to the relation between technoeconomic analyses in a closed system and economic analyses of the benefits of international electricity exchange, studies show that the flexible technologies that can efficiently integrate fluctuating RES, at the same time, prove feasible in the sense that they make an economic profit from trading on international markets.

The main focus in this chapter has been on the challenge of integrating fluctuating renewable energy into the electricity supply. However, the implementation of a renewable energy system has at least one additional major challenge, namely, the limitations to biomass resources available for energy and the complexity of the transportation needs. The influence of this challenge and how to analyze it will be one of the main topics of the next two chapters.

Chapter 6

Analysis

Smart Energy Systems and Infrastructures

With contribution by Frede Hvelplund, Poul Østergaard, Bernd Möller, Brian Vad Mathiesen, David Connolly, and Anders N. Andersen

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In recent years, a number of new terms and definitions of subenergy systems and infrastructures have been promoted to define and describe new paradigms in the design of future energy systems such as *smart grid*, *fourth generation district heating*, and *power to gas*. All these infrastructures are essential new contributions and represent an important shift in paradigm in the design of future renewable energy strategies. However, they are also all subsystems and sub-infrastructures, which cannot be fully understood or analyzed if not properly placed in the context of the overall energy system. Moreover, they are not always well defined and/or are defined differently by different institutions.

This chapter introduces the concept of *smart energy systems*. As opposed to, for instance, the *smart grid* concept, which puts the sole focus on the electricity sector, smart energy systems include the entire energy system in its approach to identifying suitable energy infrastructure designs and operation strategies. The typical smart grid sole focus on the electricity sector often leads to the definition of transmission lines, flexible electricity demands, and electricity storage as the primary means to deal with the integration of fluctuating renewable sources. However, as already highlighted in Chapter 5, because of the nature of wind power and other renewable energy sources, they are neither very effective nor cost-efficient. The most effective and least-cost solutions are to be found when the electricity sector is combined with the other sectors, such as the heating sector and/or the transportation sector. Moreover, as will be explained in this chapter, the combination of electricity and gas infrastructures may play an important role in the design of future renewable energy systems.

This chapter starts by discussing the challenges as well as the concepts and definitions of various smart grids and energy systems. Then it presents the results of a list of studies relevant to the understanding of the challenges of the different energy infrastructures and how to meet these. One main point is that these analyses are contextual and, in order to do a proper analysis, one has to define the overall energy system in which the infrastructure should operate. Another main point is that different subsectors influence one another and one has to take such an influence into consideration if the best solutions are to be identified. Moreover, this chapter gives an example of how to apply concrete institutional economics in times of economic crisis. This focus is of particular relevance to investment-intensive technologies with long lifetimes such as infrastructures.

1. DEFINITIONS[1]

In this section, definitions of smart infrastructures are discussed in the light of the subject of this book, i.e., the design and implementation of future renewable energy systems.

Smart Electricity Grid

As highlighted in Chapter 5, the large-scale integration of renewable energy sources into existing energy systems as well as the implementation of 100 percent renewable energy systems involve the challenge of coordinating fluctuating and intermittent renewable energy production with the rest of the energy system. Especially with regard to electricity production, meeting this challenge is essential since electricity systems depend on an exact balance between demand and supply at any time. The need for change in the current electricity grid and power design and operation to meet this challenge has been recognized and discussed for several years under different labels.

Rosager and Lund (1986) and Lund (1990) published on the subject as early as 1986, by which time the idea of a regulation hierarchy was introduced to manage distributed generation without causing feedback in the system. Later, the subject was discussed under the label "Distributed generation" (Lund 2003a; 2003b), and was also a part of the discussion of individual innovative technological concepts such as vehicle to grid (V2G) as described in Chapter 5. Parallel to the previously mentioned discussion regarding the large-scale electricity grid, for many years similar discussions have been part of the debate on the design of microgrids as well as local, regional, and national energy systems.

In 2005, Amin and Wollenberg wrote a paper called "Towards a Smart Grid". The paper points out that the key elements and principles of operating interconnected power systems were established before the 1960s, i.e., before the emergence of extensive computer and communication networks.

1. The definitions of thermal grids and fourth generation district heating in this chapter are based on valuable inputs and discussions with Professor Sven Werner, Halmstad University in Sweden; Professor Svend Svendsen, Technical University of Denmark; and Robin Wiltshire, Building Research Establishment in Watford, UK.

Today, computation is used at all levels of the power network. However, coordination across networks is still not being used to its full potential. As Amin and Wollenberg emphasized, practical methods, tools, and technologies are allowing "power grids and other infrastructures to locally self-regulate, including automatic reconfiguration in the event of failures, threats or disturbances". They did not include a definition of smart grid in the paper; however, it can be understood from the context that a *smart grid* is a power network using modern computer and communication technology to achieve a network that can better deal with potential failures.

Later, the discussion of the need for changes in future power infrastructures were related to the "smart grid" concept in a large number of reports and papers. Many of them, such as Crossley and Beviz (2009) and Orecchini and Santiangeli (2011), argued for the need for smart grids to facilitate better integration of fluctuating renewable energy. Thus, the concept of smart grids is widely used, but even so there is no consensus with regard to the definition. As the promotion of smart grids has been included in several political strategies and research programs, the concept has been defined. However, even though the definitions have many similarities, there are important differences between them. The following are four such definitions:

A smart grid *is an electricity grid that uses information and communications technology to gather and act on information, such as information about the behaviors of suppliers and consumers, in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity.*

(U.S. Department of Energy 2012)

Smart Grids ... *[concern] an electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies.*

(SmartGrids European Technology Platform 2006)

A Smart Grid *is an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it—generators, consumers and those that do both—in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety.*

(European Commission 2011a)

Smart grids *are networks that monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users .... The widespread deployment of smart grids is crucial to achieving a more secure and sustainable energy future.*

(International Energy Agency 2013)

As can be seen, the general essence seems to be the use of information technology on electricity grids. However, it varies slightly if this use concerns only suppliers or both suppliers and consumers and if the ability of the grid has a focus on intelligent or cost-efficient integration, and if the purpose is to raise security and safety or secure a more sustainable energy future or both. However, it is evident that all definitions take a sole focus on the electricity grid.

One important aspect that appears in some definitions and discussions is the bidirectional power flow, i.e., the consumers also produce to the grid. This is different from the traditional grid in which there is a clear separation between producers on the one side and consumers on the other side, resulting in a unidirectional power flow. Consequently, concepts mentioned earlier such as regulation hierarchies, distributed generation, and V2G concepts as well as many microgrids all become smart grids or part of the smart grid concept.

These definitions as well as papers and approaches regarding smart grids all seem to predominantly focus on the electricity sector. Only Orecchini and Santiangeli (2011) emphasized the need for the intelligent management of a complete set of energy forms including electricity, heat, hydrogen, and biofuels.

This chapter emphasizes why smart grids should not be seen as separate from the other energy sectors and what the integration of the other sectors means in terms of identifying proper solutions to the integration problem. Two main points can be emphasized: First, it does not make much sense to convert the electricity supply to renewable energy if this is not coordinated with a similar conversion of the other parts of the energy system. Second, this coordination makes it possible to identify additional and better solutions to the implementation of, e.g., smart electricity grids, compared to the solutions identified with a sole focus on the sector in question.

The subject of this book is the design and implementation of future renewable energy systems and, in this context, the following definition has been chosen:

> *Smart electricity grids* are defined as electricity infrastructures that can intelligently integrate the actions of all users connected to them—generators, consumers, and those that do both—in order to efficiently deliver sustainable, economic, and secure electricity supplies.

Smart Thermal Grids (District Heating and Cooling)

As we will see in Chapter 7, the design of future renewable energy systems is typically based on a combination of fluctuating renewable energy sources such as wind and solar power on the one hand and residual resources such as waste and biomass on the other hand. In relation to waste and biomass, a pressure on the resources is expected due to the environmental impact and future alternative demands for food and material. To ease the pressure on the biomass resources and the investments in renewable energy, feasible solutions to future renewable energy systems involve substantial elements of energy conservation and energy efficiency measures.

District heating has an important role to play in the task of making these scarce resources meet the demands. District heating comprises a network of pipes connecting the buildings in a neighborhood, town center, or whole city, so that they can be served from a centralized plant or a number of distributed heat producing units. This approach allows the use of any available source of heat. Compared with a scenario without district heating, the inclusion of district heating in future renewable energy systems allows the use of combined heat and power (CHP) together with the utilization of heat from waste-to-energy and various industrial surplus heat sources as well as the inclusion of geothermal and solar thermal heat. In the future, these industrial processes may involve various procedures of converting solid biomass fractions into bio(syn)gas and/or different types of liquid biofuels for transportation fuel purposes, among other things.

To be able to fulfill its role in future renewable energy systems, district heating will have to be able to

1. Supply low-energy buildings with low-temperature district heating
2. Distribute heat in networks with low grid losses
3. Recycle heat from low-temperature sources and integrate renewable heat sources such as solar and geothermal heat
4. Be an integrated part of the operation of smart energy systems (i.e., integrated smart electricity, gas, and thermal grids)

Consequently, the present district heating system must undergo a radical change into low-temperature district heating networks interacting with low-energy buildings as well as smart electricity grids. In the European Commission's (2011b) Energy 2020—A Strategy for a Competitive, Sustainable, and Secure Energy, the need for "high efficiency cogeneration, district heating, and cooling" is highlighted (page 8). This paper launches projects to promote, among other things, "smart electricity grids" along with "smart heating and cooling grids" (page 16). In recent state-of-the-art papers (Werner 2005, Persson and Werner 2011) and discussions (Wiltshire and Williams 2008, Wiltshire 2011), these future district heating technologies have been defined as fourth generation district heating technologies and systems (4GDH). Werner (2004) defined the first three generations in the following way:

The *first generation* of district heating systems using steam as a heat carrier was introduced in the United States in the 1880s, and almost all district heating systems established until 1930 used this technology. Today, steam-based district heating is an outdated technology because of high losses and safety reasons. The technology is still used in, among other places, Manhattan, Paris, and partly in Copenhagen, but replacement programs have been successful in Hamburg and Munich.

The *second generation* used pressurized hot water as a heat carrier, with temperatures typically above 100 °C. These systems emerged in the 1930s and dominated all new systems until the 1970s. Remains of this technology can still be found in the older parts of the current water-based district heating systems.

The *third generation* was introduced in the 1970s and gained a major share of all extensions in the 1980s. Pressurized water is still the heat carrier, but supply temperatures are usually below 100 °C. This technology is used for all replacements in Central and Eastern Europe and the former USSR. All extensions and all new systems in China, Korea, Europe, the United States, and Canada use this third generation technology.

The development of these three generations has been aimed at lower distribution temperatures, the creation of components requiring less material, and prefabrication, resulting in lower manpower involvement at the construction sites. Following these identified directions, a future fourth generation of district heating technologies should embrace lower distribution temperatures, assembly-oriented components, and more flexible materials.

For obvious reasons, district heating has higher potential in countries with cold climates than countries with warm climates. However, in warm climates, district cooling may be an option and, in some countries, both types of networks and/or a combination would be desirable. In principle, district cooling can be applied in two different ways. One solution is to use a district heating network to distribute heat, which then by individual absorption units is turned into cooling in the individual building. This option is well suited for locations at which both heating and cooling of buildings is required during different seasons of the year. Moreover, the network can be used to supply both cooling and hot water to the building at the same time. The other solution is to produce central cooling and distribute the cold water. This option has the advantage of being able to include "natural" cooling, such as cold water from rivers or harbors. With regard to smart cooling, the challenge in principle is the same as for heating; i.e., to optimize temperature levels and thereby decrease losses in the grid as well as in production.

On this basis, the following definition has been derived.

Smart thermal grids are defined as a network of pipes connecting the buildings in a neighborhood, town center, or whole city, so that they can be served from centralized plants as well as from a number of distributed heating or cooling production units including individual contributions from the connected buildings.

The concept of smart thermal grids can be regarded as a parallel to smart electricity grids. Both concepts focus on the integration and efficient use of potential future renewable energy sources as well as the operation of a grid structure allowing distributed generation, which may involve interaction with consumers. Further, both concepts involve the use of modern information and communication technologies such as smart meters.

The two concepts, however, differ in the sense that smart thermal grids face their major challenges in, e.g., the utilization of low-temperature heat sources and the interaction with low-energy buildings, while smart electricity grids face their major challenges in the integration of fluctuating and intermittent renewable electricity production as well as in securing the reliability and safety of the grid.

4GDH systems are consequently defined here as a coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems by providing heat supply to low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources can be integrated with the operation of smart energy systems. The concept involves the development of an institutional and organizational framework to facilitate suitable planning, cost and motivation structures.

Smart Gas Grids

In terms of implementing future renewable energy systems, existing natural gas grids face similar challenges as the other grids. To understand the specific challenge of the gas grid, two characteristics of the implementation of 100 percent renewable energy systems must be emphasized. One is that the biomass resources available for energy purposes are limited due to demands for food and materials as well as biodiversity. Furthermore, they are limited to such a degree that it is hard to see how biomass alone could cover current energy demands in the transportation sector. The other characteristic is that a transportation system based solely on renewable energy—as we will see later in this and the following chapter—requires some sort of biomass-based gas and/or liquid fuel to supplement the direct use of electricity. The point is that for the sake of transportation, some biomass needs to be turned into either gas or liquid fuel. Moreover, biomass in the form of gas helps in achieving better flexibility and efficiencies in future CHP and power plants.

However, not only biomass is relevant to gas production, but electricity in "power to gas" systems may also be highly relevant to boost and supplement the limited biomass resources. Such technologies may have substantial synergies if they are combined with the production of gas from biomass in technologies such as fermentation, gasification, and hydrogenation. These will be elaborated on later in this chapter.

The two major challenges of smart gas grids compared to existing natural gas grids are, first, that the smart grid has to deal with a bidirectional flow as opposed to the existing unidirectional flow, and second, that the smart gas grid needs to handle different types of gas with different characteristics including different heating values.

On this basis, the following definition has been derived.

Smart gas grids are defined as gas infrastructures that can intelligently integrate the actions of all users connected to it—suppliers, consumers, and those that do both—in order to efficiently deliver sustainable, economic, and secure gas supplies and storage.

As mentioned earlier, the concept of smart gas grids is similar to other smart grids. All concepts focus on the integration and efficient use of potential future renewable energy sources as well as the operation of a grid structure allowing distributed generation, which may involve the interaction with consumers. Further, all concepts involve the use of modern information and communication technologies such as smart meters.

The three concepts, however, differ in terms of their major challenges. *Smart thermal grids* face their major challenge in the temperature level and the interaction with low-energy buildings. *Smart electricity grids* face their major challenge in the integration of fluctuating and intermittent renewable electricity production. *Smart gas grids* face their major challenge in mixing gases with different heating values and in the efficient use of limited biomass resources. It should be emphasized that the three concepts supplement one another and all of them are to be regarded as necessary in the implementation of renewable energy systems.

Smart Energy Systems

As illustrated previously, all smart grids are important contributors to future renewable energy systems. However, each individual smart grid should not be seen as separate from the others or separate from the other parts of the overall energy system. First, it does not make much sense to convert, e.g., the electricity supply to renewable energy if this is not coordinated with a similar conversion of the other parts of the energy system. Second, better solutions arise for the implementation of the smart energy system and the individual sectors if their implementation is coordinated.

In other words, there are several synergies connected to taking a coherent approach to the complete smart energy system compared to looking at only one sector. This does not only apply to finding the best solution for the total system, but also to finding the best solutions for each individual subsector. As already highlighted in Chapter 5, one can find better and cheaper solutions to the electricity balancing problem if including, e.g., the heating sector in the analysis compared to only looking at the electricity sector. Such synergies include the following:

- Electricity for heating purposes makes it possible to use heat storage instead of electricity storage, which is both cheaper and more efficient. Moreover, it provides a more flexible CHP production.
- Electricity for heating may be used for balancing in regulating power markets, etc.
- Biomass conversion to gas and liquid fuel needs steam, which may be produced in CHP plants, and produces low-temperature heat, which may be utilized by district heating and cooling grids.
- Biogas production needs low-temperature heat, which may be supplied more efficiently by district heating compared to being produced at the plant.
- Electricity for gas such as hydrogenation makes it possible to use gas storage instead of electricity storage, which is cheaper and more efficient.

- Energy savings in the space heating of buildings make it possible to use low-temperature district heating which, in addition, makes it possible to utilize better low-temperature sources from industrial surplus heat and CHP.
- Electricity for vehicles can be used to replace fuel and provide for electricity balancing.

Based on these considerations, the following definition has been made.

Smart energy systems are defined as an approach in which smart electricity, thermal, and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system.

The analysis of smart energy systems calls for tools and models that can provide similar and parallel analyses of electricity, thermal, and gas grids. As described in Chapter 4, EnergyPLAN is one such tool, since it can do hour-by-hour analysis of all these grids including the storage and interaction between them.

The following sections describe a number of studies relevant to the understanding of smart energy systems and infrastructures, in which the EnergyPLAN tool has been used.

2. THE ROLE OF DISTRICT HEATING[2]

This Section is Courtesy of Guest Writers Brian Vad Mathiesen and Bernd Möller

This section is based on Lund et al.'s (2010) article "The Role of District Heating in Future Renewable Energy Systems". Based on the case of Denmark, this paper analyzes the role of district heating infrastructure in future renewable energy systems. It defines a scenario framework in which the Danish system is converted to 100 percent renewable energy sources in the year 2060 including reductions in space heating demands by 75 percent. Through a detailed EnergyPLAN energy system analysis of the complete national energy system, the consequences in relation to fuel demand, CO_2 emissions, and cost are calculated for various heating options, including district heating as well as individual heat pumps and micro-CHPs.

The study includes the entire heating sector with a focus on the 24 percent of the Danish building stock that has individual gas or oil boilers today, and which is located relatively close to existing district heating areas. These could be substituted by district heating or a more efficient individual heat

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2. Excerpts reprinted from *Energy* 35, Henrik Lund, Bernd Möller, Brian Vad Mathiesen, and Anders Dyrelund, "The Role of District Heating in Future Renewable Energy Systems", pp. 1381–1390 (2010), with permission from Elsevier.

source. As elaborated in the following, in this overall perspective, the best solution will be to combine a gradual expansion of district heating with individual heat pumps in the remaining houses. This conclusion is valid in the present systems, which are mainly based on fossil fuels, as well as in a potential system based 100 percent on renewable energy.

In many countries around the world, the ability to heat and supply hot water to buildings is essential. Today, it is intensively being discussed how to do so in the best way in future energy systems in which the combustion of fossil fuels should be reduced or completely avoided. In the present discussion, one can identify at least two different views. One view states that future low-energy buildings could completely remove the need for heating or even, by the use of, e.g., solar thermal energy, be plus energy houses producing more heat than they demand. The other view states that the excess heat production from industries, waste incineration, and power stations may also be used together with geothermal energy, large-scale solar thermal energy, and large-scale heat pumps to utilize excess wind energy for house heating. In the first case, a district heating network may not be needed while, in the latter case, a district heating network becomes essential.

Regardless of the view adopted, the main point here is that it cannot be concluded from purely a house heating perspective whether one district heating strategy fits better than the other in terms of implementing future renewable energy systems. One has to include the rest of the energy system to evaluate how to use the available resources in the overall system in the best way, and how to combine energy savings and efficiency measures with renewable energy to eliminate fossil fuels at the lowest possible cost for society. Consequently, Lund et al.'s paper seeks to perform an advanced energy system analysis of the whole national energy system comparing different options of house heating in the present as well as in future energy systems to evaluate the impact of different heating options on the total fuel demand and CO_2 emissions.

Geographical Information System tools have been used to create a heat atlas and identify potential scenarios and the cost of expanding district heating. The methodology and data are described further in Möller (2008) and Möller and Lund (2010). The year 2006 has been chosen as a starting point for the study. The total house heating consumption has been identified as 60.1 TWh/year, of which 27.9 TWh are supplied from district heating and 32.2 are supplied from individual boilers and heaters. Compared to the situation in 2006 (in the following referred to as the reference situation), the following scenarios of potential expansion of district heating were defined and identified:

- *Scenario 1:* All buildings within areas defined as existing or planned district heating areas are connected to the system, which increases the district heating demand from 27.9 to 31.6 TWh/year.
- *Scenario 2:* All areas supplied by natural gas for individual boilers in the direct vicinity of existing district heating areas are converted to district heating, which increases the share further from 31.6 to 37.6 TWh/year.

- *Scenario 3:* Further natural gas areas of a distance of up to 1 km from existing grids and up to 5 km from large central district heating plants are converted to district heating, which increases the share from 37.6 to 42.3 TWh/year.

The analysis of district heating versus various kinds of individual heating has been carried out with regard to the energy system from 2006, as well as future energy systems, leading to a vision of an energy supply based on 100 percent renewable energy. The energy system analysis of the complete Danish energy system has been carried out by means of the EnergyPLAN model. First, the energy system model was calibrated in order to adjust it to the output of Danish energy statistics from 2006 as well as a business-as-usual projection made by the Danish Energy Agency (January 17, 2008). Compared to the 2006 situation, the future energy systems include more wind power, heat savings, and better CHP and power plants, etc.

It must be emphasized that the reference scenario by no means represents a comprehensive identification of the optimal solution of a Danish 100 percent renewable energy system. Here, the scenario solely serves as a proper framework for analyzing whether conclusions with regard to district heating in the present system will also be valid in a probable future 100 percent renewable energy system. The focus is on the framework conditions related to the heat supply, and the scenario is not comprehensive regarding transportation and industrial sectors.

In the analysis, special attention has been paid to the hourly modeling of district heating demands in relation to reductions in the demand for space heating. The starting point is the annual district heating demand in 2006 of 35.77 TWh, divided into a net heat demand of 28.35 TWh and grid losses of 7.42 TWh. This demand has been subject to a typical hourly distribution, as shown in Figure 6.1. In the scenarios of reduced space heating demands, the shape of

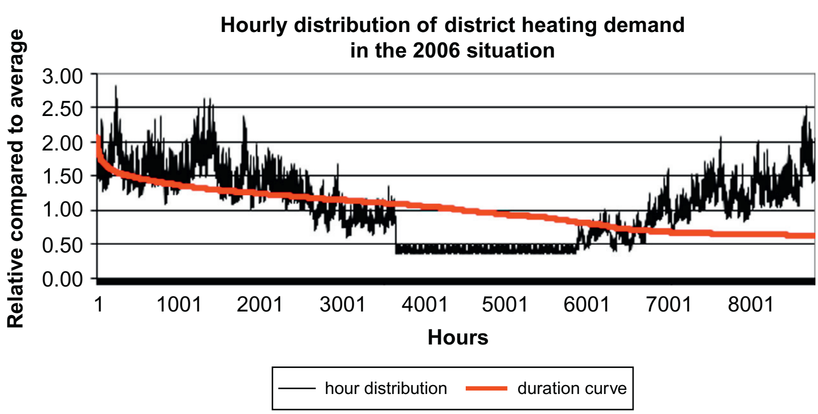

FIGURE 6.1 Hourly distribution of district heating demand in the 2006 situation.

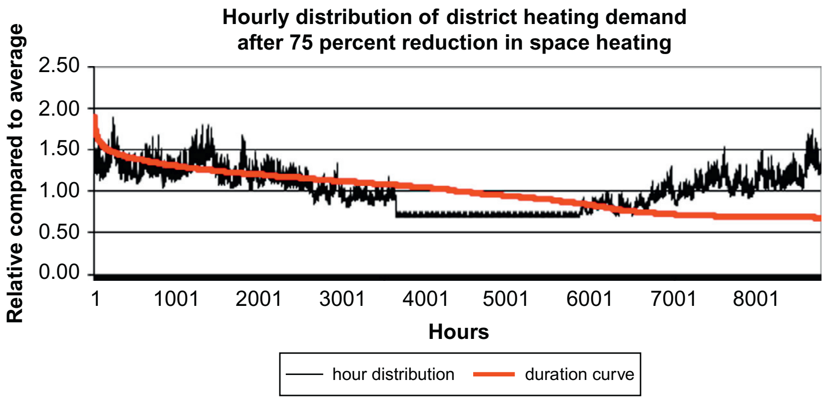

FIGURE 6.2 Hourly distribution of district heating demand in a situation in which space heating demands have been reduced by 75 percent.

the duration curve as well as the hourly distribution has been adjusted, as shown in Figure 6.2, representing the case of a 75 percent reduction in the space heating demand. In this case, the grid loss and the demand for hot water have not been adjusted in the same way as the space heating demand.

The analysis defines and compares the 10 following heating technologies:

1. *Ref.:* Existing individual oil, natural gas, and biomass boilers.
2. *HP-gr:* Individual heat pumps using ground heat including electric heating for peak load assuming an average coefficient of performance (COP) of 3.2. (In the case of space heat reductions, the COP decreases due to an increasing share of hot water demands to 3.1 at 25 percent savings, 3.0 at 50 percent savings, and 2.8 at 75 percent savings, respectively.)
3. *HP-air:* Individual heat pumps using air including electric heating for peak load assuming an average COP of 2.6 (in the case of savings reduced to 2.5, 2.4, and 2.3, respectively).
4. *EH:* Individual electric heating with a COP of 1.
5. *MiCHP:* Individual fuel cell natural gas micro-CHP units with an electric output of 30 percent and a heat production of 60 percent. The CHP unit supplies 60 percent of the peak demand. The rest is covered by a natural gas boiler.
6. *H2-CHP:* Individual micro-CHP units based on hydrogen assuming 45 percent electric output and 45 percent heating output. The CHP unit supplies 60 percent of the peak demand. The rest is covered by a boiler. Hydrogen is supplied via a gas pipeline system and produced on electrolysis assuming an efficiency of 80 percent. The system makes use of hydrogen storage equal to one week's average production.
7. *DH-Ex:* District heating without investment in new production units apart from increasing the capacity of peak-load boilers.

8. *DH-chp:* District heating in combination with an expansion of the CHP capacity at existing CHP plants.
9. *DH-HP:* District heating in combination with adding large-scale heat pumps to the CHP plants assuming a COP of 3.5.
10. *DH-EH:* District heating in combination with adding electric boilers to the CHP plants.

As explained in Chapter 5, the 2006 situation with increasing imbalances in the electricity supply caused by wind power and CHP calls for solutions like heat pumps and electric boilers to increase the flexibility of the system. This is the reason for including the different district heating alternatives. These alternatives are only used for the 2006 system. In the future scenarios of 2020, 2040, and 2060, it is assumed that a good balance between CHP units, heat pumps, and peak-load boilers has been implemented and that, consequently, a potential increase in district heating has been followed by a marginal increase in all three types of units.

The cost estimate is made as a socioeconomic calculation excluding taxes and subsidies as explained in Chapter 3. It is based on a simple calculation of saved fuel and maintenance costs compared to additional investment cost by use of a real interest of 3 percent. The cost of individual solutions is based on an estimate of actual prices in Denmark as shown in Table 6.1. The prices apply to a typical average house with a heat demand of 15 MWh/year. The prices shown in the table relate to the 2006 level of heat demand and have been reduced in scenarios with reduced heat demands. Electrolyzers for hydrogen production are assumed to be community installations equal to an investment cost of 2700 EUR per household. For heat pumps based on ground heat, the heat pumps have an expected lifetime of 15 years, while the ground heat source pipes have a lifetime of 40 years.

For electric heating and heat pumps, an increased cost of expanding the electric grid has been included based on the following estimate:

> Investments in low-voltage grids account for 0.013 EUR/kWh and the increase in peak-load production is included as an additional demand for transmission and production, corresponding to 1000 EUR/kW for a lifetime of 30 years.

The cost of increasing district heating based on the heat atlas model's calculation of the scenarios is shown in Table 6.2 together with the cost assumption of additional production units that have to be added if district heating demands are increased.

Fuel cost is analyzed on the basis of world market prices plus the cost of transporting the fuels to the relevant end users. Three world price levels were identified equivalent to oil prices of 55 USD, 85 USD, and 115 USD/barrel, respectively. With regard to biomass, the prices have been assumed to follow variations in coal prices. The analysis has used the price level of 85 USD/barrel as a base level with the other two levels added as sensitivity factors. However, in the future

TABLE 6.1 Cost of Individual Heat Technologies for a Typical House with a 15 MWh/Year Heat Demand

Heat prod. Technology		Unit	Central Heating	Storage/ Electrolyzer	O&M (Fixed) EUR/year	O&M (Fixed) % of Invest.
Oil boiler	EUR/unit lifetime (year)	6000 15	5400 40	1300 40	320	2.5%
Biomass boiler	EUR/unit lifetime (year)	6700 15	5400 40	1300 40	380	2.8%
Natural gas boiler	EUR/unit lifetime (year)	4000 15	5400 40		200	2.1%
Micro-FC CHP on natural gas	EUR/unit lifetime (year)	6700 10	5400 40		330	2.8%
Micro-FC CHP on hydrogen	EUR/unit lifetime (year)	6000 10	5400 40	2700 15	270	2.4%
District heating excellent pipes	EUR/unit lifetime (year)	2000 20	5400 40		70	0.9%
Electric heating including hot water	EUR/unit lifetime (year)	1100 20	2700 40		30	0.9%
Heat pump ground heat	EUR/unit lifetime (year)	13400 15/40	5400 40		110	0.6%
Heat pump air	EUR/unit lifetime (year)	6700 15	5400 40		110	0.6%

For scenarios with reduced space heating demand the cost has been reduced.

100 percent renewable energy scenario in which no fossil fuels are left, the analysis was based on the high price level assuming biomass prices equivalent to similar types of fossil fuels. Consequently, biomass for individual houses is assumed to have the price of wood chips, while biogas/syngas is assumed to have a price equivalent to that of light oil.

TABLE 6.2 Cost of Expanding District Heating Networks and of Adding Production Units

Unit	Investment MEUR	Lifetime Year	O&M (fixed) Percent of Investment	O&M (Variable) EUR/unit
Peak-load boilers	0.15 per MWth	20	3.0%	0.15 EUR/ MWhth
Small CHP plants	0.95 per MWe	20	1.5%	2.70 EUR/MWhe
Large CHP plants	1.35 per MWe	30	2.0%	2.70 EUR/MWhe
Heat pumps	2.70 per MWe	20	0.2%	0.27 EUR/MWhe
Electric boilers	0.15 per MWe	20	1.0%	1.35 EUR/MWhe
District heating Scenario 1	1070 in total	40	1.0%	0
District heating Scenario 2	4430 in total	40	1.0%	0
District heating Scenario 3	10,470 in total	40	1.0%	0

It should be noted that, in such projections, the coal price is expected to be substantially lower than the price of oil and natural gas. In the Danish system, a combination of large coal-based and small- and medium-sized natural gas-based CHP plants are operated at the Nord Pool electricity market, which means that coal will replace natural gas in certain situations.

The cost calculation does not include external costs related to, e.g., pollution and health, apart from a CO_2 emission trade cost of 23 EUR/ton. With regard to the exchange of electricity on the Nordic Nord Pool market, the analysis is, as a starting point, based on the expectations of the Danish energy authorities, which stated that the future average price level would be 47 EUR/MWh in combination with CO_2 trading prices of 23 EUR/ton. In the energy system analysis conducted in the EnergyPLAN model, this average price has been distributed on an hourly basis using the hourly distribution of the year 2005 and following the same methodology as described in Chapter 5.7.

An analysis has been made of the present system as well as the potential future energy systems of 2020 and 2060. First, a comparison of the consequences of applying the 10 different heating options to scenario 1 is shown. This scenario involves the houses within district heating areas that at present are not connected to the network. The resulting fuel demand of each option is illustrated in Figure 6.3.

Illustrated in Figure 6.3, the reference (pillar 1, Ref), the houses of scenario 1 are supplied by heat from individual boilers based on oil, natural gas, or

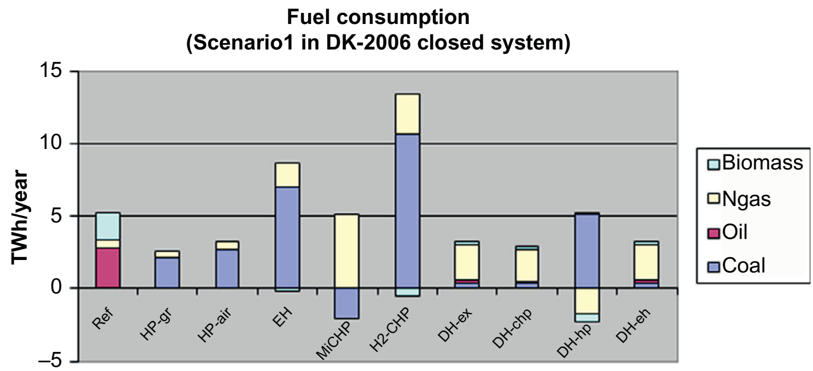

FIGURE 6.3 Fuel demands of 10 options of supplying scenario 1 houses with heat.

biomass. The resulting fuel demand is 5.25 TWh/year. If the supply of all houses was converted to heat pumps (pillars 2 and 3, HP), the resulting fuel demand of the system would be reduced to 2.55 and 2.23 TWh/year, respectively. This conversion would replace the fuel demand in individual boilers by a demand for electricity that would mostly be produced by coal-fired power plants because of the price relation between coal and natural gas. However, this electricity demand would also increase the possibility of utilizing existing CHP plants (coal as well as natural gas) in a better way. In principle, the same would be the case if electric heating supplied all buildings (pillar 4, EH). However, the fuel demand would increase to 8.44 TWh/year due to the inefficiency of electric heating compared to heat pumps. A very small amount of biomass is saved because CHP plants can be operated for a longer period of time and can save fuel on peak-load boilers, some of which are fueled by biomass.

If the supply of all buildings is converted to micro-CHP units on natural gas (pillar 5, MiCHP), the demand for natural gas increases and the demand for coal decreases, since the electricity produced by the micro-CHP units reduces the production at the coal-fired power stations. Altogether, the net fuel demand is reduced to only 2.95 TWh/year. If, instead, the micro-CHP units utilize hydrogen (pillar 6, H2-CHP), the resulting fuel demand increases to as much as 12.87 TWh/year because of the demand for electricity for the electrolyzers. Furthermore, the CHP units produce electricity, which saves coal, but the demand for electricity in this alternative by far exceeds the production. It should be noted that both micro-CHP options assume the existence of a gas distribution network, which is not present in most areas of the scenario.

If all buildings are connected to the district heating network in which they are located (some to small CHP plants fueled by natural gas and others to large CHP plants fueled by coal), the general picture is that the fuel demand will decrease. This is a consequence of expanding the use of CHP. If no additional investments are made in production units, except increasing the peak-load boiler capacity, the fuel demand is 3.20 TWh/year (pillar 7, DH-ex). It can be further reduced to 2.86 TWh/year if a total CHP capacity of 400 MWe is added (pillar 8, DH-chp). If heat pump capacity is added instead (pillar 9, DH-hp), the fuel consumption will be 2.93 TWh/year. However, in such a scenario, due to the price relation between coal and natural gas, the system will save natural gas at the small CHP units and increase the electricity production at the large coal-fired plants. In this case, the investment in electric boilers (pillar 10, DH-eh) will result in the same fuel demand as the investment in peak-load boilers. This is caused by the design of the present system, which will result in almost no cheap excess electricity production.

In Figure 6.4, the CO_2 emissions are shown for the same analysis. As can be seen, the overall picture is the same as for the fuel demand. The exception is micro-CHP units based on natural gas, which show a remarkable reduction in CO_2 emissions. This is caused by the combined effect of increasing CHP while, at the same time, replacing coal by natural gas.

In Figure 6.5, the cost is shown for the same analysis. Again the overall picture is very much the same. The district heating solutions are among the cheapest options and the high cost of district heating networks is not dominating when compared to the total costs of all options.

The same calculations have been made for all three district heating scenarios, and the results show the same overall picture in all cases. However, the cost-effectiveness of district heating decreases along with increased costs in the district heating networks in scenarios 2 and 3 compared to scenario 1. Gradually, the heat pump option becomes competitive with the district heating solutions.

The next step has been to make the same calculations for the 100 percent renewable energy system in the year 2060. The results are shown in Figure 6.6. Here, the district heating option has been calculated for only one solution, since it is expected that a suitable combination of heat pumps, CHP units, and peak-load boilers has already been established in the future. Consequently, the district heating option involves a coordinated investment in the expansion of all three types of production units.

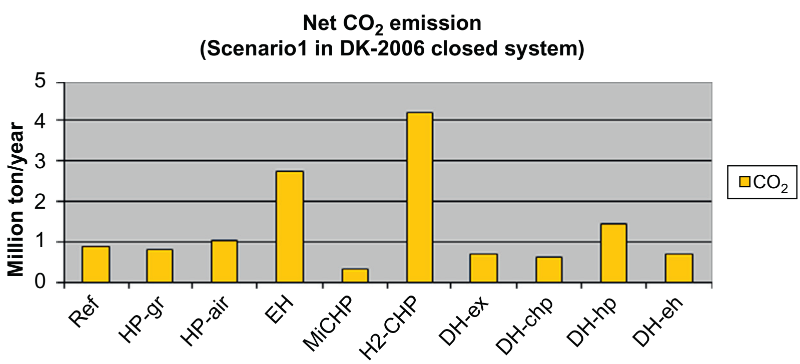

FIGURE 6.4 CO_2 emission of the 10 heating options applied to scenario 1.

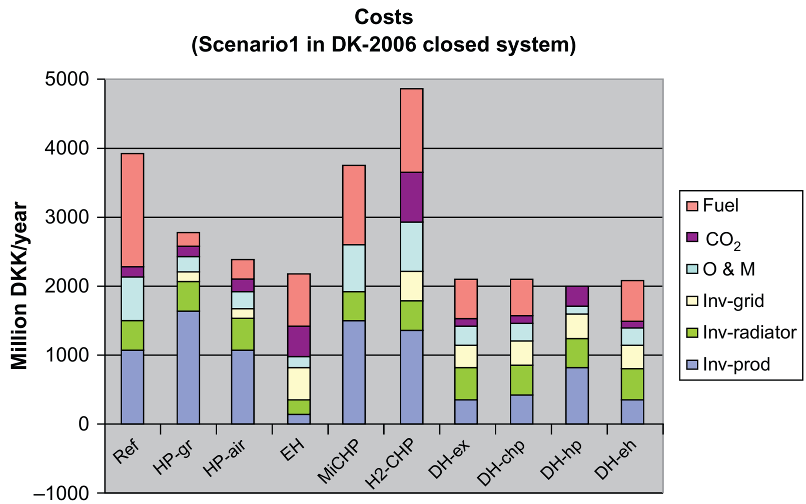

FIGURE 6.5 Total annual cost of the 10 heating options applied to scenario 1.

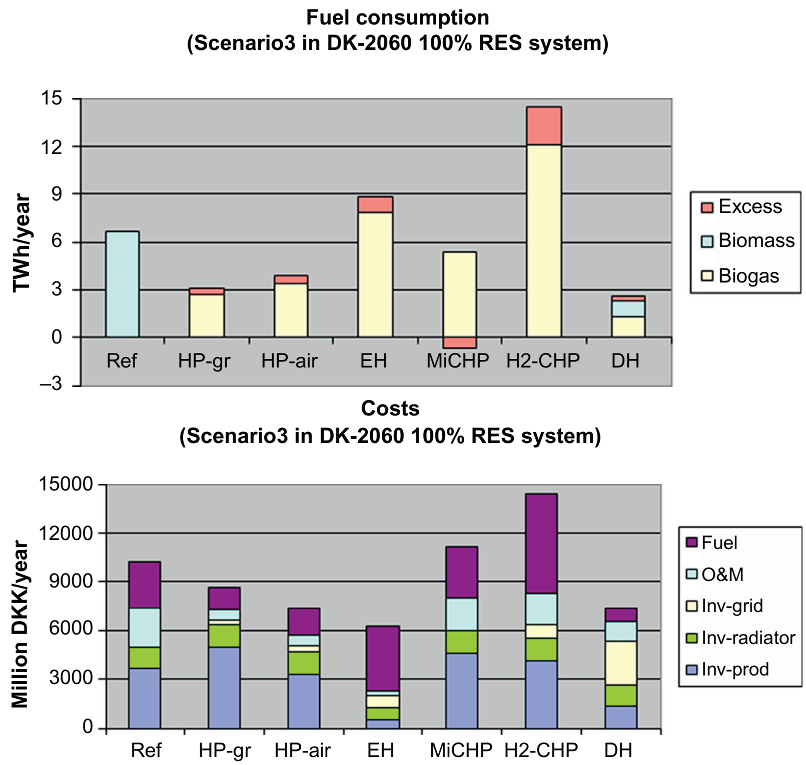

FIGURE 6.6 Fuel demands and total cost of different heating options of scenario 3 seen in a future 100 percent RES system year 2060.

In the 100 percent renewable energy system, the expansion of wind power leads to an excess electricity production of 3.2 TWh. The energy system analysis includes the factor that some of the heating options utilize such excess production better. Moreover, it should be highlighted that the space heating demand has decreased by as much as 75 percent.

Compared to the present 2006 system, the overall picture now shows that electricity-consuming options (electric heating and heat pumps) improve, while electricity-producing options (CHP) deteriorate. In general, this change is caused by the excess electricity production from wind turbines. It should be emphasized that the ability of the hydrogen fuel cell option depends on the hydrogen storage, which has been defined here as an electrolyzer capacity of 3200 MWe in combination with a hydrogen storage of 200 GWh, corresponding to the production of approximately 14 days. Electric heating seems to have a low cost. However, the fuel demand is high and, consequently, such an option is extremely sensitive to shifting fuel prices. Moreover, this solution puts pressure on the need for biomass and other renewable energy sources.

Consequently, the best solutions again seem to be individual heat pumps and district heating, while individual CHP options do not seem to be desirable either in terms of fuel efficiency or from an economic point of view.

All in all, the analysis shows that a substantial reduction in fuel demands and CO_2 emissions as well as cost can be achieved by converting to district heating. This conclusion seems to be valid for the present energy systems as well as for a future scenario aiming at a 100 percent renewable energy supply in 2060, even if the space heating demand is reduced to as much as 25 percent of the present demand. However, other options than boilers exist, which have also been analyzed as in the following:

Micro-CHP based on fuel cells on hydrogen. This solution does not seem to be able to reduce fuel demands, CO_2 emissions, or cost in the present system or in a future 100 percent renewable energy system. The efficiency is simply too low and the cost too high. Moreover, better and more cost-effective solutions can be found to deal with the problem of excess electricity production from wind power and CHP.

Micro-CHP based on natural gas seems to be an efficient way to reduce fuel demands and especially CO_2 emissions in the short term. CO_2 emissions are reduced both by expanding CHP and by converting from coal to natural gas in the overall system. The solution is, however, very expensive compared to district heating because of the substantial investments in micro-CHP units in various buildings. In the long-term perspective, in a 100 percent renewable energy system, the solution is not competitive regarding fuel, CO_2 emissions, or cost reduction compared to district heating and not even compared to individual boilers based on biomass.

With the high oil and gas prices of 2008 and, at the same time, low coal and Nord Pool electricity prices, *electric heating* is a socioeconomically

reasonable alternative, mainly because of the saved central heating system cost. In the short term, this is not valid for houses that already have central heating. In the long-term perspective, electric heating is bad for fuel demands and CO_2 emissions. Moreover, this alternative becomes very sensitive to potential increases in future fuel demands and prices.
Individual heat pumps seem to be the best alternative to district heating. In the short term, heat pumps are at the same level as district heating in terms of fuel efficiency, CO_2 emissions, and cost. The cost is a little higher in areas close to the district heating system but a little lower in houses farther away. In the long-term perspective, in a 100 percent renewable energy system, the fuel efficiency is high and, regarding cost, the solution is more or less equal to district heating. However, it is highly dependent on the distance to existing district heating grids.

To all the alternative options it is relevant to add solar thermal energy. However, this option has not been included in the analysis presented here.

In an overall perspective, the conclusion seems to be that the best solution will be to combine a gradual expansion of district heating with individual heat pumps in the rest of the areas. The analysis indicates that the optimal solution will be to expand district heating from the present 46 percent to somewhere between 63 and 70 percent.

It must, however, be emphasized that the analysis is based on a gradual improvement of district heating technologies in accordance with the concept of smart thermal grids. This involves, among other initiatives, a decrease in temperature in combination with a reduction in space heating demands including a reduction in the return temperature of the heat from consumers. Therefore, it is crucial to continue the present development in such a direction. Moreover, the expansion of district heating will help utilize the heat production from waste incineration and industrial excess heat production, which has been included in the analysis. Additionally, district heating helps the integration of geothermal heating, biogas production (supply of heat), and solid biomass such as straw.

3. ECONOMIC CRISIS AND INFRASTRUCTURE INVESTMENTS[3]

This Section is Courtesy of Guest Writer Frede Hvelplund

This section is based on Lund and Hvelplund's (2012) article "The Economic Crisis and Sustainable Development: The Design of Job Creation Strategies by Use of Concrete Institutional Economics". The paper presents concrete institutional economics (see Chapter 3) as an economic paradigm to understand how

3. Excerpts reprinted from *Energy* 43, Henrik Lund and Frede Hvelplund, "The Economic Crisis and Sustainable Development: The Design of Job Creation Strategies by Use of Concrete Institutional Economics", pp. 191–200 (2012), with permission from Elsevier.

the request for renewable energy and related infrastructures in times of economic crisis can be used to generate jobs as well as economic growth. In most countries, including European countries, the United States, and China, the implementation of renewable energy solutions involves the replacement of imported fossil fuels by substantial investments in energy conservation and renewable energy. In this situation, it becomes increasingly essential to develop economic thinking and economic models that can analyze the concrete institutions in which the market is embedded. As a follow-up on the previous section, this section presents such tools and methodologies and applies them to the case of the Danish heating sector in terms of a specific investment program for district heating. The case shows how investments in this kind of infrastructure can be made in a way that has a positive influence on job creation and economic development, as well as public expenditures.

As explained in Chapter 3, the use of choice awareness methodologies with regard to concrete institutional economics involves the following three-step procedure:

Step 1: Analyze the technical scenarios and find the best ones. Concrete institutional economics recognizes that an economic balance of products and production factors such as labor will not be established automatically. Unemployment can develop and persist for years and decades. Deficits on the state budget can increase and lead countries into a debt trap without any automatic processes re-establishing financial balances. Therefore, feasibility studies of energy scenarios should also take into account and evaluate the effects of different technical scenarios on employment and public finances. Furthermore, positive effects on these macroeconomic indicators should be a part of the project evaluation process when looking for the best alternative.

Step 2: Analyze the present institutional and political contexts and find the hindrances to the best technical scenarios. This could be tariff and tax conditions supporting increased energy consumption, ownership design that hinders the local acceptance of wind power projects, the lack of financial possibilities for people who want to improve the energy standard of their houses, tax deduction rules supporting accelerating traffic development, etc. Altogether, these different institutional conditions may identify projects that are not implemented under the present institutional conditions, despite being both economically and environmentally feasible from social and economic points of view.

Step 3: Design the required institutional scenarios to implement the best technical solutions as described in step 1.

To illustrate this theoretical point of departure and these methodologies, a case is used based on the previous section on district heating. As already explained, the case involves the heating of the 24 percent of the Danish building stock which is now being heated by individual boilers fueled by oil, natural gas, or biomass and which is located relatively close to existing district heating areas. Based on the findings in the previous section, the case concerns the replacement of these boilers by district heating in urban areas in combination with individual heat pumps in the remaining buildings during a period of 10 years. This replacement involves the following:

- Expansion of district heating from the present 46 percent to 65 percent of the Danish heat market, equal to 80 percent of the buildings in question
- Individual heat pumps in the remaining buildings, equal to 20 percent of the buildings in question
- Gradual improvement of the district heating technology and operation introduced, among others by lowering the temperature in the distribution system along with implementing energy conservation in the buildings
- Additional investments in the district heating production plants including the addition of heat pumps and solar thermal, geothermal, and biomass boilers to the existing CHP plants

The economic calculation is based on the same investment costs as in the previous section, with the addition of new data to include the calculation of consequences for the balance of payment and job creation. All investments are assumed to have an import share of 40 percent, operation and maintenance an import share of 20 percent, and fossil fuels an import share of 80 percent. The remaining costs are assumed to generate jobs in Denmark at an average of 2 person-years per 1 million DKK (equal to approximately 135,000 EUR). Salary constitutes 80 percent of this and the rest is capital income or savings.

In the analyses of the influence on governmental expenditures, including saved unemployment benefits as well as increases in income taxes, a net plus of 300,000 DKK (40,000 EUR) is used per person-year, equal to the general expectations used by the Danish Ministry of Finance. This amount includes any additional effects arising from VAT, etc.

Different versions of the investment plan in terms of different production units were analyzed by use of the EnergyPLAN model and are reported in Lund and Hvelplund (2012). Along the lines of the previous section, the result shows that Danish society in general will be able to decrease the cost of heating the buildings in question by investing in district heating and individual heat pumps. Fuel costs are replaced by investments, but the annual investment costs are lower than the costs of the fuel saved when paid during their technical lifetime using a real interest of 3 percent.

The total additional net investment amounts to approximately 9 billion EUR; 13 billion EUR must be invested, while 4 billion EUR of investment can be saved compared to the reference. Table 6.3 illustrates the annual investment and operation costs, given that the alternative is implemented over a period of 10 years from 2011 to 2020. As shown, this implementation plan requires substantial net investments, which will gradually result in substantial

TABLE 6.3 Costs and Job Creation

MDKK	All Years	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
District heating grid	58,000	5800	5800	5800	5800	5800	5800	5800	5800	5800	5800	0
DH house installations	9240	924	924	924	924	924	924	924	924	924	924	0
Individual heat pumps	11,550	1155	1155	1155	1155	1155	1155	1155	1155	1155	1155	0
Large-scale heat pumps	6000	600	600	600	600	600	600	600	600	600	600	0
Peak-load boilers	4000	400	400	400	400	400	400	400	400	400	400	0
Biomass boilers	5000	500	500	500	500	500	500	500	500	500	500	0
Solar thermal	5600	560	560	560	560	560	560	560	560	560	560	0
Geothermal	1400	140	140	140	140	140	140	140	140	140	140	0
Total new investments	**100,790**	**10,079**	**10,079**	**10,079**	**10,079**	**10,079**	**10,079**	**10,079**	**10,079**	**10,079**	**10,079**	**0**
Saved oil boilers	11,400	1140	1140	1140	1140	1140	1140	1140	1140	1140	1140	0
Saved biomass boilers	8400	840	840	840	840	840	840	840	840	840	840	0
Saved Ngas boilers	10,460	1046	1046	1046	1046	1046	1046	1046	1046	1046	1046	0

Continued

TABLE 6.3 Costs and Job Creation—Cont'd

MDKK	All Years	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Total saved investments	**30,260**	**3026**	**3026**	**3026**	**3026**	**3026**	**3026**	**3026**	**3026**	**3026**	**3026**	**0**
Net investments	**70,530**	**7053**	**7053**	**7053**	**7053**	**7053**	**7053**	**7053**	**7053**	**7053**	**7053**	**0**
Increased O&M	8438	70	211	352	492	633	774	914	1055	1195	1336	1406
Saved O&M	−9609	−80	−240	−400	−561	−721	−881	−1041	−1201	−1361	−1521	−1602
O&M net change	**−1171**	**−10**	**−29**	**−49**	**−68**	**−88**	**−107**	**−127**	**−146**	**−166**	**−185**	**−195**
Fuel net change	**−19,722**	**−164**	**−493**	**−822**	**−1150**	**−1479**	**−1808**	**−2137**	**−2465**	**−2794**	**−3123**	**−3287**
Total costs	49,637	6879	6531	6182	5834	5486	5138	4790	4441	4093	3745	−3482
Import costs	12,200	2688	2421	2154	1887	1620	1353	1087	820	553	286	−2669
Employment	74,874	8382	8220	8057	7894	7731	7569	7406	7243	7081	6918	−1627

fuel cost savings. The net investments will have a negative influence (positive net import) on the balance of payment in the beginning. However, due to the saved import of fossil fuels, this influence is reduced and will end up being positive (negative net import). When measured over the total lifetime of the investment, the effect is both substantial and positive. The net investments made during the 10-year implementation period also result in the creation of approximately 7000–8000 jobs each year during the entire 10-year period.

However, the implementation of the alternative has an influence on the governmental expenditures in several ways. First of all, the alternative cannot be implemented without the formulation of an active energy policy, since some of the investments are not feasible to the investors with the current taxes and subsidies. Second, since oil and natural gas consumption is currently taxed, the government will lack this income when these fuels are replaced. Finally, the creation of jobs will generate additional income taxes.

In Table 6.4, an estimate is made of the extent of the different consequences. This is an estimate, since VAT and multiplication effects have not been included. Moreover, due to the very complex taxation system in Denmark, not all effects have been calculated in detail. However, the table provides a good overview of the magnitude of the influence of the different measures.

In Table 6.4, the top lists the current taxes as input; next, all the changes in relevant fossil fuel consumption are listed and divided into the relevant taxation categories. Based on these two types of input, a calculation is made: first, of the decreases in taxes on oil and natural gas for individual boilers compared to the reference, and, second, of the increases in other taxes, i.e., on electricity for heat pumps. As can be seen, the government will lose 140 MDKK in taxes on oil and natural gas in the first year, gradually rising to 2800 MDKK after 10 years, when the strategy is fully implemented. Approximately 50 percent of this loss is compensated for by increases in the taxation of electricity for heat pumps.

However, in return for the net loss in fuel taxes, the government benefits from the job creation in two ways. First, governmental contributions to unemployment benefits are saved. Next, the income taxes are increased. In total, this effect raises the income by 2500 MDKK/year in the beginning, slightly decreasing to 2000 MDKK in 2020.

The net effect (if the plan could be implemented without any subsidies or similar) is a positive contribution to the governmental expenditures of approximately 2500 MDKK in 2011, decreasing to approximately 750 MDKK in 2020.

A survey of the barriers to making the investments feasible on the market has resulted in the following public regulation measures to be taken:

- A subsidy for heat pumps and solar thermal power of 20 percent in the first 2 years should be introduced and gradually decreased to 15, 10, and 5 percent, respectively, over the period.

TABLE 6.4 Net Effects on the Governmental Expenditures

				DKK/ M3	DKK/ kWh	MDKK/ GWh
Input data	Saved unemployment benefits:	0.12 MDKK/ Man-year	Individual natural gas	2.629	0.239	0.239
	Increased income tax	0.18 MDKK/ Man-year	Industry natural gas	2.629	0.239	0.239
			Heat from heat pump		0.208	0.208
			Heat from boilers		0.208	0.208
			Heat from CHP	2.620	0.238	0.238
			Individual gas oil	2.469	0.247	0.247
			Industry oil	2.469	0.274	0.247
			Individual HP (elec.)		0.545	0.545

TABLE 6.4 Net Effects on the Governmental Expenditures—Cont'd

MDKK	All Years	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Subsidy (solar and HP)		20	20	15	15	10	10	5	5	0	0	0
Employment	**74,874**	**8382**	**8220**	**8057**	**7894**	**7731**	**7569**	**7406**	**7243**	**7081**	**6918**	**−1627**
GWh/year												
MDKK	**All Years**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Natural gas (individual)	−24,600	−205	−615	−1025	−1435	−1845	−2255	−2665	−3075	−3485	−3895	−4100
Natural gas (industry)	−15,240	−127	−381	−635	−889	−1143	−1397	−1651	−1905	−2159	−2413	−2540
Total natural gas CHP	*−3060*	*−26*	*−77*	*−128*	*−179*	*−230*	*−281*	*−332*	*−383*	*−434*	*−485*	*−510*
Tax free part (0.38/ 0.62	−1875	*−16*	*−47*	*−78*	*−109*	*−141*	*−172*	*−203*	*−234*	*−266*	*−297*	*−313*
Taxed natural gas CHP	−1185	−10	−30	−49	−69	−89	−109	−128	−148	−168	−188	−197
Natural gas (boiler)	−9360	−78	−234	−390	−546	−702	−858	−1014	−1170	−1326	−1482	−1560
Gas oil (boiler)	−12,420	−104	−311	−518	−725	−932	−1139	−1346	−1553	−1760	−1967	−2070
Oil (industry)	−17,160	−143	−429	−715	−1001	−1287	−1573	−1859	−2145	−2431	−2717	−2860
Heat from heat pump	38,700	383	963	1613	2258	2903	3548	4193	4838	5483	6128	6450
Electricity to individual HP	4878	41	122	203	285	366	447	528	610	691	772	813
MDKK losses in taxes		−140	−421	−701	−981	−1262	−1542	−1823	−2103	−2384	−2664	−2804
Additional taxes		71	212	353	495	636	777	919	1060	1201	1343	1413

Continued

TABLE 6.4 Net Effects on the Governmental Expenditures—Cont'd

Net decrease in taxes		**−70**	**−209**	**−348**	**−487**	**−626**	**−765**	**−904**	**−1043**	**−1182**	**−1321**	**−1391**
Saved benefits		1006	986	967	947	928	908	889	869	850	830	−195
Increased income taxes		1509	1480	1450	1421	1392	1362	1333	1304	1275	1245	−293
MDKK	**All Years**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Net influence before policy means		**2445**	**2257**	**2069**	**1881**	**1693**	**1506**	**1318**	**1130**	**942**	**754**	**−1879**
Subsidy solar and heat pumps		−232	−232	−174	−174	−116	−116	−58	−58	0	0	0
Compensation natural gas companies		−56	−56	−56	−56	−56	−56	−56	−56	−56	−56	−56
Tax release individual heat pumps		−14	−41	−68	−96	−123	−151	−178	−205	−233	−260	−274
Tax release large heat pumps		−23	−68	−114	−159	−204	−250	−295	−341	−386	−431	−454
Policy means total		**–325**	**–397**	**–412**	**–485**	**–499**	**–573**	**–587**	**–660**	**–675**	**–747**	**–784**
Net influence on government expenditures		**2120**	**1860**	**1657**	**1396**	**1194**	**933**	**731**	**470**	**267**	**7**	**–2663**

- The natural gas companies should be compensated for loans in the natural gas grid that have not yet been paid, so the remaining consumers will not have to pay for those leaving the system.
- Current taxes on electricity for small- as well as large-scale heat pumps should be reduced.

All in all, these subsidies and tax reductions will increase the governmental expenditures by approximately 300 MDKK in the first year, increasing to approximately 800 MDKK/year after 10 years.

As shown in Table 6.4, when all these measures are introduced and calculated, the net consequences for the government ends at a profit of approximately 2 billion DKK in the first year, gradually decreasing to zero over a period of 10 years.

Consequently, the case illustrates how the economic crisis enables the implementation of essential elements of future renewable energy solutions and infrastructures which generate jobs without having a negative influence on the governmental expenditures.

A core element of concrete institutional economics is the analysis of the specific institutional context of the market in question including the fact that such institutions differ from one country to another and change from one period to another. Consequently, even though the need for concrete institutional economics may apply to many different cases, the results of the Danish case under the present conditions cannot necessarily be applied to other countries and/or other situations. One needs to make a specific analysis of the country in question and may find it relevant to include issues such as the involvement of foreign company laborers, or foreigners in general, as well as a commitment to sustainable development and anti-corruption. However, in times of the economic crisis, a number of different countries are likely to come to similar conclusions regarding the possibilities of designing strategies that further the combination of economic growth and the implementation of sustainable development.

4. ZERO ENERGY BUILDINGS AND SMART GRIDS[4]

This section is based on Lund, Marszal, and Heiselberg's (2011) article "Zero Energy Buildings and Mismatch Compensation Factors". The paper takes an overall energy system approach to analyzing the integration of zero energy and zero emission buildings (ZEBs) into the electricity grid. The integration issue arises from hourly differences in energy production and consumption at the building level, and these differences result in the need for an exchange of electricity via the public grid, even though the building has an annual net-exchange of zero.

4. Excerpts reprinted from *Energy and Buildings* 43, Henrik Lund, Anna Marszal and Per Heiselberg, "Zero Energy Buildings and Mismatch Compensation Factors", pp. 1646–1654 (2011), with permission from Elsevier.

A ZEB combines highly energy-efficient building designs and technical systems and equipment to minimize the heating and electricity demand with on-site renewable energy generation, typically including a solar hot water production system and a rooftop photovoltaic (PV) system. However, heat pumps and small micro-CHP units, preferably based on biomass fuels, have sometimes been taken into consideration as well.

A ZEB can be off-grid or on-grid. For the grid-connected ZEBs, the combination of a reduced demand and an on-site production of heat and electricity to reach zero raises the issue of the hourly difference between demand and production and how to deal with this difference. How do you solve the problem that a building that combines conservation with production, such as PV, may have a zero net energy input on an annual basis, but at the same time exchanges huge amounts of electricity with the public grid? Should the building itself compensate for the need for exchange or should the problem be solved at the aggregated level?

Measures at the individual building level could be either flexible demand or energy storage. However, this section argues that, when seen in the view of optimizing the complete overall energy system, these differences should not be dealt with at the individual building level, but rather at an aggregated level. Compared to the aggregated level, a solution at the individual level is not economically feasible. Moreover, individual solutions involve a risk of making things worse. Of course the measure "flexible demand" should be carried out at the building level, but the aim should not be to level out the need for exchange at the individual building in question. Instead, the flexible demand should aim at contributing to the compensation of the aggregated exchange of many buildings.

To be able to quantify the need for exchange, the following four types of ZEBs have been defined:

1. *PV ZEB:* Building with a relatively small electricity demand and a PV installation
2. *Wind ZEB:* Building with a relatively small electricity demand and a small on-site wind turbine
3. *PV-solarthermal-heatpump ZEB:* Building with a relatively small heat and electricity demand and a PV installation in combination with a solar thermal collector, a heat pump, and heat storage
4. *Wind-solarthermal-heatpump ZEB:* Building with a relatively small heat and electricity demand and a wind turbine in combination with a solar thermal collector, a heat pump, and heat storage

An existing building aiming for zero emissions has been used to quantify the relation between heat and electricity demand, namely, a single-family house constructed in the town of Lystrup, Denmark. The building was constructed in 2009 as a demonstration house of the project "Active houses" built by VHR Holding. The house is 190 m^2 with the following energy demand:

- Domestic hot water: 18.3 kWh/m^2 (66 MJ/m^2) per year
- Space heating: 15 kWh/m^2 (54 MJ/m^2) per year

- Electricity for operating the house: 6.7 kWh/m^2 per year
- Electricity for household: 13.2 kWh/m^2 per year
- PV electricity production: 29.1 kWh/m^2 per year
- Solar thermal: 11 kWh/m^2 (40 MJ/m^2) per year
- Heat pump thermal output: 22.4 kWh/m^2 (81 MJ/m^2) year

Based on the data for the ZEB in Lystrup, the following expected annual figures have been used for the PV-solarthermal-heatpump ZEB:

- Heat demand: 6.3 MWh/year
- Electricity demand: 3.8 MWh/year
- Solar thermal: 2.1 MWh/year
- PV production: 5.5 MWh/year
- Heat pump: converting 1.7 MWh$_e$/year (5.5–3.8) into 4.2 MWh$_{th}$, i.e., having a COP of 2.5
- In the calculation, a heat storage capacity of 17 kWh, which equals one day's average heat demand, is added to level out variations in the hot water consumption and the solar thermal production.

The same figures are used for the wind-solarthermal-heatpump ZEB only replacing the PV production with a wind turbine. It could be a small on-site wind turbine or a share of a larger wind turbine depending on the definitions of ZEB. However, the following calculation represents both cases. A principle of these two ZEBs is shown in Figures 6.7 and 6.8. The other two buildings, i.e., the PV ZEB and the Wind ZEB, are based on the same figures excluding

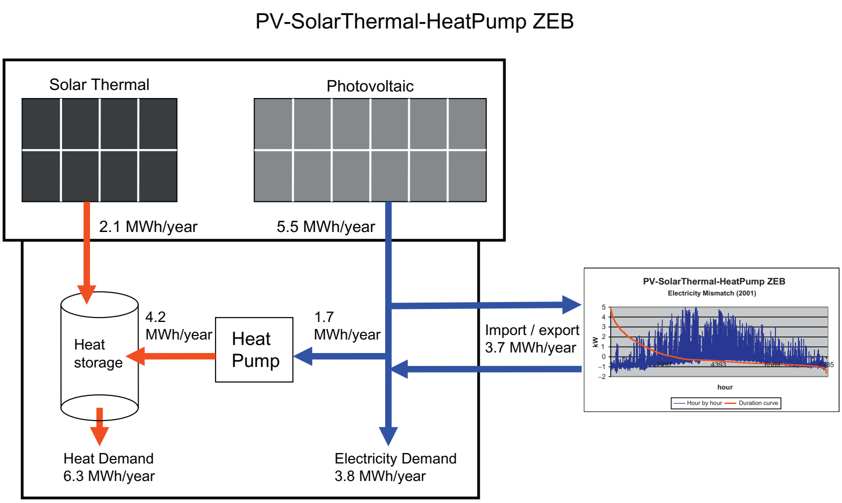

FIGURE 6.7 Principle diagram of the PV-solarthermal-heatpump ZEB with an expected annual net heat and electricity demand of zero, but with a substantial exchange of electricity. The electricity exchange has been calculated as the average ZEB contribution at the aggregated level.

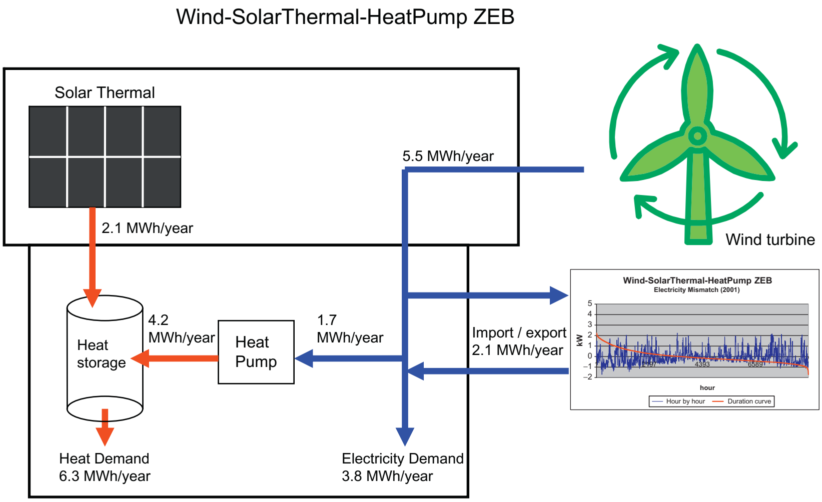

FIGURE 6.8 Principle diagram of the wind-solarthermal-heatpump ZEB with an expected annual net heat and electricity demand of zero, but with a substantial exchange of electricity. The electricity exchange has been calculated as the average ZEB contribution at the aggregated level.

the heat demand, i.e., an electricity demand of 3.8 MWh/year and a similar PV or wind production.

The connection of ZEBs to the public electricity grid and the need for exchange and compensation should not be dealt with at the individual level. It should be compensated for at the aggregated level for the following reasons:

First, the cost of investing and operating one large battery of 10,000 kWh is substantially lower than operating a thousand 10 kWh batteries, among others, because large batteries make it possible to utilize new battery technology, like vanadium redox flow batteries.

Second, other options exist at the system level that can provide the same regulation at even lower cost. As explained carefully in Chapter 5, such options include changing the regulation of existing small CHP plants, introducing large-scale heat pumps at existing CHP and district heating supplies, using electricity in the transportation sector, or even introducing electricity storage systems such as compressed air energy storage. Consequently, one will save money dealing with these problems at the aggregated level.

Third, the influence of the individual building is leveled out at the aggregated level. One may compare it to the design of power supply systems. Power plants are not designed to meet the needs of the number of consumers multiplied by the maximum consumption of each consumer. In such case, one would make huge overinvestments in transmission lines and power stations. The sum of maximum consumption never happens for the simple reason that not all consumers peak in consumption at the same time. At the aggregated level, individual consumptions are leveled out. The same concerns differences created by changes in electricity demand and PV or wind power production at the individual building level. The exchange of one building is partly compensated for by exchanges of other buildings, and the attempt to compensate for each need for exchange individually will lead to situations in which one building is charging a battery at the same time as another building is discharging a battery, leading to unnecessary losses. Seen from the viewpoint of the electricity supply system, it is not the individual "one building exchange" that is interesting; it is the sum of the exchange from all buildings that counts. One would make significant overinvestments and inefficient operation of the system if one tried to compensate for each exchange at the individual level compared to the aggregated level.

Fourth, one risks making things worse. The reason is that exchange, from the individual building point of view, per definition is looked upon in a negative light. If there is a need for exchange, it is defined as a problem that has to be solved. However, from the viewpoint of the electricity supply system, exchange is not necessarily negative; it may also be positive.

This is illustrated by Figure 6.9, which shows the variation of the electricity demand in western Denmark in a week in February 2001. The electricity consumption is high during the day and low during nights and weekends. This variation is typical for all countries even though the specific shape of the electricity demand curve differs from one country to another. From the electricity supply point of view, any exchange that decreases the demand during the night and increases it during the day is negative. This exchange will increase the demand for capacity and increase the production of expensive units during peak hours and only save less expensive units during base load hours. However, for the same reason, exchange resulting in the opposite, i.e., a decrease during peak load and an increase during base load, creates a positive exchange for the

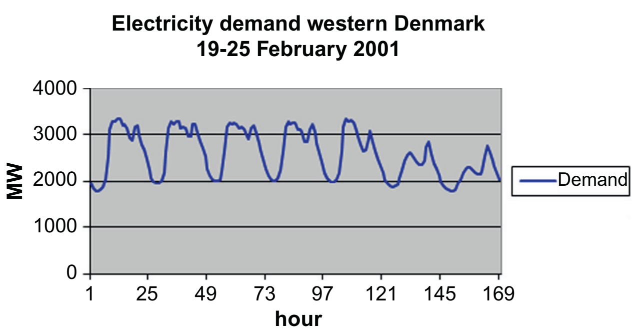

FIGURE 6.9 Hourly fluctuations in the electricity demand of western Denmark in February 2001. A mismatch arising from a ZEB that consumes electricity during night hours and produces electricity during day hours is a positive mismatch that should not be compensated for.

system. Consequently, such an exchange should not be compensated for, and if investments in flexible demand or storage systems are made at the building level to minimize this exchange, this will only make things worse.

Figures 6.10 and 6.11 compare the fluctuations of the same electricity demand with the exchange of PV ZEB and Wind ZEB, respectively, with an

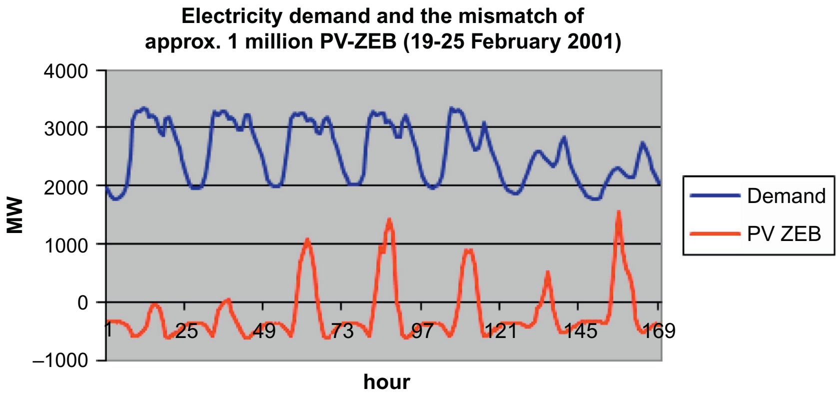

FIGURE 6.10 The mismatch of approximately 1 million PV ZEBs compared to the hourly fluctuations in the electricity demand of western Denmark in February 2001. It is based on actual PV production during the same week in February, taking into account the leveling out between approximately 267 PV installations.

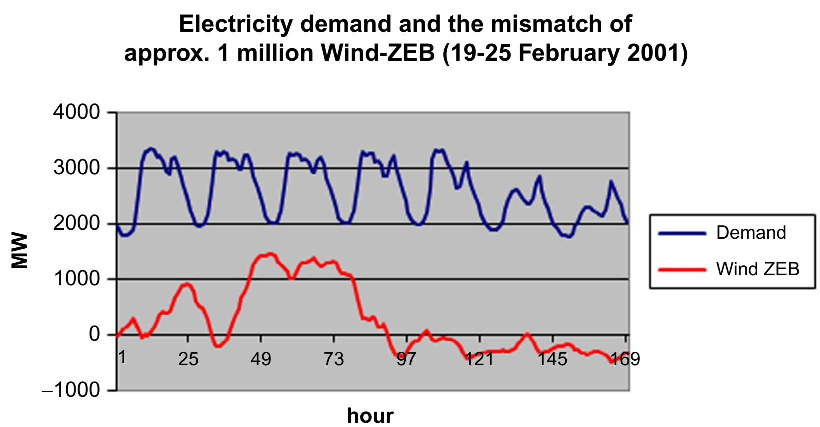

FIGURE 6.11 The mismatch of approximately 1 million Wind ZEBs compared to the hourly fluctuations in the electricity demand of western Denmark in February 2001. It is based on actual wind power production during the same week in February, taking into account the leveling out between the numbers of wind turbines in western Denmark the same year.

annual electricity demand of 3.8 MWh. The calculation of the need for exchange is based on the actual electricity production from PV collectors and wind turbines in western Denmark in the same week of February 2001, using the same data, which was explained in Chapter 5.2. The fluctuations are shown at the aggregated level and represent approximately 1 million ZEBs. As one can see, the difference between the buildings' electricity demand and PV production generally results in a positive exchange for the system, while the difference between demand and wind power gives both a positive and a negative exchange. It should be noted that 1 million ZEBs is an unrealistic number in Denmark in the foreseeable future, and here this number only serves to illustrate the principle on the diagrams. Moreover, the discussion here does not take into account possible limitations in local distribution grids leading to voltage drops.

The above case illustrates how important it is to include the design and operation of ZEBs into the coherency of the overall energy system if the aim is to identify the most efficient and least-cost integration of combinations of energy efficiency and renewable energy measures. An attempt to deal with this integration without taking the overall energy system into account is likely to lead to overinvestments and inefficient operation at the individual building level, as well as in the overall system as a whole.

5. FUTURE POWER PLANTS AND SMART ENERGY SYSTEMS[5]

This Section is Courtesy of Guest Writers Anders N. Andersen, Poul Østergaard, Brian Vad Mathiesen, and David Connolly

This section is based on Lund, Andersen, Østergaard, Mathiesen, and Connolly's (2012) article "From Electricity Smart Grids to Smart Energy Systems—A Market Operation Based Approach and Understanding". By describing the case of Skagen CHP plant located in the northern part of Denmark and how this plant is designed and operated, the paper provides an example of what future power plants could look like according to the approach of smart electricity grids as part of a future smart energy system based on renewable energy. An interesting point about the case is that some of the major requirements for smart grids and smart energy systems have already been implemented and have been in operation for several years now. It is also interesting to note that these changes were implemented as a consequence of Skagen CHP plant making active use of the opening of the Nordic electricity market Nord pool.

5. Excerpts reprinted from *Energy* 42, Henrik Lund, Anders N. Andersen, Poul Alberg Østergaard, Brian Vad Mathiesen, and David Connolly, "From Electricity Smart Grids to Smart Energy Systems—A Market Operation Based Approach and Understanding", pp. 96–102 (2012), with permission from Elsevier.

The step from the present energy system via large-scale integration of renewable electricity toward 100 percent renewable energy poses a challenge to the operation of the electricity grid, as well as to the CHP and power plants, which have to produce power when the wind is not blowing and the sun is not shining. As already described in Chapter 5, to meet this challenge, improvements will be necessary in grid stability, while also creating more flexible electricity production. This means that future power plants will have to look quite different from the way they do now. The main challenges are described as follows.

First, there is a much greater need for technical *flexibility*. The future power plants will have to be able to change production much faster than most nuclear and coal-fired steam turbines can today. Moreover, they have to be able to stop production within 1 hour and run again soon after; again something that today's steam turbines cannot do.

Second, power plants need to be able to survive *financially* with reduced annual production. Along with increasing the share of RES to, e.g., 50 percent in 2020 as planned in Denmark, and maybe further to 80 percent in a 100 percent renewable energy system, the annual production hours of the power plants will decrease accordingly. In Lund and Mathiesen (2012), it has been calculated that a power station that today on average typically has approximately 4000 production hours/year, may only have 1200 hours/year in the future. This poses a financial challenge to the power stations. How can they survive and make a profit with so few hours of production?

Third, it will be a challenge to maintain *grid stability* and provide similar auxiliary services such as regulating power. Today, in most countries, the task of maintaining grid stability (frequency and voltage) is handled by the large steam turbines and/or hydro power generation. In the future, however, grid stabilization should be managed also when the power plants are not producing.

Fourth, power plants should be mostly *CHP plants*. To achieve the most efficient use of fuels in the system, power stations producing only electricity should be at a minimum. All these units should be able to supply heat to district heating and/or cooling as well as biomass conversion and industrial purposes. Consequently, power stations should be CHP plants while also meeting the challenges above.

The question is whether it is possible to design a future power plant that can meet all of these challenges and at the same time be feasible. The case of Skagen can be used to illustrate how this might be done. Skagen is already a CHP plant, and it is supplemented with a waste incineration boiler and an electric boiler as well as contribution from industrial surplus heat. Consequently, the case of Skagen illustrates how a CHP plant can be supplemented with other heat-producing units. Moreover, the case illustrates the significance of including distributed CHP and renewable power production units in the task of grid stabilization, i.e., securing voltage and frequency stability for the electricity supply.

Unit	Size
CHP capacity	13 MWe and 16 MJ/s (three 4.3 MWe natural gas units)
Heat storage	250 MWh
Peak load boilers	37 MW
Electric boiler	10 MW
Compression heat pump	Under consideration

FIGURE 6.12 Technical specifications and illustration of Skagen CHP plant.

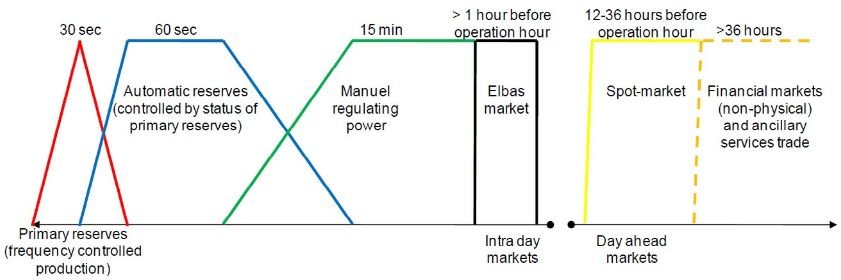

FIGURE 6.13 The main electricity markets (typical for many market-based systems).

The case of Skagen presents a technical design for potential flexible energy systems that will be able to balance production and demand, while also fulfilling voltage and frequency stability requirements of the grid. It also illustrates how this operation has already been implemented in a few places in Denmark.

Skagen CHP plant has three gas engines, heat storage, a gas peak-load boiler, and an electric boiler, as listed in Figure 6.12. Moreover, Skagen CHP plant receives heat from an incineration plant and waste heat from industry, and is considering investing in a large-scale heat pump.

The organization of the Danish electricity markets, as part of the Nordic system, is shown in Figure 6.13. As shown, the market is divided into a day-ahead spot market and a number of regulating power markets. The specific organization varies from one European system to another, but the principle shown in Figure 6.13 is typical for most countries.

Access to the different markets was granted for small CHP plants, like the one in Skagen, along the time line listed below:

- Day-ahead spot market in January 2005
- Regulating power market in 2006
- Automatic primary reserve market in November 2009

Skagen CHP plant has been operating in the day-ahead spot market for several years and was one of the first small CHP plants to enter the regulating power market. Since November 2009, Skagen CHP plant has also been operating in the automatic primary reserve market.

The simultaneous operation of the plant in all these markets is done in the following sequence. Bids are given a day ahead on the spot market. Bids for electricity production from the CHP units are given on the basis of alternative costs of supplying heat from the gas boiler or the electric boiler. In the calculation of the bids, the heat storage option is carefully taken into account. The calculation of the bids is described in Andersen and Lund (2007) and considerations to optimize the heat storage investment are described in Lund and Andersen (2005).

The CHP units can be operated in the regulating power market in the following two ways: If operation in the spot market is won, a downward regulation can be offered; if not, an upward regulation can be offered. The reverse situation applies to the electric boiler. Additionally, the CHP units can be operated in the automatic primary reserve market. This is done by offering the CHP plants to the spot market at full capacity minus 10 percent. If the bid is won, the same unit can be offered for a ±10 percent operation in the primary automatic reserve market. The same principle can be applied to the electric boiler. Figure 6.14 illustrates the operation of the plant on a day in May 2010.

Figure 6.14 shows that on Thursday, May 13, 2010, the three CHP units traded their full load in the spot market during the well-paid hours in the middle of the day and in the evening. On Friday, May 14, the three CHP units

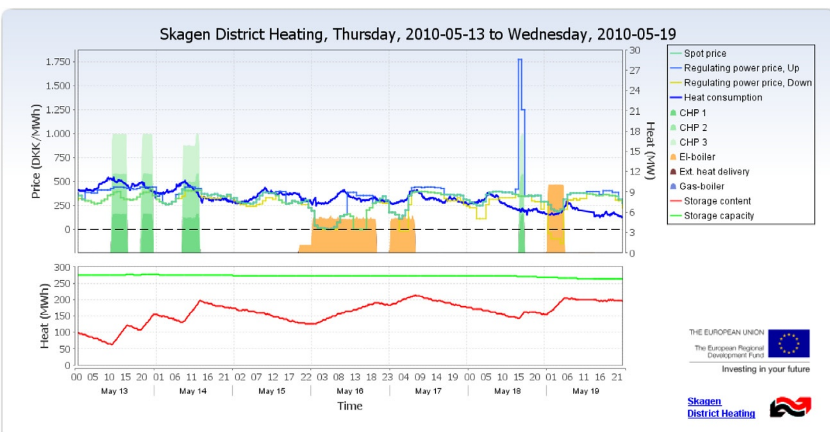

FIGURE 6.14 The operation of Skagen CHP plant on the spot market, the regulating power market, and the primary reserve market on May 13–19, 2010; www.emd.dk/desire/skagen.

were traded in the spot market during the well-paid hours in the middle of the day; however, it was not at full load, and the remaining capacity was traded in the primary reserve market. On Sunday, May 16, the electric boiler ran at half load, allowing it to be both positive primary reserve (reducing consumption) and negative primary reserve (increasing consumption). On Tuesday, May 18, all three CHP units were activated in the regulating power market for an upward regulation. The following day, the 10 MW electric boiler was activated in the regulating power market for a downward regulation.

Another interesting example of Skagen CHP plant's regulating potential occurred on March 25, 2011, as displayed in Figure 6.15. In the first four hours of the day, Skagen won the negative primary reserve with the 10 MW electrical boiler. Hence, it operated below full capacity. A little before 3 A.M., Skagen won a downward regulation in the regulating power market, so the electric boiler increased its output to approximately 4 MW. At the same time, Skagen still performed the frequency regulation, which it had won in the primary reserve market. After 4 A.M., Skagen had not won any additional primary reserve, so the electric boiler was offered at full capacity (i.e., 10 MW) for downward regulation in the regulating power market, winning it for a full hour. From 4 to 8 P.M., only part of the CHP units were sold in the spot market, which made it possible to offer both positive primary reserve and negative primary reserve during these 4 hours.

The online operation of Skagen CHP plant and the prices of the spot market and the balancing market can be seen at www.emd.dk/desire/Skagen.

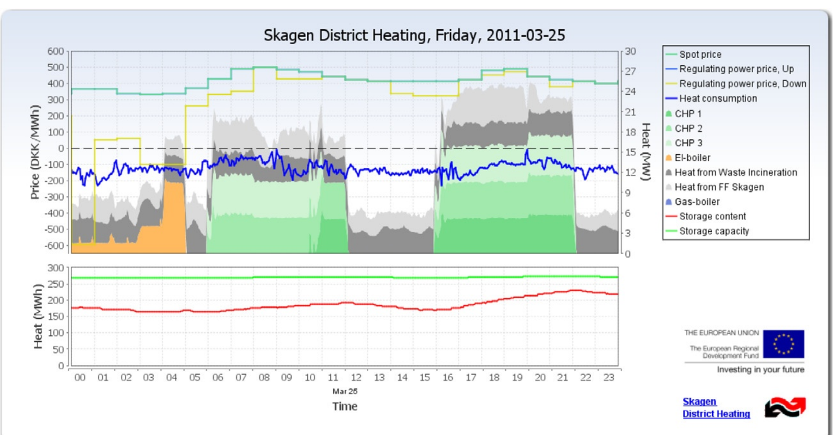

FIGURE 6.15 The operation of Skagen CHP plant on the spot market, the regulating power market, and the primary reserve market on March 25, 2011; www.emd.dk/desire/skagen.

The investment cost related to the involvement of Skagen CHP plant in the primary reserve market has been surprisingly low. The cost of control equipment for the existing CHP units, which made it possible to offer ± 1.4 MW, has been only 27,000 EUR and the cost of the 10 MW electric boiler has been 0.7 million EUR.

As illustrated above, Skagen CHP plant is an example of a power plant that, to a large extent, can meet the requirements of future power stations listed in the beginning of this section. Skagen is a CHP plant and it provides flexible production, which can change from one hour to another between producing and consuming electricity. At the same time, the plant plays an active role in the grid stabilization and regulating power tasks. Skagen has done this with relatively few utilization hours on the CHP unit, and it allows substantial inputs of wind in the electricity supply. It also enables the use of waste incineration and industrial surplus heat in the heat supply, while still surviving financially. This ability to provide high power inputs for only a few hours may even be expanded substantially in the future, if Skagen saves the existing engines for the power reserve market when these have to be replaced by new ones. Considering the fact that Denmark has a huge number of small CHPs of similar capacity in its system, this solution can be copied and together these plants may form a coherent solution for the whole system in the future.

Regarding smart grids and smart energy systems, the flexible operation of Skagen CHP plant illustrates the significance of including distributed CHP and renewable power production units in the task of grid stabilization, i.e., ensuring voltage and frequency stability of the electricity supply. Today, in most countries, electricity is produced either by hydro power or by large steam turbines on the basis of fossil fuels or nuclear power. Fluctuating and intermittent renewable power production constitutes only a small part of the production. Until now, the tasks of balancing supply and demand and securing frequency and voltage on the grid have been managed only by such large production units.

However, the opening of the spot market, and later both the regulating power market and the primary reserve market, has made it possible for small distributed CHP plants to enter these markets. The case of Skagen CHP plant equipped with CHP units, heat storage, and electric boilers illustrates how small plants can provide valuable grid stabilization at very low additional investment and operating costs. Moreover, this case illustrates how the perception of the electricity sector as part of a complete renewable energy system paves the way for better and more cost-effective solutions to smart grid applications, compared to looking at the electricity sector as a separate part of the energy system. Consequently, a smart energy system approach may prove beneficial compared to a sole smart electricity grid approach.

6. RENEWABLE ENERGY TRANSPORTATION FUEL PATHWAYS[6]

This Section is Courtesy of Guest Writers David Connolly and Brian Vad Mathiesen

This section is based on a chapter in Mathiesen, Connolly et al.'s (2014) report "CEESA 100% Renewable Energy Transport Scenarios Towards 2050". The report is a result of the Coherent Energy and Environmental System Analysis (CEESA) project partly financed by the Danish Council for Strategic Research. Furthermore, the report is a background report to the CEESA 100 percent renewable energy scenario, which is presented in Chapter 7. As explained in Chapter 7, the basic finding in the CEESA project—as well as similar studies shown in Chapter 7—is that the biomass available for energy use is limited, while biomass-based gas or liquid fuels are required in the transportation sector to supplement the direct use of electricity. This forms a challenge to the system design in terms of identifying suitable renewable energy transportation fuel pathways.

Considering the renewable resources available to produce electricity and the limitations associated with biomass, maximizing the use of electricity and minimizing the use of bioenergy in the transportation sector are key considerations. Overall, five distinct pathways have been analyzed in detail here (see Table 6.5): electrification, fermentation, bioenergy hydrogenation (includes biomass and biogas), CO_2 hydrogenation, and co-electrolysis. All these pathways are

TABLE 6.5 Transportation Fuel Pathways Considered in CEESA and Their Principal Objective

Pathway Considered	Principal Objective
Direct electrification	Use electricity as the primary transportation fuel
Fermentation	Convert straw to a fuel suitable for transportation (i.e., ethanol) using a fermenter
Bioenergy hydrogenation	Gasify a biomass resource OR use anaerobic digester to produce biogas; afterward boost its energy potential as a transportation fuel using hydrogen from steam electrolysis
CO_2 hydrogenation (CO_2Hydro)	Create a fuel without any direct biomass consumption using hydrogen from steam electrolysis and sequestered carbon dioxide
Co-electrolysis	Create a fuel without any direct biomass consumption by co-electrolyzing steam and sequestered carbon dioxide

6. Excerpts reprinted from Brian Vad Mathiesen, David Connolly et al. (2014) "CEESA 100% Renewable Energy Transport Scenarios Towards 2050".

described in detail in the report along with an overall comparison. A separate energy flow diagram is available for each pathway outlining the electricity and biomass required to produce 100 PJ of the primary fuel. However, for practical reasons, only the principal pathway diagrams have been included in the following.

At the current stage, it is uncertain to which degree the future transportation system ends up using a liquid fuel or a gas (or a combination of both) to supplement the direct use of electricity. For that reason, the following pathways have been made for both a gas and a liquid fuel. However, in order to create the pathways, the final fuel had to be defined to identify the conversion losses. For the gas alternative, methane is chosen, which is very close to natural gas, and natural gas-based vehicles are already well established, with over 10 million vehicles worldwide.

For various reasons, methanol is assumed to be the preferred liquid fuel in a 100 percent renewable energy system. Methanol is the simplest alcohol with the lowest carbon content and the highest hydrogen content of any liquid fuel. Furthermore, methanol can be used in internal combustion engines as a replacement for petrol with relatively few modifications. This has already been proven in the United States when ~20,000 methanol cars and 100 refueling stations were in use in the mid-1990s (Bromberg and Cheng 2010). It is also being proven in China at present, where over 200,000 methanol vehicles are being introduced over 5 years (Methanol Institute China 2011). It is worth noting, however, that dimethyl ether (DME) could also be used since it is the first derivative of methanol and it is very suitable as an alternative to conventional diesel (Pontzen et al. 2011). The efficiency lost when choosing DME compared to methanol can be gained due to the higher efficiencies of diesel engines compared to petrol engines. Therefore, the transportation demands displayed in the flow diagrams are similar for both methanol and DME from a well-to-wheel perspective.

For all fuels, a passenger transportation demand (pkm) and a freight transportation demand (tkm) are displayed, since they can be used for either one or the other demand in all cases except one (i.e., battery electrification). The specific energy consumption is shown in Table 6.6 based on vehicle efficiencies from the Danish Energy Agency (2008). By assessing the energy losses from production to consumption, it is possible to compare each of the pathways in terms of the resources that they require and the transportation demand that they meet. The following sections describe some of the pathways individually and these are then compared to one another.

Direct Electrification

Electricity can be used as a direct transportation fuel in two ways: by delivering it to the end user or by using batteries as a storage medium. To date, rail and buses (i.e., trolleybuses) are the only modes of transportation where electricity is delivered directly to the end user. The key limitation is the infrastructure

TABLE 6.6 Specific Levels of Energy Consumption Used to Estimate the Transportation Demand that can be Met by the Transportation Fuels Produced

	Passenger Transport		Freight Transport	
Fuel	Load Factor (p/vehicle)	Specific Energy Consumption (MJ/pkm)	Load Factor (t/vehicle)	Specific Energy Consumption (MJ/tkm)
Electric rail	84.00	0.34	278	0.31
Electric car	1.50	0.32	n/a	n/a
Methanol/DME	1.50	1.15	12	1.90
Methane	1.50	1.57	12	2.65
Ethanol	1.50	1.50	12	3.30

Based on data from the 2010 reference and vehicle efficiency estimates by the Danish Energy Agency (2008).

required since a cable must be available to the end user at all times. This requires high initial investment costs and also restricts the feasible routes. However, once the infrastructure is in place, due to the high efficiency of rail, a relatively high transportation demand of 300 Gpkm or 325 Gtkm can be met when 100 PJ of electricity is available (see Figure 6.16).

To increase the route flexibility of electrification, batteries can be used. Several electrical and hybrid electrical vehicle technologies are already commercially available today (Hansen, Mathiesen, and Connolly 2011). Thus, from a technical point of view, it seems to be realistic to implement these technologies in the near future. As outlined in Figure 6.17, this is also a very efficient

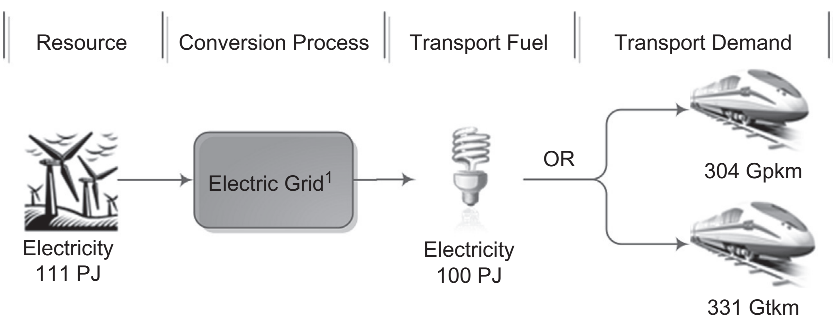

FIGURE 6.16 Direct use of electricity by the end user for transportation. [1]Assuming 10 percent loss for the electric grid.

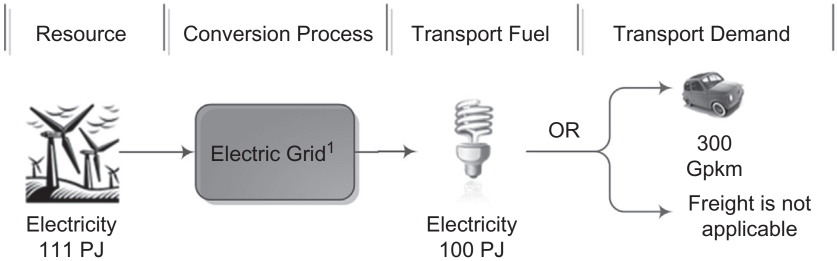

FIGURE 6.17 Direct use of electricity for transportation using battery storage. [1]Assuming 10 percent loss for the electric grid.

pathway. However, batteries come with a number of key limitations, particularly their energy density.

In comparison to liquid fuels, batteries can store very little energy relative to their weight. Direct electrification is thus not suitable for all modes of transportation such as trucks, aviation, and marine transportation. In a 100 percent renewable energy system, some form of fuel with high energy density (such as methanol/DME or methane) will also be necessary to supplement direct electrification.

Fermentation

The principal objective in the fermentation pathway is to convert straw to ethanol by use of a fermenter. Even though this process itself has a limited efficiency of approximately 25 percent, as only the cellulose is fermented, a number of byproducts produced from hemicellulose and lignin can subsequently be used to create other fuels. Since a variety of options are available, two distinct pathways are presented here.

The first fermentation pathway is the “fuel optimized” option. It is designed to produce the maximum amount of useful fuel with minimum input. For example, in this pathway, the lignin and residual sugars from the fermenter are hydrogenated to create an “oil slurry”, which is well suited as a fuel for marine diesels. In addition, the C5 sugars can be converted into conventional diesel and be used for trucks. From the hydrogenation process, there are also byproducts of coke and inorganic materials, which can be utilized in a number of ways, i.e., gasified and hydrogenated, to produce more fuel such as methanol/DME or simply burned in a power plant to produce electricity. At present, it is unclear which option would be most suitable in a 100 percent renewable energy system.

The second fermentation pathway is the “energy optimized” option. It is designed to maximize the energy available in the fuels created. In this process, the CO_2 from the fermenter is hydrogenated in the same way as in the fuel optimized process. However, the lignin and residual sugars are gasified instead of hydrogenated. Due to the high salt content present in all agricultural residues, it is assumed that this will require both low- and high-temperature gasifiers. Once again, the losses associated with wood gasification are assumed for both

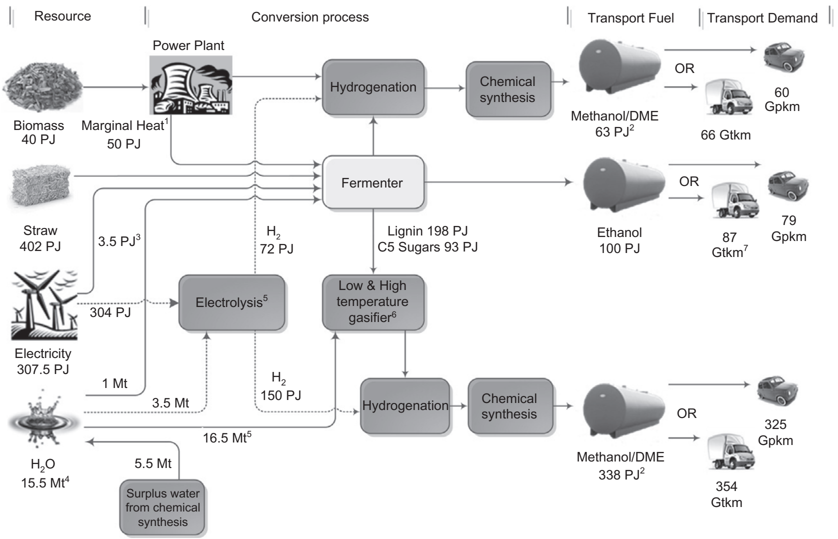

FIGURE 6.18 Energy optimized fermentation pathway. [1]Assuming a marginal efficiency of 125 percent and a steam share of 12.5 percent relative to the straw input. [2]A loss of 5 percent was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage. [3]Assuming an electricity demand of 0.8 percent relative to the straw input. [4]This is the net demand for water, i.e., it is reduced by the water recycled from hydrogenation. [5]Assuming an electrolyzer efficiency of 73 percent for the steam electrolysis. [6]Assuming the same conversion process as for cellulous gasification and hydrogenation to methanol, but the round-trip losses have been doubled since there are two gasifiers here (low and high temperature) and there is uncertainty in relation to the gasification of lignin and C5 sugars. [7]Assumed that ethanol trucks require approximately 25 percent more fuel than diesel equivalents, based on the difference between ethanol and diesel cars.

low- and high-temperature gasifiers, which are optimistic assumptions. After gasification, the gas is hydrogenated to produce syngas, which can be converted to methanol/DME using chemical synthesis. The final energy flows of the energy optimized fermentation process are displayed in Figure 6.18.

Bioenergy Hydrogenation

The principal objective of the bioenergy hydrogenation pathway is to create a transportation fuel from bioenergy, which is boosted by hydrogen from steam electrolysis. In this way, the energy potential of the bioenergy resource is maximized. Here, three different bioenergy pathways have been considered:

1. Biomass hydrogenation to methanol
2. Biomass hydrogenation to methane
3. Biogas hydrogenation to methane

A variety of biomass feedstocks can be used in this process; wood gasification is already being commercialized on a large scale, while the gasification of biomass from energy crops and straw is currently in the demonstration phase. Once biomass has been gasified, it is hydrogenated using hydrogen from steam electrolysis. Hydrogenating the biomass increases the energy content and the energy density of the original biomass, thus reducing the share of biomass needed. The resulting syngas is transformed into a transportation fuel using chemical synthesis, which is already a well-established technique used by the fossil fuel industry for converting coal and natural gas into liquid fuels.

In this study, the energy and mass balance assumed for biomass hydrogenation is based on the hydrogenation of cellulous to both methanol and methane. The resulting energy flow diagram for the case of methane is outlined in Figure 6.19. The diagram for methanol is quite similar. In practice, additional conversion procedures could also be necessary for biomass gasification, since a wide variety of different technologies are to be utilized. For example, oxygen could be used to gasify the biomass and it is also assumed here that all of the carbon is utilized in the reaction. If this is not possible in practice, further losses may occur. However, the overall demand for biomass and hydrogen per unit of methanol produced is indicative of the future demand if this pathway is chosen.

Biogas hydrogenation is also included here based on two reactions: first, the gasification of glucose, which occurs in an anaerobic digester, followed by

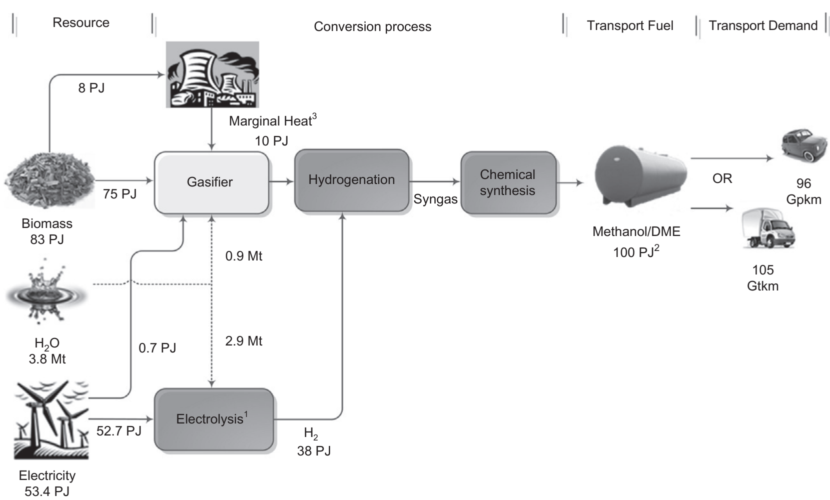

FIGURE 6.19 Steam gasification of biomass, which is subsequently hydrogenated to methanol. [1]Assuming an electrolyzer efficiency of 73 percent for the steam electrolysis. [2]A loss of 5 percent was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage. [3]Assuming a marginal efficiency of 125 percent and a steam share of 13 percent relative to the biomass input.

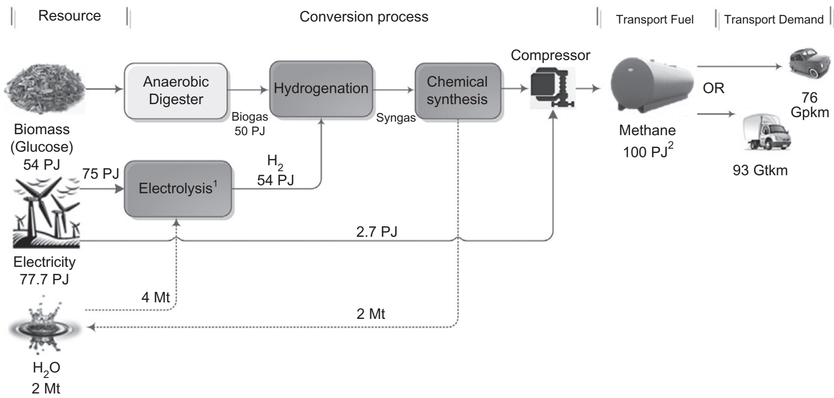

FIGURE 6.20 Production of biogas from biomass, which is subsequently hydrogenated to produce methane. [1]Assuming an electrolyzer efficiency of 73 percent for the steam electrolysis. [2]A loss of 5 percent was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.

the hydrogenation of the resulting CO_2. When glucose is gasified, it results in a gas that contains approximately 50 percent methane and 50 percent CO_2 by volume. In practice, the mix is usually 55–70 percent methane, 30–45 percent CO_2, and 1–2 percent other elements, since the feedstock is never pure glucose. Hence, the estimates here assume a slightly higher CO_2 output than typically obtained from anaerobic digesters. Since methane is typically the major component in biogas from anaerobic digesters, the CO_2 contained in the biogas is hydrogenated to methane. The resulting flow diagram for biogas hydrogenation is presented in Figure 6.20.

It is possible to convert the resulting methane to methanol by reforming it to a synthetic gas and then synthesizing the gas to methanol using high pressure. The reforming step is a very energy intensive process, since it is a strongly endothermic reaction. This process requires a large external energy supply, while the second phase of conversion from syngas to methanol is negligible, since it only requires a suitable catalyst. However, a total of approximately 20–30 percent of the fuel is lost during the transition from methane to methanol.

The CO_2 hydrogenation (CO_2Hydro) pathways combine carbon dioxide and hydrogen gases, followed by a chemical synthesis to produce a fuel for transportation. The principal objective of these pathways is to create a fuel that does not require any direct biomass input by using steam electrolysis and sequestered carbon dioxide. Separate pathways are included for methanol/DME and methane based on these energy and mass balances. The hydrogen can be produced by steam electrolysis, which requires electricity and water. To collect the carbon dioxide, carbon capture and recycling (CCR) from biomass power plants may be an option. However, one could also consider carbon trees (Lackner, 2009). Therefore, a total of four pathways can be described: two using CCR and

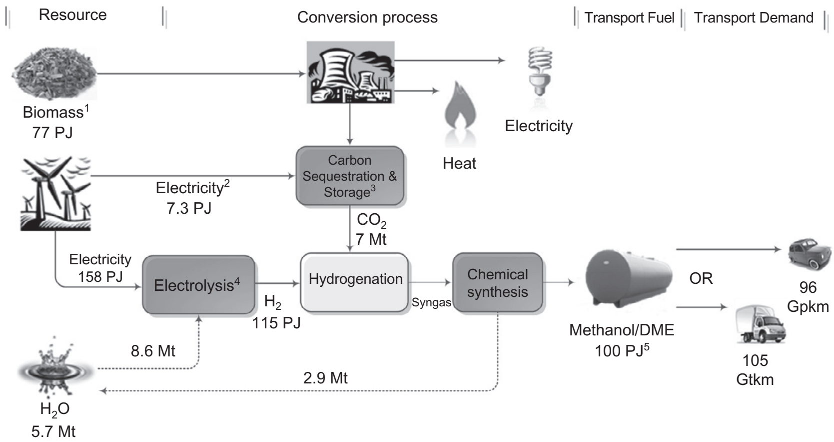

FIGURE 6.21 Hydrogenation of carbon dioxide sequestered using CCR to methanol/DME. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO_2 for capturing carbon dioxide from coal-fired power plants. [3]CCR is used in CEESA since it is currently a cheaper alternative to carbon trees. If carbon trees were used here, they would require approximately 5 percent more electricity. [4]Assuming an electrolyzer efficiency of 73 percent for the steam electrolysis. [5]A loss of 5 percent was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.

two using carbon trees either producing methane or methanol/DME. The alternative of CO_2 hydrogenation to methanol/DME using CCR is illustrated in Figure 6.21.

According to the latest research (Danish Energy Agency, 2008; Lackner, 2009), there is only a 5 percent difference in the electricity demand required to sequester the carbon dioxide in these two pathways. The key difference is that carbon trees do not require any combustible fuel in the energy system. However, if biomass is already used in the power plants, these two pathways are almost identical in terms of energy consumption. The only key difference between the two carbon sequestration options is the cost: Currently, the estimated cost for CCR is approximately 30 EUR/tCO_2 (Danish Energy Agency, 2008), while for carbon trees, it is approximately 200 USD/tCO_2 (Lackner, 2009).

Co-electrolysis

The co-electrolysis pathways are quite similar to the CO_2Hydro pathways. Their principal objective is to create a fuel that does not require any direct biomass input. However, instead of using carbon dioxide, the co-electrolysis pathway combines hydrogen with carbon monoxide gas followed by a chemical synthesis to produce either methanol/DME or methane. To do so, steam and carbon dioxide are broken down at the same time in one electrolyzer unit, hence the name co-electrolysis. Like in the CO_2Hydro pathway, the carbon dioxide can be obtained using either CCR or carbon trees, which again leads to the

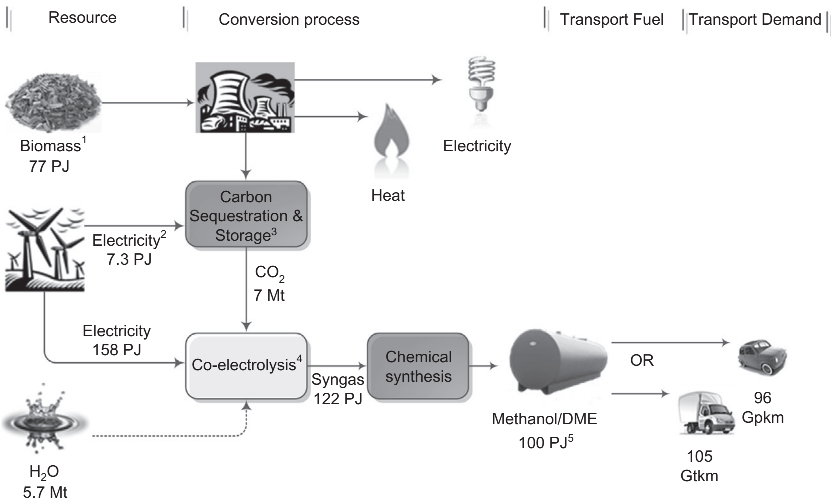

FIGURE 6.22 Co-electrolysis of steam and carbon dioxide which is obtained using CCR to methanol/DME. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO_2 for capturing carbon dioxide from coal-fired power plants. [3]CCR is used in CEESA since it is currently a cheaper alternative to carbon trees. If carbon trees were used here, they would require approximately 5 percent more electricity. [4]Assuming a co-electrolyzer efficiency of 78 percent: 73 percent for steam and 86 percent for carbon dioxide. [5]A loss of 5 percent was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.

definition of four pathways. The alternative of co-electrolysis to methanol/DME using CCR is illustrated in Figure 6.22.

Once again, if biomass is being utilized in the electricity and heat sectors, the key difference between these two forms of carbon sequestration is the cost. In comparison to the CO_2Hydro pathway, co-electrolysis requires a lower water input, but there is no excess water from the reaction. Hence, the net water demand is the same for both pathways.

Comparison

Using the energy flow diagrams presented in Figures 6.18–6.22, it is possible to compare each of the pathways by identifying the electricity and bioenergy required to produce 100 Gpkm for passenger transportation and 100 Gtkm for freight transportation.

This comparison confirms that direct electrification is the most sustainable form of transportation in terms of the resources consumed. It requires the lowest amount of electricity compared to all of the pathways and it does not require any direct bioenergy consumption. Battery electrification is also a very efficient pathway, but as mentioned previously, in a 100 percent renewable energy system, this will need to be supplemented by some form of high energy density fuel.

The energy optimized fermentation process in Figure 6.18 can be compared directly to the biomass hydrogenation in Figure 6.19, since these both use a combination of electricity and biomass. A quantitative comparison clearly shows that biomass hydrogenation requires slightly less electricity and biomass. However, this analysis of differences between the two is not sufficient to make a conclusive decision on which future pathway to utilize, which is similar to the conclusions drawn in previous research in Sweden (Grahn 2004). From a qualitative perspective, however, the difference between these two pathways is much more significant. Both the fuel optimized and energy optimized fermentation processes are very complex and include numerous conversions that are very uncertain, especially the gasification of coke and lignin. Since the conversion loss figures for the gasification of coke and lignin are currently not available, the conversion losses for cellulous gasification were assumed here, which is an optimistic assumption. In addition, the fermentation processes include an array of interactions between different subpathways for its byproducts (i.e., hydrogenation and gasification). In comparison, the biomass hydrogenation process consists of only one principal interaction (i.e., gasification of biomass). Further, the biomass hydrogenation process finishes with a chemical synthesis, meaning that the choice of fuel produced is very flexible, whereas the fermentation pathway will always be partially restricted to ethanol and, more specifically for the fuel optimized process, to marine diesels. Based on this, the biomass hydrogenation process at present:

- Is more efficient
- Requires less bioenergy and therefore land
- Provides more flexibility to the energy system
- Is subject to less uncertainty

Therefore, in the CEESA 100 percent renewable energy scenario to be presented in Chapter 7, biomass hydrogenation is used to simulate the direct use of biomass as a liquid fuel and so the output methanol/DME is referred to as *bio-methanol/DME*. It is essential to note that the principle of boosting the biomass resource with electricity is the same in both the fermentation and the biomass hydrogenation pathways. Hence, the modeling carried out in CEESA is indicative of the energy flows represented in fermentation as well. However, based on existing knowledge biomass hydrogenation seems more likely to achieve its technological development targets.

The remaining pathways, CO_2Hydro and co-electrolysis, do not require any direct biomass input, and they both require the same amount of electricity. However, the CO_2Hydro pathway uses steam electrolysis, which is already a well-established technology whereas co-electrolyzers are still under development. Therefore, CO_2Hydro is used in CEESA when simulating liquid fuel, which does not require any direct biomass input and so the output methanol/DME is referred to as *syn-methanol/DME*. Both the CO_2Hydro and co-electrolysis pathways represent the same principle, which is the use of electricity and captured CO_2 to create liquid fuel. Therefore, although the CO_2Hydro pathway is used in CEESA, the results are indicative of those that would also be achieved with co-electrolysis.

It is critical to recognize that biomass hydrogenation and CO_2Hydro have been chosen to represent two uniquely different methods in the future transportation sector: one which boosts a biomass resource and one which uses captured CO_2. This does not mean that the biomass hydrogenation pathway will be used instead of bioethanol or that CO_2Hydro will be used instead of co-electrolysis. In the future, the ultimate decision will depend on the technological development and demonstration of these facilities on a large scale. It is clear that these two principles will need to be applied in some way to achieve a 100 percent renewable energy system, depending on the residual bioenergy resource available.

Looked upon from a smart grid and smart energy systems point of view, it is evident that all fuel pathways described in this section to supplement the direct use of electricity involve hydrogenation and/or biomass conversion technologies that produce gas or liquid fuel. The different pathways will typically benefit from integration with the rest of the systems in one or more of the following aspects:

- The conversion requires heat and/or produces heat and, consequently, will benefit from integration with CHP and/or district heating.
- The conversion involves electricity inputs and, consequently, benefits can be achieved by replacing electricity storage with gas or liquid fuel storage, which is typically more efficient and cheaper. Moreover, regulation and even overinvestment in capacities of the electrolyzers may be used to integrate more fluctuating renewable electricity supplies.
- The gas produced needs to be stored and/or distributed and, consequently, one will benefit from the use of a smart gas grid. Since the production units may benefit from being distributed (e.g., to avoid the transportation of manure and/or to better integrate them with efficient heating solutions), a smart grid that can handle bidirectional flows will be relevant.
- Since the fuel pathways have the potential to participate in several smart grids and their related sectors, the identification of optimal solutions implies a smart energy systems approach.

7. REFLECTIONS

Reflections and conclusions on the analyses of smart energy systems and infrastructures in this chapter are made regarding principles and methodologies, as well as the implementation of renewable energy systems in Denmark and other countries.

Principles and Methodologies

As mentioned in the beginning of this chapter, the transformation into renewable energy systems poses a challenge of substantial changes to the infrastructures to carry the energy, i.e., the electricity grid, the gas grid, and the district heating and cooling grids. All such grids face the common challenge of the integration of an efficient use of potential renewable energy sources as well as the operation of a grid structure allowing for distributed activities involving interaction with consumers and bidirectional flows. To meet this challenge, all grids will benefit from the use of modern information and communication technologies as an integrated part of the grids at all levels.

On such a basis, this chapter has defined the future concept of a *smart electricity grid*, *smart thermal grids*, and a *smart gas grid*. The three concepts have a lot of similarities; however, they also differ in the major challenges connected to each of them. Smart thermal grids face their major challenges in the temperature level and the interaction with low-energy buildings. Smart electricity grids face their major challenges in the reliability and in the integration of fluctuating and intermittent renewable electricity production. Smart gas grids face their major challenges in mixing gases with different heating values and in the efficient use of limited biomass resources.

Each of the three types of smart grids provides important contributions to future renewable energy systems. However, each individual smart grid should not be seen as separate from the others or separate from the other parts of the overall energy system. First, it does not make much sense to convert one sector to renewable energy if this is not coordinated with a similar conversion of the other parts of the energy system. Second, this coordination makes it possible to identify additional and better solutions to the implementation of smart grid solutions within the individual sector, compared to the solutions identified with a sole focus on the sector in question.

Consequently, this chapter has promoted the concept of smart energy systems defined as an approach in which smart electricity grids, smart thermal grids as well as smart gas grids are combined and coordinated to identify synergies among them to achieve an optimal solution for each individual sector as well as for the overall energy system.

The analysis of smart energy systems calls for tools and models that can provide similar and parallel analyses of grids of electricity, heating, cooling, and gas. As described in Chapter 4, EnergyPLAN is one such model, since the tool can do hour-by-hour analysis of all four grids including storage and the interactions among them.

Conclusions and Recommendations

As concluded in Chapter 5, the large-scale integration of renewable energy should be considered a way to approach renewable energy systems. The same conclusion can be made regarding smart energy systems and infrastructures. The long-term relevant systems are those in which renewable energy sources are combined with energy conservation and system efficiency improvements, and in such regard the implementation of future energy infrastructures becomes crucial.

Seen from this perspective, Chapter 5 lists seven recommendations on how to deal with the integration of large-scale renewable energy. A main point is that the most efficient and least-cost solutions are not to be found within one sector but when sectors of electricity, heat, and transportation are combined. Moreover, the importance of including distributed flexible CHP plants and electricity-to-transportation systems in the task of grid stabilization is emphasized. Chapter 6 adds to the points of Chapter 5 with the following recommendations:

1. District heating faces the challenge of supplying future low-energy buildings and at the same time utilizing low-temperature sources from, e.g., CHP and industrial processes. This challenge can be met by the development of low-temperature district heating grids, here defined as 4GDHs.
2. If the challenges of future district heating grids are met, the best heating solution, looked upon from an overall system point of view, seems to be a combination of district heating in urban areas with individual heat pumps in the rest of the system. In the current system, this solution shows substantial reductions in fuel demands and CO_2 emissions, while in a future 100 percent renewable energy system, it reduces the need for renewable energy sources including the need for biomass. This seems to be valid even if the space heating demand is reduced by as much as 75 percent.
3. Grid-connected low-energy houses such as zero energy buildings, which include on-site production in terms of PV, wind power, and solar thermal, should not try to balance supply and demand at the individual building level. Such problems are better dealt with at an aggregated level. At the individual level, one is likely to implement an expensive solution with greater losses and at the same time increase the risk of worsening instead of helping the integration of fluctuating renewable energy into the electricity supply.
4. The nature of renewable energy systems calls for future power stations to be flexible CHP plants that can supply grid stabilization when they produce as well as consume electricity, at the same time as they can survive financially with small utilization hours on the CHP unit. Such *smart energy systems* and *smart electricity grid* requirements cannot be met by existing nuclear and coal-fired steam turbine technologies.
5. The opening in recent years of electricity markets for supplying regulating power and automatic primary reserve has created examples of the implementation of relevant future power plants. These examples show how small CHP plants can provide flexible production, which can change from one hour to another between producing and consuming electricity, while taking an active role in the grid stabilization and regulating power tasks. These CHP plants produce with relatively few utilization hours on the CHP unit and allow substantial inputs of wind in the electricity supply, along with inputs of waste incineration and industrial surplus heat in the heat supply, while still surviving financially. However, it should be noted that some sort of capacity payment may have to support the CHP plants.

6. The ability to provide high power inputs for only a few hours may even be expanded substantially in the future if existing small CHP plants save their existing engines for the power reserve market when they have to be replaced by new ones. Considering the fact that Denmark has a large number of small CHPs in its system, together these may form a coherent solution for the whole system in the future.
7. Limitations in the biomass resources available in combination with the need for gas or liquid fuel in the transportation sector to supplement the direct use of electricity call for pathways in which the conversion of biomass is boosted with hydrogen from electrolysis. Looked upon from an energy system integration point of view, such pathways call for a new smart gas grid in which different gas inputs from local production are stored and distributed in a bidirectional flow handling gas inputs of potentially different heating values.
8. The need for power to gas (or power to liquid) for transportation makes it possible to replace the potential long-term need for electricity storage with gas (or liquid) storage, which is both cheaper and more efficient. Consequently, the integration of renewable energy into the electricity supply should not only include the measure of direct use of electricity for transportation, but also the need for power to gas/liquid.
9. In times of unemployment and economic crisis, the investment in the transformation toward renewable energy systems represents an option in which jobs can be created and economic growth can be increased, while public expenditures are not negatively affected but can even be improved. This is valid especially for projects with high investments and long lifetimes such as infrastructure projects. To be able to identify and implement these options, one will benefit from taking a concrete institutional economics approach.

Chapter 7

Analysis

100 Percent Renewable Energy Systems

With contribution by Brian Vad Mathiesen, Wen Liu, Xiliang Zhang, and Woodrow W. Clark II

The implementation of 100 percent renewable energy systems adds to the challenge of integrating renewable energy sources (RES) into existing energy systems on a large scale as well as to the implementation of smart energy infrastructures. Not only must fluctuating and intermittent renewable energy production be coordinated with the rest of the energy system, but the size of the energy demand must also be adjusted to the realistic amount of potential renewable sources. Furthermore, this adjustment must address the differences in the characteristics of different sources, such as biomass fuels and electricity production from wind power.

The design of suitable energy systems must consider both conversion and storage technologies. Renewable energy will have to be compared not to nuclear or fossil fuels, but to other sorts of renewable energy system technologies, including conservation, efficiency improvements, and storage and conversion technologies—for example, wind turbines versus the need for biomass resources. The selection of technologies is complex, not only considering the differences in hourly distributions of the technologies, but also in terms of the identification of a suitable combination of changes in conversion and storage technologies.

The design of renewable energy systems involves three major technological changes: energy savings on the demand side, efficiency improvements in energy production, and the replacement of fossil fuels by various sources of renewable energy. Consequently, the analysis of these systems must include strategies for integrating renewable sources into complex energy systems, which are influenced by energy savings and efficiency measures. The design of 100 percent renewable energy systems can be addressed at the project level as well as the national level, and, at some point, the global level. At the project level, this chapter describes the efforts of the Los Angeles Community College District to implement a 100 percent renewable energy system for each of its nine college campuses. At the national level, three studies of Danish cases are presented. As already mentioned in Chapter 5, Denmark is a front-runner in that respect and therefore represents a suitable case for the analysis of large-scale integration as well as the development of 100 percent renewable energy systems. Finally, these examples are taken to the near-global level by discussing the options of applying the same approach and methodologies to China.

In Denmark, savings and efficiency improvements have been important parts of the energy policy since the first oil crisis in 1973. Hence, by means of energy conservation and the expansion of combined heat and power (CHP) and district heating, Denmark has been able to maintain the same level of primary energy supply for a period of 40 years, in spite of the fact that the GDP has increased by more than 100 percent in the same period (from 1972 to 2012). Moreover, almost 25 percent of the fossil fuels have been replaced by RES. In the same period, transportation and electricity consumption as well as the heated space area have increased substantially.

Thus, Denmark provides an example of how renewable energy development strategies constituted by a combination of savings, efficiency improvements, and RES can be implemented. As described in Chapters 5 and 6, Denmark is now facing two problems: how to integrate the high share of intermittent electricity from RES and how to include the transportation sector in future strategies when limitations on the biomass resource are taken into consideration. Taking this development of strategies a step further, the implementation of renewable energy systems is not only a matter of implementing savings, efficiency improvements, and RES, it also becomes a matter of introducing and adding flexible energy conversion and storage technologies and designing integrated energy system solutions. Moreover, the analysis of these strategies calls for an integrated *smart energy systems* approach.

According to estimations by the Danish Energy Agency from 1996, the realistic biomass potential for energy purposes in Denmark corresponds to 20–25 percent of the present total primary energy supply. Meanwhile, Denmark has great potential for other sorts of renewable energy, especially wind power. In many ways, Denmark provides a typical example of the situation in many countries: the transportation sector is totally fueled by oil, and although the biomass potential is not big enough to replace fossil fuels, the potential of intermittent renewable sources is substantial.

Based on the cases of the United States, Denmark, and China, this chapter presents a series of studies that analyzes the problems and perspectives of converting the present energy system into a 100 percent renewable energy system. Three Danish case studies are presented. The first study is a one-person university study that applies the information presented in Chapter 5 to the analysis of a coherent renewable energy system. The second study is based on the technical inputs of members of the Danish Society of Engineers (IDA). The input to the study is the result of the organization's Energy Year 2006, during which 1600 participants at more than 40 seminars discussed and designed a model for the future energy system of Denmark. The third study is the result of the collaboration of researchers from five Danish universities, partly financed by the Danish Council for Strategic Research, doing a coherent energy and environmental systems analysis (CEESA) of the transformation into 100 percent renewable energy systems. The study might be seen as a follow-up to the first IDA plan, in which an important further step was taken regarding the smart energy systems analysis of the integration of the transportation fuel pathways mentioned in Chapter 6. Among others, hour-by-hour analyses of electricity and district heating are supplemented with similar hour-by-hour calculations for gas.

All three Danish case studies analyze the design of coherent and complex renewable energy systems, including the suitable integration of energy conversion and storage technologies. Furthermore, all studies are based on detailed hour-by-hour simulations carried out with the EnergyPLAN model.

The American and Danish cases at the project and national levels are then discussed in relation to applying the same analyses to China. The energy demand in China has risen rapidly and reached an unprecedented level due to the massive economic growth and modern development. Since 1978, China's GDP has been increasing at a rate of 10 percent annually and the average energy consumption has risen by 5.2 percent. After 2001, the primary energy consumption has soared through an average annual increase of 9 percent during 2001–2011, and the GDP has increased by 11 percent in the same period. There is little doubt that the energy demand in China will continue to grow, driven by the country's highly energy-intensive economy and strong GDP growth.

1. THE LOS ANGELES COMMUNITY COLLEGE DISTRICT CASE

This Section Is Courtesy of Guest Writer Woodrow W. Clark II

This section describes the effort of the Los Angeles Community College District (LACCD) to implement a 100 percent renewable energy system for each of its college campuses. LACCD is the largest college system in the United States, with nine campuses serving over 180,000 students and two new satellite campuses. The map in Figure 7.1 shows the locations of the nine college campuses. All of the campuses are dependent on a central power grid. However, in the future, all of them will be "off the grid". The strategy is to change from fossil fuels to renewable energy and storage while meeting most of the energy demands of the college community.

In 2001 and 2002, the LACCD Board decided to replace 45 buildings with new ones, according to the U.S. Green Building Council standards, called LEED (Leadership in Environmental and Energy Design). Each campus has from 30 to 40 buildings. The nine college campuses had been built in the 1980s but not upgraded or modernized since then. With a growing concern about "green buildings", the LACCD administration wanted to improve the buildings on each campus to conserve energy and water and manage waste,

FIGURE 7.1 The nine Los Angeles Community College campuses.

while being more efficient in the campus buildings. But how and who pays for this? In 1999, the California legislature passed a bill and signed it into law that allowed local residents to vote and tax themselves for school buildings, not including costs for faculty or staff hiring. Two-thirds of the voters needed to pass bond (financing) measures for the funds in schools from kindergarten through community college (K–14).

In 2002 and 2003, the local community voted for more than 3 billion USD in bond funds to support the building programs. By mid-2007, the LACCD decided to make each of its colleges "energy independent and carbon neutral" through the use of renewable energy, primarily solar, but also geothermal and wind power, as well as storage devices and distributed renewable solar thermal energy systems. On each campus, these technologies and systems would provide heating and cooling to multiple buildings. The programs were successful, and in November 2008, the local community granted another bond fund of more than 4.3 billion USD to make all of the colleges energy independent and carbon neutral (Clark and Eisenberg 2008).

Most campuses have a power demand from 4 to 6 MW, which renewable energy and storage systems should be able to accommodate. The LACCD is an example of agile and flexible energy systems, in which the colleges generate

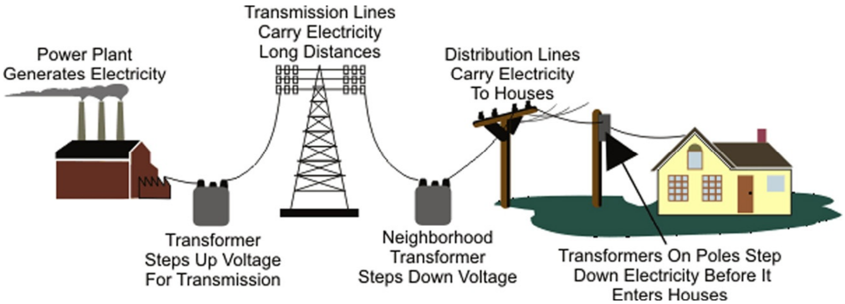

FIGURE 7.2 Principal diagram connecting the nine campuses to the public grid.

renewable energy for themselves, while other buildings, private businesses, and homes in the community are connected to the central power grid, which is placed far from the community. Figure 7.2 shows how such communities can also provide for the energy independence of homes and businesses by implementing smart and sustainable supplies.

Renewable energy is a critical component of LACCD's sustainable building program, which has the objective of making all nine colleges energy independent. This was to be achieved by reducing overall energy consumption, increasing energy efficiency, and producing energy through a combination of alternative energy methods: solar, wind, biomass, geothermal, hydrogen generation, and storage technologies. It is also achieved by continuing the expansion of the curricula to prepare students for "green-collar" jobs. The district's plan was not implemented due to political and economic reasons. Only a few projects were done as East Los Angeles College, for example, where a 1.2 MW solar farm was completed in 2008, which generates nearly 2 million kWh of electricity annually, meeting nearly 45 percent of the college's electricity demand and saving 270,000 USD in utility costs.

On-site renewable energy projects that use solar technologies for governmental institutions, including colleges and universities, are approved for construction by the Division of the State Architect. The private sector and businesses do not need such approvals. Flexible energy generation systems or the combination of central grid and on-site power are known as "agile energy systems" (Clark and Bradshaw 2004) and are illustrated in Figure 7.3.

The basic concept for the LACCD is that each campus can generate its entire baseload demands through renewable energy technologies. Part of the LACCD's renewable energy program has already had a significant, long-term economic impact at the local (municipal and county), state, and national levels. First, the district will save approximately 12 million USD (just over 1 million USD per campus) in energy costs annually by becoming energy independent. As demonstrated in Table 7.1, the primary renewable technology for achieving this goal is solar panels. The Google campus map of Mission College, however, shown in

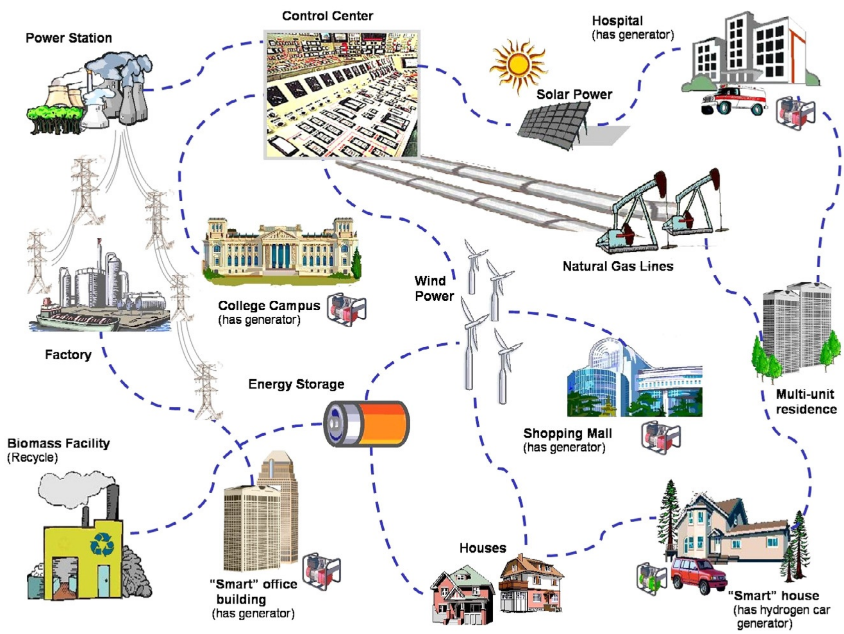

FIGURE 7.3 Principal diagram of agile energy systems.

Figure 7.4, demonstrates how other renewable technologies are also being planned and implemented.

The district can direct some resources toward faculty and students and thus design a sustainable development curriculum, which it has done on all nine campuses. Implementing LACCD's renewable energy and energy efficiency programs allows the district to meet and exceed its own electricity demands (especially during peak periods), thus providing a replicable model for other colleges, universities, cities, and states to do the same. It is difficult to assess the economic impact as a dollar amount tied to such measures or as the number of high-paying jobs involved in implementing renewable energy programs or conserving natural resources, but it already appears to be significant.

LACCD's sustainable building program requires that new construction that is funded 50 percent or more by voter-approved funds meets or exceeds U.S. Green Building Council LEED and trade certification standards. This program was stopped and cut back due to overspending and misappropriation of funds. The nearby Beverly Hills Unified School District (BHUSD) had administrators and staff who were taking funds for themselves by misrepresenting and misusing public funds (Clark and Fast, 2008). There is a need for strong due diligence and California State Law requires Citizen Oversight Committees for public bonds funds. Legal action was taken in the BHUSD as well as other public school districts around California. Furthermore, the bond financing has come

TABLE 7.1 Renewable Energy Program: Solar Project Summary

Campus	Technology	Energy-producing Capability (in MW)	Project Cost (in millions of USD)
East Los Angeles College	Solar: parking structure, rooftop, thin film	3.4	34.6
Los Angeles City College	Solar: parking structure, rooftop, thin film	2.8	28.2
Los Angeles Harbor	Solar: parking structure, rooftop, thin film	3.1	30.3
Los Angeles Mission	Solar: parking structure, rooftop, thin film	4.6	47.0
Northeast (satellite)	Solar: parking structure, rooftop, thin film	0.5	4.9
Pierce	Solar: parking structure, rooftop, thin film	4.1	44.2
Los Angeles Southwest	Solar: parking structure, rooftop, thin film	3.9	32.7
Los Angeles Trade-Tech	Solar: parking structure, rooftop, thin film	1.3	17.9
Los Angeles Valley	Solar: parking structure, rooftop, thin film	3.6	38.3
West	Solar: parking structure, rooftop, thin film	3.0	30.0
		Total 30.3	308.10 USD

under question due to both its high interest rates (especially during the current U.S. and global economic crises) and long-term obligation to the local communities.

Agile sustainable communities such as colleges can be in a variety of configurations and can use the combination of on-site power generation (such as solar panels on roofs or wind turbines that are specifically designed for buildings) and central grid power systems for power generation. The local power generation from solar and wind sources, for example, allows public and government buildings, like city hall, fire and police departments, and public schools and universities, to generate their own power while staying connected to the central power grid. Increasingly, more and more private businesses have been

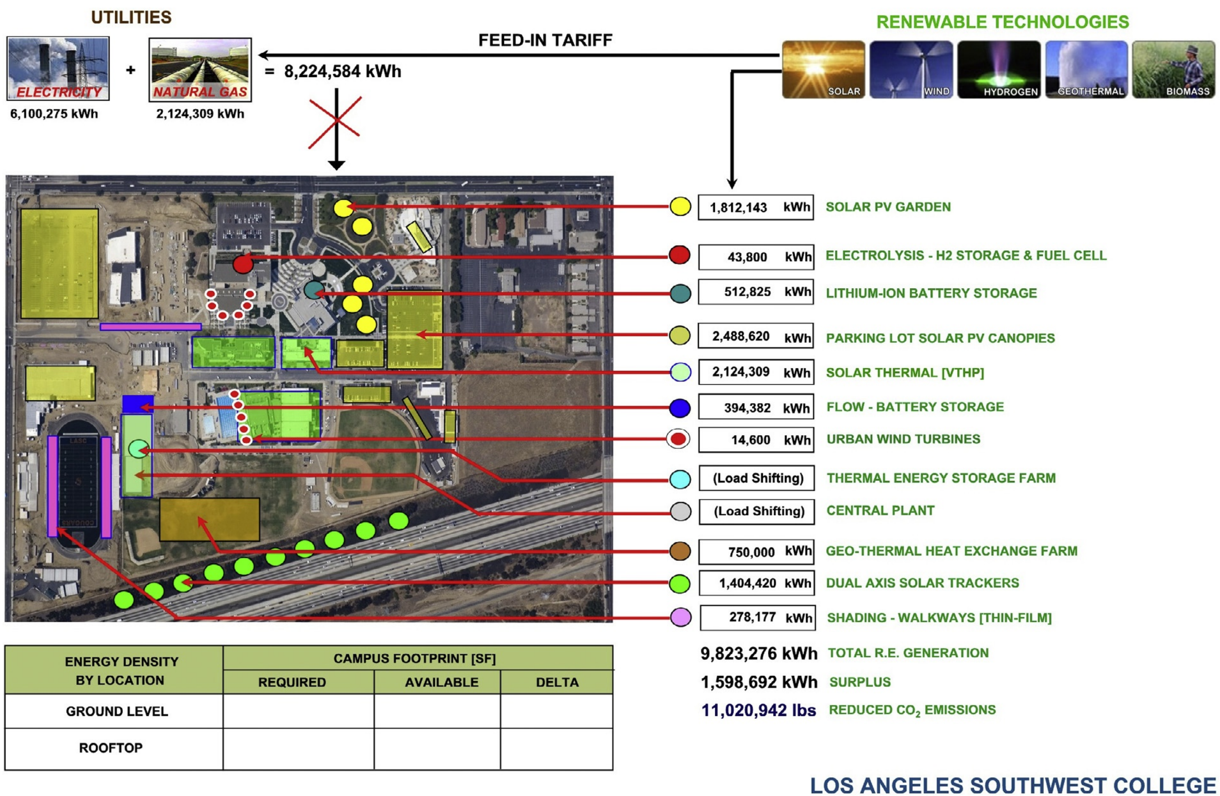

FIGURE 7.4 Google map showing the variety of technologies in the system.

following the public sector leadership. The Google map in Figure 7.4 shows a variety of renewable energy and storage technologies that are now incorporated into the campus plans.

In conclusion, renewable energy systems and communities are flexible (agile) infrastructure systems because they are able to include both on-site renewable energy and central grid power-generation systems. An agile system can adapt due to change in such a way that innovation is welcomed rather than opposed. Agile energy systems are resourceful and are adept at developing ways to avoid or to solve conflicts while deconstructing socioeconomic barriers that slow down effective solutions to problems.

Such renewable energy systems foster and promote diversity along with dynamic growth. This growth can create a change applying knowledge, intellectual capital, financing mechanisms, and advanced technologies such as wind power, geothermal, solar thermal, photovoltaic (PV), CHP, fuel cells, and hydrogen options together with conservation and load management.

No one standard or uniform set of circumstances or technologies fits all communities and regions. Geothermal resources are not found everywhere, nor are sunshine and wind, but the combination of these renewable resources along with new technologies for storage, such as fuel cells and flywheels, provides for hybrid technologies that create firm baseloads and dependable power. Such systems can replace or complement conventional fossil fuel systems or be used in the transition to 100 percent renewable, energy-independent, on-site, and distributed energy systems.

2. THE FIRST APPROACH TO COHERENT RENEWABLE ENERGY SYSTEMS[1]

This section is based on Lund's (2007a) article "Renewable Energy Strategies for Sustainable Development". On the basis of the many studies described in Chapter 5 and the case of Denmark, this article discusses the problems and perspectives of converting the present energy system into a 100 percent renewable energy system. The conclusion is that this conversion is possible. The necessary renewable energy sources are present, and if further technological improvements of the energy system are made, a 100 percent renewable energy system can be created. Most important are the technological conversion of the transportation sector and the introduction of flexible energy system technologies.

This article refers to the RES potential in Denmark as estimated by the Danish Energy Agency in 1996 as part of the Danish government's energy plan, Energy 21 (Danish Ministry of Environment and Energy 1996). The estimate, which is shown in Table 7.2, dates back more than 10 years, and today it seems that some of the potential is underestimated. This is particularly true regarding

1. Excerpts reprinted from *Energy*, 32/6, Henrik Lund, "Renewable Energy Strategies for Sustainable Development", pp. 912–919 (2007), with permission from Elsevier.

TABLE 7.2 Potential RES in Denmark

Renewable Energy Source	Potential
Wind power (onshore)	5–24 TWh/year
Wind power (offshore)	15–100 TWh/year
PV (10–25% of houses, 100–200 kWh/m^2)	3–16 TWh/year
Wave power	17 TWh/year
Hydropower	~0 TWh/year
Total electricity	**40–160 TWh/year**
Solar thermal (individual houses)	6–10 PJ/year
Solar thermal (district heating)	10–80 PJ/year
Geothermal	>100 PJ/year
Total heat	**100–200 PJ/year**
Straw	39 PJ/year
Wood	23 PJ/year
Waste (combustible)	24 PJ/year
Biogas	31 PJ/year
Energy crops	65 PJ/year
Total biomass fuel	**182 PJ/year**

Source: *Danish Energy Agency, 1996.*

the offshore wind potential, which is very dependent on technological development. The potential is considered higher today, and is expected to increase in the future along with the growth in the size of the wind turbines. Furthermore, it should be noted that the theoretical biomass potential in the survey from 1996 is estimated to be as high as 530 PJ/year, assuming that all farming areas are converted into energy crops, and 310 PJ/year, in the case that Denmark is self-supplied by food and the remaining areas are converted into energy crops. Again, this estimate is more than 10 years old, and biomass resources in particular have recently been discussed, indicating that the potential may be even higher if a selection of crops is made with the concerted purpose of both producing food and energy. However, this increase in potential should be coordinated with the future needs for food and material. Nevertheless, the total potential of 180 PJ/year, including only a minor share of energy crops, is to be considered a business-as-usual scenario in terms of food production. All in all, the RES potential is sufficient, and only a small share is used today. In Figure 7.5, minimum and maximum levels of potential are compared to the present primary energy supply in Denmark, represented by the year 2003.

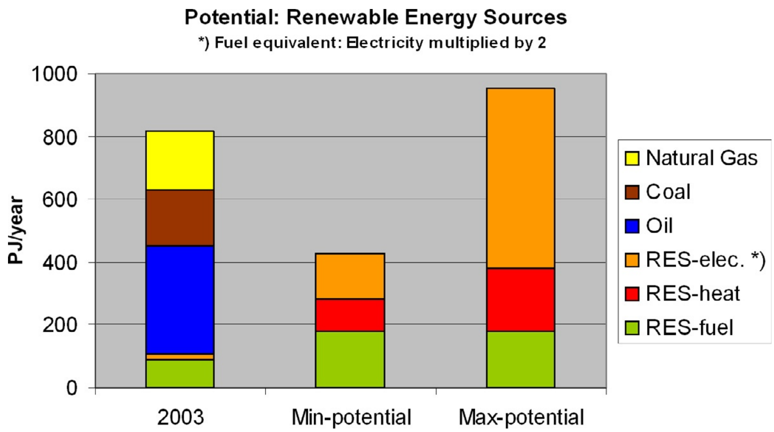

FIGURE 7.5 Potential of RES in Denmark as estimated in 1996 and compared to the primary energy supply in 2003.

The Danish energy supply is traditionally based on fossil fuels. Denmark has a very limited hydropower potential, and during the 1960s and 1970s, the electricity supply was dominated by large oil- and coal-fired steam turbines located near the big cities. However, after the first oil crisis in 1973, Denmark became a leading country in terms of implementing CHP, energy conservation, and renewable energy. Consequently, when this study was made, the Danish energy system had changed from a situation in 1972 in which 92 percent of a total supply of 833 PJ was based on oil into a situation in 2005 in which only 41 percent of 850 PJ was oil based. In the same period, transportation and electricity consumption, as well as the heated space area, had increased substantially. Today, the share of electricity produced from CHP is as high as 50 percent, and approximately 30 percent of the electricity demand is supplied by wind power. Figure 7.6 illustrates the development from 1972 until 2005, as well as future expectations resulting from the reference scenario described in Chapter 5: the 2020 projection made by the Danish Energy Agency in 2001. Figure 7.7 shows the energy flow of the system in the present situation.

When analyzing the possibilities of continuing the development and replacing more fossil fuels by RES, two problems arise. One is the transportation sector, which is almost totally fueled by oil. Consumption has increased from 140 PJ in 1972 to an expected 180 PJ or more in 2020. Thus, the transportation sector accounts for most of the expected oil consumption. Another problem is the integration of electricity produced from CHP and wind power. Until recently, CHP stations were not operated to balance fluctuations in wind power. As a consequence, Denmark has had problems of excess electricity production in periods of strong winds, if these coincided with the operation of CHP stations.

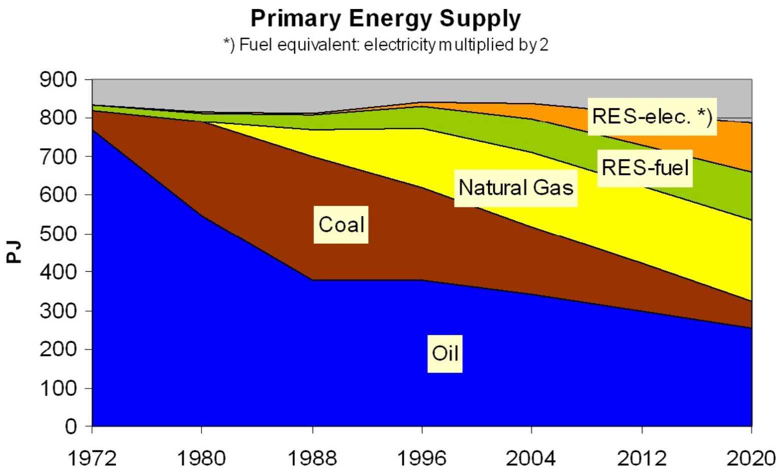

FIGURE 7.6 Primary energy consumption in Denmark, including future expectations.

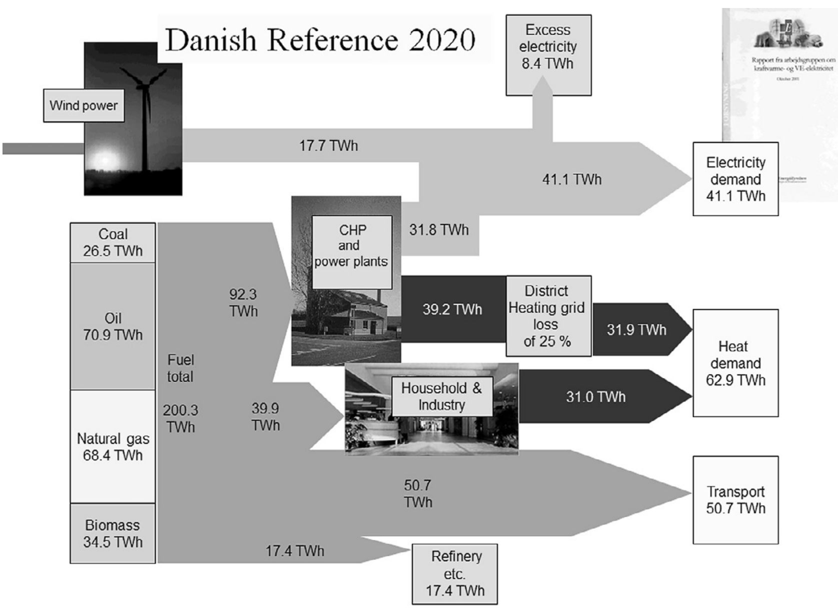

FIGURE 7.7 Principal diagram of the energy flow in the Danish reference energy system in the year 2020.

The aim of the analysis is to evaluate whether a 100 percent renewable energy system is a possibility for Denmark and to identify key technological changes and suitable implementation strategies. As a starting point for the analysis, it is assumed that the design of renewable energy systems involves three major technological changes: energy savings on the demand side, efficiency improvements in the energy production, and the replacement of fossil fuels by various RES. Consequently, the following technological changes of the reference (Ref 2020) have been identified for the analysis of the first step (STEP 1) of converting the Danish energy system into a renewable energy system:

- *Savings*: A 10 percent decrease in electricity demand, district heating, and heating for households and industry.
- *Efficiency*: A combination of better efficiencies and more CHP. Better efficiencies are defined as 50 percent electricity output and 40 percent heat output of CHP stations. This can be achieved either by partly implementing fuel cell technology or by improving existing steam turbine/engine technologies. More CHP is defined as the conversion of 50 percent of fuels for individual houses and industry into CHP, partly through district heating.
- *RES*: An increase in biomass fuels from 34 to 50 TWh/year (125–180 PJ/year) and the addition of 2.1 TWh of solar thermal to district heating and 5000 MW of PV to electricity production.
- *All*: A combination of the three preceding measures.

It should be noted that these technological changes are moderate compared to the maximum potential. Thus, it is both possible and realistic to save more than 10 percent as well as to replace more than 50 percent by CHP, and so forth.

As STEP 1, the consequences of each of the three technological changes have been analyzed as well as the combination of the three. The results are shown in Figure 7.8 in terms of primary energy consumption. Figure 7.8 shows that an increase rather than a decrease in fuel consumption is the main tendency. This is because the technological changes of STEP 1 lead to a substantial increase in excess electricity production. More CHP, better efficiencies, less demand (savings), and more intermittent resources all create a higher excess production, unless measures are taken to prevent these problems. The resulting excess production is given in Table 7.3.

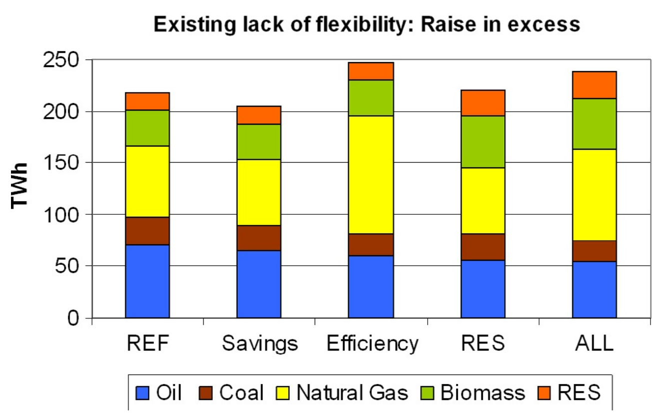

FIGURE 7.8 STEP 1: Primary energy supply, year 2020, in the reference Ref 2020 compared to the three technological changes of STEP 1, including excess electricity production.

TABLE 7.3 Resulting Primary Energy Supply and Excess Electricity Production of the Three STEP 1 Technological Changes Compared to the Reference Ref 2020

TWh/Year	REF	Savings	Efficiency	RES	All
Total fuel consumption	218	205	248	220	238
Excess electricity production	8.4	9.6	45.5	11.7	48.2

As a general tendency, the intention to decrease fossil fuels leads to increased excess electricity production. One way to avoid excess electricity production is to use it for domestic purposes. In STEP 2, such an analysis has been carried out in order of priority. In the case of excess production: (1) CHP units are replaced by boilers, (2) boilers are replaced by electric heating, and (3) the production from wind turbines and/or PV is simply reduced. This is a rather simple and inexpensive way of avoiding excess production. The results are shown in Figure 7.9.

Now, all technological improvements result in a decrease in fuel consumption. However, the decrease is small, since most of the benefits derived from technological improvements are lost in the excess production. Another problem is the high share of oil used for transportation. This shows that the problem of integration becomes important when implementing savings, efficiency measures, and RES, as does the issue of including transportation. Consequently, in STEP 3, the following changes have been analyzed:

- *Transportation*: Oil for transportation is replaced by electricity, according to a scenario described by Risø National Laboratory and discussed in Chapter 5

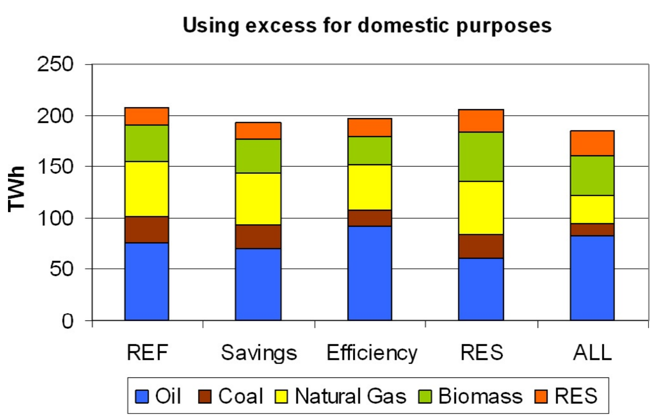

FIGURE 7.9 STEP 2: Equal to Figure 7.8, but without excess electricity production (the excess production is used to replace fuels by simple and inexpensive measures).

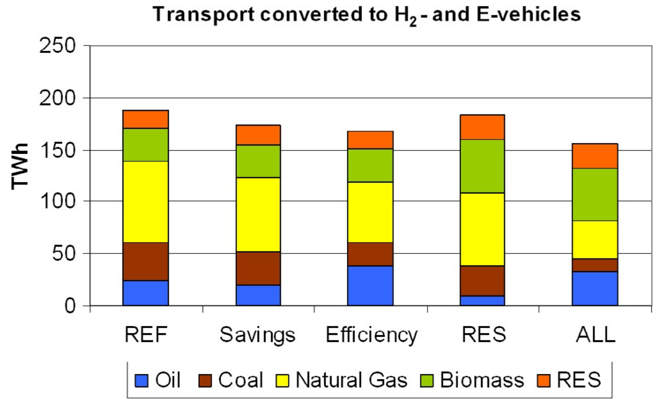

FIGURE 7.10 STEP 3: Primary energy consumption (same as Figure 7.9) when oil for transportation is replaced by electricity for electric (E) vehicles and hydrogen (H_2) vehicles.

(Nielsen and Jørgensen 2000). Vehicles weighing less than 2 tons are replaced by battery vehicles and hydrogen fuel cell vehicles. In this scenario, 20.8 TWh of oil is replaced by 7.3 TWh of electricity. Here, the same ratio has been used for converting the total oil consumption of 50.7 TWh in the reference system Ref 2020 into an electricity consumption of 17.8 TWh. The electricity demand has been made flexible within the time period of one week and has a maximum capacity of 3500 MW. The results are shown in Figure 7.10. In this case, both the reference Ref 2020 and all three STEP 1 alternatives result in a decrease in fuel consumption.

STEP 4 adds more flexibility in terms of heat pumps and CHP regulation together with electrolyzers:

- *Flexible CHP and heat pumps*: Small CHP stations are included in the regulation together with heat pumps added to the system. A 1500 MWe heat pump capacity with a coefficient of performance of 3.5 has been analyzed.
- *Electrolyzers and wind regulation*: Electrolyzers have been added to the system and, at the same time, wind turbines have been included in the voltage and frequency regulation of the electricity supply.

In STEP 4, together with these measures of flexibility, wind power was added to the system until the resulting fuel consumption was equal to the available biomass resources of 180 PJ (50 TWh/year). The results are given in Figure 7.11. In this case, the main question is how much wind power is needed to fulfill the objective. The resulting wind power capacity is given in Table 7.4.

As seen, the Danish energy system can be converted into a 100 percent renewable energy system when combining 180 TJ/year of biomass with 5000 MW of PV and between 15 and 27 GW of wind power. In the reference, 27 GW of wind power is required, while in the combination with savings and efficiency improvements, the necessary capacity is reduced to 15 GW. With an

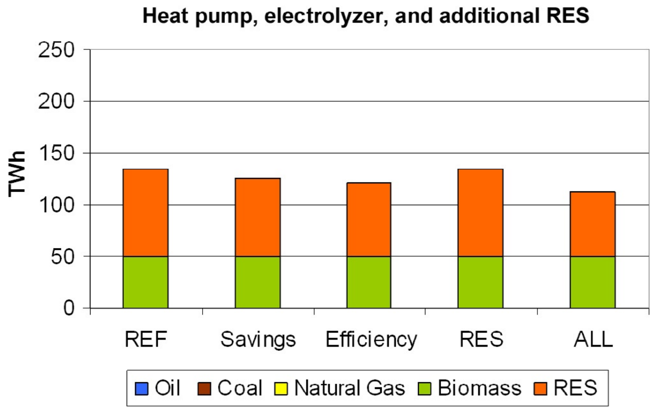

FIGURE 7.11 STEP 4: Primary energy consumption (same as Figure 7.10) when adding flexible energy systems and converting to 100 percent RES.

TABLE 7.4 Resulting Fuel Consumption and Required Wind Power Capacity

Capacity	REF	Savings	Efficiency	All
Total fuel consumption (TWh/year)	134	125	121	112
Wind Power (GW)	27.1	22.1	18.6	15.6
Annual wind investment (MW/year)	900	740	620	520
Lifetime = 30 years				

expected average lifetime of 30 years, the total capacity of 15 GW of new offshore wind power can be reached by installing 500 MW/year. Subsequently, the 15 GW can be maintained by a continuous replacement of 500 MW each year. Since 3 GW have already been installed, the total capacity can be reached within approximately 25 years.

In Figure 7.12 and the upper part of Figure 7.13, the primary energy supply and the energy flow of such a system are illustrated. The two figures are comparable to Figures 7.6 and 7.7. Altogether, the study indicates that a 100 percent renewable energy system based on domestic resources is physically and technically possible in Denmark. However, it should be emphasized that the proposal presented here is based on a conversion of the entire transportation sector into a combination of electrical and hydrogen fuel cell vehicles. Such a conversion may prove unrealistic for the entire sector. The obvious technological alternative is to convert into biofuels instead, as discussed in Chapter 5. In Figure 7.13 (bottom diagram), the consequences of this conversion are shown, based on the solution already described in Chapter 5.

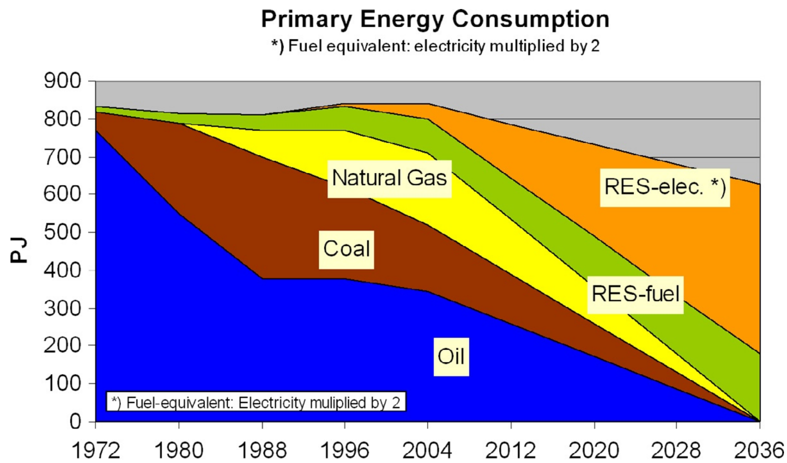

FIGURE 7.12 Primary fuel consumption if the Danish energy system is converted into 100 percent RES.

As the two diagrams in Figure 7.13 show, the choice between electricity/hydrogen-based or biofuel-based transportation technologies has a major impact on the size of the resulting primary energy supply of the system. In particular, the amount of biomass required is affected. The results emphasize the importance of further developing electric vehicle technologies and indicate that biofuel transportation technologies should be reserved for the areas of transportation in which the electricity/hydrogen solution proves insufficient. This issue is included in the investigations of the next two examples.

3. THE DANISH SOCIETY OF ENGINEERS' ENERGY PLAN[2]

This section is based on Lund and Mathiesen's (2009) article "Energy System Analysis of 100 Percent Renewable Energy Systems", which presents the methodology and results of an overall energy system analysis of a 100 percent renewable energy system. The input to the system is the result of the Danish Society of Engineers' project Energy Year 2006, in which a model for the future energy system of Denmark was discussed and designed.

As in the previous chapter, the energy system analysis has been performed using the EnergyPLAN model, including hour-by-hour simulations, leading to the design of a flexible renewable energy system with the ability to balance the electricity supply and demand. The results are detailed system designs and energy balances for two energy target years: 2030, with 45 percent renewable

2. Excerpts reprinted from *Energy*, 34/5, Henrik Lund and Brian Vad Mathiesen, "Energy System Analysis of 100 Percent Renewable Energy Systems", pp. 524–531 (2009), with permission from Elsevier.

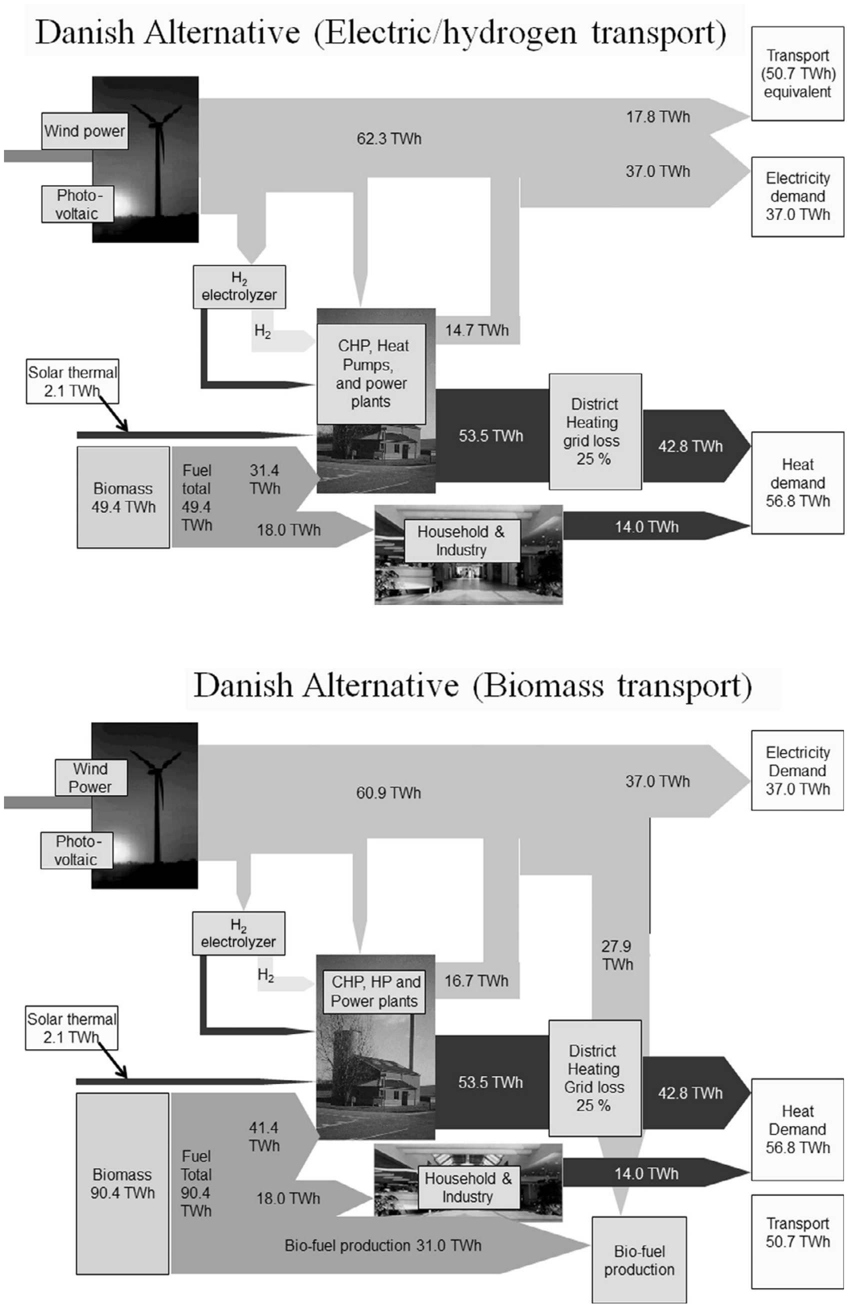

FIGURE 7.13 The energy flow in a Danish 100 percent renewable energy system. The top diagram is based on electric and hydrogen fuel cell vehicles referring to Figure 7.12, and the bottom diagram refers to the biofuel alternative.

energy, demonstrating the first important steps on the way toward a 100 percent renewable energy system (IDA 2030), and 2050, with 100 percent renewable energy from biomass and combinations of wind, wave, and solar power (IDA 2050).

The analysis concludes that a 100 percent renewable energy supply based on domestic resources is physically possible and that the first step toward 2030 is economically feasible to Danish society. However, Denmark will have to consider to which degree the country should rely mostly on biomass resources, which will involve the reorganization of the present use of farming areas, or rely mostly on wind power, which will involve a large share of hydrogen or similar energy carriers leading to certain inefficiencies in the system design.

In the project of the Danish Society of Engineers, the method applied to the design of a future energy system in Denmark was a combination of two phases: a creative phase involving the inputs of a number of experts and a detailed analytical phase involving technical and economic analyses of the overall system and feedback on each individual proposal. In a back-and-forth process, each proposal was formed in such a way that it combined the best of the detailed expert knowledge with the ability of the proposal to fit well into the overall system in terms of technical innovation, efficient energy supply, and socioeconomic feasibility.

First, the Danish Society of Engineers appointed 2006 as the "Energy Year" in which the organization aimed at making specific proposals to advocate an active energy policy in Denmark. The targets formulated for the future Danish energy system, 2030 (IDA 2030), were the following: (1) to maintain the security of energy supply, (2) to cut CO_2 emissions by 50 percent by 2030 compared with the 1990 level, and (3) to create employment and increase exports in the energy industry by a factor of four. The target of maintaining the security of supply referred to the fact that Denmark, at that time, was a net exporter of energy from the production of oil and natural gas in the North Sea. However, the reserves are expected to last for only a few more decades. Consequently, Denmark will soon either have to start importing energy or develop domestic renewable energy alternatives.

Based on these targets, the work of the Danish Society of Engineers was divided into seven themes under which three types of seminars were held: a status and knowledge seminar, a future scenario seminar, and a roadmap seminar. The process resulted in a number of suggestions and proposals on how each theme could contribute to the national targets.

The contributions involved a number of energy demand-side management and efficiency measures within households, industry, and transportation, together with a wide range of improved energy conversion technologies and renewable energy sources, emphasizing energy efficiency, CO_2 reduction, and industrial development. All proposals were described in relation to a Danish 2030 business-as-usual reference (Ref 2030). These descriptions involved technical consequences as well as investment and operation and maintenance costs.

In a parallel process, all proposals were analyzed technically in an overall energy system analysis using the EnergyPLAN computer model. The energy system analysis was conducted in the following steps:

1. First, the Danish Energy Agency's official business-as-usual scenario for 2030 (Ref 2030) was recalculated using the EnergyPLAN model. It was possible, on the basis of the same inputs, to come to the same conclusions regarding annual energy balances, fuel consumption, and CO_2 emissions. Consequently, a common understanding of Ref 2030 was established.
2. Second, each of the proposals for year 2030 was defined as a change of the reference system, and a first rough alternative was calculated including all changes. The creation of this system led to a number of technical and economic imbalances, and, consequently, proposals of negative feasibility were reconsidered and suitable investments in flexibility were added to the system.

In the EnergyPLAN model, the analysis was done by basing the operation of the system on a business economic optimization of each production unit. This optimization included taxes and involved electricity prices on the international electricity market. The calculation of the socioeconomic consequences for Danish society did not include taxes. This calculation was based on the following basic assumptions:

- World market fuel costs equaled an oil price of 68 USD/barrel (with a sensitivity of 40 USD and 98 USD/barrel).
- Investment and operation costs were based on official Danish technology data, if available, and if not, on the input from the "Energy Year" experts.
- An interest real rate of 3 percent was used (with a sensitivity of 6 percent).
- Environmental costs were not included in the calculation, apart from CO_2 emission trade prices of 20 EUR/ton (with a sensitivity of 40 EUR/ton).

A technical analysis and a feasibility study were conducted of each individual proposal. Since many of the proposals were not independent in nature, the analysis was conducted for each proposal, in both the reference business-as-usual system (Ref 2030) and the alternative system (IDA 2030). One proposal, the insulation of houses, may be feasible in the reference but not in the alternative system: for instance, if solar thermal was applied to the same houses or if the share of CHP was increased as part of the overall strategy. Consequently, several of the contributions and proposals had to be reconsidered and coordinated with other contributions.

The proposed alternatives of the Danish Society of Engineers (IDA 2030 and 2050) were compared to both the present situation (2004) and to a business-as-usual reference scenario for 2030 (Ref 2030), assuming that the gross energy consumption (primary energy supply) would rise from 850 PJ in 2004 to 970 PJ in 2030. The IDA 2030 and 2050 alternatives were defined as a series of changes to the business-as-usual reference in 2030. IDA 2030 is an alternative for the year 2030, and IDA 2050 is a 100 percent renewable energy system alternative for 2050. The different energy systems were comprehensive, also including natural gas consumption on the drilling platforms in the North Sea and jet fuel for international air transportation.

After completing the back-and-forth process of comparison and discussion among experts and the overall systems analysis, the proposals of IDA 2030 ended up as follows:

- Reduce space heating demand in buildings by 50 percent
- Reduce fuel consumption in industry by 40 percent
- Reduce electricity demand in private households by 50 percent and in industry by 30 percent
- Supply 15 percent of individual and district heating demands by solar thermal
- Increase electricity production from industrial CHP by 20 percent
- Reduce fuel consumption in the North Sea by 45 percent through savings, CHP, and efficiency measures
- Slow down the increase in transportation demand through tax reforms
- Replace 20 percent of road transportation with ships and trains
- Replace 20 percent of the fuel for road transportation with biofuels and 20 percent with electricity
- Replace natural gas boilers by micro–fuel cell CHP, equal to 10 percent of house heating
- Replace individual house heating by district heating CHP, equal to 10 percent
- Replace future power stations constructed after 2015 by fuel cell CHP stations, equal to 35–40 percent of the total amount of power stations in 2030
- Increase the total amount of biomass resources (including waste) from 90 to 180 PJ in 2030
- Increase wind power from 3000 to 6000 MW in 2030
- Introduce 500 MW wave power and 700 MW PV power
- Introduce 450 MWe heat pumps in combination with existing CHP systems and flexible electricity demand to achieve a better integration of wind power and CHP into the energy system

It should be emphasized that the proposal of adding heat pumps and flexible demand was an outcome of the overall energy systems analysis process, which pointed out that the potential of flexible production should be exploited in the best possible way to overcome balancing problems in electricity and district heating supplies. Especially regarding CHP stations based on solid oxide fuel cell technology, the stations should exploit the potential for changing production quickly without losing efficiency and within the full range of loads.

The results of the socioeconomic feasibility study and the export potential are shown in Figures 7.14 and 7.15. Figure 7.14 illustrates the economic costs related to Denmark's energy consumption and production in Ref 2030 and in IDA 2030, respectively. In Figure 7.15, the business potential of IDA 2030 is shown, calculated as expected exports in 2030 and compared to the data of 2004.

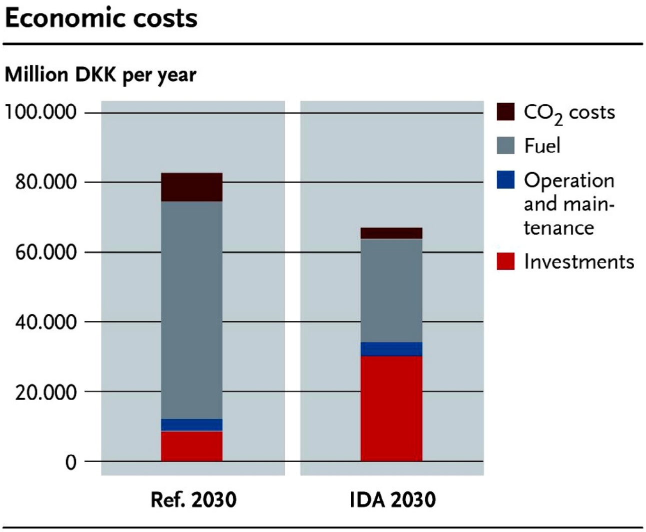

FIGURE 7.14 Economic costs of IDA 2030, the energy plan for 2030 of the Danish Society of Engineers.

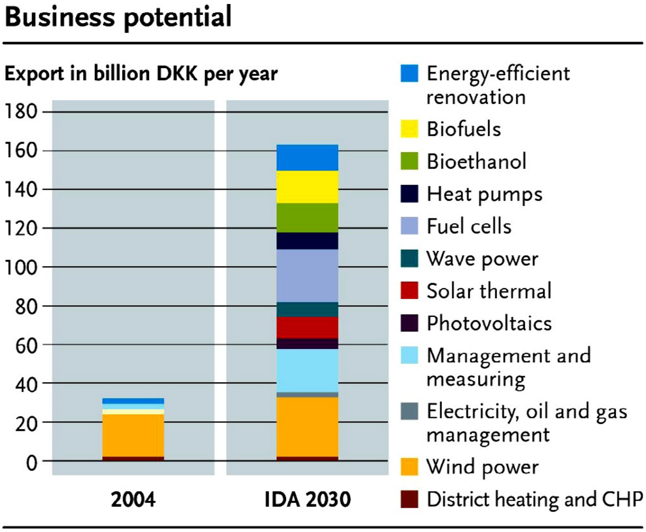

FIGURE 7.15 Business potential of IDA 2030.

Socioeconomic feasibility is calculated as annual costs, including fuel and operation, and annual investment costs based on a certain lifetime and interest rate. The feasibility study has been carried out with three different oil prices (as mentioned previously), and the IDA 2030 alternative is compared with Ref 2030, assuming that the average oil price is applicable 40 percent of the time, and the low and high oil prices each are applicable 30 percent of the time.

Compared to Ref 2030, the IDA 2030 alternative converts fuel costs into investment costs and also has lower total annual costs. Such a shift in cost structure is very sensitive to two factors: the interest rate and the estimation of the size of total investment costs. Consequently, sensitivity analyses have been made. In the first analysis, the interest rate has been raised from 3 to 6 percent, and in the other, all investment costs have been raised by 50 percent. In both cases, the IDA 2030 alternative is competitive to the reference.

Figure 7.15 gives an indication of the export potential of IDA 2030. This potential has been estimated on the basis of the Danish development of wind turbine manufacturing and is considered a very rough estimate. However, the estimate provides valuable information on both the different relevant technologies and the size of the total potential. The socioeconomic feasibility and the CO_2 emissions of the two energy systems, Ref 2030 and IDA 2030, are shown in Figure 7.16. All measures have been evaluated marginally in both Ref 2030 and IDA 2030. As can be seen, the back-and-forth process has led to the identification of measures that are predominantly feasible. However, some proposals with negative feasibility results have been included in the overall plan for other reasons. Some have good export potential, whereas others are important to be able to reach the final target of 100 percent renewable energy in the next step, and yet others have important environmental benefits.

The socioeconomic feasibility shown in Figures 7.14 and 7.16 is calculated for a closed system without any exchange of electricity on international markets. On the basis of these calculations, a separate study was conducted of the potential benefits of electricity exchange to assess whether the IDA 2030 energy system in this respect differed from the reference system Ref 2030. The evaluation was done for the three different fuel price levels and the two CO_2 emission trade cost levels, as well as for the three Nordic hydropower circumstances: wet, normal, and dry years. The results are shown in Figure 7.17 in terms of socioeconomic net revenues for Danish society. Moreover, the diagram shows the import and export of each system: Ref 2030 and IDA 2030.

The net revenue from exchange is calculated in the EnergyPLAN model by comparing the results of a reference calculation of a closed system to the results of a calculation of an open system. The closed system has no exchange, while the open system benefits from exchange by selling electricity when the price exceeds the marginal production costs of the Danish energy system and buying electricity when the price is lower than the marginal costs. The modeling takes into consideration bottlenecks among the countries. The whole procedure of calculation is based on the assumption that each of the electricity production units optimizes its business economic revenues.

As can be seen in Figure 7.17, Denmark will be able to profit from the exchange of electricity on the Nordic Nord Pool market in all situations. The net revenue is typically on the order of 500–1000 million DKK/year. In years with low fuel prices and high electricity market prices, revenues are primarily earned from exporting, while in years with high fuel prices and low electricity prices, revenues are earned from importing electricity. It should be mentioned

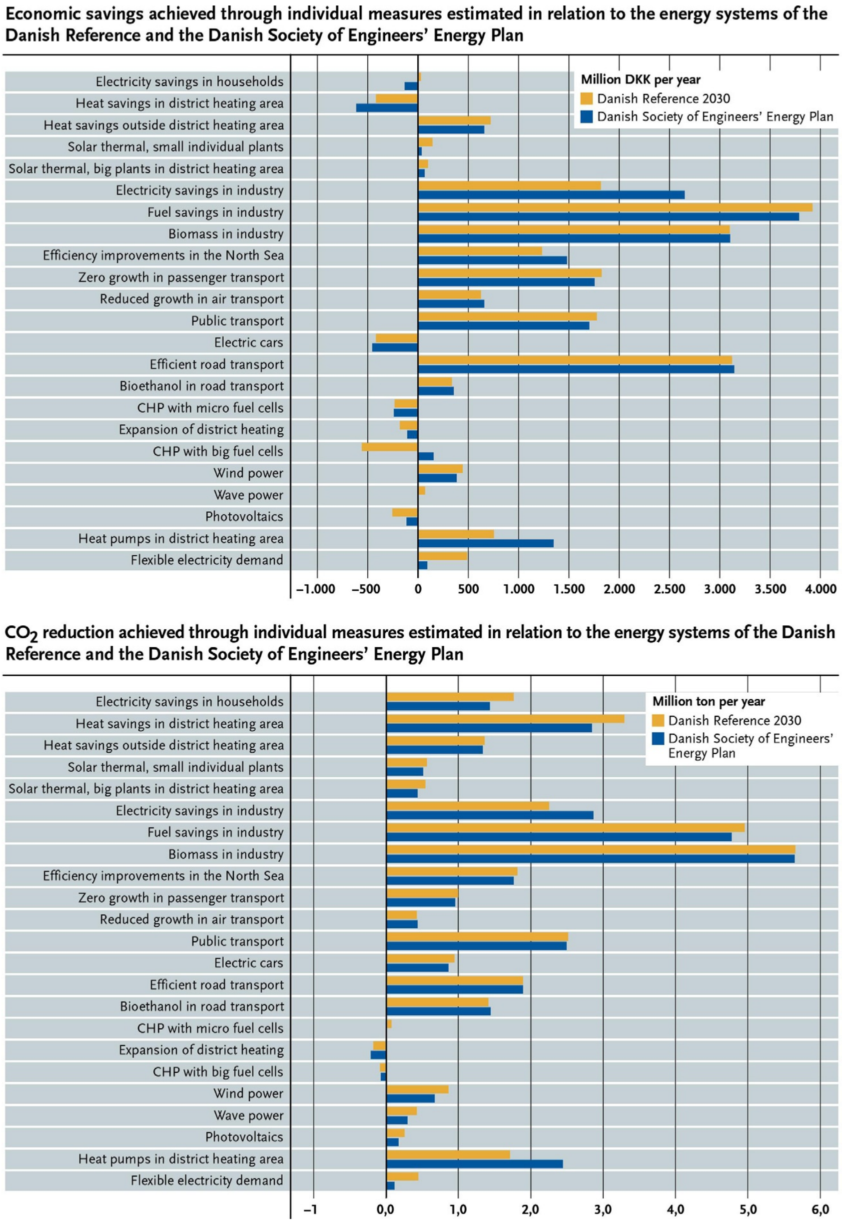

FIGURE 7.16 Feasibility and CO_2 emission reduction of each of the individual measures.

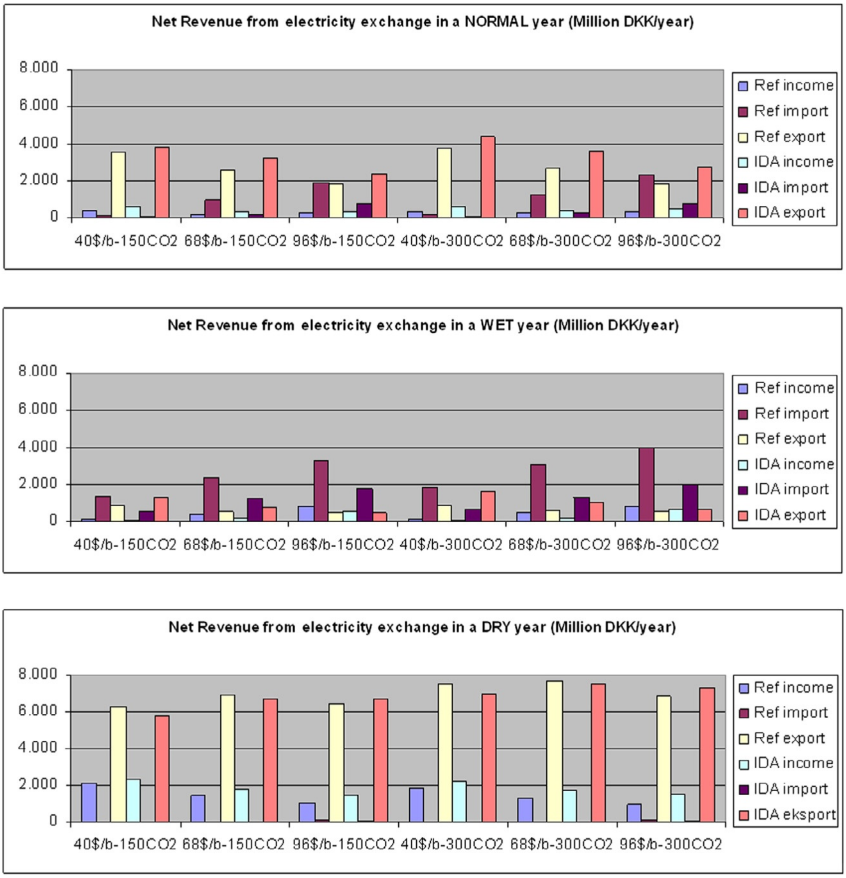

FIGURE 7.17 Net revenue from electricity exchange for Ref 2030 and IDA 2030 at different fuel prices, CO_2 emission trading prices, and under different hydro power circumstances: wet, normal, and dry years, which are determined by the hydropower reservoirs of the Nordic electricity supply system.

that not all combinations are equally probable. The electricity market price will, to some extent, follow the changes in the fuel price levels.

A comparison of the reference Ref 2030 and IDA 2030 has been made by calculating the average net revenues during a period of years in which the following conditions occur:

- Wet, normal, and dry years are 3:3:1.
- Low, medium, and high fuel prices are 3:4:3.
- Low and high CO_2 emission trading prices are 1:1.

Based on these ratios, the average net revenues of the IDA 2030 system are 585 million DKK/year compared to the 542 million DKK/year of Ref 2030.

Based on this analysis, it is only fair to say that the two systems can benefit equally from the exchange of electricity on the Nord Pool market. However, compared to the total annual cost of 60–80 billion DKK/year, the net revenue gained from the exchange of electricity is only marginal. The important economic benefits come from the fuel savings achieved by changing the system from Ref 2030 to IDA 2030.

To achieve a 100 percent renewable energy supply, the following additional initiatives were proposed by the steering committee, thus extending the IDA 2030 energy system and creating the IDA 2050 system:

- Reduce heat demand in buildings and district heating systems by another 20 percent compared to the year 2030.
- Reduce fuel demand in industry by another 20 percent.
- Reduce electricity demand by another 10 percent.
- Stabilize transportation demand at the 2030 level.
- Expand district heating by 10 percent.
- Convert micro-CHP systems from natural gas to hydrogen.
- Replace oil and natural gas boilers by heat pumps and biomass boilers in individual houses.
- Replace 50 percent of road goods transportation with trains.
- Replace remaining fuel demand for transportation equally with electricity, biofuels, and hydrogen.
- Supply 3 TWh of industrial heat production from heat pumps.
- Replace all CHP and power stations with fuel cell–based, biogas, or biomass gasification.
- Supply 40 percent of the heating demand of individual houses by solar thermal.
- Increase wave power from 500 to 1000 MW.
- Increase PV power from 700 to 1500 MW.

The necessary wind power and/or biomass resources were calculated as residual resources and had to be increased, as described in the following.

The 100 percent renewable energy system for 2050 (IDA 2050) has been calculated in more than one version. First, all the proposals just mentioned were simply implemented, which led to a primary energy supply consisting of 19 PJ of solar thermal, 23 PJ of electricity from RES (wind, wave, and PV), and 333 PJ of biomass fuels. In this scenario, wind power is equal to the figure of the year 2030: 6000 MW installed capacity. A figure of 333 PJ of biomass fuels, however, may be too high. According to the latest official estimate when the study was conducted, Denmark had approximately 165 PJ of residual biomass resources, including waste. Residual resources consist of straw that is not needed for livestock, biogas from manure, organic waste, and waste from wood industries. However, the potential of biomass fuels from the change of crops was considered to be huge. Denmark, for example, grows

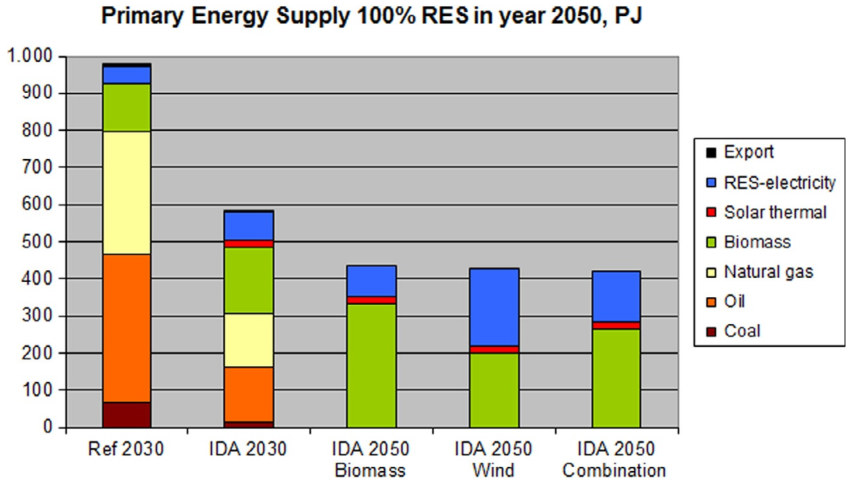

FIGURE 7.18 Primary energy supply for three versions of the 100 percent renewable energy system, IDA 2050, compared to the reference, Ref 2030, and the proposal for the year 2030, IDA 2030.

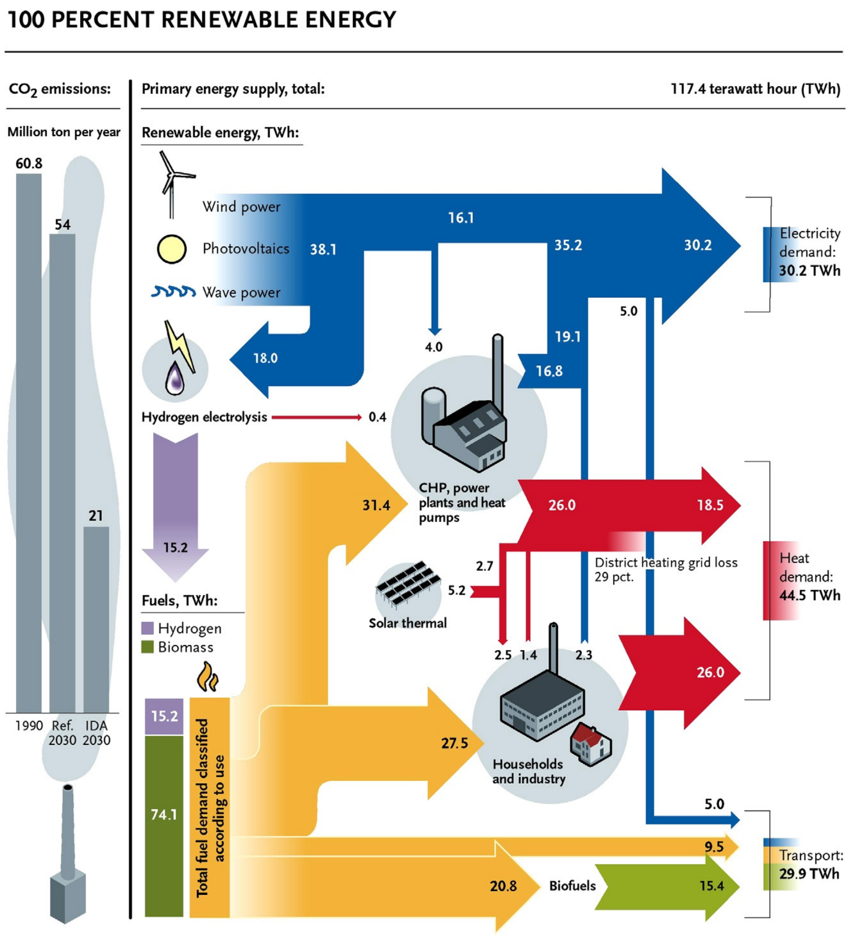

FIGURE 7.19 Flow diagram of the 100 percent renewable energy system (IDA 2050).

a lot of wheat that can be replaced by other crops such as corn, leading to a much higher biomass production while maintaining the same output for food. This reorganization of the farming areas together with a few other options may lead to total biomass fuel potential as high as 400 PJ (Mathiesen, Lund, and Nørgaard 2008).

The analyses proposed a compromise with 10,000 MW of wind power and 270 PJ of biomass fuels. All three versions are shown in Figure 7.18. The energy flow of the system is illustrated in Figure 7.19, and the primary energy supply and the resulting CO_2 emissions are shown in Figure 7.20.

On the basis of the first version of the 100 percent renewable energy scenario, it was analyzed how much the need for biomass fuels would decrease if more wind power was added. If wind power is raised from 10,000 to 15,000 MW, then a rise in electricity to 200 PJ will lead to a decrease in biomass fuel consumption to 200 PJ. It should, however, be emphasized that this replacement leads to a significant increase in the demand for hydrogen as an energy carrier, which results in considerable efficiency losses.

The primary energy supply is expected to increase from approximately 800 PJ in 2004 to nearly 1000 PJ in the business-as-usual reference (Ref 2030). If the proposed IDA 2030 plan is implemented, the primary energy supply will fall to below 600 PJ and CO_2 emissions will decrease by 60 percent compared to the year 1990.

If the 100 percent renewable energy system proposed for 2050 (IDA 2050) is implemented, the primary energy supply will fall to approximately 400 PJ, and the CO_2 emission will, in principle, be equal to zero. However, some waste is included in the biomass resources, of which some will result in a minor CO_2 emission. Moreover, it should be mentioned that Denmark will still contribute to greenhouse gas emissions from gases other than CO_2. In total, however, the Danish greenhouse gas emissions will decrease by approximately 80 percent.

The IDA Climate Plan

This Section Is Courtesy of Guest Writer Brian Vad Mathiesen

Three years after creating the IDA Energy Plan, the Danish Society of Engineers in 2009 made a follow-up and an extension of the study in terms of an IDA Climate Plan. The follow-up was part of a joint effort of engineering societies from various countries to contribute to the COP15 meeting in Copenhagen in 2009. As described by Mathiesen, Lund, and Karlsson (2011), the IDA Climate Plan added to the previous study among others by including not only the energy sector but all sectors contributing to greenhouse gas emissions. Further, the study involved additional efforts regarding transportation and biomass as well as an estimate of the influence on health costs and on job creation based on applied concrete institutional economics.

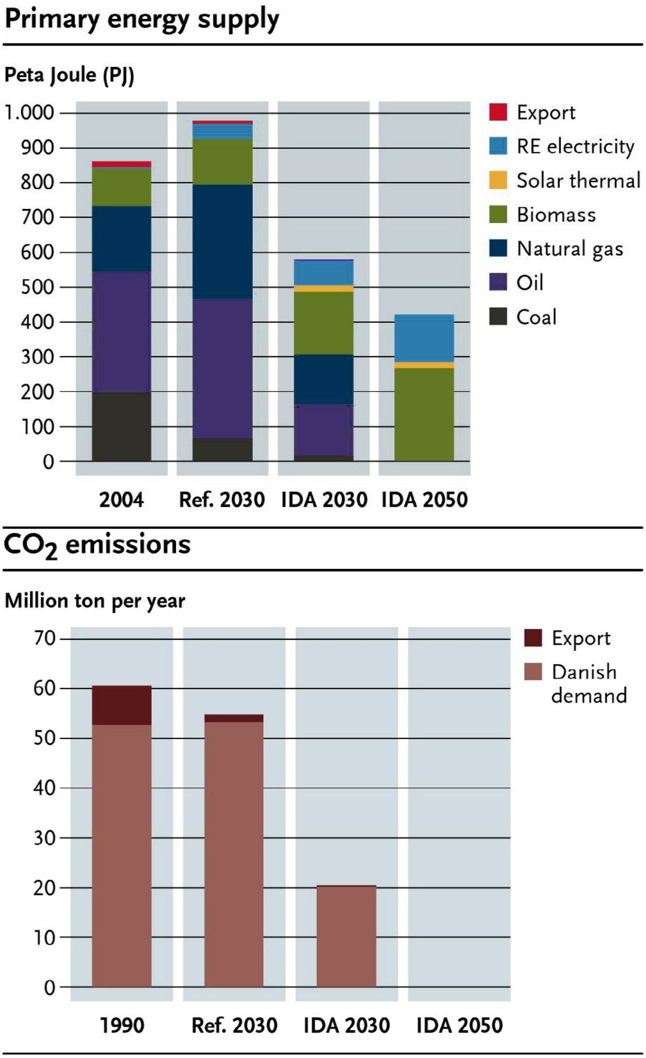

FIGURE 7.20 Primary energy supply and CO_2 emissions. CO_2 emissions are divided into domestic electricity demand and electricity net exports.

Again, the conclusion is that a 100 percent renewable energy system is possible, but the balance between a large consumption of biomass and a large amount of electricity for direct use or for the production of synthetic fuels appears to be a challenge. In combination with changes in the agricultural sector and including the extra contribution from aviation, the emission of greenhouse gases can be reduced to 10 percent in 2050 compared to 2000 levels.

The change from a conventional energy system to a renewable energy system provides socioeconomic savings, because the savings achieved in fuel costs are higher than the annual cost to be paid for the additional investments. On top of this, there is a benefit for the health of the population, which increases the socioeconomic savings. Further, if the changes are implemented relatively early in the period, there is a potential for exports and related jobs. In all cases, the changes will increase the number of jobs, even if the commercial potential for increased exports is not met. These results indicate the possibility of continuing economic growth while implementing climate mitigation strategies.

4. THE CEESA COHERENT 100 PERCENT RENEWABLE ENERGY SCENARIO[3]

This Section Is Courtesy of Guest Writer Brian Vad Mathiesen

This section is based on a part of a chapter in Lund, Hvelplund et al. (2011), “Coherent Energy and Environmental System Analysis”. The report is the result of the CEESA project partly financed by the Danish Council for Strategic Research. Beyond the IDA energy and climate plans, the CEESA project applies and implements several of the smart energy system points of Chapter 6 to the analysis of a 100 percent renewable energy scenario. This involves, among others, the fuel pathways described and the hour-by-hour analysis of the gas grid as described and emphasized in Chapter 6.

As in the IDA plans, the aim of the CEESA scenarios is to design a 100 percent renewable energy system by the year 2050. A focus point is that this transition highly relies on the technologies that are assumed to be available within the specified time horizon and which may have different effects on the biomass consumption. To highlight this, the CEESA project has identified scenarios based on three different assumptions regarding the available technologies. This methodology allows a better optimization and understanding of the energy systems. To enable a thorough analysis of the different key elements in 100 percent renewable energy systems, two very different 100 percent renewable energy scenarios and one recommendable scenario have been designed:

- *CEESA 2050 Conservative*: The conservative scenario is created using mostly known technologies and technologies that are available today. This scenario assumes that the current market can develop and improve existing technologies. In this scenario, the costs of undeveloped renewable energy technologies are high. Very little effort is made to push the technological

3. Excerpts reprinted from Lund, Hvelplund et al. (2011), “Coherent Energy and Environmental System Analysis”, Department of Development and Planning, Aalborg University, Aalborg 2011.

development of new renewable energy technologies in Denmark or at a global level. However, the scenario does include certain energy efficiency improvements of existing technologies, such as improved electricity efficiencies of power plants; more efficient cars, trucks, and planes; and better wind turbines. Moreover, the scenario assumes further technological development of electric cars, hybrid vehicles, and bio-DME/methanol production technology (including biomass gasification technology).

- *CEESA 2050 Ideal*: In the ideal scenario, technologies still in the development phase are included on a larger scale. The costs of undeveloped renewable energy technologies are low, due to significant efforts to develop, demonstrate, and create markets for new technologies. For example, the ideal scenario assumes that fuel cells are available for power plants, and biomass conversion technologies (such as gasification) are available for most biomass types and on different scales. Co-electrolysis is also developed and the transportation sector moves further toward electrification compared with the conservative scenario.
- *CEESA 2050*: This scenario aims to be a "realistic and recommendable" scenario based on a balanced assessment of realistic and achievable technology improvements. Less co-electrolysis is used and a balance is implemented between bio-DME/methanol and syn-DME/methanol in the transportation sector. This is the main CEESA scenario.

In all scenarios, energy savings and direct electricity consumption are given a high priority, and all scenarios rely on a holistic smart energy system approach as explained in Chapter 6. This includes the use of heat storages, district heating with CHP plants, and large heat pumps as well as the integration of transportation fuel pathways with the use of gas storage. These smart energy systems enable a flexible and efficient integration of large amounts of fluctuating electricity production from wind turbines and PVs. The gas grids and liquid fuels allow long-term storage, while the electric vehicles and heat pumps allow shorter-term storage and flexibility.

Transportation Fuel Pathway

The transportation sector poses two main problems in the transition to renewable energy: First, the obvious easily accessible source, biomass, is limited, and second, the increase in the transportation demands is historically high. The scenarios include a suggestion for a new transportation system, with a medium increase in demands (except goods) and more rail transportation. To replace oil and keep the biomass consumption at a low level, the following strategy is applied: focus is placed on maximizing the use of electricity in the transportation sector, and, where liquid fuels are needed in some cars, vans, trucks, and aviation, priority is given to DME/methanol.

With DME/methanol fuels, conventional cars can be used in the short term (up to 3 percent blend), and with minor changes in vehicles, the share can be increased. In the CEESA scenarios, bio-DME/methanol is produced from a combination of gasified biomass and hydrogen from electrolyzers and not from waste products. In the longer term, land-use effects can be lowered further by replacing bio-DME/methanol with syn-DME/methanol, which requires co-electrolyzers and carbon sequestration, as explained in Chapter 6 regarding the fuel pathways. This strategy reduces the biomass use and allows the integration of more wind and PV power into the energy system in general, i.e., the transportation sector becomes an important part of the smart energy system.

As explained in Chapter 6, it is too early to know if the liquid fuel DME/methanol solution is the best alternative as other options exist such as a gas methane solution or even a combination. However, approximately the same energy balances can also be achieved with a gas solution as considered here for the liquid solution. DME/methanol is used in the scenarios for the concrete calculations to illustrate the principle of using biomass resources in combination with electrolyzers to replace fossil fuels in the transportation sector in the short term. In the longer term, carbon from other sources than biomass is used to replace larger amounts of fossil fuels without putting further strain on the biomass resource. Other types of fuels that fulfill this principle could also be relevant in the future, but the scenarios show that this principle can reduce the biomass consumption significantly.

All three technology scenarios above are designed in a way in which renewable energy sources, such as wind power and PV, have been prioritized, taking into account the technological development in the scenarios and the total costs of the system. Moreover, they are all based on decreases in the demand for electricity and heat as well as medium increases in transportation demands. Consequently, none of the scenarios can be implemented without an active energy and transportation policy. However, sensitivity analyses are conducted in terms of both a high energy demand scenario as well as the unsuccessful implementation of energy saving measures. These analyses point in the direction of higher costs, higher biomass consumption, and/or an increased demand for wind turbines. The important differences between the scenarios are highlighted in Table 7.5.

In the *conservative* technology scenario, wave power, PV, and fuel cell power plants are not included and emphasis is put on bio-DME/methanol and on direct electricity consumption in the transportation sector. The electrolyzers are based on known technology in this scenario. Smart energy systems and cross-sector system integration are required between the electricity systems and district heating sectors, as well as in the transportation system and gas grid in all scenarios. The integration of the transportation system and gas grids is, however, not as extensive in the conservative scenario as it is in the ideal scenario. In the *ideal* scenario, wave power, PV, fuel cells and a number of other

TABLE 7.5 Main Differences among the 100 Percent Renewable Energy Scenarios in CEESA

	CEESA 2050 Conservative	CEESA 2050 Ideal	CEESA 2050
Renewable Energy and Conversion Technologies			
Wind power	12,100 MW	16,340 MW	14,150 MW
PV	—	7500 MW	5000 MW
Wave power		1000 MW	300 MW
Small CHP	Engines	Small fuel cell CHP	Engines/Fuel cells Gas turbine
Large CHP and power plants	Gas turbine combined cycle/ combustion	Large fuel cell combined cycle CHP/PP	Combined cycle/large fuel cell combined cycle CHP/PP
Gasification for electricity and power production	Yes partly	Yes	Yes
Transport			
Direct electricity	13%	23%	22%
Bio-DME/methanol	87%	0%	44%
Syn-DME/methanol	—	77%	34%
Bio-DME/methanol plants	Yes	No	Yes
Electrolyzers for bio-DME/methanol plants	Yes	No	Yes
Co-Electrolyzers for syn-DME/methanol plants	No	Yes	Yes

technologies are used to their full potential, while in the *recommendable* scenario, the technologies are assumed to be developed to a degree in which they can make a substantial contribution.

Primary Energy and Biomass Resources

The levels of primary energy consumption for 2050 for the three scenarios and the reference energy system are compared in Figure 7.21. Compared to the reference energy system, all the scenarios are able to reduce the primary energy supply to a level of approximately 500 PJ. There are, however, large differences among the scenarios regarding the use of biomass as illustrated in Figure 7.22. In the conservative technology scenario, a 100 percent renewable energy system

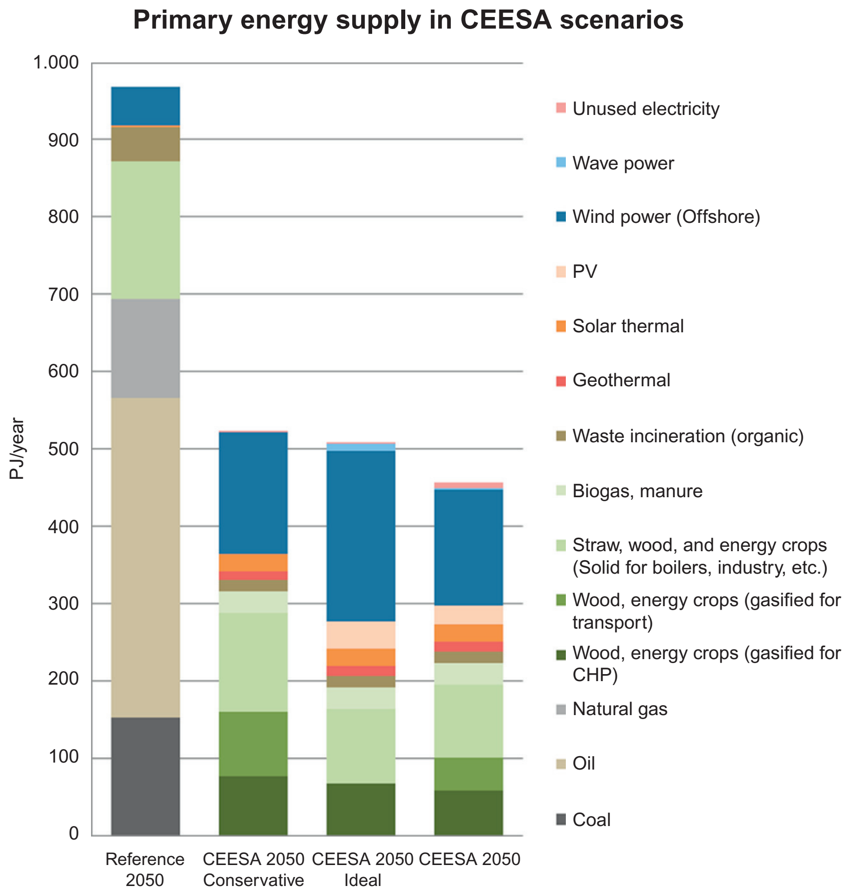

FIGURE 7.21 Primary energy supply in the 2050 reference energy system and the three CEESA 100 percent renewable energy scenarios.

is possible with a total biomass consumption of 331 PJ. The ideal technology scenario can decrease this consumption to 206 PJ of biomass. In the CEESA 2050 recommendable scenario, the biomass consumption is 237 PJ and thus 30 PJ higher than in the ideal and 96 PJ lower than in the conservative scenario, respectively.

The CEESA project includes a careful examination of the pathways to provide biomass resources. The starting point is an overview of the number of residual resources in terms of straw, wood, and biogas from manure, etc., summing up to approximately 180 PJ/year. A shift in forest management practices and cereal cultivars could increase the potential further to approximately 240 PJ/year by 2050. The 180 PJ/year could also be increased to 200 PJ by enacting

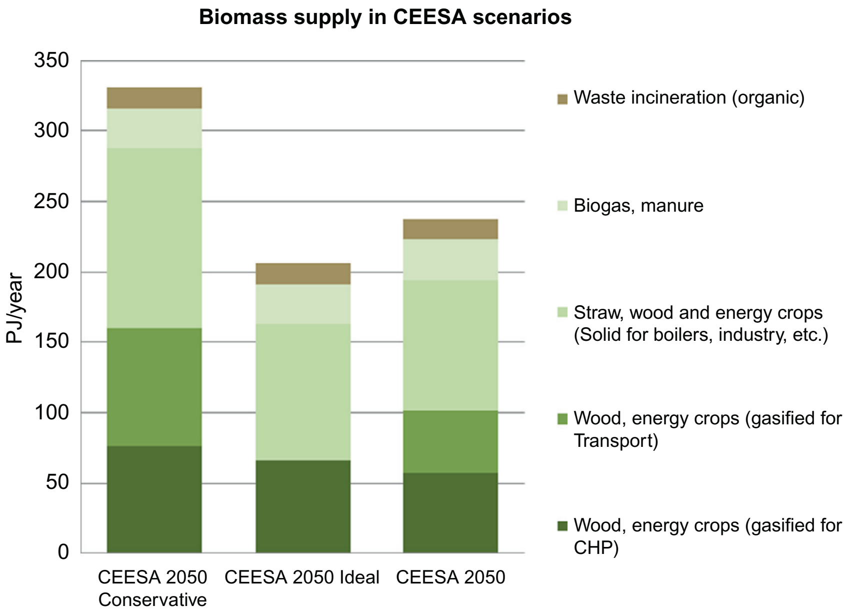

FIGURE 7.22 Biomass supply in the three CEESA 100 percent renewable energy scenarios.

dietary changes. This potential represents the use of residual resources only. This means that the CEESA 2050 recommendable scenario is kept within the boundaries of residual resources, and the CEESA 2050 conservative scenario illustrates that an active energy and transportation policy is required to stay within these limits. It should be noted that a target of 240 PJ/year by 2050 implies a number of potential conflicts due to many different demands and expectations from ecosystem services; it requires the conversion of agricultural land otherwise allocated to food crop production to energy crop production, potentially reducing food and feed production. All crop residues must be harvested, potentially reducing the carbon pool in soils. A way to reduce these potential conflicts is to reduce the demand for biomass for energy or to further develop agriculture and forestry to increase the biomass production per unit of land.

If biomass in a future non-fossil society has to cover the production of materials currently based on petrochemical products, even more pressure will be put on the biomass sector. To meet these demands, 40–50 PJ would have to be allocated to that purpose. It should be noted that, in addition to the 240 PJ of residual biomass resources, waste resources are also available amounting to 33–45 PJ or a total of approximately 280 PJ. In this respect, CEESA 2050 recommendable and ideal scenarios would enable the allocation of biomass resources to the materials currently based on petrochemical products.

Based on the "realistic and recommendable" scenario, a roadmap toward 2050 has been designed and compared to a business-as-usual reference development. It should be noted that this reference was designed before the Danish Parliament decided to aim for a 100 percent renewable energy system by 2050. The current primary energy supply in Denmark (fuel consumption and renewable energy production of electricity and heat for households, transportation, and industry) is approximately 850 PJ, taking into account the boundary conditions applied to transportation in this study, in which all transportation is accounted for, i.e., national/international demands for both passenger and freight transportation. If new initiatives are not taken, the energy consumption is expected to decrease marginally until 2020, but then increase gradually until 2050 to about 970 PJ. The reference energy system follows the projections from the Danish Energy Agency from 2010 until 2030, and the same methodology has then been applied here to create a 2050 reference energy system. The measures relating to savings, transportation, renewable energy, and the integration of the electricity, heat, transportation, and gas sectors can reduce the primary energy supply to 473 PJ in CEESA 2050. The primary energy supply is illustrated in Figure 7.23. The energy flows in the CEESA 2050 recommendable 100 percent energy system are illustrated in a Sankey diagram in Figure 7.24.

In CEESA, the greenhouse gas emissions from fossil fuels are reduced significantly in the energy system. In Figure 7.25, the greenhouse gas emissions from the energy system in the CEESA scenario are illustrated in relation to the reference energy system, including an extra contribution from aircraft due to discharges at high altitudes. In 2050, the emissions are not zero due to aviation, but the emissions from these sources have been reduced to 2 percent compared to the level of the year 2000. Greenhouse gas emissions from industrial processes and from agriculture or land use changes are not included in this figure.

The CEESA scenarios document that it is possible to find technical solutions for a 100 percent renewable energy system. However, a certain technological development becomes essential in the coming years, notably in enabling the efficient direct use of electricity in the transportation sector with better electric, hybrid electric, and plug-in-hybrid electric vehicles and in biomass gasification technologies (small and large scale). The results also show that if these technologies are not developed sufficiently, the biomass consumption could be larger than in the CEESA 2050 conservative scenario.

In CEESA, a 100 percent renewable energy system has been designed, which may potentially be supplied by domestic residual biomass resources. It must, however, be emphasized that there are no objectives in the CEESA project against international trade with biomass. The scenario recommended in CEESA, however, ensures that Denmark does not merely become dependent on imports of biomass, replacing the dependence on imports of oil, natural gas, and coal, which is the case in the reference scenario (once Denmark does not have any resources left in the North Sea). It also ensures that the biomass

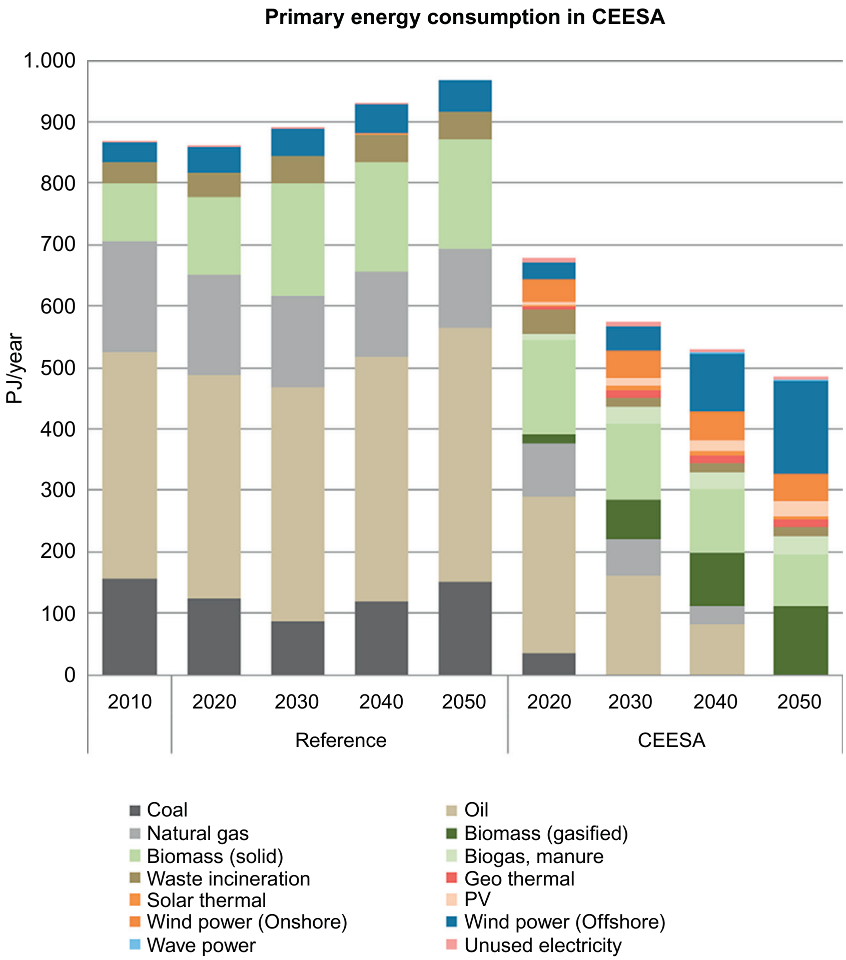

FIGURE 7.23 Primary energy supply in CEESA.

consumption is within the limits of the Danish residual biomass resources. Looking at the global residual resources, the residual biomass potential is higher per person in Denmark, however, implying that Denmark should go even lower than the domestic residual biomass resources available.

Smart Energy Systems and Cross-Sector Integration

In all three scenarios, hour-by-hour energy system analyses have been used to increase the share of wind turbines to an amount ensuring that the unused electricity consumption, also referred to as excess electricity, is lower than 0.5 TWh (1.8 PJ). These analyses also ensure that the heat supply and gas supply are

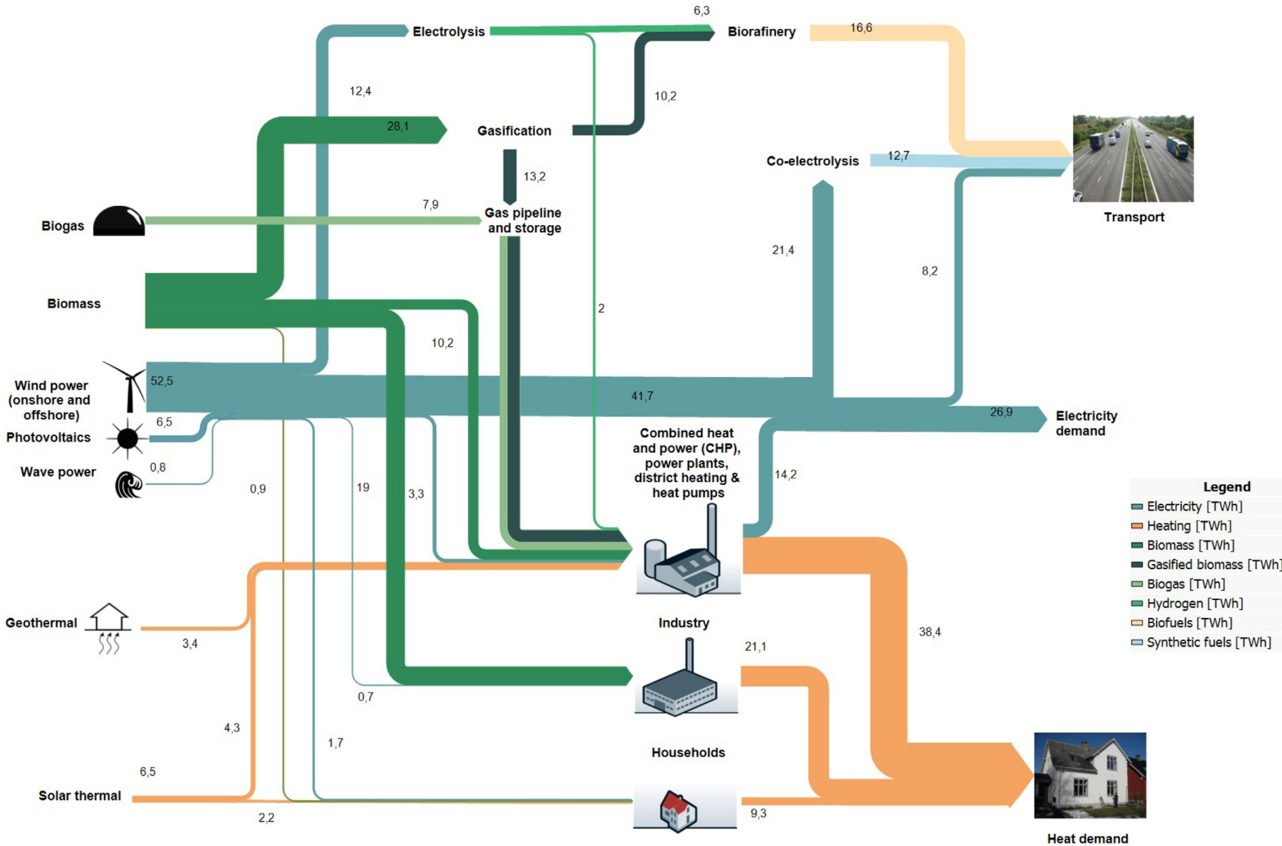

FIGURE 7.24 Sankey diagram of the CEESA 2050 100 percent renewable energy scenario.

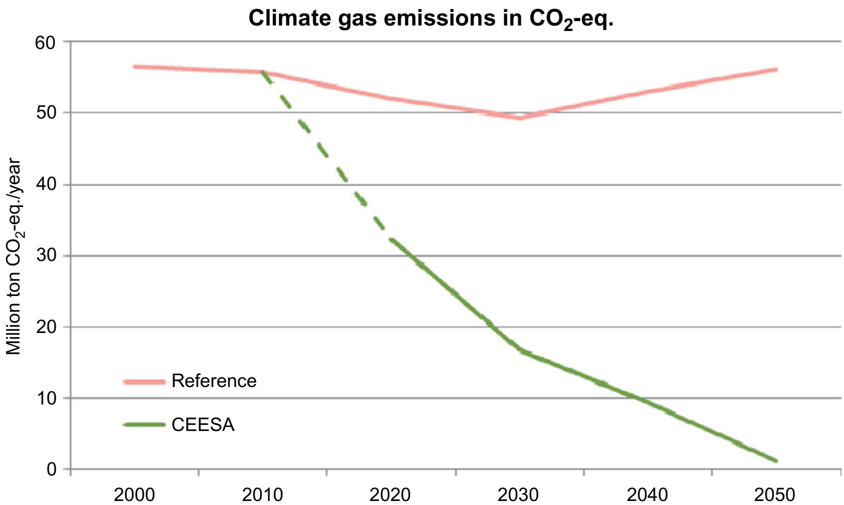

FIGURE 7.25 Emissions of greenhouse gases in CEESA.

balanced. To achieve this balance, a smart energy systems approach has been applied in the following way.

The integration of sectors is very important in 100 percent renewable energy systems to increase fuel efficiency and decrease costs. The first, and most important, step is the integration between the heating and the electricity sectors. In Denmark, this is already implemented to a large extent, and approximately 50 percent of the electricity demand is produced by CHP plants. This integration requires thermal storages of today's sizes (about 8 hours of average production), a boiler, and district heating networks to enable the flexible operation of the CHP plants, as already implemented in the Danish energy system. This can reduce the fuel consumption and help integrate fluctuating wind power efficiently. As concluded in Chapter 5, around 20–25 percent of the wind power can normally be integrated without significant changes in the energy system. With more than 20–25 percent wind power, the next step in the integration is to install large heat pumps. In the CEESA scenarios, a significant amount of onshore and offshore wind power is installed by 2020. By then, approximately 40 percent of the electricity demand can be covered by these sources.

This results in some imbalance in the electricity grid, and heat pumps alone are not able to ensure the balance. The transportation sector needs to be integrated into the energy system with more than 40–45 percent wind power. As a consequence, some electric vehicles are implemented and flexible demand is included in households and industry. This, however, is not sufficient. Thus, small amounts of electrolyzers based on known alkaline technology are also implemented to facilitate wind power integration and for the production of bio-DME/methanol in combination with gasified biomass. This also enables the integration of larger amounts of renewable energy into the transportation sector.

In 2030, a larger proportion of electric vehicles are included and it is assumed that they are able to charge according to a price mechanism. To make sure that electric vehicles can fulfill this function, the low-voltage grid needs to be enforced in some areas. The electricity production from onshore and offshore wind power in combination with PVs is then approximately 60 percent in 2030.

In CEESA 2050, more and new technologies are necessary to make sure that the renewable energy is integrated efficiently into the system and that fossil fuels are being replaced totally. Hence after 2030, the share of electrolyzers for hydrogen production for bio-DME/methanol is gradually increased to provide larger amounts of liquid fuels to the transportation sector, while the electrolyzers themselves are also more efficient. Also, carbon capture is utilized to produce syn-DME/methanol without using biomass.

In the CEESA 2050 energy system, gasified biomass and gas grid storages are also utilized in combination with the electric vehicles, fuel production in the transportation sector, and the district heating systems. This creates an energy system in which smart energy systems are integrated and the storage options are used in combination to enable the final scenario.

The CEESA project has taken a closer look at the balancing of gas supply and demand. The hourly activities of all gas-consuming units, such as boilers, CHP, and power plants, as well as production, such as biogas and gasification (syngas) units (including hydrogenation), have been calculated and analyzed regarding the need for import/export, gas storage, or flexibility and extra capacities in the gas-producing units. This analysis is reported for the CEESA 2050 scenario in the following.

First, the annual need for import/export was calculated in the case of no gas storage and no extra capacities in the production units. Then, similar analyses were made with storage capacities gradually being increased from zero to 4000 GWh. In all scenarios, the need for import is equal to the needed export on an annual basis, since the systems are designed to have a net import of zero. However, the need for import/export decreases along with increases in the domestic storage capacity. The results are shown in Figure 7.26, which indicate that a storage capacity of about 3000 GWh is able to completely remove the need for import/export.

The current Danish natural gas storage facilities have a gas content of 17,000 GWh in Stenlille in Jutland and 7600 GWh in Lille Torup in Zealand. The work content of the storages is smaller, approximately 6500 and 4800 GWh, respectively. This means that the total current storage capacity assuming natural gas quality is 11,350 GWh. If we assume that the gas quality in the entire grid is lowered to biogas standard, the storage would be reduced to approximately 6800 GWh, as the capacity is reduced by 40 percent. As illustrated in Figure 7.26, this indicates that the current storage capacity is more than twice as large as required in the CEESA 2050 scenario, even when assuming no extra capacity at the gasification plant, i.e., no flexibility in the production of syn-gas.

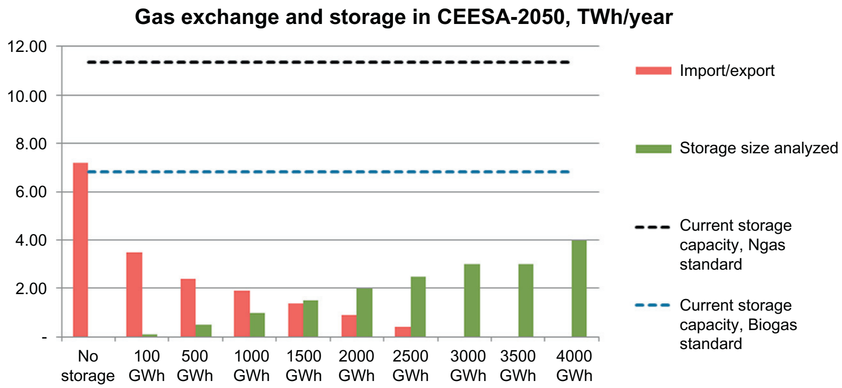

FIGURE 7.26 Annual gas exchange and storage analyses in CEESA 2050 in TWh/year.

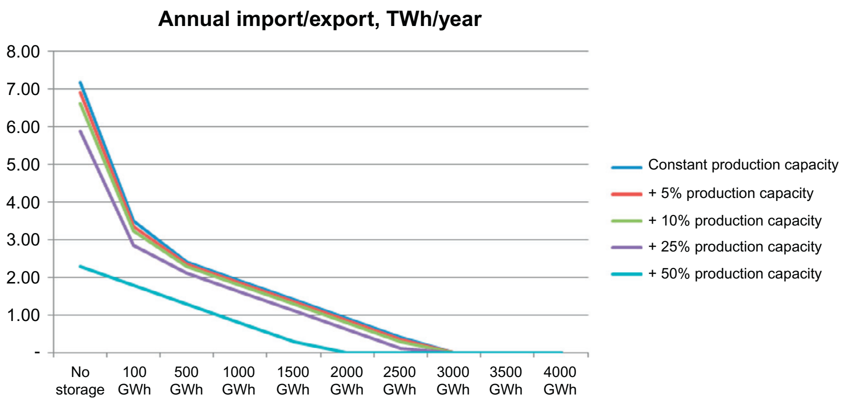

FIGURE 7.27 Annual gas exchange and storage analyses in CEESA 2050 in TWh/year and with different levels of surplus capacity.

Next, to analyze the influence of adding flexibility and extra capacity to the gas-producing units, the analysis of gas storage was repeated while gradually increasing the production capacities as illustrated in Figure 7.27. As can be seen, an increase in production flexibility and capacity decreases the need for storage capacities. In the CEESA 2050 scenario, it was chosen to include 25 percent overcapacity in combination with a storage capacity above 3000 GWh.

One important learning outcome from the hourly analysis of the complete system including both electricity and gas balances is that relatively cheap gas storage capacities (which in the Danish case are already there) can be used to balance the integration of wind power into the electricity grid. Consequently, in the CEESA 2050 scenario, it is possible to decrease excess electricity production to nearly zero at the same time as high fuel efficiencies are achieved by using heat and gas storages. No electricity storage is included and, as already explained in Chapter 5, investments in electricity storage would not be profitable due to the very limited hours of utilization. Furthermore, it would not be efficient, either. The reason why heat and gas storage is more effective than electricity storage is that electricity has to be converted into heat and gas anyway because of the demand for heat and fuels in the transportation sector.

Cost and Job Estimates Based on Concrete Institutional Economics

CEESA is implemented over a period from now until 2050 by continuously replacing technologies, buildings, and vehicles when their lifetime expires. Hence, many of the elements of the current energy and transportation systems in society will need to be replaced even if the scenarios in CEESA are not implemented. Therefore, as a point of departure of this study, the expenses included are calculated as the extra costs generated through investment in better facilities in comparison to the reference energy system. However, exceptions to this may be seen.

The socioeconomic costs are calculated as annual expenses in each of the years 2020, 2030, and 2050, including an interpolated approximation for 2040. The annual costs in CEESA's energy systems are compared with the costs of the reference in each of the applicable years. The costs are categorized as fuel costs, operation and maintenance costs, and investment costs. The investment costs are transformed to an annual cost using a real interest rate of 3 percent. Furthermore, the investment costs have been further divided into investment costs in the energy sector and extra investment costs in the transportation system. The transportation investment costs included are additional to the annual investment already made in the current (2010) system (approximately 28 billion DKK in road and rail). The economic analyses are based on the latest assumptions regarding fuel prices and CO_2 quota costs, which were defined by the Danish Energy Agency (2011). Three fuel price levels are used. The middle price level is based on current fuel price projections for 2030, which correspond to an oil price of 113 USD/barrel according to the Danish Energy Agency (2010 prices). The high fuel price is based on the prices in the spring/summer of 2008 and corresponds to an oil price of 159 USD/barrel (2010 prices). The low price level is based on assumptions which the Danish Energy Agency used in its forecast in July 2008 and corresponds to an oil price of 70 USD/barrel (2010 prices). Calculations are also done with long-term CO_2 quota costs of 35 EUR/ton and 70 EUR/ton for 2030 and 2050, respectively. The energy systems have been analyzed with higher biomass costs than in these assumptions, which does not, however, change the overall results. The CO_2 quota costs do not include all potential costs, such as flooding, for example, but are only anticipated quota costs. If these types of effects are included in the calculation, the energy systems in CEESA will have an economic advantage compared to the reference energy system.

As illustrated in Figure 7.28, a first result of the work in CEESA is that the total annual energy and transportation system costs can now be quantified to approximately 170 billion DKK/year. As illustrated, the costs of the reference

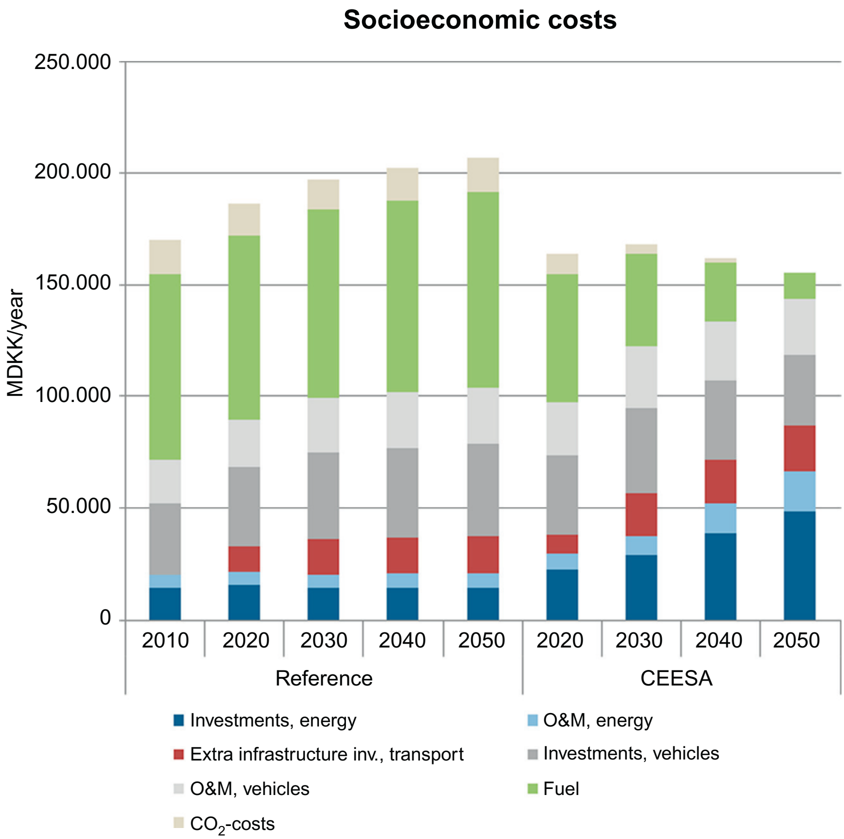

FIGURE 7.28 Socioeconomic costs in the reference energy system and in CEESA from 2010 to 2050. Extra infrastructure costs are relative to 2010 total costs.

increase gradually. This is mainly due to increased costs in the energy system and also due to the investments required in road infrastructure and new vehicles, which are necessary to meet the high increase in the transportation demand. In CEESA, the investment costs increase significantly; however, for the energy and transportation systems, these infrastructure investments are necessary to improve the efficiency of the technologies utilized, to reduce demands, and to consequently reduce the demand for fuel. Since the savings associated with these investments are larger than the initial investments, there is an overall decrease in costs in the CEESA scenarios. In conclusion, the 2020 energy and transportation systems in CEESA are more than 20 billion DKK less costly than in the reference energy system. This means that, by implementing known technologies, it is possible to implement changes that provide lower socioeconomic costs than the current energy and transportation systems. In the longer term, the costs of the CEESA scenario are rather stable; however, large investments are made to meet a 100 percent renewable energy system. The CEESA 2020 energy and transportation systems even have lower costs than the current systems (approximately 7 billion DKK). Continuing the business-as-usual path will only enhance the socioeconomic savings achieved by changing to a renewable energy system combined with energy savings.

The CEESA scenarios also propose energy systems that are more robust to fluctuations in fuel prices. It is worth noting that Danish society currently spends 50–100 billion DKK/year (7–15 billion EUR/year) depending on whether the fuel costs are low or high (the high costs represent real costs experienced in 2008). In the future, one must expect that the world will continue to experience fluctuating fuel prices—neither constantly high nor constantly low. Hence, energy and transportation systems less dependent on fuels such as the systems proposed in CEESA are less vulnerable. In addition to the potential economic savings in the renewable energy system scenarios mentioned previously, society can benefit from savings related to health costs, commercial potential, and extra employment effects.

As a starting point for the estimation of the employment effect, the annual costs in the reference energy system and the CEESA scenarios are divided into investments and operations. An implementation of the CEESA scenarios includes increasing investment costs and increasing costs for biomass, but also lower costs for fossil fuels. These changes will enable higher Danish employment levels while also improving the balance of payments. The effects on the amount of jobs in the energy sector and the effects on the balance of payment can be further increased if the commercial potential in the form of increased exports is also realized.

In the CEESA scenarios, expenditures on fuels are reduced while expenditures on operation and maintenance are increased. CEESA also involves a heavy shift from the imports of fuel to investments including an increase of more than a quarter of a trillion, which is dispersed between now and 2050. For each cost type, an import share has been estimated based on experiences from previous collections of foreign exchange and employment data for investments in energy facilities, infrastructure, and buildings. In relation to the previous data, a general upward adjustment of the import share has been done, as this, from experience, is known to increase. The data sources and methodology are the same as in Chapter 6.3 regarding the economic crisis and infrastructure investment.

Employment effects have been estimated on the basis that two jobs are created for each million DKK based on the share that is left after removing the import share. This includes derived jobs in the finance and service sectors. It should be emphasized that these estimates are subject to uncertainties and, again, it is emphasized that they are based on adjusted figures from previously collected data. The extra employment created in Denmark by the implementation of the CEESA scenarios compared with the reference has been estimated by the use of these methods and is assumed to correspond to approximately 20,000 jobs. Jobs will be lost in the handling of fossil fuels, but jobs will be created through larger investments in energy technology than in the reference, as well as larger investments in energy savings. In the reference energy systems, large investments are made in roads, while in the CEESA scenarios, these are replaced by jobs and investments in rail infrastructure.

It is important for a number of reasons to place the large employment effort as early as possible in the period. The first reason is that the labor force as a share of the total population is falling in the entire period to the year 2040 and, therefore, the largest labor capacity to undertake a change of the energy system is present in the beginning of the period. The second reason is that the Danish North Sea resources will run out during the next 20 years. Hence, it is important to develop the energy systems and changes as early as possible in the period.

The above-mentioned effects on employment do not include job creation as a result of increased exports of energy technology, i.e., the commercial potential. These advantages will be an additional benefit of implementing the CEESA scenarios. With the assumption of a 50 percent import share, an annual export of 200 billion DKK would generate up to 170,000 jobs, depending on the location of the exports without an ambitious implementation of the scenarios, the extent of unemployment, and the potential employment of these people in other export trades. In relation to this, it should be noted that all other things being equal, a share of Danish labor will be made available as the oil and gas extraction in the North Sea comes to an end. In addition, the energy system is more effective and also less vulnerable to fluctuations in energy prices. Hence, this can increase the competitiveness of Danish society and of Danish businesses.

5. THE POTENTIAL OF RENEWABLE ENERGY SYSTEMS IN CHINA[4]

This Section Is Courtesy of Guest Writers Wen Liu and Xiliang Zhang

This section is based on Liu, Lund, Mathiesen, and Zhang's (2011a) article "Potential of Renewable Energy Systems in China", which discusses the perspectives of renewable energy systems in China and analyzes whether the methodologies described in previous parts of this chapter, or similar methodologies, can be applied to China to create a future renewable energy system.

Today, China's energy consumption has influenced the energy demand on a global scale significantly, since China has become both the largest energy consumer and CO_2-emitting country in the world. This dramatically increasing energy consumption means that the domestic energy production cannot meet the demand. By 1993, China became a net crude oil importer, and only 19 years later, in 2012, the Chinese net oil imports reached 285 Mtoe. Thereby, China ranks

4. Excerpts reprinted from *Applied Energy* 88, Liu, Lund, Mathiesen, and Zhang, "Potential of Renewable Energy Systems in China", pp. 518–525 (2011a), with permission from Elsevier.

as the world's second largest oil importer after the United States and accounts for about 59% of the global oil demand. China became a net importer of primary energy in 1997 and, since then, energy security and the maintenance of the balance of energy production and consumption have been vital problems in the country. The country's long-lasting fossil fuel-dominated energy structure, which is mainly based on coal, brought severe challenges to the goal of maintaining environmental protection and decreasing greenhouse gas emissions.

Given the fact that the amount of fossil resources is finite, and focusing on the aims to fill the gap between domestic energy production and consumption as well as to maintain high economic growth, it is essential and meaningful for China to integrate renewable energy into future sustainable energy development strategies. China is endowed with an abundant reserve of renewable energy sources, which are currently underexploited and which offer a significant potential for renewable energy system development.

Through a review of the Chinese energy supply and consumption in the past three decades, it can be concluded that the share of renewable energy has increased steadily and has begun to play a role in the energy structure. However, the energy supply and consumption structure, which is dominated by fossil fuels, especially coal, has basically remained the same. Although China has made some achievements in decreasing the energy intensity, the energy demand in China is expected to continue to grow, driven by the country's highly energy-intensive economy and strong GDP growth. Meanwhile, energy conservation is an absolutely necessary strategy for China to stabilize its energy demand.

In Liu, Lund, Mathiesen, and Zhang (2011a) a review is made of potential renewable energy sources in China and, as a follow-up, Liu, Lund, and Mathiesen (2011b) highlight some of the barriers to and potential for the large-scale integration of wind power into the existing Chinese energy system. Similar to the case of Denmark shown in Table 7.2, the potential for renewable energy sources in China has been categorized into electricity, heat, and biomass fuel (see Table 7.6). It should be noticed that the potential listed here is shown as a range. With the expected future technological, economic, and social development, the potential may increase, as, e.g., geothermal energy and biomass fuels are not considered here.

In Figure 7.29, the potential for renewable energy sources is compared with the present gross energy consumption as well as the energy demand prediction for China in 2015 and 2030. In Figure 7.30, the potential for electricity supplied by renewable energy is compared with the electricity consumption in 2011 and 2030. The minimum potential for renewable energy sources in China is smaller than the country's current energy consumption, while the maximum potential for renewable energy sources is larger than the estimated energy demand in 2030. A more optimistic tendency appears in the comparison between the potential renewable energy sources of electricity and the future electricity demand. The minimum and maximum potential for electricity supplied by renewable energy sources exceed both the current electricity demand and the

TABLE 7.6 Potential renewable energy sources in China

Renewable energy sources	Unit	Potential
Wind	TWh/yr	7644-24700
Photo Voltaic	TWh/yr	1296-6480
Tidal energy	TWh/yr	>620
Wave	TWh/yr	>1500
Hydro power	TWh/yr	2474-6083
Total electricity	TWh/yr	13434-39383
Solar thermal	PJ/yr	6000-30000
Geothermal	PJ/yr	1000
Total heat	PJ/yr	7000-31000
Straw	PJ/yr	5561-6440
Wood	PJ/yr	4332-5210
Waste (combustible)	PJ/yr	1170-3454
Biogas	PJ/yr	1258-2517
Energy crops	PJ/yr	3660-10500
Total biomass fuel	PJ/yr	15981-28121

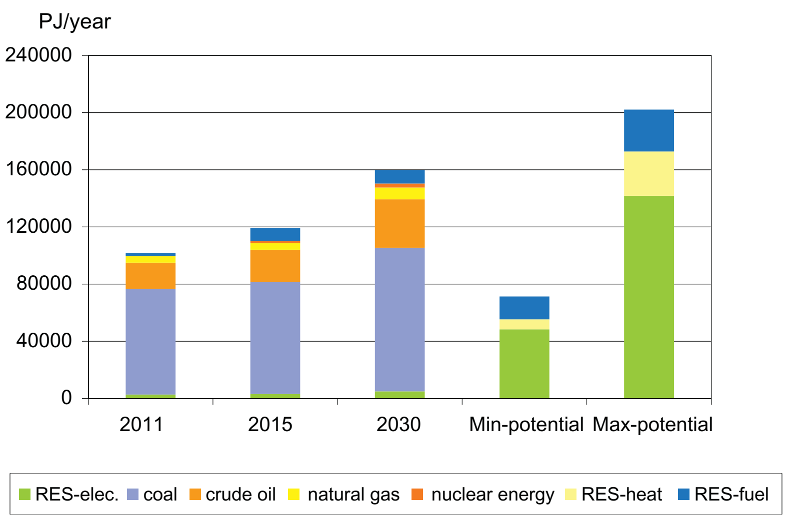

FIGURE 7.29 Potential for renewable energy sources in China compared to the primary energy consumption.

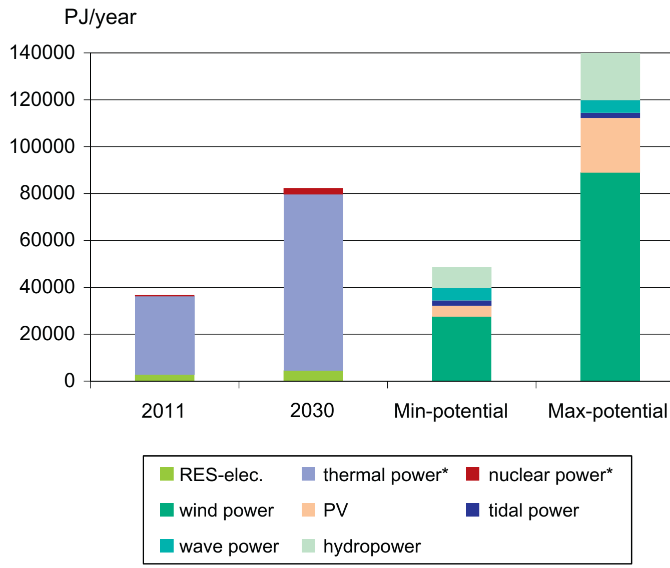

FIGURE 7.30 Potential for renewable energy electricity in China compared to the electricity consumption (*fuel equivalent: electricity multiplied by 3).

demand in 2030, respectively. This shows the possibility for renewable energy sources to cover the future energy consumption in China.

The total amount of potential renewable energy sources per capita in Denmark and China are 137 and 103 GJ/capita, respectively. Figure 7.31 presents the result of the comparison. As shown, although the territories, population, and

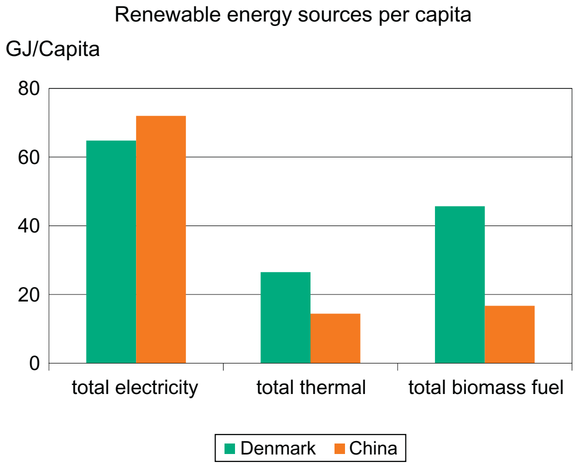

FIGURE 7.31 Comparisons of renewable energy sources per capita and per area in Denmark and China.

renewable energy sources differ significantly, the total amount of potential renewable energy sources per capita is less than twice as high in Denmark as in China. The climate situation in China is more suitable for agriculture, but Denmark owns more potential biomass fuel per capita. The Danish cultivated land area is about 4900 square meters per capita, corresponding to four times the cultivated land area per capita in China.

Three kinds of indexes are compared between China and Denmark in Table 7.7. As illustrated, the energy demand per capita was distinctly lower in China than in Denmark in 2011. The electricity demand per capita in China was about half of that in Denmark, and the heat demand per capita in China was only about one-eighth of that in Denmark. However, in relation to energy intensity, one GDP unit in China required more energy consumption than in Denmark. The gross energy consumption per GDP in China was about five times higher than in Denmark. In terms of the replacement of fossil fuel by renewable energy sources, the shares of renewable energy in the energy consumption and the domestic energy supply in China were both lower than the shares in Denmark.

The substantial renewable energy supply potential and the low energy demand per capita, as well as distinct differences in energy efficiency and renewable energy deployment, give China the opportunity to design and approach future renewable energy systems.

In conclusion, China is facing two severe challenges of maintaining the energy balance as well as handling environmental pollution. Both challenges are rooted in

TABLE 7.7 Comparison of energy demand and energy intensity in China and Denmark

Type	Index (2011)	Unit	China	Denmark
Energy demand	Primary energy supply per capita	GJ/ capita	65.39	159.40
	Gross Energy Consumption per capita	GJ/ capita	75.16	144
	Electricity demand per capita	*GJ/ capita*	*10.23*	*20.30*
	Heat demand per capita	*GJ/ capita*	*2.35*	*18.82*
Energy intensity	Primary energy supply per GDP[a]	TJ/ Million USD	12.75	2.65
	Gross Energy Consumption per GDP[a]	TJ/ Million USD	14.55	3.03
Renewable energy	Share of Total Gross Energy Consumption	%	8.4	17.0
	Share of Total Domestic Electricity Supply	%	19.3	29.3

[a] *2011 exchange rate*

the inappropriate economic and energy structures that have changed little in the past three decades. Energy demands in China will continue to grow driven by the country's highly energy-intensive economy and strong GDP growth. In order to fill the increasing gap between domestic energy production and consumption and to change the inappropriate energy structure, it is essential and meaningful to integrate renewable energy into future energy systems in China.

Today, renewable energy is at a rapid development stage; however, compared with the potential, renewable energy is presently underexploited in China. There is much room and promise for developing large-scale renewable sources in the future energy system, especially along with technological and economic development.

There is no obvious difference in the renewable energy resources per capita between China and Denmark. However, the energy demand per capita in China is distinctly lower compared with Denmark and the energy efficiency gap between the two countries is distinct. The methodologies used to design a 100 percent renewable energy system for Denmark and to analyze typical technological changes in terms of energy conservation, energy efficiency, and renewable energy integration are applicable to China. On this basis, it is reasonable to propose the issue for discussion and conduct further analyses of a 100 percent renewable energy system in China.

6. REFLECTIONS

Reflections on the analyses of 100 percent renewable energy systems in this chapter are made regarding the principles and methodologies, as well as the implementation of renewable energy systems in Denmark and other countries.

Principles and Methodologies

From a methodology point of view, it can be concluded that the design of future 100 percent renewable energy systems is a very complex process. On the one hand, a broad variety of measures must be combined to reach the target, and on the other, each individual measure has to be evaluated and coordinated with the new overall system. In the IDA Energy Plan case, this process has been implemented by combining a creative phase involving the inputs of a number of experts and a detailed analytical phase with technical and economic analyses of the overall system, providing feedback on the individual proposals. In a back-and-forth process, each proposal was formed in such a way that it combined the best of the detailed expert knowledge with the ability of the proposal to fit well into the overall system, in terms of technical innovation, efficient energy supply, and socioeconomic feasibility. In the CEESA case, the process was carried out in collaboration with approximately 25 researchers from five Danish universities and companies with quite different backgrounds and fields of expertise. A key focus in the project was the biomass resources available for Denmark, in combination with the identification of transportation fuel pathways to add to the design of 100 percent renewable energy systems with a smart energy systems approach; i.e., trying to identify and make use of the synergies between the different subsystems to achieve an optimal solution for the overall system as well as for the individual sectors.

Conclusions and Recommendations

Based on the cases of the LACCD and Denmark, this chapter presented a series of studies on the challenges and perspectives of converting present energy systems into a 100 percent renewable energy system. Moreover, the perspective of applying the methodologies to China was discussed. The three studies of Denmark each include two or three alternatives that are based on either biomass or wind power. The main data of all eight alternatives are listed in Table 7.8.

TABLE 7.8 Main Data of the Eight Alternative 100 Percent Renewable Energy Systems

	First Approach		IDA Energy Plan (IDA 2050)			CEESA 100 Percent RES Scenarios		
	EV/ H_2FC	Biofuels	Biomass	Main	Wind	Conserv.	Ideal	CEESA
Demands (TWh/year)								
Electricity	37.0	37.0	30.2	30.2	30.2	26.9	26.9	26.9
Heating (including process)	56.8	56.8	44.5	44.5	44.5	68.8	68.8	68.8
Transportation (electricity)	17.8	—	5.0	5.0	5.0	27.7	57.6	39.9
Transportation (biomass)	—	50.7	24.9	24.9	24.9	31.1	0	14.3
Primary Energy Supply								
Biomass (PJ/year)	180	325	333	270	200	331	206	237
Solar thermal (PJ/year)	8	8	19	19	19	23.3	23.3	23.3
Geothermal (PJ/year)	—	—	—	—	—	9.8	12.5	12.4
PV (GW installed)	5	5	1.5	1.5	1.5	—	7.5	5
Wave (GW installed)	—	—	1	1	1	—	1	0.3

Seen in relation to the Danish case, the conclusion is that a 100 percent renewable energy supply based on domestic resources is physically possible and that the first step toward 2030 is feasible for Danish society.

All three studies show that, when reaching a high share of intermittent resources in combination with CHP and savings, the development of renewable energy strategies becomes a matter of introducing and adding flexible energy conversion and storage technologies and designing integrated energy system solutions. The first study identifies specific improvements of system flexibility as essential to the conversion of the energy system into a 100 percent renewable energy system. First, oil for transportation must be replaced by other sources. Given the limitations on the Danish biomass resource, solutions based on electricity become key technologies. Moreover, these technologies increase the potential for including wind power in the ancillary services to maintain the voltage and frequency of the electricity supply.

The next improvement involves including small CHP stations in the regulation as well as adding heat pumps to the system. These technologies are of particular importance because they provide the possibility of changing the ratio between electricity and heat demand while maintaining the high fuel efficiency of CHP. The third key point is to add electrolyzers to the system and, at the same time, create the basis for further inclusion of wind turbines in the voltage and frequency regulation of the electricity supply.

Based on the implementation of these three key technological changes, the analyses of the first study show that the Danish energy system can be converted into a 100 percent renewable energy system, by combining 180 TJ/year of biomass with 5000 MW of PV and 15–27 GW of wind power. In the reference, 27 GW of wind power is necessary, while in combination with savings and efficiency improvements, the required capacity is reduced to around 15 GW. Thus, the first study emphasizes the importance of implementing energy conservation as well as efficiency improvements in the supply sector.

In the first study (IDA Energy Plan), electric or hydrogen fuel cell vehicles are introduced in the entire transportation sector. If this solution is replaced with biofuel-based transportation technologies, the need for biomass resources may be nearly doubled. Consequently, the first study also emphasizes the importance of further developing electric vehicle technologies. Moreover, it indicates that biofuel transportation technologies should be reserved for the areas of transportation in which the electricity/hydrogen solution proves insufficient.

The second study (IDA Climate Plan) goes a step further, especially regarding energy conservation and the design of a coherent transportation solution. The study implements energy conservation measures at a high level, and, as a consequence, energy demands will decrease compared to the first study. On the other hand, the transportation technologies applied in the second study are much more differentiated and include the combination of electric vehicles and biofuel technologies, which increases the demand compared to the first study. Regarding the design of a suitable transportation solution, it must, however, be emphasized that both studies are far from coherent or optimized. Nevertheless, the studies do provide a sufficient overview of the principal possibilities.

The second study shows that Denmark can convert into a supply of 100 percent renewable energy constituted by 280 PJ/year of biomass, 19 PJ of solar thermal, 2500 MW of wave and PV, and 10,000 MW of wind power. It should be emphasized that the 280 PJ/year of biomass does not include all conversion losses. However, the study shows how biomass resources can be replaced by more wind power, and vice versa, and points out that Denmark will have to consider to which degree the country should rely mostly on biomass resources or on wind power. The solution based on biomass will involve the use of present farming areas, while the wind power solution will involve a large share of hydrogen or similar energy carriers leading to certain inefficiencies in the system design.

The third study (CEESA) adds to the two previous studies as it goes into more detail with the discussions and analyses of several important issues. First, a further step has been taken in the discussion and identification of suitable transportation fuel pathways, and some of the potential pathways have been quantified and integrated into the overall identification of a roadmap toward a 100 percent renewable energy system in 2050. A DME/methanol-based pathway has been used for the concrete calculations of the scenarios to illustrate the principle of using biomass resources in combination with electrolyzers to replace fossil fuels in the transportation sector in the short term. In the longer term, carbon from other sources than biomass is used to replace larger amounts of fossil fuels, without putting further strain on the biomass resource. It is too early to know if a liquid fuel DME/methanol solution is better than, for instance, a gas methane solution or a combination. However, approximately the same energy balances can be achieved with a gas solution.

Next, the study furthers the discussion on the influence of technological development. Three different scenarios, each representing different assumptions regarding the availability of technologies, are compared. The analyses indicate that especially technological development in electric cars, hybrid vehicles, and vehicles to utilize either DM/methanol and/or methane gas becomes essential. Moreover, bio-DME/methanol or methane production technologies (including biomass gasification and electrolyzers) are important in the short or medium term and should be supplemented by carbon capture technologies in the longer term.

Finally, the study emphasizes and illustrates the importance of applying a smart energy systems approach to the identification of a suitable 100 percent renewable energy systems design. In particular, the study combines the analysis of gasified biomass and gas grid storages, in combination with the electric vehicles and fuel production in the transportation sector, as well as the district heating systems. This creates an energy system into which smart energy systems are integrated and the storage options are used in combination to enable the final scenario. The analyses ensure that there is an hourly balance in the gas supply and demand, while the results indicate that the capacity of the current Danish salt cavern storage facilities is more than sufficient to facilitate this balancing.

All three studies apply the EnergyPLAN energy systems analysis tool and together they illustrate how such a tool can be used to design 100 percent renewable energy solutions, as well as form the basis for an evaluation of systems based on the use of concrete institutional economics.

Chapter 8

Empirical Examples

Choice Awareness Cases

With contribution by Paul Quinlan

This chapter returns to the discussion of the theoretical framework by presenting a number of cases of energy investments that have occurred since 1982. Choice Awareness strategies have been applied to the specific decision-making processes of these cases. Typically, the cases involve the design and introduction of concrete technical alternatives and/or other Choice Awareness strategies. The cases refer to a large series of publications and documentation mentioned in each section. The overall purpose of the chapter is to deduce what can be learned from the cases regarding the Choice Awareness theses and strategies formulated in Chapters 2 and 3.

The cases use the research method described in Chapter 3. Most cases are based on my personal involvement and that of my colleagues at Aalborg University. Basically, our involvement has had a twofold purpose. First, we intended to raise the awareness of choice in specific situations and thereby help society make better decisions. Second, we wished to observe and learn how different actors react to the existence of alternatives. In that way, the description and promotion of concrete technical alternatives, as well as institutional alternatives in specific decision-making processes, can be regarded as our way of applying a "questionnaire" to the complex system of actors involved in the process. From their reactions, we can observe and learn. Among other aspects, we are able to identify institutional barriers to new energy technologies and thereby form a platform for the design of concrete public regulation measures and institutional alternatives.

The cases are listed chronologically, and they consist of the application of mainly the two first Choice Awareness strategies: the description and promotion of concrete technical alternatives and the use of feasibility studies based on concrete institutional economics. However, as mentioned, the same cases also form the basis for applying the two other Choice Awareness strategies: the design of concrete public regulation measures, including institutional changes, and proposals to improve the democratic infrastructure, as indicated in the coming sections.

The cases in this chapter focus on the descriptions of technical alternatives and socioeconomic evaluations. In the debates, I contributed to this aspect, while my colleague, Frede Hvelplund, contributed to the design of institutional alternatives. However, it should be emphasized that technical alternatives and institutional alternatives create an important synergy and should be seen together. In most of the cases, the description of technical alternatives led to the proposal of some sort of public regulation measures.

In some cases, the institutional proposals are directly related to the case issue, such as in the Aalborg heat planning case in which specific changes in energy taxation were proposed, or in the Biogas case in which a comprehensive series of public regulation measures was designed to implement a scheme of large-scale biogas stations. In other situations, the information from several cases forms the input to the design of comprehensive institutional alternatives. One such institutional alternative has been described in the book by Hvelplund and colleagues (1995) called *Democracy and Change*.[1]

1. CASE I: NORDKRAFT POWER STATION (1982–1983)

The case of Nordkraft power station is basically the story of a decision-making process that in the beginning was based on only one project proposal. It is also the story of how the introduction of a concrete technical and radically different alternative reveals the extent to which the main proposal is linked to existing organizations. It shows the severe institutional barriers that the radically different alternative meets, even though this alternative may provide an environmentally better solution at the same costs. The case description is based on the book *When ELSAM Makes Plans. Aalborg, Brønderslev ... Pieces of the Puzzle* (Lund and Bundgaard 1983)[2] and the article "When ELSAM Taught Aalborg All about Planning" (Lund 1984).[3]

Nordkraft (North Power) was the name of both the power station and the utility company located in the center of Aalborg until approximately 2000. Nordkraft was one of seven similar power stations and companies constituting the joint electricity supply of West Denmark: Jutland and Funen. The cooperative was named ELSAM, which managed the joint financing of the power companies and made the decisions on which company should be the next to implement a new unit.

In 1967, ELSAM decided to build a new unit at Nordkraft. That unit ended up having the most unfortunate life that any power station unit could possibly have. It was built as an oil-fired steam turbine of ~250 MW of electric power,

1. Translated from Danish: *Demokrati og forandring*.
2. Translated from Danish: *Når ELSAM Planlægger. Aalborg, Brønderslev ... brikker i spillet*.
3. Translated from Danish: *Da ELSAM lærte Aalborg om planlægning*.

and it started to produce in August 1973, only a few months before the beginning of the first oil crisis. It continued its production during the time of the two oil crises but was given relatively low priority in the ELSAM cooperation because of high oil prices. In the early 1980s, it was decided to convert the power unit into a coal-fired unit, which meant a substantial extra investment, since the boiler had to be rebuilt and expanded to approximately twice its size. Moreover, coal storage and harbor facilities had to be adjusted. The conversion into coal was completed in the mid-1980s, exactly when oil prices dropped again. The unit was then operated on coal during periods of low oil prices up to around the turn of the century. Then the unit was demolished only a few years before oil prices rose again. The life of this power station unit clearly demonstrates the difficulty of adjusting to shifting oil prices.

The following case is based on the discussion that took place in the early 1980s on whether to convert the unit from oil- to coal-based production.

The "No Alternative" Situation

The first coal unit plans were introduced to the public by ELSAM in 1980, and, consequently, the issue became part of the debate during the city council elections in Aalborg in 1981. The obvious alternative to coal was natural gas from the Danish North Sea, and several city council candidates expressed their preference for natural gas. The national natural gas grid was not yet completed; however, in June 1982, the Danish government and Parliament decided to accelerate the project. Consequently, natural gas became a realistic alternative when the project was discussed in late 1982 and early 1983.

Nordkraft supplied not only electricity, but the power station also supplied heat produced by combined heat and power (CHP) to the district heating of Aalborg city, which the municipality of Aalborg managed. It is important to note that it was a joint ELSAM decision that Nordkraft was an oil-fired station, whereas most of the other power stations in the ELSAM area were coal fired. Consequently, the electricity and heat consumers of Nordkraft did not pay a higher price for fuel than the other power station consumers. Internally, within ELSAM, the power stations defined common average prices of coal and oil, which were used at all power stations. The Nordkraft consumers, consequently, did not personally suffer from the mistake of opening an oil-based unit only a few months before the first oil crisis. The extra costs were shared among all electricity consumers within the ELSAM area.

During the decision-making process, in 1982, ELSAM suggested a change in the contract between the power station and the municipality. The aim of this change was to raise the amount paid by heat consumers if the authorities did not approve the coal project. The political chair of the technical committee of Aalborg, who was also a member of the board of representatives of Nordkraft, suggested to the board of representatives that the price of heating was likely to increase if the authorities did not examine the project proposal (in its present version) in a satisfactory way—presumably implying satisfactory to ELSAM.[4]

Confronted with the threat of increased heating prices, the city council approved the ELSAM coal project (see Figure 8.1). This approval was made without analyzing or describing the natural gas alternative. However, in accordance with Danish Planning law, the physical planning procedure included a public participation phase. In this phase, the city council received 700 written objections

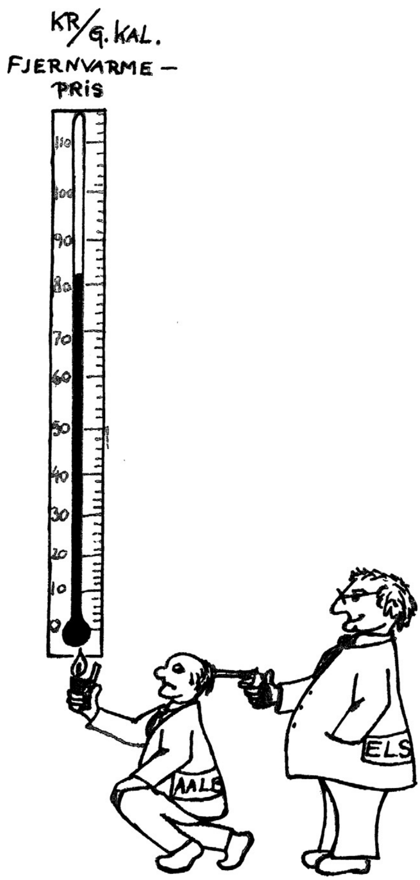

FIGURE 8.1 Drawing from 1983 illustrating the threat from ELSAM against Aalborg to raise the heat prices if the city council did not approve the plans to convert into coal.

4. Translated from Danish: . . . *Nordkrafts formand antydede overfor repræsentantskabet, at en forhøjelse af varmeprisen var sandsynlig, hvis ikke behandlingen af forslaget (i dets nuværende form) hos plan—og miljømyndigheder ikke forløb tilfredsstillende—formentlig underforstået for elsammenslutningen (ELSAM).* Aalborg Stiftstidende, December 16, 1982.

from local citizens, mostly arguing against the environmental problems arising from coal and the lack of proper analyses and suggestions of alternatives.

The local radio station asked the managing director of Nordkraft, P. E. Nielsen,

Could you imagine that the project, which has now really met a lot of resistance, will not be approved—that it will not be implemented?[5]

Nielsen replied,

I cannot imagine which other alternative one would suggest instead.[6]

What the managing director could not do—suggest alternatives—was instead done by local citizens, as illustrated in Figure 8.2.

The Concrete Alternative Proposal

As a member of a local nongovernmental organization (NGO),[7] I participated in the design and promotion of a concrete alternative representing radical technological change. Our motivation was based on our firm belief that the coal project would

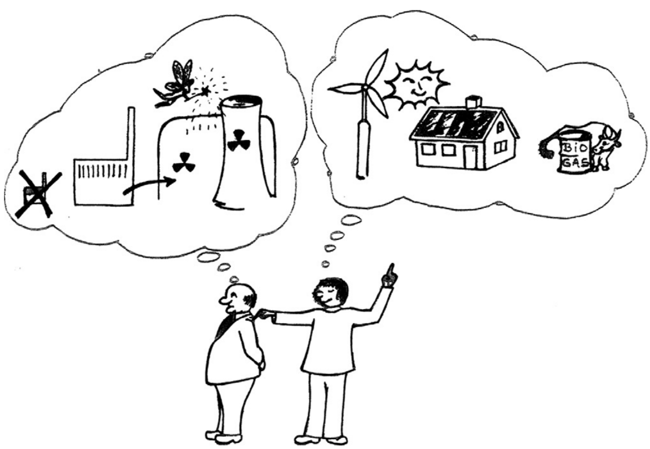

FIGURE 8.2 Drawing from 1983, illustrating the situation in which the managing director of Nordkraft power company needed the help of local citizens in order to be able to imagine any alternatives to coal.

5. Translated from Danish: *Har du fantasi til at forestille dig, at det projekt, som nu altså har mødt en del modstand, at det ikke kommer igennem—at det ikke bliver gennemført*? Nordjyllands radio, April 27, 1983.
6. Translated from Danish: *Jeg har ikke fantasi til at forestille mig, hvad man så vil stille i stedet for*. Nordjyllands radio, April 27, 1983.
7. The NGO, called Aalborg Energy Office, was the local group of three national energy organizations and movements: Cooperating Energy Offices, the Danish Antinuclear movement (OOA), and the Danish Organization for Renewable Energy.

increase pollution, anticipate the upcoming heat planning in Aalborg, and deteriorate the possibilities of introducing renewable energy (Lund and Bundgaard 1983).

The alternative, which is illustrated in Figure 8.3 in a sketch from 1983, consisted of three elements. The first was to convert Nordkraft into a natural

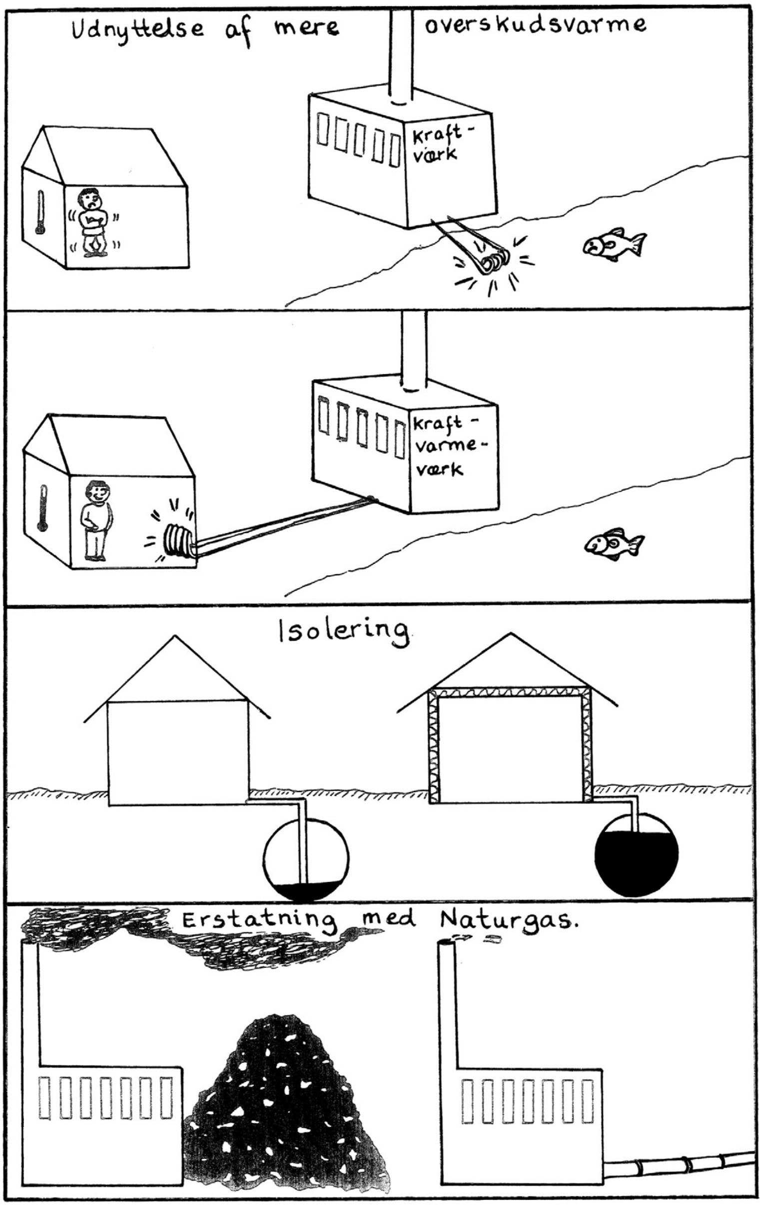

FIGURE 8.3 Drawing from 1983 illustrating the alternative to the investment in a coal-fired Nordkraft.

gas-fired station. This conversion would cost only 20 million DDK compared to the estimated cost of 640 million DKK of the conversion to coal. The coal project required a completely new boiler double the size of the old one, while the natural gas solution could use the existing boiler. The next step was to insulate approximately 8000 houses and thereby save 1600 TJ of expensive gas oil in houses outside the district heating area. Finally, the plan was to invest in small CHP stations on existing district heating grids in small towns and villages in Northern Jutland. This investment would make it possible to expand the CHP production. Not all electricity production at Nordkraft was used to the benefit of CHP, simply because of the lack of district heating demand compared to the capacity of Nordkraft. Consequently, by replacing part of the production by small CHP units, one could expand the amount of heat produced by CHP, thereby reducing fuel consumption.

The investments of the alternatives amounted to only 320 million DKK compared to 640 million if Nordkraft was to be converted to coal. Moreover, the alternative would *reduce* the primary energy consumption by 3300 TJ/year, partly by energy conversion and partly by CHP expansion, while the coal project would *replace* almost 6000 TJ/year. Whether the 3300 TJ savings would prove cost-effective compared to the replacement of 6000 TJ/year of oil by coal naturally depended on fuel prices. In the promotion of the alternative, the actual fuel prices of the previous 12 years (from 1970 to 1982) were applied to the coming future period, and in this calculation, the alternative came out with an economically better result than the coal project, even when environmental benefits were not included.

Later, I made a calculation on the basis of actual oil and coal prices between 1985 and 2000, both years included (see Figure 8.4). The cost of converting Nordkraft into a coal-based production, 640 million DKK, has been compared to the economic benefit of replacing an annual amount of 6000 TJ of oil by coal.

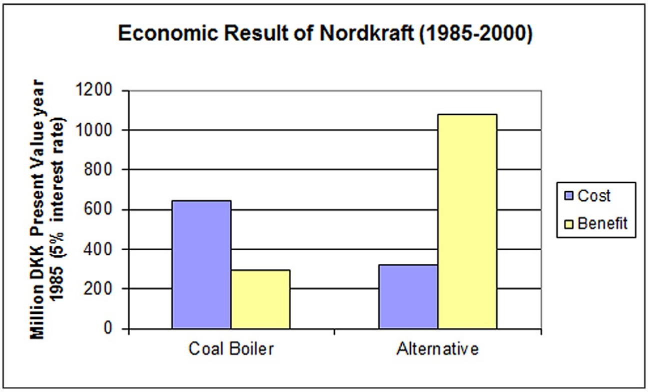

FIGURE 8.4 Feasibility of the conversion of Nordkraft to coal compared to the alternative of CHP and energy conservation. Investment costs are compared to a present value of annual savings between 1985 and 2000 based on actual coal and oil prices.

The benefit has simply been identified as the actual price difference between coal and fuel oil when delivered to a Danish power station. To compare investment costs and savings, the annual savings were converted into the present value of 1985 using an interest rate of 5 percent. In the same way, the benefits of saving an annual amount of 1700 TJ of fuel oil and 1600 TJ of gas oil were identified for the alternative.

The calculation was not based on actual production data of Nordkraft, and the differences in operation costs between coal and fuel oil were not included. In the alternative, the price of natural gas was determined at the level of the fuel oil price. Thus, the calculation represents an estimate. Nevertheless, the result clearly indicates that the project of converting Nordkraft to coal was hardly beneficial to society, the power companies or the electricity consumers. Meanwhile, if it would have been possible to implement the alternative, the saved fuel would have made such a project cost-effective.

Conclusions and Reflections

In the end, Nordkraft was converted into a coal-fired station. The following observations can be made from the case: the initial proposal put forward by the power company was a *one, and only one, alternative* proposal. The proposed technology fit well into the existing organizations of the power companies. No radically different alternatives were presented to the public when the proposal was to be approved.

City council members expressed their preference for an alternative based on natural gas, but such an alternative did not even form part of the basis for the decision-making process. Local citizens seemed to be the only ones who were free to describe and promote a concrete technical alternative. The citizens analyzed this alternative, indicating that it would prove cost-effective compared to the project of conversion to coal. Since then, a calculation based on the exact fuel prices of the lifetime of Nordkraft coal power station has shown that the local citizens were right when they claimed that their alternative was competitive. Actually, it was preferable both in terms of environment and economics.

The main point to be deduced from the preceding observations is that, in this case, the institutional set-up could not identify and implement the best alternative by itself. The alternative entailed a radical technological change; that is, it could not be implemented without introducing changes in institutions, including the existing organizations.

The discourse of the power companies focused on the optimization of the fuel use within the existing technical and organizational set-up. The identification of alternatives that represented radical technological change was not a part of their interests or perception of reality, and even if it was, the implementation of such alternatives would be out of their reach, since it would involve investments in the insulation of private houses as well as CHP units in district heating companies owned by others.

The discourse of the city council focused on maintaining low district heating prices. Moreover, the council also had to manage urban and environmental concerns in the physical planning process. Again, the implementation of insulation and CHP outside the municipality was out of their reach. On the other hand, natural gas was an option within the reach and perception of the city council. However, the city council did not have the power or the resources to ensure a proper analysis and description of such an alternative when faced with the risk of substantially increasing district heating prices.

The proposal of radically different technological alternatives had to come from citizens outside the power companies and the city council. The existence of alternatives could raise public awareness of the fact that, from a techno-economic point of view, choice *did* exist. As a result, 700 citizens claimed that alternatives should be discussed and included in the debate. However, given the institutional set-up, such radically different technological alternatives could not be implemented. Institutional changes had to be implemented at a higher level.

2. CASE II: AALBORG HEAT PLANNING (1984–1987)

The case of Aalborg Heat Planning is the story of how the municipality by law was forced to choose an inconvenient solution and how the municipality sought to exclude this choice from the decision-making process. The inconvenient solution represented a radical technological change in the direction of small CHP plants and renewable energy as opposed to coal. The solution was "inconvenient" because it would mean higher heating prices for the consumers. However, it would also mean a better environment, and, in an overall socioeconomic evaluation (as defined by the authorities), it proved more cost-effective to Danish society than the other alternatives. The law stated that the municipality had to choose the alternative with the best socioeconomic feasibility. The case description is based on the books *Low Taxes on Coal Spoil the Heat Planning—A Commented Collection of Documents from the Heat Planning Process in Aalborg* (Hvelplund and Lund 1988)[8] and *Energy Taxation and Small CHP Plants* (Lund 1988).[9]

The case illustrates some of the basic mechanisms of excluding technical alternatives from the public discussion. However, it also shows how the description and promotion of concrete technical alternatives can lead to the identification of institutional barriers and promote the design of institutional alternatives.

In 1979, the Danish Parliament passed a law on heat supply. According to the law, all municipalities had to conduct a heat-planning procedure in which

8. Translated from Danish: *De lave kulafgifter ødelægger varmeplanlægningen—en kommenteret aktsamling fra varmeplanlægningen i Aalborg*.
9. Translated from Danish: *Energiafgifterne og de decentrale kraft/varme-værker*.

different heat supply options were described, analyzed, and compared. The overall objective of the law was to

promote the best socioeconomic use of energy for the heating and hot water supply to houses and to reduce the energy supply's dependency on oil.[10]

When asked how to include externalities such as environmental considerations in the socioeconomic feasibility studies, the Danish Ministry of Energy answered, "The socioeconomic analysis has to describe and compare all costs and benefits".[11] In practice, this is done by combining an economic calculation and a description of relevant externalities, typically including the environment, energy security, balance of payment, and job creation. However, the assessment and identification of the best solution should include all relevant considerations.

The Alternatives in Question

The heat-planning procedure included a public discussion phase, and, consequently, in the late summer of 1984, the municipality distributed to all households a written invitation to participate in the discussions. The invitation put forward three alternatives as illustrated in Figure 8.5 (left). In all of the

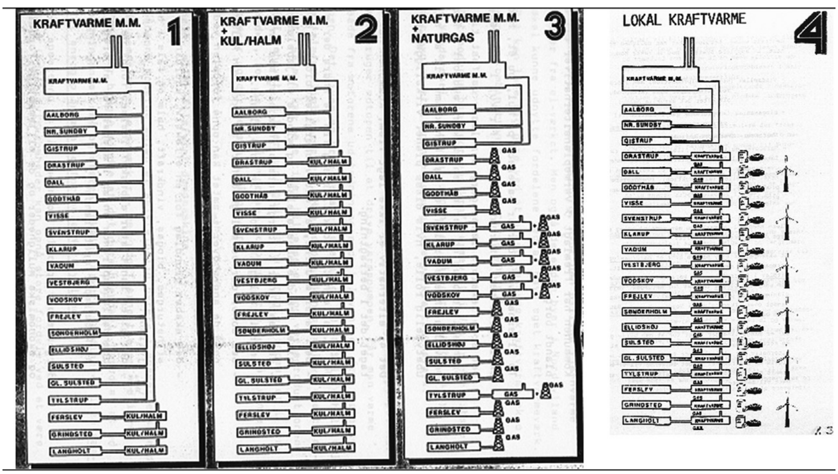

FIGURE 8.5 Illustration from 1984. On the left, the three official alternatives proposed by the municipality consisting of a choice between efficient coal in CHP or inefficient boiler solutions. On the right, the citizens' alternative 4, proposing CHP based on natural gas to pave the way for renewable energy.

10. Translated from Danish: *A fremme den mest samfundsøkonomiske anvendelse af energi til bygningers opvarmning og forsyning med varmt vand og at formindske energiforsyningens afhængighed af olie*. Law on heat supply included in Hvelplund and Lund (1988).

11. Translated from Danish: *Den samfundsøkonomiske analyse skal beskrive og sammenholde de samlede fordele og ulemper*. Letter from the Danish Ministry of Energy, February 29, 1984. In Hvelplund and Lund 1988.

alternatives, the main city area of Aalborg would continue to be supplied with district heating from Nordkraft CHP station, which, as mentioned in the previous section, was now based on coal. The issue in question was how to supply the small suburban areas, towns, and villages around Aalborg with heat. The municipality proposed three alternatives. One was to expand the district heating system of Aalborg to most of the small urban areas. This alternative would mean that all heating would be based on coal, but it would be an efficient use of coal, since it would all be CHP production. The two other alternatives suggested using boilers for heat-alone production either in small district heating systems and/or as individual boilers using natural gas. The fuel would be coal, straw, or natural gas. Both alternatives would involve the replacement of coal, but these productions would not be as efficient, since they would not benefit from CHP.

As part of the public discussion phase, I and six other students and teachers from Aalborg University proposed a fourth alternative that was simply to build small CHP stations based on natural gas in all areas. We illustrated the alternative as shown in Figure 8.5 (right). Our intent was to pave the way for renewable energy in the forms of wind power and biogas. The main idea was to have both an efficient CHP production and, at the same time, avoid the use of coal. We presented three advantages of alternative 4 compared to the others. In terms of *energy efficiency*, alternative 4 was substantially better than alternatives 2 and 3. For two reasons, it was also slightly better than alternative 1. First, one could save district heating losses in huge pipelines of 10–15 km from Aalborg to the small urban areas. Second, the efficiency of the small natural gas units was slightly better than the efficiency of Nordkraft coal unit.

In terms of *environment*, alternative 4 was the best solution, since it would either replace coal by natural gas when compared to alternative 1 or save substantial amounts of fuel when compared to alternatives 2 and 3. Alternative 4 would pave the way for renewable energy, since a system of small gas engine units would ease the introduction of biogas and, at the same time, provide a better integration of wind power than a coal-fired steam turbine.

Often such an environmentally better solution would be more costly than other alternatives. However, if the costs of cleaning SO_2 emissions from coal were included in the calculations, alternatives 1 and 4 came out equally cost-effective from an economic point of view. And since the natural gas/CHP solution had further benefits with regard to energy security, balance of payment, and CO_2 emissions, and these externalities according to the authorities were to be included in the overall assessment, it was concluded that alternative 4 was the best solution.

Though alternative 4 was preferable in terms of socioeconomics as defined by the authorities according to the law, the implementation would still mean increasing prices for the consumers compared to the coal alternative. The reasons for this were to be found in the institutional set-up of the Danish energy taxation system. The energy tax on coal was only 27 DKK/GJ compared to a tax of 51 DKK/GJ on natural gas. Moreover, this tax was only to be paid for the fuel used for heat and not the fuel used for electricity production. Also, an administrative practice had developed in which coal-fired steam turbines were only taxed a small part of the fuel (typically around 40 percent), while natural gas engines were taxed a major part (typically 60 percent). A detailed description and analysis of the administrative practice and the consequences are presented in Lund (1988).

All in all, in accordance with the law, the alternative involving natural gas and CHP should be chosen, since it proved to have the best socioeconomic feasibility. However, the municipality wanted to implement the CHP and coal alternative, since it proved to have the best consumer heat prices.

Choice-Eliminating Strategies

As mentioned, the group from Aalborg University described and promoted alternative 4: small CHP stations based on natural gas paving the way for future renewable energy systems. The proposal was discussed in the newspaper, and we mailed it to the municipality as part of the public discussion phase in 1984. The municipality answered that no decision had been made and that they would closely follow the development within natural gas-based CHP stations.

In the following years, two occurrences took place that helped the promotion of the natural gas-based CHP alternative. First, an agreement was made between the government and the major opposition party to expand small CHP stations on domestic resources by 450 MW. Second, the Danish Energy Agency issued a report that concluded that natural gas-based CHPs proved socioeconomically cost-effective, even in small urban areas.

Nevertheless, in February 1987, the newspaper stated that the Municipality of Aalborg would now decide on the matter. References were made to calculations showing that the best heat prices would be achieved by implementing alternative 1; that is, coal-based district heating from Nordkraft was to be supplied to 10 surrounding urban areas. We asked for the report and could see that alternative 4 had not even been analyzed.

We protested in the local newspaper. The city council postponed the decision for 2 weeks and invited my colleague, Frede Hvelplund, and me to analyze the alternatives together with the municipality administration. We soon agreed on the premises and chose one of the small towns, Frejlev, as an example. Both parties made a series of calculations and met on April 6, 1987, to compare the results.

Our calculations showed that natural gas-based CHP was the best solution in a socioeconomic perspective, whereas, regarding heating prices, the result depended somewhat on the expectations of future fuel prices. The calculations of the municipality administration confirmed that natural gas-based CHP was the best solution in terms of socioeconomic feasibility. However, their calculations showed that coal-fired central CHP would provide the lowest consumer heating prices.

The fact that the two calculations came to the same result regarding socioeconomic feasibility caused a major problem for the city council. According to the law, they were supposed to choose natural gas CHP, but they wanted coal. The city council had its next meeting on April 13, and the committee on heat supply discussed the matter at a meeting on April 9.

Then something happened: when sending out documents prior to the city council meeting, the two calculations of April 6 were not included. Instead, the municipality administration made a new calculation dated April 9, which was distributed to the committee at the meeting. This calculation showed, in terms of socioeconomics, that coal was even slightly better than small natural gas-fired CHPs. However, these calculations did not include all the environmental and energy security benefits of the natural gas alternative. Consequently, even based on the new calculation, natural gas would still be best in an overall socioeconomic assessment as defined by the law, but this issue was not mentioned.

We responded by sending our calculations of April 6 directly to the city council members before the city council meeting on April 13. At the meeting, some city council members raised a discussion on whether it was appropriate for university employees to write a letter using the university's letterhead (see Figure 8.6). On the following day, the issue was presented on the front page of the local newspaper: "City Council Criticizes Aalborg University's Use of Letterhead Writing Paper".[12] The contents written on the paper were not discussed. Instead the city council decided to implement coal-based alternative 1.

Soon thereafter, the Danish Minister of Education, Bertel Haarder, who was a member of the same political party as the city council member leading the discussions on the writing paper, made an official inquiry to the university, and we were investigated. However, the rector of Aalborg University, Sven Caspersen, concluded that we acted correctly regarding the use of the official university writing paper.

According to the heat-planning procedure, the heat plan of Aalborg had to be approved first by the county and then by the Danish Energy Agency. The process is described in more detail in Hvelplund and Lund (1988). The result was that the Danish Energy Agency attempted to make the municipality conduct further analyses, but in the end, they had to give up, and the coal-based alternative was approved.

Conclusions and Reflections

In a way, the case of Aalborg heat planning takes over where the Nordkraft case stops. From the Nordkraft case, it could be learned that given the existing institutional set-up, radical technological alternatives could not be implemented. Institutional changes had to be made at a higher level. In the Aalborg heat

12. Translated from Danish: *Byrådskritik af AUC's brevpapir*. Aalborg Stiftstidende, April 14, 1987. In Hvelplund and Lund 1988.

Byrådskritik af AUC's brevpapir

14/4-87

Repræsenterer de, som bruger det, AUC?

Af
EIGIL MORTENSEN

AALBORG: AUC-forskerne, som i 11. time søede tvivl om de beregningsmæssige grundlag for Aalborgs varmeplan, blev udsat for en voldsom kritik i Aalborg Byråd i går. Repræsenterer de universitetet eller er de privatpersoner?

- Er det AUC eller blot et par mennesker, som er ansat på universitetet og bruger AUC's brevpapir? spurgte tidligere forsyningsrådmand Henning Larsen (V). Det er altid de samme to underskrifter. Det kan fremstå, som om det er et officiel forskningsprojekt.

- Det er ikke første gang, supplerede Hans Brusgaard (K). Vi har utallige gange fået brev fra to, som tilfældigvis er ansat på AUC. Enten skrives der på universitets vegne med rektors underskrift eller også privat. Med eget brevpapir og egne frimærker. Det er urimeligt med denne metode. Jeg agter fremover at arkivere den slags lodret, såfremt det ikke klart fremgår, hvem der skriver. I magistratens 2. afdeling ligger der en dynge breve, der er skrevet på AUC brevpapir. Jeg kan da heller ikke skrive privat på kommunens brevpapir og give indtryk af, at det er byrådet. Jeg er glad for AUC og centrets samarbejdet med byens erhvervsliv og kommunen, men dette går ikke.

Også Arne Kristensen (Å) vendte sig skarpt mod brug af AUC's officielle brevpapir - og porto - til private breve, hvorimod både Niels Aage Helenius (S) og forsyningsrådmand Kirsten Hein (SF) gav udtryk for, at det måtte være en intern sag for AUC.

Forsyningsrådmanden lagde dog ikke skjul på, at hun har opfattet brevene som officielle tilkendegivelser fra universitetet.

- Bestemt ikke, fastslog Henning Larsen. Det er et problem for os, at vi ikke ved, hvem der skriver.

Det blev aldrig opklaret, om AUC-forskerne har blandet sig i varmeplanen på universitetets eller egne vegne.

Bortset fra SF-gruppen - minus Kirsten Hein - afviste samtlige byrådsmedlemmer forskernes kritik af embedsmændenes beregninger.

Henning Larsen (V): Er det AUC eller...?

FIGURE 8.6 After receiving the results of inviting two university staff members to join the municipality in analyzing heat-planning alternatives, the city council criticized the staff members for using the letterhead of the university when proposing an alternative heating plan while disregarding the contents written on the paper.

planning case, such changes at a higher level had to some extent been made by introducing the heat planning procedures that supported the choice of the socioeconomic least-cost solution in accordance with the purpose of the law.

Some important lessons were learned from this case. Three alternatives were put forward by the municipality, none of which represented the combination of CHP and other fuels than coal. Such solutions did not fit well into the interests and perceptions of the city council and the municipality-owned district heating company and were thus disregarded in the definition of optional alternatives to be discussed in the public participation phase. Alternatives representing radical technological change had to come from the university and local citizens. The case reveals some interesting choice-eliminating mechanisms and strategies:

- When addressing the public discussion phase, the municipality simply left out certain alternatives.
- When such alternatives were proposed by the citizens, the municipality disregarded these in the comparative analyses.
- When comparative analyses showed an inconvenient result, new analyses were made.
- Only the analyses that showed the most convenient results were put forward to the city council.
- When citizens mailed inconvenient results to the city council, the contents of the analysis were disregarded; instead, a discussion of the letterhead used was initiated, presumably to incriminate the senders.

This case confirms what was learned from the Nordkraft case by showing that the existing institutional set-up could not identify and implement the best alternative by itself. The main point of this case is that it is not efficient to tell by law what to do if the institutional market set-up makes it profitable to do something completely different. If the institutional set-up of the energy taxation system favors coal at the cost of, among others, natural gas, the local municipalities are faced with a principal request to choose solutions that are expensive for heat consumers. In this situation, the municipalities will seek to disregard other alternatives than the one with the lowest heating prices. In the case of Aalborg, the county council and the Danish Energy Agency failed to make the municipality live up to the words and the intentions of the law.

However, the case also illustrates how institutional barriers can be identified by the introduction and discussion of concrete technical alternatives. As a follow-up on this case, we promoted concrete proposals on how to change the Danish energy taxation system to create a situation in which the socioeconomic best solution would also generate the best consumer heat prices.

3. CASE III: THE EVALUATION OF BIOGAS (1990–1992)

The evaluation of the feasibility of large-scale biogas stations in Denmark in 1991 is a story of how traditional cost-benefit studies may provide irrelevant information and, consequently, may draw the wrong conclusion. Traditional cost-benefit studies based on applied neoclassical economics simply do not take into consideration the real-life economic situation and do not refer to the politically decided overall economic goals of the government. In this case, the information was inadequate for making recommendations on how to best achieve the politically defined economic objectives of the Danish Parliament of that time. The case shows how feasibility studies that include such considerations can be done and how such studies can provide information that is relevant to the decision-making process. The case description is based on the books

Socio-Economic Evaluation and Measures. Based on the Case of Biogas (Lund 1992a)[13] and *Feasibility Studies and Public Regulation in a Market Economy* (Hvelplund and Lund 1998a).

In 1990, the Danish Energy Agency was in the process of evaluating the status of large-scale biogas stations to define a new biogas development strategy. Fifteen reports were made, one of which evaluated the socioeconomic impact of biogas stations (Risø 1991), and another addressed the design of suitable public regulation measures for the implementation of large-scale biogas stations (Lund 1992a).

The analysis of the socioeconomic impact of biogas stations (the Risø report) concluded that biogas stations were not economically feasible for Danish society. This conclusion created a problem for the report addressing the design of public regulation. It was contradictory to support a massive implementation of biogas stations in Denmark if biogas was not socioeconomically feasible for Danish society. Why, then, write a report on public regulation?

Consequently, Aalborg University conducted another analysis of the socioeconomic feasibility of biogas and described a public regulation strategy (the AAU report). This report concluded that the Risø evaluation method, based on an applied neoclassical cost-benefit study, disregarded the political and economic objectives of Danish society. It was shown that the implementation of a biogas scenario indeed would be of socioeconomic benefit to Danish society when seen in relation to the aims of the Danish Parliament.

The Applied Neoclassical Cost-Benefit Analysis

The economic evaluation of biogas made by Risø was, according to the report, carried out as a cost-benefit analysis based on neoclassical welfare economic theory and methodologies aiming at comparing socioeconomic costs and benefits of implementing large-scale biogas stations. The analysis was conducted in the form of present value calculations of three different existing biogas stations over 20 years: Fangel, Davinde, and Lintrup. The three stations were then compared to relevant reference stations. The two first biogas stations, Fangel and Davinde, had oil-fired district heating stations as their reference alternatives, whereas the Lintrup biogas station had a natural gas-fired district heating system as its reference alternative. The prices used in the calculations were market prices, excluding value-added tax (VAT) and energy taxes. The price prognoses used for fossil fuel were based on the official prognoses from the Danish Energy Agency. The results of these calculations are shown in Table 8.1, not including the environmental benefits.

As Table 8.1 shows, the projects are assessed as not socioeconomically feasible. The Risø report also made calculations that included the environmental

13. Translated from Danish: *Samfundsøkonomisk Projektvurdering og Virkemidler Med biogasfællesanlæg som eksempel.*

TABLE 8.1 Risø Report, 1991 Socioeconomic Results, Not Including Environmental Benefits

Million DKK	Fangel	Davinde	Lintrup
Investment	26.7	4.3	45.2
Present value	−15.2	−5.1	−26.8
Annual surplus	−1.4	−0.5	−2.5

TABLE 8.2 Risø Report, 1991 Socioeconomic Results, Including Environmental Costs

Million DKK	Fangel	Davinde	Lintrup
Annual surplus	−0.9	−0.4	−2.2

benefits of biogas, based on the following emissions and socioeconomic costs: SO_2 14 DKK/kg; NO_x 8 DKK/kg; and CO_2 100 DKK/ton. The socioeconomic results including these environmental costs are shown in Table 8.2.

Based on the results in Tables 8.1 and 8.2, the Risø report concluded that

the costs of energy produced by large-scale biogas facilities are approximately twice as high as the costs of energy produced by a reference station, even when certain agricultural and environmental conditions are included in the evaluation,[14]

and the main report concluded that the existing large-scale biogas facilities were not socioeconomically feasible.

Feasibility Study Based on Concrete Institutional Economics

The main problem of the preceding cost-benefit analysis is that it does not provide sufficient information relevant to the specific decision-making process. When the authorities formed the committee, they asked it to

provide the basis for deciding whether or not to expand the energy system by implementing large-scale biogas stations in Denmark.[15]

14. Translated from Danish: *Beregningerne viser, at energi produceret på et biogasfællesanlæg er cirka dobbelt så bekosteligt som energi produceret på et reference-energianlæg, selv når visse landbrugs—og miljømæssige forhold er inddraget i beregningerne* (Risø 1991).
15. Translated from Danish: . . . *at frembringe et grundlag for en stillingtagen til, om der er basis for en bredere udbygning med biogasfællesanlæg i Danmark* (Danish Energy Agency 1991).

However, the preceding study did not systematically adapt its analysis to the specific situation. This adaptation could have been performed by systematically asking and answering the questions *what* should be analyzed, for *whom* is the analysis made, and *why* conduct the analysis?

The feasibility study conducted in the AAU report (Lund 1992a) involved a thorough analysis of those issues and comes to the following conclusions:

> **Question**: *What should be studied?*
> **Answer**: The socioeconomic feasibility of the biogas scenarios. This means that the study should have a long-term perspective that also integrates the study of technological changes.
> **Question**: *For whom and why?*
> **Answer**: The study is essentially done for the Danish Parliament, which demands this information be used for deciding the future biogas strategy.

This means that the parameters applied to measure whether biogas is economically good or bad should be relevant to official energy policy objectives as well as to the overall economic objectives of the Danish Parliament. Consequently, a thorough description of these objectives was included in the feasibility study. Regarding the parliamentary energy policy, the analysis showed that both the official energy plan of that time, Energy Plan 81 (Danish Ministry of Energy 1981), and the Danish law on heat supply declared that their main purpose was to secure and promote socioeconomically best solutions. When defining the term *socioeconomics*, the official energy plan emphasized the balance of payment and job creation as important considerations to include.

The analysis of the overall parliamentary economic objectives showed that the financial statement of the authority (Danish Ministry of Finance 1991) emphasized the problem of unemployment. Good results had, in the previous years, been achieved with other economic factors, but the unemployment rate had risen. The authorities targeted unemployment as the important problem to address in the coming period.

All in all, the analysis revealed that energy solutions that would increase employment, improve the balance of payment, decrease pollution, and increase GDP were important measures to fulfill the aims of the Danish Parliament. The analysis also showed that labor was a rather abundant resource, as unemployment mounted to 350,000 in 1990, equal to more than 10 percent of the workforce.

When returning to the applied neoclassical cost-benefit analysis, it is important to note that the study presumes full employment and does not consider foreign debt a problem. In all calculations, positive effects on technological development, balance of payment, state finance, and employment were given no value, although such effects were given high priority by the Danish Parliament.

As a consequence, the AAU study included the preceding effects in its socioeconomic analyses. Calculations were made of a biogas scenario, assuming that

TABLE 8.3 AAU Study: Three Examples of the Consequences of the Biogas Scenario

	Example 1: (0 Million DKK Extra Tax per Year)	Example 2: (1500 Million DKK Extra Tax per Year)	Example 3: (750 Million DKK Extra Tax per Year)
GDP (million DKK/year)	+1000	0	+500
Employment effects (persons)	+5000	0	+2500
Governmental expenditures (million DKK/year)	+200	+1200	+700
Balance of payment (million DKK/year)	+300	+900	+600

50 percent of all manure in Denmark from cattle, pigs, and poultry was used for biogas production. The outcome of this analysis is shown in Table 8.3.

The analysis revealed that if consumers were to pay the same price for heat and electricity as in the reference, the government had to provide a subsidy equal to 300 million DKK/year. However, Denmark would decrease its net imports (the decrease in import of fuel minus the increase in import of goods to construct the biogas stations) by 450 million DKK/year and increase its GDP by 750 million DKK/year. Such a situation is a token of a positive change. In the study, it is emphasized that the Danish government can choose to benefit from this positive situation *either* by seeking to decrease foreign debts *or* by seeking to raise employment.

In Table 8.3, three examples are presented in which the biogas investment program is supplemented with different degrees of increases in income taxes (or other taxes). The three examples differ from one another. Thus, example 2 includes 1500 million DKK/year in extra tax used to maintain total buying power and production at a constant level. Example 3 has exactly the same biogas scenario but with 750 million DKK/year in extra tax. Example 1 has no extra tax at all. The three examples show the different possibilities of the biogas scenario.

The positive socioeconomic effects are mainly caused by saved imports due to a decrease in oil and coal imports; increased employment because of the high employment effects linked to building, maintaining, and running biogas stations; and increased incomes and, consequently, increased taxes, which improve the public finances. This increase in income to the governmental budget more than compensates for the subsidies that must be given to motivate the construction of biogas stations.

TABLE 8.4 AAU Study: The Resources and Environmental Effects of the Biogas Scenario Compared to the Reference Scenario

	Biogas Scenario (50%)	Reference: Oil for Heat and Coal for Electricity	Environmental Advantages of Biogas
Primary energy supply in total (TJ/year)	16,196	18,720	—
Fossil fuel consumption (TJ/year)	468	18,720	18,252
CO_2 emission (1000 ton/year)	34	1494	1460
SO_2 emission (ton/year)	470	5840	5370
NO_x emission (ton/year)	2780	2783	—

The resources and environmental effects are shown in Table 8.4, which illustrates that when relating the socioeconomic feasibility of biogas to the goals of the Danish Parliament, the biogas scenario demonstrates higher economic and environmental performance in all important areas. When including employment effects, balance of payment effects, and effects on the state finances, this scenario is, therefore, indeed cost-effective from a socioeconomic point of view.

Conclusions and Reflections

When the Danish Parliament wanted to know if biogas was suitable for society, a cost-benefit analysis methodology based on applied neoclassical economics was chosen without further consideration. This type of analysis was not wrong, but it was irrelevant in relation to the specific political context and objectives. The calculations were right when seen isolated from the specific real-life economic situation of Danish society in the 1990s. It was correct to conclude that biogas stations had not yet reached a stage at which they were economically feasible in the existing institutional context and when applying existing market prices. But seen from the government's point of view—and this is the relevant standpoint in this case—the biogas scenario just described was socioeconomically feasible, as it pursued and satisfied essential governmental aims better than the references did.

The methods applied here to establish the context and measure the relevance of a certain alternative show the strength of applying the Choice Awareness strategy. When political aims and programs involving elements of radical technological change are in question, it is recommended to conduct feasibility studies based on concrete institutional economics. The main point of the case is that proper attention should be paid to the identification of political and economic objectives when conducting a socioeconomic feasibility study.

4. CASE IV: NORDJYLLANDSVÆRKET (1991–1994)

The case of Nordjyllandsværket is the story of how the power company of West Denmark at that time, ELSAM, in 1992, was given permission to construct a 400 MW coal-fired power station, although the Danish Parliament had decided not to build any more coal-fired power stations. This case shows how the creation of a "no alternative" situation played an important role in the decision-making process. Furthermore, it reveals some of the mechanisms applied to the elimination of choice. This case, however, also influenced a subsequent parliamentary decision to change the institutional set-up of market conditions for small CHP stations. Hereby, the Danish Parliament opened up for the investments in small CHP stations of more than 1000 MW capacity in the mid- and late 1990s. The case description is based on the report "Danish Energy Policy and the Expansion Plans of ELSAM" (Hvelplund, Illum, Lund, and Mæng 1991)[16] and the books *An Alternative to ELSAM's Planned Two Power Stations* (Lund 1992b),[17] *Public Regulation and Technological Change. The Case of Nordjyllandsværket* (Lund and Hvelplund 1994),[18] *Collection of Documents on the Nordjyllandsværket Case, Volumes I and II* (Lund and Hvelplund 1993), and *Does Environmental Impact Assessment Really Support Technological Change?* (Lund and Hvelplund 1997).

In 1990, the Danish government decided on the energy plan Energy 2000 (Danish Ministry of Energy 1990). The plan is an example of a political wish for radical technological change. At that time, more than 90 percent of the Danish electricity supply was based on large coal-fired power stations. The power companies were organized to operate this exact technology. However, according to Energy 2000, coal-fired power stations were to be phased out and replaced by many small production units based on natural gas and renewable energy, such as CHP and wind power. Moreover, the annual increases in electricity demands were to be slowed down.

16. Translated from Danish: *Dansk energipolitik og ELSAMs udvidelsesplaner—et oplæg til en offentlig debat* (Hvelplund, Illum, Lund, and Mæng 1991).

17. Translated from Danish: *Et Miljø—og Beskæftigelses Alternativ til ELSAMs planer om 2 kraftværker—en viderebearbejdelse af det tidligere fremsatte. Alternativ til et kraftværk i Nordjylland* (Lund 1992).

18. Translated from Danish: *Offentlig Regulering og Teknologisk Kursændring. Sagen om Nordjyllandsværket* (Lund and Hvelplund 1994).

In 1991, shortly after the Danish Parliament adopted the CO_2 emission reduction targets of Energy 2000, ELSAM applied for permission to construct a new power station unit. The station, a 400 MW coal-fired power station called Nordjyllandsværket (the North Jutland power station), was to be located outside Aalborg, the main city in Northern Jutland. The application was submitted along with another application for a 400 MW natural gas-fired power station by Fredericia, in southeastern Jutland, Skærbækværket. Together they were to form part of a total solution for the whole ELSAM area, that is, Jutland and the island of Funen, constituting approximately half of the electricity supply of Denmark.

The application was sent to the Danish Energy Agency in accordance with the Danish electricity supply law. The Danish Energy Agency had to examine whether new power production capacity was needed before permission could be granted. In this case, the main problem was that the parliamentary energy plan, Energy 2000, had three scenarios identifying how to achieve the objective of CO_2 reduction by 2005, and none of those scenarios included any additional coal-fired power stations.

However, the situation in the Danish government was complex. The coalition government had changed, and the party of the Minister of Energy behind Energy 2000 was replaced by a new minister who was in favor of the new coal-fired power stations. (The details in this complex situation are described in the references at the beginning of this case.) On the one hand, the minority government wanted to approve the new power stations. On the other hand, Parliament still supported the Energy 2000 plan. Consequently, the government and the power companies had to explain to the public how they could back up the Energy 2000 plan while approving the implementation of a completely opposite solution.

The No Alternative Situation

In the case of Nordjyllandsværket, the political decision makers were asked to choose one, and only one, solution. The board of representatives of the local power company, Nordkraft, which was part of ELSAM, was asked to approve the plans for a new coal-fired power station by voting either for or against the suggestion. The consequences of a *yes* were obvious, but the consequences of a *no* were not suitably described. The year before, some of the representatives had asked for a study of an alternative based on natural gas. Such an alternative involved the replacement of the old facilities of the existing power station in the center of Aalborg, Nordkraft, by a combined cycle CHP power station based on natural gas. Furthermore, the CHP station should be adjusted to the district heating demands of Aalborg and thereby be somewhat smaller than the planned coal-fired unit. Even though this alternative had been examined and indeed was requested by some of the representatives, it was not put forward in the decision-making process, when the decision was made in the power companies, or when the application was examined by the Danish Energy Agency. Everyone was asked to choose a coal-fired power station—or nothing.

In that situation, some of my colleagues and I described and put forward a concrete alterative to the two power stations (Hvelplund, Illum, Lund, and Mæng 1991; Lund 1992b). This alternative made it possible to evaluate the many arguments in a relevant context. In principle, the choice was very simple, and everyone had the premises for participating in the discussion. But ELSAM and the government had a problem. The installation of a coal-fired power station was contradictory to the Energy 2000 policy, and that conflict was not to be revealed during the public debate. The situation created a number of arguments, which seemed right but were wrong. Here are some of the statements:

- Because Nordjyllandsværket is a CHP station, it fits well into the strategy of Energy 2000.
- Nordjyllandsværket will replace 30-year-old power stations. Therefore, it is good for the environment.
- The construction of new large power stations will not present any barriers to the construction of small CHP stations.
- The feasibility of the power stations is good, even if governmental electricity savings programs are successful.
- ELSAM and the Danish Energy Agency do agree on the prognoses for future electricity demands.
- It is necessary to vote for the two power stations to support the export of Danish know-how.

All of these statements sounded true, and each had arguments to support it. But put into the relevant context, they all proved wrong. For example, it was true that Nordjyllandsværket was constructed as a CHP extraction station (which can be operated as CHP as well as a power-only station). However, due to the size and the location of the station, the project did not allow any increase in the numbers of households being supplied from CHP. Consequently, it did not comply with the Energy 2000 strategy of expanding CHP in Denmark.

The Alternative Proposal

Two versions of alternatives to the official proposal were designed. The first version was made as part of a discussion paper issued in 1991 in due time before the project was to be approved by the Danish Energy Agency (Hvelplund, Illum, Lund, and Mæng 1991). The alternative simply consisted of electricity savings in combination with small CHP and the preceding combined cycle CHP unit based on natural gas and located in the town center of Aalborg. The alternative was designed in such a way that it could save or produce the same amount of energy and provide or save the same amount of capacity as the proposed 400 MW coal-fired power station. In concrete terms, it consisted of 100 MW savings, 100 MW small CHP stations, and a 200 MW natural gas-based CHP station in Aalborg.

The construction prices of the alternative were exactly the same as those of the planned coal-fired power station—namely, 2.8 billion DKK—and the annual direct operation costs were also the same. But regarding the environmental impact, as well as the Danish balance of payment and job creation, the alternative came out with much better results than the coal-fired power station. Our conclusion was that the investment in Nordjyllandsværket would increase the problems related to environment, economy, and unemployment in Danish society and also work contradictory to the implementation of the Danish Parliament's energy policy. Better alternatives did exist that could provide or save the same amount of electricity and, at the same time, contribute to solving environmental problems, improving the economics, and creating jobs. We argued that these alternatives should be examined before deciding on the implementation of new coal-fired power stations.

ELSAM responded to the first alternative by criticizing certain factors: a present value had not been calculated, the potential locations of CHP stations had not been specified, investments in district heating pipelines were missing, and the rate of employment was not correct. All in all, ELSAM agreed that the alternative was much better for the environment, but the costs of this alternative were underestimated, and the estimation of job creation was wrong, according to ELSAM, which did not comment on the substantial improvements of the balance of payment. Moreover, ELSAM argued on the discount of building two power stations at the same time: one in Northern Jutland based on coal and one in Southern Jutland based on natural gas.

Consequently, we made a new and more detailed version of the alternative in which both of the two new power stations were included. Moreover, we made present value calculations and included investments in district heating pipelines, and so forth. In Tables 8.5 and 8.6, the alternative is compared to the ELSAM proposal, and present value calculations are given of both alternatives.

As can be seen in Table 8.6, the alternative is composed in such a way that it produces or saves the same amount of energy as the ELSAM proposal. Moreover, the alternative proposal provides or saves even more capacity than the reference. The alternative is identical to the ELSAM proposal in terms of the following points:

- The present value is 15 billion DDK calculated over 30 years using a discount real rate of 7 percent.
- The annual electricity production and capacity produced or saved are the same.
- The cost of foreign currency is the same in the *construction* phase.
- The annual natural gas consumption is more or less the same. In ELSAM's proposal, the consumption is 14,200 TJ/year, while in the alternative, it is *either* 9200 TJ/year *or* 17,200 TJ/year combined with 8000 TJ/year of saved gas oil in individual boilers.

TABLE 8.5 The ELSAM Project Proposal

Capacity (MW)	Electricity Production (GWh/Year)	Cost Present Value, 30 Years, 7 Percent (Billion DKK)		Sum (Billion DKK)
340	1700	**Nordjyllandsværket**		
		Power station	3.1	
		District heating pipeline	0.1	
		New transmission line	0.3	
		Operation and maintenance	1.5	
		Coal (13,600 TJ/year)	2.9	7.9
340	1700	**Skærbæk**		
		Power station	2.1	
		Operation and maintenance	0.5	
		Ngas electricity (13,000 TJ/year)	4.4	
		Ngas heat (1200 TJ/year)	0.4	
		Saved coal heat (1200 TJ/ year	−0.3	7.1
6400	3400	Sum		15.0

The alternative differs from the ELSAM proposal in terms of the following points:

- The alternative contributes to a better environment by simultaneously replacing both the two power stations and approximately 60,000 individual oil and gas boilers or district heating boilers with the same effect. Sulfur and nitrogen emissions are reduced by 84 and 22 percent, respectively, and CO_2 emissions by as much 62 percent.
- The need for foreign currency in the *operation* phase is halved.
- Job creation is increased in the construction phase as well as in the operation phase. Moreover, the alternative provides much more flexibility in the creation of jobs, both in terms of when and where these jobs are created.
- The houses, which have been insulated, will provide a better quality of living. This benefit was not included in the calculation.
- The need for high-voltage transmission lines is reduced (see the following section).
- The construction of large ELSAM power stations takes 6 years, and they have to be built in parallel, while the small units of the alternative can be built within 1–3 years and can easily be built over a period of time. Consequently, Danish society can use this flexibility to wait and see if new capacity is needed or if electricity saving programs succeed.

TABLE 8.6 The Alternative Project Proposal

Capacity (MW)	Electricity Production (GWh/Year)	Cost Present Value, 30 Years, 7 Percent (Billion DKK)		Sum (Billion DKK)
200	1000	**Electricity savings**		
		Investment	1.3	
		Reinvestment after 15 years	0.5	1.8
100	500	**CHP on natural gas**		
		CHP station	0.6	
		District heating system	0.6	
		Operation and maintenance	0.4	
		Natural gas (net 2000 TJ/year	0.7	2.3
100	500	**CHP on biomass straw**		
		CHP station	2.3	
		Operation and maintenance	1.4	
		Straw (6000 TJ/ear)	1.5	
		Saved natural gas (4000 TJ/year)	−1.3	3.9
280	1400	**Ngas combined cycle, Aalborg**		
		CHP station	1.6	
		Operation and maintenance	0.4	
		Ngas electricity (10,700 TJ/year)	3.6	
		Ngas heat (500 TJ/year)	0.2	
		Saved coal heat (1700 TJ/year)	−0.4	5.4
0–60		Insulation of houses (during a period of 30 years)		
		Investment	1.7	
		Saved cost (0–1700 TJ/year)	−0.1	1.6
680–740	3400	Sum		15.0

Discussion of the Alternative

One of the interesting aspects of the Nordjyllandsværket case is that the alternative was subject to a detailed technical discussion between ELSAM, my colleagues, and me. ELSAM argued that electricity savings could not be considered as part of the alternative, since such savings would be implemented, if feasible, independently from the power station project. We refuted this by proving how the ELSAM project was based on an electricity demand prognosis that presumed that the parliamentary electricity saving program was not implemented. Without this prognosis, the Energy Agency could not approve the application, since the additional capacity would not be necessary.

ELSAM argued that the new power stations would produce during more hours than assumed in our calculations. ELSAM stated 6000 hours/year against our assumption of 4360 hours. We countered by arguing that this would probably be true for the first couple of years, because the power stations were new and more efficient than the old ones. However, for the same reason, production hours would decrease over 30 years as the new stations became old themselves. Seen in relation to an average power station lifetime, the average production hours of the system were approximately 4000 hours.

ELSAM claimed that it would not be possible to implement small CHP stations because they would exceed the technical potentials. In the application to the Energy Agency, ELSAM assumed a maximum potential of 600 MW. It was not possible to implement more, ELSAM claimed. Therefore, the alternative could not be accomplished. We argued that the potential was much higher and referred to an official report identifying a potential of at least 890 MW. Later, in the mid- and late 1990s, a total capacity of more than 2000 MW was built.

Moreover, ELSAM argued that the cost of a new transmission line related to the building of Nordjyllandsværket could not be included in the calculations, since the line would be established whether or not Nordjyllandsværket was built. As described in the following section, the statement afterward made it difficult for ELSAM to explain that the need for the transmission line was not connected to Nordjyllandsværket.

The alternative was later discussed in the public debate on the power station proposals. The debate continued for a couple of years and involved letters from ELSAM to local politicians, various radio and newspaper interviews, approval procedures of the local county and the Energy Agency, and even a discussion in the Danish Parliament. In Lund and Hvelplund (1994) and Hvelplund (2005), a detailed description of the many facets of the process is presented, and one of the elements—the environmental assessment—is further examined later in this chapter.

Conclusions and Reflections

This case represents a situation in which the parliament decided to implement a radical technological change. According to the official energy plan, Energy 2000, Denmark was to replace large-scale steam turbine power stations based on coal with, among others, small CHP stations based on domestic resources and energy conservation measures. These policies represent a radical technological change as the organizations linked to the big power stations would have to be partly replaced by other organizations.

If parliament policies were implemented, an additional central power capacity would not be necessary. Even in this situation, the power companies proposed to build another new coal-fired steam turbine. The power company ELSAM, together with politicians in favor of this technology, did seek to make the argument in the public debate that no contradiction existed between the coal-fired power station and the energy plan Energy 2000, which did not include any new coal-fired power stations. The description and promotion of a concrete technical alternative in accordance with Energy 2000 provoked responses from ELSAM and revealed that alternatives did exist. The existence of alternatives made ELSAM exercise a series of choice-eliminating mechanisms and strategies.

Danish society was not powerful enough to avoid the central power stations, which fit well into the organizations of existing power companies. However, the Danish Parliament was powerful enough to promote small CHP stations more or less simultaneously with the approval of the central power stations. Therefore, the whole matter ended with the choice of both: two big power stations and a whole program of small CHP stations; even though such a large amount of additional power was not necessary. As one politician of the local county put it:

It is nice to live in a country which is so rich that we can afford to build two power stations even if we only need one.[19]

Building the two power stations created a situation of significant overcapacity. ELSAM argued against the politicians that this would not create any problems. We (Lund and Hvelplund 1994) argued that this was indeed a problem. Among other problems, the overcapacity would create the basis for implementing bad sales price agreements for electricity sold from wind power and small CHP. This result was confirmed in 2002, when the Danish Economic Council made an economic evaluation of whether the expansion of small CHP and wind power had been good for society. As we will see later in this chapter, the evaluation was based on the presumption that, because of the overcapacity created by the two big power stations, the capacity of the small CHP stations did not have any value in the calculation.

The above facts from the preceding observations support and add to the lessons learned from the Nordkraft case. The institutional set-up was not able to identify and implement the best alternatives by itself. In this case, a core element was that the plan of the Danish Parliament entailed a radical technological change.

The discourse of the power companies focused on the importance of finding a solution that would satisfy the internal power balance between the seven-member power companies of ELSAM. The identification and implementation of small CHPs, wind power, and energy conservation were not part of their interest or perception of reality. And even if they were, the implementation would be out of their reach.

Even in a situation in which the parliament had decided on a plan including the elimination of new coal-fired power stations, the interest of the existing organizations was so strong that they would still promote such an alternative. As in the case of Nordkraft, the proposal representing a radical technological change had to come from outside the organizations linked to the existing

19. County council member Karl Bornhøft during the discussion of Nordjyllandsværket.

technologies of coal-fired power stations. The promotion of a concrete technical alternative was subject to public discussions at the local municipality and county level as well as at the national level, including the parliament. It contributed to the public awareness that alternatives existed that would fulfill parliamentary objectives better than another coal-fired power station.

This case revealed several levels of institutional barriers to the implementation of radical technological change, including the awareness of the democratic infrastructure, as emphasized in Chapter 3. Afterward, this awareness was used to propose changes in public regulation as well as the improvement of the democratic infrastructure, as described in the book *Democracy and Change* by Hvelplund, Lund, Serup, and Mæng (1995).

The design of the concrete technical alternative was helped and qualified because ELSAM led a policy of complete openness in terms of providing access to all technical and economic data. Consequently, it was possible, to a large degree, to base both the reference and the alternative on the same data and main assumptions. This openness indeed raised the level of debate. However, as we will see in the next case, after introducing a liberalization of the electricity sector, many such data became inaccessible, which created a barrier to a competent public debate.

5. CASE V: THE TRANSMISSION LINE CASE (1992–1996)

The case of the transmission line is the story of how the power company ELSAM did almost anything to avoid the presence of concrete alternatives to a new 400 kV airborne transmission line between the cities of Aalborg and Aarhus. ELSAM even ended up withholding technical data on the grounds of "national security", thus claiming that concrete alternatives that had been designed and promoted by local citizens were based on "incorrect" data. The case description is based on the books *Evaluation of the Need for a High-Voltage Transmission Line between Aalborg and Århus* (Andersen, Lund, and Pedersen 1995),[20] *Public Regulation and Technological Change. The Case of Nordjyllandsværket* (Lund and Hvelplund 1994),[21] and *Does Environmental Impact Assessment Really Support Technological Change?* (Lund and Hvelplund 1997).

ELSAM proposed investing in a new transmission line, which was part of a centralized system that was well suited for the ELSAM organization. However, the idea of a centralized system opposed the wishes of a majority of politicians and the ideas of decentralization expressed in the parliamentary energy plan Energy 2000, as described in the previous section.

20. Translated from Danish: *Vurdering af behovet for en højspændingsledning mellem Aalborg and Århus*.

21. Translated from Danish: *Offentlig Regulering og Teknologisk Kursændring. Sagen om Nordjyllandsværket* (Lund and Hvelplund 1994).

In November 1991, ELSAM asked for an approval of a high-voltage transmission line between Aalborg and Aarhus, and the Danish Energy Agency granted permission in January 1992. In accordance with the law on electricity supply, the Danish Energy Agency should have evaluated whether the new transmission line proposed was consistent with the overall energy plans and policies. However, the Energy Agency never made a proper review of this question. The Energy Agency never asked if the assumptions behind the ELSAM calculations were in accordance with the parliamentary energy policy of Energy 2000, and it never assessed whether the transmission line was necessary to secure the supply.

After the permission was given, the local county of Northern Jutland had to attend to the physical planning process and make an environmental impact assessment of the project, which involved a public participation phase. In principle, the politicians and the public had to weigh the costs of environmental damage against the benefits of security of supply. The local county carefully described the prospective damage to nature, but ELSAM could not—or would not—provide an equally careful description of how and to which extent the transmission line would improve the security of supply.

Three river valleys in untouched nature had to be used for 50 meter high voltage towers. The transmission line was supposed to cross beautiful Mariager Fiord and a huge meadow area between Rold Forest and the famous Lille Vildmose marshland. Massive interests of nature protection were at stake. But what exactly did Danish society gain from paying such a price? How would the transmission line improve the security of supply? This question was posed again and again by the local citizens, but ELSAM refused to answer it.

Shifting Arguments for the Need

ELSAM's reasons for constructing a new high-voltage transmission line changed substantially as time went on. First, it was caused by building Nordjyllandsværket. In the expansion plans of ELSAM from 1991 (ELSAM 1991), Nordjyllandsværket was named "NEV B3" (unit number 3 at NEFO Vendsysselsværket, the location of the new unit), and the transmission line in question was named "400 kV NEV-TRI". ELSAM stated the following reasons for the need for the new transmission line:

When NEV B3 is put into operation, limitations on the simultaneous operation of NEV B3 and the transmission line to Sweden will sometimes occur. Therefore, it is recommended that the grid for the sake of the exploitation of NEV B3 and the line to Sweden is increased.[22]

22. Translated form Danish: *Når NEV B3 er idriftsat, vil der i en række driftssituationer være begrænsninger på samtidig udnyttelse af NEV B3 og Konti-Skan 2. I NUP87 blev det derfor indstillet, at nettet af hensyn til udnyttelsen af NEV B3 og Konti-skan 2 udbygges med....* ELSAM Netudvidelsesplan 1991, p. 29.

The citation thus says that the need for the new transmission line was based on the construction of Nordjyllandsværket. Consequently, when analyzing Nordjyllandsværket, we included the cost of the transmission line of 300 million DKK in the calculation, as shown in Table 8.5. However, now ELSAM changed their view and said:

The transmission line 400 kV NEV-TRI is to be constructed regardless of whether Nordjyllandsværket is built or not. Consequently, Henrik Lund cannot save 300 million in the alternative as calculated.[23]

But if it was not caused by Nordjyllandsværket, why did Denmark then need the transmission line? ELSAM put forward several arguments: security of supply, reserve capacity in the case of renovation of other transmission lines, and electricity transit, as well as the implementation of the old centralization plan from the 1960s. Local politicians expressed the opinion that transit was not a valid reason to compensate for the environmental consequences of locating such high-voltage towers in nature. In 1992, ELSAM stated in an article:

Transmission lines are always built for the sake of security of supply in Jutland-Funen,[24]

and

It is the strict policy of ELSAM that transmission lines are never built for the sake of transit.[25]

The hesitation of ELSAM in presenting any specific calculations to the public, thus documenting the need for the new transmission line, must be viewed in the light of these facts. ELSAM did not want to reveal that the need was a direct consequence of the construction of Nordjyllandsværket. Neither did ELSAM want to reveal that the need was also related to transit. Moreover, ELSAM did not want to show the public that the new transmission plan was one further step in the direction of the centralization plans arising in the 1960s and thereby a contradiction to the political wishes expressed in Energy 2000.

Local citizens made several requirements directly to ELSAM to see the documentation for the improvements in security of supply, but ELSAM would not hand over any calculations. A national newspaper also tried to access this information, but ELSAM responded:

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23. Translated from Danish: *Højspændingsledningen "400 kV NEV-TRI" skal bygges uanset om Nordjyllandsværket etableres. Henrik Lund kan derfor ikke spare de 300 mio.kr., han regner med i den alternative plan*. ELSAM, February 27, 1992. In Aktsamlingen, aktstykke 1i.

24. Translated from Danish: *Ledningerne bygges altid af hensyn til forsyningssikkerheden i Jylland-Fyn. ELSAMposten*. August 1992. In Aktsamlingen, aktstykke 3i.

25. Translated from Danish: *Det er ELSAMs helt klare politik, at ledningerne aldrig bygges af hensyn til transit*. ELSAMposten, August 1992. In Aktsamlingen, aktstykke 3i.

We have no obligation to let a random civic association evaluate our calculations.[26]

Then the local county made a formal request for further information to the Danish Energy Agency. It answered by returning a calculation made by ELSAM, which still claimed that the new transmission line was needed because of security of supply. However, that calculation did not account for any improvement in the security of supply.

Security of Supply

The ELSAM calculation, which was supposed to support the claim that the transmission line was needed to provide security of supply, revealed the following two conditions:

- An existing 150 kV line will be due to overload in the future, in case 1000 MW must be transmitted from Northern Jutland to the south of Denmark. The overload will occur if all the following assumptions are fulfilled simultaneously: all three power stations in Northern Jutland (including Nordkraft and Nordjyllandsværket) are producing full power, both connections to Sweden are importing full power, the consumers in Northern Jutland demand only 60 percent of full load, *and* the existing 400 kV southward transmission line is out of order.
- The line is only due to overload if all assumptions occur simultaneously. Overload only occurs if 1000 MW are to be transmitted, while 700 MW can be handled without any overload. This means that *if* one power station is not producing, *if* one connection to Sweden is not used for import, *if* Northern Jutland has maximum electricity consumption, or *if* the existing 400 kV line is not out of order, then there is no overload.

The decisive question regarding the security of supply was, in the preceding situation, would there be a need for 1000 MW in the rest of the ELSAM area? That question was never asked by the Danish Energy Agency, and, consequently, it granted an approval without knowing the answer.

We, the local citizens, had to evaluate the question ourselves, which we did, as illustrated in Table 8.7. And the answer was clear. There was no need for the transmission line in terms of security of supply. No electricity consumer could be identified who would be out of electricity if the new transmission line was not built and who, in the same situation, would have electricity if the transmission line was built. In fact, no consumer would be out of electricity supply at all, whether or not the transmission line was built. The whole issue had nothing to do with security of supply. It was solely related to the use of the many power stations in Northern Jutland—all too many, one may argue.

26. Translated from Danish: *Vi har ikke pligt til at lade en vilkårlig borgerforening vurdere vore beregninger*. Det fri Aktuelt, July 23, 1992.

TABLE 8.7 Overview of Need for Transmission Capacity

Capacity in Northern Jutland	
Sweden I	300 MW
Sweden II	300 MW
Nordkraft power station	240 MW
Vendsysselsværket	295 MW
Nordjyllandsværket	350 MW
Sum	1485 MW
Consumption in Northern Jutland (60 percent load)	−443 MW
Possible transmission to the rest of ELSAM	1042 MW
Capacity in the ELSAM area	
Installed capacity by year 1998	5619 MW
Of which full available power	4852 MW
Of which in Northern Jutland	−1185 MW
Remaining capacity in the rest of ELSAM	3667 MW
Consumption in the rest of ELSAM (60 percent load)	−2247 MW
Full available spare capacity in ELSAM	1420 MW

As shown in Table 8.7, it is correct that a situation can be identified in which Northern Jutland could export 1042 MW. However, in such a situation, there would be no need for 1042 MW in the rest of the ELSAM area. On the contrary, a full available spare capacity of 1420 MW would be present, even if Northern Jutland was not exporting at all. Consequently, no electricity consumer in ELSAM would be out of electricity.

Given this evidence, ELSAM provided a series of new calculations, which the local citizens asked to see. However, this time ELSAM withheld the calculations by referring to national security matters. If terrorists knew all the technical data of the transmission line system, it would be easy for them to know which tower to blow up, ELSAM argued, and this view was backed up by the Danish Ministry of Defense.

Concrete Technical Alternatives

Local citizens also proposed concrete technical alternatives to the 400 kV transmission line and asked to have these alternatives properly designed and included in the discussions. The local county of Northern Jutland could not conduct such studies, and they could not make ELSAM do it either. As local citizens, we developed a series of alternatives and presented these to the public several times. Finally, these alternatives were described and carefully evaluated in the report from 1995 mentioned at the beginning of this section.

In the report, a detailed assessment of the transmission line systems was made similar to the situation defined in Table 8.7, and the preceding conclusions were confirmed. The transmission line was not necessary in terms of security of supply. Then, the following technical alternatives were defined:

1. A direct current high voltage cable
2. A 150 kV alternating current high voltage cable instead of a 400 kV airborne transmission line
3. To close down the two old power stations, Nordkraft and Vendsysselsværket, when the new power plant Nordjyllandsværket is put into operation
4. To reinforce the existing 150 kV transmission line system

All of these alternatives were able to remove the overload which ELSAM claimed to be the reason for needing the 400 kV airborne transmission line.

Alternative 4 is of special interest regarding the conflict between ELSAM, which wanted a centralized system, and the Danish Parliament's Energy 2000, which planned for a decentralized system. In the case of a centralized system, the system would benefit from strong 400 kV connections between the big power stations located near the big cities. However, in a decentralized system with a high amount of widely distributed small CHP stations and wind turbines, the system would better benefit from a strong local grid. This could be accomplished by reinforcing the existing 150 kV grid.

The report included a calculation of the consequences of *not* putting Nordjyllandsværket into operation. In such a situation, there was no overload at all. Consequently, the first statement of ELSAM was confirmed; namely, that the reason for establishing the transmission line was directly related to Nordjyllandsværket.

Later, ELSAM claimed that the calculations of the local citizens were performed using incorrect data. The calculations were based on the latest technical grid data published in 1991 and 1992. However, ELSAM claimed to have slightly changed the data, but due to national security, the data were no longer publicly accessible.

Conclusions and Reflections

The case of the transmission line illustrates how the power station company ELSAM proposed technical solutions that fit well into their existing organization and how the Energy Agency was not capable of analyzing how such a technical solution contradicted the idea of the Danish Parliament's energy plan Energy 2000. The Energy Agency was also unable to conduct an analysis of alternatives relevant to the implementation of the parliamentary energy policies. The case also reveals the following choice-eliminating mechanisms:

- ELSAM presented one—and only one—technical alternative.
- ELSAM changed its argument along the way and ended up emphasizing that the need was based solely on security of supply.

- ELSAM withheld the assumptions behind their calculations from the public, even in a situation in which the local politicians and the public were supposed to evaluate the benefit of security of supply against the damage to nature.
- When ELSAM was forced to reveal their calculation, it became evident that there was no need for the transmission line in terms of security of supply.
- ELSAM withheld any further calculation and data by referring to national security.
- ELSAM argued that the alternatives put forward by local citizens were based on incorrect data. ELSAM withheld small changes in the data for national security reasons.

A main point to be learned from this case is that the existing institutional set-up cannot identify or promote alternatives representing radical technological change. Such alternatives cannot be expected to come from organizations linked to existing technologies. In this case, the discourse of the power companies was focused on maintaining and expanding the transmission line infrastructure that would help along an energy supply based on central power stations, such as the existing ones. Changing the strategy by expanding the local grid and thereby helping the introduction of small CHP plants and distributed wind turbines was not within their interest or perception of reality. However, in this case, unlike Nordkraft and Nordjyllandsværket, they would have been able to implement such an alternative. Most of the local 150 kV transmission lines were owned and operated by the same organizations as the proposed 400 kV transmission line systems.

As in the former cases, the proposal representing a radical technological change had to come from outside the organizations linked to the existing technologies of coal-fired power stations. Again, the promotion of a concrete technical alternative was subject to public discussions. It contributed to raising the public awareness that alternatives existed that would fulfill the political wishes of environmental protection and still provide energy security.

The case revealed several levels of institutional barriers to the implementation of radical technological changes, including the awareness of the democratic infrastructure, as emphasized in Chapter 3. This awareness was later used to propose changes in the public regulation as well as improvements in the democratic infrastructure, as described in *Democracy and Change* (Hvelplund, Lund, Serup, and Mæng 1995).

Regarding the openness of technical data, this case differs from the former case of Nordjyllandsværket. In the Nordjyllandsværket case, the design of a concrete technical alternative was helped and qualified because ELSAM led a policy of complete openness in relation to all technical and economic data. In this case, data were held back and used to incriminate the technical status of the alternatives designed and promoted by the local citizens.

6. CASE VI: EUROPEAN ENVIRONMENTAL IMPACT ASSESSMENT PROCEDURES (1993–1997)[27]

The case of the European Environmental Impact Assessment (EIA) directive illustrates how planning procedures aimed at promoting cleaner technology alternatives to, among others, coal-fired power stations, failed to even accomplish the description of such alternatives. As shown in the previous cases, alternatives representing radical technological change cannot be expected to come from organizations linked to the existing technologies. Therefore, to implement technological change, it is necessary to consider other proposals. In principle, the EIA procedure proposes an assessment of alternatives, including alternatives representing radical technological change. This case description is based on the book *Does Environmental Impact Assessment Really Support Technological Change?* (Lund and Hvelplund 1997).

This study is based on the cases of Nordjyllandsværket and the transmission line between Aalborg and Aarhus, as described in previous sections. Moreover, the study includes a similar case of a planned power station in Copenhagen, called Avedøreværket.

In 1985, the European Union (EU) decided on a directive on EIA (European Council 1985). It was based on the preventive principle: to eliminate the pollution source rather than attempting to counteract it subsequently. According to the Danish implementation of the directive, an EIA must review the main alternatives to the project in question and assess the environmental consequences of each alternative. If this is done properly, EIAs can assist in raising Choice Awareness and help local citizens and upcoming new technology industries with a proper assessment of their cleaner technologies, including public discussions on the alternatives.

Implementation of the EIA Principles in Denmark

According to the 1985 EU directive on EIA, all EU Member States must commission an assessment of the environmental consequences of certain types of projects, including power stations, before a building permission will be granted. The EU directive was adopted on the basis of the assumption that the best environmental policy consists in preventing pollution or nuisance, rather than counteracting the effects subsequently.

In Denmark, the EU EIA procedure was implemented in the planning legislation, and the EU directive was translated into Danish law in 1989. Compared to the EU EIA directive, Danish law was more stringent on two counts: Danish

27. Excerpts reprinted from *Environmental Impact Assessment Review*, 17/5, Henrik Lund and Frede Hvelplund, "Does Environmental Impact Assessment Really Support Technological Change? Analyzing Alternatives to Coal-Fired Power Stations in Denmark", pp. 357–370 (1997), with permission from Elsevier.

law used existing planning procedures for public participation and it clearly stipulated that alternatives should be described and assessed. The aim of the EU EIA directive or the Danish EIA legislation is not to compel the use of a specific solution. Rather, the aim is to promote cleaner technologies by providing information on the environmental consequences of a solution, before permission is granted for a project with major environmental impact. EU legislation requires only that the environmental situation is taken into account, not that the environmentally best solution is chosen. The Danish implementation, on the other hand, contains specific requirements: that the assessment must include an outline of the main alternatives and that public participation is ensured in two phases.

Nonetheless, the Danish implementation of the directive was fragmented and thus weakened. At that time, Denmark was divided into 14 counties (see Figure 8.7), each with an elected regional council and a professional administration. At the regional level, the Environmental Act and the Planning Act were administered by different departments. In the case of a new power station, the EIA was the responsibility of the authorities of the region in question. The EIA was carried out with public participation according to the Planning Act, which involved the publication and distribution of a proposal followed by public hearings, but the EIA of cleaner technology alternatives was beyond the Planning Act's normal procedure.

FIGURE 8.7 The problems of geographical boundaries. The map of Denmark on the left shows the boundaries of the regional administrations. The region of Northern Jutland is shown by a hatched signature. The map of Denmark on the right indicates ELSAM's supply area. A new coal-fired power station is included in the supply of the whole area but must be placed in one of the regions. Alternatives in the form of reductions in power consumption, decentralized CHP, and renewable energy must be dispersed throughout the whole supply area and, therefore, involve several regions.

Example 1: Nordjyllandsværket

As mentioned previously, my colleagues and I designed and promoted an alternative that could be expected to produce the same amount of electrical power and heat as Nordjyllandsværket but with less fuel and less pollution. The cleaner technology alternatives to Nordjyllandsværket should cover the same geographical area as the existing supply area: Jutland and Funen. Physically, the geographical locations differ. Where Nordjyllandsværket is placed in Northern Jutland, the decentralized cogeneration units and energy conservation would be located in the smaller towns, closer to the consumers.

Table 8.8 shows the most significant alternatives proposed to Nordjyllandsværket. The following describes why two EIAs were presented. Both assessments were subject to our objections to the Nature Protection Appeal Board under the Planning Act. All of the alternatives shown in Table 8.8 were included in the complaints from us to the first and the second Appeal Boards about deficiencies in the EIAs.

In the summer and autumn of 1993, the North Jutland Regional Authority prepared an EIA of Nordjyllandsværket. Prior to its preparation, my colleagues and I, with reference to the EU EIA directive, called the Regional Authority's attention to two of the alternatives presented in Table 8.8. However, the Regional Authority claimed that it was not their responsibility to make an environmental assessment of these alternatives.

TABLE 8.8 Alternatives to Nordjyllandsværket, with Supply Areas and Geographical Locations

Alternative	Supply Area	Geographical Location
ELSAM's proposal		
Nordjyllandsværket (400 MW coal-fired power station)	Jutland/ Funen	Aalborg
Alternatives		
1. Natural gas-fired combined cycle station in Aalborg	Jutland/ Funen	Aalborg
2. Natural gas-fired station at Nordjyllandsværket	Jutland/ Funen	Aalborg
3. Environmental alternative (combination)	Jutland/ Funen	Jutland/Funen
4. "Only one station", such as Fredericia	Jutland/ Funen	Fredericia
5. Location south of Trige (avoids need for high-voltage lines)	Jutland/ Funen	Such as Aarhus
6. Brundtland Plan (combination)	Jutland/ Funen	Jutland/Funen

Later, in a written reply (North Jutland Regional Authority 1993), the Regional Authority emphasized that the terminology "description of alternatives" should be understood as alternative locations and designs. According to this definition, the Regional Authority was convinced that it was irrelevant to include alternative modes of production, such as cleaner technologies or a division of Nordjyllandsværket into smaller units.

Consequently, a number of citizens complained about the EIA report to the Nature Protection Appeal Board, the statutory appeals body under the Planning Act. The Nature Protection Appeal Board's first decision (Nature Protection Appeal Board 1993) was distinct and precise:

1. An EIA must not only include alternative locations but also other significant alternatives.
2. An EIA must perform a more or less thorough examination of the environmental advantages and disadvantages of each of the alternatives considered as well as their locations. The regional planning authority has the responsibility, more or less, of revealing the environmental consequences of alternatives arising from public participation.
3. An EIA must include information on the background for the desired location regarding environmental impact.
4. An EIA of an electric power station must consider that high-voltage lines are connected from the station. This situation must be dealt with in the impact assessment.
5. The question of cleaner technology must be dealt with if the question is significant for the assessment of whether one can avoid, reduce, and, if possible, neutralize threats to the environment.

The Nature Protection Appeal Board did not state that their decision was valid only within the geographical boundaries of the region. They concluded that the listed conditions were not fulfilled and that the Amendment to the Regional Plan was invalid.

The North Jutland Regional Authority issued a new EIA for Nordjyllandsværket in December 1993. Again, this assessment did not fulfill the EU EIA conditions or the conditions formulated by the Nature Protection Appeal Board in its first decision. The impact assessment was thus unsuitable as a basis for public discussion. It listed a number of alternatives that could not be compared, and two of the alternatives were not assessed regarding their environmental impact. Nothing was said about the background for the desired location in terms of environmental impact; no environmental assessment of any part of the high-voltage transmission lines that would result from Nordjyllandsværket was included, and the analysis did not treat the question of cleaner technology.

Again, a complaint about these deficiencies was submitted to the Nature Protection Appeal Board. The Board's second decision (Nature Protection Appeal Board 1994) did not comment specifically on any of the points presented in the complaint. Regarding the alternatives, the Board concluded that the EIA conducted by the Regional Authority was satisfactory. The Board agreed with the Regional Council stating that the Council was unable to conduct an EIA of the energy policy alternatives to Nordjyllandsværket and was therefore not compelled to do so.

Nonetheless, the Nature Protection Appeal Board indicated one problem in the impact assessment: it should have included an alternative with decentralized CHP within the Northern Jutland region. However, the Board determined by a vote, with nine for and two against, that this deficiency was insufficient to declare the assessment invalid. In practice, the consequence was that the regional councils were not required to assess environmentally cleaner technology alternatives to large coal-fired power stations at the project level. These power stations have always formed part of a plan to supply the whole Jutland/Funen area, but per se they will always be placed in only one of the regions. Cleaner technology alternatives, which were necessary for the fulfillment of the Danish Parliament's CO_2 goals, would be valid for the same supply area as a large coal-fired power station, but they consist of technologies that are dispersed over several administrative regions. The decision of the Nature Protection Appeal Board stated that the Regional Authority was not compelled to include alternatives that were located outside the region. With this decision, cleaner technology alternatives were typically excluded.

Example 2: High-Voltage Transmission Lines

As mentioned earlier, together with Nordjyllandsværket, ELSAM wished to construct a high-voltage transmission line from the new generating station in Aalborg southward to the city of Aarhus, which is a distance of approximately 100 kilometers. As described, all documentation supporting the need for this line assumed the establishment of Nordjyllandsværket, and the construction of the transmission line is considered a consequence thereof.

According to the EU directive, an EIA must include all direct and indirect environmental impacts of the proposed project. In a written reply to a question from one of the complainants, the EU directorate-general XI (environment) said that a high-voltage transmission line is considered an impact arising from the project that should be assessed, according to Article 3 in the EU directive. But the North Jutland Regional Authorities had not included the high-voltage transmission line in the EIA of Nordjyllandsværket; therefore, it was included in the complaints to the Nature Protection Appeal Board. The Appeal Board's first decision was in general precise, but vague in its reply to the transmission line question. According to the Board, the EIA should have included the first part of the route of the high-voltage transmission line in question to reveal its environmental consequences. The meaning of this formulation was unclear, because a line between two points only has importance if the whole line is considered in the same way that half of a bridge has no importance. In the concept phase of the second EIA, the complaints emphasized that the Regional

Authority should obtain the necessary calculations to establish whether the line was justified, also in the event that Nordjyllandsværket was not constructed. The Authority did not do this; instead, it made an environmental assessment of the station's linkage to the high-voltage grid. This is a distance of a few hundred meters and has never been part of the preceding high-voltage connection between the new power station and Aarhus.

The complainant received a letter from the Danish Energy Agency that confirmed that all the submitted documentation for the high-voltage line had assumed the construction of Nordjyllandsværket. Even though the Regional Authority had not obtained the necessary information and even though no documentation had been submitted that substantiated the need for the line without the power generation station, the Nature Protection Appeal Board's only comment was "No information has been presented which can give cause to a new consideration of this question". Later, it was decided that an individual EIA should be made of the high-voltage line, but the relationship between Nordjyllandsværket and the line was never subject to an EIA.

Example 3: Avedøreværket

In 1995, a power company on the island of Zealand (SK Energy) applied for permission to build a 460 MW multifuel power station, Avedøreværket unit II, close to Copenhagen. It was a multifuel station because it was designed to use a combination of coal, natural gas, and biomass. In reality, the main fuel was thought to be coal. The Avedøre II station was to be ready for production in 2003.

Seen from an EIA viewpoint, the building of the Avedøre station had the same problem as Nordjyllandsværket: cleaner technology alternatives were not assessed. In this case, the alternative technologies were heat conservation in the Copenhagen area and electricity conservation and cogeneration outside the county of Copenhagen.

In the foreword to the EIA of the Copenhagen County, it is stated: "In that way, the evaluations are solely performed within the geographical area of the county of Copenhagen" (Copenhagen County 1996). This was noticed by OOA, a public interest organization on Energy and Environment, which then sent a complaint to the Minister of Environment and Energy, mentioning the need for including alternatives outside the county of Copenhagen in the EIA procedures (OOA 1996). The Minister did not respond to this letter by changing the EIA procedures. In the following months, a public debate arose regarding the lack of compatibility between the official Danish CO_2 reduction goal and the establishment of a new, mainly coal-fired station. Public resistance to a coal-fired station (caused by the rather obvious lack of a thorough description of alternatives) resulted in the Minister's rejection of the application in the autumn of 1996. The power companies did not give up their plan and quickly changed their application project into a power station based on natural gas. This new application was approved by the Minister on March 31, 1997.

The approval was motivated mainly by the proposed change of fuel. Again, no analyses were presented of the cleaner technology alternatives. This case also shows that Danish EIA procedures cannot ensure that cleaner alternatives from outside the region in question are included in the assessment.

Conclusions and Reflections

When implemented into Danish legislation, the EU EIA directive did require the assessment of alternatives to coal-fired power stations. Such a procedure involved a public participation phase, in which alternative proposals could be made, and the procedure was based on the principle of prevention rather than subsequent counteraction against pollution. Consequently, the whole program in principle aligned with the idea of Choice Awareness by securing a proper description of cleaner technology alternatives. However, in practice, the preceding cases reveal a different reality.

The case of Nordjyllandsværket indicates that serious analyses are not conducted as a matter of course of the decentralized alternatives to large coal-fired power stations in Denmark. The main problem is that the regional administrations are responsible for the preparation of the EIA. The law does not require alternatives that extend beyond the boundaries of a regional authority to be assessed. In the example of Nordjyllandsværket, permission was granted without a proper examination of cleaner technology alternatives.

The example of the high-voltage transmission line between Nordjyllandsværket and the city of Aarhus indicates that it cannot be assumed that a serious analysis is conducted of the relationship between a new power station and a new high-voltage transmission line. This was not the case when it was documented that the justification of the transmission line assumed the existence of the new power station.

The example of Avedøre II is similar to the case of Nordjyllandsværket. It shows that the Danish EIA procedures cannot ensure that cleaner alternatives from outside a region are included in an assessment. In this case, permission was granted to a new natural gas-fired power station before a proper assessment of decentralized cleaner technology alternatives was made.

All in all, the cases reveal that because EIA is implemented on a restricted, regional basis, it does not support the radical technological change represented by cleaner technology alternatives. The responsibility for the preparation of the EIA is given to the regional authorities on the basis of a law that does not require the assessment of alternatives if these extend the geographical boundaries of a regional authority. Thus, one cannot be sure that serious analyses are made of cleaner technology alternatives to large coal-fired power stations.

The main point to be learned from these cases is that an existing institutional set-up may hinder the identification and promotion of relevant and better alternatives if such alternatives represent radical institutional change. The discourse of the power companies aims to identify and promote projects that are relevant within their organizational interests and perception of reality. The discourse of the county council and administration focused on job creation and the identification of proper solutions within the borders of the county. It was outside their interest and perception of reality to evaluate and analyze alternatives outside their jurisdiction.

The fact that a cleaner technology alternative that did not form part of the discourse of the power companies and the county council would officially be rejected on a council meeting was a big problem. To avoid this, the alternative was eliminated beforehand. Even though a proper description and evaluation of a cleaner technology alternative were the basic ideas of the EIA legal procedures, the legal authorities were not able to secure that such an alternative was presented and evaluated.

7. CASE VII: THE GERMAN LAUSITZ CASE (1993–1994)[28]

The German Lausitz case illustrates how, in East Germany after the reunification, massive investments were made in rebuilding both the electricity and the heat supply. However, the rebuilding was done without introducing or expanding the use of CHP and thus deriving substantial fuel saving benefits. By the end of 1992, two of my colleagues at Aalborg University and I were invited to design an alternative, which was introduced and discussed in the debate. The discussion of the alternative revealed how energy conservation and CHP did not fit well into the existing organizations. Thus, representatives of the German brown coal industry heavily criticized the alternative. The case description is based on the books *Rebuilding without Restructuring the Energy System in East Germany* (Hvelplund and Lund 1998b), *Erneuerung der Energiesysteme in den neuen Bundesländern—aber wie?* (Hvelplund, Knudsen, and Lund 1993), and *Kommentar zur Kritik der Lausitzer Braunkohlen AG an der Aalborg Universität-Studie* (Hvelplund, Knudsen, and Lund 1994) and the chapter "Energy Planning and the Ability to Change. The East German Example" in *Institutional Change and Industrial Development in Central and Eastern Europe* (Hvelplund and Lund 1999).

At the end of 1992, two environmental organizations[29] in Lausitz asked us to design an alternative to the further expansion of brown coal in the electricity supply of East Germany. The study was financed by Bündnis 90, who at that time was represented in the regional parliament (Landtag) of Brandenburg.

The survey included an area from Berlin in the north to the border of the Czech Republic in the south, as shown in Figure 8.8. However, Berlin was only partly included in the study. The area encompassed approximately 40 percent of the population of the former East Germany. The area had a comprehensive

28. Excerpts reprinted from *Energy Policy*, 26/7, Frede Hvelplund and Henrik Lund, "Rebuilding without Restructuring the Energy System in East Germany", pp. 535–546 (1998), with permission from Elsevier.

29. Netzwerk Dezentrale Energienutzung e.V. and Grüne Liga e.V., Cottbus.

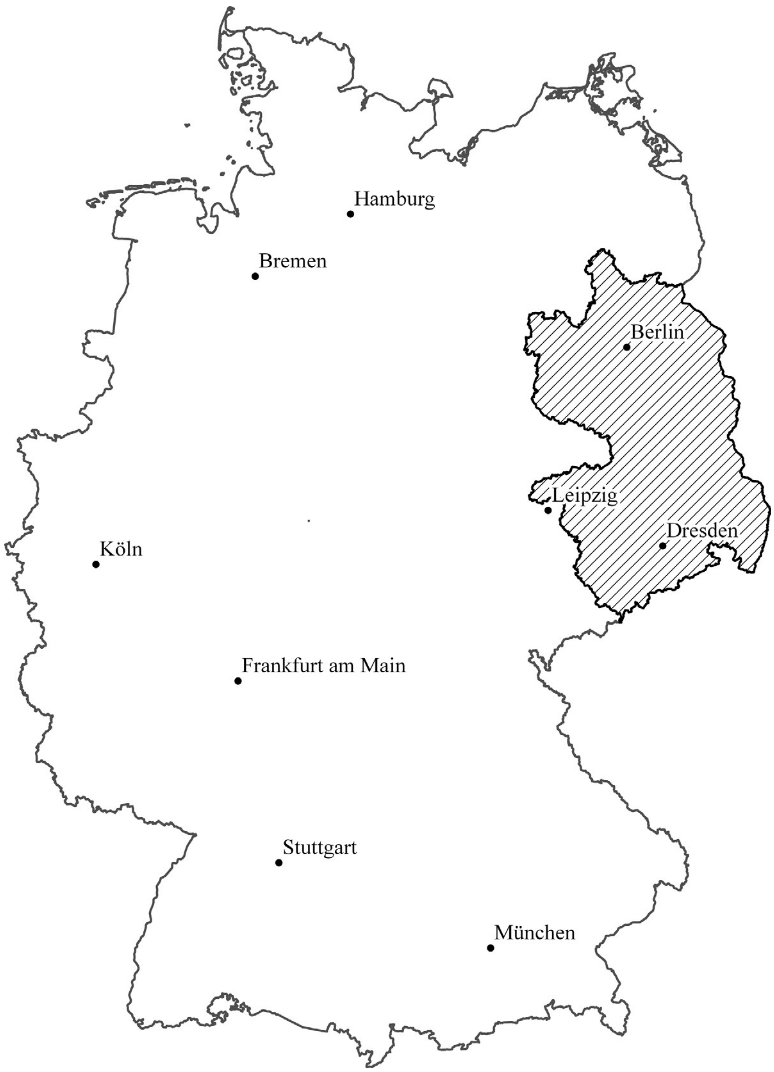

FIGURE 8.8 The Lausitz area covered by the study.

production of brown coal and several large-scale power stations based on brown coal. From 1960 to 1980, the government eliminated 70 villages and rehoused 30,000 citizens to access the coal resources. Moreover, the mining of coal had a severe negative impact on the groundwater of the area.

The planned and, at that time, already partly implemented restructuring of the East German energy system was unique. For approximately 10 years it was planned to spend 60,000 million DM on this restructuring. Such an extensive investment in changing the energy system of a country within such a short period of time was historic. An extraordinary situation like this case offers the opportunity to modernize the energy system—investing in the most appropriate and most developed technologies wherever possible. But the most important factor was to implement the necessary modernization of the institutional structure of the energy organization. In the German case, this could create a situation in which East Germany became an example to follow for other East European countries that needed the same development. Several export possibilities could emerge from such a position.

Unfortunately, what happened at that time was the complete opposite: a completely new system was built, but it was not modernized. Thus, the worst of all situations was created. East Germany had a new but outmoded energy system that could not be expected to fulfill future environmental demands. Many energy installations have a lifetime of 20–40 years. In this case, East Germany would be placed in a worse situation than most other countries in terms of energy supply and environmental impact.

The main problem with the rebuilding plans was that the obvious opportunity of using CHP was not seized. Huge investments were made in new brown coal power stations together with the environmental improvements of old ones, and the heating of houses based on brown coal briquettes was replaced by natural gas in individual boilers.

This situation happened because of a policy to maintain the existing brown coal production in East Germany for a period of time. Two arguments supported this policy. First, there were good reasons to maintain the existing 17,000 jobs in the brown coal areas, as these areas had already experienced high unemployment figures. Second, brown coal, a domestic resource, was considered a good solution in terms of energy security. Both the national government and the local government in Brandenburg were in favor of the policy.

According to the reference strategy, the electricity capacity would be expanded by building new brown coal-fired power stations and by renovating the best of the old ones. In the Lausitz region, it was planned to invest 15,000 million DM in building or renovating a total capacity of 7200 MW. All power stations were placed next to brown coal mines at the two locations, Jänschwalde and Boxberg/Schwarze Pumpe, far from most urban areas. In practice, this made it impossible to fully exploit the potential of CHP. The planned use of CHP only comprised a minor district heating capacity and heat for a plasterboard production. Only 5 percent of the potential would be exploited in Jänschwalde, and only 11 percent would probably be used in Boxberg/Schwarze Pumpe.

The very lack of CHP in the system made it necessary to use large amounts of oil and natural gas for house heating. The expected development was analyzed and is described in the references listed in the beginning of this section. The analyses showed two characteristics of the reference strategy. First, within the house heating sector, East Germany would become dependent on large imports of foreign fuels, such as natural gas and oil. Thus, the argument of using brown coal for electricity production due to reasons of energy security did not involve the entire energy sector. Second, as most of the house heating boilers in the former East Germany were old and would have to be replaced by new gas and oil boilers, the reference strategy would lead to major investments—not only in big power stations but also in central heating systems and gas and oil boilers in detached houses, apartment buildings, and district heating stations. For the whole East German area, these investments were estimated at approximately 35,000 million DM.

The Alternative

An alternative to the reference was designed to raise awareness in East Germany of the possibility of modernizing the entire energy system while rebuilding it. The alternative entailed the benefits achieved from energy conservation, CHP, and renewable energy. Regarding energy conservation in the demand system, the alternative strategy proposed a 20 percent reduction in heat demand and a 15 percent reduction in electricity demand compared with the reference. The investments needed to achieve these targets were included in the cost analysis. The 20 percent cut in heat demands could be achieved simply by means of a number of technical improvements of heating system regulation, such as thermostat valves and the change from serial to parallel radiators.

Regarding efficiency improvements in the supply system, the alternative proposed a substantial use of CHP in combination with heat pumps to replace, among others, electric heating. The marginal fuel consumption for electric heating is twice the fuel consumption of gas and oil boilers and 5–10 times the marginal fuel consumption of CHP. Therefore, the alternative was designed with the purpose of avoiding electric heating and promoting district heating based on CHP. All electric heating was substituted by central heating systems, and district heating systems and CHP were proposed in most urban areas.

The house heating net consumption in the Lausitz supply area was calculated as 190 PJ/year, covering hot water and space heating of private households and office buildings as well as industry that could be supplied by district heating (approximately 10 percent). Based on demographic data for all cities, towns, and rural areas, the total energy consumption was categorized according to different town sizes. The survey showed that by connecting 80–90 percent of the potential households in all urban areas to a district heating system, it was possible to produce 131 PJ/year of the total 160 PJ/year from CHP. This corresponded to approximately 80 percent of the market. Here, a district heating loss of 20 percent and a supply of 131 PJ/year were assumed to lead to a CHP heat production of 157 PJ/year.

To meet the heat demand, a total CHP heat capacity of 5000 MW was required. The capacity was divided into 2000 MW heat/1600 MW electric power from natural gas and 3000 MW heat/1900 MW electric power from hard coal. Meanwhile, the CHP units also had to supply a reserve capacity for a certain wind power effect. Therefore, the alternative proposed a total investment in 2000 MW electric power based on natural gas and 2500 MW electric power based on hard coal to establish a suitable technical framework for the integration of wind power.

Regarding renewable energy, the alternative proposed an extensive use of wind power and biomass resources. The resources of the area were estimated, and the alternative strategy was based on the use of 50 percent of the potential resources in the year 2010 with wind turbines producing electricity for the grid, straw substituted for coal in the CHP units, wood substituted for oil in individual boilers, and biogas substituted for natural gas in CHP units. Moreover, solar thermal energy was included in the strategy for the production of hot water in the detached houses that were not supplied with district heating. This measure equaled a 20 percent decrease in the fuel consumption of these houses. Figure 8.9 shows the fuel flow diagrams.

Figure 8.9 illustrates how savings, CHP, and renewable energy substantially decreased the use of fossil fuels and thereby CO_2 emissions in the alternative compared to the reference. An economic feasibility study of the reference as well as the alternative was made by comparing the total costs of each solution during a period of 20 years. The study was based on the fuel prices of the early 1990s, including brown coal sales prices from the Lausitz mining company LAUBAG. The prices of biomass resources were based on existing prices in Denmark. Construction and maintenance costs were exact prices for Jänschwalde and Boxberg/Schwarze Pumpe in combination with Danish construction prices for small CHP stations and similar technologies.

A comparison based on the described assumptions showed that the costs of the alternative were slightly lower than those of the reference. However, in this first draft version, the alternative strategy had two political disadvantages: it meant fewer jobs and a higher import of fuels than the reference. These two disadvantages were a direct consequence of the extensive use of imported hard coal. Meanwhile, the higher efficiency of the alternative could also be achieved by using other fuels. Therefore, two other possibilities were analyzed: one in which hard coal was substituted by brown coal, processed into "brown coal dust" with a low content of water, and one in which hard coal was substituted by natural gas and the extensive use of biomass resources.

When compared to the reference, the analysis of the three variants of the alternative gave the following results:

- *Electricity and heat consumption*: The reference and the three variants of the alternative produced or saved exactly the same amounts of electricity and heat.
- *Primary energy supply*: The three variants of the alternative cut down fuel consumption by 50 percent compared with the reference. This is due to the demand-side efficiency, the use of CHP, and the substitution of electric heating.
- *Environment*: The alternative reduced CO_2 emissions to between 20 and 40 percent of the reference emissions. This was partly due to the low fuel consumption and partly due to the use of renewable energy.

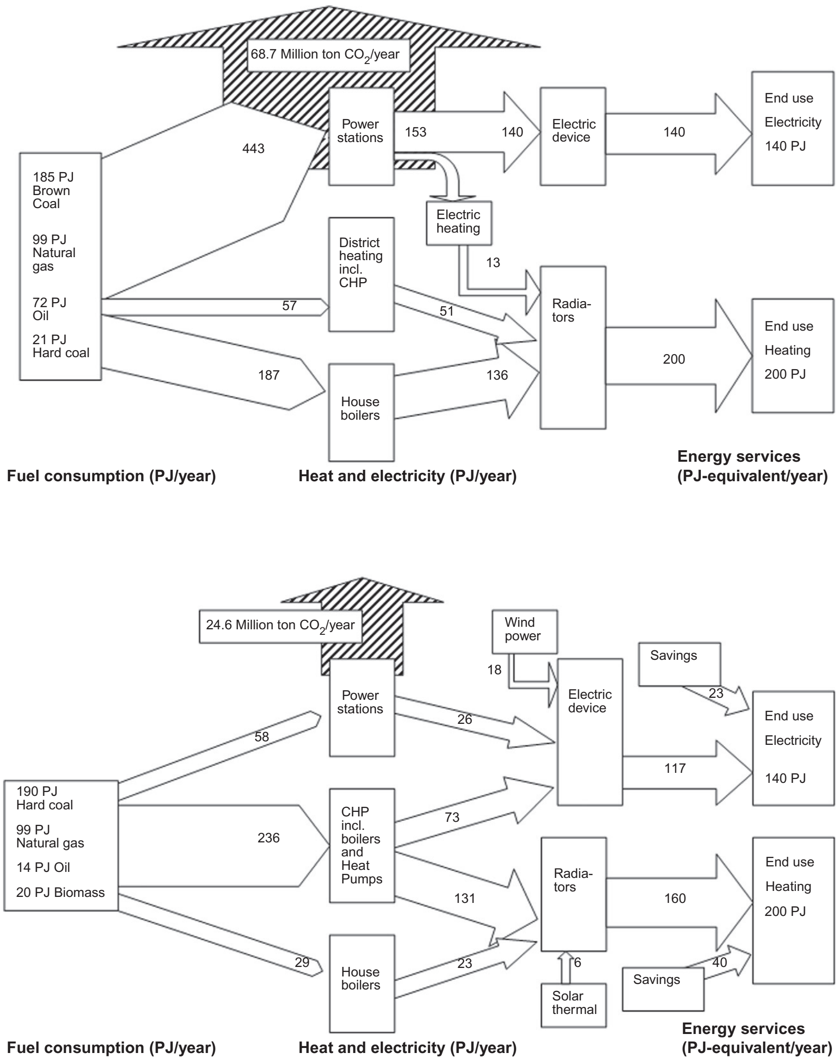

FIGURE 8.9 Energy flow of the reference and the alternative.

- *Economic feasibility*: Based on the fuel prices of the early 1990s, the alternative had more or less the same total costs as the reference. The variant based on hard coal was 8 percent cheaper, while the variant based on natural gas and biomass was 12 percent more expensive. It may be surprising that the very large investment in district heating and CHP in all variants of the alternative did not make them less cost-effective than the reference. This is because the reference also implied huge investments in changing the house heating system: natural gas boilers, central heating, and natural gas pipe systems.

- *Employment*: The hard coal variant created fewer jobs than the reference. On average, over the 20-year period, the employment effects of the reference corresponded to 55,000 jobs. The brown coal and the biomass variants of the alternative had more or less the same employment effects, while the hard coal variant was expected to provide 46,000 jobs.
- *Energy security*: The reference strategy would need to import 72 PJ/year of oil, while the alternative strategy required only 14 PJ/year. Moreover, the reference emptied the storage of domestic brown coal resources in a rate of 485 PJ/year, contrary to the alternative that used only between 0 and 209 PJ/year. The hard coal variant of the alternative was dependent on an import of hard coal of 190 PJ/year. In case of supply failures in the future, the hard coal could be substituted by brown coal processed to "brown coal dust" with low water content. Therefore, the brown coal variant as well as the hard coal variant provided a better solution in terms of energy security than the reference. The natural gas and biomass variants resulted in a dependence on imported natural gas of 209 PJ/year versus the other variants and the reference using only 99 PJ/year.

Conclusions and Reflections

The East German energy system ended up being restructured but, unfortunately, not modernized. The system was changed from a system based completely on brown coal to a system in which electricity production was still based on brown coal and house heating was based on oil and natural gas. Only a very small percentage of house heating was based on CHP. The restructuring would bring the CO_2 emission down from 20 ton/inhabitant in 1989 to 13 ton/inhabitant in year 2010, which was still much higher than the EU average of 8 ton/inhabitant.

By the design and promotion of a concrete technical alternative, it was shown that alternatives did exist, which not only restructured but also modernized the energy system. The implementation of such a radically different technological alternative could reduce East German CO_2 emissions to below 7 tons per inhabitant. The alternative strategy was based on CHP, conservation, and renewable energy. Total costs and the employment effect were approximately the same in the two strategies.

However, the alternative was not implemented. Instead, it was heavily criticized by the coal mining industry (Hvelplund, Knudsen, and Lund 1994). My colleagues and I used the discussion of the concrete technical alternative to examine and analyze the institutional reasons for not modernizing the East German energy system while rebuilding it. This analysis is described in the references listed in the beginning of this section.

The analysis showed that the economy of the East German power companies depended on a continuation of brown coal-based centralized power production and separated heat production based on oil and gas. Furthermore, these companies had a cost structure with a high element of "fixed costs", and therefore low short-term marginal costs. In periods with excess capacity, this cost structure motivated a rather aggressive behavior on the market. This tendency was enforced by the strong obligation imposed on the power companies to be "stock price locomotives" for their parent companies.

As Hvelplund (2005) described in detail, the German VEBA concern owned both electricity and oil companies, and the economically optimal solution to the concern as a whole was both to operate power stations on brown coal and, at the same time, sell oil and natural gas to private households. Consequently, even though the expansion of CHP had the potential of increasing sales from the power production units, it would still mean a loss compared to the sale of oil and gas. The optimal solution was to avoid CHP.

Again, the main lesson from this case is that, given the institutional set-up, society could not identify and implement the best alternatives. The discourse of the brown coal power and mining companies aimed to maintain and renew the existing technologies. The alternatives, including decentralized CHP stations, energy conservation, and renewable energy, did not form any part of their interest or perception. Such alternatives representing radical technological change could not originate from the organizations linked to the brown coal technologies.

The discourse of the VEBA concern focused on the optimization of the earnings of the concern as a whole, and since that involved power and mining companies as well as oil companies, the alternatives based on CHP, energy conservation, and renewable energy were not in their interest.

The description of alternatives based on radical technological change had to come from outside the existing organizations, and when they were promoted by local citizens and NGOs, they were heavily criticized by the brown coal industry. Based on this case, we identified a number of institutional barriers to the implementation of new technologies, and we advocated that clear and non-bureaucratic rules had to be defined regarding the conditions for technical connection to the public grid. Price conditions based on the long-term "avoided marginal cost" principle (including external costs) had to be established. Likewise, financial possibilities had to be arranged for organizations that wanted to invest in new technologies. Institutional and organizational preconditions of this kind do not automatically evolve on the market.

8. CASE VIII: THE GREEN ENERGY PLAN (1996)[30]

The case of the Green Energy Plan is the story of how the description of concrete technical alternatives can be used to raise Choice Awareness in the public debate on national energy policy. The Green Energy Plan was published by the

30. Excerpts reprinted from *Environmental & Resource Economics*, 14/3, Henrik Lund, "A Green Energy Plan for Denmark", pp. 431–440 (1999), with permission from Springer Science+Business Media.

Danish General Workers' Union and introduced in the spring of 1996 as an input to the public debate on the future energy system of Denmark. The official Danish energy plan, Energy 21 (Danish Ministry of Environment and Energy 1996), was adopted soon after the public debate. The case description is based on the books *Elements of a Green Energy Plan Which Can Create Job Opportunities* (Lund 1996), *Feasibility Studies and Public Regulation in a Market Economy* (Hvelplund and Lund 1998a), and *A Green Energy Plan for Denmark. Job Creation as a Strategy to Implement Both Economic Growth and CO_2 Reduction* (Lund 1999b).

The Green Energy Plan is based on the observation that normally the cost of implementing CO_2 reduction policies is considered a threat to both economic growth and employment. The plan shows that, to some extent, CO_2 reduction goals can be implemented that create jobs, and such strategies can help economic growth.

The Green Energy Plan involved a number of initiatives, which Denmark could choose to implement as a supplement to the official energy policies. The plan was made on the basis of a total evaluation of environment, economics, balance of payment, consumption, and employment. Primarily, the aim was to enable Denmark to continue the reduction of CO_2 emissions. This should be achieved by means of long-term, investment-dependent alterations in the infrastructure, which would thus develop toward a more decentralized renewable energy system. The changes in question would require investments, but these would provide an improved employment situation and a better environment.

The Design of the Concrete Technical Alternative

The public discussion of a new Danish energy policy in 1995 was based on the fact that the former official energy plan from 1993 had proven insufficient in terms of meeting the CO_2 emission targets defined by the Danish Parliament. According to these targets, CO_2 emissions should be cut by 20 percent in 2005 compared to 1988. Consequently, the environmental consideration of the Green Energy Plan focused on the establishment of an energy system that would reduce CO_2 emissions and meet the targets. Thus, the Green Energy Plan defined the 1993 official strategy as a reference and presented an alternative comprising the following elements:

- *Switch from electric heating to central heating*: In the Danish energy system, the fuel consumption of electric heating was twice as high as the fuel consumption of central heating from individual gas or oil boilers and four times as high as the marginal fuel consumption of heat from CHP. In the reference, it was intended to switch from electric heating to central heating in areas with natural gas or district heating. The Green Plan proposed that the switch from electric heating should also be implemented outside these areas.
- *Improved insulation and low-temperature district heating*: In 1996, the large Danish urban centers were supplied with district heating from large

coal-fired CHP stations with steam turbines. The fuel consumption for district heating in these stations depended on the temperature level of the district heating system. Therefore, a double gain could be achieved by improving the insulation of houses in these cities and towns, and thereby reduce the demand for district heating, and by making the heat production of steam turbine stations more effective.

- *Utilization of natural gas in district heating*: In 1996, natural gas used for individual house heating without CHP was widespread in Denmark. Fuel savings could be achieved by installing individual micro-CHP units in the houses or by introducing district heating in combination with CHP. The latter solution was suggested in the Green Energy Plan.
- *Dispersed use of biomass*: The Green Energy Plan proposed the construction of biogas stations corresponding to the use of 100 percent of the organic industrial waste produced and 50 percent of the manure from livestock farming.
- *Wind turbines*: The Green Energy Plan chose a development in which a wind power capacity of 3000 MW would be reached by 2015. The economic calculations assumed that a number of the turbines were established at offshore wind farms, where construction prices were higher.
- *Further training and energy conservation*: The Danish industrial sector had a great potential for reducing its electricity consumption. The problem was to identify and implement these savings. Therefore, the Green Energy Plan suggested that electricity savings were implemented by means of an environmental training program for all industrial workers. On the basis of the Danish experience, the Green Energy Plan expected that such a training program would result in a 20 percent reduction of the electricity consumption of industry.

Evaluation and Comparisons

A computer model was constructed to calculate the Green Energy Plan and the reference. Later, the model served as the basis for the development of both the EnergyBALANCE and the EnergyPLAN models. The model was calibrated by applying the figures of the years 1988 and 1993; thus, the energy balances used corresponded to the Danish Energy Agency's energy statistics.

The cost estimation was based on the investment and operation costs of 1995. A certain technological development was considered in the case of heat and power production, and an improvement in efficiency was assumed throughout the period. In the cases of wind turbines and solar thermal technology as well as biogas and gasification, technological development was expressed in the form of falling construction and operation prices. Furthermore, calculations were made for two different developments in fuel prices. According to the first development, all fuel prices were constant, corresponding to the 1995 world market level. In the other scenario, an actual price increase for fossil fuels was included (in accordance with the projections of the Danish Energy Agency).

The Green Energy Plan was compared with the reference on the assumption that the Green Energy Plan was implemented from 1996 to 2015, and both years were included in the model. Detailed technical calculations were made for the years 2005 and 2015, assuming that half of the above-mentioned measures would be implemented by 2005, and all of them by 2015. In comparison with the reference, the implementation of the Green Energy Plan had the following consequences:

- *Environment and fuel consumption*: The total fuel consumption in the Danish energy sector (excluding transportation) would be reduced by 5 percent, and fossil fuels would be reduced by 9 percent by 2005. When including fuel consumption for transportation, CO_2 emissions would be reduced by 20 percent by 2005 compared with 1988. For 2015, the Green Energy Plan proposed an additional reduction of CO_2 emissions by 34 percent in comparison with 1988.
- *New power generation capacity*: In addition to the two power stations, Nordjyllandsværket and Skærbæk, which were already under construction, the reference involved the establishment of two more power stations each of 400 MW before 2005 and six or seven additional stations from 2005 to 2015. However, the Green Energy Plan proved that new power production capacity (except for the stations under construction) would not be needed until 2015. The increased development of decentralized CHP, the implementation of low-temperature district heating in larger urban areas, energy conservation in the industrial sector, and the replacement of electric heating made the construction of new power stations before 2015 unnecessary.
- *Costs, foreign exchange, and employment*: With constant fuel prices, the Green Energy Plan would increase the total annual costs (investments, fuel, and operation) from 27 to 32 billion DKK (not including taxes or subsidies). This was largely due to the increased investments. Foreign exchange consumption would experience a minor rise in the beginning (0.7 billion DKK p.a. in 1996) but would fall thereafter; thus, in 2015, foreign exchange savings would be achieved (0.6 billion DKK p.a. in 2015). With minor increases in fuel prices (according to the latest forecasts from the Danish Energy Agency, where prices were expected to rise from 25 to 50 percent), the additional expenditures would fall to approximately 4 billion DKK p.a., and the savings in foreign exchange would be 1.4 billion DKK p.a. in 2015.

Thus, the Green Energy Plan involved a number of additional Danish investments. In the reorientation period, the plan's effect on the balance of payments would, to a large extent, be neutral.

Regardless of the fuel prices, the reference used an employment parameter of slightly less than 40,000 people. The implementation of the Green Energy

Plan would increase employment by ~12,000 in 1996 and rise to the additional employment of ~17,000 by 2015.

- *Public finance accounts*: In the model, a calculation was made of the net effect that the implementation of the Green Energy Plan would have on public finances. The calculation included increased taxation revenues and reduced social benefit payments, reductions in energy levies, and the resulting profits of the natural gas companies (which in Denmark were owned by the government and the municipalities). Furthermore, the secondary effects from the increased turnovers in the national community were included. A Danish subsidy of between 0.10 and 0.27 DKK/kWh to electricity produced from renewable energy and decentralized CHP was calculated, assuming that the existing level would remain constant until 2005, thereafter being gradually reduced to 50 percent by 2015.

An estimate of the consequences on public finances was made presupposing that the employments of 12,000–17,000 additional people would cause neither bottleneck problems nor rising wages. At that time, there were 250,000–300,000 unemployed in Denmark. The result of the estimate is shown in Table 8.9. As seen, the implementation of the Green Energy Plan would mean a net additional income to public finances of 1 billion DKK/year in 2005 rising to 1.2 billion DKK in 2015.

The additional income shown in Table 8.9 was calculated on the assumption that consumer prices (total energy costs for households and industry) would

TABLE 8.9 Green Energy Plan Net Effect on Public Finances, Not Including Public Regulation Costs

Billion DKK	2005	2015
Additional costs	4.7	5.2
Foreign exchange costs	0.2	−0.6
Employment effect	13,000	18,000
Reduced benefits	+1.5	+2.0
Increased tax	+1.3	+1.7
Natural gas company deficit	−0.2	−0.5
Reduced energy levies	−1.1	−1.4
Energy subsidies	−1.1	−1.4
Secondary effects	+0.6	+0.8
Effect on public finances	+1.0	+1.2

remain the same in the Green Energy Plan as well as in the reference. It was calculated to what extent public finances would have to contribute to maintain the average purchasing power and competitiveness at the same level in the two alternatives. The public regulation means were as follows:

- Changes in the regulation of electricity tariffs
- Prohibition of the use of electrical residential space heating after the year 2000
- Specifically aimed subsidies
- Improved insulation standards for houses offered for sale
- Continuation of the CO_2 levy and the subsidies for renewable energy (but with a gradual reduction so that the subsidies would be reduced by 50 percent through a 20-year period)
- Conversion from natural gas in individual boilers to district heating based on CHP
- Training programs in electricity-saving behavior for industrial employees
- More research, such as in straw gasification
- Subsidies for biogas and gasification stations

According to the Green Energy Plan, an implementation of these measures would cost approximately 1.3 billion DKK p.a. in public finances. Thus, these costs were similar to the expected increase in revenue to public finances, as shown in Table 8.9. Therefore, the Green Energy Plan could possibly be implemented in such a way that the effect on public finances would be negligible.

Conclusions and Reflections

The Green Energy Plan illustrated how a concrete technical alternative could be designed that would improve the environment and energy efficiency of Denmark by replacing imports of fossil fuels by domestic investments in energy conservation, efficiency improvements, and renewable energy. The feasibility study showed how this reorientation would mean a small increase in the total direct costs of energy supply. However, it would also allow Danish society to use the available resources of 250,000–300,000 unemployed individuals to both gain an increase in economic growth and improve the environment. The plan was developed by the General Workers' Union to influence the design of Danish energy policies in the public debate prior to the governmental energy plan Energy 21, which was decided soon thereafter.

This case illustrates that while alternatives based on radical technological changes, as shown in the previous cases, cannot be expected to originate from the organizations linked to the existing technologies, such alternative proposals can come from other organizations, such as the General Workers' Union.

In the case of Nordjyllandsværket, the institutional set-up made the local workers' unions support a coal-fired power station because of the related operation and construction work, even though the job creation figures were low compared with the alternative of CHP, energy conservation, and renewable energy. The problem was that the investments required were not supported by the power companies that had the money. Moreover, the jobs would be spread all over, and many would be outside the area of the local unions. Therefore, these alternatives were out of reach and were not part of the perception of the local organizations.

This case shows that, when the government enables a discussion of alternatives at a higher level and when this discussion is not linked to specific jobs in specific local regions, it becomes possible to describe, analyze, and discuss how to implement alternatives that fulfill the objectives of energy security, environment, and job creation.

Also illustrated by this case is that the design and economic evaluations of alternatives cannot be performed with applied neoclassical economics. These methodologies cannot provide the relevant information on whether the different alternatives fulfill relevant political objectives. However, the information can be found by applying the methodology of concrete institutional economics.

9. CASE IX: THE THAI POWER STATION CASE (1999)[31]

The case of Prachuap Khiri Khan in Thailand is a story about the importance of including all relevant objectives in a feasibility study. This case represents a feasibility study in which a planned new 1400 MW coal-fired power station and a proposed technical alternative were assessed in relation to a wide range of specific and general official development objectives for Thailand. An interesting aspect of the Thai case is that the government had defined clear political objectives for Thai society. Consequently, it was possible to make a strict evaluation of the project and compare it to a concrete alternative. The case shows that the plans to implement a coal-fired power station at Prachuap Khiri Khan were indeed not very rational regarding the fulfillment of the goals of Thai society and that alternatives could be identified that were more suitable. The case description is based on the articles "Sustainable Energy Alternatives to the 1400 MW Coal-Fired Power Plant Under Construction in Prachuap Khiri Khan. A Comparative Energy, Environmental and Economic Cost-Benefit Analysis" (Lund et al. 1999) and "Feasibility of a 1400 MW Coal-Fired Power-Plant in Thailand" (Lund, Hvelplund, and Nunthavorakarn 2003), and the book *Feasibility Study Cases* (Lund, Hvelplund, and Sukkumnoed 2007).

This case is based on the result of a workshop arranged by the Thai-Danish Cooperation on Sustainable Energy and Sustainable Energy Network for Thailand, which took place in Bangkok in 1999. The workshop resulted in the report "Sustainable Energy Alternatives to the 1400 MW Coal-Fired Power Plant Under Construction in Prachuap Khiri Khan" (Lund et al. 1999). Power sector

31. Excerpts reprinted from *Applied Energy*, 76/1-3, Henrik Lund et al., "Feasibility of a 1400 MW Coal-Fired Power Plant in Thailand", pp. 55–64 (2003), with permission from Elsevier.

development projects are well known to be contentious issues in many countries around the world. This was also the case of the planned 1400 MW coal-fired power station in Prachuap Khiri Khan. On the one hand, an institutionalized community of public power companies, private power producers, and industrial companies was setting the pace for establishing a power sector based on fossil fuels. On the other hand, Thai society was badly affected by an economic crisis, unemployment, and the degradation of natural habitats. The political system was facing the difficult task of regulating the energy sector to meet the social and economic objectives of Thailand in the most efficient way. Politicians and stakeholders who wanted to establish a rational basis for decision making needed to continuously examine whether the situation and development were rational and, if not, whether alternatives existed that could accommodate the societal and economic targets more effectively.

The Hin Krut Power Station in Prachuap Khiri Khan

The Hin Krut power station project in Prachuap Khiri Khan was located at the Kok Ta Horm village, in the Thongchai subdistrict of the Prachuap Khiri Khan province. The owner of the project was Union Power Development Co., Ltd., a joint venture based on 85 percent foreign capital. The joint venture proposed its project in June 1995, received the initial power purchase agreement in December 1996, and signed a 25-year independent power production contract with the Electricity Generating Authority of Thailand (EGAT) in June 1997.

In the meantime, locals and environmentalists were increasingly concerned about the project's negative impact on the surrounding environment. The coal-based power station would not contain scrubbers to reduce sulfur dioxide emissions and was therefore expected to become a hazard to the local people's health. Because of disputes surrounding the project, it was still awaiting the government's permission when the feasibility study was made in 1999. Though already contracted, the electricity authority EGAT was able to cancel the project by paying a compensation of approximately THB 5–6 billion (110–140 million USD) to Union Power.

The coal-fired station was expected to have an installed capacity of 1400 MW from two 700 MW units. Union Power expected the station to consume 3.85 million tons of hard coal per year, producing 7125 GWh/year at an efficiency of 44.77 percent. The construction costs of the turnkey station were 900 million USD plus an additional 300 million USD to cover the costs of, for instance, financing and consulting. Thus, the expected construction price was THB 45 billion (1.2 billion USD). The expected operation and maintenance costs were THB 450 million per year (12 million USD per year).

Union Power projected a coal price of 40 USD/ton, which, according to the electricity authority EGAT, was similar to the prevailing cost of coal. Furthermore, EGAT expected the real price for coal to increase by 2.08 percent per year. According to the contract, Union Power would receive both a fixed payment, covering the available power supply of the station (capacity payment), and a reimbursement of variable costs associated with fuel consumption and operation and maintenance.

The actual payment terms were kept confidential, but the agreement between the electricity authority EGAT and another producer was known to include a capacity payment of 422 THB/kW per month (11.3 USD). According to the agreement, EGAT was obliged to pay this amount whether or not the power station produced electricity. This favorable contract was intended to secure an internal rate of return of 15 percent to the investor.

Official Economic Objectives for Thailand

The official social and economic objectives of developing Thai society were formulated by the Thai government in the 8th National Development Plan 1997–2001 (NESDB 1996). The National Energy Policy Office of Thailand (NEPO) was obliged to develop policies, management plans, and measures related to Thailand's energy sector in accordance with the National Economic and Social Development Plan and government policies to be presented to the National Energy Policy Council. In other words, NEPO was required to relate all plans and base all decisions on the wide range of official objectives defined in the National Economic and Social Development Plan and other government policies.

The 8th National Development Plan was influenced by an economic crisis in Thailand in 1997 and was considered to be a turning point in the way in which it recognized the globalization process and the need for a continuous and long-range process of planning, decision making, implementation, monitoring, and evaluation. The plan was said to be moving toward a holistic, people-centered development. The social and economic objectives formulated in the plan were intended to form the basis for planning and decision making in all economic sectors, and thus issues including economic policy, security of supply, employment, rural development, technological innovation, the environment, and others. Energy plans and projects were also to be assessed on this basis.

In the feasibility study (Lund et al. 1999), a careful assessment was made of the different official social and economic objectives of Thai society. All private and public energy sector projects should be assessed in terms of their ability to provide the following:

- A sufficient energy supply
- Reasonable energy prices
- High energy efficiency
- High-cost efficiency
- Low import content
- New products for export
- More and better employment
- Positive effect on public budgets

- Rural development
- Decentralization of the planning and decision-making process
- Technological innovation
- A healthy environment

The Design of a Concrete Technical Alternative

To show the influence that the preceding objectives could have on the results of the feasibility study, an alternative to the coal-fired reference was designed for comparison. The alternative consisted of three components: industrial CHP based on biomass, demand-side management (DSM), and micro–hydro power. The alternative combined the use of indigenous fuels with Thai industrial and technological development and intended to create employment, technological innovation, export opportunities, and other benefits. The alternative had been carefully composed to consist of 1000 MW industrial CHP based on biomass, 350 MW DSM, and 40 MW micro–hydro power (see Table 8.10). Consequently, the alternative provided exactly the same capacity as the 1400 MW reference coal-fired power station.

- The alternative was generally composed to meet the official social and economic objectives for Thailand—that is, it should be cost-effective, reliable, stimulate employment, and rely on indigenous resources. The micro–hydro power component of the alternative was not likely to prove cost-effective in the short term. It was, however, included due to its potential positive impact on technology development, employment, and others, in the long term.
- Each element of the alternative exploited only a minor part of the estimated technical potential for that element, which meant that this type of alternative was generally applicable to future coal-fired projects in Thailand (see Table 8.10).
- From 2001 to 2010, the coal-fired power station was expected to replace electricity produced by oil-fired steam turbines with an efficiency of 33 percent. Over the 10-year construction period, the alternative was

TABLE 8.10 Alternative Compared to the Estimated Technical Potential of Thailand

	Alternative	Estimated Thai Potential
Industrial CHP	1000 MW	10,000 MW
Biomass resources	2200 ktoe/year	20,000 ktoe/year
DSM	350 MW	2200 MW
Micro–hydro power	40 MW	8000 MW

consequently supplemented by such units. All costs of the supplemental electricity production were included in the feasibility study.

- The alternative and the coal-fired power station produced (or saved) identical amounts of electricity, both in total and year by year.
- While the coal-fired power station was to be constructed over a maximum of 2 years, the alternative exploited the surplus capacity in power production, which was expected to be available until 2010, spreading the construction efforts over a 10-year period from 2000 to 2010. This would also give industry time to develop and market even better biomass CHP and micro–hydro power technologies.

Comparative Feasibility Study

The alternative and the coal-fired reference were modeled in a period of 25 years and compared in terms of their energy and environmental and economic characteristics. Economic costs were calculated using factor prices, that is, investment costs and operation and maintenance (O&M) costs excluding VAT and other taxes. The economic investment costs of the coal-fired power station were represented by the capacity payment that the electricity authority EGAT had agreed to pay Union Power as an independent power producer instead of implementing the power station project themselves. However, for the employment calculation, the actual investment costs according to Union Power were used. Please refer to the report "Sustainable Energy Alternatives to the 1400 MW Coal-Fired Power Plant Under Construction in Prachuap Khiri Khan" for further details on conditions and assumptions, as well as specific technoeconomic data used in the analyses (Lund et al. 1999).

Regarding the primary energy supply, the final energy consumption of the coal-fired station over a 25-year period was found to be 68 PJ/year, adding up to 1689 PJ. Meanwhile, the alternative was to be introduced over a period of 10 years, and the final energy consumption would be at the highest level in the beginning, when the alternative depended on the electricity production from older, low-efficiency oil-fired power stations. Consequently, the fuel consumption would decrease from an initial 86 PJ/year in 2001 to approximately 2 PJ/year in 2010 and onward. The very low net fuel consumption of approximately 2 PJ/year was partly due to the high savings achieved by replacing old boilers in the industry by new CHP stations and partly from introducing DSM and hydro power with no fuel consumption. The total energy consumption of the alternative reached 468 PJ.

Regarding environmental consequences, the implementation of the alternative would do the following:

- Reduce fuel consumption by 72 percent over a period of 25 years
- Reduce emissions of CO_2 by 670 million tons over a period of 25 years

- Reduce emissions of SO_2 by 1.5 million tons over a period of 25 years
- Reduce emissions of NO_X by 1.5 million tons over a period of 25 years

Regarding production costs and consequences for the balance of payment, the net present value of economic costs was almost the same for the coal-fired power station at Prachuap Khiri Khan and the alternative, totaling approximately THB 150 billion when using an annual discount rate of 7 percent on 1.60 THB/kWh of electricity produced. The division between capital costs, O&M costs, and fuel costs influenced the effect on, for example, employment and rural economy. While the production costs of the coal-fired power station at Prachuap Khiri Khan included 53 percent capital costs, 44 percent fuel costs, and only 3 percent O&M costs, the alternative involved 39 percent capital costs, 40 percent fuel costs, and 22 percent O&M costs. The total cost of the coal-fired power station at Prachuap Khiri Khan was THB 117 billion in foreign currency, while the import cost of the alternative was only THB 39 billion. Furthermore, the feasibility study showed that the coal-fired power station at Prachuap Khiri Khan only contributed THB 35 billion to Thailand's economic wealth (GDP), while the alternative contributed THB 115 billion. The implementation of the alternative would thus do the following:

- Imply practically identical economic costs of 1.60–1.62 THB per kWh of electricity produced over a period of 25 years
- Incur lower capital and fuel costs but higher O&M costs, which indicates an advantageous contribution to employment and rural economy
- Save foreign currency worth THB 78 billion (2.1 billion USD), thereby reducing the negative impact on Thailand's balance of payment by 67 percent
- Contribute an additional THB 80 billion to Thailand's GDP

The coal-fired power station only created 0.2 million man-years of employment over a period of 25 years, an average of approximately 7000 man-years per year. The alternative created 1.8 million man-years over a period of 25 years, an average of approximately 71,000 man-years for every year of the period. The implementation of the alternative would consequently do the following:

- Create an additional 1.6 million man-years over a period of 25 years; that is, when the coal-fired power station at Prachuap Khiri Khan created 1 man-year, the alternative would create 10 man-years
- Create an additional approximately 64,000 man-years for every year over the period

Regarding the consequences for the rural economy (i.e., economic activity that stems from biomass production and O&M activities), the net present value of the economic activities contributing to the rural economy was THB 5 billion for the coal-fired power station, while the alternative contributed THB 93 billion. The implementation of the alternative would thus do the following:

- Contribute to the rural economy an additional THB 88 billion; that is, every time the coal-fired power station contributed THB 1 billion to the rural economy, the alternative would contribute THB 19 billion

Regarding the consequences of public finances (primarily from personal income taxes), the net present value of the public revenues created by the coal-fired power station was THB 7 billion, while the alternative would create public revenues of THB 22 billion. The implementation of the alternative would consequently do the following:

- Contribute an additional THB 15 billion to the public revenues; that is, every time the coal-fired power station at Prachuap Khiri Khan contributed THB 1 billion to public revenues, the alternative would contribute THB 3.3 billion

Conclusions and Reflections

Two energy projects were analyzed and compared in relation to national Thai objectives: the planned coal-fired power station at Prachuap Khiri Khan (reference) and the biomass, energy efficiency, and micro–hydro power alternative (alternative). The feasibility study showed that the proposed alternative in all aspects was equal to or better than the reference. The alternative was noticeably better in terms of imports; creation of employment; and contribution to Thailand's GDP, public revenues, rural economy, technology development, and the environment, whereas the alternative was almost equal to the reference in terms of economic production costs. The main economic results are summarized in Table 8.11.

TABLE 8.11 Summary of Main Economic and Employment Results

Main Economic Results (Billion Baht)	Reference	Alternative	Difference
Economic costs	152	153	1
Import costs	117	39	−78
GDP contribution	35	115	80
Income revenue contribution	7	22	15
Rural economy contribution	5	93	88
Main Employment Results (Discounted at 7% per year)			
Employment (man-years/year)	7009	34,976	27,968
Rural (man-years/year)	1527	28,311	26,784

The feasibility study of the Prachuap Khiri Khan power station had three main implications for technological innovation in the Thai energy sector. First, it enabled energy planning to link with broader aspects of sustainable development and national development goals. Therefore, energy planning was no longer recognized as a stand-alone exercise that aimed only to meet system demand and reliability with the old technological system. The study stressed very clearly the importance of pursuing an intersectoral policy. Second, it raised public awareness of the potential benefits of renewable energy development in the longer term and broader perspective, especially the social benefits that had previously been little discussed in Thai society. The increasing public awareness urged the Thai government to introduce more programs that supported renewable energy development. In 2001, the Thai government developed a strategic plan for renewable energy. Two years later, it decided to set-up targets for overall renewable energy development and for each specific renewable technology. Third, the feasibility study provided the opportunity and tools for meaningful public participation in validating government decision making, which could prevent excessive and inappropriate investments. In this case, in 2001, the Thai government opened its doors to public discussion, partly based on this feasibility study. In 2002, the Thai government decided to postpone the construction of the power station and change its location and fuel. In short, the feasibility study represented one of the essential tools for Thai society to collectively find its most appropriate development path and reach its own development goals and objectives.

The main lesson to be learned from this case is that it supports several of the previous cases in the observation that organizations linked to existing technologies cannot be expected to invent or to implement alternatives representing radical technological change. These alternatives do not form part of their discourses, interests, and perceptions. Moreover, such organizations will automatically use economic evaluation methods (based on applied neoclassical economics) focusing on the objectives that are included in the interests and perception of the existing technologies. This perception does not include political objectives if these imply radical technological change. The latter aspect becomes especially visible in the Thai case in which the political objectives were well defined.

The design and promotion of alternatives based on radical technological changes had to come from NGOs and local citizens. To show how these alternatives would meet official political objectives better than the coal-fired power station, feasibility studies had to be made on the basis of concrete institutional economics including the identification of relevant political aims and objectives. The national energy policy office did not conduct such a systematic analysis, even though the legal procedures required that an evaluation of the project should be made regarding the national Thai development plan. Instead, the analysis had to come from outside the energy authorities.

10. CASE X: THE ECONOMIC COUNCIL CASE (2002–2003)

In 2002, the Danish Economic Council made an evaluation of the Danish energy policies of the 1990s. This evaluation represents a story of how applied neoclassical economics may be blind to relevant real-life technical and economic circumstances as well as relevant political goals. Instead of analyzing and recognizing the real-life economic situation of the 1990s, in which unemployment, among other issues, was a major problem, the methodology disregarded such issues and implicitly presupposed that the economic situation was optimal. Instead of measuring the success of energy policies against politically well-defined economic objectives, such as decreasing unemployment, improving the balance of payment, and creating technological and industrial development, the methodology excluded these issues from the evaluation. The case description is based on the book chapter "Feasibility Study Cases" (Lund, Hvelplund, and Sukkumnoed 2007) and the articles "Economic Council Assessment of Wind Power and Small CHP Is Based on Incorrect Assumptions" (Lund 2002a),[32] "Saved Operation Costs and Saved Capacity Are Missing" (Lund 2002b),[33] and "A Better Society without Wind Power and CHP?" (Lund 2002c).[34]

This case study is supplemented with alternative calculations in accordance with the Choice Awareness strategies. Thus, the case illustrates both the difference between applied neoclassical ideology and feasibility studies based on a concrete institutional economy and the consequences of designing feasibility studies in one way or the other.

As already explained in the previous sections and chapters, Denmark has conducted an active and innovative energy policy for many years. From 1972 to 1990, the major objective of the policy was to decrease dependency on oil imports, while during the 1990s, Danish energy policy mainly aimed at reducing CO_2 emissions, as expressed by several national energy plans and further supported by the Kyoto Protocol. In the 1970s and 1980s, the strategic objective of protecting energy security was met by energy savings in combination with an increased domestic production of oil and natural gas and the replacement of oil with other fuels, mainly coal and natural gas. Houses were insulated, and power stations replaced oil with imported coal. In the 1990s, a number of environmental energy policy measures were adopted, including the expansion of wind power and the replacement of more than a hundred district heating boilers with small-scale CHP stations distributed throughout the country.

In the spring of 2002, the Danish Economic Council (DEC) published an evaluation of the environmental impact of Danish energy policy measures

32. Translated from Danish: *Vismands vurdering af vindkraft og decentral kraft/varme bygger på fejl i forudsætningen.*

33. Translated from Danish: *Sparet drift og anlæg medregnes ikke.*

34. Translated from Danish: *Et bedre samfund uden vindkraft og kraft/varme?*

implemented during the 1990s. The analysis was carried out as a cost-benefit analysis based on applied neoclassical economics. Costs were calculated as investment and maintenance costs, while benefits were calculated as saved fuel costs and environmental benefits. Additionally, the analysis calculated tax and consumer misallocations, which were included as costs. The study included a number of different policy measures and reached the general conclusion that resources had not been used in the most cost-effective way, since many of the elements revealed negative net results. Consequently, the main recommendation of the DEC was that cost-benefit analyses should be used much more in the future to avoid making the same mistake again.

The expansion of wind power and small-scale CHP stations was included in the analysis, and as a side effect of the study, the results showed that these investments had a negative net result, meaning that Denmark should never have made such investments. However, this statement was the result of an analysis that included a premise of overcapacity that would lead to negative results for almost any new investment, including traditional technologies such as coal-fired steam turbines. Benefits relating to employment, balance of payment, and technological innovation were either not included or were underestimated due to the premises of the applied neoclassical cost-benefit methodology.

Consequently, the study provides an excellent example of the consequences that applied neoclassical premises may have on the implementation of elements of radical technological change. The following description is based on a critique of the Economic Council's evaluation that my colleagues and I presented (Lund 2002a, 2002b, 2002c; Serup and Hvelplund 2002). The critique was discussed in the Danish public debate after the publication of the study, together with critiques from others as well. Two important elements were emphasized in the discussion. The first was excluding the capacity benefits of wind power and small CHP stations, illustrating how the new technologies were evaluated on the premises of the old technologies to such an extent that the old technologies became even less cost-effective when evaluated on the same premises. The second was ignoring benefits of employment, import savings, and technological innovation.

Missing Capacity Benefits (Unfair Premises)

The results of the cost-benefit analyses were divided into a number of Danish energy policy measures in the 1990s. Three of the elements are discussed here: namely, the investments in small-scale CHP stations totaling 826 MW, private wind turbines totaling 1769 MW, and wind turbines owned by the utility companies with a total capacity of 1098 MW. The results of the analysis made by the DEC are shown in Table 8.12.

As Table 8.12 shows, the DEC concluded that neither small CHP stations nor wind power was economically feasible to Danish society. They all resulted in a deficit in the cost-benefit analysis. In the cost-benefit study, all prices are

TABLE 8.12 Results of the Danish Economic Council's Cost-Benefit Analysis

Billion DKK Consumer Prices Year 2002	826 MW Small-Scale CHP Stations Built 1992–1998	1769 MW Private Wind Turbines Built 1992–2011	1098 MW Utility Wind Turbines Built 1992–2008
COST			
Investment	12.2	20.6	8.0
Maintenance	8.9	6.7	2.6
Tax dislocation	1.7	0.6	0.1
Consumer misallocation	0.5	0.8	0.4
Sum	23.3	28.7	11.1
BENEFIT			
Saved fuel	2.1	9.9	4.4
Saved capacity	—	—	—
Saved maintenance	—	—	—
Environmental benefit	16.5	14.8	6.0
Sum	18.6	24.7	10.4
Net benefit	−4.7	−4.0	−0.7

Source: *Danish Economic Council 2002.*

given in terms of *consumer prices*. In this specific case, the consumer price derives from factor prices (market prices of construction, maintenance, and fuel costs) multiplied by a factor of 1.25, equal to the Danish VAT percentage. Moreover, the prices are converted into 2002 prices by applying an annual inflation of 2 percent, while the present value is calculated on the basis of an interest rate of 6 percent.

Small-scale CHP stations totaling 826 MW were built between 1992 and 1998. The cost of this investment was calculated on the basis of a survey made by the Danish Energy Agency, leading to a total cost of 5.3 billion DKK. These investments corresponded to approximately 12 billion DKK, when calculated as described previously.

The crucial premise of the cost-benefit calculation is this sentence in the Economic Council's main report:

The reason for the negative net result is first of all the fact that Denmark had plenty of electricity production capacity.[35]

35. Translated from Danish: *Årsagen til tabet er først og fremmest, at der i udgangspunktet var rigelig elproduktionskapacitet i Danmark*. Danish Economic Council 2002, p. 16.

TABLE 8.13 Same Calculations as in Table 8.12 but with Saved Capacity and Maintenance Included

Billion DKK Consumer Prices Year 2002	826 MW Small-Scale CHP Stations Built 1992–1998	1769 MW Private Wind Turbines Built 1992–2011	1098 MW Utility Wind Turbines Built 1992–2008
Cost			
Investment	12.2	20.6	8.0
Maintenance	8.9	6.7	2.6
Tax dislocation	1.7	0.6	0.1
Consumer misallocation	0.5	0.8	0.4
Sum	23.3	28.7	11.1
Benefit			
Saved fuel	2.1	9.9	4.4
Saved capacity	14.8	4.8	2.4
Saved maintenance	7.2	4.3	2.9
Environmental benefit	16.5	14.8	6.0
Sum	40.6	33.8	15.7
Net benefit	+17.3	+5.1	+4.6

Furthermore, in the attachment, it states:

Consequently, only variable fuel costs at the power stations are saved.[36]

The analysis did not include saved variable maintenance costs, and no explanation was given for this omission. To illustrate the importance of this crucial premise, the critics made a calculation including the benefits of both saved investments and saved O&M costs (Lund 2002a). Table 8.13 shows the result. As can be seen, the deficit of Table 8.12 is now turned into a surplus for all three technologies.

The calculation was based on the alternative costs related to the production of electricity at coal-fired power stations, with capital costs of 8 million DKK/MW and maintenance costs of 60 DKK/MWh, as per the official expectations of the Danish Energy Agency. In these calculations, small-scale CHP stations were assigned a capacity factor of 100 percent, while wind power was assigned a capacity factor of 20 percent. The 20 percent represents the capacity likely to be available with the same probability as the capacity of big power stations.

36. Translated from Danish: ... *og dermed kun har sparet brændselsudgifter på kraftværkerne*. Danish Economic Council 2002, p. 210.

For small CHP stations, the saved capacity costs amounted to 6.6 billion from 1992 to 1998. Meanwhile, after including inflation and projected consumer prices according to a 2002 value, as previously described, the costs corresponded to 14.8 billion DKK in the analysis. Following the same procedure, the saved maintenance costs totaled 7.2 billion DKK. Table 8.13 shows how much this influences the results. A negative result totaling 9.4 billion DKK for all three elements was converted into a surplus of 27 billion DKK. Consequently, the premise of not including capacity payment due to overcapacity totally dominated the analysis.

However, this premise is not related to the question of whether small CHP stations are better or worse than big power stations; it only expresses that if no new power stations are needed, it cannot pay to build them. This premise would probably result in negative figures of almost any power station investment. To illustrate this point, the same cost-benefit analysis was conducted for two large power stations built in the same period, 1996 and 1998, respectively. Each power station had a capacity of 400 MW, which made them comparable to the 826 MW capacity of small-scale CHP stations. The two power stations were evaluated on exactly the same premises and according to the same methodology as shown before in the DEC study, with the results as shown in Table 8.14.

TABLE 8.14 Cost-Benefit Analysis of 800 MW Large Power Stations Conducted by Applying the Same Method as in Table 8.12

Billion DKK Consumer Prices Year 2002	400 MW Coal-Fired Power Station Year 1998	400 MW Natural Gas-Fired Power Station Year 1996	Sum
COST			
Investments	5.3	4.2	9.5
Maintenance	2.1	0.8	2.9
Tax dislocation	—	—	—
Consumer misallocation	—	—	—
Sum	7.4	5.0	12.4
BENEFIT			
Saved fuel	1.0	−4.7	−3.7
Saved capacity	—	—	—
Saved maintenance	—	—	—
Environmental benefit	0.1	3.4	3.5
Sum	1.1	−1.3	−0.2
Net benefit	−6.3	−6.3	−12.6

As Table 8.14 shows, the results of building large power stations totaling 800 MW were even more negative than the results of building small-scale CHP stations with a total capacity of 826 MW. The large power stations with a total capacity of 800 MW had a deficit of 12.6 billion, while the small-scale CHP stations with a total capacity of 826 MW had a deficit of only 4.7 billion. It should again be emphasized that both calculations assumed that no new capacity was needed and that no maintenance costs could be saved.

The cost-benefit analysis concluded that, on the basis of the premise of overcapacity (because both wind turbines and large and small power stations were built), no power production units should have been built; they all came out with a negative result. The problem was that *if* society had followed the advice and no power capacity had been built, then the premise of overcapacity would not be valid, and, consequently, the results made no sense.

Meanwhile, one can ask the question: "How should Denmark have provided new capacity during the 1990s to achieve the lowest possible cost?" The answer can be found in Tables 8.12 and 8.14. Small-scale CHP stations should be preferred to big power stations. Consequently, one can conclude that the premise of overcapacity is not valid, as it leads to the erroneous conclusion that small-scale CHP is not a cost-effective option.

Balance of Payment, Employment, and Technological Innovation

The DEC made the assumption that the effects that innovation, employment, and the balance of payment had on the green energy policy in the 1990s had no societal value. The Danish energy policy of the 1990s resulted in an increase in the export of green energy technologies from 4 billion DKK in 1992 to 30 billion DKK in 2001. Using an import share of 50 percent, the net effect of this export on the balance of payment was around 15 billion DKK in 2001. Thus, the export of these technologies became as large as, for instance, the very important export of Danish bacon or as important as the effects of the Danish North Sea oil adventure in relation to the balance of payment.

The DEC was criticized (Serup and Hvelplund 2002) for not including such positive effects in their cost-benefit analysis, but they refused to attribute these effects to the energy policy in the 1990s, and they would not accept the suggestion that export should be accredited a benefit value in their analyses. They argued that the Danish surplus on the balance of payment and the international financial situation at the time meant that the positive balance of payment effects of a given technology were of no importance.

The counterarguments to this position were (1) Denmark still had a rather considerable foreign debt of ~200 billion DKK, and (2) the positive Danish balance of payment was caused by, among other factors, self-sufficiency in oil and gas, resulting in a balance of payment net income of ~15 billion DKK per year. This positive effect is expected to disappear, as Danish oil wells will gradually run dry from 2005 to 2020. Finally, the positive Danish balance of payment was also the result of the preceding net effect of the export of green energy technologies, corresponding to 15 billion DKK.

A former member of the DEC presented similar arguments, and the Danish Minister of Foreign Affairs even stated that successful export was the backbone of Danish economic development. The export subsidies from the Danish Export Council showed exports of 6 DKK for each DKK of subsidy. This number was an indication of the politicians' *willingness to pay*, leading to the conclusion that an export of 6 DKK had a societal value of 1 DKK. This meant that an export of 30 billion DKK in 2001 could be accredited an extra social value of 5 billion DKK and, consequently, the export values could be included in the analysis based on a political "willingness to pay" principle.

If the annual export of green energy technologies from 1992 to 2001 and the expected effects until 2011 were included in the calculations, the accumulated 2001 value of these benefits amounted to between 40 and 60 billion DKK, depending on the interest rate and prognoses for export after 2001. These 40–60 billion DKK should be added to the benefits shown in Tables 8.12 and 8.13. As can be seen, the inclusion of the balance of payment effect of the energy policy of the 1990s totally changed the results of the calculations.

Moreover, the employment effects were also important to consider. The development of the green energy sector in Denmark created around 30,000 new Danish jobs. Thus, among others, these technologies contributed to the relatively low unemployment rate in Denmark in 2002 compared with other European countries. The employment linked to these technologies was, to a large extent, located in rural areas, where unemployment was relatively high compared with the Danish average.

The DEC argued that unemployment in general was not a problem in Denmark and that the people employed in the green energy sector, especially the wind power sector, would have been employed in other sectors if the green energy sector had not existed. They also argued that the energy policy of the 1990s had no specific innovation effects and therefore excluded this type of consideration from their analysis. Thus, no systematic analysis was made of the innovation effects of the energy policy in the 1990s, and it is rather obvious that the analytical tools linked to neoclassical economic theory cannot be used for such analyses. Nevertheless, the hypothesis assuming that innovation effects may be of great significance is still valid, and an analysis based on concrete institutional economics involving innovation theory may be able to qualify and quantify these effects.

Conclusions and Reflections

The discussion on the results of the Danish Economic Council's analysis in 2002 illustrates how traditional cost-benefit thinking may experience severe problems when applied to the evaluation of political strategies and technological change. Thus, this method was unable to integrate objectives of decreasing unemployment and improving the balance of payment by increasing exports in the Danish case.

Based on the premise of overcapacity, the Economic Council concluded that wind power and small-scale CHP were not cost-effective options. However, this premise would characterize other production units, including traditional power stations, as even less cost-effective. Consequently, the premise of overcapacity is not valid for the analysis of wind power and small-scale CHP. After correcting these misleading assumptions, the result changed its characterization of wind power and CHP from "not cost-effective" to "cost-effective". If the value of exports was included on the basis of a "willingness to pay" principle, the feasibility would even be improved. This case illustrates the importance of relating the feasibility studies of a certain case to the context and the objectives of the decision makers for whom the analyses are intended.

The main point of this case is that applied neoclassical cost-benefit analyses are blind to the relevant benefits of new technologies in terms of fulfilling political objectives, including balance of payment, job creation, and industrial innovation. Moreover, the interests and perceptions of the organizations linked to the old technologies seem to influence the concrete design of applied cost-benefit analyses to such an extent that new technologies, such as wind power and small CHP stations (but not old technologies such as coal-fired power stations), are evaluated on premises that would characterize any technology as "not cost-effective".

The institutional set-up of the Danish Economic Council was not capable of applying the same premises to a similar analysis of the old technologies. This analysis had to come from outside. When promoted by others, this analysis faced heavy resistance from the representatives of the DEC. Even the obviously incorrect premise that *variable* operation costs were not saved in the DEC analysis when CHP and wind power replaced the electricity production of larger coal-fired power stations was defended by the Economic Council.

Instead, the main purpose and main conclusion of the DEC study seemed to be to advocate using the same type of applied neoclassical cost-benefit analyses, presumably to avoid that the politicians "made the same mistakes again". In this case, this meant that the politicians should be prevented from promoting new technologies to fulfill the political objectives of, among others, job creation and industrial development. Instead, they should accept the premises of applied neoclassical economics, meaning that the benefit of such objectives is not included in the calculation.

The DEC study methodology leaves the politicians with a Catch-22 choice (see Chapter 2). Based on the assumption of overcapacity, the DEC advocates that the politicians should never have allowed the implementation of wind power and small CHP plants nor should they have allowed big power stations. However, if they had followed such advice and not allowed any of the three investments, no overcapacity would have occurred in the system, and then all three investments should have been made. Nevertheless, the least-cost solution would have been to invest in wind power and small CHP and not large-scale power stations. Unfortunately, the DEC study failed to identify that fact and instead advocated the opposite solution.

11. CASE XI: THE NORTH CAROLINA CASE (2006–2007)

This Section Is Courtesy of Guest Writer Paul Quinlan

The case of the North Carolina Renewable Energy and Energy Efficiency Portfolio Standard describes how a resource assessment and feasibility analysis was used to pass the first renewable energy portfolio standard in the southeast region of the United States. The major public electric utilities were forced to negotiate a law to include renewable energy and energy efficiency measures in their generation portfolio. This was due to the release of a state commissioned report, conducted by an independent consultant, which found that significant resources were available and that these could be employed in a cost-effective way. The case description is based on the books *Analysis of a Renewable Portfolio Standard for the State of North Carolina* (La Capra Associates 2006) and *A Study of the Feasibility of Energy Efficiency as an Eligible Resource as Part of a Renewable Portfolio Standard for the State of North Carolina* (GDS Associates 2006).

The state of North Carolina maintains a regulated electric market, thereby maintaining a monopoly system of utilities across the state. The North Carolina Utilities Commission (Commission) regulates all aspects of service provided by the three public or investor-owned electric utilities. These vertically integrated utilities manage generation facilities and transmission and distribution systems. The Commission also maintains limited oversight over more numerous but smaller electric membership cooperatives and municipality-owned electric utilities. These entities purchase the majority of their power through wholesale contracts and deliver the electricity to customers in their service territories.

Duke Energy Carolinas (Duke) and Progress Energy Carolinas (Progress) are the two largest utilities in the state, providing approximately 96 percent of the utility-generated electricity consumed in the state and providing service to roughly two-thirds of North Carolina customers. Within the regulated electric market of North Carolina, both utilities rely heavily on coal and nuclear resources for generation. In 2007, Progress produced 49 percent of its generation from coal resources and an additional 39 percent of generation from nuclear resources. In the same year, Duke generated 51 percent and 45 percent of its electricity from coal and nuclear facilities, respectively (North Carolina Utilities Commission 2008).

With the utilities' business model focused on nonrenewable fuel sources, renewable energy and energy efficiency measures were notably absent or undervalued in long-term integrated resource plans submitted to the Commission. The utilities also put forward arguments downplaying the availability and reliability of these resources. Critics argued that the state lacked significant renewable resources and that the limited resources available were intermittent, unreliable, and costly to develop. Political decision makers, including members of the Commission and lawmakers at the General Assembly, highly respected the utility position because they were the entity that, for decades, had generated and supplied reliable electricity to North Carolina.

Early attempts to enact a Renewable energy Portfolio Standard (RPS) requirement demonstrate the lack of choice that existed in North Carolina. Many U.S. states adopted RPS mandates requiring a certain level of electric generation from renewable resources. A bill introduced in North Carolina in 2005 would have required 10 percent of electric generation to come from renewable resources by the year 2016. The bill lacked political support and was drastically altered in the Committee on Agriculture, Environment, and Natural Resources. The sweeping overhaul, coupled with a general lack of support, resulted in the bill faltering without passing either chamber of the General Assembly. In the same year, Duke announced plans to construct a new coal unit in western North Carolina.

Resource Assessment and Feasibility Study

The failure of the RPS legislation prompted the Commission to organize a meeting among stakeholders to discuss the potential of studying the issue in greater detail. Following the meeting, the Environmental Review Commission of the General Assembly issued a formal request for the Commission to undertake a study to examine the potential costs and benefits of enacting an RPS in North Carolina. The Commission was directed to employ an experienced consultant to conduct the analysis and be available for follow-up discussions with state decision makers.

The Commission began by forming an RPS Advisory Group representing ratepayers, electric utilities, and environmental organizations to assist and provide input throughout the process. Members evaluated bids received by the state and provided assistance in the selection of La Capra Associates as the project consultant. The RPS Advisory Group also provided input to determine the scope of the study, sources of data to be used as input, analytic methods and models to be employed, assumptions to be made, and sensitivity analysis to be performed.

In the process, the research of La Capra Associates focused on four questions:

1. Which amounts of new renewable resources and energy measures are feasible in North Carolina?
2. If an RPS was implemented in North Carolina, which impact would it have on electricity rates?
3. Which other potential benefits and costs, aside from rate impacts, might result from an RPS?
4. Which other key issues must be considered relative to renewable energy development or an RPS in North Carolina?

The final report, released in December 2006, found that North Carolina could meet a moderate RPS requirement involving 5–10 percent of electric generation from new renewable resources (La Capra Associates 2006). The resource assessment identified roughly 3400 MW of new renewable capacity that could feasibly be developed. This included onshore wind resources, hydro resources, landfill gas, animal waste, and biomass resources pertaining to waste from wood and agricultural crops. The assessment did not include offshore wind or solar PV capacity estimates. Offshore wind was excluded because of the lack of a permitted and developed project in the United States. The assessment noted that solar PV is not constrained by technical or practical considerations but rather by the current level of installed costs.

A companion report evaluated the feasibility of incorporating energy efficiency as an eligible resource in a potential RPS in North Carolina (GDS Associates 2006). This assessment, which included solar thermal applications, found that pursuing commercially available and cost-effective energy efficiency measures could reduce electric energy use by 14 percent by the year 2017.

La Capra Associates coupled these energy efficiency measures with new renewable resources to assess the feasibility and impact of six potential RPS scenarios. As noted, the report confirmed the feasibility of establishing a modest RPS scenario in North Carolina. The RPS scenarios were also compared to a baseline scenario focused on new conventional fuels to determine the impact on electricity rates in North Carolina. The analysis found that the implementation of an RPS requirement would have a marginal impact on electric rates. For example, a 10 percent RPS requirement allowing an expanded mix of renewable resources and energy efficiency measures resulted in a monthly increase of 0.38 USD for a residential customer consuming 12,000 kWh per year.

The report also explored additional economic and environmental benefits and identified several positive benefits to be achieved from the implementation of an RPS mandate. Five of the six RPS scenarios resulted in a net increase in jobs relative to the baseline conventional fuel scenario. Permitting energy efficiency as a qualifying RPS resource resulted in the greatest increase in net jobs. The RPS scenarios also resulted in a 6–54 percent increase in property tax revenues. Other noted benefits included the displacement of environmental impacts from conventional fuel extraction and reductions in carbon dioxide and other pollutant emissions.

Finally, the report highlighted design elements that would be important considerations for political decision makers. This included applicability requirements for electric utilities, the identification of eligible renewable resources, and the establishment of alternative compliance payments. To encourage the success of any RPS requirement, improvements to net metering and interconnection standards and the potential need for transmission upgrades to accommodate wind energy developments were also noted as elements worth consideration.

The final report was well received by stakeholders and political decision makers in North Carolina. The acceptance from such a diverse mix of stakeholders was possible because the report and results originated from an independent consultant. In addition, the contribution of the RPS Advisory Group in the selection of La Capra Associates provided confidence that the results represented a fair and balanced assessment and analysis.

Even though the utilities were represented in the RPS Advisory Group and supported the final report, they were quick to highlight the challenges and shortcomings. A Progress representative downplayed renewable energy by noting that it "comes at a higher cost than traditional resources" and questioned whether the public would accept the construction of hundreds of wind turbines across the state (Murawski 2006). Meanwhile, public comments filed at the Commission by Duke stressed that new baseload generation was required in the six RPS scenarios analyzed. The utility also suggested that renewable energy would be difficult to implement because of technological, regulatory, economic, and public support issues. Further, energy efficiency measures would require a more detailed analysis using comprehensive utility planning models (Duke Energy Carolinas 2007).

The release of the resource assessment and feasibility analysis provided the foundation for a major revision of energy policy in North Carolina. A bill establishing an RPS mandate was promptly introduced in the General Assembly, and political decision makers established stakeholder negotiations involving electric utilities, environmental organizations, industry representatives, and a variety of other groups. One of the first modifications was the inclusion of a provision allowing public electric utilities to begin the cost recovery of generation facilities before they became operational. This practice was discontinued decades earlier after ratepayers had incurred construction costs for facilities that were never completed. If RPS negotiations were allowed to proceed, the public electric utilities would use the opportunity to secure significant benefits in return. After 6 months of negotiations, a carefully crafted bill emerged for lawmaker consideration and ultimate adoption.

In August 2007, the governor signed into law a renewable energy and energy efficiency portfolio standard for North Carolina. The law requires public electric utilities to provide 12.5 percent of their retail sales from renewable energy and energy efficiency resources by the year 2021. Electric membership cooperatives and municipality-owned electric utilities are required to provide 10 percent of their retail sales from renewable energy and energy efficiency resources by the year 2018. Eligible renewable resources include solar PV, solar thermal, geothermal, tidal energy, wind energy, small hydroelectric, combined heat and power, and biomass resources from agricultural waste, animal waste, wood waste, energy crops, and landfill methane. Special provisions also require the development of solar energy and animal waste resources.

Conclusions and Reflections

The case represents a major success for North Carolina as the passage of the renewable energy and energy efficiency portfolio standard is notable for a number of reasons. First, North Carolina was the twenty-fifth state to adopt an RPS mandate. More important, it was the first state in the Southeast—a region heavily dependent on nonrenewable fuels—to legislatively mandate an RPS requirement. In addition, the policy is notable because of North Carolina's growing population and high electricity demand. Accounting for these factors, North Carolina ranks as a leader among U.S. states in terms of new renewable energy generation and energy efficiency required under statewide RPS obligations.

The main lesson to be learned from this case is that the resource assessment and feasibility analysis conducted by La Capra Associates was essential to overcoming the institutional power of the major public electric utilities and their choice-eliminating strategies. The utilities consistently relied on these strategies to impede the discussion of nonrenewable alternatives in North Carolina. The companies failed to include and value renewable energy and energy efficiency alternatives in their long-range integrated resource plans. They argued that renewable energy technologies would be unreliable and would increase electricity rates. Since the vertically integrated utilities had provided reliable electricity to North Carolina customers for decades, political decision makers tended to respect these views and failed to consider alternatives.

The execution of the resource assessment and feasibility analysis was critical in terms of providing a politically viable alternative. The formation of an RPS Advisory Group that included utility representation provided legitimacy to the selection of La Capra Associates and the assumptions used throughout the report. The Group also ensured that the report addressed objectives that would be important to political decision makers. For example, the report detailed a variety of RPS options and explored the potential economic impact of each.

In the end, the findings of the report confirmed the existence of significant renewable resources in North Carolina and provided an alternative choice to the rapid expansion of nonrenewable generation in the state. The results also demonstrated that the inclusion of energy efficiency into an RPS requirement would provide an alternative choice with comparable costs to the development of nonrenewable fuel sources. The utilities continued their attempt to eliminate the RPS as a valid option despite the evidence, questioning the construction of hundreds of wind turbines and reiterating the need for conventional baseload generation.

Eventually, the major utilities turned their effort to extracting a significant benefit from the RPS bill. The utilities exerted direct and indirect power to insist on the cost recovery provision during the construction of new non-renewable generation. By exerting their power during the stakeholder negotiations, the utilities were able to remove the discussion of a bill purely focused on an RPS requirement as a viable choice for North Carolina. Renewable energy advocates were required to accept these cost recovery provisions for non-renewable resources as a trade-off, thereby allowing the development and passage of the carefully crafted RPS legislation in North Carolina.

12. CASE XII: THE IDA ENERGY PLAN 2030 (2006–2007)

The case of the IDA Energy Plan 2030 illustrates how concrete descriptions of a technical alternative plan can provide information that macroeconomic models, based on applied neoclassical theory, are unable to identify. The IDA Energy Plan 2030 was made by the Danish Society of Engineers, as already described in Chapter 7. The plan proposed concrete technical measures to decrease CO_2 emissions, maintain the security of supply, and exploit Danish business potentials. If implemented, the plan would imply more or less the same direct costs as the business-as-usual reference presented by the Danish Energy Agency. Consequently, the benefits achieved regarding the environment, energy security, and business potentials were additional and did not involve costs from a pure economic point of view, when compared to the reference. However, the plan emphasized that the measures proposed would not be implemented per se under the existing institutional conditions. The parliament and the government would have to pursue an active energy policy. If implemented, the IDA 2030 plan would increase the share of renewable energy from 15 to 45 percent. The case description is based on the books *The Energy Plan 2030 of the Danish Society of Engineers, Background Report. Technical Energy Systems Analysis, Socio-Economic Feasibility Studies and Estimation of Business Potentials* (Lund and Mathiesen 2006)[37] and *Socio-Economic Costs of Increasing Renewable Energy and Energy Conservation* (Danish Ministries of Transport and Energy, Taxation and Finance 2007).[38]

As already described in Chapter 7, the plan was the result of the Organization's Energy Year 2006 with more than 40 seminars involving more than 1600 participants. The plan was published in December 2006, soon after the prime minister, in his opening speech to the Danish Parliament in October 2006, pronounced that a 100 percent renewable energy share was the long-term target for Danish society.

Later, in January 2007, the Danish government announced a proposal of the first steps to be taken. This was published as a small paper describing some overall targets to be reached by the year 2025. The paper was to be followed by concrete proposals for public regulation measures to be discussed by the

37. Translated from Danish: *Ingeniørforeningens Energiplan 2030, baggrundsrapport. Tekniske energisystemanalyser, samfundsøkonomiske konsekvensvurdering og kvantificering af erhvervspotentialer*.
38. Translated from Danish: *Samfundsøkonomiske omkostninger forbundet med udbygning med vedvarende energi samt en øget energispareindsats*.

government and the opposition parties to develop a common Danish energy plan and define a policy based on a huge majority.

One of the proposed targets announced by the Danish government in January 2007 was to increase the share of renewable energy in Denmark from 15 to 30 percent by 2025. When asked by the press why the increase should not be larger if the overall goal was to reach 100 percent, the representatives of the government answered that this would be too expensive for Danish society, referring to a socioeconomic loss of 5 billion DKK.

This answer provided an interesting contradiction to the IDA Energy Plan in the public discussions. On one hand, the government claimed that it would cost 5 billion DKK to reach a 30 percent share of renewable energy; on the other hand, the IDA Energy Plan claimed that a share of 45 percent could be reached without any extra costs. In fact, Danish society would save approximately 15 billion DKK/year, if the IDA Energy Plan was implemented.

The debate led to a number of interesting discussions. One focused on the interest rate used in the calculations. The IDA Energy Plan applied a 3 percent rate, while the government insisted on using a rate of 6 percent. This discussion raised the critique from several Danish economists, who claimed that the 6 percent rate was too high and would mean that the benefit of long-term investments was underestimated. Moreover, the rate of 6 percent was high compared to the rate used in similar countries such as Sweden, Germany, the UK, and many other European countries (Andersen 2007).

Another issue was the fuel price. The IDA Energy Plan used the average oil prices in 2006 equal to an oil price level of 68 USD/barrel, while the government used only 50 USD/barrel. However, in the beginning, it was impossible to provide a specific explanation for the difference between the IDA Energy Plan and the government's plan for the simple reason that the governmental calculations were not published. However, after being criticized for referring to secret calculations, three ministries published a small paper of seven pages on February 8, 2007 (referred to in the beginning of this section). This paper is indeed an interesting subject of investigation. It represents a classic example of applied neoclassical economics and is based on the existing institutional set-up to such a degree that the outcome becomes irrelevant to the decision-making process.

The main difference between the two calculations is that the ministries assumed that no change would take place in existing institutions, while the IDA Energy Plan calculated the costs independently from present taxation, and so forth. Thus, as described in Chapter 7, the IDA Energy Plan was based on a specific identification of a number of investments and was therefore able to account for the exact number of wind turbines and CHP stations included in the analysis. It was thus able to identify the resulting costs in terms of investment as well as fuel, operation, and maintenance. However, the ministries' calculations were, according to their own statement, the result of *a macroeconomic model based on simplified and general assumptions.*[39]

Consequently, the ministries were not able to account for the renewable energy sources used in their calculations or the investment costs assumed. When calculating on the basis of the macroeconomic model, the ministries, among other things, assumed that

the existing regulation of the fuels chosen is maintained "and renewable energy is promoted" by applying a consistent subsidy rate.[40]

It seems as if the whole evaluation was made on the basis of existing institutions and taxation rates. Regarding the calculation of energy conservation, such assumptions become particularly obvious in the following statement.

Fundamentally, the calculations are based on the assumption that a number of socioeconomically cost-effective energy conservation investments are not implemented due to different barriers, inexpedient market incentives, or the lack of knowledge among the actors.[41]

Thus, the ministries acknowledged both the presence of institutional barriers to the implementation of socioeconomically cost-effective investments and the existence of such investments. However, they made the calculations on the assumption that these barriers would remain and came to the conclusion that the implementation of energy savings and renewable energy was costly to society because it would require a lot of subsidies. The subsidy itself was not the main problem, but in the macroeconomic models, the idea that such subsidies may cause a distortion in relation to market equilibrium generally creates a problem. However, the ministries did not comment on the fact that the above-mentioned barriers to the implementation of socioeconomically cost-effective investments did actually constitute such a distortion. Nor did they comment on the possibility that the removal of the barriers would likely remove a distortion rather than create one.

39. Translated from Danish: *Omkostningsberegningerne er fremkommet i en generel økonomisk model, der bygger på forenklede og generelle antagelser*. Danish Departments of Transport and Energy, Taxation and Finance, 2007, p. 3.
40. Translated from Danish: . . . *de nuværende reguleringer af brændselsvalg fastholdes* . . . and . . . *VE fremmes ved en ensartet støttesats*.... Danish Departments of Transport and Energy, Taxation and Finance, 2007, p. 2.
41. Translated from Danish: *Beregningerne er grundlæggende baseret på en antagelse om, at en række samfundsøkonomisk fordelagtige energibesparelser ikke gennemføres som følge af forskellige blokeringer, uhensigtsmæssige incitamenter på markedet eller manglende viden om mulighederne hos aktørerne*. Danish Departments of Transport and Energy, Taxation and Finance, 2007, p. 6.

Conclusions and Reflections

The IDA Energy Plan and the ministries agreed on the fundamental fact that potential socioeconomically cost-effective investments did exist, which were not implemented due to different institutional market barriers.

The IDA Energy Plan identified a number of cost-effective investments in renewable energy, energy conservation, and efficiency measures simply by comparing the needed investments to the saved fuel and operation costs. Based on these observations, the IDA Energy Plan recommended that both the Danish Parliament and the government led an active energy policy, thus removing barriers to the implementation of economically feasible investments.

The ministries used applied neoclassical theory in the form of macroeconomic models when they calculated the costs of implementing renewable energy and energy conservation. In such models, no changes in existing market institutions are assumed. Moreover, a present situation of equilibrium is assumed: "We are living in the best of all worlds". Thereby, the models assume that the present market institutions provide the optimal use of resources in society. Based on these assumptions, the introduction of subsidies is expected to distort the market mechanism, which will then increase the costs of society. In the Danish case, the government decided to go for a moderate objective on the basis of this calculation.

In short, the ministries' calculations provided the information that if Denmark had no institutional market barriers (and consequently no socioeconomically feasible investments to promote), the cost of increasing the share of renewable energy and other investments would be high. However, since Denmark actually had institutional market barriers (which both parties agreed to be the case), the IDA Energy Plan was able to identify socioeconomically feasible investments, which could be implemented if these barriers were removed in the proper way.

The mistake arose when the assumptions behind the ministries' calculations were not communicated, and the politicians drew the conclusion that renewable energy could not be increased without substantial socioeconomic costs. This conclusion was wrong. The IDA Energy Plan 2030 showed that the politicians indeed did have a choice. Socioeconomically feasible investments could be made if the institutional barriers were removed—in other words, if the politicians decided for an active energy policy.

Again, the main lesson to be learned here is that applied neoclassical economics—in this case in the form of macroeconomic models assuming that we are already living in the best of all worlds—are blind to the benefits that could be achieved by introducing alternatives based on radical technological change. Moreover, these models are blind to the identification of institutional barriers and therefore cannot contribute with relevant information to the political decision-making process. The models cannot define the best alternative, nor can they provide relevant information on how to implement the alternatives.

13. SUMMARY

In this chapter, a number of cases were examined that all represent empirical examples of applying Choice Awareness strategies to specific decision-making processes. All of the cases concern energy investments since 1982. They all focus on collective decision making in a process involving many people and organizations that represent different interests and discourses, as well as different levels of power and influence. Moreover, they all involve political objectives of implementing often radical technological change in society, that is, measures that imply significant institutional changes. Regarding the Choice Awareness theses and strategies formulated in Chapters 2 and 3, the following can be learned from these cases.

Existing Organizations Initiate Old Technology Proposals

In most cases, proposals were made by organizations that were linked to existing technologies, and projects were proposed that fit well into these organizations. Typically, only one proposal was put forward. No alternatives representing radical technological change were proposed by the organizations.

- *Nordkraft*: The power companies proposed a coal-based and centralized solution. No alternatives involving energy conservation, the expansion of CHP, or renewable energy were put forward by the power companies.
- *Aalborg Heat Planning*: Three alternatives were put forward; none of these representing the combination of CHP and other fuels than coal.
- *Nordjyllandsværket*: The power companies proposed a coal-fired power station. A natural gas alternative suggested by members of the board of representatives was left out of the decision-making process. No alternatives based on renewable energy were put forward by the power companies.
- *Transmission line*: The power companies proposed a 400 kV airborne connection, which was originally part of a centralized power supply plan from the 1960s. Technical alternatives that fit better into decentralized energy supply systems were never proposed by the power companies.
- *Lausitz*: The power and mining companies proposed a renovation and expansion of existing coal-fired power stations and thereby implicitly suggested to heat the houses without using CHP. No proposals to combine the introduction and expansion of CHP with savings and renewable energy were made by the power and mining companies.
- *Prachuap Khiri Khan*: The power companies proposed to build a large coal-fired power station based on imported hard coal. No technical alternative involving DSM, CHP, and the use of domestic biomass resources was presented by the power companies.
- *North Carolina*: The utilities failed to include and value renewable energy and energy efficiency alternatives in their long-range integrated resource plans.

From these cases, it can be observed that organizations linked to existing technologies will initiate project proposals within their organizational framework. One cannot expect alternatives representing radical technological change to originate from these organizations. It is outside their discourse, and it is not within their interest or perception.

Objectives of Radical Technological Change Are Disregarded

In several cases, the proposals have been contradictory to the parliamentary energy objectives expressed or to other politically defined objectives or wishes.

- *Nordkraft*: Local city council members expressed preference for an alternative based on natural gas but did not have the power or the resources to even ensure a proper description of this alternative.
- *Aalborg Heat Planning*: The law told the municipality to choose the socio-economically best solution. However, this solution did not fit well into the preference of the city council and was disregarded in the definition of potential alternatives discussed in the public participation phase.
- *Nordjyllandsværket*: The proposal was in conflict with the official parliamentary energy plan, Energy 2000, which did not suggest that Denmark should build new big coal-fired power stations. Instead, Denmark was to expand CHP.
- *Transmission line*: The official parliamentary energy plan, Energy 2000, advocated changes from a centralized to a decentralized supply system.
- *Prachuap Khiri Khan*: The power station proposal ignored the fulfillment of a number of relevant and well-defined political objectives of the Thai society regarding economics, environment, rural development, job creation, and industrial innovation.

From these cases, it can be observed that, even when political decisions have been made implying the wish for radical technological change, the organizations linked to existing technologies will continue to initiate project proposals within their organizational framework.

Alternatives Must Come from Someone Else

Alternatives representing radical technological change had to come from others. When these alternatives were introduced, the existing organizations sought to eliminate them from the decision-making processes:

- *Nordkraft*: Local citizens were the ones who described and promoted a concrete technical alternative. The alternative was analyzed by the citizens themselves, and the analysis showed that it would have clear advantages compared to the projected conversion to coal.

- *Aalborg Heat Planning*: Alternatives representing radical technological change came from the university and local citizens. When these alternatives were introduced, the municipality responded by disregarding them in the comparative analyses. Then (when comparative analyses showed an inconvenient result), new analyses were made, and the inconvenient analysis was withheld from the city council, and, finally, a discussion of the letterhead used was initiated instead of a discussion of the contents of the proposal.
- *Nordjyllandsværket*: Alternatives involving energy conservation and the expansion of CHP and renewable energy came from the university and local citizens. When the alternatives were introduced, the power companies tried to eliminate the choices from the debate. The choice-eliminating strategies included hiding differences in the prognoses of the electricity demand.
- *Transmission line*: The proposal of technically different alternatives came from local citizens. When these alternatives were introduced, the power companies tried to eliminate the choice from the debate. The choice-eliminating strategies included (1) claiming that the alternatives were not technically possible; (2) when technical calculations made by the citizens proved the opposite, claiming that the analyses were based on incorrect data; and (3) withholding the correct data by referring to the risk of endangering "national security".
- *Lausitz*: Local civic organizations involved foreign researchers in the design of alternatives based on energy conservation, CHP, and renewable energy, and the local civic organizations had to promote these alternatives themselves. When the alternatives were introduced into the debate, they were heavily opposed by the power and mining companies.
- *Prachuap Khiri Khan*: Local energy organizations designed and promoted an alternative based on energy demand management, CHP, and domestic biomass resources. When the alternative was introduced into the debate, it was heavily opposed by the power companies and potential investors.
- *North Carolina*: The selection of La Capra Associates was essential to overcome the institutional power of the public electric utilities.

Institutional Change Is Essential

For society, it is not an efficient public regulation measure to force existing organizations to act at variance with their interests. This measure has to be supplemented by institutional changes.

- *Aalborg Heat Planning*: The authorities failed to force the municipality to choose the socioeconomically best solution, when this solution resulted in increasing consumer heat prices compared to less favorable alternatives.
- *Nordjyllandsværket*: The authorities failed to stop new coal-fired power stations, as prescribed by Energy 2000.

- *European EIA procedures*: The legal procedures failed to ensure the description of cleaner alternatives, when these alternatives represented radical technological change.

Applied Neoclassical Economics Provide Irrelevant Information

When the evaluation of technological change, such as the introduction of renewable energy systems, is based on applied neoclassical economics, the analyses often ignore relevant political objectives and instead provide information that is irrelevant to the political decision-making process.

- *Biogas*: The cost-benefit analysis based on applied neoclassical economics was not capable of relating the case to the most important economic objectives of the government and the Danish Parliament of the time, that is, job creation and the improvement of the balance of payment.
- *Economic Council*: The cost-benefit analysis was not able to relate the case to the government's political objectives of job creation, improvement of the balance of payment, and industrial innovation. Moreover, the evaluation of new technologies was made solely on the premises of coal-fired power stations. For example, not even the saved variable operation costs of coal-fired power stations were included as a benefit when electricity production was replaced by wind power and small CHP. Wind power and small CHP were analyzed on the assumption of overcapacity that would characterize any investment as not cost-effective. The same assumption was not used in relation to coal-fired power stations.
- *IDA Energy Plan 2030*: The analyses made by the ministries were based on the assumption that barriers to socioeconomically feasible investments would not change. Moreover, the macroeconomic models generally assumed that society found itself in an optimal situation in which the market would provide the best allocation of resources, even though institutional barriers hindering the implementation of socioeconomically feasible investments had been defined.
- *North Carolina*: The execution of resource assessment and feasibility analysis was critical in terms of providing a politically viable alternative.

Concrete Institutional Economics Provide Relevant Information

When the evaluation of technological change is based on concrete institutional economics, it is possible to relate the change in question to relevant political objectives and thus provide information that is relevant to the political decision-making process.

- *Biogas*: The analysis showed how the implementation of biogas could help fulfill all relevant political objectives of Danish society, including job creation and economic growth, better than the reference.

- *Prachuap Khiri Khan*: The analyses revealed that an alternative consisting of energy demand management, CHP, and renewable energy could meet the relevant and well-defined political objectives of Thai society better than a coal-fired power station, when these political objectives were included in the design of the analysis.
- *Economic Council*: The method based on concrete institutional economics showed that when relating the analysis to relevant political objectives, the overall characterization of the technologies in question changed from “not cost-effective” to “cost-effective”.
- *IDA Energy Plan 2030*: The economic calculation based on well-described specific investments identified an alternative that would be able to improve economic growth and create industrial development. However, institutional change was required for society to implement the strategy and achieve these benefits.
- *North Carolina*: The results demonstrated that the inclusion of energy efficiency into the requirements would provide an alternative choice with comparable costs to the development of nonrenewable fuel sources.

Concrete Alternatives Raise Choice Awareness

The design and promotion of concrete technical alternatives raise the awareness that society has a choice and make it possible to discuss choices in public.

- *Nordkraft*: An alternative representing energy conservation, the expansion of CHP, and renewable energy was put forward and was subject to public discussion.
- *Aalborg Heat Planning*: An “alternative 4” representing the combination of CHP and natural gas was put forward and was subject to public discussion.
- *Nordjyllandsværket*: An alternative based on small CHP and renewable energy was put forward and was subject to public discussion.
- *Transmission line*: Several technical alternatives, including proposals that fit better into decentralized energy supply systems, were put forward and were subject to public discussion.
- *Lausitz*: An alternative combining the introduction and expansion of CHP in combination with savings and renewable energy was put forward and was subject to public discussion.
- *Green Energy Plan*: A plan was designed that would improve the environment and, at the same time, create the basis for economic growth. The plan was put forward and was subject to public debate prior to the introduction of the governmental energy plan, Energy 21.
- *Prachuap Khiri Khan*: A technical alternative involving DSM, CHP, and the use of domestic biomass resources was put forward and was subject to public discussion.
- *IDA 2030 Energy Plan*: A concrete alternative aimed at decreasing CO_2 emissions, improving energy security, and creating industrial development

was put forward and was subject to public discussion in the debate of new Danish energy policies.

- *North Carolina*: The concrete alternative of renewable energy and energy efficiency was, in the end, implemented into the portfolio standard.

Concrete Alternatives Help Identify Institutional Barriers

The existence of concrete technical alternatives makes it possible to identify institutional barriers to the implementation of radical technological change and design public regulation measures to overcome these barriers.

- *Aalborg Heat Planning*: It was possible to identify fuel taxation rules that constituted a barrier to the implementation of the socioeconomically least-cost solutions prescribed by the law on heat supply and to design concrete public regulation measures to overcome this barrier.
- *Nordjyllandsværket*: It was possible to identify how the existing organization of the power companies involved mechanisms that would automatically lead to the wish for a new power station. Moreover, a number of mechanisms were revealed that led to the proposals of "new-corporative" as opposed to "old-corporative" regulation (see Chapter 3)
- *Transmission line*: The discussion on "national security" led to an amendment of the law, thus including utility companies in the Danish legal act of public access to information.

14. CONCLUSIONS

True choices between relevant alternatives are essential when society is to implement political objectives implying radical technological change. However, the cases presented clearly indicate that the true choice will not appear by itself.

The organizations linked to existing technologies are typically those that take on the responsibility for proposing new projects. However, the institutional set-up of such organizations implicitly entails that they cannot generate proposals that imply radical technological changes; it is outside their discourse, interests, and perception. Even if they made such proposals, it would be out of their reach to implement these. Consequently, the set-up by default does not involve the true choice. On the contrary, it will repeatedly result in Hobson's Choice: choose a project that fits well into the existing organizations or no project at all. Also, when political decisions have been made implying the wish for radical technological change, the organizations linked to existing technologies will still continue to initiate project proposals within their organizational framework.

In all cases presented, alternatives representing radical technological change had to come from outside the organization representing the existing technologies. When these alternatives were introduced, the existing organizations sought to eliminate them from the decision-making processes by use of various means.

Consequently, the elimination of true choice is twofold. First, those organizations that typically make the proposals cannot generate proposals of radical technological change. It is outside their discourse. Second, if such proposals are promoted by others, the same organizations will seek to eliminate these proposals from the decision-making process. It is not in their interest to do otherwise.

The proper evaluation of alternatives representing radical technological change cannot be done by using applied neoclassical economics in the form of applied cost-benefit analyses and macroeconomic equilibrium models. As illustrated by the preceding cases, the existing institutional set-up seems to be tailored to the practical application of these models to such an extent that they cannot analyze other alternatives and identify those that will fulfill relevant political economic objectives in the best way. Moreover, the models are not designed to assist the identification of relevant market barriers and failures to implement the socioeconomically best solutions.

The introduction of concrete technical alternatives contributes to raising the public awareness of true choice. Discussions arising from this awareness and public debates will contribute to the identification of institutional barriers at all levels: from market barriers, such as taxation rules, to barriers within the democratic infrastructure, such as the design of the committees that provide information to the political decision-making processes.

Chapter 9

Conclusions and Recommendations

This book has unified and deduced the learning and results of a number of separate studies related to the coherent understanding of how society can perceive and implement renewable energy systems. The subject has been dealt with by combining two aspects: the formulation of a *Choice Awareness* theory used as a theoretical framework approach to understanding how major technological changes, such as renewable energy, can be implemented both at the national and international levels, and the development of an energy system analysis method and tool for the design of *renewable energy systems*, including the results of various analyses. In this chapter, the results are presented as conclusions related to principles and methodologies as well as recommendations for the practical implementation of renewable energy systems in Denmark and in similar countries.

1. CONCLUSIONS

Conclusions are made first regarding Choice Awareness and then with regard to renewable energy systems.

Choice Awareness

Two Choice Awareness theses were formulated in Chapter 2. Based on discourse and power theory, the theses assume that the perception of reality and the interests of existing organizations will seek to hinder radical institutional changes by which these organizations will lose power and influence. Choice Awareness theory states that one key factor in this manifestation is the societal feeling of having either *a choice* or *no choice*.

The first thesis states that when society defines and seeks to implement objectives that will imply radical technological change, the influence of existing organizations will often seek to create a perception indicating that society has no choice but to implement technologies that constitute existing positions. The results of such influence will take various forms and will typically be based on the applied neoclassical assumption that the existing institutional and technological set-up is defined by the market and that the market works in such a way that it will, by definition, identify and implement the best solutions.

The second thesis of the Choice Awareness theory argues that in this situation, society will benefit from focusing on Choice Awareness; that is, raising the awareness that alternatives *do* exist and that it is possible to make a choice. Four key strategies for raising Choice Awareness were presented.

The *description and promotion of concrete alternatives* are core strategies in Choice Awareness. They are the essential first steps that must be taken to change the focus of a public discussion. Typically, the promotion of a concrete alternative will lead to two changes. First, it becomes obvious that society indeed does have a choice, and second, the focus of the discussion changes from "Yes, it is bad, and so what?" to "Which of the alternatives is the best solution?"

The next strategy is to *consider the relevant economic objectives of the society in question* and include these in economic feasibility studies. Choice Awareness theory is based on the observation that in societal decision-making processes involving radical technological change, existing institutional interests will try to influence the process in the direction of no choice. This influence includes the use of feasibility studies based on methodologies and assumptions supporting existing organizational interests. Consequently, Choice Awareness involves the awareness of how feasibility studies are and should be carried out. The combination of business and socioeconomic analyses can reveal institutional barriers to the implementation of suitable new technologies.

The third strategy is to *propose concrete public regulation measures*. These measures to implement radical technological change cannot be designed on the basis of the aforementioned preconditions of applied neoclassical economic theory. The main problem is that the necessary technical solutions often require new organizations and new institutions. In general, the applied neoclassical model considers the institutional conditions as given and does not consider them to be modifiable via public regulation.

The last strategy emphasizes that *public decision making does not occur in a political vacuum*. The decision-making process is shaped by various political and economic interest groups in society that strive to protect their profits or pursue their values. It is therefore important to be aware of the fact that, typically, existing technologies are well represented in the democratic decision-making infrastructure, whereas potential future technologies are weakly represented, if they are represented at all. Therefore, the strategy advocates leading a "new-corporative" regulation in which the representatives of new technologies are given high priority in various committees.

Chapter 8 presented 12 empirical cases that applied Choice Awareness strategies to specific decision-making processes related to energy investments since 1982. They all concerned collective decision making in a process involving many persons and organizations representing different interests and discourses as well as different levels of power and influence. In addition, they all involved political objectives of implementing radical technological change in society, that is, changes that would imply significant institutional changes.

The cases represent situations in which politically decided objectives call for the proposal of alternatives representing radical technological change. Regarding Choice Awareness theses and strategies, the following can be learned from the cases.

In general, the cases started out with one, and only one, alternative introduced by existing organizations and fitting well into such organizations. No alternatives representing radical technological change were ever proposed by the same organizations. The cases clearly illustrate how alternatives representing radical technological change cannot be expected to come from the organizations linked to existing technologies. Such alternatives simply do not form part of their perception of the problem and its solution. Furthermore, even if these alternatives were proposed, they could hardly be implemented by the same organizations, since such activities would be out of their reach.

In several cases, the proposals presented have been contradictory to parliamentary energy objectives or other politically defined objectives or wishes. Existing organizations disregarded the political objectives if they implicated radical technological change. Instead they presented proposals that fit well into their own institutional and organizational set-up.

In all cases, it was possible to identify alternatives based on radical technological changes that were likely to fulfill the political objectives better than the proposals of existing organizations. However, these alternatives were presented by others, such as universities, nongovernmental organizations, or local citizens.

When radical alternatives were introduced, the existing organizations sought to eliminate the choice of these alternatives from the decision-making process. The cases show a wide range of such eliminating mechanisms including the following:

- Disregarding inconvenient alternatives
- Downplaying contradictions to official forecasts of energy demands
- Withholding technical data with reference to national security
- Withholding inconvenient results from political decision makers
- Discussing the letterhead used instead of the content of the letter to incriminate the senders

The socioeconomic feasibility of a radical technological change is often evaluated on the basis of applied neoclassical economics. The cases show how such analyses ignore relevant political objectives and provide information that is irrelevant to the political decision-making process. However, when conducting feasibility studies based on concrete institutional economics, it is possible to relate the case in question to relevant political objectives and provide information that is relevant to the actual political decision-making process.

Consequently, the cases confirm the first Choice Awareness thesis that states that in a situation of radical technological change, the influence of existing organizations will often seek to create a perception indicating that society has no choice but to implement technologies that will save and constitute existing positions.

Regarding the second Choice Awareness thesis, the cases show that the design and promotion of concrete technical alternatives raise the awareness that society has a choice and makes it possible to discuss this choice in public. In almost all cases, the existence of a concrete alternative has given rise to public debates. Moreover, the existence of concrete technical alternatives makes it possible to identify institutional barriers to the implementation of radical technological change and design public regulation measures to overcome these barriers.

The cases show that it is not an efficient public regulation measure for society to force existing organizations to act against their interests. Thus, in the Aalborg Heat Planning case, the authorities failed to force the municipality to choose the socioeconomically best solution, when this solution would result in higher consumer heat prices compared to less socioeconomic alternatives. In the case of Nordjyllandsværket, the authorities failed to implement the Energy 2000 to stop new coal-fired power stations, and in the case of European Environmental Impact Assessment procedures, Danish practice failed to ensure that proper analyses of relevant cleaner alternatives were made. Such a measure has to be supplemented by institutional changes in the form of changing the market conditions and making it possible for the organizations of new business areas to enter. Consequently, these cases confirm the second thesis of the Choice Awareness theory by showing that society will benefit from raising the awareness that alternatives *do* exist and that it is possible to make a choice.

The article "Choice Awareness: The Development of Technological Choice in the Public Debate of Danish Energy Planning" (Lund 2000) described how Danish energy policy, for a period of 25 years, was formed by a process of conflicts. This process led to the implementation of radical technological changes, and Denmark shows remarkable results on the international stage. This ability to act as a society has been possible despite the conflicts between representatives of the old and the new technologies. Official energy objectives and plans have been developed in a constant interaction between Parliament and public participation, in which the description of new technologies and alternative energy plans has played an important role. Public participation, and thus the awareness of choices, has been an important factor in the ultimate decision-making process. The conflict-ridden debates should therefore be seen as necessary conditions for further improvements of energy initiatives and programs.

Renewable Energy Systems

The method of designing concrete technical alternatives based on renewable energy technologies has been described and applied to the preceding cases. A distinction has been made among three implementation phases: introduction, large-scale integration, and 100 percent renewable energy systems. In the development of tools and methods for the design and evaluation of renewable energy system alternatives, the two latter phases have been emphasized.

The energy system analysis tool, EnergyPLAN, has been described, and the method and tools have been discussed in relation to the theoretical framework of Choice Awareness. In accordance with the idea of Choice Awareness, the overall aim of the EnergyPLAN model is to analyze energy systems with the purpose of assisting the design of alternatives based on renewable energy system technologies. Regarding Choice Awareness, the following key considerations can be highlighted.

The EnergyPLAN model can make a consistent and comparative analysis of different energy systems based on fossil fuels and nuclear as well as renewable energy systems. When the reference energy system is described, EnergyPLAN makes it possible to conduct a fast and easy analysis of radically different alternatives without losing coherence and consistence in the technical assessment of even complex renewable energy systems.

The EnergyPLAN model seeks to enable the analysis of radical technological changes. The model describes existing fossil fuel systems in aggregated technical terms, which can thereby be changed fairly easily into radically different systems, for example, systems based on 100 percent renewable energy sources (RES). The model divides the input in market-economic analyses into taxes and fuel costs, thereby making it possible to analyze different institutional frameworks in the form of different taxes. Moreover, if more radical institutional structures are to be analyzed, the model can provide purely technical optimizations. This makes it possible to separate the discussion of institutional frameworks, such as specific electricity market designs, from the analysis of fuel and/or CO_2 emissions alternatives. EnergyPLAN has not incorporated the institutional set-up of the electricity market of today as the only optional institutional framework.

The model can calculate the costs of the total system divided into investment costs, operational costs, and taxes, such as CO_2 emission trading costs. Thus, the model is able to provide data for other socioeconomic feasibility studies, such as data including balance of payment, job creation, and industrial innovation. Examples of such studies were given in Chapters 7 and 8.

Regarding the three different implementation phases, the model includes a high number of different technologies relevant for renewable energy systems. Consequently, it serves as a useful tool for making detailed and comprehensive analyses of a wide spectrum of large-scale integration possibilities as well as 100 percent renewable energy systems. Chapter 5 discussed the essence of a wide range of studies of the Danish energy system in which the EnergyPLAN model was applied to the analysis of large-scale integration of renewable energy. At present, the Danish energy system is already characterized by a relatively high share of renewable energy and is therefore suitable for the analysis of further large-scale integration.

Following the presentation of these studies, Chapter 5 presented a method of comparing different energy systems in terms of their ability to integrate RES on a large scale. The question in focus was how to design energy systems with a high ability to use intermittent RES. These systems must be designed in such a way that they can cope with the fluctuating and intermittent nature of RES, especially with regard to the electricity supply.

From a methodological point of view, this raises the problem of how to deal with fluctuations of the same installed capacity of RES, such as photovoltaic (PV), wind, wave, and tidal power, since they differ from one year to the next. To deal with these problems, excess electricity production diagrams have proven to be a suitable and workable methodology. In these diagrams, each energy system is represented by only one curve, which shows the ability of the system to integrate fluctuating RES representing several years of different hour-by-hour fluctuations. The diagrams have proven usable for PV, wind, and wave power.

Moreover, the analyses show that in the design of systems that are suitable for large-scale integration of RES, it is important to distinguish between two different issues. The first issue is concerned with *annual amounts* of energy, that is, that on an annual basis, the supply of electricity, heat, and fuel must meet the corresponding demands. The other issue is concerned with *time*—that the supply of energy must meet the temporal duration of the same demands. The latter is of special importance to the electricity supply.

Regarding such recommendations, there is much to learn from the analyses. Conversion technologies may improve the efficiency of the system, such as heat pumps, and at the same time, feature the possibilities of cost-effective and efficient storage options. On the other hand, "pure" electricity storage technologies, such as compressed air energy storage and hydrogen/fuel cell systems, only contribute marginally to the integration of fluctuating RES, and they also have a low feasibility.

Chapter 6 discussed the essence of a number of studies related to the challenge for future energy infrastructures, and defined concepts of *smart electricity grid*, *smart thermal grids*, and *smart gas grid*. These three concepts have similarities in terms of grid structures allowing for distributed activities involving interaction with consumers and bidirectional flows. To meet this challenge, all grids will benefit from the use of modern information and communication technology as an integrated part of the grids at all levels. However, they also differ in their major challenges. Smart thermal grids face major challenges in the temperature level and the interaction with low-energy buildings. Smart electricity grids face major challenges in the reliability and in the integration of fluctuating and intermittent renewable electricity production. Smart gas grids face major challenges in mixing gases with different heating value and in the efficient use of limited biomass resources.

From a methodological point of view, the main point in Chapter 6 is that each of the three types of smart grids is an important contribution to future renewable energy systems, but each individual smart grid should not be seen as separate from the others or separate from the other parts of the overall energy system. Consequently, Chapter 6 promoted the concept of *smart energy systems* defined as an approach in which smart electricity grids and smart thermal grids as well as smart gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system.

One important example of such a synergy was already highlighted in Chapter 5, that is, the option of using heat storage instead of electricity storage when realizing that some electricity has to be converted to heat preferably by the use of heat pumps to implement an efficient and least-cost overall renewable energy systems solution.

Chapter 6 highlighted another important synergy when coordinating smart electricity and gas grids. A survey of potential pathways for providing gas or liquid fuel to the transportation sector to supplement the direct use of electricity points to the need for power to gas from electrolysis to boost the conversion of biomass into gas. This need for power to gas for transportation makes it possible to replace the potential long-term need for electricity storage with gas storage, which is both cheaper and more efficient. Consequently, the identification of integration of renewable energy into the electricity supply should not only include the measure of direct use of electricity for transportation but the power to gas need as well. Chapter 7 presented recent results achieved by applying the EnergyPLAN tool to the design of 100 percent renewable energy systems. The question was how to compose and evaluate these systems. The chapter treated the principal changes in the methods of analysis and evaluation of such systems compared to systems based on fossil fuels with or without large-scale integration of renewable energy. The implementation of 100 percent renewable energy systems adds to the challenges of integrating RES into existing energy systems on a large scale as well as designing future smart energy infrastructures. Not only must fluctuating and intermittent renewable energy production be coordinated with the rest of the energy system, but the energy demands must also be adapted to an economically realistic integration of potential renewable sources. Furthermore, this adjustment must address the differences in the characteristics of different sources, such as biomass fuels and electricity production from wind power.

Based on the case of Denmark, Chapter 7 presented three studies that analyzed the problems and perspectives of converting the present energy system into a 100 percent renewable energy system. The first study was a one-person university study that applied the analyses in Chapter 5 to the analysis of a coherent renewable energy system. The second study was based on the technical input from members of the Danish Society of Engineers (IDA). In the third study CEESA, a group of interdisciplinary researchers, made further investigations into, among other things, pathways to produce gas or liquid fuel to supplement the direct use of electricity in the transportation sector. All three studies analyzed the design of coherent and complex renewable energy systems, including the suitable integration of energy conversion and storage technologies. Furthermore, the studies were based on detailed hour-by-hour simulations carried out by use of the EnergyPLAN model.

From a methodological point of view, it can be concluded that the design of future 100 percent renewable energy systems is a very complex process. On the one hand, a broad variety of measures must be combined to reach the target, and on the other hand, each individual measure has to be evaluated and coordinated with the new overall system. In the case of the IDA energy plan, the process has been achieved by combining a creative phase, involving the inputs of a number of experts, and a detailed analysis phase with technical and economic analyses of the overall system, providing feedback on the individual proposals. In a back-and-forth process, each proposal was formed in such a way that it combined the best of the detailed expert knowledge with the ability of the proposal to integrate into the overall system, in terms of technical innovation, efficient energy supply, and socioeconomic feasibility.

2. RECOMMENDATIONS

In his opening speech to Parliament in October 2006, Danish Prime Minister Anders Fogh Rasmussen announced the government's long-term objective for Danish energy policy: 100 percent independence from fossil fuels. When asked directly, the Prime Minister answered that nuclear sources would not form part of the solution. In other words, the long-term target is to convert to 100 percent renewable energy. This governmental objective has been repeated several times since then, one of which was in the constitutional agreement of a new coalition government headed by Prime Minister Helle Thorning-Schmidt when it came to power in 2011 (Danish Government, 2011).

In 2012, a huge majority in Parliament reached a new Energy Agreement (Danish Ministry of Climate, Energy, and Building, 2012). The agreement contains a wide range of ambitious initiatives, bringing Denmark a good step closer to the target of 100 percent renewable energy in the energy and transportation sectors by 2050. The main expected results for 2020 are more than 35 percent renewable energy in final energy consumption, approximately 50 percent of electricity consumption to be supplied by wind power, and 34 percent reduction in greenhouse gas emissions compared to 1990.

Consequently, since 2006, Denmark has been in a situation in which society has defined and sought to implement objectives that would imply radical technological change. How to fulfill the target of 100 percent renewable energy is a matter of collective decision making in a process involving many individuals and organizations representing different interests and discourses as well as different levels of power to influence the decision-making process. Choice Awareness theory states that one key factor in the manifestation is the societal feeling of having either a choice or no choice. In the following section, some important recommendations are listed that can be derived from this book and applied to the Danish situation. The list is not comprehensive and should be seen as only a few typical and representative examples.

100 Percent Renewable Energy Systems

The basic recommendation is to raise the awareness that an energy system based on 100 percent renewable energy is an option. Based on the case of Denmark, this book presented three studies of the technical challenges and perspectives of converting present energy systems into a 100 percent renewable energy system. Each study involved two or three alternatives that were based on either biomass or wind power. Among other things, the studies concluded that a 100 percent renewable energy supply based on domestic resources was physically possible in Denmark and that the first step toward 45 percent in 2030 was feasible for Danish society.

The first study identified some key improvements of system flexibility as essential to the conversion of the energy system into a 100 percent renewable system. The analyses showed that the Danish energy system could be converted into a 100 percent renewable energy system when combining 180 TJ/year of biomass with 5 GW PV and 15–27 GW wind power. In the reference, 27 GW wind power was necessary, while in combination with savings and efficiency improvements, the needed capacity was reduced to around 15 GW. Thus, the first study emphasized the importance of implementing energy conservation as well as efficiency improvements in the supply sector.

The second study went a step further, especially regarding energy conservation and the design of a coherent transportation solution. The study suggested the implementation of energy conservation measures at a high level and, as a consequence, energy demands decreased compared to the first study. On the other hand, the transportation technologies applied in the second study were much more differentiated and included the combination of electric vehicles as well as biofuel technologies, which increased the energy demand compared to the first study.

The second study showed that Denmark would be able to convert its supply into 100 percent renewable energy constituted by 280 PJ/year of biomass, 19 PJ/year of solar thermal, 2.5 GW wave and PV, and 10 GW wind power. Moreover, the study showed how biomass resources could be replaced by more wind power, and vice versa, and pointed out that Denmark would have to consider to which degree the country should rely mostly on biomass resources or on wind power. The solution based on biomass would involve the use of present farming areas, while the wind power solution would require a large share of hydrogen or similar energy carriers leading to certain inefficiencies in the system design.

The third study adds to the previous two by going into more detail with the discussions and analyses of several important issues. First, the discussion and identification of suitable transportation fuel pathways are taken a step further, and one of the potential pathways is quantified and integrated into the overall identification of a roadmap toward a 100 percent renewable energy system in 2050. Next, the study furthers the discussion on the influence of technological development. Three different scenarios, each representing different assumptions regarding the availability of technologies, are compared.

Finally, the study emphasizes and illustrates the importance of applying a smart energy systems approach to the identification of a suitable 100 percent renewable energy systems design. In particular, the study combines the electric vehicles and fuel production in the transportation sector as well as the district heating systems with the analysis of gasified biomass and gas grid storages in combination. This creates an energy system in which smart energy systems are integrated and the storage options are used in combination to enable the final scenario. The analyses ensure that there is an hourly balance in the gas supply and demand and document that the capacity of current Danish salt cavern storage facilities is more than sufficient to facilitate this balancing.

All three studies apply the EnergyPLAN tool and illustrate how such a tool can be used to design a 100 percent renewable energy solution as well as form the basis for an evaluation of such systems based on the use of concrete institutional economics.

Large-Scale Integration of Renewable Energy

All of the preceding studies of 100 percent renewable energy systems show that when reaching a high share of intermittent resources in combination with CHP and savings, the development of renewable energy strategies becomes a matter of introducing and adding flexible energy conversion and storage technologies and designing integrated energy system solutions. Regarding the short and medium term of the large-scale integration of renewable energy, it is essential to see these efforts in the perspective of approaching renewable energy systems. The point is that RES should not be regarded as the only measure when conducting analyses of large-scale integration. The long-term relevant systems are those in which such measures are combined with energy conservation and system efficiency improvements. In systems with a high share of CHP, excess electricity production can best be dealt with by giving priority to the following technologies.

First, the combined heat and power (CHP) stations should be operated in such a way that they produce less when the RES input is high and more when the RES input is low. Such measures have already partly been implemented in Denmark. However, when increasing the share of wind power, the measure will lead to an inefficient use of boilers instead of CHP. Such consequences have been seen in recent years in Denmark. Therefore, the next step is to add heat pumps and maybe additional heat storage capacity to the CHP stations and operate the system in such a way that further RES can be efficiently integrated. Such measures will result in an integration of up to 40 percent of fluctuating RES into the electricity supply without losing the overall system efficiency. The economic feasibility of the investments in heat pumps proves very high for Danish society. Moreover, the investment in wind power has been substantially improved. Third, electricity should be used in the transportation sector, preferably in electric vehicles. These measures will serve as an efficient improvement of the integration of fluctuating RES.

However, in the short and medium term, attention should be paid to the basic assumption that the perception of reality and the interests of existing organizations will seek to hinder radical institutional changes through which these organizations may lose power and influence. Often these institutional interests will seek to create a perception indicating that society has no choice but to implement technologies that will support existing positions. These mechanisms can be observed in the present situation.

It is clear that coal is not part of the long-term objective of an energy supply based on 100 percent renewable energy, nor are flexible large steam turbines a good solution for future power plants as explained in Chapter 6. Nevertheless, organizations that make a profit from burning coal first involved themselves in the promotion of coal in combination with carbon capture technology. As described in Chapter 2, the message from these organizations was clear in 2008: Denmark and Europe had no choice but to burn coal and introduce carbon capture. Afterward, the same organizations changed strategy and now, among other things, are trying to replace coal with biomass, however, still mostly in existing steam turbine plants. As explained in Chapter 6, this technology will not be able to meet the requirements of future renewable energy systems.

The fact that existing organizations linked to the steam turbine technology first promote changes in terms of adjustments to the existing technology rather than get involved in the implementation of radical technological changes is completely in accordance with the Choice Awareness theory. The advice to governments is to ask for specific alternatives to compare.

Prior to 2010, the Danish company DONG involved itself in the promotion of a large coal-fired power station in northern Germany. This was later given up, but it serves as a good example of the problems with building new coal-fired power stations and what to do about them.

The New Coal-Fired Power Station in Germany

Given the European energy policies of increasing the share of CHP and renewable energy and decreasing CO_2 emissions, a new large coal-fired power station is not the first thing that comes to mind as an obvious solution, and the import of hard coal will not be beneficial to European energy security or the balance of payment. However, this is exactly the proposal that DONG presented and was promoting in northern Germany prior to 2010. This technology fits well into the existing organization of DONG, which operates several coal-fired power stations in Denmark and has a very competent and skilled department with expertise in the design and construction of these power stations.

Based on the experience of, for example, the Nordjyllandsværket case, one should expect a series of half-true statements declaring that the power station will provide environmental benefits because it replaces old power stations and that the power station uses CHP, even though the town near the location is small compared to the size of the station and this will only be symbolic.

When confronted by the fact that a coal-fired power station with a construction time of 5 years and a lifetime of maybe 30 years represents a solution that will cause CO_2 emission problems to Europe in the long term, the answer seems to be carbon-capturing technologies. Consequently, society is confronted with the questions: "Is this a good solution? Why not build some more coal-fired power stations if carbon capture can solve the problems?" In these situations, the advice of this book is to insist on comparing the solution in question with the relevant alternatives—in other words, to create Choice Awareness. The idea is to change the discussion from whether such a new coal-fired power station is good or bad to which alternative is the best for fulfilling relevant political objectives.

Figure 9.1 shows an example of such an alternative. It should be emphasized that the diagram represents a sketch of the principles of the alternative. It is not based on exact data regarding heating demands. However, on the basis of the

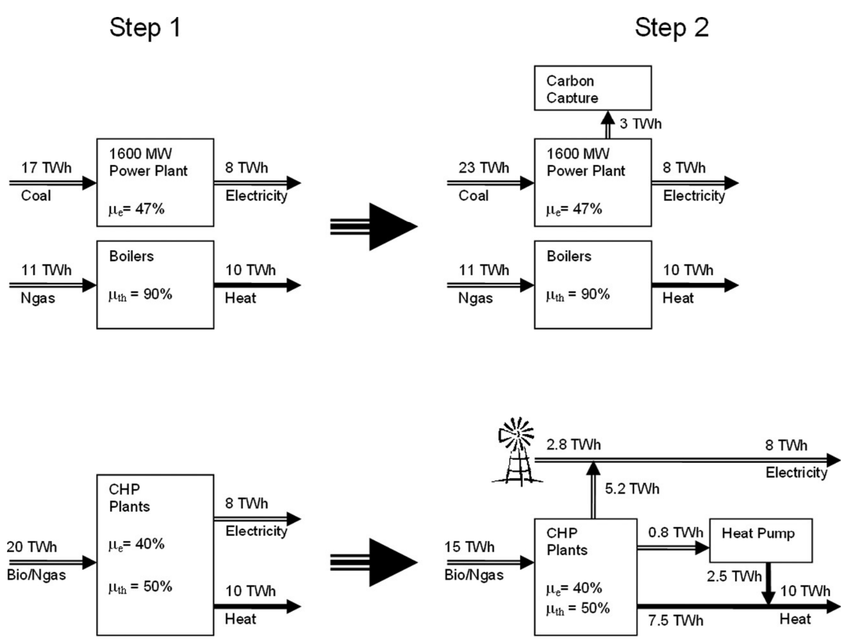

FIGURE 9.1 Coal-fired power station reference leading to carbon capture compared to the alternative of CHP leading to an efficient use of biomass and a better integration of wind power.

cases described in Chapter 8, the figure is likely to represent a realistic example. The reference is a 1600 MW coal-fired power station as proposed by DONG (Step 1) and adding a carbon-capturing station (Step 2). The power station is assumed to have an efficiency of 47 percent, and the carbon-capturing station is assumed to consume between one-quarter and one-third of the power produced at the power station.

Apart from coal, the main problem related to the reference proposal is that it is far from fully exploiting the potential of CHP. Consequently, the alternative is (Step 1) to build a number of small CHP stations located in the towns and villages of the surrounding district. Later (Step 2), heat pumps and heat storage capacities will be added, and these flexible energy systems will be exploited to increase the share of wind power. The small CHP stations may be fueled with a combination of natural gas (it is likely that the houses are heated by natural gas) and local biomass resources, such as biogas and straw.

As Figure 9.1 illustrates, the reference leads to an increase in the import of coal, which is needed to fuel both the power production and the carbon capture. The alternative, on the other hand, is capable of decreasing fuel consumption and avoiding the import of huge amounts of hard coal. The development in the primary energy supply of the two alternatives is shown in Figure 9.2.

When met by such project proposals, the recommendation to the politicians is to insist on seeing proper descriptions and analyses of the alternatives. The draft shown here may lead to a refinement or change in the main proposal, or it may even lead to the formulation of better alternatives. The point is to raise awareness of the fact that society has a choice. The solution that fits best into the interests of the existing organizations is seldom the only or best option.

Slowdown in Onshore Wind Power

According to the theories in this book, one could also expect that existing organizations relating to fossil fuel-based production would perceive climate change problems as a less severe threat, which can be handled by use of technologies within the existing institutional framework. If renewable sources are to be

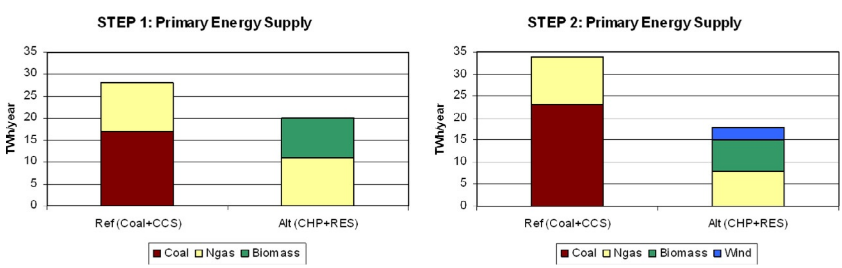

FIGURE 9.2 Primary energy supply (fuel) of the coal-fired power station and carbon capture reference compared to the alternative of CHP and renewable energy meeting the same annual demands of 8 TWh electricity and 10 TWh heating.

implemented according to this perception, the renewable technologies that fit into the framework of these organizations will be preferred.

As discussed in Chapter 2, one example of this can be seen in the debate on how to expand wind power in Denmark. The most cost-effective way is to increase the number of onshore wind turbines. From many years of experience, Danish society knows that this can be done if institutional frameworks are established in which neighbors own shares of the wind turbines and make a profit. Danish society also knows that if neighbors are not involved, they are likely to protest against this solution.

However, based on the argument that wind power should adjust to the market, the institutional framework for neighbor-owned wind turbines has been abolished, and instead the government wants to expand offshore wind farms. These wind farms are not economically competitive compared to onshore wind turbines, and they increase the need for subsidy. However, offshore wind farms correspond perfectly to the institutional framework of existing power companies.

Figure 9.3 illustrates the actual development of Danish wind power up until 2008. As can be seen, the expansion was stopped before 2004. The increase in the Danish wind power capacity happened in the 8 years prior to 2004. Thus, during 1996–2003, 315 MW on average was added each year, amounting to 80 percent of the accumulated installed wind power capacity in Denmark. During 2004–2008, only 5 MW on average was added each year.

In 2004, a majority in the Danish Parliament agreed to expand wind power in Denmark. However, for many years such an agreement was not implemented

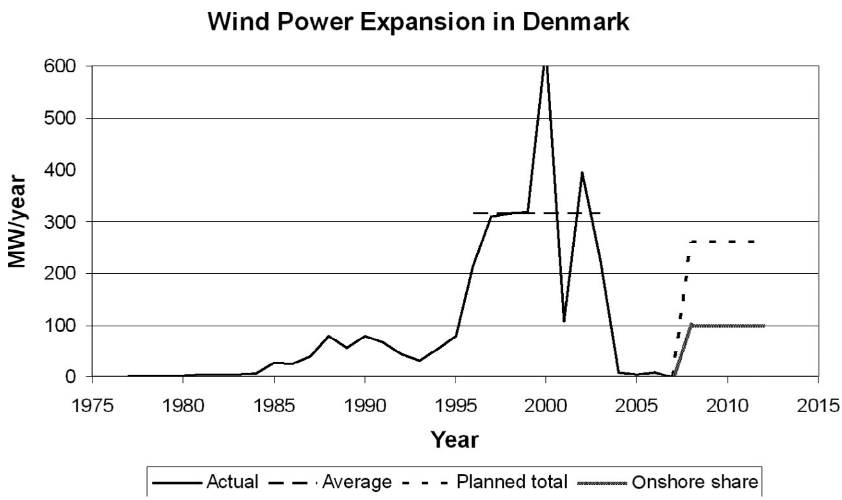

FIGURE 9.3 Expansion of wind power in Denmark. From 1996 to 2003, an average of 315 MW/year was built, corresponding to 80 percent of the total capacity. The succeeding expansion was planned to include mainly offshore wind power.

because, among other reasons, the local ownership arrangement was canceled. Then in 2008, a majority in Parliament agreed to expand wind power (Danish Government 2008). The total expansion during 2008–2012 increased the share of wind power from 20 percent to nearly 30 percent of the electricity demand. However, the rate of onshore wind power was small. Most of the new capacity was planned to be offshore wind farms and ended up being very expensive. Even so, resistance from local neighbors was feared, and a compensation arrangement was reached. Moreover, the government was confronted with a conflict in which it tried to force the municipalities to identify proper areas for wind power. Even though expressing positive preferences for wind power, many city councils found themselves in an unpleasant situation regarding the reaction of future neighbors of wind farms, and the government was faced with the dilemma of whether to force the implementation or to accept delays or reductions in the targets.

Afterward, as part of a new agreement, Parliament agreed to increase the share of wind power to nearly 50 percent by 2020. Again, a substantial part of the wind turbines are offshore and expected to increase the share of subsidies from Danish electricity consumers.

The recommendation to the politicians is to reinvent the former local ownership arrangement in a modernized version and to implement the institutional changes to make it possible and desirable for local citizens and neighbors to own shares of wind turbines. Such institutional changes are required to increase onshore wind power in Denmark in a least-cost way as well as in a way that involves neighbors and citizens in a positive manner.

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