

6

Energy and Economy

Convening Lead Author (CLA)

Kurt Yeager (Electric Power Research Institute and Galvin Electricity Initiative, USA)

Lead Authors (LA)

Felix Dayo (Triple "E" Systems Inc., USA)

Brian Fisher (BAEconomics, Australia)

Roger Fouquet (Basque Centre for Climate Change, Spain)

Asmerom Gilau (Triple "E" Systems Inc., USA)

Hans-Holger Rogner (International Atomic Energy Agency, Austria)

Contributing Authors (CA)

Marianne Haug (University of Hohenheim, Germany)

Richard Hosier (World Bank, USA)

Alan Miller (International Finance Corporation, USA)

Sabine Schnitteger (BAEconomics, Australia)

Review Editor

Nora Lustig (Tulane University, USA)

Contents

Executive Summary	388
6.1 Introduction	389
6.2 Basic Drivers of Energy Demand	390
6.2.1 Demographic and Income Changes.....	390
6.2.2 The Move to Modern Energy Carriers—Advances in Electricity.....	393
6.2.3 Economic Production Processes.....	394
6.3 Challenges of Projecting Energy Demand	395
6.4 Relationship Between Economic Growth And Energy Demand	396
6.4.1 Industrialized Countries.....	397
6.4.2 Developing Countries.....	399
6.4.3 Small and Medium Enterprises.....	400
6.5 The Prices and Costs of Energy	400
6.5.1 Prices as Market Signals.....	400
6.5.2 Costs Associated with Energy Supply and Use.....	401
6.5.3 Externality Costs.....	401
6.5.4 Resource Depletion as an Externality.....	403
6.5.5 Discounting and Discount Rates.....	404
6.5.6 The Impact of Long-Term and Short-Term Energy Demand.....	405
6.5.7 Energy Markets and Energy Price Subsidies.....	406

6.6	Investments in Energy	407
6.6.1	Investment Characteristics and Trends	407
6.6.2	Energy Supply Investments	408
6.6.3	Energy End-Use Investments	409
6.7	Financing	410
6.7.1	The Constraints	410
6.7.2	Energy Efficiency Investment Constraints	410
6.7.3	Financing Energy Efficiency	411
6.7.4	Financial Sources and Instruments	412
6.8	Technology Innovation and Diffusion	414
6.9	Institutional Change	416
6.10	Conclusion	416
	References	418

Executive Summary

The three most basic drivers of energy demand are economic activity, population, and technology. Longer-term trends in economic growth for a particular economy depend on underlying demographic and productivity trends, which in turn reflect population growth, labor force participation rate, productivity growth, national savings rate, and capital accumulation (USEIA, 2011).

Several historic shifts are likely to fundamentally alter global demographics over the coming decades. First, as developing nations move from poverty to relative affluence, there is a fundamental shift from agriculture to more energy-intensive but much more productive commercial enterprises. Second, labor forces in the developed countries are aging considerably, which has implications on many fronts, including energy use and employment structures. Third, for the first time the majority of the world's population has become urbanized, with the largest urban centers emerging in developing regions where energy access is a serious constraint. All of these will have immense impacts on the level and quality of energy demand and on concerns about energy security.

Global energy security and sustainability in the twenty-first century will depend less on the total global population than on incomes and their distribution. This in turn will depend to a large extent on how effectively the lack of energy services, which now limit economic opportunities in the less developed regions, is addressed. In addition, energy security will depend on the ability of countries to maintain reliable sources of energy to meet their needs.

As economies develop, countries' energy needs and priorities change. The evolution of demand at different stages of economic development changes. As economies develop, as happened with industrialized countries, the tendency is to adopt more efficient technologies for the provision of energy services, and the composition of economic activities change with energy intensity tending to decline over time.

Prices play several essential roles in economic production and demand. Most importantly prices send signals to buyers and sellers. Yet it is important to distinguish between prices and costs. There are four types of costs: monetary costs, opportunity costs, environmental (and health) costs, and sociopolitical costs. Most consumers are predominantly exposed to monetary costs and less to the other ones, although these are also important.

Renewable energy technologies, energy efficiency, advanced energy technologies and their associated products and services have been among the most rapidly growing sectors for investment in recent years, with major developing countries becoming investment leaders rather than simply technology transfer followers. In spite of this progress, the total public and private funding of energy-related research, development, and deployment remains much less than the amount needed for the transition to a sustainable, climate-constrained world.

Due to their importance as major contributors to job creation and economic growth, small and medium enterprises are potential leaders in business model transformation in many parts of the world.

6.1 Introduction

The primary role of Chapter 6 is to define the nature and magnitude of the demands on local and global energy systems arising from economic activity. Energy is not an end in itself but rather the means for providing energy services. The energy system is driven by the demand for energy services – a demand that in turn is driven by population and demographic trends, by the level of economic activity and income, and by technological and structural changes. In essence, providing energy services involves investment, operating costs and, if applicable, fuel costs.

Energy fuels the economy, which provides for the establishment of necessary energy infrastructures – from resource and material extraction to the technologies producing electricity as well as other energy carriers and end-use equipment to deliver the desired energy services. The economy is also the financier of energy systems and of its components and energy flows. A central question is: how much energy do economies need to function smoothly and thus being able to augment social development and well-being.

At the same time, economic and demographic developments play a fundamental role along with other drivers (e.g. technology) and GEA sustainability goals (e.g., access, security, and environmental and climate protection) in determining the energy needs and structure of energy systems. Chapter 6 focuses on these two drivers central to GEA. Both were assumed exogenously so as to be in the middle of the range in the literature (see Chapter 17). However, the convergence of per capita gross domestic product (GDP) was assumed to be stronger than in other median economic projections. In order not to subtract from the energy focus of GEA, single, median GDP and population projections were chosen.

An important reason is that economic and demographic developments like other GEA goals are in themselves necessary dimensions of sustainability. The relative GDP convergence enhances the achievement of other GEA goals and enables the transformation of energy systems and achievement of sustainable development. For example, economic development furthers technological change through higher investments and more rapid capital turnover.

Given the long time frames under consideration, serious attention to incorporating highly energy efficient end-use technologies has the decisive potential to address the major energy related challenges addressed in GEA (Goldemberg et al., 1985).

Infrastructures such as power plants, roads, railways, buildings, and so on are inherently long-lived, with service times counted in decades to half-centuries and more. Longevity means stability and inertia at the cost of short-term flexibility. Still, energy systems are constantly in flux – at rates often difficult to detect in the short run at the level of supply. Rates can be much faster on the energy demand side, as energy-using appliances, plants, and equipment have much shorter lifetimes than

supply-side infrastructures. The shorter lifetimes are directly related to the growth and changing mix of goods and services provided by the economy.

The evolving energy system epitomizes technology change and innovation. Technology is the crucial tether between the energy system and the economy, especially the modern economy¹. Energy and economy evolve in tandem, and technology defines which energy carriers and services the system can provide and which the economy can demand. The industrial revolution was powered by coal, which provided industries and households with a much more concentrated fuel. This enabled a higher productivity with respect to wood fuels and which boosted economic progress and urbanization. In the nineteenth century, abundant access to coal increased productivity and stimulated economic development.

Today access to modern forms of energy or rather secure, clean, affordable energy carriers fundamentally defines the modern economy. Electricity is key in this regard, as it is most compatible with the needs of the modern economy. It is more than just an energy carrier in the strict physical sense. Electricity enables all kinds of transactions – from information exchange to transportation. Its productivity in economic production and consumption as well as cleanliness at the point of use is second to none. The factors contributing to income disparities within and between countries can be traced to many reasons that vary across countries and regions. A lack of access to modern energy carriers and services is one of these contributing factors (Modi et al., 2005).

The world is now in the midst of an unparalleled period of dramatic growth in multiple parameters, also known as “the great acceleration” (see also Chapter 3). Major populous developing countries are actively and successfully pursuing industrialization and socioeconomic development with concomitant growth in demand for energy-intensive goods and services. As a consequence, energy demand is rising rapidly compounded by population trends. If current trends continue, human beings will use more energy over the next half-century than in all of recorded history. Energy demand on this scale will put increasing pressure on global energy resources and distribution networks. This is unsustainable without a fundamental transformation of the energy system. The unsustainability, however, has many other elements than resource availability, including energy services for economies and poverty alleviation, as well as addressing various social and environmental and health dimensions, security and peace (see also Chapters 2–5).

The dominant fossil energy resources today, especially oil, are concentrated in only a few regions. Energy security – that is, the potential disruption of supply – is viewed by many countries as a potential threat to their economic well-being (see also Chapter 5).

¹ Technology is more than just hardware and includes a range of factors from cultural aspects to education and training (Arthur, 2009).

Providing access to energy services involves the conversion of primary energy resources as well as the manufacturing (and construction) of required technologies and distribution networks. These activities take material from the environment and inevitably split them into desirable products and wastes of various forms. The latter are returned to the environment, increasingly at levels beyond the carrying capacities of ecosystems, and threatens to have environmental damages undermining economic gains.

Achieving the partly conflicting objectives of environmental protection and economic gains will require substantial input from the economy in the form of finance as well as research, development, and deployment (RD&D). The *2009 World Energy Outlook* of the International Energy Agency (IEA, 2009a) estimated that US\$20 trillion will be required over the next 25 years just to meet the projected increase in global energy demand by 2030. Similarly, the GEA pathways from Chapter 17 show that the transformation of the energy system would require dedicated efforts to increase global energy-related investments to between US\$1.7 trillion and US\$2.2 trillion annually, compared with about US\$1.3 trillion in annual investments today (see also Chapter 24). Out of this total, about US\$300 to US\$550 billion of efficiency-related investments are required on the demand-side of the pathways. This includes only the efficiency-increasing part of the investment to improve energy intensity beyond historical improvement rates. The full demand-side investments into all energy components of appliances might thus be significantly higher. Total investments into energy supply and efficiency-related investments at the demand-side correspond in sum to a small fraction (about 2%) of global GDP. Future transitions with a focus on energy efficiency achieve the targets at more modest cost and thus represent the lower bound of the investment range (see Chapter 17 for further details).

Current modest levels of investment in clean energy facilities and energy efficiency measures contrast starkly with these immense investment requirements. Furthermore, significantly strengthened innovation will also be essential to support the continued development of new solutions to these critical energy challenges, as governments and industry struggle to expand new energy resources and new ways to use existing resources in a sustainable manner.

The demands of a changing energy paradigm have wider institutional implications. The institutions created over the past several decades are struggling to remain relevant in the face of profound geopolitical and economic changes (outside the domain of their membership). New institutional frameworks more suited to the needs of today are urgently needed. These institutions would need to support the delivery on the goals of access to affordable modern energy carriers and end-use conversion, enhanced energy security, climate change mitigation, and health and environment.

In the twenty-first century, a global energy system for sustainable societies must reflect multiple objectives that include energy availability,

affordability, security, and consistency with climate change goals (see also Chapters 2–5). These have been further complicated by the usual market implementation issues that have been aggravated by the current global economic crisis.

The required energy system transformation will be difficult to accomplish without some transformation of the world economy – a process that will be complex and characterized by marked clashes of interest. This transformation will therefore require a long-term vision and sustained cooperation among a large array of diverse stakeholders at both the national and international level, coupled with strong public policy support and private-sector engagement.

6.2 Basic Drivers of Energy Demand

The three most basic drivers of energy demand are population, economic activity per capita, and technology performance. Based on these fundamentals, this century is likely to see major shifts in energy demand and development. According to a recent UN report (UNFPA, 2011), global population by 2050 is projected at 9.3 billion, a revision upwards from previous reports (UNDESA, 2004). Virtually all this projected population growth will occur in the developing world. By comparison, the present world population is 7 billion, and was only 2 billion as recently as 1930.

This unprecedented massive global population growth over little more than a century is arguably one of the most defining events of our era. The past century also represents a period of intense technological expansion, which has fundamentally increased humanity's ability to harness energy. This has contributed to changing the historic equilibrium between human fertility and mortality. As a result, average life expectancy worldwide more than doubled over the last century from 32 to 67 years, and it continues to increase steadily.

6.2.1 Demographic and Income Changes

Extending population projections beyond 2050 depends on uncertain fertility, mortality, and migration assumptions. Researchers at the International Institute for Applied Systems Analysis (IIASA) have addressed this uncertainty constraint by developing probabilistic population projections that reflect a realistic range of uncertainty (Lutz and Samir, 2010). Table 6.1 outlines these projections through 2100 for 13 major world regions. The results suggest that the world population will most probably peak by 2050 at slightly less than 9 billion² and remain above 8 billion through at least the remainder of this century. Yet the probabilistic shifts in population distribution among the continents

2 A more recent study by the UNFPA (2011) has adjusted this figure slightly upward to 9.3 billion as mentioned above.

Table 6.1 | Population projections.

	Total Population (millions)		
	2010	2050	2100
North Africa	208	307 (+48%)	324–346 (+56%–+66%)
Sub-Saharan Africa	799	1,617 (+102%)	2,074–2,247 (+160%–+180%)
North America	339	427 (+26%)	421–468 (+24%–+38%)
Latin America	595	834 (+40%)	909–977 (+53%–+64%)
Central Asia	65	96 (+48%)	101–108 (+55%–+66%)
Middle East	215	359 (+67%)	392–417 (+82%–+94%)
South Asia	1,625	2,289 (+41%)	2,016–2,140 (+24%–+32%)
China & CPA	1,468	1,342 (–9%)	829–881 (–56%–+40%)
Pacific Asia	542	699 (+29%)	649–689 (+20%–+27%)
Pacific OECD	152	137 (–10%)	85–103 (–44%–+32%)
Western Europe	462	449 (–3%)	320–364 (–31%–+21%)
Eastern Europe	120	94 (–22%)	54–60 (–55%–+50%)
Former Soviet Union	228	169 (–26%)	103–111 (–55%–+51%)
WORLD	6,816	8,816 (+29%)	8,280–8,920 (+21%–+31%)

Source: Lutz et al., 2008.

during this time are dramatic. Europe and China are projected to have population reductions on the order of 40–50% by the end of the century, while Africa and the Middle East are likely to double their populations and Latin America and Central Asia are expected to have population increases on the order of 50%.

Four historic shifts, revealed in the most recent United Nations population data, are likely to fundamentally alter global demographics over the next several decades (UNFPA, 2011). First, the relative demographic weight of the world's industrialized nations is forecast to decline by at least 25%, with a corresponding shift of economic power to developing nations. As these nations move from poverty to relative affluence, there is a fundamental shift from agriculture to more energy-intensive commercial enterprises. Second, the labor forces in the industrialized countries will age considerably. Third, most of the world's expected population growth will be concentrated in today's poorest countries, which typically lack employment, capital, and educational opportunities.

Finally, the majority of the world's population is becoming urbanized, with the largest urban centers found in the world's poorer regions, where energy access typically remains a serious economic constraint. All of these shifts point to substantial growth of demand in developing countries where energy systems are notoriously underdeveloped and therefore open early and sizable prospects for an effective energy system transformation. Expanding systems simply offer more opportunities for market penetration of new technologies than stagnating or shrinking systems. Being a multiplier of demand for goods and services including energy, however, population remains a major driver of, especially adverse, impacts (Campbell et al., 2007). Given the absolute limits of the planet, as illustrated by the need to limit concentrations of climate-altering pollutants, reductions in population growth trends can give valuable additional decades to resolve energy and other problems before these planetary limits are reached. There is no coercion implied here, as studies show that there are hundreds of millions of women wishing to control their family size who do not have access to modern

contraceptive technologies (Cleland et al., 2006). Analyses show, for example, that doing so could lower CO₂ emissions from energy use by 30% in 2100 over what is projected otherwise (O'Neill et al., 2010). Providing reproductive health services to these women is also an equity issue as all women, not just those in rich countries, ought to have access to such services (Prata, 2009). It is also an important health issue as spacing births, which, along with reducing growth rates, gives men and women access to contraception, which has major benefits for both child and maternal health (Smith and Balakrishnan, 2009).

In light of these enormous demographic challenges, the global economy is significantly underperforming mainly in industrialized countries, while developing economies performances are not sufficient to provide for everybody. Given the annual addition to the world of about 40 million workers and the average levels of GDP per worker, the world economy has to generate at least \$500 billion in additional output each year just to employ new workers (Martin, 2005). At current growth rates, tens of millions of workers will remain unemployed. Unfortunately, the issue of how to achieve sustainable world economic growth is still not being effectively addressed. Education is the key. As Lutz et al. (2008) point out, "education is a long-term investment associated with near-term costs, but in the long term it is one of the best investments societies can make in their future."

Nearly 80% of the people in the world continue to have inadequate purchasing power parity (PPP) to afford basic needs and thus live in poverty (Chen and Ravallion, 2008). Lack of access to modern forms of energy is a constraint on the economic and social progress for a large fraction of this population. Indeed, due to extreme poverty³, huge rural and urban populations are being largely excluded from the social and economic development processes in which markets are a part. Unless this growing demand for energy is met by cleaner, safer, and more efficient energy technologies, the negative impacts on global health and environmental will continue to grow.

The economic prosperity of the world's population is, however, rapidly increasing. Barring a cataclysmic crisis, global economic output is projected to increase at the rate of 3–4% over the next several decades (IEA, 2011; USEIA, 2011). As a result, and as was the case in the last century, global income will most likely increase far faster than population. Indeed, stabilization of the world's population has been shown to be a direct result of increased prosperity. In 2000, the poorest half of the world's population owned only about 1% of total global wealth (Davies et al., 2008). This extreme poverty is decreasing as nations develop and their standards of living steadily improve.

The rise in world affluence holds promise for improved well-being but also comes with significant ecosystem risks if prevailing patterns of energy

demand, supply, and waste persist. Since the Industrial Revolution, economic development and expansion have been tied to increased energy use, and this link remains strong today. Without the grand transformation in the global energy system as explored in GEA, fossil fuels will remain the dominant energy source through at least the middle of the century under any achievable circumstances – a definite challenge for achieving greenhouse gas (GHG) stabilization at 450 ppm. Fossil fuels with carbon capture and storage (CCS) or moving beyond fossil fuels to cleaner, renewable and other non-carbon energy sources will require a much larger and sustained commitment as well as accelerated upfront investments. In 2009, non-fossil fuel energy resources provided approximately 22% of the world's primary energy supply (see Chapter 11). Providing adequate energy supplies at minimum GHG emissions begins with the large-scale adoption of currently best available technologies (BAT) and practices (Pacala and Socolow, 2004; IPCC, 2007) but eventually will require a major upscaling of this BAT. In either case this only occurs when people have the incentives to adopt innovative technologies and are willing to forego excessive current consumption for future benefit. Investing in BAT and technological progress is a major concern, as the demands for short-term returns on investment constrain the strategic development opportunities on which those returns ultimately depend.

The challenges facing rural regions over the next 50 years are significant. Fertility rates are much higher than in urban areas, where health care and education are relatively advanced and available. Not only will these rural regions be the source of a large portion of the world's population growth, but they must be able to help feed the world. Only about 13% of global land area is arable, and the average population density in the developing world is expected to increase from about 60 people/km² to around 96 people/km² by 2050. This compares to an industrial-world stable population density of about 25 people/km² and poses unprecedented problems of land use and preservation in the developing world (UNDESA, 2004).

Countries' energy priorities and services demand change dramatically as their economies develop. Thus global energy security and sustainability in the 21st century will depend less on the total global population than on population incomes and how that income is distributed. Nations are very different with respect to their incomes. For example, member countries of the Organisation for Economic Co-operation and Development (OECD) currently account for approximately 18% of the world's population but for almost three quarters of GDP. By comparison, China and India represent some 37% (20% and 17%, respectively) of the world's population and about 11% of global GDP in terms of market exchange rates (MER) (World Bank, 2011ba). Even if expressed in units of Purchasing Power Parity (PPP), their share of global GDP was below 25% in 2010 (GEA scenario database, see www.globalenergyassessment.org).

Figure 6.1 depicts the disparity of income measured in terms of GDP per capita across 11 world regions in 2005. The level of primary energy use appears to mirror the level of affluence in a region, and there is a

3 Currently defined as per capita income of less than US₂₀₀₅\$ 1.25 per day (Chen and Ravallion, 2008).

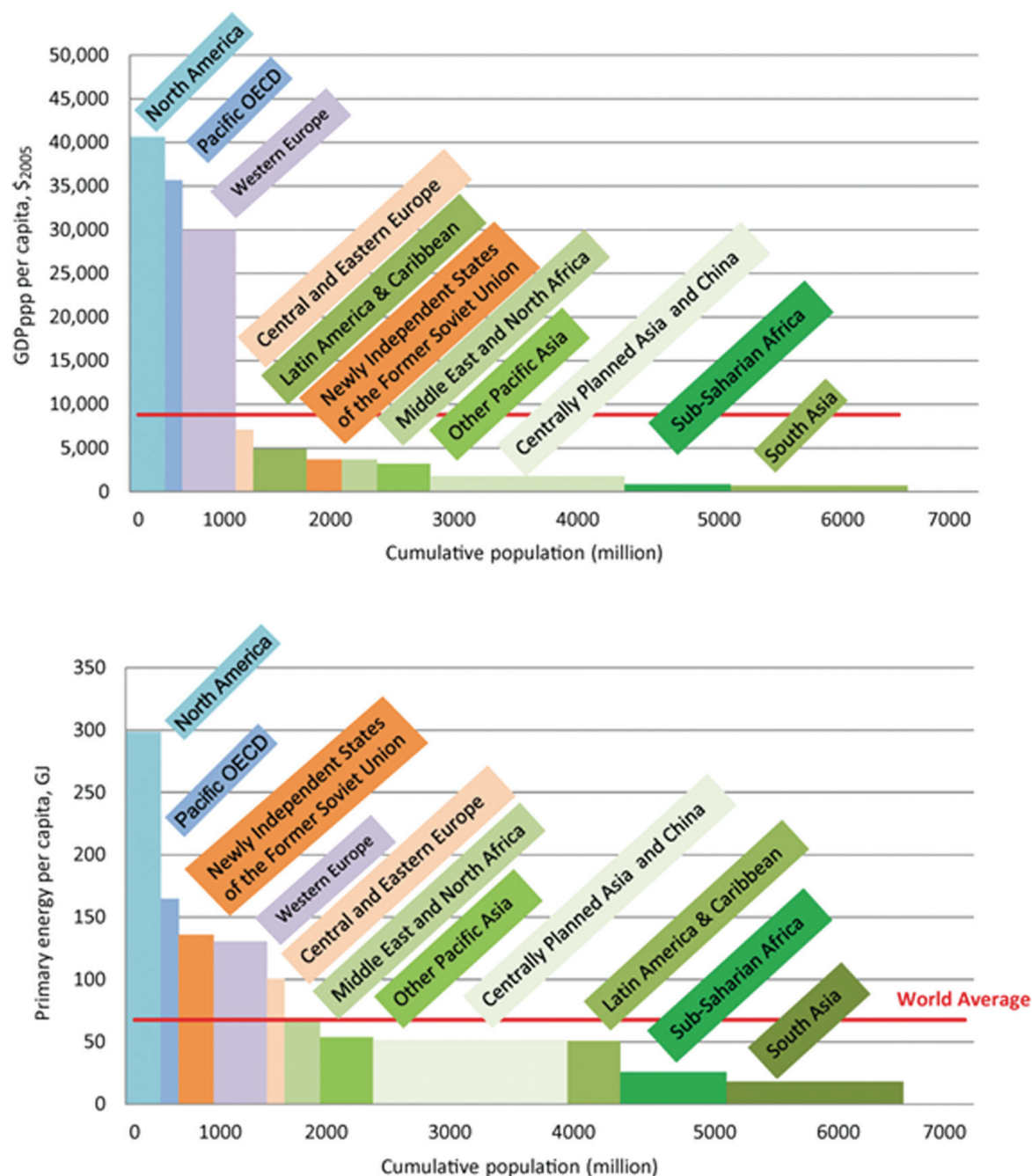


Figure 6.1 | Regional disparities in income and energy use per capita in 2005.⁴

common understanding that the access to clean and affordable energy is critical for achieving the Millennium Development Goals (MDGs) and enabling sustainable economic development. The UN Advisory Group on Energy and Climate Change (AGECC) defines energy access⁵ as

“access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses” (AGECC, 2010).

⁴ Figure 6.1 depicts the large income and energy use disparities between major regions and countries. However, it is important to note that access disparities within nations are typically greater than between nations.

⁵ For definitions of energy access, see Chapters 2 and 19.

6.2.2 The Move to Modern Energy Carriers—Advances in Electricity

Electricity provides the essential key to energy access and enables technical innovation and productivity growth – the lifeblood of a modern

society. Electricity's central role in achieving economic and environmental progress is broadly accepted throughout the world, depending on how the electricity is produced (see Chapters 3 and 4). The determining factor is whether nations will find the leadership and make the commitment necessary to harness and expand electricity's unique capabilities. Ironically, the electronic technological revolution that electricity has enabled over the past decades has largely been ignored by the electricity supply industry itself (Galvin and Yeager, 2009).

The pacing factor is the necessary investment for the innovative technologies that are needed to replace today's generally centralized and aging electricity infrastructure and establish a truly intelligent global electricity infrastructure spanning from generation to end use. The accelerated growth of intermittent renewable technologies combined with the introduction of smart grids may make it possible to transform them into useful and valuable fuels. Of equal importance is that electricity provides a continuous efficiency improvement opportunity, i.e., the inherent intelligence that comes from the incorporation of modern digital electronic monitoring and control technology throughout the electricity delivery and utilization networks.

While renewable technologies are desirable for providing clean energy carriers to the unconnected, especially in rural areas, one must not ignore the ongoing urbanization trend and industrialization aspirations of developing countries. Cities have a much higher energy demand density per hectare than rural settlements. Energy-intensive industries represent large-scale off-take nodes. While supply densities of renewables or distributed electricity generation are consistent with the demand densities and offer opportunities in cities as well, metropolitan areas will continue to require a certain share of baseload electricity from large central conversion facilities such as large scale hydro, nuclear, or fossil fuels with CCS.

Today, global electrification is distributed very unevenly (see Chapters 2 and 19). The highest proportion of people without electricity is concentrated in rural sub-Saharan Africa and South Asia – regions that are also projected to have very high population growth this century. A realistic and universally achievable goal over the next decades is therefore to eliminate the electrification gaps for the 1.4 billion people without access today and to even more by 2030 under business-as-usual conditions (see also Chapters 17, 19, and 23). This goal is not just a matter of equity but an essential prerequisite for eliminating extreme poverty and stabilizing population in fast-growing developing regions. In order to keep pace with the world's growing population and to provide the foundation for the corresponding economic development, electricity must reach at least an additional 100 million people per year for at least the next 30 years. This is more than twice the current rate.

6.2.3 Economic Production Processes

In the context of the economic production process, the output of which is measured in terms of GDP, energy is but one production factor. It is

a necessary but not sufficient input⁶ to the production process.⁷ Other essential production factors are capital, labor, land, and materials. A simple production function then would take on the following form: $GDP = f(\text{capital, labor, energy, land, materials and know-how})$.⁸ The contribution of each factor (or input quantity) to output depends on the state of development of an economy, physical conditions and location (e.g., climate, geography, land), relative factor prices, and factor productivity as well as social and cultural conditions. Within certain limits production factors can substitute each other.

The ease of substitution is a matter of relative production factor prices, availability of factors, vintage of technologies, and lock-in in existing infrastructures, timelines, etc. For example, as an agriculture-based economy advances, higher incomes make labor more expensive (or more productive elsewhere in the economy), and rural workers are progressively replaced by machines (capital), energy (fuel for the machines), and materials. In the case of rising energy prices, substitution of capital and materials for energy can lower the physical energy input to the economy (although the economic value of the input may not change due to the higher prices of fuel and technology). Efficiency improvements are largely a substitution of capital and know-how for energy. Using the production function approach, the optimal energy input and thus energy demand can be determined by a first-order derivation of the production function where the marginal productivity equals the factor price.

Figure 6.2 presents three capital-energy combinations – all of which produce identical outputs (isoquant) both in terms of quantity and quality (labor and materials remain constant). Option A is an energy-intensive process but uses little in terms of capital (investment). Option B is much more energy-efficient but requires a more capital-intensive production structure. The most economically efficient option then is determined by the combined effect of the respective factor costs – that is, the price of fuel p_E , capital p_K (interest and depreciation), labor p_L (wages), and materials p_M . If factor costs, say for energy, were to include externalities (which generally is not yet the case), this would make energy more expensive, hence change the slope of the optimal factor combination (dashed line in Figure 6.2), i.e., from point C to B (lower energy – higher capital input). Therefore policies enforcing the internalization of externalities would encourage capital for energy substitution (for identical energy services) or change the nature of energy services demanded. Similarly energy subsidies reduce the incentive to deploy capital and energy efficiency measures resulting in higher energy use than otherwise.

6 According to the laws of thermodynamics nothing can be changed without energy input (or rather exergy consumption).

7 While long recognized for its many limitations, economic output is predominantly measured as GDP, either at market exchange rates or purchasing power parities even though alternative measures have been proposed.

8 Production functions found in the economic literature are way more complex than the illustrative example presented here. A more detailed discussion of production functions is beyond the scope of this chapter.

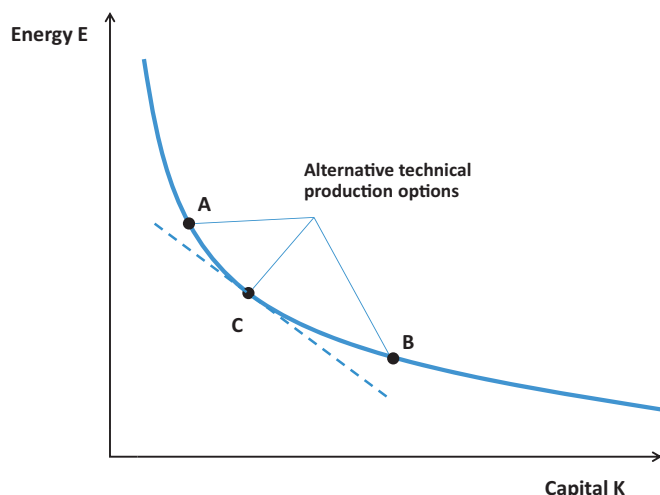


Figure 6.2 | Capital-energy substitution frontier.

Production costs $C = p_K K + p_E E + p_L L + p_M M$

The optimal factor combination results when

$dC = 0 = p_K dK + p_E dE$ (as dL and dM are zero by assumption) or

$$\frac{dE}{dK} = -\frac{p_K}{p_E}$$

which at constant factor costs leads to the dashed straight line with the slope $-p_K/p_E$ shown in Figure 6.2. The cost optimal factor combination results where the line touches the output isoquant – that is, Option C.

Generally it takes longer for substitution processes to materialize for a variety of reasons, ranging from system inertia and lock-in to the availability of capital and finance costs. The vintage structure of the capital stock and thus the natural rate of capital replacement due to wear and tear are ideal dates for the introduction of more-efficient plant and equipment or building stock. In the short run, a recently opened new factory or apartment building is unlikely to modify its heating and cooling equipment in response to, say, higher natural gas prices. If prices remain at elevated levels for extended periods of time, displacement of natural gas by inter-fuel substitution or efficiency improvements become economically attractive. Refurbishment of an aging building stock, the early retirement of boilers in a factory, or relocation of energy-intensive manufacturing process to a lower energy cost area are routine economic decision processes based on cost functions and relative factor prices.

6.3 Challenges of Projecting Energy Demand

In generating projections of future energy requirements, a key difficulty arises because the demand for energy derives from the demand for various services required by the industrial production of goods and services as well as buildings and energy-using appliances, such as refrigerators or cars. Energy demand therefore depends on evolving personal

preferences and behavior, including how the demand for energy services evolves at different stages of economic development (Haas et al., 2008). A variety of approaches have been used to estimate energy demand on the basis of the use of different types of energy-dependent services. They include:

- “bottom-up” approaches that evaluate the mix of economic activities and the energy intensity of these activities for each sector of the economy (Schipper and Meyers, 1992);
- approaches that consider the relationship between the demand for energy services and efficiency improvements in service provision (Ayers and Warr, 2009); and
- detailed studies of the price of energy services (such as lighting), economic development, and the consumption of energy services (Nordhaus, 1997; Fouquet and Pearson, 2006; Fouquet, 2008).

Since the early 1970s, a large number of empirical studies of energy demand have also sought to identify the effect of real incomes on energy demand (Griffin, 1993; Espey, 1998; Hunt and Ninomiya, 2003; Espey and Espey, 2004). In general, the estimates from these statistical analyses show that the income elasticity of the demand for energy is positive (i.e., rising incomes will lead to increased energy use). However, the magnitude of these elasticities⁹ differs by stage of development. In industrialized countries, the estimated income elasticities tended to be less than one (e.g., a 10% increase in income would result in an increase in energy use of less than 10%). Judson et al. (1999) analyzed data from OECD and non-OECD countries and concluded that income elasticities are lower at low levels of economic development, rise substantially at medium levels, and fall at higher levels. Hence the state of economic development and the standard of living of populations in a given region strongly influence the link between economic growth and energy demand (USEIA, 2011).

Based on empirical evidence, the evolution of demand at different stages of economic development can be described as follows (Fouquet, 2008). The demand for energy rises rapidly at early stages of economic development as an economy evolves from an agrarian economy and industrializes, with an associated increase in mining and manufacturing activities. Industrialization is also associated with a rapid rise in demand for heating and for freight transport. As the industrialized economy matures, the demand for energy by the industrial sector continues to grow in absolute terms but declines relative to the household and service sectors, in part because energy-intensive imports are substituted for domestic production. Household demand for energy continues to grow in absolute terms and rises with disposable incomes because of increased demand for space, heating and cooling, and individual transportation.

⁹ Income elasticity of energy demand is the ratio of percentage change of energy demand to the percentage change of income.

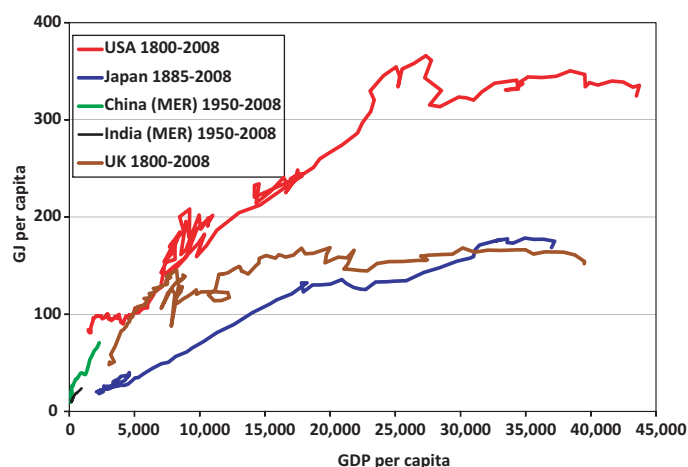


Figure 6.3 | Primary Energy Use per capita (GJ) versus GDP (at market exchange rates in US₂₀₀₅\$) per capita. Data sources: US, Japan: updated from Grubler, 1998, UK: Fouquet, 2008, India and China: IEA, 2010b and World Bank, 2010. Note: Data are for the United States (1800–2008), United Kingdom (primary and final energy, 1800–2008), Japan (1922–2008), China (1950–2008), and India (1950–2008). For China and India, also GDP at purchasing power parities (PPP, in International₂₀₀₅\$) are shown.

While it might be expected that the demand for energy will reach a saturation point at high levels of development, the evidence available to date suggests that if new, more-efficient technologies reduce the amount of energy required to operate appliances and equipment, the implied cost reduction often serves, everything else being equal, to stimulate additional energy-dependent activities. This is referred to as the rebound effect and arises because improvements in energy efficiency effectively decrease the cost of energy services, leading to additional disposable income and so potentially increases demand (see Chapter 22). Consumers and businesses change their behavior – they may raise thermostat levels in the winter, cool their buildings more in the summer, buy more appliances and operate them more frequently, or drive their vehicles more (IEA, 2005). However, as the price of energy services is what matters, higher fuel prices may well outweigh the benefits of more-efficient appliances, plants, equipment, and infrastructures. Data for the United States and Japan suggest that once annual per capita income levels exceed US\$30,000, per capita energy use no longer increases with GDP (see Figure 6.3) and that total energy demand is largely a function of population and prices. However, it can be argued that per capita energy use in the United States is higher than shown in Figure 6.3 as it excludes embedded energy, i.e., the energy content of imported goods and services as energy-intensive materials, mining, processing and manufacturing occur abroad. Likewise, accounting for embedded energy would reduce per-capita energy use of export-driven Japan.

A simple approach to present the energy – economy link is by way of demand functions such as the aggregate top-down relation:

$$E = POP \times \frac{GDP}{POP} \times \frac{E}{GDP}$$

where energy demand (E) is the product of population (POP), per capita income (GDP/POP), and the energy intensity of the economy (E/GDP), usually measured in megajoules per unit of economic output or GDP.

For all countries, population growth is a modest to strong driver of energy demand. The income effect in terms of GDP and GDP per capita is positive and generally larger in developing countries, where small improvements in per capita income translate into an over-proportional use of energy services. Energy intensities vary from region to region depending on the stage of economic development, geographic and climate conditions, and energy prices, but intensities have been declining in most countries and regions and thus are chiefly responsible for keeping energy demand growth in check globally. Figure 6.4 shows the average growth rates of primary energy, population, primary energy per capita, primary energy and electricity intensities of GDP for four consecutive 10-year periods in the World, OECD, Reforming Economies, Middle East and Africa, Asia, Latin America and Caribbean.

As described above, the relationship between energy availability and economic growth has been the subject of many studies, but no clear causality has emerged. Instead, the research suggests that the direction of causality differs as energy efficiency becomes a higher priority among countries, especially between industrialized and developing countries. In industrialized countries, the link now appears to be relatively weak, with energy use decoupled from economic growth. In developing countries, energy demand and economic growth have been more closely correlated in the past, with demand tracking or exceeding the rate of economic expansion (USEIA, 2011). These countries are still in the process of building their human and physical capital, which is inherently more energy-intensive than the operation of well-developed infrastructures.

6.4 Relationship Between Economic Growth and Energy Demand

As noted earlier, economic growth and energy demand are linked, but the strength of that link varies among regions and their stages of economic development. The state of economic development and the standard of living of individuals in a given region strongly influence the link between economic growth and energy demand. Advanced economies with high living standards have a relatively high level of energy use per capita, but they also tend to be economies where per capita energy use is stable or changes very slowly. In industrialized countries, there is a high penetration rate of modern appliances and motorized personal transportation equipment. To the extent that spending is directed to energy-using goods, it often involves purchases of new equipment to replace old capital stock. The new stock is often more efficient than the equipment it replaces, resulting in a weaker link between income and energy demand (USEIA, 2011).

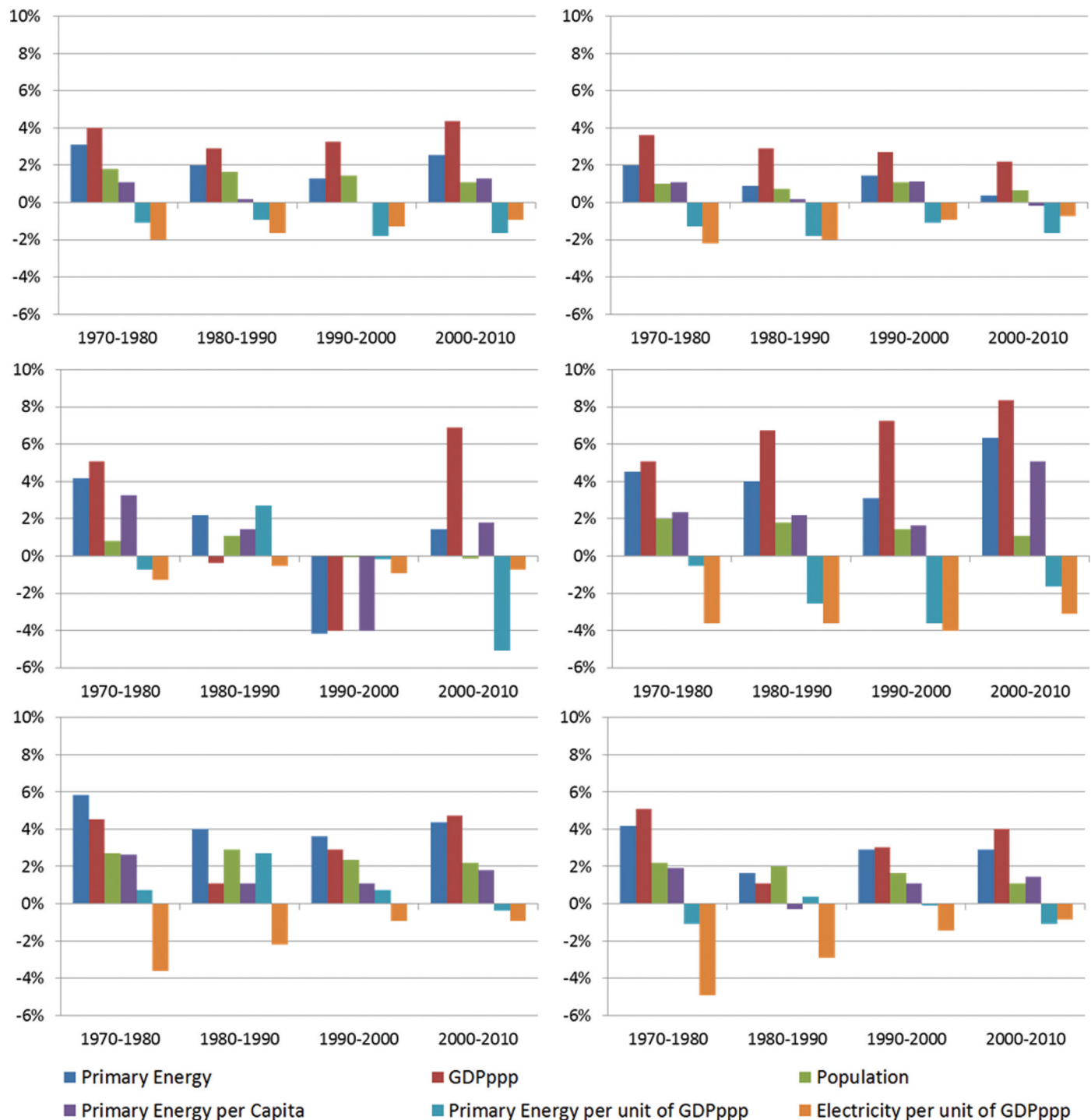


Figure 6.4 | Annual growth rates of indicators for primary energy demand, GDP, population changes and selected indicators for four ten-year time-periods and different regions (World, OECD, REF: reforming economies, ASEA, MAF: Middle East and Africa, LAC: Latin America and Caribbean). Source: data from GEA database.

6.4.1 Industrialized Countries

Historically, and beginning with the industrial revolution, increased energy use has fueled economic development in advanced industrialized societies (Fouquet, 2008). The first industrial revolution, which began in the eighteenth century, merged into the second industrial revolution around 1850, when technological and economic progress gained momentum

with the development of steam-powered ships, railways, and, later in the nineteenth century, the internal combustion engine and electrical power generation. Although a number of social and non-energy factors were responsible for the productivity increases of that era, there is agreement that the transition to the use of available energy sources such as coal coupled with technology innovations accounted for the impressive growth results achieved during this era (Landes, 1969; Ayers and Warr, 2009).

A commonly observed characteristic of this development is that advanced industrialized countries use less energy per unit of economic output and more energy per capita than poorer societies do (Toman and Jemelkova, 2003). Figure 6.5 shows the energy intensity of various regional economies in 2005. In contrast to energy use per capita, OECD countries have generally lower energy intensities than developing and transition countries. The latter are less efficient in their economic production, which indicates a large potential for efficiency improvements as these regions industrialize and adopt the best available technologies.

The stylized trend in energy intensity is for a rapid increase of industrialization, reaching a high plateau, and then a decline, especially when services begin to dominate the economic production. Changes in the demand for energy services associated with structural shifts in the economy are especially important in explaining the upward trend in energy intensity with industrialization. This rise is often exaggerated, however, by the lack of estimates of non-commercial energy sources. When wood fuel is included in statistical studies, and even human and animal power, there appears to be a more gradual rise in energy intensity (Schurr et al., 1960; Nilsson, 1993; Fouquet, 2008).

A more reliable observation is that as industrialized countries adopt more-efficient technologies for energy supply and use and as the composition of economic activities changes, energy intensity tends to decline over time (Nakićenović, 1996). In the last 30 years, the dominant driver for the declining trends in energy intensity have been technical improvements (Liu and Ang, 2007). Also, despite variability across countries, energy intensities tend to converge (Markandya et al., 2006; Liu and Ang, 2007). Even then, total energy use and energy use per capita continue to rise in most industrialized countries.

One of the first major studies of the relationship between energy use and economic growth in industrialized economies was undertaken in the United States for the period from 1947 to 1974. Although that study found that economic growth had a causal effect on energy demand (Kraft and Kraft, 1978), subsequent studies (Yu and Choi, 1985; Erol and Yu, 1987; Abosedra and Baghestani, 1989; Hwang and Gum, 1991; Cheng, 1995) alternately confirmed or rejected these conclusions (Soytas and Sari, 2003).

More recent studies suggest that the direction of any causality is country-specific. Soytas and Sari (2003) re-examined the relationship between economic growth and energy supply in the top 10 emerging economies and G7 countries and found that growth of GDP raised energy demand in the United States and in Italy, but that energy use raised GDP growth in Turkey, France, Germany, and Japan. The authors' conclusion was that in the long run, restriction on energy use, which reduces productivity, may harm economic growth, and that this may in fact have occurred in Turkey, France, Germany, and Japan. Another recent study of about 100 countries tested for causality between energy and GDP and found that causality from energy to GDP is more prevalent in OECD countries than in developing countries (Chontanawat et al., 2008).

At the aggregate level, the OECD region has seen steadily declining population growth rates over 40 years, caused by and large by an aging population and low fertility rates (see Figure 6.4). GDP per capita growth rate also declined steadily from 2.5% during the 1970s to less than 1.5% between 2000 and 2010 (GEA Database). Everything else being equal, population and per capita income together would have caused total primary energy demand to expand on average by 2.7% annually between 1970 and 2010. In reality, primary energy demand

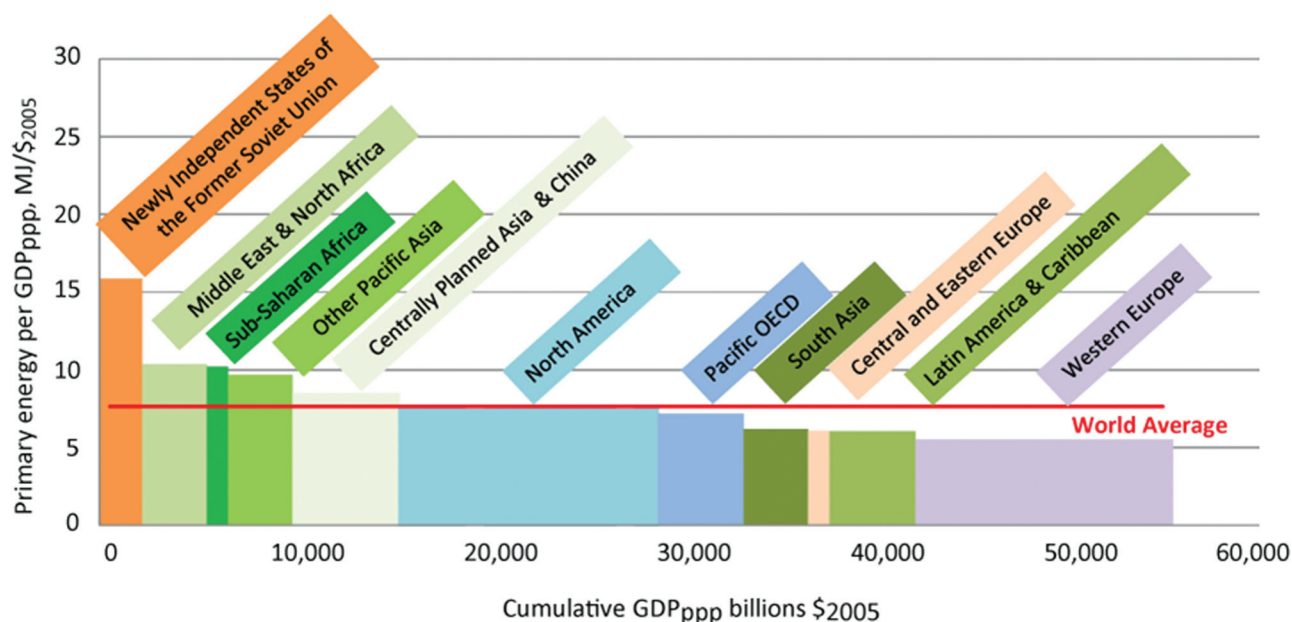


Figure 6.5 | Primary energy intensities across regions in 2005. Source: data from GEA Scenario Database.¹⁰

¹⁰ See www.globalenergyassessment.org

grew only by little more than 1.1% per year as a result of energy innovation, efficiency improvements, and structural economic change but also due to policy and energy price responses, all of which reduce the average energy input required for the production of one unit of GDP. The OECD graph clearly depicts how during the 1990s low energy prices slowed down energy intensity improvements with energy demand growth rebounding (see Figure 6.4). The first decade of the this century is marked by a very modest growth in primary energy due to higher prices, policy incentives stimulating efficiency improvements, and consequent lower energy intensities leading to negative growth rates of per capita energy and electricity demand.

6.4.2 Developing Countries

Despite fluctuations in global economic growth, some countries are consistent regional economic growth leaders¹¹. The dynamics and influence of these countries, particularly China, India, Brazil, and South Africa, will be critical in terms of shaping not only the developing world but global energy, economic, and climate change mitigation trends. The enormous investment needs in energy infrastructure by these countries in the coming decades will provide a unique window of opportunity for sustainable, low-carbon energy development. At the same time, they will continue to face the challenges of sustaining economic growth and eliminating poverty.

A proper understanding of the type and direction of causality between energy use and economic growth in developing countries would help illuminate the role of energy in the future evolution of these countries' economies. Soytaş and Sari (2003) concluded that there is bi-directional causality in Argentina and causality running from GDP to energy use in Korea. An earlier paper tested for co-integration between total energy use and real income of six Asian nations: India, Pakistan, Malaysia, Singapore, Indonesia, and the Philippines. Masih and Masih (1996) concluded the existence of unidirectional causality from energy to income for India, unidirectional causality from income to energy for Indonesia, and mutual causality for Pakistan. The pertinent inferences that were drawn by the authors from these conclusions were that improving living conditions and providing goods and services will require more energy services, and therefore an energy carrier is necessary. How much of this energy carrier is needed will depend on the energy end-use efficiency achieved in converting the energy carrier to energy services.

Another paper, based on data sets from 18 developing countries, refuted the neutrality hypothesis and concluded that energy use generally causes GDP growth and not vice versa (Lee, 2005). A recent paper focusing on China used a co-integration analysis and an error-correction model to examine the long-term equilibrium relationship between GDP

and energy supply and use in 1980–2005 (Wang et al., 2008). It concluded that the two variables are co-integrated but specifically that the growth of GDP forcefully drives the growth of energy supply to increase while energy has a little effect on GDP. Based on this analysis, they concluded that if scientific actions were taken regarding development in the energy sector by: keeping a reasonable economic growth rate; optimizing industrial structures; exploring the use of high-efficiency energy utilization, and developing energy technology, then reducing the country's energy intensity by 20% in five years is achievable.

Despite not many publications being available on the causality between energy and economic development in Africa, Wolde-Rufael (2009) provided a good introduction to this issue and examined the relationship between energy use and economic growth for 17 African countries in a multivariate framework that included labor and capital as additional variables. He found the existence of causality between energy use and economic growth in 15 of the 17 countries. In Kenya and Zambia, energy relative to labor and capital was the most important determinant of economic growth, but causality running from energy use to economic growth was marginally rejected. In 11 countries, energy was not even the second most important factor when compared with capital and labor. Even though energy's contribution relative to output was not so high as that of capital or labor, its contribution to output growth was still relatively high in Algeria (29%), Cameroon (41%), South Africa (23%), and Tunisia (44%). Energy made the least contribution to economic growth in Côte d'Ivoire, Gabon, Senegal, Sudan, and Zimbabwe (Wolde-Rufael, 2009).

An important observation is that for most African countries energy appears to be a smaller factor in economic growth and not as important as labor and capital. In contrast, for many industrialized and developing Asian economies energy is a relatively important contributing factor (Soytaş and Sari, 2003; Soytaş and Sari, 2006). This conclusion is consistent with the economic growth, energy supply, and use realities of most African countries. Many of these nations are characterized by low economic development, which is reflected in their limited energy development and consumption. In many cases energy supplies are unreliable and the infrastructure needed to meet the needs and demands are lacking.

There is also the issue of consumers lacking access to commercial energy markets. All these characteristics of the energy sector tend to decouple energy supplies and use as drivers for economic growth and development. What is clear is that African countries must endeavor to find ways to direct investments into energy infrastructure development as well as to reduce inefficiencies in energy supplies and use in order to stimulate and promote sustainable economic development. In recent years, a number of African nations have become oil producers, boosting GDP and offering a source of funding for the development of energy infrastructure. Nevertheless, the proximity of oil production does not imply that more energy will get to African households and smaller businesses. Instead, coherent policies will be needed to ensure that the infrastructure and supply reach them.

11 Defined as large emerging economies with global impacts on demand and supply balances.

Despite the many studies which estimate the effect of energy on economic development in developing economies, the research is fraught with difficulty. First, many low-income economies are predominantly agrarian. Much of their energy services are provided through muscular effort of human and animal power, which is not included in energy statistics. Similarly, a great deal of the heating, either for cooking or warming space and water, is fueled using biomass, which is also omitted from most estimates of energy use. Few econometric studies of the causality of energy on GDP (or for that matter, of GDP on energy) incorporate these traditional fuels. Also, time series studies in developing countries are based on few data points, and cross-sectional analysis suffers from a great deal of economic, political, institutional, social, and cultural factors that are hard to include as variables. Thus, conclusions about the smaller influence of energy on GDP in developing economies compared with post-industrial ones must be taken with some caution (Chontanawat et al., 2008).

6.4.3 Small and Medium Enterprises

In both developing and developed countries, small and medium enterprises (SMEs) are major contributors to job creation and economic growth (UNCTAD, 2001). The figure and facts below show the important role of SMEs and the need to take them into account when examining the energy and economy nexus in any economy.

SMEs account for over 90% of the number of businesses in the world and for 50–60% of worldwide employment (USAID, 2009). Their contribution to GDP and employment share increases when national economies mature and branch out. In an evolutionary view to the economic structure, they are crucial in providing diversity (“mutations”) in goods and services offered, from which the evolving preference structure of consumers choose. They are the backbone of innovative and dynamic technology development, often crucial in bridging the “valley of death” between lab and the marketplace. In emerging economies and liberalized markets they can also be important vehicles of social mobility. Evidence shows that SMEs have played a major role

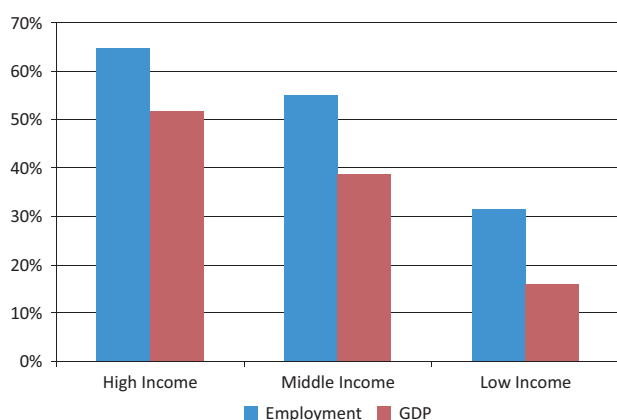


Figure 6.6 | SME contribution to employment and GDP. Source: Yago, 2007.

in the growth and development of all the leading economies in Asia (UNCTAD, 2001).

Access to reliable, affordable, high-quality modern forms of energy is vital for SMEs to operate efficiently and profitably. Large enterprises can afford back-up generators and often benefit from preferential tariff structure and supply security from the utilities. SMEs in contrast pay the highest electricity and modern fuel prices (USAID, 2009), and energy expenses of SMEs in developing countries commonly range from ten to more than 65 percent of the total costs of production. The estimated costs of intermittent electricity provision in several African economies ranges in the order of magnitude of 5–10% of GDP (World Bank, 2011 a); the dominant share of this is due to effects on SMEs

Even within the energy sector, SMEs can provide important technology initiatives. The commercialization of formerly unconventional tight and shale gas deposits in the US was largely led by small and medium size energy companies, and significantly changed the supply security of the US gas market. Also in Europe (particularly in Denmark and Germany) small and medium sized enterprises contributed to technology development and reshuffling of the energy markets. A condition was the effective liberalization (and unbundling of supplier and network operator for grid based energy carriers) and democratization of access to energy markets, e.g., through feed-in-tariff structures.

6.5 The Prices and Costs of Energy

6.5.1 Prices as Market Signals

Prices play several essential roles in the economic production and consumption process. Most important, prices send signals to buyers and sellers. When market prices change, they provide incentives to consumers and producers, and demand and supply of goods and services adjust accordingly. Higher prices may signal scarcity and provide incentives for buyers to purchase less of that good or service or look for alternatives. Higher prices can also adversely affect the affordability of basic services and thus extend poverty. For producers, higher prices stimulate additional supplies and increase sales. In short, prices regulate the quantities of goods and services supplied and consumed. If prices increase because of demand exceeding available supplies, they also are a way to let producers know what consumers demand.

Prices also determine income and profit. For producers, price times the quantity sold results in the total revenues, which – when corrected for production costs and taxes – become income. For consumers prices determine affordability, and price time the quantity purchased governs the disposable income left for other activities.

It is important to distinguish between prices and costs. While the price of a commodity or service represents indeed costs to the buyer (the cash outlay at the time of purchase), from the perspective of the consumer

there are other economically relevant “cost” factors – ranging from inconvenience and individual preference to regulation and externalities. For example, in terms of direct costs, heating a home with coal would still be the cheapest way in many jurisdictions. When affordable, however, most home owners prefer fuels such as natural gas. It is simply more convenient (no shuffling of coal, easy temperature control, no extra space for coal storage), cleaner, and more benign for the environment. Moreover, coal combustion in residential areas is banned in many communities. In essence, the price includes a component of willingness-to-pay for the avoidance of inconvenience. In the absence of monopolistic supply situations, price in a competitive market is to a large part a matter of opportunity costs.

Producers or sellers determine the price of providing the fuel, with production cost usually lower than the sales price and with the difference being profit. Sellers test the market and explore what prices consumers are willing to bear and adjust supply in response to demand.

6.5.2 Costs Associated with Energy Supply and Use

The economic literature often distinguishes four types of costs: monetary costs, opportunity costs, environmental and health costs, and sociopolitical costs (Schipper and Meyers, 1992). Most consumers are predominantly exposed to monetary costs – that is, the money they pay for the goods and services they consume, such as the monthly electricity bill or the price at the pump when filling up the car. Enterprises purchasing raw materials, compensating workers (paying wages), servicing debt and dividends, or paying property taxes are also paying monetary costs.

Opportunity costs represent the value of alternative uses of investments, labor, materials, and so on if used for other economic purposes instead of for the supply or use of energy. For example, what is the cost of sequestering carbon by growing trees on a tract of fallow public land? In particular, what is the value of the land, which could well be zero “cost” because the land currently does not earn any rent? In terms of opportunity costs, the cost of the land is to be measured as the value of the output that could be received from that land if used for other activities, such as a shopping mall or soccer pitch.

Health and environmental costs include the premature deaths, injuries, and illnesses suffered by workers in energy supply industries as well as the public at large as a result of effluents and accidents associated with energy supply; damages to buildings, infrastructures, agriculture, and forestry productivity, tourism, and so on; climate change, overloading the carrying capacities of ecosystems, and loss of biodiversity; and nuisance from noise and odor, congestion, or visual blight (Schipper and Meyers, 1992).

Sociopolitical costs include adverse impacts on energy security, geopolitical relations, income distribution, or land use patterns resulting from

energy supply and use. Also included are undesired impacts on cultural, community, and family values.

While the monetary costs associated with energy supply and use are fully paid by the producer or user, this is only partially the case for the opportunity, health and environmental, and sociopolitical costs. Insofar as these are not incorporated into the monetary costs, they are called “externalities.”

6.5.3 Externality Costs

Externalities arise when an economic agent enjoys benefits or imposes costs without having to make a payment for doing so. As such, externalities can be positive or negative. For example, the adverse health and environmental damages (hidden costs) caused by fossil-sourced electricity generation that are not compensated by the producer are negative externalities. At the same time, the cheaper electricity (without externalities) enjoyed by consumers and that contribute to overall welfare generation represent positive externalities. Factoring external costs into the market price of energy (“internalization”) would raise prices. It would send correct pricing signals to the marketplace and thus change the merit order of investment and operating decisions as well as reduce demand and emissions, with subsequent lower externalities.

Negative externalities are often associated with using public goods provided by the environment for free (e.g., air, soil, water, landscape, ecosystem services). To reduce these, a utility needs to take countermeasures, such as installing pollution abatement equipment or making compensation payments for the damages caused. Identifying, measuring, and monetizing externalities are particularly important steps for the quantification of hidden costs and assessment of the effectiveness of policy instruments aimed at internalizing external costs. Since private enterprise normally does not incorporate external costs in investment decision-making, government intervention is necessary to “internalize externalities” resulting from energy supply and use. According to the International Energy Agency, “governments are best positioned to assess, on a broad scale, the social and environmental costs and benefits associated with power generation, as well as the energy security aspects of, for example, a high dependence on natural gas imports destined to the power sector” (IEA/NEA, 2010).

With the exception perhaps of climate change, the internalization of externalities has been inextricably linked with socioeconomic development. As incomes and welfare grow, parts of the health and environmental impact costs have been increasingly internalized through regulation, such as mandatory emission abatement, caps on effluents or waste charges, higher wages compensating for occupational risks, employer-paid insurance schemes, and user fees. As regards climate change, cap-and-trade arrangements such as the European Emission Trading System, carbon taxes, mandatory performance standards, etc. are tools for internalizing the costs of using the atmosphere as a carbon

dioxide waste repository. Their individual effectiveness depends on several factors ranging from levels of caps, tax rates and assessed penalties to rigor to implementation (enforcement) and possibilities of leakage.

The evaluation or monetization of externalities is highly controversial. While the evidence that externalities are real is generally unquestioned, their quantification has been fraught with uncertainties arising from issues of boundaries (what to include) to the valuation of loss of life. Externalities attributed to emissions from energy supply and use have been assessed using the impact pathway approach – that is, the pathway from emissions through dispersion, exposure, physical impact, and damage to the monetization of the damage costs to individuals or society at large (Rabl and Spadaro, 1999; Ricci, 2010). Controversy usually emerges in the last steps of this chain.

Other methodologies include the willingness to pay (WTP) and willingness to accept (WTA) approaches (Markandya and Boyd, 2002). Both WTP and WTA are closely related to the valuation of opportunity costs. WTP/WTA can be interpreted as the willingness to pay for the avoidance of a damage cost or the financial compensation for any damage inflicted that is deemed acceptable. Paying tolls for the use of a highway to avoid congestion and reduce commuting time is an example for WTP. (Note: the congestion charge presents a positive externality for motorists who stay on the regular roads that now are less congested.) Accepting a higher wage for a risky construction job is an example for WTA.

Several studies have attempted to quantify externalities, most of which focus on electricity generation (EU, 2003; Ricci, 2010). The latest systematic analysis of external costs of various electricity supply technologies and their associated chains is available from the European Commission's CASES project (Markandya et al., 2010). Figure 6.7 provides the summary results for the 27 countries of the European Union (EU), estimated for the period 2005–2010.

Human health impacts due to classic air pollutant emissions and the adverse consequences of GHG emissions dominate the external costs across all technologies. On a life-cycle basis, renewables and nuclear power emit only a few grams of GHGs per kWh. The full technology chain for nuclear energy includes the front end of the fuel cycle, power plant construction and operation, the back end of the fuel cycle (including reprocessing), the construction of interim and final repositories, and plant decommissioning. The main contributors to GHG emissions are plant construction (emissions from cement and material production and component manufacturing) and, in the case of nuclear power, enrichment of uranium (depending on enrichment technology and fuel mix used for the electricity input) (Rogner, 2010).

Due to the higher amount of GHG emissions and air pollutants along their respective energy chains from resource extraction, conversion, transmission and distribution to end-use, fossil-based electricity generation followed by biomass-sourced technologies have considerably

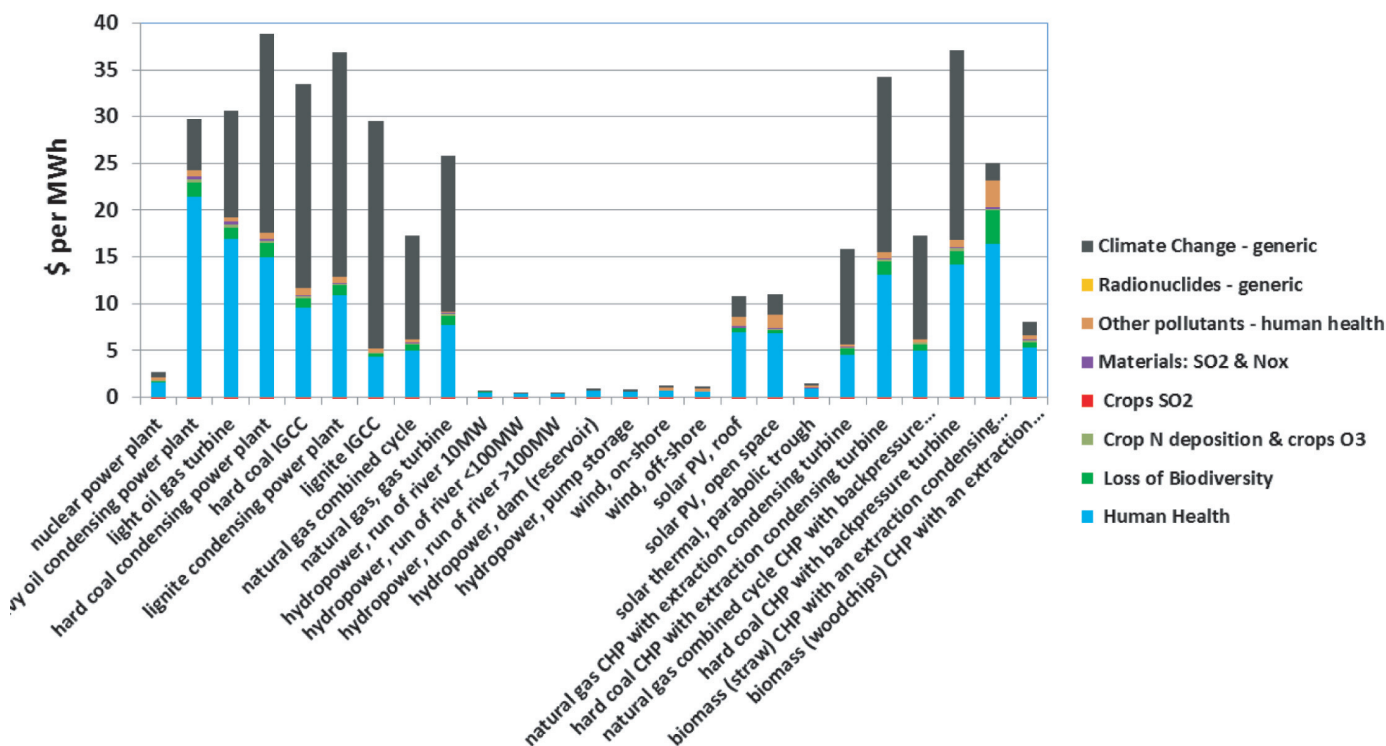


Figure 6.7 | Average external costs for the European Union. Source: Markandya et al., 2010.

higher external costs than renewables and nuclear power, generally ranging between 8.1 and 39.0 US\$/MWh which is more than nuclear power and most non-biomass renewables technologies. Externalities are also location dependent as well as how wide the boundaries of the analysis are drawn, i.e., what is included in the analysis and what is not, especially with respect to indirect factors.

Finally, a few words of caution: In addition to the uncertainties associated with quantifying externalities, the external cost data discussed here are dynamic over time and highly nonlinear. Technology change affects the overall economic and environmental performance of energy conversion technologies (higher efficiency, better abatement equipment, etc.). Effluent reductions often result from capital turnover of retired plant and equipment by new technology. Next, the costs are highly nonlinear because of either saturation or threshold effects, which have different implications:

- An example of a saturation effect is found in certain disease risks from air pollution in which an increase in pollution causes a much larger increase in health burden for populations living in relatively clean environments than the same pollution increase causes in populations already living with high pollution levels.
- An example of a threshold effect is found in the impact of acid precipitation on some ecosystems in which the environment is able to absorb extra acid up to a point without much damage but above that level (sometimes called a “tipping point”), the damage increases dramatically.

Moreover, external costs vary considerably from location to location, depending on population density, geography, land use patterns, wind speeds and direction, regulations, and so on.

6.5.4 Resource Depletion as an Externality

Resource economics finds its roots in the perception that natural nonrenewable resources are being extracted too quickly and sold too cheaply for the good of future generations – that is, their excessive cheapness has given rise to wasteful use and inefficiency. As Harold Hotelling noted in 1931, “contemplation of the world’s disappearing supplies of minerals, forests and other exhaustible assets has led to demands for regulation of their exploitation” (Hotelling, 1931).

A dynamically efficient allocation occurs when the present value of marginal profit or marginal scarcity rent for the last unit produced is equal across various time periods. Therefore, for resource markets to be in equilibrium, the marginal profit from resource sales must rise at the rate of interest (see Figure 6.8). Then owners of resource stocks are indifferent between extracting the marginal unit of the resource and leaving it in the ground, since the return on holding the resource stock as an asset is equal to the return on alternative interest-bearing assets (SAUNER,

2000). It also implies that if there is no substitute for a resource that is essential to society, there is no maximum resource price. The efficient extraction path may then be identified by noting that the resource stock must reach zero in infinite time.

The rationale behind what is known as Hotelling’s Rule is that as a finite resource is produced, less will be available in the future – causing scarcity rent, and thus the resource price, to rise. Increasing prices reduce the quantities demanded by the market and preserve the resource for future use.

In the presence of an alternative technology or a substitute for the resource (usually referred to as backstop technology), the resource price rise is capped at the level when the backstop becomes economically viable (backstop price). In Figure 6.8, the backstop price is the flat part of the price path (P_b), which, once reached, causes discontinuation of production. At this point (T), the resource is said to be “economically exhausted” even though there is plenty of the resource remaining in the ground (Q_T).

However, Hotelling’s approach to efficient resource extraction trajectories ignored production costs, technical progress in exploration and

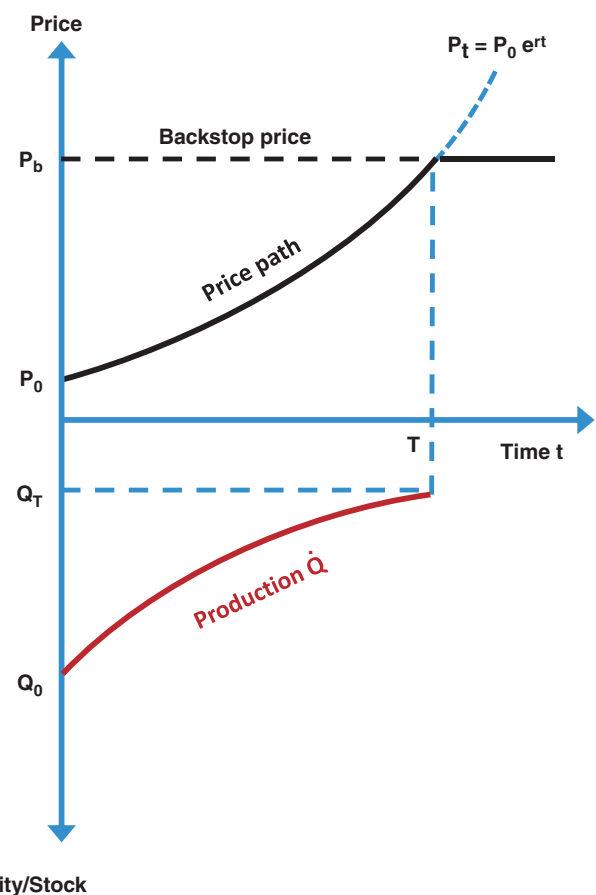


Figure 6.8 | The role of backstop technologies in capping resource prices.

production technologies, and new discoveries. Over the years, several authors have extended the analysis and included these essential real-life aspects in the analysis (e.g., Hartwick and Hageman, 1993; Krautkraemer, 1998, for extraction costs; Dasgupta and Heal, 1979, for exploration and new discoveries).

The questions of interest are whether the historically observed resource prices bear any relation to the Hotelling rule and, more important in relation to the “peak oil” debate, to what extent the observed price paths are an indication of resource growing scarcity over time.

Barnett and Morse (1963) analyzed mineral resource prices between 1870 and 1957, finding that prices fell. They attributed this to new discoveries, to technological progress in resource extraction and processing, and to substitution of alternative materials. Periods of increasing prices have been noted, such as oil prices during the 1970s, but they were attributed to geopolitical tension and Organization of Oil Exploiting Countries supply restrictions (Barnett and Morse, 1963). Lack of investment in exploration and production capacity by producer countries and an unforeseen strong demand growth have been blamed for the oil price hikes during the first decade of this century (IEA, 2008b).

Berck and Roberts (1996) offer three possible explanations for stagnant or decreasing resource prices: technological progress in resource exploration, extraction, and processing; high natural abundance (so scarcity is not yet an economic problem); and environmental or policy constraints limiting production or use where the physical occurrence of the resource is not the limiting factor and the resource is not therefore economically scarce (SAUNER, 2000). Norgaard (1988) attributes the failure of resource prices to rise to the shortsightedness of markets. Increased scarcity is not a sufficient indicator as long as markets are not capable of reflecting it. Markets are simply not farsighted enough for the intertemporal arbitrage function required for price paths to be determined by resource scarcity.

The expectation that innovation and technical progress may reduce the cost of the backstop technology below the scarcity rent trajectory well before existing stocks approach depletion is another explanation for prices staying below scarcity rents. The threat of a cheap backstop encourages depletion of reserves more quickly rather than restricting production and causing prices to rise.

Regarding projections of future energy resource price paths that usually reflect Hotelling’s rising scarcity rents (Manne and Schrattenholzer, 1986). Berck and Roberts (1996) found that the probability of rising rents depends on the econometric model used and the assumption about the size of resource stocks.

A final issue on trends in resource prices is the divergence between long run prices of energy and of energy services. Nordhaus (1997) and Fouquet (2011) showed that over decades or more these price trends tend to diverge. This implies that studying long run trends in energy

prices, and the apparent resource scarcity, indicates only partially the prices and incentives facing consumers, who benefit from technological development. Indeed, resource scarcity and higher energy prices tend to encourage the adoption of energy efficiency measures that after accounting for all implementation and transaction costs involved, lower energy service prices. So, despite some threats of resource scarcity, the long run trends in energy service prices have been downwards since the Industrial Revolution (Fouquet, 2011). Thus, although there may be short- and even medium-term scarcity related to individual fuels, it is questionable whether consumers are likely to face rising long run trends in energy service prices (Nordhaus, 1997; Fouquet, 2011).

6.5.5 Discounting and Discount Rates

Generally, the discount rate accounts for the time value of money. It reflects the general attitude that money available today is worth more than the same amount in the future. It is expected that deferred consumption, say by investing in bonds issued by a utility, should earn interest. The discount rate then determines the present value of future interest payments received by the investor. The discount rate also reflects the risk and uncertainties associated with an investment – that is, higher risk projects command higher returns, hence higher discount rates. In short, discounting is a critical step in determining whether a project or investment is desirable and is used as a tool to make costs and benefits with different time paths or different risks to the investor comparable. Arguments for why costs and benefits with different time profiles are not comparable typically make several points (Dasgupta and Pearce, 1972; Arrow et al., 1996). The first is that individuals expect their level of consumption to increase in the future, so that the marginal utility of consumption can be expected to diminish. Alternatively, individuals can have a positive pure time preference either because they are generally impatient or myopic or because they perceive a risk associated with not being alive in the future. A second argument for discounting future costs and benefits takes the perspective that capital is productive and that resources acquired for a particular project can be invested elsewhere, generate returns, and so have an opportunity cost.

Discount rates are key elements in most energy investment decisions, especially when the choice is between high upfront investments but low operating costs versus low upfront and higher operating costs (essentially all technologies potentially involved in large scale energy system transformation share the common characteristic of higher upfront investment costs and lower operating costs than traditional forms of energy service supplies). Public policy considerations affect the choice of the social discount rate and opportunity costs more than private sector entities where competitive returns on investment commensurate with the (perceived) risks determine discount rates.

Choosing the appropriate social discount rate has long been contentious. Setting the social discount rate too high could preclude many socially desirable projects or investments from being undertaken, while

setting it too low risks encouraging a lot of economically inefficient investments. Further, a relatively high social discount rate, by attaching less weight to benefit and cost streams that occur in the distant future, favors projects with benefits occurring at earlier dates, while a relatively low social discount rate favors projects with benefits occurring at later dates. The choice of the social discount rate affects not only the ex-ante decision of whether a specific project deserves funding but also the ex post evaluation of its performance (Zhuang et al., 2007).

At an individual level, the discount rate affects inter-temporal consumption decisions. Insofar as the choice of energy requires the purchase of energy-using capital equipment, the amount of investments consumers choose to make will depend on the perceived financial profitability. There is evidence that consumers use high implicit discount rates, hindering the adoption of energy-efficient technologies. Specific causes of high implicit discount rates include a lack of information about the cost and benefits of efficiency improvements, a lack of knowledge on how to use available information, uncertainties about the technical performance of investments, a lack of sufficient capital to purchase efficient products (or capital market imperfections), a low income level, high transaction costs for obtaining reliable information, and risks associated with investments (Train, 1985; Lutzenhiser, 1993; Jaffe and Stavins, 1994b; Jaffe and Stavins, 1994a; Howarth and Sanstad, 1995).

In the case of low-income populations, capital scarcity, liquidity constraints, and high transactions costs associated with borrowing can result in households having particularly high implicit discount rates. Hausman (1979) and Train (1985) also argue that implicit discount rates vary inversely with income. Evidence from India suggests that these high implicit discount rates among poor consumers can hinder the adoption of cleaner-combusting, more efficient and convenient fuels and technologies (Reddy and Reddy, 1994; Ekholm et al., 2010). Due to the fact that the use of high implicit discount rates may be a function of asymmetric information, bounded rationality, low incomes, and/or transaction costs, it is argued that policy instruments may affect the implicit discount rate used by consumers by targeting those market imperfections (Howarth and Sanstad, 1995). In the study by Ekholm et al. (2010), the availability of easy and cheap microfinance, for instance, influenced consumer choices regarding cooking fuels and technologies by lowering the costs of borrowing and making upfront capital stove purchases more affordable. In many richer industrialized countries as well, studies have shown that financial incentives that lower the upfront cost of investments can influence individuals' technology adoption and investment decisions (WEC, 2008).

6.5.6 The Impact of Long-term and Short-term Energy Demand

The price of energy is but one element in determining the price of an energy service. It is the price of the service – the combination of the prices of service technology (building, heating system, vehicle, or light

bulb) and the fuel (and convenience) – rather than the price of the fuel alone that matters to consumers.

Demand for a particular fuel then derives from the demand for energy services provided by that fuel, the price of the fuel, and the techno-economic performance of the conversion technology and related infrastructure. For heating services this would include the building envelope, the boiler, the heat distribution system (in short, labeled “service technology”), and possibly any environmental compliance plus, of course, climatic conditions and the preferred indoor temperature.

Here the time horizon plays an essential role. In the short term the service technology is “fixed” and represents a “sunk” cost, which explains the focus on day-to-day oil price movements or the adjusted structure of electricity rates. In the longer run, services technologies as well as infrastructure are replaced (“capital turn-over”) as they reach the end of their service times (see Chapter 1). This opens the opportunity of replacing the aged and underperforming equipment with more-efficient and cleaner models and designs. How quickly the energy-related capital stock can be replaced and to what degree best-available technologies will be adopted depends, however, on several constraints, ranging from access to finance, individual preferences to information, policy incentives, and market transparency (IEA, 2010b). Moreover, consumers attempt to optimize their utility of using energy for meeting the desired energy services over time. Especially, the market penetration of service technologies with high upfront investment costs is largely determined by the underlying individual discount rate described earlier.

Figure 6.9 depicts the interplay between short-term and long-term demand responses to a generic one-time energy price rise. The point of

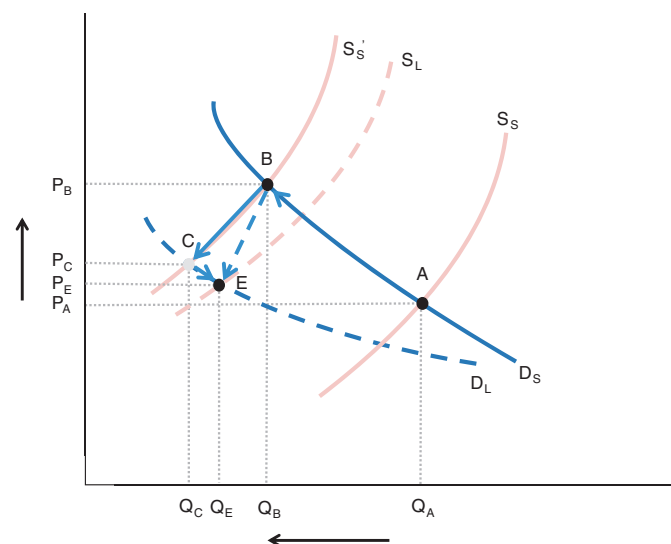


Figure 6.9 | Short and long-term demand/supply responses to a price increase due to a loss of supply capacity. Source: adapted from Samuelson et al., 1988.

departure is a market equilibrium situation at point A (that is, demand and supply functions intersect for demand Q at the market clearing price P_A). A price increase to P_B caused by a loss of supply capacity due to a geopolitical conflict induces short-term demand responses. A steep rise in gasoline prices leaves most consumers with little choice in the short run: pay the high price at the pump, drive less, or shift to other modes of transportation (behavioral adaptation). All this results in a movement from point a along the short term demand curve to point b. The option of purchasing a more efficient car usually arises when the current vehicle approaches the end of its economic service life. In the graph, demand moves along the short-run demand curve D_S , characterized by the fixity of existing capital infrastructure. The loss of supply capacity shifts the supply curve S_S to S'_S .

Although demand is reduced to point Q_B , consumers pay an overall higher energy bill than before despite the cutback in use. In the longer run, when more-efficient appliances, vehicles, and capital in general penetrate the marketplace or when buildings are progressively better insulated, demand declines further to Q_C , now determined by the new long-term demand curve D_L , which represents the efficiency, technology, and infrastructure adjustments undertaken in response to the price increases. The shift of the demand curve and lower demand reduce supply requirements, and prices drop to P_C . In the interim, higher prices also simulate energy supply-side measures, (e.g. additional exploration, additional mining capacity, etc.) which effectively easing the pressure on prices. The combination of demand and supply-side responses leads to the new equilibrium E. Market clearing now occurs at demand Q_E (lower than Q_B but higher than without the supply side response Q_C) and at a market price P_E .

The production function represents the energy supply to economy link needed for providing key services, including information exchange, transportation, heating and cooling. In contrast, the demand function represents the economic income effect on the demand for energy services influenced by economic growth and development. Regardless of the methodology applied, the influence of economic activity on energy demand is unquestioned. Equally unquestioned is the importance of energy input for economic production, process, and economic development, but the relationship between energy and economic growth is not unidirectional. A major source of uncertainty, however, concerns the dominance over time of relationships between the economy and energy requirements to fuel the economy, on the one hand, and energy as the driver of economic (GDP) growth, on the other. As such, energy plays a vital role in economic development and growth, and it underpins countries' ability to provide employment for their populations. Increased production requires more energy inputs, while greater disposable income increases the demand for heating, cooling and mobility. More generally, the demand for energy is likely to vary at different stages of economic development, with the availability of resources and technologies, according to economic, social, and institutional structures and policies, and across cultures.

6.5.7 Energy Markets and Energy Price Subsidies

While markets are playing a growing role in funding energy investment, significant impediments continue to fundamentally constrain progress in moving toward an energy system and supply patterns for a more sustainable society. Key issues include energy prices that are not cost-reflective, and energy subsidies which distort markets. Energy subsidies and cross-subsidies have profound effects on countries' ability to lift incomes and economic growth by making energy affordable. Feed-in tariffs for low-carbon electricity generation are policy tools for guiding action and channeling investment into socio-politically desirable directions, assisting technology learning (cost buy-down) and reducing investor risks. In essence, subsidies absorb risks and costs private sector entities are not willing to bear for reasons of competitiveness and profitability. However, if not time-bound and performance based, subsidies in the longer run do not create incentives for energy suppliers to recover their costs and invest in a timely manner, discourage new entrants and private-sector investment, and undermine the pursuit of energy efficiency objectives.

Many hundreds of statistical studies have been undertaken to assess the responsiveness of the demand for different forms of energy – including electricity, natural gas, oil and oil products, coal, or total demand for all forms of energy – to changes in prices. Irrespective of the form of energy considered, the demand for energy is typically price-elastic, so that energy use declines as the price of energy increases (and vice versa). A recent study of energy use expenditure in the United States between 1970 and 2006, for instance, found that use of all forms of energy declines in response to energy price increases (Kilian, 2008), although there are important differences across different forms of energy. The study identified a short-run (over one year) price elasticity of gasoline of -0.48 (so that a 10% price increase in gasoline will reduce consumption by 4.8%), and a price elasticity of electricity of -0.15 (so that a 10% electricity price increase will reduce consumption by 1.5%). Elasticities of energy demand with respect to price are typically higher over the longer term, as users have time to adjust, either by switching to alternative fuels or by conserving energy.

In the normal course of events, rising energy prices associated with a scarcity of energy resources would therefore tend to discourage use, but at a minimum it would ensure that energy is not “wasted” and that GHG emissions are not created needlessly. The prevalence of energy price subsidies, in particular subsidies of fossil fuels, however, fundamentally undermines this objective. In some countries (mostly industrialized market economies) energy markets have been deregulated so that prices for energy carriers and services provided to consumers are broadly cost-reflective. Many countries, however, including many developing nations, have administered energy pricing regimes that are not cost-reflective and that entail significant cross-subsidies from one sector (for instance, industry) to others, such as the residential or agricultural sectors. Thus a recent extensive survey found that 37 countries account

for over 95% of global subsidized fossil fuel consumption, leading to higher levels of consumption than would occur without price distortions (IEA, 2010a; World Bank, 2010). Overall subsidies amounted in 2008 to US\$557 billion (an increase of US\$215 billion from 2007).

Phasing out these subsidies would provide a clear incentive to use energy in a more efficient manner and would facilitate the switch from fossil fuels to less GHG-intensive energy sources. Modeling undertaken by the IEA (2010b) indicates that phasing out energy subsidies between 2011 and 2020 would:

- cut global energy demand by 5.8% by 2020;
- cut global oil demand by 6.5 million barrels per day in 2020, predominately oil used in the transport sector; and
- reduce carbon dioxide emissions by 6.9% by 2020, the equivalent of 2.4 Gt of carbon dioxide.

Subsidized energy prices that do not reflect the costs of producing and supplying that energy (including the cost of the very significant infrastructure required to do so) encourage wasteful consumption, but they will also not provide sufficient compensation to producers. Timely investments to meet growing demand are therefore not undertaken by existing utilities; the incentives for new investors to enter the market are similarly removed. While low energy prices may promote access to modern energy carriers in the short term, in the longer term such policies discourage investment in the energy sector, thereby constraining supplies and economic development.

Policies to phase out subsidies for kerosene, liquefied petroleum gas (LPG), and electricity must be carefully designed not to restrict access to essential energy services, as these fuels often are used to meet the basic needs of the poor people. IEA (2010b) analysis indicates that today 1.4 billion people around the world are still without access to electricity and around 2.7 billion people rely on traditional biomass as their primary source of energy (see Chapter 2). However, subsidies to kerosene, LPG, and electricity in countries with low levels of modern energy access (that is, with electrification rates below 95% or access to modern fuels below 85%), represented just 11% of the US\$557 billion in consumption subsidies in 2008.

Furthermore, while fuel subsidies are often justified on the grounds that they help address income inequality and provide assistance to low-income groups, in practice such subsidies represent inadequately targeted transfers, with most of the benefit accruing to the largest consumers of oil products, who are typically not the poorest members in the society (World Bank, 2010). A reduction in subsidies combined with a more effective system of taxation would enable government revenues to be better targeted at income transfers, with the broader aim of supporting investments in education, health, and physical infrastructure to assist in economic development (Barnes et al., 2008).

6.6 Investments in Energy

6.6.1 Investment Characteristics and Trends

The transition to modern energy systems is characterized by increasing investment levels in technology and infrastructure. Investments are necessary for energy resource extraction, energy conversion to usable fuels, transmission and distribution systems, and end-use infrastructures. In principle, there are two major categories of investments that are intimately interrelated: investment in the expansion of (and replacement of retired) technologies and infrastructures under competitive or regulated market conditions and investment in innovation, development, and commercialization, including market formation. While the first category is important for supporting energy system growth – from mobilizing upstream exploration and resource extraction to energy conversion and supporting access to energy services, especially in the short-run for balancing demand and supply – it is the second category that enables energy system evolution and transformation, and hence progress in terms of socioeconomic development and environmental protection. The second category is also dependent on policy support, especially market formation.

Market-formation investments include public and private investments in the early stages of technological diffusion and are sometimes also referred to as “niche market” investments. In the energy domain, these investments include policies with respect to certain technologies (such as feed-in tariffs or production tax credits) and public procurement. They also include private investments that may take advantage of markets created by government policies, such as renewable performance standards or price instruments like carbon taxes (UNDESA, 2011).

Market-formation investments in the energy sector as a whole are difficult to track, because many transactions are unreported, the ways of measuring market-formation investments are not yet harmonized internationally, and efforts to track such investments are only relatively recent.

Investment in infrastructure growth and innovation are interlinked, as investment in innovation is a prerequisite for the development of improved and better-performing technologies and processes. Investment in growth and replacement of plant and equipment creates market opportunities for the diffusion of innovative technologies, whereas growth generally offers larger penetration opportunities than mere replacement in an otherwise stagnant market. Using the natural rate of capital turnover for the introduction of innovative technologies has lower transaction costs.

Investment is deferred consumption, and all the features of risk, discount rates commensurate with the risk, present value considerations, opportunity costs, and of course demand discussed earlier apply equally here as well. Energy sector investment time horizons are long-term: investments are made over periods of up to 15 years before the first

revenues are received, and capacities are built to last for 15–60 years and more. The long lifetime of energy sector capital means a slow turnover of its capital stock – a limiting factor to speedy energy system transformation. The recent financial economic crises and the uncertainty in financial markets about the indebtedness of key industrialized countries have made energy infrastructure a highly risky proposition, resulting in underinvestment in key energy sector areas (exploration, production capacity, transmission, and distribution grids). Nationalistic policy solutions focusing on the short run without a global vision (such as of energy system transformation or a global international environmental agreement) further aggravate uncertainty for private-sector investors and result in lock-in effects for the little investment that takes place. The risk premium on such investment and the widening demand-supply gap lead to higher energy prices until additional investment is forthcoming. However, absent solid and predictable energy policy objectives and long-term policy targets which are hugely important ingredients for investor confidence, such investment is unlikely forthcoming.

Since 1980, global total annual investments have fluctuated between 21 and 24% of gross world product with at times a significantly higher share in developing countries and a slightly lower share in the industrialized world (UNCTAD, 2007; IMF, 2011). The share of capital formation allocated to the energy sector is estimated at about 4–8% of total investment, or 1.0–1.8% of GDP. These figures exclude energy-related investments at the end use of the energy system (buildings, heating systems, cars, refrigerators, etc.) that are delivering the energy services that consumers demand.

At the country level, especially for small but energy-exporting countries, the share of energy supply-related investments of GDP can be much higher than the global share and at times can amount to 5–10% of GDP or more.

6.6.2 Energy Supply Investments

Data on energy supply investments are extremely limited, so the literature typically relies on limited surveys or on model estimates (multiplying statistical data and/or estimates on capacity expansion with average technology-specific investment costs to derive total energy supply investments). Energy supply modeling studies have been available since the mid-1990s in academia (e.g., Nakicenovic and Rogner, 1996; Nakicenovic et al., 1998; Riahi et al., 2007) as well as from the work of the IEA, particularly the *World Energy Investment Outlook* (IEA, 2003); the *Energy Technology Perspectives* (IEA, 2006b; IEA, 2008a); and the recurrent projections of the *World Energy Outlook* (WEO) (e.g., IEA, 2006a; IEA, 2007; IEA, 2008b; IEA, 2009a; IEA, 2010a; IEA, 2011), which also contain unique survey data on energy supply investments, particularly in the oil and gas industry.

A common feature (and drawback) of all modeling studies is that energy sector investments are not reported for their corresponding base year values but instead as cumulative totals of the projection period of typically

30 years. The absence of published base year input data for energy sector investment projections not only reduces the credibility of the studies, it also makes an assessment of current investment levels and structure and a comparison among the different studies almost impossible.

The assessment in this section summarizes available information by drawing on the only modeling study that has disclosed its underlying base year energy investment numbers (Riahi et al., 2007) and the surveys reported in IEA's WEO (IEA, 2006a; IEA, 2007; IEA, 2008b; IEA, 2009a; IEA, 2010a; IEA, 2011). Because of the significant price escalation observed for energy sector investments (particularly for oil and gas since 2004), the Riahi et al. (2007) estimate (which refers to year 2000 investments and price levels) can be considered a lower bound, assuming recent price escalations will not remain permanent. Conversely, the IEA numbers can be considered as an upper-bound estimate of investments in energy supply. Comparing and making sense of investment estimates or quotes from different sources is fraught with uncertainty as boundaries of what is included in a particular estimate and what is not, which price basis and exchange rate has been applied, etc. are rarely clearly specified and documented.

Despite differences and uncertainties in estimated supply-side investments per supply category, the available data suggest a range of energy supply-side investment during the mid 2010s of US\$700 billion a year to some US\$840 billion a year (in 2005 dollars). Investments are dominated by electricity generation and by transport and distribution (T&D), at some US\$500 billion. Fossil fuel supply, particularly the “upstream” component (exploration and production), accounts for US\$250–400 billion annually, mostly for oil and gas.

Renewables are still relatively minor players under current energy market conditions despite substantial subsidy support for market formation. Liquid and gaseous biofuels account for US\$20 billion, including US\$8 billion for Brazilian ethanol (UNEP/SEFI/NEF, 2009). Large-scale hydropower (approximately US\$2005\$40 billion for annual capacity additions of between 25 and 30 gigawatts) accounts for some 17% of current supply-side investments. Nevertheless, it should be noted that investments in renewable investments are increasing significantly in recent years. According to REN21 Global Status Report (2011), investments in renewables amounted to 211 billion in 2010 up from 160 billion from the previous year and five times the size of similar investments in 2004.

Exploration and resource extraction are the prime components of upstream investment in fossil fuel supply, although detailed data are difficult to come by due to proprietary issues and clear separation from extraction investment. Major differences also exist for electricity transport and distribution infrastructure investments, for which only modeling study data are available, and estimates differ by about a factor of three. The IEA WEO (2008b) projection of average annual electricity T&D infrastructure investments of US\$230 billion over the period 2007–2015 appears high, possibly due to large replacement investments in OECD countries, and is comparable to corresponding electricity generation capacity expansion investments.

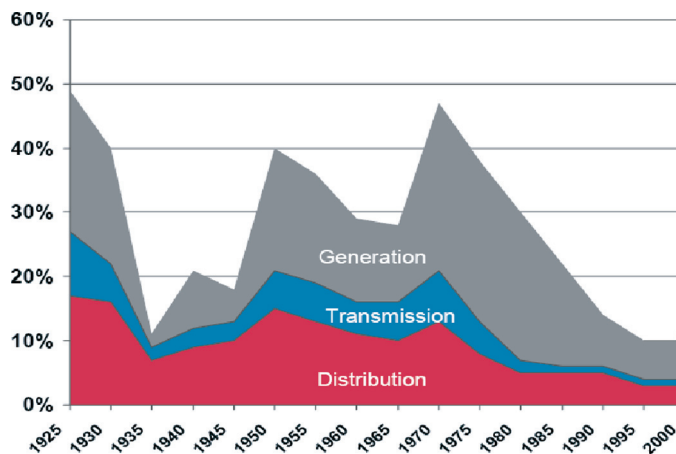


Figure 6.10 | Declining investments (as share of revenues) in the US electricity sector, 1925–2000. Source: Modified from EPRI, 2003.¹²

Given the scarce data available on time trends of supply-side energy investments, an intriguing empirical finding from the United States, however, shows a significant decline in energy supply-side investments for electricity generation in the second half of the twentieth century (see Figure 6.10.) The declining investments (as a share of revenues) in the US electricity sector suggest a substantial thinning of resources available for capital turnover and diffusion of new technologies as a twin result of slowing demand growth and energy sector deregulation and liberalization. At present, it remains unclear if this trend is a specific phenomenon of OECD countries or of US electricity supply (an increasingly deregulated sector), but the example supports the conclusion that better current and longitudinal data on energy sector investments are needed for both in-depth analysis and improved decision-making.

6.6.3 Energy End-use Investments

Investment in energy efficiency, appliances, heating systems, and related infrastructure (buildings, factories) throughout the economy is a necessary prerequisite for the energy system transformations needed.

The decentralized nature of these investments by private households (and their corresponding classification as consumer expenditures rather than investments) and by firms (whose energy-specific investments go unrecorded) explains the absence of energy end-use investment numbers in the literature. The small-scale nature and formidable definitional challenges of these numbers also contribute to their absence.¹³ This lack

of data, or even of model estimates, introduces a serious challenge in both energy modeling and policy, because the potentially largest opportunity for energy demand (and emissions) reduction is either entirely ignored or assumed to cost nothing.¹⁴ Customary energy and climate policy models deal with energy end-use costs by either “assuming away” missing data by exogenous (and policy-independent) autonomous energy efficiency trends or by considering investment costs for the incremental component of energy end-use investments related to improved energy efficiency, which in itself provides a formidable definitional and data challenge.

GEA addressed the gap and presents the first global, bottom-up estimate of total investment costs in energy end-use technologies (see Chapter 24). Volume data (production, delivery, sales, and installations) and cost estimates to approximate total investment costs in 2005 are estimated for both end-use technologies and their specific energy-using components.¹⁵ Low and high sensitivities around central estimates are included, taking into account uncertainties in both volume and cost assumptions. The intention is to provide a first-order, educated guess benchmark for comparison with supply-side investments. Supporting data and a discussion text are posted on the GEA Chapter 24 website to document the assumptions underlying the estimates here, to solicit feedback and comments, and to invite further research in this critical area.¹⁶

To ensure comparability between supply-side and demand-side investments, a clear definition unit of analysis and boundaries is needed. Supply-side investments are quantified at the level of the power plant, refinery, or liquefied natural gas terminal. These are complex, integrated technological systems with energy conversion technologies at their core. These energy-conversion components are configured within their corresponding technological system to provide a useful service to intermediate users (e.g., utilities, fuel distributors, pipeline, or shipping companies).

The demand-side analogues are the aircraft, vehicle, refrigerator, or home heating systems. Although generally less complex, each of these technological systems similarly has an energy conversion technology at its core (e.g., the jet engine, internal combustion engine, compressor, boiler, or refrigerator). In addition, each is configured to provide a useful service to final users.

¹² More recent data indicates that the trend persists to today. According to the Edison Electric Institute (EEI), for example, which publishes annual utility revenue and investment reports, there has not been any significant change in the percentage of revenues being invested in infrastructure over the past 10 years.

¹³ For instance, it is far from trivial to discern the energy component in the total investments of a new building. Depending on where the systems boundary is drawn, one could look at the heating and air conditioning system, including that part of the building structure that determines its energy use (insulation, windows). Indeed, the entire building structure may be considered.

¹⁴ Some studies include incremental energy end-use technology investments associated with additional energy efficiency gains above a typical “business as usual” scenario (e.g., IEA, 2009b). Apart from introducing additional definitional ambiguities (i.e., what constitutes incremental investments?), the modeling is usually only done for a few technologies (e.g., transport), which limits its usefulness for informed policymaking.

¹⁵ Available data do not allow a further disaggregation into those subcomponents of investments on energy efficiency improvements, which remain an important future research task.

¹⁶ See chapter 24 at www.globalenergyassessment.org

With demand-side technologies, however, this definition of the unit of analysis is problematic. Investments in (and performance of) end-use technologies are dependent on investments in associated infrastructure, such as airports, roads, and buildings. Is it meaningful to quantify the investment cost of a home heating system without quantifying the investment cost of the home and the insulation level that determine the dimensioning of the home heating system in the first place? Is the end-use technology to consider the furnace or the building?

Although the same issue exists on the supply side, it is largely addressed by additionally quantifying investment costs in associated T&D infrastructures in policy models, as comprehensive statistics are also lacking on the supply side. The problem on the demand side is that the same approach would result in a sum of the total investment costs in all building structures, roads, railways, ports, airports, industrial machinery, equipment, and appliances. Such an exercise would amount to a *reductio ad absurdum*.

A pragmatic pathway out of this system boundary ambiguity is to provide a range of estimates for a range of system boundaries of energy end-use technologies. An initial broader definition and data set describe end-use technologies as the smallest (or cheapest) discrete units that can be purchased by final consumers. This implies boilers and air conditioning units, not houses, and dishwashers and ovens, not kitchens. A second, narrower definition and data set describe the specific energy-using components of these end-use technologies. This implies engines in cars and light bulbs in lighting systems. Table 24.12 (see Chapter 24) summarizes these distinctions for the technologies analyzed. In some cases (e.g., industrial motors, mobile heating appliances), a distinct energy-using component was not identified.

The investments in 2005 in end-use technologies are estimated at US\$1–3.5 trillion; the estimate in 2005 in the energy-using components of these end-use technologies is on the order of US\$100–700 billion.

Given these definitional problems, the appropriate point of comparison for estimates of supply-side investment costs is a range spanning the narrow category of “energy-using components” at the lower end to the broader category of “end-use technologies” at the upper end. Taking also into account the extent of end-use technologies missing from this analysis, the range of demand-side investment costs is conservatively on the order of US\$300 billion–4 trillion. This compares with the range of supply-side investment costs on the order of US\$950 billion a year.

The upper bound of demand-side investment outlays is five times higher than the supply-side equivalent whereas the latter is likely a (potentially substantial) underestimate. It is noteworthy that the GEA findings align well with the IEA estimation that demand-side investment needs exceed supply-side investment needs by a factor of 4.5 in climate policy scenarios (IEA, 2008b).

6.7 Financing

6.7.1 The Constraints

The need for a shift in emphasis to higher efficiency and low emissions technologies implies the need for accelerated and up-front energy-related investments over the next several decades. However, even existing low-cost clean technologies in energy supply as well as at end use, particularly when they entail long-lived capital assets and infrastructures, will take decades to fully penetrate the energy sector. Given the long lead times for new technology development, deploying advanced technologies on a large scale after 2025 requires a strong policy response and creation of market incentives today, especially in order to facilitate innovation in such technologies. For example, market incentives to move from obsolete electromechanical to real time electronic, internet-based control of energy delivery and end-use devices would have a major positive impact on energy efficiency.

6.7.2 Energy efficiency investment constraints

Achieving even cost effective improvements in energy efficiency is commonly hindered by a range of market and non-market barriers and failures and many of them can be described as principal-agent problems. The extraordinary large number of actors involved, fragmented institutional framework and often comparatively small size of individual investment needs for energy efficiency improvements and long payback time make this market little attractive for individual investors. Regional energy agencies and energy service companies (ESCOs), together with developing banks, gathered experience with energy efficiency contracting. Almost always, both financiers and end users require some degree of independent assessment. For example, where a trusted ESCO might be able to fully meet the needs of both parties, usually the financier or the end user still wish to have some level of independent technical assessment. Choices then need to be made concerning the degree of outsourcing. Among end users, major industrial enterprises often may conduct technical assessments largely in-house, with perhaps only some very specialized expertise acquired from outside. Building owners, on the other hand, usually outsource nearly all of the project development and assessment effort. The situation among financiers also varies: some development finance institutions may have quite sophisticated in-house technical assessment capacity, whereas many commercial banks will contract out such work to trusted partners. In all cases, energy efficiency investment financing mechanisms must include efficient and cost-effective organizational and institutional arrangements for delivering marketing and technical assessment requirements in which incentives of all the parties are properly aligned. In each respective economic environment, this is likely to include differing combinations of in-house expertise and outsourcing arrangements.

Box 6.1 | Barriers to Energy Efficiency Improvements

Barriers to achieving cost saving investments in energy efficiency include:

Low or underpriced energy. Low energy prices undermine incentives to save energy.

Regulatory failures. Consumers who receive unmetered heat lack the incentive to adjust temperatures, and utility rate-setting can reward inefficiency.

A lack of institutional champion and weak institutional capacity. Energy-efficiency measures are fragmented. Without an institutional champion to coordinate and promote energy efficiency, it becomes nobody's priority. Moreover, there are few energy-efficiency service providers, and their capacity will not be established overnight.

Absent or misplaced incentives. Utilities make a profit by generating and selling more electricity, not by saving energy. For most consumers, the cost of energy is small relative to other expenditures. Because tenants typically pay energy bills, landlords have little or no incentive to spend on efficient appliances or insulation.

Consumer preferences. Consumer decisions to purchase vehicles are usually based on size, speed, and appearance rather than on efficiency.

Higher up-front costs. Many efficient products have higher up-front costs. Individual consumers usually demand very short payback times and are unwilling to pay higher up-front costs. Preferences aside, low-income customers may not be able to afford efficient products.

Financing barriers and high transaction costs. Many energy-efficiency projects have difficulty obtaining financing. Financial institutions usually are not familiar with or interested in energy efficiency, because of the small size of the deal, high transaction costs, and high perceived risks. Many energy service companies lack collateral.

Products unavailable. Some efficient equipment is readily available in high-and middle-income countries but not in low-income countries, where high import tariffs reduce affordability.

Limited awareness and information. Consumers have limited information on energy-efficiency costs, benefits, and technologies. Firms are unwilling to pay for energy audits that would inform them of potential savings.

Lack of capacity in terms of trained people and regulatory frameworks in the energy using sectors (Chapters 8–10 and Chapter 25).

6.7.3 Financing Energy Efficiency

Success in capturing a bigger share of the large numbers of financially attractive energy efficiency retrofit projects has proven stubbornly difficult, primarily because the intrinsic nature of the projects and their broader setting make it hard for effective markets to develop naturally. In some countries, price distortions may undermine incentives, but in most sectors in Brazil, China, and India, and many other countries, this is not the case, as project financial returns are high in most instances. Flow of information about energy efficiency opportunities is far from perfect, but it has improved. In some countries, the required technical or managerial expertise is lacking, but in the case of Brazil, China, and India the issue is more how to bring existing strong expertise to

bear. For energy efficiency investments to be made, energy efficiency concepts must be marketed to enterprises, and specific projects must be identified, designed, and appraised. This requires marketing, project development, and technical assessment skill, typically provided by local energy efficiency experts. Human and organizational capacity is needed to define target markets and market outreach strategies, identify project opportunities, design appropriate project packages at end-user facilities, assess financial returns and the risks influencing delivery of the project cost savings cash flow, and understand the incentives to participate by each of the designated parties. For countries such as Brazil, China, and India, the main issue is how to most efficiently access existing project development capacity (Taylor et al., 2008).

Keeping transaction costs reasonable is often a major challenge, especially given the relatively small size of energy efficiency loans. Design of programs to achieve this requires creativity and innovation. For example, for their general and energy efficiency lending to SMEs, Indian banks have relied on new geographical and industry-specific clustering approaches. For investment delivery mechanisms integrating project development and financing to be successful in increasing energy efficiency project investment, they should build upon the following principles: Delivery mechanisms need to be customized, based on a careful diagnostic review of the local institutional environment, including the financial sector, local capacities for technical assessment, the energy efficiency market, and the role of government. Such diagnostic review critically requires local expertise.

End users need to face commercial terms for the financing and technical services being provided as the best foundation for the creation of an energy efficiency market. End-user subsidies tend to ultimately undermine sustainable market development, because they are usually short-lived and can create market distortions and unrealistic expectations. However, concessional financing has often proven valuable to help buy down the high costs and risks of starting up new commercially oriented programs, build necessary new capacity, and assume risks with new approaches. Appropriate incentives must be included for the various actors in each mechanism to participate. Particularly important are incentives to generate deal flow. Combined with the last point, this implies a focus on organizational and institutional arrangements (“deal structuring”) that deliver positive incentives for all actors without relying upon long-term market-distorting subsidies (Taylor et al., 2008).

6.7.4 Financial Sources and Instruments

Following are some of the main financial instruments used to support energy efficiency policies:

A. State or Municipal Bonds: Given the magnitude of needs, the high degree of public ownership in the energy sector of the project countries and the limited funds available from external sources, this is one of the most important financial sources.

B. Grants: Many bilateral and multilateral partners provide grants under different programs for financing energy efficiency. Some of the most important international organizations include the United Nations Development Program, the United Nations Environment Program, the World Bank and the Global Environment Facility (GEF) – the financial mechanism of the United Nations Framework Convention on Climate Change (UNFCCC). In the Global Environment Facility, climate change activities are currently divided into four areas: (a) removing barriers to energy efficiency and energy conservation; (b) promoting the adoption of renewable energy by removing barriers and reducing implementation costs; (c) reducing the cost of low greenhouse gas emitting technologies and (d) supporting the development of sustainable transport.

C. Loans: These are mostly provided by many actors including banks – both private and public development banks, international financial institutions, and private investors. International Financial Institutions (IFIs) have increased their role in this important category of financial instrument. Their involvement can provide political motivation to pursue energy sector reform and promote investment. IFIs can play a particularly important role in low income developing countries by building up a standardized risk data base and enhancing the quality of governance. This would both facilitate the use of appropriate investment instruments and help the international investment community achieve the confidence needed to invest in low income countries. This underscores the catalytic role that IFIs can play in promoting policies that stimulate and stabilize internal cash generation, and attract substantially higher levels of commercial and private investment.

D. Equity financing: Under these arrangements, investors take a whole or fractional share of ownership, and thus sharing both risks and benefits from that investment. The types of investors under this category are very diverse including institutional, government, and private investors.

E. Leasing: Under a leasing contract, a lessor conveys to a lessee the right to use a piece of property for an agreed period of time against payment or a series of payments. It is sometimes chosen to be the mechanism, which provides the project owner with necessary equipment under performance contracting.

F. Tax and customs tariffs incentives: Another option for countries to promote measures in energy efficiency is through stimulating utilities or the market for technology distribution and providers of energy efficiency services. This may also be called a form of indirect financing. Yet another is to diminish or abolish customs tariffs on imported energy efficiency equipment.

G. Revolving fund: This is a financial scheme aimed at establishing sustainable financing for a row of investment projects. The fund may include loans or grants and aims at becoming self-sustainable after its first capitalization. The objective is to invest in profitable projects with short payback time, be repaid, and use the same fund to finance new projects. It can be established as a bank account of the owner or as a separate legal entity. There are several parties in a revolving fund: The owners can be either public or private companies, organizations, institutions or authorities. The operator of the fund can be either its owner or an authority appointed by him. External donors and financiers provide contributions to the fund in the form of grants, subsidies, loans or other types of repayable contributions. The borrowers can be either the project owners or contractors. According to the conditions of the revolving fund, savings or earnings gained from projects should be paid back to the fund within a fixed period of time, at certain time intervals. The revolving fund, as financial instruments has its advantages and drawbacks.

H. Venture Capital: Venture capital is particularly important for investments in new technology. By providing early up-front investment finance

to companies that have high potential but also high risk, venture capital plays an important role in innovation. It could also play an important role in the setting of new businesses with little or not operating history or that are too small to raise their own funding. The trust placed by venture capital to launch many of these could be essential.

I. Energy Service Companies: Although not a financial instrument *per se*, ESCOs constitute an indirect way to attract capital to investments or third party financing. The ESCOs may fulfill the functions of project

identification, planning, implementation and financing. Financing is obtained through contractual relations between the ESCO and the project owner; the investment is carried out by the ESCO and is financed from the costs savings achieved. There are two types of contracts. The first is a guaranteed savings contract, in which payments from the project owner are made according to savings achieved. The second might not include the ESCO in the contract but it makes the project owner liable to cover the capital outlays; payments to the ESCO from the project are not related to the actual savings achieved.

Box 6.2 | Financing Mechanisms

Very large investments will be required to develop new energy technologies and also to increase their uptake throughout the world. Almost all growth in energy demand over the coming four decades will occur in non-OECD countries, where financing capacity is weakest with the exception of the large emerging economies like China and Brazil. The availability of finance and transfer of clean energy technologies into these markets is often considered essential. IFIs and Multilateral Development Banks are expected to play a central role in the process of technology transfer. According to a recent study, multilateral development banks are increasing their role in energy finance in developing countries significantly (BNEF, 2010). From 2008 to 2009, loans to developing countries increased three-fold to some \$21.1 billion. Some national development banks, both in OECD countries which invest in developing countries, as well as some in developing countries such as the BNDES, Brazilian Development Bank, have also become major actors and suppliers of energy finance. Over the past five years, KfW of Germany has had financial cooperation commitments for energy projects in developing countries amounting to €3.8 billion KfW, 2011.

The overall contribution of the World Bank Group to energy investments over the past 20 years had been varying considerably, with a lowest point at about US\$1 billion in 2004, but had been increasing since then to about US\$ 7 billion in 2009 and over US\$10 billion in 2010, of which \$4.9 billion went to renewables. Compared to the overall portfolio of World Bank investments, the energy sector contributed about 15% of World Bank lending in that time period. Compared with the global investment in the energy sector of many hundred billion and exceeding several trillion if end use-investments are included, these contributions are just a small share of the total investment capital needed (World Bank, 2011a).

The GEF – an operating entity of the financial mechanism of the UNFCCC – has been a key contributor to helping countries eliminate market barriers to the introduction of new technologies and catalyzing energy investments in developing countries. Up to 2009, the GEF has allocated some US\$ 2.7 billion to support climate change mitigation projects in developing countries and economies in transition. It has also leveraged an additional \$17.2 billion in project co-financing, most of which are energy-related projects. This has resulted in more than 1 billion tons of greenhouse gas emission being avoided between 1991 and 2009, thanks to the support of the GEF. The portfolio of GEF projects is diverse. The energy efficiency portfolio ranges widely from district-heating to efficient lighting, industrial energy efficiency and pioneering guarantees for energy efficiency investments. Through its life-time, the GEF has provided support to over 40 different technologies, many of which were new to the countries into which they were introduced.

The Climate Investment Fund is another more recent and specialized financing mechanism of various development banks set up to provide climate change funding pending the setting up of the Green Climate Fund being established under the UN Framework Convention on Climate Change. It contains two funds of direct relevance to the funding of energy. The Clean Technology Fund which provides concessional finance at as significant scale to help developing countries formulate projects that can be included in the National Appropriate Mitigation Actions emerging from the climate change negotiations and a second one for scaling up renewable energy in low-income countries.

Lastly, it is also important to mention that as a result of the recent financial and economic crisis, many countries such as the Republic of Korea, China, and many others have set up stimulus packages with a significant focus on green investments and the promotion of investments in low carbon technologies. Many of these middle income countries are also playing an increasingly important role in trilateral arrangements as well as south-south cooperation for technology transfer and finance.

6.8 Technology Innovation and Diffusion

In its sixteenth meeting of the Conference of the Parties of the UN Framework Convention on Climate Change, and more specifically in its Cancun Agreements (UNFCCC, 2010), the Parties recognized that “deep cuts in global greenhouse emissions are required...with a view to reducing greenhouse gas emissions so as to hold the increase in global temperature below 2 degrees above pre-industrial levels...”. The Intergovernmental Panel on Climate Change have also called for reductions of 50% or greater in global GHG emissions to keep the concentration of these gases below 450 ppm (IPCC, 2007). According to the IEA, achieving this objective would require “major improvements in efficiency and rapid switching to renewables and other low carbon technologies, such as carbon capture and storage (CCS)” and “deployment and development of technologies still under development, whose progress and ultimate success are hard to predict” (IEA, 2008a). Such a shift, “if achievable, would certainly be unprecedented in scale and speed of deployment” IEA, 2008a). The World Bank similarly states that addressing climate change “requires ... widespread diffusion of renewable energy technologies... and breakthroughs in technologies from batteries to carbon capture and storage” (World Bank, 2010).

While there is a general recognition that new technologies will need to be developed for a transition to a less energy-intensive and emissions-intensive world, neither public nor private funding of energy-related research, development, and deployment is remotely close to what is required (World Bank, 2010). (See Box 6.3.)

In absolute terms, public energy-related RD&D expenditures in the OECD have declined since 1980 and fell by almost half from then to 2000, to

around US\$10 billion, before rebounding to US\$15 billion in 2008. The expenditures reported for 2009 reach an unprecedented high of US\$23 billion (in 2009 prices and exchange rates), with fossil fuels and technologies absorbing the lion's share (US\$3.8 billion) of the increase of US\$8 billion from 2008 (IEA, 2011).

Private energy RD&D, estimated at US\$40–60 billion a year, far exceeds public spending (Chapter 24). At 0.5% of revenue, private expenditures on energy RD&D remain small, however, for instance, compared with 8% of revenues invested in RD&D in the electronics industry and 15% of revenues in the pharmaceuticals sector (World Bank, 2010). (Note: the latter are largely non-energy-related.) Taken overall, the energy-related figures pale in comparison to estimates of required RD&D expenditures in the order of US\$100–700 billion a year (World Bank, 2010).

Within the OECD, Japan spends 0.08% of GDP on research and development (R&D), compared with the 0.03% of GDP average for the high- and upper-middle-income members of the OECD (World Bank, 2010). By contrast, in the United States the share of public and private R&D fell from 10% to 2% between 1980 and 2006 (Weiss and Bonvillian, 2009). Total energy R&D now accounts for less than 1% of the annual revenues of the US energy sector. Weiss and Bonvillian offer several explanations for this decline:

- deregulation of energy markets, which has increased competition and led to cutbacks in discretionary expenditures, including R&D;
- an extended period of relatively low energy prices; and
- a mature and cost-competitive sector, which has generally tended to deter new entrants and potential competitors.

Box 6.3 | The Role of Entrepreneurial Innovators

The path to global sustainability will require nearly US\$2 trillion annually of primarily private sector investment, plus making hundreds of thousands of sites available for often locally controversial energy facilities and training hundreds of thousands of energy workers at all levels each year. Governmental institutions that support innovation are generally unprepared for this challenge. The energy sector is also dominated by large, risk-averse corporations with strong interests in preserving their comfortable status quo and with a resulting history of underinvestment in innovation.

The role of entrepreneurial innovators will thus be crucial. However, the energy sector has not been very encouraging to entrepreneurial innovators for several decades.¹⁷ Also the priority of avoiding risk at all costs of most governmental organizations has deterred investors in entrepreneurial firms from entering energy markets. This is particularly true for governmental regulatory agencies that have typically put protecting the incumbent industries they regulate ahead of innovation goals. This has inhibited the reallocation of economic resources from the established to the new entrepreneurial organizations that necessarily lead transformative innovation (see also Chapters 24 and 25).

¹⁷ Entrepreneurs in wind and solar PV have been successful in some countries, including: Germany, Spain, Denmark and Bangladesh.

The process of technology deployment and adoption is widely seen as being about much more than the technical aspects or performance of some piece of equipment. This is particularly true in developing countries, where many factors influence technology adoption and where capacity building will be crucial to enable developing countries to adopt new technologies (Tomlinson et al., 2008). Technology “diffusion” then covers the process of understanding, using, and replicating technologies, as well as adapting them to local conditions and integrating them with other technologies (IPCC, 2000).

The increasing importance of investment flows to promote technology is the focus of current research to promote climate-friendly development. The majority of global investment and technology diffusion occurs via the private sector in the form of corporate R&D, venture capital or asset financing arrangements, or funds raised in public markets (UNEP/SEFI/NEF, 2009). Studies assessing technology transfer and diffusion in developing countries have accordingly noted that openness to trade is a necessary prerequisite for successful transfer.

A second key factor for facilitating technology transfer (see also Chapter 25), which relates directly to the incentives for private firms to undertake R&D, is intellectual property rights (IPRs). Predictable and clearly defined IPRs can stimulate technology transfer from abroad, while weak IPR enforcement discourages foreign firms from investing in R&D activities, licensing new technologies, and investing in domestic enterprises abroad (World Bank, 2010). For example, foreign subsidiaries of global wind equipment producers have registered very few patents in Brazil, China, India, or Turkey, all of which have weak IPR regimes.

At the same time, there are trade-offs. IPRs may hamper innovation if a patent blocks other useful inventions by being too broad in scope, or they can hamper technology transfer if firms refuse to license their technology. To date, overly restrictive IPRs have not been identified as a material barrier to transferring renewable energy production capacity to middle-income countries (ICHRP, 2011), but this situation may change if patenting activity accelerates in photovoltaics and biofuels and if equipment supplier consolidation continues in the wind sector (World Bank, 2010). The World Bank (2010) therefore highlights a role for high-income countries in ensuring that:

- excessive industry consolidation in the renewable energy sectors does not reduce incentives to license technology to developing countries;
- national policies do not prevent foreign firms from licensing publicly funded research for clean technologies of global importance; and
- concerns over IPRs and the transfer and innovation of clean technologies are considered in international treaties such as those of the World Trade Organization.

The importance of the RD&D effort for developing new low-emissions technologies and the observed shortfall in activity suggests that there is an ongoing role for government in this area. The role of governments is threefold and extends beyond energy RD&D: first, in general support for knowledge creation (education, support for international science and technology cooperation, and information exchange); second, in supporting basic and applied energy technology R&D via direct public R&D expenditures as well as by creating and maintaining appropriate incentives for private sector R&D; and third, creating favorable market deployment incentives as well as removing existing barriers for the adoption of more-efficient and cleaner energy technologies.

Broadly speaking, government has a role in RD&D where there are specific “market failures” that will inherently limit private RD&D, but it also needs to put in place a framework in which research activities and innovation are facilitated (IPCC, 2007). There are many market failures that can prevent technology development and deployment. A fundamental failure occurs when prices do not reflect the full costs of the service rendered. Subsidized consumer prices are one example.

Another prominent example, as described earlier, is the failure to internalize the health and environmental damage costs from fossil fuel combustion, especially the costs caused by climate change. Failing to charge the full costs sends the wrong signal to the marketplace and results in overuse of services and underinvestment in more-efficient and cleaner technologies and processes. The net result is reduced demand for climate-friendly technologies and private-sector incentives stimulating innovation. Failures of this type can be addressed by establishing a corresponding market mechanism, for instance in the form of a carbon price, or by removing subsidies.

Additional market failures include monopolistic market structures, different incentives between short-run first-cost minimization (e.g., apartment buildings) by contractors and operating costs over the longer term, access to finance for technologies with higher up-front investment and transaction costs, lack of institutional support, and limited awareness and information.

More generally, new technologies usually face a range of technical and market hurdles and associated uncertainties about entering into widespread commercial use, including innovation uncertainty, technology performance, cost, financial risks, lengthy timescale for deployment, and very large sunk costs. Here governments have a role to play by putting in place the enabling “infrastructure” required to support RD&D and innovation, including the rule of law, open markets, the protection of intellectual property, and the movement of goods, capital, and people.

Several promising efficient and environmentally benign technologies are in their infancy and thus require public RD&D support, while others are more mature and need primarily market incentives for deployment

and diffusion. Providing effective deployment incentives is therefore another area for public-sector involvement. These include corrections of the market failures just mentioned, financial incentives (tax credits, carbon prices, fuel taxes, technology rebates, time-limited subsidies), a reliable and predictable regulatory framework, institutional arrangements (e.g., energy service companies), public procurement, promotion, and education.

6.9 Institutional Change

In the face of the profound demographic changes occurring throughout the world, the institutions that were created over the past three decades to help ensure energy security are struggling to remain relevant. The rapid changes of the last few decades point to the need for a more nimble mechanism or system that could help address the complexity of security, global environmental and social and economic concerns, and so on. In order to be effective, this mechanism or system would need to balance the interests of governments, importers, and exporters while aligning with the needs of the private and state-owned firms that provide most of the energy infrastructure investment.

A broad-based cooperative leadership coalition for positive change is the indispensable but missing ingredient needed to transform the energy systems that sustainable societies would require. There is no shortage of governance institutions in today's energy markets. What is missing is a practical strategy for setting effective norms for governing the global energy economy. The basic problem lies in the massive economic and political risks inherent in new projects, particularly those that supply energy across national borders and thus face a multitude of uncertainties. Longtime antagonists must work together to create a shared vision of, and an implementation commitment to achieving, a new, sustainable global energy strategy. This means setting clear goals to address the pivotal challenges of energy access, security, poverty, health, climate change and environment and crafting the necessary policies and practices to achieve these goals. The key challenges can be overcome through a blend of carefully targeted policy initiatives that build on the power of the market, plus public-private partnerships for financing and technology development.

Support for new "green" or low-carbon technologies is a second area where a governance vacuum has made progress difficult. Firms are not likely to invest the trillions of dollars needed to develop energy infrastructure in the coming decades without credible signals that governments are serious about establishing and maintaining policies that enable the private sector to confidently cash in on their investments. Based on experience, a sharper focus on energy investments is likely to be much more successful than the more typical broader multilateral governmental agreements on foreign investments.

6.10 Conclusion

Following are the main conclusions and key messages of the chapter:

- Energy is not an end in itself but a prerequisite for economic development (including for the achievement of the Millennium Development Goals), and for the achievement of growth.
- Energy is crucial for the necessary transition to a more equitable and sustainable world and one where all have access to the energy services required for comfort and for a secure and healthy livelihood.
- Energy service demand is a function of population and income, as well as technology. While more affluence may lead to a demand for more energy intensive services it could also lead to a demand for cleaner energy carriers.
- The immense global population increase of the past century has been matched by a period of intense technological expansion that has increased the capacity to harness energy more efficiently and effectively. The reality is that while technology has expanded dramatically, for the most part it is not yet being commercially implemented to meet the 21st Century needs.
- Electricity provides the essential key to energy access, and is the energy prime mover enabling technical innovation and productivity growth. Filling the global electrification gaps to an ever-growing 1.4 billion people today is an essential requirement for eliminating extreme poverty and global security threats.
- A healthy economy is needed to ensure that the energy demands are met, that investments and infrastructure work is carried out and that resources for Research and Development flow to meet the needs and requirements for a sustainable future.
- Most clean technologies are capital-intensive however; they also lower energy demand and fuel consumption. Proper incentives and financial schemes to promote their development are essential.
- Prices play an essential role in the production and consumption process by sending important signals to sellers and buyers. But it is important to distinguish between prices and costs.
- Ideally, the life-cycle cost is what matters when assessing the costs of energy carriers (rather than the cost of fuels or capital costs being accounted for separately as is often the case).
- While monetary costs associated with energy supply and use are fully paid by the producer and/or user, this is only partially the case for other costs associated with "externalities."

- Energy, capital, labor and materials are, within limits, substitutes of each other and the optimal mix is a matter of their relative factor prices.
- Demand responds to price changes – slowly in the short-run because lock-in effect leaves little room for immediate fuel switching and efficiency improvements but in the longer run, it does respond more profoundly through capital replacement (e.g., buildings, refurbishment, new technologies, process adaptation, etc.) and market penetration effects.
- As incomes rise energy demand grows but eventually the tendency is for this growth to take place slower than GDP.
- Investment in R&D drives innovation and is the key for technology improvements, for new technologies to emerge and for a lower energy intensive production of GDP.
- Required investments in clean energy systems are staggering and require investors with a long-term vision – usually with the support of governments which would ideally come in to provide the strategic policy certainty and level playing field for private sector involvement.
- The shift to higher efficiency and more sustainable forms of energy require accelerated and up-front energy-related investments over the next several decades that will need to be sustained and supported by coherent and coordinated policy and regulatory frameworks to mitigate the many existing constraints.
- Although investments in clean energy systems in recent years have been impressive and continue growing, much more is required for the energy transitions that GEA necessitates, including to avoid lock-in effects associated with obsolete energy infrastructures with little short-term flexibility.
- Subsidies change the relative merit order based on private cost only, and can, if well designed, reflect the externalities in market conditions. Subsidies are required for transitions to energy systems supporting a sustainable future.
- Overall energy system performance (intensities, cleanliness, affordability) is more dependent on investments in end-use infrastructures and technologies than on traditional energy sector investment although the latter are also important.
- Energy transitions do not happen in isolation. They require a robust public policy framework and an adequate institutional infrastructure to help make things happen. The evidence shows that major policy and institutional reforms are necessary to lead us into the energy transitions that the GEA necessitates.

References

- Abosedra, S. and H. Baghestani, 1989:** New Evidence on the Causal Relationship between U.S. Energy Consumption and Gross National Product. *Journal of Energy Development*, **14**(2): 285–292.
- AGECC, 2010:** *Energy for a Sustainable Future*. The United Nations Secretary-General's Advisory Group on Energy and Climate Change (AGECC), New York, NY, USA.
- Arrow, K. J., W. R. Cline, K.-G. Maler, M. Munasinghe, R. Squitieri and J. E. Stiglitz, 1996:** Intertemporal Equity, Discounting, and Economic Efficiency. In *Climate Change 1995: Economic and Social Dimensions of Climate Change*. J. P. Bruce, L. H. and E. F. Haites (eds.), Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK and New York, NY, USA., pp. 125–144.
- Arthur, W. B., 2009:** *The Nature of Technology: What It Is and How It Evolves*. The Free Press, New York, NY, USA.
- Ayers, R. U. and B. Warr, 2009:** *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Edward Elgar Publishing Ltd., Cheltenham, UK.
- Barnes, J., D. Brumberg, M. E. Chen, D. B. Cook, J. Elass, M. El-Gamal, M. Gillis, J. González-Gómez, P. R. Hartley, D. Hertzmark, A. M. Jaffe, Y. J. Kim, N. Lane, D. Li, D. R. Mares, K. Matthews, K. B. Medlock, R. Soligo, L. Smulcer, R. Stoll and X. Xu, 2008:** *The Global Energy Market: Comprehensive Strategies to Meet Geopolitical and Financial Risks—the G8, Energy Security, and Global Climate Issues*. Baker Institute Policy Report #37, James A. Baker III Institute for Public Policy of Rice University, Houston, TX, USA.
- Barnett, H. and C. Morse, 1963:** *Scarcity and Growth: The Economics of Natural Resource Availability*. Johns Hopkins University Press for Resources for the Future, Baltimore, MD, USA.
- Berck, P. and M. Roberts, 1996:** Natural Resource Prices: Will They Ever Turn Up? *Journal of Environmental Economics and Management*, **31**(1): 65–78.
- BNEF, 2010:** *Weathering the Storm – Public Funding for Low-Carbon Energy in the Post Financial Crisis Era*. United Nations Environment Programme Sustainable Energy Finance Alliance (UNEP SEF Alliance) and Bloomberg New Energy Finance (BNEF), London, UK.
- Campbell, M., J. Cleland, A. Ezech and N. Prata, 2007:** Return of the Population Growth Factor. *Science*, **315**(5818): 1501–1502.
- Chen, S. and M. Ravallion, 2008:** *The Developing World Is Poorer Than We Thought, but No Less Successful in the Fight Against Poverty*, Policy Research Working Paper No. 4703, The World Bank, Washington, D.C., USA.
- Cheng, B. S., 1995:** An Investigation of Cointegration and Causality between Energy Consumption and Economic Growth. *Journal of Energy Development*, **21**(1): 73–84.
- Chontanawat, J., L. C. Hunt and R. Pierse, 2008:** Does Energy Consumption Cause Economic Growth?: Evidence from a Systematic Study of over 100 Countries. *Journal of Policy Modeling*, **30**(2): 209–220.
- Cleland, J., S. Bernstein, A. Ezech, A. Faundes, A. Glasier and J. Innis, 2006:** Family Planning: The Unfinished Agenda. *The Lancet*, **368**(9549): 1810–1827.
- Dasgupta, A. K. and D. W. Pearce, 1972:** *Cost-Benefit Analysis: Theory and Practice*. Palgrave Macmillan, Basingstoke, UK.
- Dasgupta, P. and G. M. Heal, 1979:** *Economic Theory and Exhaustible Resources*. Cambridge University Press, New York, NY, USA and Cambridge, UK.
- Davies, J. B., S. Sandström, A. Shorrocks and E. N. Worlff, 2008:** *The World Distribution of Household Wealth*. Discussion Paper No. 2008/3, United Nations University World Institute for Development Economics Research (UNU-WIDER), Helsinki, Finland.
- Ekholm, T., V. Krey, S. Pachauri and K. Riahi, 2010:** Determinants of Household Energy Consumption in India. *Energy Policy*, **38**(10): 5696–5707.
- EPRI, 2003:** *Electricity Technology Roadmap: Meeting the Critical Challenges of the 21st Century*. Project Number: 1010929, Electric Power Research Institute (EPRI), Palo Alto, CA, USA.
- Erol, U. and E. S. H. Yu, 1987:** On the Casual Relationship between Energy and Income for Industrialized Countries. *Journal of Energy Development*, **13**(2): 113–122.
- Espey, J. A. and M. Espey, 2004:** Turning on the Lights: A Meta-Analysis of Residential Electricity Demand Elasticities. *Journal of Agricultural and Applied Economics*, **36**(1): 65–81.
- Espey, M., 1998:** Gasoline Demand Revisited: An International Meta-Analysis of Elasticities. *Energy Economics*, **20**(3): 273–295.
- EU, 2003:** *World Energy Technology and Climate Policy Outlook 2030 (WETO)*. Directorate-General for Research, Energy, European Commission, Brussels, Belgium.
- Fouquet, R. and P. J. G. Pearson, 2006:** Seven Centuries of Energy Services: The Price and Use of Light in the United Kingdom (1300–2000). *Energy Journal*, **27**(1): 139–177.
- Fouquet, R., 2008:** *Heat, Power and Light: Revolutions in Energy Services*. Edward Elgar Publishing Ltd., Cheltenham, UK and Northampton, MA, USA.
- Fouquet, R., 2011:** Long Run Trends in Energy-Related External Costs. *Ecological Economics*, **70**(12): 2380–2389.
- Galvin, R. and K. Yeager, 2009:** *Perfect Power – How the Microgrid Revolution Will Unleash Cleaner, Greener, and More Abundant Energy*. McGraw-Hill, New York, NY, USA.
- Goldemberg, J., T. B. Johansson, A. K. N. Reddy and R. H. Williams, 1985:** Basic Needs and Much More with One Kilowatt Per Capita. *Ambio*, **14**(4/5): 190–200.
- Griffin, J. M., 1993:** Methodological Advances in Energy Modelling: 1970–1990. *The Energy Journal*, **14**(1): 111–124.
- Grubler, A., 1998:** *Technology and Global Change*. Cambridge University Press, Cambridge, UK.
- Haas, R., N. Nakicenovic, A. Ajanovic, T. Faber, L. Kranzl, A. Müller and G. Resch, 2008:** Towards Sustainability of Energy Systems: A Primer on How to Apply the Concept of Energy Services to Identify Necessary Trends and Policies. *Energy Policy*, **36**(11): 4012–4021.
- Hartwick, J. M. and A. P. Hageman, 1993:** Economic Depreciation of Mineral Stocks and the Contribution of El Serafy. In *Toward Improved Accounting for the Environment*. E. Lutz (ed.), World Bank, Washington, D.C., USA.
- Hausman, J. A., 1979:** Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables. *Bell Journal of Economics*, **10**(1): 33–54.
- Hotelling, H., 1931:** The Economics of Exhaustible Resources. *Journal of Political Economy*, **39**(2): 137–175.
- Howarth, R. B. and A. H. Sanstad, 1995:** Discount Rates and Energy Efficiency. *Contemporary Economic Policy*, **13**(3): 101–109.
- Hunt, L. C. and Y. Ninomiya, 2003:** *Modelling Underlying Energy Demand Trends and Stochastic Seasonality: An Econometric Analysis of Transport Oil Demand*

- in the UK and Japan. School of Economics Discussion Papers 107, Surrey Energy Economics Centre (SEEC), School of Economics, University of Surrey, Surrey, UK.
- Hwang, D. and B. Gum, 1991:** The Causal Relationship between Energy and Gnp: The Case of Taiwan. *Journal of Energy Development*, **16**(2): 219–226.
- ICHRP, 2011:** *Beyond Technology Transfer – Protecting Human Rights in a Climate-Constrained World*. International Council on Human Rights Policy (ICHRP), Geneva, Switzerland.
- IEA, 2003:** *World Energy Investment Outlook 2003*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA, 2005:** *The Experience with Energy Efficiency Policies and Programmes in IEA Countries – Learning from the Critics*. IEA Information Paper, H. Geller and S. Attali, International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA, 2006a:** *World Energy Outlook 2006*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA, 2006b:** *Energy Technology Perspectives 2006 – Scenarios & Strategies to 2050*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA, 2007:** *World Energy Outlook 2007*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA, 2008a:** *Energy Technology Perspectives 2008 – Scenarios & Strategies to 2050*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA, 2008b:** *World Energy Outlook 2008*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA, 2008b:** *Energy Technology Perspectives: Energy Technology Perspectives to 2050*. International Energy Agency – OECD, Paris.
- IEA, 2009a:** *World Energy Outlook 2009*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA, 2009b:** *World Energy Outlook*. International Energy Agency, Organization for Economic Cooperation & Development, Paris.
- IEA, 2010a:** *World Energy Outlook 2010*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA, 2010b:** *Energy Statistics and Balances: Online Database*. International Energy Agency (IEA) of the Organization for Economic Co-operation and Development (OECD), Paris, France <http://www.iea.org/stats/index.asp> (accessed 25 August, 2011).
- IEA, 2011:** *World Energy Outlook 2011*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD), Paris, France.
- IEA/NEA, 2010:** *Projected Costs of Generating Electricity, 2010 Edition*. International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development and the Nuclear Energy Agency (NEA), Paris, France.
- IPCC, 2000:** *Ipcc Special Report – Methodological and Technological Issues in Technology Transfer*. Special Report of IPCC Working Group III, World Meteorological Organisation (WMO), United Nations Environment Programme (UNEP), and the Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland.
- IPCC, 2007:** *Mitigation of Climate Change*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 B. Metz, O. R. Davidson, P. R. Bosch, R. Dave and L. A. Meyer, Cambridge University Press, Cambridge, UK and the Intergovernmental Panel on Climate Change (IPCC), Switzerland, Geneva.
- Jaffe, A. B. and R. N. Stavins, 1994a:** The Energy Paradox and the Diffusion of Conservation Technology. *Resource and Energy Economics*, **16**(2): 91–122.
- Jaffe, A. B. and R. N. Stavins, 1994b:** The Energy-Efficiency Gap What Does It Mean? *Energy Policy*, **22**(10): 804–810.
- Judson, R. A., R. Schmalensee and T. M. Stoker, 1999:** Economic Development and the Structure of the Demand for Commercial Energy. *The Energy Journal*, **20**(2): 29–58.
- KfW, 2011:** *Action by KfW Entwicklungsbank*. KfW Banking Group, Frankfurt, Germany http://www.kfw-entwicklungsbank.de/ebank/EN_Home/Sectors/Energy/Action_by_KfW_Entwicklungsbank/index.jsp (accessed 1 August, 2011).
- Kilian, L., 2008:** The Economic Effects of Energy Price Shocks. *Journal of Economic Literature*, **46**(4): 871–909.
- Kraft, J. and A. Kraft, 1978:** On the Relationship between Energy and Gnp. *Journal of Energy Development*, **3**(2): 401–403.
- Krautkraemer, J. A., 1998:** Nonrenewable Resource Scarcity. *Journal of Economic Literature*, **36**(4): 2065–2107.
- Landes, D., 1969:** *The Unbound Prometheus*. Cambridge University Press, Cambridge, UK.
- Lee, C.-C., 2005:** Energy Consumption and Gdp in Developing Countries: A Cointegrated Panel Analysis. *Energy Economics*, **27**(3): 415–427.
- Liu, N. and B. W. Ang, 2007:** Factors Shaping Aggregate Energy Intensity Trend for Industry: Energy Intensity Versus Product Mix. *Energy Economics*, **29**(4): 609–635.
- Lutz, W., J. C. Cuasema and W. Sanderson, 2008:** The Demography of Educational Attainment and Economic Growth. *Science*, **319**(5866): 1047–1048.
- Lutz, W. and K. C. Samir, 2010:** Dimensions of Global Population Projections: What Do We Know About Future Population Trends and Structures? *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**(1554): 2779–2791.
- Lutzenhiser, L., 1993:** Social and Behavioral Aspects of Energy Use. *Annual Review of Energy and the Environment*, **18**: 247–289.
- Manne, A. S. and L. Schrattenholzer, 1986:** International Energy Workshop: A Progress Report. *OPEC Review*, **10**(3): 287–320.
- Markandya, A. and R. Boyd, 2002:** *Airpacts Economic Valuation*. University of Bath, UK, for the International Atomic Energy Agency (IAEA), Vienna, Austria.
- Markandya, A., S. Pedrosa-Galinato and D. Streimikiene, 2006:** Energy Intensity in Transition Economies: Is There Convergence Towards the Eu Average? *Energy Economics*, **28**(1): 121–145.
- Markandya, A., A. Bigano and R. Porchia, Eds. 2010:** *The Social Costs of Electricity: Scenarios and Policy Implications*. Edward Elgar Publishing Limited, Cheltenham, UK.
- Martin, P., 2005:** *Migrants in the Global Labor Market*. Prepared for the Policy Analysis and Research Programme, Global Commission on International Migration (GCIM), New York, NY, USA.

- Masih, A. M. M. and R. Masih, 1996: Energy Consumption, Real Income and Temporal Causality: Results from a Multi-Country Study Based on Cointegration and Error-Correction Modelling Techniques. *Energy Economics*, **18**(3): 165–183.
- Modi, V., S. McDade, D. Lallement and J. Saghir, 2005: *Energy Services for the Millenium Development Goals*. Energy Sector Management Assistance Programme (ESMAP), United Nations Development Programme (UNDP), UN Millenium Project, and the World Bank, New York, NY, USA.
- Nakicenovic, N. and H.-H. Rogner, 1996: Financing Global Energy Perspectives to 2050. *OPEC Review*, **20**(1): 1–23.
- Nakicenovic, N., A. Grubler and A. McDonald, Eds. 1998: *Global Energy Perspectives*. Cambridge University Press Cambridge, UK.
- Nakićenović, N., 1996: Freeing Energy from Carbon. *Daedalus*, **125**(3): 95–112.
- Nilsson, L. J., 1993: Energy Intensity Trends in 31 Industrial and Developing Countries 1950–1988. *Energy*, **18**(4): 309–322.
- Nordhaus, W. D., 1997: *Beyond the Cpi: An Augmented Cost of Living Index (Acoli)*. Cowles Foundation Discussion Papers 1152, Cowles Foundation for Research in Economics, Yale University, New Haven, CT, USA.
- Norgaard, R. B., 1988: Sustainable Development: A Co-Evolutionary View. *Futures*, **20**(6): 606–620.
- O'Neill, B. C., M. Dalton, R. Fuchs, L. Jiang, S. Pachauri and K. Zigova, 2010: Global Demographic Trends and Future Carbon Emissions. *Proceedings of the National Academy of Sciences*.
- Pacala, S. and R. Socolow, 2004: Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science*, **305**(5686): 968–972.
- Prata, N., 2009: Making Family Planning Accessible in Resource-Poor Settings. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **364**(1532): 3093–3099.
- Rabl, A. and J. V. Spadaro, 1999: Damages and Costs of Air Pollution: An Analysis of Uncertainties. *Environment International*, **25**(1): 29–46.
- Reddy, A. K. N. and B. S. Reddy, 1994: Substitution of Energy Carriers for Cooking in Bangalore. *Energy*, **19**(5): 561–571.
- REN21, 2011: *Renewables 2011 – Global Status Report*. Renewable Energy Policy Network for the 21st Century (REN21), Paris, France.
- Riahi, K., A. Grubler and N. Nakicenovic, 2007: Scenarios of Long-Term Socio-Economic and Environmental Development under Climate Stabilization. *Technological Forecasting and Social Change*, **74**(7): 887–935.
- Ricci, A., 2010: *Policy Use of the Needs Results*. New Energy Externalities Development for Sustainability.
- Rogner, H.-H., 2010: Innovating for Development: Nuclear Power and Sustainable Development. *Journal of International Affairs*, **64**(1): 137–163.
- Samuelson, P. A., W. D. Nordhaus and J. McCallum, 1988: *Macroeconomics – Sixth Canadian Edition*. McGraw-Hill Ryerson Ltd, Toronto, Canada.
- SAUNER, 2000: *Sustainability and the Use of Non-Renewable Resources (SAUNER) – Summary Final Report*. Contract ENV4-CT97–0692, University of Bath, UK; University of Stuttgart, Germany and Montanuniversität Leoben, Austria.
- Schipper, L. and S. Meyers, 1992: *Energy Efficiency and Human Activity – Past Trends, Future Prospects*. Stockholm Environment Institute, Stockholm, Sweden and Cambridge University Press, Cambridge, UK.
- Schurr, S. H., B. C. Netschert, V. F. Eliasberg, J. Lerner and H. H. Landsberg, 1960: *Energy in the American Economy, 1850–1975*. Johns Hopkins Press, Baltimore, MD, USA.
- Smith, K. R. and K. Balakrishnan, 2009: Mitigating Climate, Meeting Mdg, and Moderating Chronic Disease: The Health Co-Benefits Landscape. In *Commonwealth Health Ministers' Update 2009*, Commonwealth Secretariat, London, UK.
- Soytas, U. and R. Sari, 2003: Energy Consumption and Gdp: Causality Relationship in G-7 Countries and Emerging Markets. *Energy Economics*, **25**(1): 33–37.
- Soytas, U. and R. Sari, 2006: Energy Consumption and Income in G-7 Countries. *Journal of Policy Modeling*, **28**(7): 739–750.
- Taylor, R. P., C. Govindarajulu, J. Levin, A. S. Meyers and W. A. Ward, 2008: *Financing Energy Efficiency – Lessons from Brazil, China, India, and Beyond*. Report No. 42529, Energy Sector Management Assistance Program (ESMAP) and the World Bank, Washington, D.C., USA.
- Toman, M. T. and B. Jemelkova, 2003: Energy and Economic Development: An Assessment of the State of Knowledge. *The Energy Journal*, **24**(4): 93–112.
- Tomlinson, S., P. Zorlu and C. Langley, 2008: *Innovation and Technology Transfer*. Chatham House and E3G, London, UK.
- Train, K., 1985: Discount Rates in Consumers' Energy-Related Decisions: A Review of the Literature. *Energy*, **10**(12): 1243–1253.
- UNCTAD, 2001: *Growing Micro and Small Enterprises in Ldc – the "Missing Middle" in Ldcs: Why Micro and Small Enterprises Are Not Growing*. UNCTAD/ITE/TEB/5, United Nations Conference on Trade and Development (UNCTAD), Geneva, Switzerland.
- UNDESA, 2004: *World Population to 2300*. ST/ESA/SER.A/236, Population Division, United Nations Department of Economic and Social Affairs (UNDESA), New York, NY, USA.
- UNDESA, 2011: *World Economic and Social Survey 2011 – the Great Green Technological Transformation*. E/2011/50/Rev.1 ST/ESA/333, United Nations Department of Economic and Social Affairs (UNDESA), New York, NY, USA.
- UNEP/SEFI/NEF, 2009: *Global Trends in Sustainable Energy Investment 2009 – Analysis of Trends and Issues in the Financing of Renewable Energy and Energy Efficiency*. United Nations Environment Programme (UNEP), Sustainable Energy Finance Initiative (SEFI) and New Energy Finance (NEF), New York, NY, USA.
- UNFCCC, 2010: *The Cancun Agreements – an Assessment by the Executive Secretary of the United Nations Framework Convention on Climate Change*. United Nations Framework Convention on Climate Change (UNFCCC), Geneva, Switzerland.
- UNFPA, 2011: *State of the World Population 2011 – People and Possibilities in a World of 7 Billion*. United Nations Population Fund (UNFPA), New York, NY, USA.
- USAID, 2009: *Energy and Small and Medium Enterprise*. United States Agency for International Development (USAID), Washington, D.C., USA.
- USEIA, 2011: *International Energy Outlook 2011*. United States Energy Information Administration (USEIA), Washington, D.C., USA.
- Wang, Y., J. Guo and Y. Xi, 2008: Study on the Dynamic Relationship between Economic Growth and China Energy Based on Cointegration Analysis and Impulse Response Function. *China Population, Resources and Environment*, **18**(4): 56–61.
- WEC, 2008: *Energy Efficiency Policies around the World: Review and Evaluation*. World Energy Council, London, UK.
- Weiss, C. and W. B. Bonvillian, 2009: *Structuring and Energy Technology Revolution*. The MIT Press, Cambridge, MA, USA.

- Wolde-Rufael, Y., 2009:** Energy Consumption and Economic Growth: The Experience of African Countries Revisited. *Energy Economics*, **31**(2): 217–224.
- World Bank, 2010:** *State and Trends of the Carbon Market*. A. Kossoy and P. Ambrosi, Carbon Finance Unit of the World Bank, Washington, D.C., USA.
- World Bank, 2011a:** *Energy Portfolio Data*. World Bank, Washington, D.C., USA <http://go.worldbank.org/ERF9QNT660> (accessed 25 August, 2011).
- World Bank, 2011b:** *World Development Indicators 2011*. World Bank, Washington, D.C., USA.
- Yago, G., 2007:** *Financing the Missing Middle – Transatlantic Innovations in Affordable Capital*. Milken Institute, Washington, D.C., USA.
- Yu, E. S. H. and J. Y. Choi, 1985:** Causal Relationship between Energy and Gnp: An International Comparison. *Journal of Energy Development*, **10**(2): 249–272.
- Zhuang, J., Z. Liang, T. Lin and F. de Guzman, 2007:** *Theory and Practice in the Choice of Social Discount Rate for Cost-Benefit Analysis: A Survey*. ERD Working Paper Series No. 94, Economic and Research Department, Asian Development Bank, Manila, Phillipines.