

# Energy Primer

Based On Chapter 1  
of the Global Energy  
Assessment (GEA)

Online Textbook  
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Online Textbook based on Chapter 1 of the Global Energy Assessment (GEA).

## Lead Authors (LA)

Arnulf Grubler (International Institute for Applied Systems Analysis, Austria and Yale University, USA)

Nebojsa Nakicenovic (International Institute for Applied Systems Analysis and Vienna University of Technology, Austria)

Shonali Pachauri (International Institute for Applied Systems Analysis, Austria)

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

Kirk R. Smith (University of California, Berkeley, USA)

## Contributing Authors (CA)

Simon De Stercke (International Institute for Applied Systems Analysis, Austria)

Reinhard Haas (Vienna University of Technology, Austria)

Peter Kolp (International Institute for Applied Systems Analysis, Austria)

Andrej Jentsch (Richtvert Energy Systems Consultancy, Germany)

Thomas B. Johansson (Lund University, Sweden)

Volker Krey (International Institute for Applied Systems Analysis, Austria)

Jordan Macknick (National Renewable Energy Laboratory, USA)

Luis Mundaca (Lund University, Sweden)

Yu Nagai (Vienna University of Technology, Austria)

Keywan Riahi (International Institute for Applied Systems Analysis, Austria)

Mathis L. Rogner (International Institute for Applied Systems Analysis, Austria)

Kjartan Steen-Olsen (Norwegian University of Science and Technology)

Lars Strupeit (Lund University, Sweden)

Jan Weinzettel (Norwegian University of Science and Technology)

*Please use the following reference for this report:*

Grubler A, Nakicenovic N, Pachauri S, Rogner H-H, Smith KR, et al., 2014: *Energy Primer*. International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1-118.

# 1 Introduction and Roadmap

Life is but a continuous process of energy conversion and transformation. The accomplishments of civilization have largely been achieved through the increasingly efficient and extensive harnessing of various forms of energy to extend human capabilities and ingenuity. Energy is similarly indispensable for continued human development and economic growth. Providing adequate, affordable energy services is a necessary (even if by itself insufficient) prerequisite for eradicating poverty, improving human welfare, and raising living standards worldwide. Without economic growth, it will also be difficult to address social and environmental challenges, especially those associated with poverty. Without continued institutional, social, and technological innovation, it will be impossible to address planetary challenges such as climate change. While all components of the energy system undergo continuous changes, the ultimate purpose of energy production and use remains unchanged: the provision of convenient and affordable energy services for human needs. Energy extraction, conversion, and use always also generate undesirable by-products and emissions – at a minimum in the form of dissipated heat. Energy cannot be created or destroyed – it can only be converted from one form to another, along a one-way street from higher to lower grades (qualities) of energy. Although it is common to discuss energy “consumption,” energy is actually transformed rather than consumed.

This Energy Primer<sup>1</sup> aims at a basic-level introduction to fundamental concepts and data that help to understand energy systems holistically and to provide a common conceptual and terminological framework before examining in greater detail the various aspects of energy systems be them technological, economic, or environmental. As such the text aims to provide a basic introductory reader suitable for the core content of any introductory-level energy class or as framing complement to more specialized energy classes. Customary energy texts usually focus on describing *current* energy industries through a supply side perspective, which this Energy Primer does not intend to duplicate. (In depth treatments of energy supply and industry aspects of energy systems are provided in Chapters 11 to 15 of the Global Energy Assessment, all available online.<sup>2</sup>)

Instead, this text was written with the intent to serve as complementary reading material that emphasizes in particular three traditionally less represented perspectives: 1) a systems view, allowing the reader to understand how the different components of our energy systems are interconnected and interdependent; 2) a focus on energy service demand as ultimate core driver of energy systems; and 3) a long-run historical context that helps the reader to understand how current energy systems have emerged and what characteristic rates of change are in these large-scale systems.

After an introduction and Primer roadmap (Section 1), Section 2 introduces the fundamental concepts and terms used to describe global energy systems (Section 2.1) and then proceeds with an overview of the most fundamental driver: the demand for energy services (Section 2.2) including global long-term trends in terms of useful and final energy. Section 2.3 then summarizes the major links between energy services and primary energy resources at the global level for the year 2005. This section also contains a summary of major energy units and scales (with technical details given in Appendix A).

Section 3 then turns to a historical perspective on energy transitions, covering both energy end-use demand and services using the United Kingdom as example (Section 3.1), as well as global energy

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<sup>1</sup> This text extends and updates Chapter 1 of the Global Energy Assessment (GEA) (Grubler et al., 2012) which draws on earlier publications with comparable content by the authors including: Goldemberg et al., 1988; Nakicenovic et al., 1996a; 1998; Rogner and Popescu, 2000; Grubler, 2004; and WEA (World Energy Assessment), 2004.

<sup>2</sup> [http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Chapters\\_Home.en.html](http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Chapters_Home.en.html)

supply and decarbonization (Section 3.2), and concludes with a brief introduction into the relationship between energy and economic growth (Section 3.3). A long historical perspective is important in understanding both the fundamental drivers of energy system transitions, as well as the constraints imposed by the typically slow rates of change in this large, capital-intensive system characterized by long-lived infrastructures (Grubler et al., 1999).

Section 4 then discusses the central aspect of energy efficiency, summarizing key concepts and measures of energy efficiency (Section 4.1), and estimates of global energy (Section 4.2) and exergy (Section 4.3) efficiencies as well as energy intensities (Section 4.4).

Section 5 provides a summary of key concepts (Section 5.1) and numbers of global energy resources that provide both key inputs and key limitations for energy systems. Fossil, fissile (Section 5.2), and renewable resources (Section 5.3) are covered comprehensively in energy and carbon terms along with a basic introduction to energy densities, which are particularly critical for renewable energy (Section 5.4).

Section 6 provides a summary of major energy flows associated with production, use, and trade of energy (Section 6.2) and energy conversions (Section 6.3) that link energy resources to final energy demands. After an introduction and overview (Section 6.1), production, use, and trade of both direct (Section 6.2.1) and indirect “embodied” energy, (Section 6.2.2) are discussed, and all energy trade flows summarized in Section 6.2.3. The discussion of energy conversions is short, as it is dealt with in customary energy textbooks and also in detail in the various chapters of GEA. After an introductory overview (Section 6.3.1), the electricity sector is briefly highlighted (Section 6.3.2).

Section 7 summarizes the main impacts of global energy systems on the human and natural environment in terms of human health impacts and airborne emissions, including greenhouse gases (Section 7.2) and other pollutants where the energy sector plays an important role (Section 7.3). These two categories of impacts are highlighted here as comprehensive global inventory data allow a comprehensive assessment. Both are central social and environmental externalities associated with all energy conversions.

Section 8 then complements the global synthesis by highlighting the vast heterogeneities in levels, patterns, and structure of energy use, by first introducing basic concepts and measures (Section 8.1), before addressing the heterogeneity across nations (Section 8.2), within nations (Section 8.3), as well as energy disparities (Section 8.4). This Section is of critical importance, given the objective of providing a global overview in this Primer. The inevitable top-down perspective involving Gigatonnes and Terawatts often glosses over differences in time, social strata, incomes, lifestyles, and human aspirations which are highlighted here.

Lastly, Section 9 provides a primer on basic economic concepts related to energy end-use and energy supply. After an Introduction (Section 9.1), costs and prices are introduced (Section 9.2). basic economic concepts relating to energy demand (Section 9.3) and energy supply (Section 9.4) are discussed as well as methods for aggregating various different cost components explained (Section 9.5). The Section concludes with a discussion of externalities drawing on illustrative EU studies (Section 9.6).

Appendix A returns to the rather technical, but nonetheless fundamental, aspect of units, scales, and energy accounting intricacies. This document uses uniformly the International System (SI) of (metric) units and has also adapted a uniform accounting standard for primary energy following GEA to achieve consistency and comparability across the different sections. This is especially important in the energy field, that to date continues to use a plethora of vernacular units and accounting methods. Appendix A also contains a more detailed exposition of the concept of levelized costs of energy (LCOE), which is a key concept on energy cost accounting.



Appendix B provides convenient summary tables of conversion and emission factors, and summarizes the various levels of regional aggregations used throughout GEA and also in this Primer.

## 2 The Global Energy System

### 2.1 Description of the Global Energy System

The energy system comprises all components related to the production, conversion, and use of energy.

Key components of the energy system comprise: primary energy *resources* which are harnessed and converted to energy *carriers*<sup>3</sup> (energy vectors such as electricity or fuels such as gasoline), which are used in *end-use applications* for the provision of energy *forms* (heat, kinetic energy, light, etc.) required to deliver *energy services* (e.g., thermal comfort or mobility). The key mediator linking all energy conversion steps from energy services all the way back to primary resources are energy conversion technologies. Energy systems are often further differentiated into an *energy supply* and an *energy end-use sector*. The energy supply sector consists of a sequence of elaborate and complex processes for extracting energy resources, for converting these into more desirable and suitable forms of *secondary energy*, and for delivering energy to places where demand exists. The part of the energy supply sector dealing with primary energy is usually referred to as “upstream” activities (e.g., oil exploration and production), and those dealing with secondary energy as “downstream” activities (e.g., oil refining and gasoline transport and distribution). The energy end-use sector provides energy services such as motive power, cooking, illumination, comfortable indoor climate, refrigerated storage, and transportation, to name just a few examples. The purpose of the entire energy system is the fulfillment of demand for energy services in satisfying human needs.

Figure 2.1 illustrates schematically the architecture of the energy system as a series of linked stages connecting various energy conversion and transformation processes that ultimately result in the provision of goods and services. A number of examples are given for energy extraction, treatment, conversion, distribution, end-use (final energy), and energy services in the energy system. The technical means by which each stage is realized have evolved over time, providing a mosaic of past evolution and future options (Nakicenovic et al., 1996a).

*Primary energy* is the energy that is embodied in resources as they exist in nature: chemical energy embodied in fossil fuels (coal, oil, and natural gas) or biomass, the potential kinetic energy of water drawn from a reservoir, the electromagnetic energy of solar radiation, and the energy released in nuclear reactions. For the most part, primary energy is not used directly but is first converted and transformed into secondary energy such as electricity and fuels such as gasoline, jet fuel, or heating oil which serve as energy carriers for subsequent energy conversions or market transactions (Nakicenovic et al., 1996a).

*Final energy* (“delivered” energy) is the energy transported and distributed to the point of retail for delivery to final users (firms, individuals, or institutions). Examples include gasoline at the service station, electricity at the socket, or fuel wood in the barn. Final energy is generally exchanged in formal monetary market transactions, where also typically energy taxes are levied. An exception are so-called

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<sup>3</sup> In the literature (e.g. Rosen, 2010, Scott, 2007, Escher, 1983) also the term *energy currency* is used to highlight the fact that different energy carriers are to a degree interchangeable and can be converted to whatever form is most suitable for delivering a given energy service task. Like monetary currencies, energy currencies are also exchangeable (at both an economic and [conversion] efficiency price). A concise compendium of energy-related concepts and terms is given in Cleveland and Morris, 2006.

non-commercial fuels – i.e., fuels collected by energy end-users themselves such as fuel wood or animal wastes, which constitute important energy sources for the poor.

The next energy transformation is the conversion of final energy in end-use devices such as appliances, machines, and vehicles into *useful energy* such as the energy forms of kinetic energy or heat. Useful energy is the last measurable energy flow before the delivery of energy services. It is measured at the crankshaft of an automobile engine, by the mechanical energy delivered by an industrial electric motor, by the heat of a household radiator or an industrial boiler, or by the luminosity of a light bulb. The application of useful energy provides energy services such as a moving vehicle (mobility), a warm room (thermal comfort), process heat (for materials manufacturing), or light (illumination).

Energy services are the result of a combination of various technologies, infrastructures (capital), labor (know-how), materials, and energy forms and carriers. Clearly, all these input factors carry a price tag and, within each category, are in part substitutable for one another. From the consumer's perspective, the important issues are the quality and cost of energy services. It often matters little what the energy carrier or the "upstream" primary energy resource was that served as input. It is fair to say that most consumers are often unaware of the upstream activities of the energy system. The energy system is service driven (i.e., from the bottom-up), whereas energy flows are driven by resource availability and conversion processes (i.e., from the top-down). Energy flows and driving forces interact intimately. Therefore, the energy sector should never be analyzed in isolation: it is not sufficient to consider only how energy is supplied; the analysis must also include how and for what purposes energy is used (Nakicenovic et al., 1996a).

Figure 2.2 illustrates schematically the major energy flows through the global energy system across the main stages of energy transformation, from primary energy to energy services, with typical examples. For an exposition of energy units see Box 1 below and Appendix A.

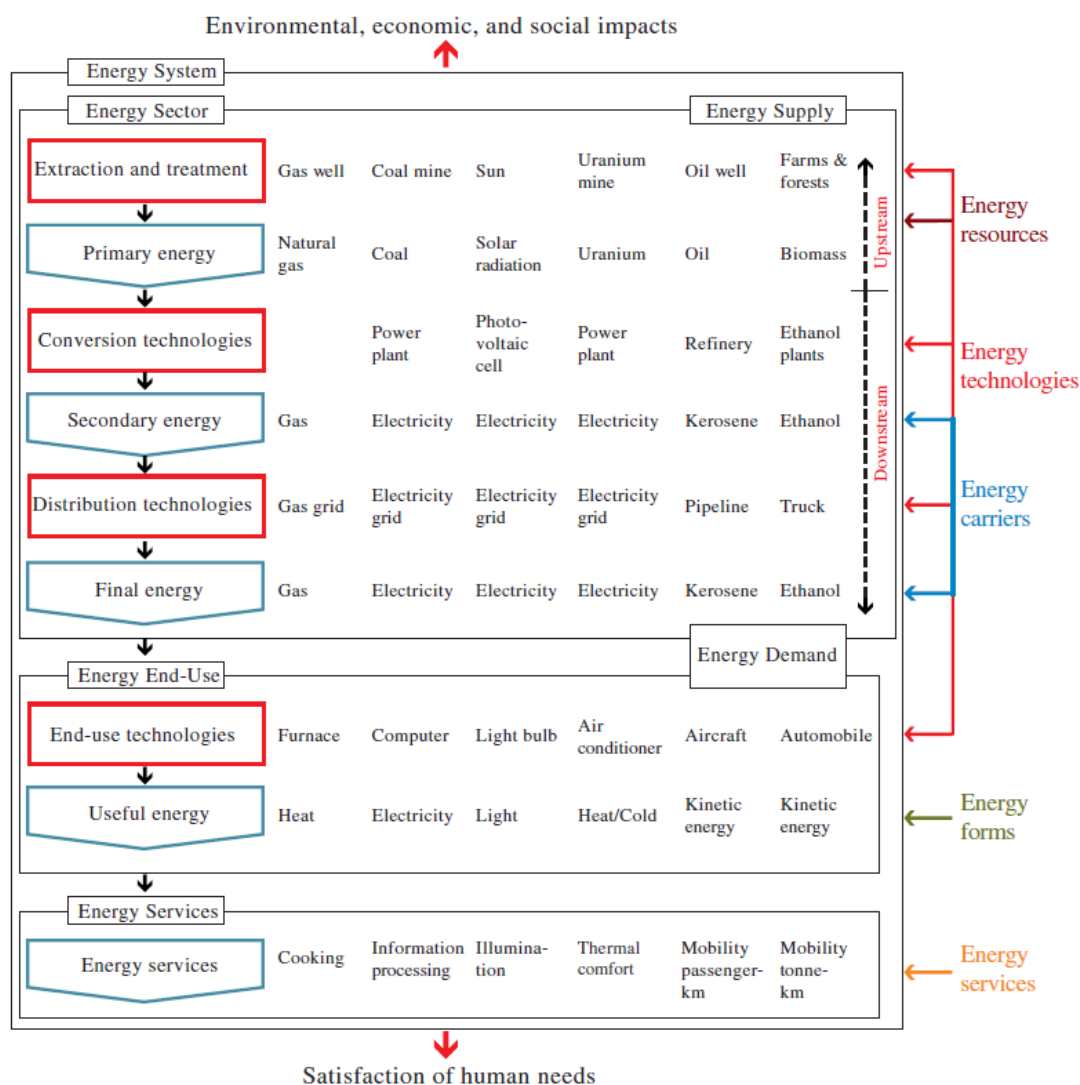


Figure 2.1. The energy system: schematic diagram with some illustrative examples of the energy sector and energy end use and services. The energy sector includes energy extraction, treatment, conversion, and distribution of final energy. The list is not exhaustive and the links shown between stages are not “fixed”; for example, natural gas can also be used to generate electricity, and coal is not used exclusively for electricity generation. Source: adapted from Nakicenovic et al., 1996a.

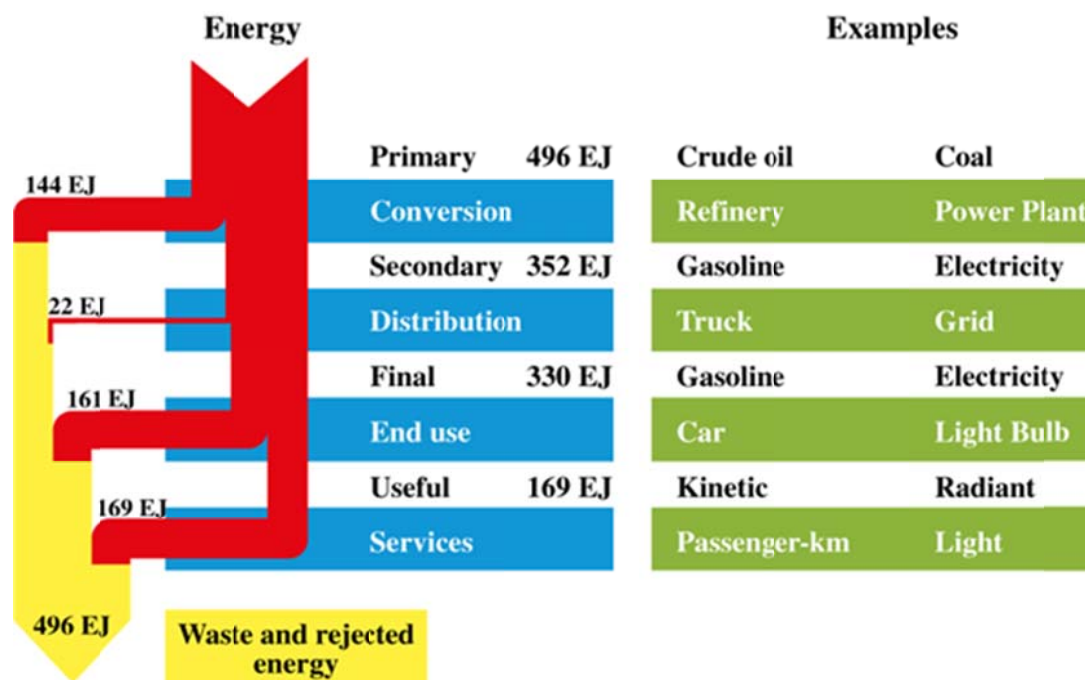


Figure 2.2. Global energy flows of primary to useful energy, including conversion losses (waste and rejected energy), in EJ for 2005. Source: adapted from Nakicenovic et al., 1998, based on IEA, 2007a; 2007b; 2010.

### Box 1. Energy Units and Scales

Energy is defined as the capacity to do work and is measured in joules (J), where 1 joule is the work done when a force of 1 newton ( $1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2$ ) is applied over a distance of 1 meter. Power is the rate at which energy is transferred and is commonly measured in watts (W), where 1 watt is 1 joule/second. Newton, joule, and watt are defined as basic units in the International System of Units (SI, French for International System of Units: *le Système international d'unités*).

Figure 2.3 gives an overview of the most commonly used energy units and also indicates typical (rounded) conversion factors. Next to the SI units, other common energy units include kilowatt-hour (kWh), used to measure electricity and derived from the joule (1 kWh – 1000 Watt-hours – being equivalent to 3600 kilowatt-seconds, or 3.6 MJ). In many international energy statistics (e.g., by the IEA and OECD) tonnes of oil equivalent (1 toe equals  $41.87 \times 10^9 \text{ J}$ ) are used. Some national energy statistics (e.g., in China and India) report tonnes of coal equivalent (1 tce equals  $29.31 \times 10^9 \text{ J}$ ).

The energy content of combustible energy resources (fossil fuels, biomass) is expressed based on either the so-called higher (HHV) or lower heating value (LHV). For non-combustible energy resources (nuclear, hydropower, wind energy, etc.) different conventions exist to convert those into primary energy equivalents. (For a detailed discussion see Appendix A). In this publication non-combustible energies are accounted for using the so-called substitution equivalent method, with 1 kWh of nuclear/renewable electricity equivalent to some 3 kWh of primary energy equivalent, based on the current global average conversion efficiency of 35%. Combustible energies are reported based on the LHV of fuels.



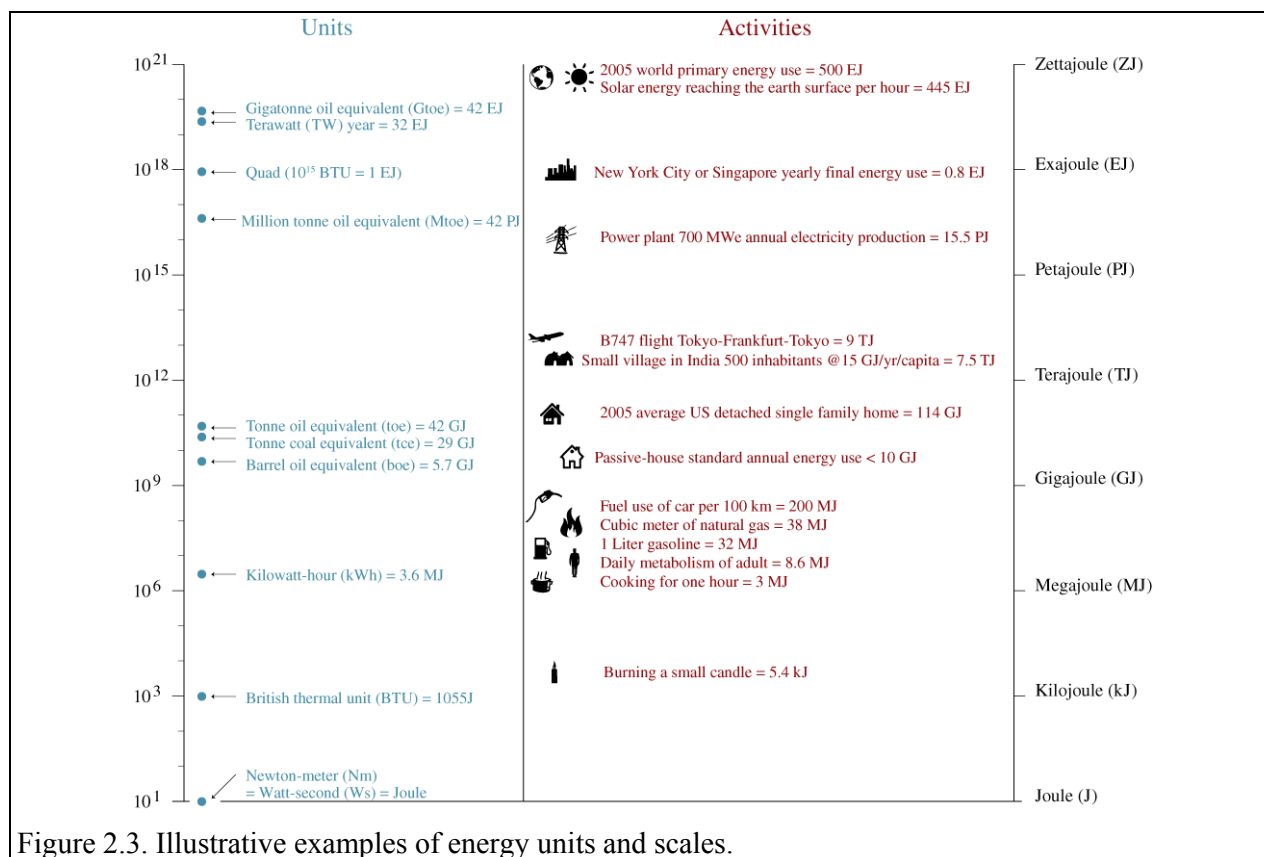


Figure 2.3. Illustrative examples of energy units and scales.

## 2.2 Energy Services

Despite the centrality of energy services for the energy system, their measurement and statistical reporting is sparse. As the different types of energy services – from passenger and goods transport to illumination, to materials produced and recycled, to information communicated – are so diverse, activity levels are non-commensurable (i.e., cannot be expressed in common units). Hence energy service levels are often assessed via their required energy inputs (useful, final, or primary energy) rather than by their actual outputs. This can distort the picture quite substantially, as those energy services with the lowest conversion efficiency (and thus highest proportional energy inputs) are over-weighted in the energy accounts. Measuring services via inputs rather than outputs can also significantly mask the enormous efficiency gains which have historically characterized technological change in energy end-use applications (from candles to white diode lighting, or from horses to electric vehicles), and which generally go unnoticed in long-term estimates of economic productivity and welfare growth (see Nordhaus, 1998).

A notable global assessment of energy service provision is given by Cullen and Allwood (2010) and summarized in Table 2.1 below. The assessment used primary energy as a common energy metric, which is problematic for energy services due to the ambiguities of primary energy accounting conventions (see Appendix A). Using primary energy inputs to characterize energy services also gives greater weight to lesser efficient energy service provision chains. A passenger-km traveled by car is accounted and weighted for by its much larger primary energy inputs (crude oil) compared to a passenger-km traveled by bicycle (food caloric intake). The multitude of energy services summarized here can be conveniently grouped into three broad categories and are treated in greater depth in separate chapters of the Global Energy Assessment: *Industry* (Chapter 8, Banerjee et al., 2012), *Transportation*

(Chapter 9, Kahn Ribeiro et al., 2012), and *Buildings* (Chapter 10, Ürges-Vorsatz et al., 2012), which are the physical structures in which the remainder of energy services are provided.

Table 2.1. Estimated levels of energy services and corresponding shares in primary energy per service type for the year 2005. Source: adapted from Cullen and Allwood, 2010.

Energy service	2005 levels	Units	As a percentage of pro-rated primary energy use (including upstream conversion losses)
Thermal comfort	30	$10^{15} \text{ m}^3\text{K}$ (degree-volume air)	19%
Sustenance (food)	28	$10^{18} \text{ J}$ (food)	18%
Structural materials	15	$10^9 \text{ MPa}^{2/3}\text{m}^3$ (tensile strength x volume)	14%
Freight transport	46	$10^{12} \text{ ton-km}$	14%
Passenger transport*	32	$10^{12} \text{ passenger-km}$	14%
Hygiene	1.5	$10^{12} \text{ m}^3\text{K}$ (temperature degree-volume of hot water)	11%
	2.8	$10^{18} \text{ Nm}$ (work)	
Communication	280	$10^{18} \text{ bytes}$	6%
Illumination	480	$10^{18} \text{ lumen-seconds}$	4%

\* The original passenger transport data have been corrected by adding non-reported categories provided by GEA Chapter 9, Kahn Ribeiro et al., 2012.

It is useful to put these rather abstract engineering-type summary estimates of energy service levels into perspective – for example, on a per capita basis for a global population of 6.5 billion in 2005. These illustrative global average levels of energy service provision should not distract from the vast heterogeneity in levels of energy service provision between rich and poor, or between urban and rural populations (see Section 8 below).

*Transport:* The 46 trillion tonne-km and 32 trillion passenger-km translate into a daily average mobility of some 13 km/day/person, and transporting on average 1 tonne/day per capita over a distance of some 20 km.

*Industry:* The structural materials summarized in Table 2.1 translate in absolute terms into close to 2 billion tonnes (Gt) of cement, 1 Gt of crude steel, some 0.3 Gt of fertilizer, 0.1 Gt of non-ferrous metal ores processed, and over 50 million tonnes of plastics produced per year (UN, 2006a, 2006b). Estimates of the global total material flows reveal a staggering magnitude of the industrial metabolism (Krausmann et al., 2009). In terms of tonnage, humankind uses each year (values for 2005) some 12 Gt of fossil energy resources, some 6 Gt of industrial raw materials and metals (ores and minerals), 23 Gt of construction materials (sand, gravel, etc.), and an additional 19 Gt of biomass (food, energy, and materials), for a total material mobilization of approximately 60 Gt/yr, or more than 9 tonnes/yr per capita on average. The use of around 10 Gt of energy thus enables the “leverage” of the mining, processing, refinement, and use of an additional 50 Gt of materials.

*Buildings:* The size of the residential and commercial building stock worldwide (2005 data) whose internal climate needs to be maintained through heating and cooling energy services is estimated to be about 150 billion  $\text{m}^2$  (including some 116 billion  $\text{m}^2$  residential and 37 billion  $\text{m}^2$  commercial floor space, see GEA Chapter 10, Ürges-Vorsatz et al., 2012) which corresponds to approximately 20  $\text{m}^2$  per person on average.

Useful energy as a common energy input denominator minimizes distortions among different energy service categories, as it most closely measures the actual energy service provided. Useful energy estimates based on the 2005 energy balances published by the International Energy Agency (IEA, 2007a and 2007b) using typical final-to-useful conversion efficiencies available in the literature (Eurostat, 1988; Rosen, 1992; Gilli et al., 1996; BMME, 1998; Rosen and Dincer, 2007) have been

developed by Grubler et al., 2012. A similar methodology was also used by De Stercke (2014) in developing a novel data set of useful energy balances for major countries, regions and the world since 1900. It should be noted that the available energy balances are based on an economic sectoral perspective, which does not always perfectly correspond with particular energy service types. For instance, transport energy use is reported by mode of transport (road, rail, sea, air) in the underlying IEA statistics, which does not allow differentiation between passenger and goods transport.

It needs also to be emphasized that different forms of useful energy (such as thermal versus kinetic energy) are not interchangeable, even when they are expressed in a common energy unit and aggregated. Global totals for useful and final energy inputs per energy service category are summarized in Table 2.2 (see also Figure 2.9 below) for the year 2005 and as historical trends in Figures 2.4 and 2.5. Regional details are given in Figures 2.6 and 2.7 below.

Table 2.2. Energy service levels, world in 2005, as estimated by their corresponding useful and final energy inputs (in EJ, and as share of total; see also Footnote 6). Source: final energy: data from IEA, 2007a and 2007b; useful energy: estimates by Grubler et al., 2012.

Energy service	Final energy [EJ]	As percentage of total final energy [%]	Useful energy [EJ]	As percentage of total useful energy [%]
Transport				
Road	66.9	20.3	13.7	8.1
Rail	2.3	0.7	1.1	0.7
Shipping	9.0	2.7	3.0	1.8
Pipelines	2.9	0.9	0.9	0.5
Air	10.3	3.1	3.0	1.8
Total transport	91.4	27.7	21.7	12.9
Industry				
Iron and steel	14.4	4.4	11.5	6.8
Non-ferrous metals	4.0	1.2	1.9	1.1
Non-metallic minerals	11.1	3.4	4.5	2.7
Other	58.7	17.8	44.3	26.3
Total industry	88.2	26.8	62.2	36.9
Other sectors				
Feedstocks	30.2	9.2	25.0	14.8
Agriculture, forestry, fishery	7.5	2.3	3.0	1.8
Residential	81.0	24.6	35.6	21.1
Commercial and other	31.4	9.5	21.0	12.5
Total other sectors	150.1	45.5	84.6	50.2
Grand Total	329.7	100.0	168.5	100.0

The largest category of energy service demands arise in industry (62 EJ of useful energy in 2005), with the dominant energy service application being (high-temperature) industrial process heat associated with the processing, manufacturing, and recycling of materials. Feedstocks refer to non-energy uses of energy, where energy carriers serve as a raw material (e.g., natural gas used for the manufacture of fertilizers), rather than as an input to energy conversion processes proper. Feedstocks are also associated with industrial activities (the chemical sector) and add another 25 EJ of useful energy to the 62 EJ of industrial energy service demands.

The residential and commercial sectors (some 57 EJ of useful energy in 2005) are dominated by the energy use associated with buildings, both in maintaining a comfortable indoor climate (heating and air conditioning), as well as various energy services performed within buildings such as cooking,

hygiene (hot water), and the energy use of appliances used for entertainment (televisions) or communication (computers, telephones). Agriculture, forestry, and fisheries are comparatively minor in terms of useful energy (3 EJ) and are only summarily included in the “other sectors” category here.

Transport is comparatively the smallest energy service category when assessed in terms of useful energy, with an estimated level of 22 EJ (some 13% of total useful energy, but due to low conversion efficiencies, some 28% in total primary energy, see Table 2.1 above). Road transportation (cars, two- and three-wheelers, buses, and trucks) are the dominant technologies for providing mobility of people and goods. Due to the low final-to-useful conversion efficiency associated with internal combustion engines (some 20% only, with 80% lost as waste heat of engines and associated with friction losses of drive trains), road transport accounts for only 8% of useful energy but for approximately 20% of total final energy. This example once more highlights the value of an energy service perspective (Haas et al., 2008) on the energy system, by looking at service outputs rather than final or primary energy inputs that overemphasize the least efficient energy end-use applications. Nonetheless, it needs to be noted that transportation is one of the fastest growing energy demand categories. This adds further emphasis on efforts to improve transport energy efficiency, which has both technological (more efficient vehicles), as well as behavioral and lifestyle dimensions (changing mobility patterns, shifts between different transport modes – e.g., by using public transportation or bicycles instead of private motorized vehicles).

Global trends since 1900 of different energy service categories at the level of useful energy are shown in Figure 2.5 and at the level of final energy in Figure 2.5.

In terms of useful energy, energy service provision for thermal comfort (low-temperature heat) and for transformation of materials and manufacturing of goods (high temperature heat), followed by industrial non-energy uses where energy serves as feedstock dominate the historical growth pattern. Stationary power (mechanical drives, mostly for industry) and mobility are comparatively smaller compared to thermal energy services. Other useful energy uses and illumination (lighting service provision) remain minor useful energy categories globally. Global useful energy demand has grown by almost a factor 30 since 1900 (from 7 EJ in 1900 to 194 EJ in 2010, De Stercke, 2014) or slightly above 3% per year which is much faster than final or primary energy, illustrating the impact of improved efficiency in energy use conversion and the increasing availability of high quality energy carriers.

Due to the different conversion efficiencies between final to useful energy, the relative shares and magnitude of final energy flows per type of demand category (Figure 2.5, following the IEA definition of demand sectors) are different compared to the useful energy perspective illustrated in Figure 2.4. Transport final energy in particular is much higher in terms of final energy compared to useful energy. Globally, final energy use has increased from some 29 EJ in 1900 to some 363 EJ in 2010 (De Stercke 2014), or a factor close to 13 (2.3%/yr annual compound growth rate).

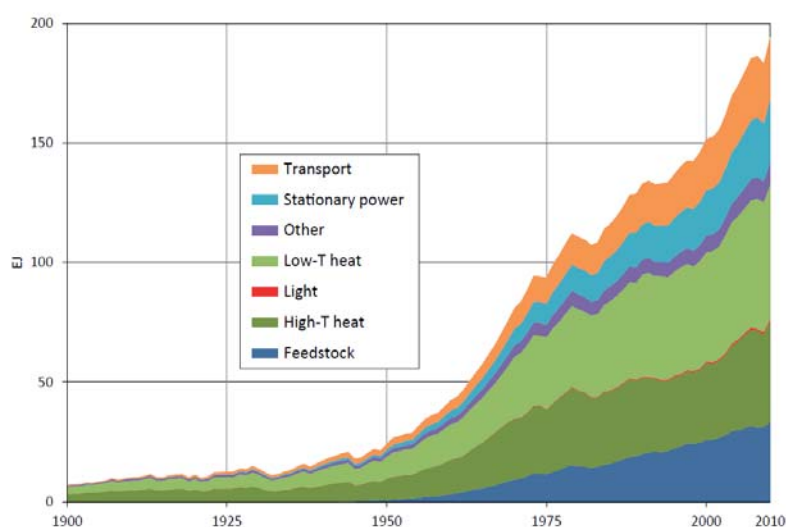


Figure 2.4. Global useful energy demand by type of energy service provision 1900-2010 (in EJ). Source: De Stercke (2014).

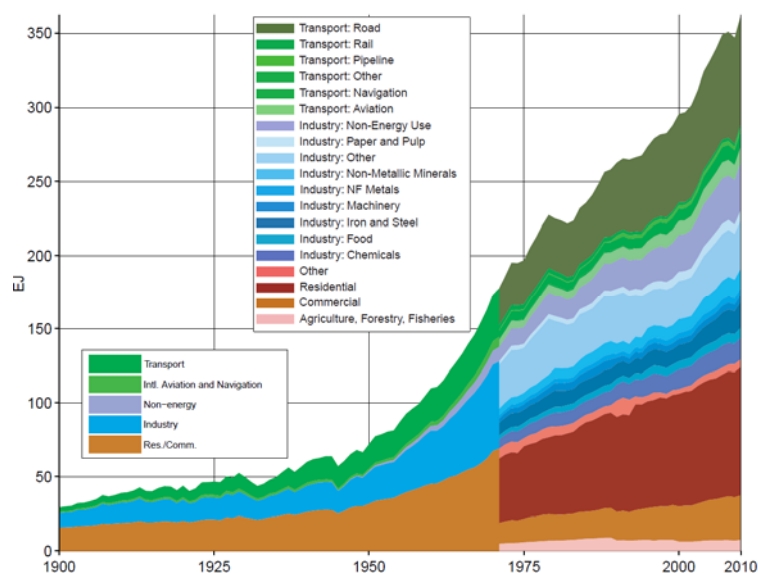


Figure 2.5. Global final energy input for different energy demand categories (in EJ), 1900-1970 from De Stercke (2014), 1971 to 2010 adapted from IEA, 2012.

Figure 2.6 shows the 2005 useful energy needs for major world regions and disaggregated by energy end-use sector. Useful energy instead of final energy gives a better indication of the relative importance of different end uses as closer to the actual energy services delivered and –as discussed above-- less distorted by the different conversion efficiencies across end-use applications.



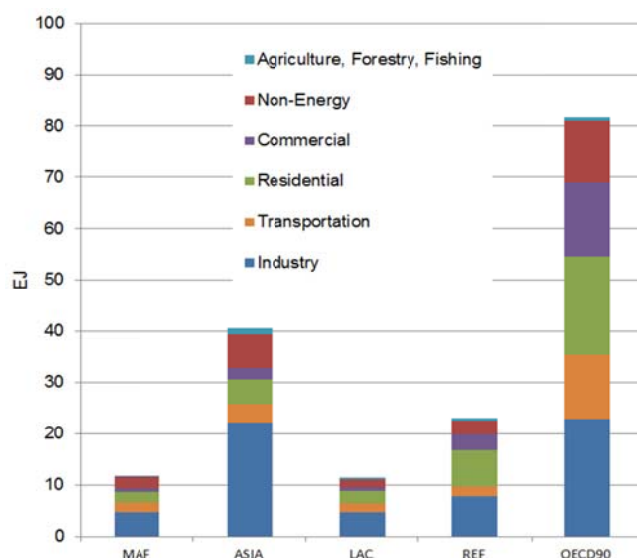


Figure 2.6. Useful energy by major energy end-use sector for five world regions for the year 2005 (in EJ) based on estimates of Grubler et al., 2012. For a definition of regions see Appendix B.

In terms of absolute amounts useful energy demand is highest in the high-income, “old” industrialized countries of the OECD region (in defined in their 1990 membership, OECD90), followed by the rapidly industrializing countries in the ASIA region and the countries in Eastern Europe and the former USSR undergoing economic reform (REF). Conversely, useful energy demand in Latin America (LAC) and the Middle East and Africa remains comparatively small.

The structure of useful energy demand is also markedly different across regions. At the global level, industry’s share is more than a third of all useful energy while in ASIA it was more than half and close to half in the Latin America (LAC) and Middle East and Africa (MAF). In contrast, industry accounted for only about a quarter of all useful energy in the OECD90 region. This illustrates the changing economic structure as a function of the level of economic output and affluence. With its highest per capita GDP, the OECD90 region portrayed the lowest shares of industrial useful energy while the rapidly developing countries in ASIA show the highest industrial shares. The OECD countries import energy-intensive goods and service lowering their domestic useful energy requirements. In contrast, commercial energy use is very high in OECD countries with about 18% and relatively low with some 5% in ASIA. ASIA also has the lowest useful energy use in transport both in term of per capita use as well as share in total useful energy. At the global level, transportation accounts for about 13% of all useful energy, in the OECD countries for about 15%, Latin America about 14%, Middle East and Africa for about 15% while in ASIA it is only about 9%. Mobility and transportation in general are positively correlated with the level of economic development and hence transport energy uses in ASIA can be expected to grow significantly with the rapid economic growth characteristic for the emerging economies of ASIA.

The differences in the economic structure and the related useful energy needs are more apparent in Figure 2.7 where the sectorial useful energy is plotted on a per capita basis (GJ per person). In addition, regions are sorted by their per capita GDP (expressed at purchasing power parities, PPP, see Section 4.4 below). These regional differences in levels and structure of energy demand illustrate the substantial heterogeneity in energy use patterns across the globe that increases with finer spatial (globe, regions, countries), economic, or social differentiation (see Section 8 below).

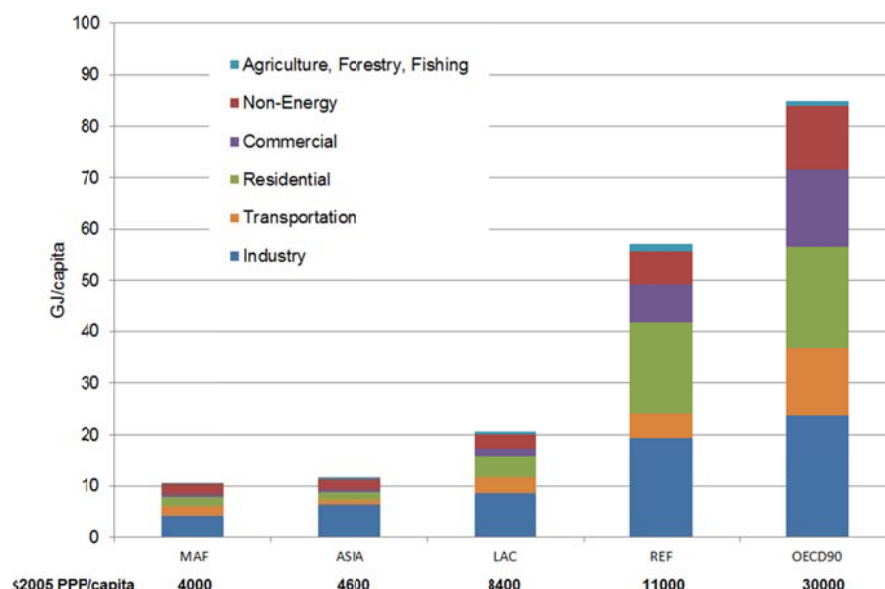


Figure 2.7. Per capita useful energy (GJ) per major energy end use and by major region in 2005, based on estimates of Grubler et al., 2012. Regions are sorted from left to right by their respective per capita income (GDP) levels (in \$2005 expressed at PPP). For a definition of regions see Appendix B.

Per capita useful energy use ranges from 10 to some 85 GJ across the regions while per capita incomes range from 4,000 to \$30,000. With higher incomes, also the useful energy requirements are higher. With increasing per capita GDP there is also a shift away from the dominance of industrial energy uses (more than half of useful energy in Middle East and Africa, ASIA, and Latin America) to less than a third in the OECD countries. Incidentally, this is also accompanied by a reduction in the share of non-energy uses which in turn are very much related with chemical and other industrial processes. With increasing affluence the economic structure shifts toward higher shares of transportation, commercial and residential sectors and corresponding useful energy uses. This is clearly visible for the OECD countries and Reforming Economies (REF) where these three sectors account for about half of all useful energy.

Thus, the structure of energy services and of useful energy use are strongly linked to the level of economic development and the structure of the economies. In so-called “post-industrial” economies, the industrial activities decline as a share of the total economy and useful energy while commercial, residential, and to a lesser extent transport increase along with associated energy services and energy uses. As industrial activities tend to be very energy intensive, this structural change leads to a leveling off of energy demand in many highly-developed economies while the embodied energy in imports increases.

### 2.3 From Energy Services to Primary Energy

Figure 2.8 illustrates the interlinkages of global energy flows from useful energy up to the level of primary energy, and also shows major energy carriers and transformations. Different primary energies require different energy system structures to match the demand for type and quality of energy carriers and energy forms with available resources.

As a result, there is great variation in the degree and type of energy conversions among different fuels in the global energy system. At the one extreme, biomass is largely used in its originally harvested form and burned directly without intervening energy conversions. At the other extreme are nuclear,

hydropower, and modern renewables that are not used in their original resource state but converted into electricity. Electricity is the energy carrier with the highest versatility of providing different energy forms required for various energy services (heat, light, mobility). Crude oil also needs to be converted (refined) to the liquid fuels required for energy end-uses (gasoline, diesel, kerosene, for cars, trucks, and aircraft), or for further secondary energy conversions (e.g., fuel oil-fired power plants generating electricity). Coal is a major input for electricity generation and for specific industrial uses (metallurgy) but is not often used in direct form outside these two applications (remaining uses for residential heating/cooking are declining rapidly due to air pollution concerns). Conversely, natural gas is a major energy carrier directly used as final energy and for end-uses, mainly due to its convenience (grid delivered, no combustion ashes to dispose of) and cleanliness. Natural gas is also increasingly being used in electricity generation, where the advent of highly efficient combined cycle power plants with flat economies of scale (i.e., costs per MW capacity are not significantly different across different plant sizes) allows fast construction of modular units. Due to the low emission characteristics of these highly efficient conversion processes, plants can also often be located in high demand density areas, thus opening up the possibility of using (“recycling”) waste heat from electricity generation for industrial and residential customers, a scheme known as cogeneration or combined heat and power production (CHP).

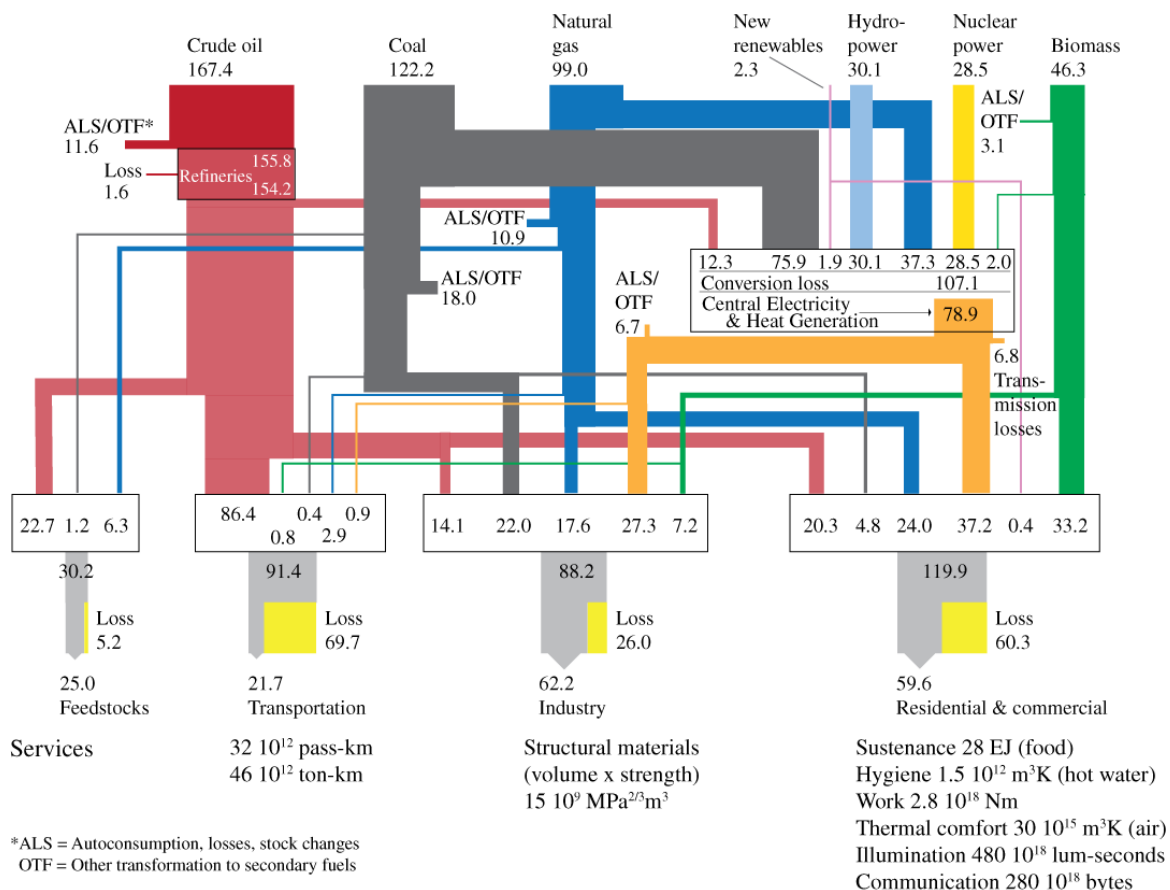


Figure 2.8. Global energy flows (in EJ) from primary to useful energy by primary resource input, energy carriers (fuels) and end-use sector applications in 2005. Source: data from IEA, 2007a; b (corrected for GEA primary energy accounting standard), and Cullen and Allwood, 2010.

From an energy systems perspective, the electricity sector assumes a special role (also the reason why it is discussed in greater depth in Section 6.3 on Energy Conversions below.) Electricity

generation is the energy conversion process that can accommodate the greatest diversity of primary energy inputs. As shown in Figure 2.8, all primary energy carriers enter to different degrees into electricity generation, from biomass, to all fossils, nuclear, hydro, and new renewables. Electricity is also a very specific energy carrier: its absolute cleanliness at the point of end-use (not necessarily at the point of electricity generation, however) and its high energy quality translate into the greatest versatility and flexibility in delivering whatever type of energy form and energy service required.

However, electricity cannot be stored easily, which means that generation needs to follow the inevitable intertemporal variations of electricity demand over the seasons, during the day, even during minute-intervals. This variation in electricity demand over time is enshrined in the concept of *load curves* that describe the instantaneous use of electric power (in Watts or typically rather GW) over time (on a daily, weekly, or monthly basis). A cumulative load curve over all of the 8760 hours of a year, sorted by declining GW load, yields a *load duration curve* (or cumulative load curve) that helps to design a whole electricity system and to dimension different types of power plants used for *peak*, *intermediate*, and *base load* electricity generation.

Overall, there is great variation in energy systems structures across different regions as a result of differences in the degree of economic development, structure of energy demand, and resource availability, among others (see also Section 8 below). These differences are summarized at the level of useful, final, and primary energy respectively for the 5 GEA regions and the world in Figure 2.9.

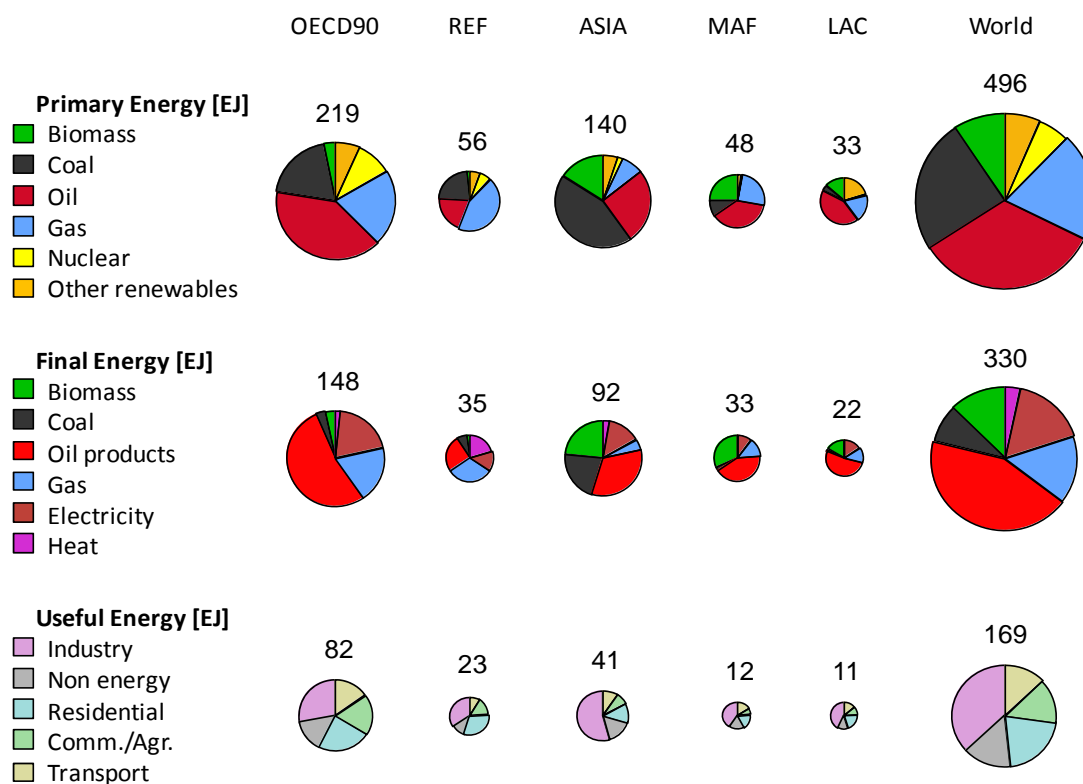


Figure 2.9. World energy use: primary energy (by fuel), final energy (by energy carrier), and useful energy (by sector/type of energy service) for the world and five GEA regions for 2005 (in EJ). Source: based on IEA, 2007a and 2007b (corrected for GEA primary accounting standard) and Grubler et al., 2012. For a definition of the GEA regions, see Appendix B.

### 3 Historic Energy Transitions

#### 3.1 Transitions in Energy End-Use (United Kingdom)

Levels and structure of energy services have changed dramatically since the onset of the Industrial Revolution, reflecting population and income growth and, above all, technological change. Due to the “granular” nature of energy services, the measurement intricacies discussed above, and the traditional focus of energy statistics on (primary) energy supply, it is not possible to describe long-term transition in energy services and energy end-use on the global scale. Long-term detailed national-level analyses are available for the United States (Ayres et al., 2003) and the United Kingdom (Fouquet, 2008), as well as (for shorter time horizons) in the form of useful energy balances for Brazil (BMME, 1998).

The long-term evolution and transitions in energy end-use and energy services is described below for the United Kingdom over a time period of 200 years. The United Kingdom is used as an illustrative example, not only due to the level of detail and time horizon of the original data available, but particularly because of its history of being the pioneer of the Industrial Revolution, which thus illustrates the interplay of industrialization, income growth, and technological change as drivers in energy end-use transitions.

Figure 3.1 illustrates the growth in energy service provision for the United Kingdom since 1800 by expressing the different energy services in terms of their required final energy inputs. Three main periods can be distinguished:

- a regular expansion of energy services in the 19th century that characterized the emergence of the United Kingdom as a leading industrial power, in which growth is dominated by industrial energy service demands and to a lesser degree by rapidly rising transportation services enabled by the introduction of steam-powered railways;
- a period of high volatility as a result of cataclysmic political and economic events (World War I, the Great Depression of 1929, and World War II) that particularly affected industrial production and related energy services; and
- a further (more moderated) growth phase after 1950, again punctuated by periods of volatility, such as the energy crisis of the 1970s (characterized by the gradual decline of industrial energy services, compensated by strong growth in passenger transportation resulting from the diffusion of petroleum-based collective, and individual transport technologies (buses, aircraft, and cars).

At present, levels of energy services appear saturated at a level of above 100 GJ of final energy input equivalent per capita. Industry (with an ever declining share) accounts for about 30% of all energy services, residential applications (with a stable share) for another 30%, and transportation (with an ever growing share) for about 40% of total energy services.



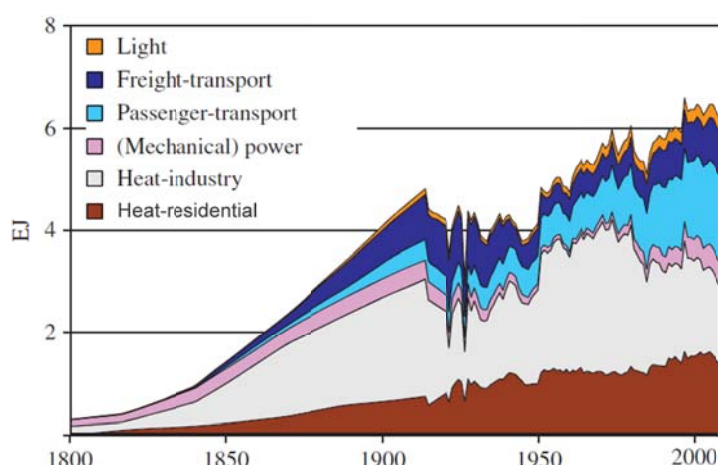


Figure 3.1. Growth in energy service demand (measured by final energy inputs) United Kingdom since 1800, in EJ. Source: data from Fouquet, 2008. Updates after 2000 and data revisions courtesy of Roger Fouquet, Basque Centre for Climate Change, Bilbao, Spain.

Figure 3.2 illustrates the evolution of the determinants of the growth in UK energy services and shows the mutually enhancing developments that led to the spectacular growth in energy services since 1800 (by a factor of 15 when measuring final energy inputs, and much more – perhaps as much as by a factor of 100 – when considering the significant improvements in the efficiency of energy service provision that have ranged between a factor of five for transportation, to up to a factor of 600 for lighting, see Fouquet, 2008). Population growth (from 10 million to 60 million people) and rising incomes (per capita Gross Domestic Product (GDP) has grown from some US\$3000 at 2005 price levels and exchange rates in 1800, to close to US\$40,000 at present) increase both the demand for energy services and the purchasing power of the population to afford traditional, as well as novel energy services. There are both *direct* as well as *indirect* growth effects on energy service demands. A larger population translates into more food to cook, more people needing housing, etc., and a corresponding growth in related energy services. Higher incomes from economic growth imply growth in energy service demand in industrial and commercial activities and related services. This growth in energy service demand is “indirect” in the sense that production-related energy services are embedded in the private consumption of goods and services by private households and public services (schools, hospitals, etc.). Lastly, higher incomes make traditionally expensive energy services (such as air transportation) affordable for larger segments of society, an effect amplified by decreasing prices for energy services resulting from energy efficiency and other technology improvements.

Improvements in the energy efficiency of service provision and other technological improvements in turn are key factors contributing to the significant lowering of energy service prices, which have declined by a factor of under 10 for heating to over 70 for lighting since 1800. In short, more consumers that became more affluent enjoy increasingly energy-efficient and cheaper energy services, which fuels growth in energy service demand (a positive feedback loop in the terminology of systems science). A narrow interpretation of this dynamic process of increasing returns to adoption (e.g., costs of technologies and energy services decline, the higher their market application) as a simple “take-back” (see Section 9 below) effect, represent a static “equilibrium” perspective of energy systems evolution. The history of technological revolutions in energy services and in energy supply suggests rather a “dis-equilibrium” interpretation of major energy transitions: the transformation is so far-reaching that the ultimate future state of the system could have never been reached by incremental

improvements in efficiency and costs of existing technologies and energy services. “Add as many mail-coaches as you please, you will never get a railroad by so doing” (Joseph A. Schumpeter, 1935).

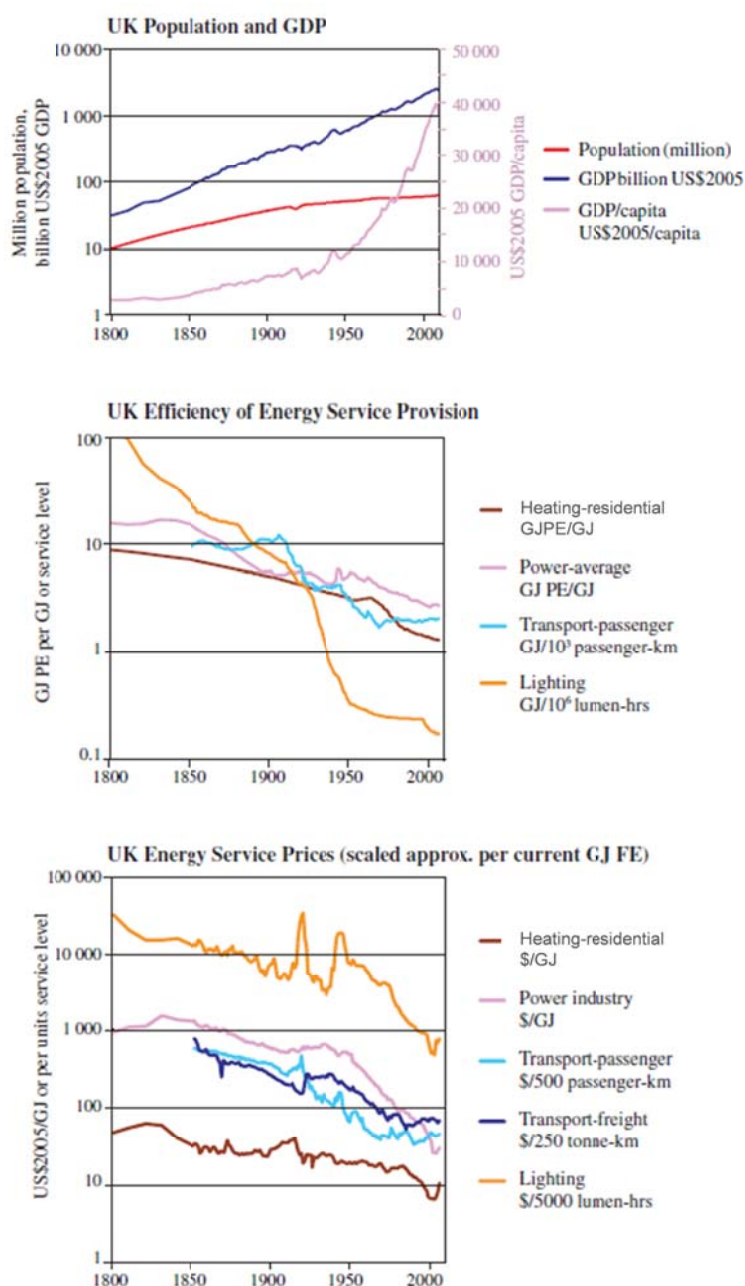


Figure 3.2. Drivers of UK energy service demand growth: population, GDP and income per capita (panel 1); efficiency of energy service provision (per GJ service demand or service activity level – panel 2); and prices of energy services (per GJ service demand or activity level, activity level units have been normalized to approximately equal one GJ of current final energy use – panel 3). Source: data from Fouquet, 2008. Updates after 2000 and data revisions courtesy of Roger Fouquet, Basque Centre for Climate Change, Bilbao, Spain.

### 3.2 Transitions in Energy Supply Systems (Global)

The history of energy transitions is a story of development interlaced with periods of crisis and shortages. The Neolithic revolution brought the first transformational change. Hunters and gatherers settled and turned to agriculture. Their energy system relied on harnessing natural energy flows, animal work, and human physical labor to provide the required energy services in the form of heat, light, and work. Power densities and availability were constrained by site-specific factors, with mechanical energy sources initially limited to draft animals and later to water and windmills. The only form of energy conversion was from chemical energy to heat and light – through burning fuel wood, for example, or tallow candles (Nakicenovic et al., 1998). It is estimated that early agricultural societies were based on annual energy flows of about 10–20 GJ per capita, two-thirds in the form of food for domesticated animals and humans, and the other third in the form of fuel wood and charcoal for cooking, heating, and early industrial activities such as ore smelting (Smil, 2010). China already experienced acute wood and charcoal shortages in the north of the country by the 13th century. In Europe, and particularly in the UK, fuel wood became increasingly scarce and expensive as forests were overexploited without sufficient replanting or other conservation measures (Ponting, 1992).<sup>4</sup>

The fuel crisis was eventually overcome through a radical technological end-use innovation: the steam engine powered by coal. The steam cycle represented the first conversion of fossil energy sources into work; it allowed the provision of energy services to be site-independent, as coal could be transported and stored as needed; and it permitted power densities previously only possible in exceptional locations of abundant hydropower (Smil, 2006). Stationary steam engines were first introduced for lifting water from coal mines, thereby facilitating increased coal production by making deep-mined coal accessible. Later, they provided stationary power for what was to become an entirely new form of organizing production: the factory system. Mobile steam engines, on locomotives and steam ships, enabled the first transport revolution, as railway networks were extended to even the most remote locations and ships were converted from sail to steam. While the Industrial Revolution began in England, it spread throughout Europe, the United States and the world (see Gales et al., 2007, Kander et al., 2008, and Warr et al., 2010).

Characteristic primary energy use levels during the “steam age,” (the mid-19th century in England), were about 100 GJ/yr per capita (Nakicenovic et al., 1998). These levels exceed even the current average global energy use per capita. By the turn of the 20th century, coal had become the dominant source of energy, replacing traditional non-fossil energy sources, and supplied virtually all of the primary energy needs of industrialized countries.

Figure 3.3 shows the exponential growth of global energy use at a rate close to 2%/yr since the advent of the Industrial Revolution. Figure 3.4 is based on the same data and shows relative shares of different primary energy sources. Substitution of traditional energy sources by coal characterized the first phase of the energy revolution – the “steam revolution” – a transformation that lasted until the early 1920s when coal reached its maximal share of close to 50% of primary energy.

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<sup>4</sup> See also Perlin (1989) on the role of wood in the development of civilization. In fact, the first coal uses in the UK date back to Roman times, and coal was already being used for some industrial applications (e.g., brewing beer) before the Industrial Revolution. The absence of new and efficient end-use technologies for coal use (the later steam engine) implied only very limited substitution possibilities of traditional biofuel uses by coal before the advent of the Industrial Revolution. Note also that the fuel wood scarcity did not cause or induce the numerous technological innovations including the steam engine that led to the Industrial Revolution. These were not caused by price escalation associated with an early “fuel wood peak,” but rather resulted from profound transformations in the social and organizational fabric and incentive structures for science and entrepreneurship (see Rosenberg and Birdzell, 1986).

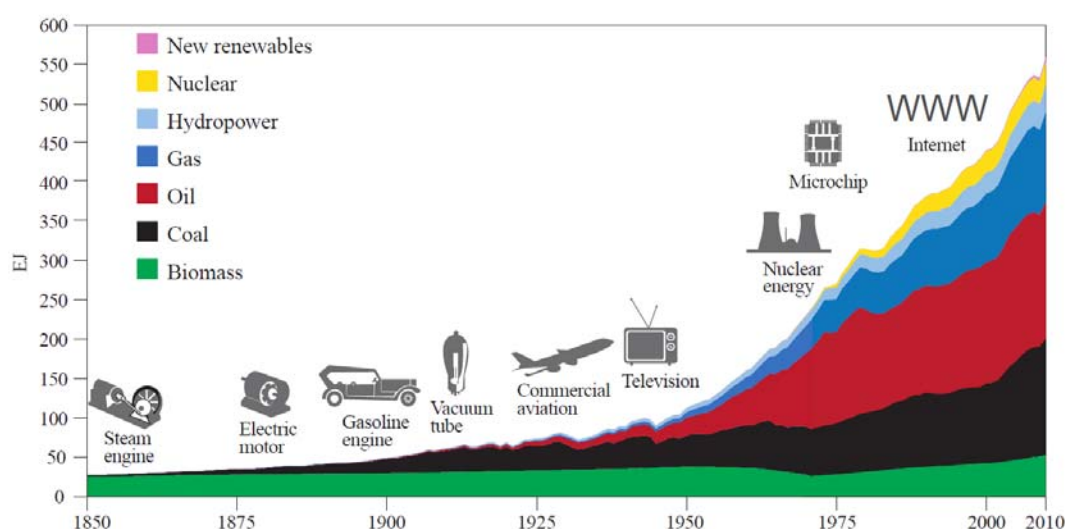


Figure 3.3. History of world primary energy use, by source (in EJ). Source: updated (IEA, 2012, BP, 2014) Grubler et al., 2012.

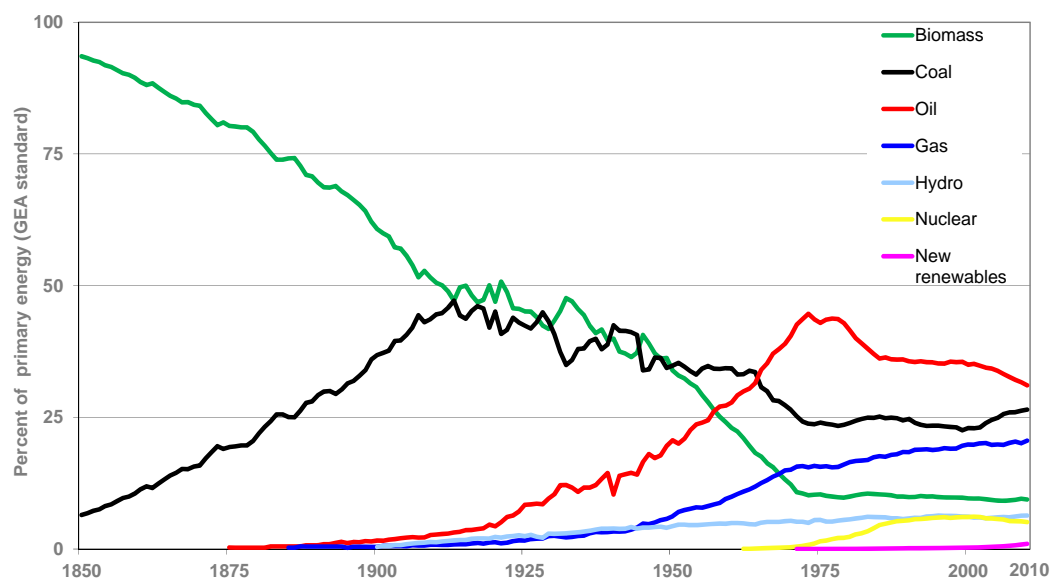


Figure 3.4. Structural change in world primary energy (in percent). Source: Figure 3.3.

The second “grand” energy transformation also lasted for about 70 years. Primary energy demand increased even more rapidly, reaching 5% or even 6% growth annually, from the late 1940s to the early 1970s. This development phase was characterized by increasing diversification of both energy end-use technologies and energy supply sources. Perhaps the most important innovations were the introduction of electricity as an energy carrier which could be easily converted to light, heat, or work at the point of end-use, and of the internal combustion engine, which revolutionized individual and collective mobility through the use of cars, buses, and aircraft (Nakicenovic et al., 1998). Like the transition triggered by the steam engine, this “diversification transformation” was led by technological innovations in energy end-use, such as the electric light bulb, the electric motor, the internal combustion engine, and aircraft,

as well as computers and the Internet, which revolutionized information and communication technologies.

However, changes in energy supply have been equally far-reaching. In particular, oil emerged from its place as an expensive curiosity at the end of the 19th century to occupy the dominant global position, where it has remained for the past 60 years. The expansion of natural gas use and electrification are other examples of important changes in energy supply in the 20th century. The first electricity generation systems were based on the utilization of small-scale hydropower, followed by a rapid expansion of thermal power-generating capacity utilizing coal, oil, and more recently, natural gas. Commercial nuclear power stations were increasingly put into operation in the period from 1970 to 1990. Renewable sources other than hydropower have become more intensively explored for electricity generation since the mid-1970s, with most of the new capacity being added during the past decade.

Despite these fundamental changes in the energy system from supply to energy end-use, the dynamics of energy system transformations have slowed down noticeably since the mid-1970s (Grubler, 2012). Figure 3.4 shows that after oil reached its peak market share of some 40% during the early 1970s, the 1990s and the first decade of the 21st century saw a stabilization of the historical decline in coal's market share, and a significant slowdown in the market growth for natural gas and nuclear. Since 2000, coal has even experienced a resurgence, mostly related to the massive expansion of coal-fired power generation in rapidly developing economies in Asia.

The shift from fuels such as coal with a high carbon content to energy carriers with a lower carbon content such as natural gas, as well as the introduction of near-zero carbon energy sources such as hydropower and nuclear, has resulted in the decarbonization of energy systems (Grubler and Nakicenovic, 1996; Grubler, 2008). Decarbonization refers to the decrease in the specific emissions of carbon dioxide (CO<sub>2</sub>) per unit of energy. Phrased slightly differently, it refers to the decrease in the carbon intensity of primary or any other energy form.

The growth in total emissions can be conveniently decomposed by the following identity (where annual percentage growth rates are additive) covering their main determinants of emissions and their growth: population, income, energy efficiency, and carbon intensity:  $CO_2 = \text{Population} \times \text{GDP/capita} \times \text{Energy/GDP} \times CO_2/\text{Energy}$  (proposed by Ehrlich and Holdren, 1971, and applied for CO<sub>2</sub> by Kaya, 1990). Due to spatial heterogeneity in trends and variable interdependence, caution is advised in interpreting component growth rates of this identity especially at the global level. Decarbonization therefore describes the trends in the carbon intensity of the Kaya identity. (For a discussion of energy intensity trends see Section 4.4 below.)

Figure 3.5 illustrates the historical trend of global decarbonization since 1850 in terms of the average carbon emissions per unit of primary energy (considering all primary energy sources). The dashed line indicates the same trend but excluding biomass CO<sub>2</sub> emissions, assuming they have all been taken up by the biosphere under a sustainable harvesting regime (biomass regrowth absorbing the CO<sub>2</sub> released from biomass burning). Historically, emissions related to land-use changes (deforestation) have far exceeded<sup>5</sup> carbon releases from energy-related biomass burning, which suggests that in the

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<sup>5</sup> Cumulative emissions of fossil fuels between 1800 and 2000 are estimated to have released some 290 GtC (gigatonnes of elemental carbon – to obtain CO<sub>2</sub> multiply by 44/12, yielding 1060 GtCO<sub>2</sub>), compared to land-use-related (deforestation, but excluding energy-related biomass burning) emissions of some 155 GtC. Total cumulative energy-related biomass carbon emissions are estimated at 80 GtC from 1800 to 2000 (all data from Grubler, 2002). Houghton (1999) estimates a net biospheric carbon flux (deforestation plus biomass burning minus vegetation regrowth) over the same time period (net emissions) of 125 GtC, which suggests that only a maximum (attributing –quite unrealistically – all residual net biospheric uptake to fuel wood) of 30 GtC (155 GtC deforestation release minus 125 GtC net biospheric emissions), or a maximum of



past, biomass, like fossil fuels, has also contributed significantly to increases in atmospheric concentrations of CO<sub>2</sub>.

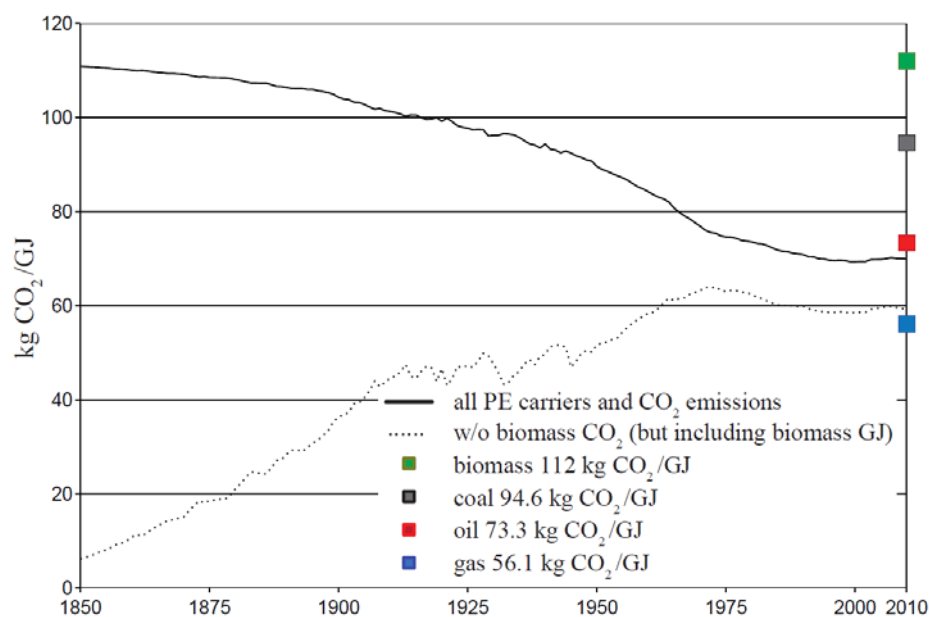


Figure 3.5. Decarbonization of primary energy (PE) use worldwide since 1850 (kg of CO<sub>2</sub> emitted per GJ burned). Note: For comparison, the specific emission factors (OECD/IPCC default emission factors, LHV basis) for biomass (wood fuel), coal, crude oil, and natural gas are also shown (colored squares). See also discussion in text. Source: updated from Grubler and Nakicenovic, 1996 and Grubler et al., 2012.

The global rate of decarbonization has been on average about 0.3% annually, about six times too low to offset the increase in global energy use of some 2% annually. Again, the significant slowing of historical decarbonization trends since the energy crises of the 1970s is noteworthy, particularly due to rising carbon intensities in some developing regions (IEA, 2009), and in general due to the slowed dynamics of the global energy system discussed above.

Decarbonization can be expected to continue over the next several decades as natural gas and non-fossil energy sources increase their share of total primary energy use. Some future scenarios (for a review see Fisher et al., 2007) anticipate a reversal of decarbonization in the long term as more easily accessible sources of conventional oil and gas become exhausted and are replaced by more carbon-intensive alternatives. Others foresee continuing decarbonization because of further shifts to low-carbon energy sources, such as renewables and nuclear energy. Nonetheless, virtually all scenarios foresee some increases in the demand for energy services as the world. Depending on the rate of energy efficiency improvement, this mostly leads to higher primary energy requirements in the future. As long

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38% (30/80) from energy-related biomass burning has been absorbed by the biosphere historically. In the past, biofuel combustion for energy can, therefore, hardly be classified as “carbon neutral.” Evidently, in many countries (at least in Northern latitudes) forests and energy biomass are harvested currently under sustainable management practices that in many cases (avoiding soil carbon releases from changing vegetation cover) will qualify as “carbon neutral.” The extent of current net carbon releases of energy-related biomass burning in developing countries remains unknown.

as decarbonization rates do not significantly accelerate, this means higher carbon emissions compared to historical experience.

### 3.3 Energy and Economic Growth

The relationship between economic growth and energy use is multifaceted and variable over time. The relationship is also two-directional: provision of adequate, high-quality energy services is a necessary (even if insufficient) condition for economic growth. Provision of adequate energy services is insufficient for economic growth in the sense that human (education) and social (functioning institutions and markets) capital as well as technology (innovation) are also important determinants of economic growth (see Barro, 1997). In turn, economic growth increases the demand for energy services and the corresponding upstream energy conversions and resource use.

Figure 3.6 summarizes the long-term history of economic and energy development for a few countries for which such long-term data (since 1800) are available. To separate the impacts of population growth, both economic output (GDP) and (primary) energy use are expressed on a per capita basis. Thereby, the usual temporal dimension of historical comparisons is replaced by an economic development metric in which countries are compared at similar levels of per capita incomes (GDP).

There are two ways of comparing GDP across different national economies depending on which exchange rate is used to convert a given national currency into a commensurable common currency (usually dollar denominated): at market exchange rates (MER) and in terms of purchasing power parities (PPP). The former are based on national accounts and official market (e.g., bank) exchange rates, while the latter are calculated based on relative prices for representative baskets of goods and services across countries denominated in an accounting currency of International\$ (that equals the US\$ in the United States). At present, differences between GDP rates denominated in MER and PPP exchange rates are comparatively minor among industrialized countries, and to simplify the exposition only MER-based GDP values are shown for the UK and Japan (MER and PPP GDPs are identical in the case of the US by definition). However, differences are significant in the case of developing economies (with PPP-based GDPs usually being larger than MER-based GDPs by a factor of two to three due to the much lower domestic price levels in developing countries –and hence the higher purchasing power of their population compared to industrialized ones), and, therefore, both GDP measures are shown in the case of China and India.

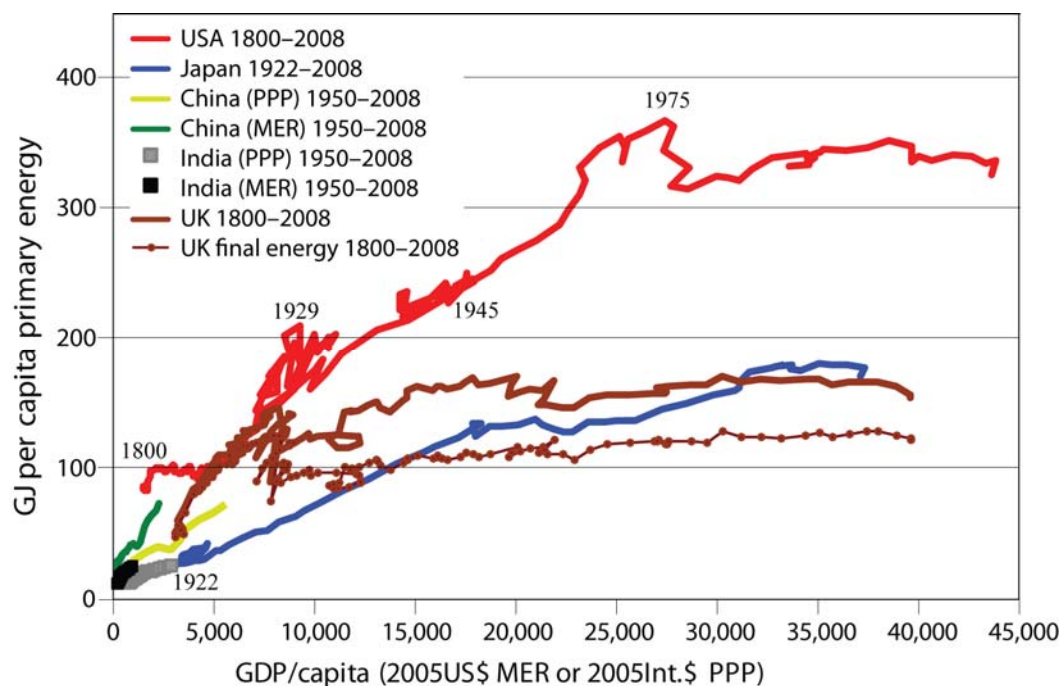


Figure 3.6. Primary energy use (GJ) versus GDP (at market exchange rates (MER) in 2005US\$) per capita. Source: USA, Japan: updated from Grubler, 1998, UK: Fouquet, 2008, India and China: IEA (2010) and World Bank (2010). Note: Data are for the United States (1800–2008), United Kingdom (primary and final 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 2005International\$) are shown.

Three observations help to understand the relationship between economic and energy growth:

- the importance of metrics;
- the overall positive correlation, that is, however, variable over time; and
- the distinctive differences in development paths among different countries and their economies.

First, both the starting points and the growth rates (the slopes of the trend lines shown in Figure 3.6) of economies are dependent on the economic metric chosen for comparing incomes across countries (MER or PPP). For instance, China's and India's GDP per capita in 1970 are estimated to have been approximately US\$170 and US\$250, respectively (in US\$2005), based on MER, and \$700 and \$1000 (in International \$2005), respectively, when based on PPP, which compares to the GDP of the US of approximately US\$1000 (at US\$2005 rates) of 200 years ago, and to that of Japan in 1885 (Based on MER. Using PPP, Japan's GDP per capita in 1885 is estimated to have been well above \$4000 (in 2005International\$).

Thus, developing countries are by no means in a better position for economic “take-off”; they are not comparatively “richer” today than today's industrialized countries were some 100 or even 200 years ago, albeit enjoying unique development opportunities due to new technologies and improved communication and trade flows (Grubler, 2004). This illustrates the time dimension of economic development that entails many decades. Developing countries are today at the beginning of a long uphill development path that will require many decades to unfold and is also likely to include setbacks, as evidenced by the historical record of the industrialized countries. However, overall levels of energy use can be expected to increase as incomes rise in developing countries.

The overall positive correlation between economic and energy growth remains one of the most important “stylized facts” of the energy development literature, even if the extent of this correlation and its patterns over time are highly variable. Although the pattern of energy use growth with economic development is pervasive, there is no unique and universal “law” that specifies an exact relationship between economic growth and energy use over time and across countries. The development trajectory of the US illustrates this point. Over much of the period from 1800 to 1975, per capita energy use in the US grew nearly linearly with rising per capita incomes, punctuated by two major discontinuities: the effects of the Great Depression after 1929, and the effects of World War II (recognizable by the backward-moving “snarls” in the temporal trajectory of both income and energy use per capita shown in Figure 3.6). However, since 1975, per capita energy use has remained remarkably flat despite continuing growth in per capita income, illustrating an increasing decoupling of the two variables as a lasting impact of the so-called “energy crisis” of the early 1970s, an experience shared by many highly industrialized countries. It is also important to recognize significant differences in timing. During the 100 years from 1900 to 2000, Japan witnessed per capita income growth similar to that experienced by the US over 200 years (Grubler, 2004). This illustrates yet another limitation of simple inferences: notwithstanding the overall evident coupling between economic and energy growth, the growth experiences of one country cannot necessarily be used to infer those of another country, neither in terms of speed of economic development, nor in terms of how much growth in energy use such development entails.

Lastly, there is a persistent difference between development trajectories spanning all of the extremes from “high energy intensity” (the US) at one end of the scale to “high energy efficiency” (Japan) at the other (see also the discussion on energy intensities in Section 4.4 below). The relationship between energy and economic growth thus depends on numerous and variable factors. It depends on initial conditions (e.g., as reflected in natural resource endowments and relative price structures) and the historical development paths followed that lead to different settlement patterns, different transport requirements, differences in the structure of the economy, and so on. This twin dependency on initial conditions and the development paths followed to explain differences among systems is referred to as “path dependency” (Arthur, 1989). Path dependency implies considerable inertia in changing development paths, even as conditions prevailing at specific periods in history change – a phenomenon referred to as “lock-in” (Arthur, 1994). Path dependency and lock-in in energy systems arise from differences in initial conditions (e.g., resource availability and other geographical, climatic, economic, social, and institutional factors) that in turn are perpetuated by differences in policy and tax structures, leading to differences in spatial structures, infrastructures, and consumption patterns. These in turn exert an influence on the levels and types of technologies used, both by consumers and within the energy sector, that are costly to change quickly owing to high sunk investment costs, hence the frequent reference to “technological lock-in” (Grubler, 2004).

The concepts of path dependency and technological lock-in help to explain the persistent differences in energy use patterns among countries and regions even at comparable levels of income, especially when there are no apparent signs of convergence. For instance, throughout the whole period of industrialization and at all levels of income, per capita energy use has been lower in Japan than in the US (Grubler, 2004). The critical question for emerging economies such as China and India is, therefore, what development path they will follow in their development and what policy leverages exist to avoid lock-in in energy- and resource-intensive development paths that ultimately will be unsustainable, which puts energy efficiency at the center of the relationship between the economic and energy systems.

## 4 Energy/Exergy Efficiency and Intensity

### 4.1 Introduction

Energy is conserved in every conversion process or device. It can neither be created nor destroyed, but it can be converted from one energy form into another. This is the First Law of Thermodynamics. For example, energy in the form of electricity entering an electric motor results in the desired output – say, kinetic energy of the rotating shaft to do work – and in losses in the form of heat as the undesired by-product caused by electric resistance, magnetic losses, friction, and other imperfections of actual devices. The energy entering a process equals the energy exiting. Energy efficiency is defined as the ratio of the desired (usable) energy output to the energy input. In the electric motor example, this is the ratio of the shaft power to the energy input electricity. Or in the case of natural gas for home heating, energy efficiency is the ratio of heat energy supplied to the home to the energy of the natural gas entering the furnace. This definition of energy efficiency is sometimes called First Law efficiency (Nakicenovic et al., 1996a).

A more efficient provision of energy services not only reduces the amount of primary energy required but, in general, also reduces costs and adverse environmental impacts. Although efficiency is an important determinant of the performance of the energy system, it is not the only one. In the example of a home furnace, other considerations include investment, operating costs, lifetime, peak power, ease of installation and operation, and other technical and economic factors (Nakicenovic et al., 1996a). For entire energy systems, other considerations include regional resource endowments, conversion technologies, geography, information, time, prices, investment finance, age of infrastructure, and know-how.

As an example of energy chain efficiency, Figure 4.1 illustrates the energy flows in the supply chain for illumination services (lighting). In this example, electricity is generated from coal in a thermal power station and transmitted and distributed to the point of end-use, where it is converted to light radiation by means of an incandescent light bulb. Only about 1% of the primary energy is transformed to illumination services provided to the end-user. In absolute terms, the majority of losses occur at the thermal power plant. The conversion of chemically stored energy from the coal into electricity comes along with the production of a significant amount of heat as a by-product of the process – which, if not used, constitutes a large part of the supply chain losses. Idle losses at the point of end-use reflect the amount of time when the light bulb is switched on with the illumination service not being needed at that moment – for example, when the user is temporarily not present in the room. This is very similar to the concept of a “load factor” referring to the capacity utilization of plant and equipment. For instance, in typical commuting situations in industrialized countries there are no more than 1.2 passengers per automobile, which is a lower load factor than for 2-wheelers (bicycles and scooters) in most cities of developing countries.

In this example, abundant opportunities for improving efficiency exist at every link in the energy chain. They include shifting to fuels that allow a higher conversion efficiency (e.g., natural gas) and more efficient conversion, distribution, and end-use technologies (e.g., combined cycle electricity generation, fluorescent or LED lighting technologies), as well as behavioral change at the point of end-use (e.g., reducing idle times). Integration of energy systems is another approach to reduce losses and improve overall system efficiency. An example of such system integration is combined heat and power production, where low temperature residual heat from thermal power production is utilized for space heating, a technique which can raise overall energy efficiency of the power plant up to 90% (Cames et al., 2006). At the point of end-use, idle losses can be reduced through changed user behavior and control technology such as building automation systems that adapt energy services to the actual needs of the user.



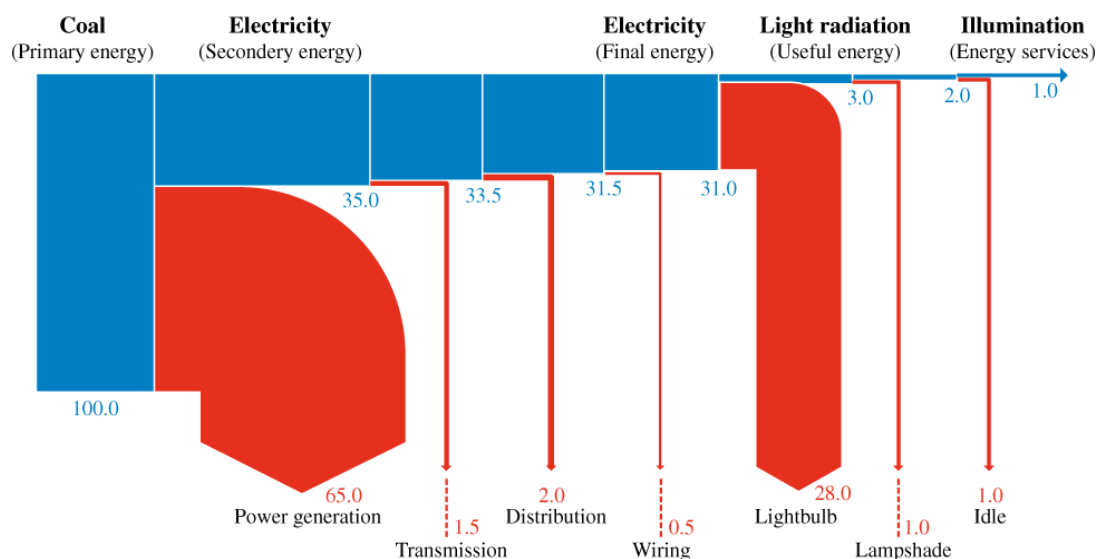


Figure 4.1 Illustrative example of the compound First Law efficiency of an entire energy chain to provide the energy service of illumination. Index: primary energy entering system = 100%.

## 4.2 Energy Efficiencies

In 2005, the global efficiency of converting primary energy sources to final energy forms, including electricity, was about 67% (330 EJ over 496 EJ; see Figure 1.2 above). The efficiency of converting final energy forms into useful energy is lower, with an estimated global average of 51% (169 EJ over 330 EJ; see Figure 2.2 above). The resulting average global efficiency of converting primary energy to useful energy is then the product of the above two efficiencies, or 34%. In other words, about two-thirds of global primary energy use does not end up as useful energy input for providing energy services but is dissipated to the environment in the form of waste heat (or what is colloquially termed energy “losses”).

## 4.3 Exergy Efficiencies

How much energy is needed for a particular energy service? The answer to this question is not so straightforward. It depends on the type and quality of the desired energy service, the type of conversion technology available, the fuel used, including the way the fuel is supplied, and the way how energy services are provided (infrastructures and organizations). Initially, energy efficiency improvements can be achieved in many instances without elaborate analysis through common sense, good housekeeping, and leak-plugging practices. Obviously, energy service efficiencies improve as a result of sealing leaking window frames or the installation of a more efficient furnace. Or if the service is transportation, getting to and from work, for example, using a transit bus jointly with other commuters is more energy-efficient than taking individual automobiles. After the easiest improvements have been made, however, the analysis must go far beyond energy accounting.

While the First Law of Thermodynamics states that energy cannot be destroyed the Second Law of Thermodynamics implies that no process is possible in which the sole result is the absorption of heat and its complete conversion into work. That means that heat and work are not of equal quality, as work can be fully converted into heat while heat cannot, even in the ideal case, be converted fully into work. As both laws are valid for all energy conversion processes, it is therefore not sufficient to consider energy efficiency, i.e., taking only First-Law aspects into account. Instead of energy analysis is a

comprehensive analysis should be based on exergy, since this property takes into account all Laws of thermodynamics.<sup>6</sup>

Here the concept that something may get lost or destroyed in every energy conversion device or transformation process is useful. This “something” is called “availability,” which is the capacity of energy to do work. Often the availability concept is called “exergy”. Exergy is defined as the maximum amount of energy that under given (ambient) thermodynamic conditions can be converted into any other form of energy; it is also known as “availability” or “work potential.” Therefore, exergy defines the minimum theoretical amount of energy required to perform a given task. The ratio of theoretical minimum energy use for a particular task to the actual energy use for the same task is called exergy efficiency (see also Wall, 2006).

Exergy can be defined as the maximum amount of work that can be obtained from a combined system of a considered mass- or energy flow and a reference environment. The reference environment is a model of the real surroundings with which an energy system under consideration could exchange heat and work, without changing its thermodynamic properties (such as temperature, pressure...). It is exactly defined in all physical properties relevant to the performed analysis (such as temperature, pressure und chemical composition).

Exergy takes the First and the Second Law of thermodynamics into account and can be calculated for all energy- and mass flows. In a simplified way, exergy can be explained as a product of energy and energy quality (Jentsch, 2010).<sup>7</sup> While the factor energy indicates that all losses of energy lead to losses of exergy as well, energy quality indicates what share of the considered energy flow can be converted into work in an ideal energy converter.

Exergy analysis has two major advantages over energy analysis: A) It takes into account the different energy quality of the various energy forms and B) it can be applied universally – to all supply chains, energy systems and even to subprocesses. This makes exergy an ideal property for the thermodynamic analysis of energy systems, as effects of both fundamental thermodynamic laws (First and Second Law of Thermodynamics) are taken into account.

The following example should help clarify the difference between energy and exergy. A well-insulated room contains a small container of kerosene surrounded by air. The kerosene is ignited and burns until the container is empty. The net result is a small temperature increase of the air in the room (“enriched” with the combustion products). Assuming no heat leaks from the room, the total quantity of energy in the room has not changed. What has changed, however, is the quality of energy. The initial fuel has a greater potential to perform useful tasks than the resulting slightly warmer air mixture. For example, one could use the fuel to generate electricity or operate a motor vehicle. The scope of a slightly warmed room to perform any useful task other than space conditioning (and so provide thermal

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<sup>6</sup> Strictly speaking there are not two, but four laws of thermodynamics. The Zeroth, First, Second and Third Law of Thermodynamics. The Zeroth Law states that if two systems are in thermal equilibrium with a third system, they must be in thermal equilibrium with each other. This law helps define the notion of temperature. The “Third Law of Thermodynamics states: The entropy of a system approaches a constant value as the temperature approaches zero. This law helps to define entropy. As the exergy definition is based on specific temperature und entropy values it takes not only the commonly known First and Second Laws of Thermodynamics into account but also the lesser known Zeroth and Third Laws of Thermodynamics as well. Therefore there is no single thermodynamic property that allows a more comprehensive analysis than exergy.

<sup>7</sup> Commonly Exergy is described as the useful part of energy. However, the applicability of this notion is limited to heat above the temperature of the environment, electricity and work. Since this explanation cannot be used to explain the exergy of heat below the temperature of the environment (commonly termed: cold) and mechanical exergy of pressurized air, it is better to conceptualize exergy as the product of energy and energy quality – as this approach can be applied universally.

comfort) is very limited. In fact, the initial potential of the fuel or its exergy has been largely destroyed. Although energy is conserved, energy quality and consequently exergy is destroyed in all real-life energy conversion processes. This is what the Second Law of Thermodynamics says.

Since exergy is a thermodynamic property which includes energy, in an ideal case with no destruction of energy quality, exergy is also conserved. Therefore a ratio of useful exergy output to total exergy input cannot exceed 100%. Consequently it is possible to calculate exergy efficiency<sup>8</sup> as the ratio of useful output to used input of exergy.<sup>9</sup>

An example should help clarify the difference between energy and exergy efficiencies. Boilers used to heat buildings are typically 70% to 80% energy efficient, with the latest best-performing condensing boiler operating at energy efficiencies greater than 90%. This may suggest that only minimal energy savings should be possible, considering these high energy efficiencies of boilers. Such a conclusion is incorrect. The quoted efficiency is based on the specific process being used to operate the boiler – combustion of fossil fuel to produce heat. The energy quality of the fuel is 100% and therefore significantly higher than that of the required heat for space heating – with an energy quality of approximately 5% at 4°C reference temperature (Jentsch, 2010). The energy efficiency of 80% gives a misleading impression that only modest improvements are possible. The exergy efficiency of 4% in this case can be expressed as a product of energy efficiency and the ratio of energy quality of useful product and fuel ( $80\% \times 5\%/100\% = 4\%$ ) which says that a 25-fold reduction in final heating energy is theoretically possible by changing technologies and practices. Thus, although significant savings cannot be attained by reducing energy losses to the surroundings there is an improvement potential in terms of matching the energy quality of the source better to the energy quality required by the service. This can be only attained by replacing the fuel-consuming boiler with another technology that is more exergy efficient.

However, in practice, the theoretical maxima of an exergy efficiency of 100% can never be achieved, since exergy destroying effects such as friction and resistance are present in all supply chains. More realistic improvement potentials for energy conversion chains might allow an improvement in the range of 50% exergy efficiency. In addition to further efficiency improvements resource and consequently primary energy consumption of energy *services* can also be decreased by a lower useful energy demand – for instance, in reducing the thermal losses of a heated or air conditioned building to its environment via better insulation of walls and windows that maintains the level of comfort and thus the level of energy service delivered.

It becomes obvious that it is not sufficient to account for energy-in versus energy-out ratios without due regard for the quality difference of demand and source – and thus, the exergy destroyed in the process. Minimum exergy destruction implies an optimal match of energy quality of demand caused by the desired energy services and the supply from the used energy sources.

There are many examples for exergy analysis of individual conversion devices (e.g., losses around a thermal power plant) as well as larger energy systems (cities, countries, the entire globe). This literature is reviewed in detail in Nakicenovic (1996a). Estimates of global and regional

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<sup>8</sup> The calculation of exergy efficiency requires significant attention to the details of definition for input and output flows – as there is potential for significant mistakes. An overview over definitions and rules applicable to exergy analysis can be found in Jentsch, 2010.

<sup>9</sup> In some sources exergy efficiency is also termed “Second Law efficiency”. However, this notion is somewhat misleading as exergy efficiency also takes energy efficiency and therefore “First law efficiency” into account. In order to avoid confusion the term “Second Law efficiency” is not used in this Primer, where we refer to exergy efficiency. Exergy efficiency is sometimes also termed exergetic efficiency.

primary-to-service exergy efficiencies vary typically from about 10% to as low as a few percent (see also Ayres, 1989, Gilli et al., 1996, and Nakicenovic et al., 1996b).

Although exergy destruction can never be totally avoided due to physical limitations such as friction and resistance, the calculation of exergy efficiencies provides a solid foundation to obtain the best energy systems possible. Energy systems with the lowest exergy efficiencies identify those areas with the largest potentials for efficiency improvement. For fossil fuels, this implies the areas that also have the highest emission mitigation potentials. However, the optimization of exergy efficiency is not only a technical task but must also overcome other barriers, such as social behavior, vintage structures, financing of capital costs, lack of information and know-how, and insufficient policy incentives.

The principal advantages of exergy efficiency are that the dimension of energy quality is taken into account and that almost all technologies can be evaluated by exergy efficiency due to the universal applicability of exergy. Often exergy analysis can be usefully extended to also consider derived ratios such as exergy per unit of activity, similar to the case of energy intensity (see Section 4.4 above). Depending on the used balance boundaries, exergy analysis can provide the basis for a just comparison of different technologies and supply chains as well as a means for the clear identification of inefficient process steps. A further advantage of exergy efficiency is that the concept can be transferred to the assessment of energy service provision, which is not possible in energy efficiency calculations. By comparing an actual configuration (a single driver in an inefficient car) with a theoretically ideal situation (a fuel-efficient car with five people in it), respective exergetic service efficiencies while maintaining the same type of energy service (i.e., not assuming commuting by bicycle) can be determined. This is important, especially as the available literature suggests that efficiencies in energy end-uses (in the conversion of final to useful energy and of useful energy to energy services) are particularly low (see Figure 4.2).

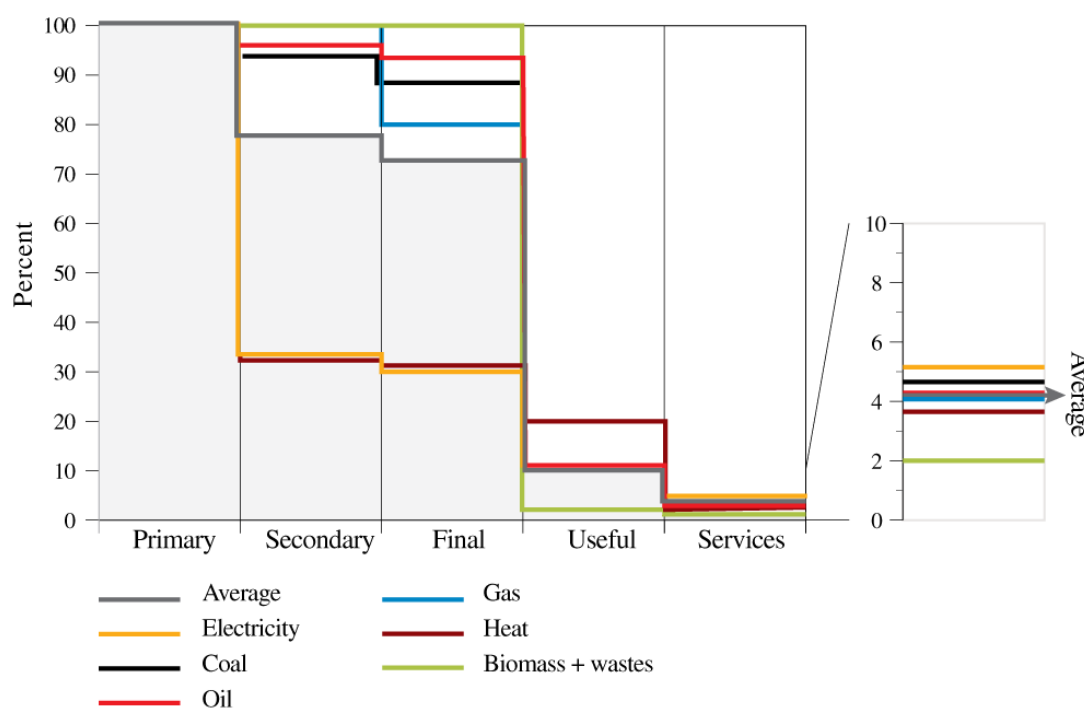


Figure 4.2 Estimated exergy efficiencies (average for OECD countries) from primary exergy (=100%) to useful exergy and to services by energy carrier (fuel). Source: adapted from Nakicenovic, 1993.

## 4.4 Energy Intensities

A related concept to that of energy efficiency is that of energy intensity. Instead of measuring input/output relations in energy terms, as is the case for energy efficiency, energy inputs are divided by a range of appropriate activity indicators that represent the energy service provided (such as tonnes of steel produced, vehicle-km driven, floorspace inhabited, monetary measures of output, number of employees, etc.) to yield energy intensity indicators. Such comparative benchmarking across countries, industries, or products, yields valuable insights into potentials for efficiency improvements related to various activities (comparing current intensities to best practice), and is applied widely in the corresponding energy efficiency improvement and greenhouse gas (GHG) mitigation literature (see Fisher et al., 2007; and the GEA end-use Chapters 8, 9, and 10, Banerjee et.al., 2012; Kahn Ribeiro et. al., 2012; Ürge-Vorsatz et.al., 2012). Extending this concept to entire energy systems and economies yields a widely used indicator of energy intensity, per unit of economic activity (GDP, which is the monetary quantification of all goods and services consumed in an economy in a given year subject to market transactions. Recall here that GDP – like energy- is a *flow* variable and, therefore, does not measure wealth or welfare which are *stock* variables.).

This parsimonious indicator is appealing because of its relative simplicity (usually a single number) and seeming ease of comparability across time and across different systems (global and/or national economies, regions, cities, etc.). However, its simplicity comes at a price. First, the indicator is affected by a number of important measurement and definitional issues (see the discussion below). Second, the underlying factors for explaining differences in absolute levels of energy intensities across economies and their evolution over time requires detailed, further in-depth analysis using a range of additional explanatory variables. They cannot be distilled from an aggregate indicator such as energy intensity of the national or global GDP.

The literature on energy intensities, their trends, and drivers is vast (for useful introductory texts see, e.g., Schipper and Meyers, 1992; Nakicenovic et al., 1996a; Greening et al., 1997; Schäfer, 2005; Bakshi and Green, 2007; Gales et al., 2007). Apart from definitional, accounting, and measurement conventions, differences in energy intensities have been explained by a set of interrelated variables including demographics (size, composition, and densities – e.g., urban versus rural population), economics (size and structure of economic activities/sectors – e.g., the relative importance of energy-intensive industries versus energy-extensive services in an economy; per capita income levels), technology and capital vintages (age and efficiency of the production processes, transport vehicles, housing stock, etc.), geography and climate, energy prices and taxes, lifestyles, and policies, just to name the major categories.

In terms of energy and economic accounting, energy intensities are affected by considerable variation depending on which particular accounting convention is used (and which is often not disclosed prominently in the reporting reference). For energy, the largest determining factors are whether primary or final energy is used in the calculations, and if non-commercial (traditional biomass or agricultural residues, which are of particular importance in developing countries) are included or not. Another important determinant is which accounting method is used for measuring primary energy (see Appendix A). For GDP, the largest difference in energy intensity indicators is the conversion rate used for expressing a unit of national currency in terms of an internationally comparable currency unit based on either MER or PPP exchange rates (see the discussion in Section 3.3 above).

Figure 4.3 illustrates some of the differences in the evolution of historical primary energy intensity for four major economies in the world: China, India, Japan, and the United States. It shows a number of different ways of measuring energy intensity of GDP. The first example can be best illustrated for the US (where there is no difference between the MER and PPP GDP measure by definition).



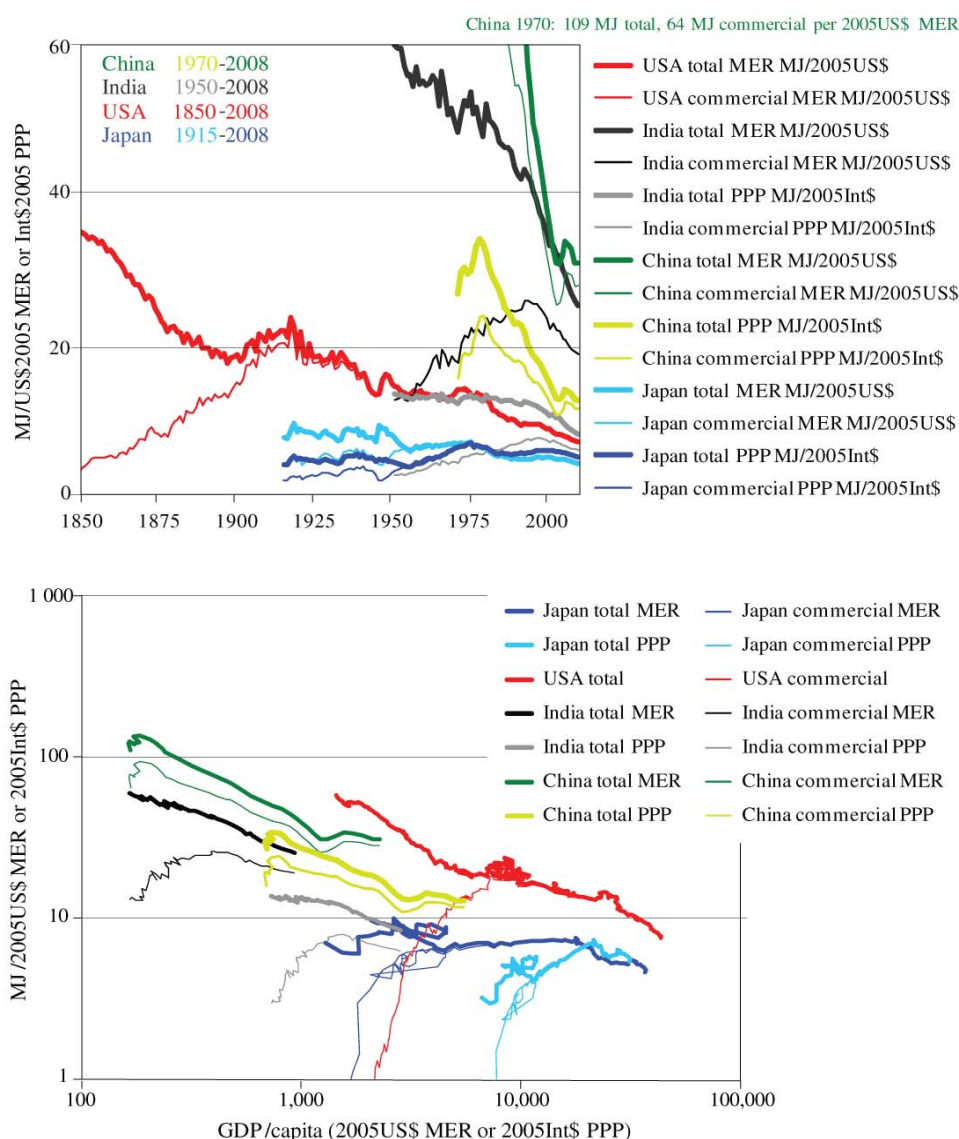


Figure 4.3. Energy intensity improvements over time (top) and against per capita income (bottom) US (1800–2008), Japan (1885–2008), India (1950–2008), and China (1970–2008). Source: see Figure 3.6. Note: Energy intensities (in MJ per \$) are always shown for total primary energy (bold lines) and commercial primary energy only (thin lines) and per unit of GDP expressed at market exchange rates (MER in 2005US\$) and for China, India, and Japan also at purchasing power parities (PPP in 2005International\$). For the United States, MER and PPP are identical.

The (thin red) curve shows the commercial energy intensity. Commercial energy intensities increase during the early phases of industrialization, as traditional and less efficient energy forms are replaced by commercial energy. When this process is completed, commercial energy intensity peaks and proceeds to decline. This phenomenon is sometimes called the “hill of energy intensity.” Reddy and Goldemberg (1990) and many others have observed that the successive peaks in the procession of countries achieving this transition are ever lower, indicating a possible catch-up effect and promising further energy intensity reductions in developing countries that still have to reach the peak. In the US,



for example, the peak of commercial energy intensity occurred during the 1910s and was higher than Japan's subsequent peak, which occurred in the 1970s (Nakicenovic et al., 1998). More important than this "hill" in commercial energy intensities is, however, a pervasive trends toward overall lower total energy (including also non-commercial energy) intensities over time and across all countries.

Figure 4.3 also shows energy intensities for China and India for two alternative measures of converting national GDP to an internationally comparable level: using MER or PPP exchange rates. In the cases of India and China, MER energy intensities are very high, resembling the energy intensities of the now industrialized countries more than 100 years ago (Nakicenovic et al., 1998). This gives the appearance of very low energy efficiency in producing a unit of economic output in China and India, and by implication in other emerging and developing countries. However, China and India's PPP-measured GDPs are much higher than official MER-based GDPs suggest (and resulting PPP-based energy intensities much lower) due to generally much lower prices in the two countries compared to industrialized countries. This translates into a more favorable PPP exchange rate of the local currency compared to MER (often by a factor of two to three). Consequently, with the same dollar amount, a consumer can purchase more goods and services in developing countries than in more industrialized countries. PPP-measured energy intensities are thus generally much lower for developing countries, indicating substantially higher energy efficiencies in these countries than would be calculated using MER.

The substantially lower energy intensity of GDP when expressed in terms of PPP rather than MER should be contrasted with the much lower energy intensity improvement rates in terms of PPP compared to energy intensities based on MER. The differences can indeed be substantial. In 2005 the energy intensity in China was about 33 MJ/US\$2005 for MER, with an average historical reduction rate of 3.3%/yr since 1971, compared with about 14 MJ per 2005 International\$ for PPP for the same year and an improvement rate of 1.9%/yr. Since 1971, China's per capita GDP in terms of MER has grown by some 7%/yr, whereas the estimated per capita GDP in PPP terms has grown by some 5%/yr, compared to a growth rate of per capita primary energy use of some 3%/yr (from 20 GJ in 1971 to 57 GJ in 2005 and 71 GJ in 2008). Therefore, caution is needed when interpreting the apparent rapid energy intensity improvements, measured by MER-based GDPs, which are reported for some countries. In theory, as countries develop and their domestic prices converge toward international levels, the difference between the two GDP measures largely disappears (see the case of Japan in Figure 4.3).

Adding traditional (non-commercial) energy<sup>10</sup> to commercial energy reflects total primary energy requirements and yields a better and more powerful measure of overall energy intensity. Total energy intensities generally decline for all four countries in Figure 4.3. There are exceptions, including periods of increasing energy intensity that can last for a decade or two. This was the case for the US around 1900 and China during the early 1970s. Recently, energy intensities are (temporarily) increasing in the economies in transition, due to economic slowdown and depression (declining per capita GDP). In the long run, however, the development is toward lower energy intensities. Data for countries with long-term statistical records show improvements in total energy intensities by more than a factor of five since 1800, corresponding to an average decline of total energy intensities of about 1%/yr (Gilli et al., 1990; Nakicenovic et al., 1998; Fouquet, 2008). Improvement rates can be much faster, as illustrated in the case of China discussed above (2–3%/yr for PPP- and MER-based energy intensities, respectively). Energy intensities in India have improved by 0.8%/yr (PPP-based) to 1.5%/yr (MER-based) over the

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<sup>10</sup> Traditional biomass fuels are often collected by end-users themselves and thus not exchanged via formal market transactions. Their collection costs in terms of effort and time can be substantial but are not reflected in official GDP estimates. (see Section 9.5 below).

period from 1970 to 2005. The much higher improvement rates of China compared to India reflects both a less favorable (less energy-efficient) starting point as well as much faster GDP per capita growth in China than in India. Faster economic growth leads to a faster turnover of the capital stock of an economy, thus offering more opportunities to switch to more energy-efficient technologies. The reverse side also applies, as discussed above for the economies in transition (Eastern Europe and the former Soviet Union): with declining GDP, energy intensities deteriorate – i.e., increase rather than decline.

It is also useful to look at long-term energy intensity trends using a more appropriate “development” metric than a simple calendar year. Even if in many aspects not perfect, income per capita can serve as a useful proxy for the degree of economic development. From this perspective, the vast differences in energy intensities between industrialized and developing countries are development gaps rather than inefficiencies in developing economies. For similar levels of income, energy intensities of developing countries are generally in line with the levels that prevailed in industrialized countries about a century ago, when these had similar low income levels (see lower graph, Figure 4.3).

However, such a perspective also reveals more clearly distinctive differences in development patterns spanning all the extremes between “high intensity” (e.g., the US) and “high efficiency” (e.g., Japan). The United States has had at all times significantly higher energy intensities than other countries, reflecting its unique condition of originally prevailing resource abundance,<sup>11</sup> coupled with a vast territory, and a comparative labor shortage that led to early mechanization and the corresponding substitution of human and animal labor by mechanical energy powered by (cheap) fossil fuels (David and Wright, 1996). The concepts of path dependency and lock-in (introduced above) describe these differences in development patterns and trajectories. Current systems are deeply rooted in their past development history. Initial conditions and incentives in place (such as relative prices) structure development in a particular direction, which is perpetuated (path dependent), ultimately leading to lock-in – i.e., the resistance to change of existing systems (due to, e.g., settlement patterns, industrial structure, lifestyles). From this perspective, a rapid convergence of levels of energy intensity and efficiency across all countries would indeed be a formidable challenge, notwithstanding that all systems can improve their energy intensities toward an “endless” innovation “frontier” in energy efficiency.

Energy intensity improvements can continue for a long time to come. As discussed above, the theoretical potential for energy efficiency and intensity improvements is very large; current energy systems are nowhere close to the maximum levels suggested by the Second Law of Thermodynamics. Although the full realization of this potential is impossible, many estimates reflecting the potential of new technologies and opportunities for energy systems integration indicate that the improvement potential might be large indeed – an improvement by a factor of ten or more could be possible in the very long run (see Ayres, 1989; Gilli et al., 1990; Nakicenovic, 1993; 1998; Wall, 2006). Thus, reductions in energy intensity can be viewed as an endowment, much like other natural resources, that needs to be discovered and applied.

## 5 Energy Resources

### 5.1 Introduction

Energy resources – or rather occurrences – are the stocks (e.g., oil, coal, uranium) and flows (e.g., wind, sunshine, falling water) of energy offered by nature. Stocks, by definition, are exhaustible, and any

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<sup>11</sup> A similar case can be found in the development history of the former Soviet Union, whose long-term economic data are, however, too uncertain for cross-country comparisons of energy intensity.

resource consumption will reduce the size of the concerned stock. Flows, in turn, are indefinitely available as long as their utilization does not exceed the rate at which nature provides them. While the concept of stocks and flows is simple and thus intriguing, it quickly becomes complex and confusing once one is tasked with their quantification (the size of the “barrel”) or recoverability (“the size and placement of the tap”). Crucial questions relate to the definition and characterization of, say, hydrocarbons in terms of chemical composition, concentration of geological occurrence, investment in exploration, or technology for extraction. Just by accounting for lowest concentration occurrences or lowest-density flow rates, stocks and flows assume enormous quantities. However, these have little relevance for an appreciation of which parts of the stocks and flows may be or become practically accessible for meeting societies’ energy service needs. Private- and public-sector energy resource assessments, therefore, distinguish between reserves and resources, while occurrences are usually ignored for reasons of lack of technical producibility or economic attractiveness. Put differently, what is the benefit of knowing the size of the barrel when no suitable tap is available?

Despite being used for decades, the terms energy reserves and resources are not universally defined and thus poorly understood. There are many methodological issues, and there is no consensus on how to compare reserves and resources across different categories fairly. A variety of terms are used to describe energy reserves and resources, and different authors and institutions have different meanings for the same terms depending on their different purpose.

The World Energy Council (WEC, 1998) defined resources as “the occurrences of material in recognizable form.” For oil, it is essentially the amount of oil in the ground. Reserves represent a portion of resources and is the term used by the extraction industry. Reserves are the amount currently technologically and economically recoverable (WEC, 2007). Resources are detected quantities that cannot be profitably recovered with current technology but might be recoverable in the future, as well as those quantities that are geologically possible but yet to be found. Occurrences include both reserves and resources as well as all additional quantities estimated to exist in the Earth’s crust.

BP (2010a) notes that “proven reserves of oil are generally taken to be those quantities that geological and engineering information indicate with reasonable certainty, which can be recovered in the future from known reservoirs under existing economic and operating conditions.” Other common terms include probable reserves, indicated reserves, and inferred reserves – that is, hydrocarbon occurrences that do not meet the criteria of proven reserves. Undiscovered resources are what remain and, by definition, one can only speculate on their existence. Ultimately recoverable resources are the sum of identified reserves and the possibly recoverable fraction of undiscovered resources, and generally include production to date.

Then there is the difference between conventional and unconventional resources (e.g., oil shale, tar sands, coal-bed methane, methane clathrates (hydrates), uranium in black shale or dissolved in sea water). In essence, unconventional resources are occurrences in lower concentrations, different geological settings, or different chemical compositions than conventional resources. Again, unconventional resource categories lack a standard definition, which adds greatly to misunderstandings. As the name suggests, unconventional resources generally cannot be extracted with technology and processes used for conventional oil, gas, or uranium. They require different logistics and cost profiles and pose different environmental challenges. Their future accessibility is, therefore, a question of technological development – i.e., the rate at which unconventional resources can be converted into conventional reserves (notwithstanding demand and relative costs). In short, the boundary between conventional and unconventional resources is in permanent flux. Occurrences are in principle affected by the same dynamics, albeit over a much more speculative and long-term time scale. Technologies that may turn them into potential resources are currently not in sight, and resource classification systems,

therefore, separate them from resources (often considering occurrences as speculative quantities that may not become technologically recoverable over the next 50 years).

In short, energy resources and their potential producibility cannot be characterized by a simple measure or single numbers. They comprise quantities along a continuum in at least three, interrelated, dimensions: geological knowledge, economics, and technology. McKelvey (1967) proposed a commonly used diagram with a matrix structure for the classification along two dimensions (Figure 5.1): decreasing geological certainty of occurrence and decreasing techno-economic recoverability (Nakicenovic et al., 1996a). The geological knowledge dimension is divided into identified and undiscovered resources. Identified resources are deposits that have known location, grade, quality, and quantity, or that can be estimated from geological evidence. Identified resources are further subdivided into demonstrated (measured plus indicated) and inferred resources to reflect varying degrees of geological assurance. The techno-economic dimension accounts for the feasibility of technical recoverability and economic viability of bringing the resource to the market place. Reserves are identified resources that are economically recoverable at the time of assessment (see the BP definition above).

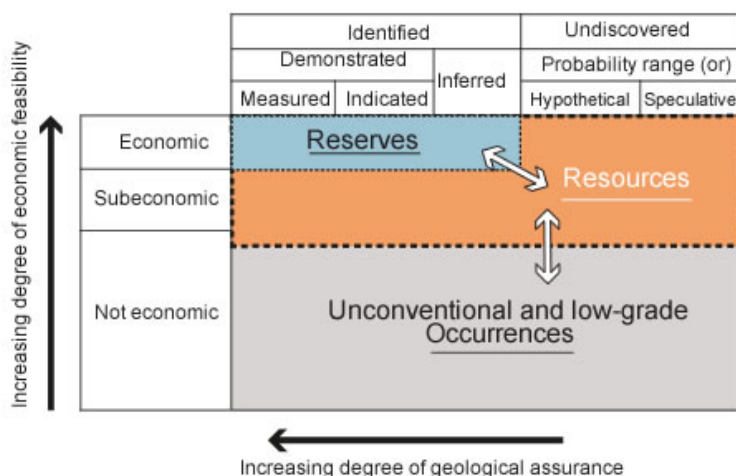


Figure 5.1. Principles of resource classification, illustrating the definition of the three fundamental concepts: reserves, resources, and occurrences. Source: adapted from McKelvey, 1967.

Undiscovered resources are quantities expected or postulated to exist under analogous geological conditions. Other occurrences are materials that are too low-grade, or for other reasons not considered technically or economically extractable. For the most part, unconventional resources are included in other occurrences.

Reserve and resource estimations, as well as their production costs, are subject to continuous revision for several reasons. Production inevitably depletes reserves and eventually exhausts deposits, while successful exploration and prospecting adds new reserves and resources. Price increases and production cost reductions expand reserves by moving resources into the reserve category and vice versa. Technology is the most important force in this process. Technological improvements are continuously pushing resources into the reserve category by advancing knowledge and lowering extraction costs. The outer boundary of resources and the interface to other occurrences is less clearly defined and often subject to a much wider margin of interpretation and judgment. Other occurrences are not considered to have economic potential at the time of classification. Yet over the very long term,

technological progress may upgrade significant portions of occurrences to resources and later to reserves (Rogner et al., 2000).

In contrast, long-term supply, given sufficient demand, is a question of the replenishment of known reserves with new ones presently either unknown, not delineated, or from known deposits presently not producible or accessible for techno-economic reasons (Rogner, 1997; Rogner et al., 2000). Here the development and application of advanced exploration and production technologies are essential prerequisites for the long-term resource availability. In essence, sufficient long-term supply is a function of investment in research and development (exploration and new production methods) and in extraction capacity, with demand prospects and competitive markets as the principal drivers.

For renewable energy sources, the concepts of reserves, resources, and occurrences need to be modified, as renewables represent (in principle) annual energy flows that, if harvested without disturbing nature's equilibria, are available sustainably and indefinitely. In this context, the total natural flows of solar, wind, hydro, geothermal energy, and grown biomass are referred to as theoretical potentials and are analogous to fossil occurrences. For resources, the concept of technical potentials is used as a proxy. The distinction between technical and theoretical potentials thus reflects the possible degree of use determined by thermodynamic, geographical, technological, or social limitations without consideration of economic feasibility.

Economic potentials then correspond to reserves – i.e., the portion of the technical potential that could be used cost-effectively with current technology and costs of production. Future innovation and technology change expand the techno-economic frontier further into the previously technical potential. For renewables, the technical and economic resource potentials are defined by the techno-economic performance characteristics, social acceptance, and environmental compatibility of the respective conversion technology – for instance, solar panels or wind converters. Like hydrocarbon reserves and resources, economic and technical renewable potentials are dynamically moving targets in response to market conditions, demand, availability of technology, and overall performance. Conversion technologies, however, are not considered in this discussion on resources. Consequently, no reserve equivalent (or economic potential) is given here for renewable resources. Rather, the deployment ranges resulting from the GEA pathways (scenarios<sup>12</sup>) are compared with their annual flows.

## 5.2 Fossil and Fissile Resources

Occurrences of hydrocarbons and fissile materials in the earth's crust are plentiful – yet they are finite. The extent of the ultimately recoverable oil, natural gas, coal, or uranium has been subject to numerous reviews, and still there is a large range in the literature – for example, for conventional oil between 5500 EJ and 13,700 EJ – a range that sustains continued debate and controversy. The large range is the result of varying boundaries of what is included in the analysis of a finite stock of an exhaustible resource – for example, conventional oil only, or conventional oil plus unconventional occurrences such as oil shale, tar sands, and extra heavy oils. Likewise, uranium resources are a function of the level of uranium ore concentrations in the source rocks considered technically and economically extractable over the long run.

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<sup>12</sup> See GEA Chapter 17, Riahi et al., 2012. The GEA pathways are normative scenarios that illustrate possible transition pathways towards a more sustainable future in which a number of policy objectives are simultaneously fulfilled including achieving universal energy access, drastic reductions in energy-related human health impacts and air pollution, improved energy security, as well as limiting climate change to below 2°C above pre-industrial levels. As a result the scenarios draw only to a limited extent on the fossil resource endowment and utilize increasingly renewable resources.



Table 5.1 summarizes the global fossil and fissile reserves, resources, and occurrences identified in the GEA and contrasts these with the cumulative resource use (2005–2100) in the GEA pathways (see GEA Chapter 17, Riahi et al., 2012).

At the low end, cumulative global oil production in GEA pathways amounts to little more than total historical oil production up to 2005 – a sign of oil approaching peak production but also of a continued future for the oil industry. At the high end, future cumulative oil production is about 60% higher than past production without tapping unconventional oil in significant quantities.

The ultimate constraint on fossil fuel resources will however not be how much we can extract from nature, but how much resulting CO<sub>2</sub> from fossil fuel combustion is tolerable from the perspective of limiting climate change “below dangerous levels”. Table 5.2 replicates the information from Table 5.1, but in terms of corresponding carbon flows and stocks (in GtC, i.e., billion tonnes elemental carbon - to obtain CO<sub>2</sub> multiply by 44/12)

Table 5.1. Fossil and uranium reserves, resources and occurrences (in ZJ, 10<sup>21</sup> J). Source: GEA Chapter 7, Rogner et al., 2012.<sup>a)</sup>

	Historical production through 2005	Production 2005	Cumulative extraction GEA scenarios 2005 - 2100	Reserves	Resources	Additional Occurrences
	[ZJ]	[ZJ]	[ZJ]	[ZJ]	[ZJ]	[ZJ]
Conventional oil	6.1	0.15	7 - 10	5 - 8	4 - 6	
Unconventional oil	0.5	0.02	0 - 0.5	4 - 6	11 - 15	>40
Conventional gas	3.1	0.09	8 - 12	5 - 7	7 - 9	
Unconventional gas	0.1	0.01	0.2 - 9	20 - 67	40 - 122	>1,000
Coal <sup>(b)</sup>	6.7	0.12	3 - 17	17 - 21	291 - 435	>140
Conventional uranium <sup>(c)</sup>	1.2	0.02	2 - 29	2	7	> 2,600
Unconventional uranium <sup>(d)</sup>	n.a.					

<sup>a)</sup> The data reflect the ranges found in the literature; the distinction between reserves and resources is based on current (exploration and production) technology and market conditions. Resource data are not cumulative and do not include reserves.

<sup>b)</sup> Additional occurrences of coal were not assessed in GEA Chapter 7, Rogner et al., 2012, estimates given are from Nakicenovic et al., 1996a.

<sup>c)</sup> Reserves, resources, and occurrences of uranium are based on a once-through fuel cycle operation. Closed fuel cycles and breeding technology would increase the uranium reserve and resource dimensions 50–60 fold. Thorium-based fuel cycles would enlarge the fissile-resource base further.

<sup>d)</sup> Unconventional uranium occurrences include uranium dissolved in seawater



Table 5.2. Fossil resources (from Table 5.1) in terms of carbon flows, in GtC.

	Historical production through 2005	Production 2005	Reserves	Resources	Additional Occurrences
	[GtC]	[GtC]	[GtC]	[GtC]	[GtC]
Conventional oil	121	3.0	100 - 160	80 - 120	
Unconventional oil	10	8	8 - 120	220 - 300	>800
Conventional gas	47	1.4	77 - 107	107 - 138	
Unconventional gas	2	0.2	306 – 1,025	612 – 1,867	>15,000
Coal	173	3.2	439 - 542	7,508 – 11,223	>3,600
Total	354	8.1	930 – 1,954	8527-13,648	>19,000

Fossil fuel reserves, i.e., currently economically and technologically recoverable quantities range between 1,000 to 2,000 GtC, resources in the order of magnitude of 10,000 GtC and additional occurrences up to 20,000 GtC. These vast carbon “endowments” can be compared to the current atmospheric CO<sub>2</sub> content of some 850 GtC. The Intergovernmental Panel on Climate Change in its 5<sup>th</sup> Assessment Report estimates that in order to limit climate change below a 2°C target, the remaining carbon budget<sup>13</sup> in terms of future emissions would have to stay below a range of 300 to maximum 1,000 GtC, i.e., even below currently recoverable fossil fuel reserves, not to mention resources or occurrences. (The IPCC range reflects different probabilities or likelihood for obtaining the 2°C target and whether or not non-CO<sub>2</sub> GHGs are taken into account (2013).) Traditionally, deposits of fossil fuels were considered a most valuable economic asset, but from a climate change perspective they represent a substantial environmental liability.

### 5.3 Renewable Resources

Renewable energy resources represent the annual energy flows available through sustainable harvesting on an indefinite basis. While their annual flows far exceed global energy needs, the challenge lies in developing adequate technologies to manage the often low or varying energy densities and supply intermittencies, and to convert them into usable fuels (see Section 5.4 below). Except for biomass, technologies harvesting renewable energy flows convert resource flows directly into electricity or heat. Their technical potentials are limited by factors such as geographical orientation, terrain, or proximity of water, while the economic potentials are a direct function of the performance characteristics of their conversion technologies within a specific local market setting.

Annual renewable energy flows are abundant and exceed even the highest future demand scenarios by orders of magnitude. The influx of solar radiation reaching the Earth’s surface amounts to 3.9 million EJ/yr. Accounting for cloud coverage and empirical irradiance data, the local availability of solar energy reduces to 630,000 EJ. Deducting areas with harsh or unsuitable terrain leads to a technical potential ranging between 62,000 EJ/yr and 280,000 EJ/yr. By 2100 the GEA pathways utilize up to 1500 EJ/yr of solar radiation (see Table 5.3). Note: The flows, potential, and utilization rates in Table

<sup>13</sup> “Limiting the warming caused by anthropogenic CO<sub>2</sub> emissions alone with a probability of >33%, >50%, and >66% to less than 2°C since the period 1861–1880, will require cumulative CO<sub>2</sub> emissions from all anthropogenic sources to stay between 0 and about 1560 GtC, 0 and about 1210 GtC, and 0 and about 1000 GtC since that period respectively. These upper amounts are reduced to about 880 GtC, 840 GtC, and 800 GtC respectively, when accounting for non-CO<sub>2</sub> forcings as in RCP2.6. An amount of 531 [446 to 616] GtC, was already emitted by 2011.” (IPCC, 2013).

5.3 are given in terms of energy input – not as outputs (secondary energy or using any accounting scheme for equivalent primary energy – see Appendix A).

The energy carried by wind flows around the globe is estimated at about 110,000 EJ/yr, of which some 1550 EJ/yr to 2250 EJ/yr are suitable for the generation of mechanical energy. (Wind, biomass, hydro, and ocean energy are all driven by the solar energy influx. Their numbers are, therefore, not additive to the solar numbers discussed above.)

The GEA pathways range of wind utilization varies between 41 EJ/yr and 715 EJ/yr. The energy in the water cycle amounts to more than 500,000 EJ/yr, of which 160 EJ/yr could theoretically be harnessed for hydroelectricity. The GEA pathways utilize between 27 EJ/yr and 39 EJ/yr compared to a technical potential estimated at 53 EJ/yr to 57 EJ/yr.

Net primary biomass production is approximately 2400 EJ/yr, which, after deducting the needs for food and feed, leaves in theory some 1330 EJ/yr for energy purposes. Accounting for constraints such as water availability, biodiversity, and other sustainability considerations, the technical bioenergy potential reduces to 160 EJ/yr to 270 EJ/yr, of which between 125 EJ/yr and 220 EJ/yr are utilized in the GEA pathways. The global geothermal energy stored in the Earth's crust up to a depth of 5000 meters is estimated at 140,000 EJ. The annual rate of heat flow to the Earth's surface is about 1500 EJ/yr, with an estimated potential rate of utilization of up to 1000 EJ/yr.

Oceans are the largest solar energy collectors on Earth, absorbing on average some 1 million EJ/yr. These gigantic annual energy flows are of theoretical value only, and the amounts that can be technically and economically utilized are significantly lower.

Table 5.3 Renewable energy flows, potential, and utilization in EJ of energy inputs provided by nature. Source: GEA Chapters 7 and 17, Rogner et al., 2012; Riahi et al., 2012 (see also GEA Chapter 11, Turkenburg et al., 2012, for a discussion of renewable resource inventories and their differences). Note: MSW = municipal (and other) solid wastes.

	Primary Energy Equivalent in 2005 [EJ]	Utilization in GEA pathways [EJ/yr]	Technical potential [EJ/yr]	Annual flows [EJ/yr]
Biomass, MSW, etc.	46	125–220	160–270	2200
Geothermal	1	1–22	810–1545	1500
Hydro	30	27–39	50–60	160
Solar	< 1	150–1500	62,000–280,000	3,900,000
Wind	1	41–715	1250–2250	110,000
Ocean	–	–	3240–10,500	1,000,000

Note: The data are energy-input data, not output. Considering technology-specific conversion factors greatly reduces the output potentials. For example, the technical 3150 EJ/yr of ocean energy in ocean thermal energy conversion (OTEC) would result in an electricity output of about 100 EJ/yr.

## 5.4 Energy Densities

The concept of energy density refers to the amount of energy produced or used per unit of land. The customary unit for energy densities is Watts per square meter (W/m<sup>2</sup>), referring to a continuous (average) availability of the power of one Watt over a year. Typical energy densities for demand as well as supply are illustrated in Figure 5.2.

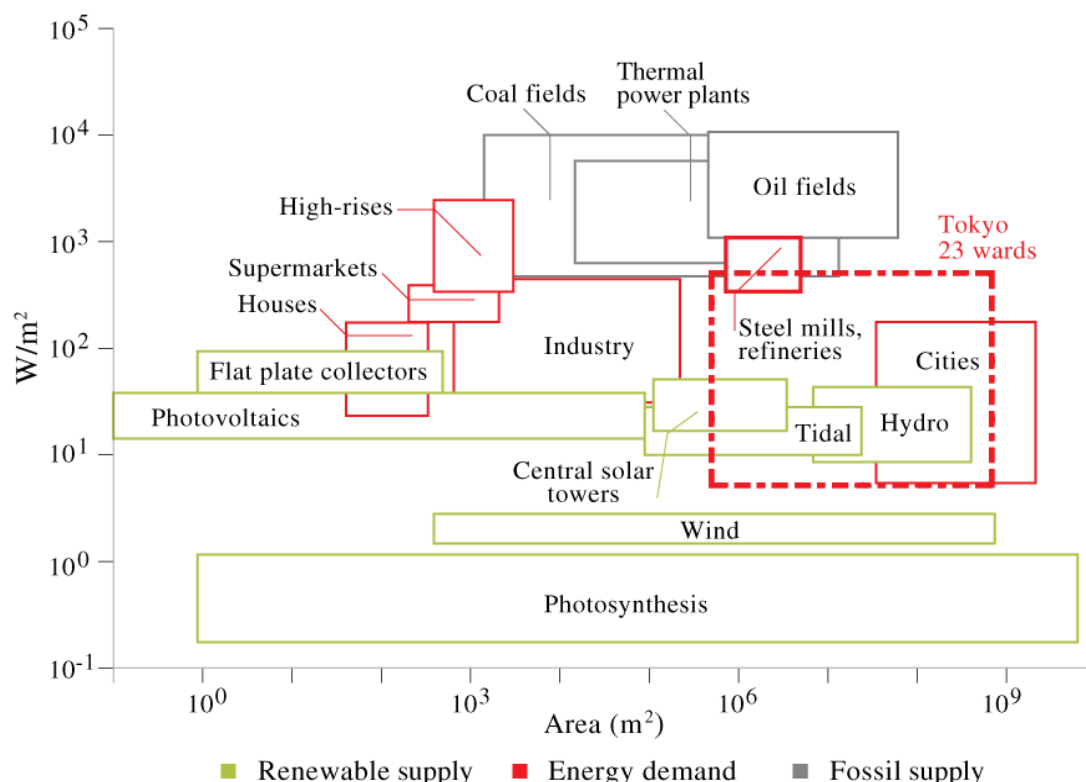


Figure 5.2 Energy densities of fossil (grey) and renewable (green) energy supply and demand (red). Source: modified and adapted from Smil, 1991.

Energy demand and supply densities have co-evolved since the onset of the Industrial Revolution. In fact, one of the advantages of fossil fuels in the industrialization process has been their high energy density, which enables energy to be produced, transported, and stored with relative ease, even in locations with extremely high concentration of energy demand, such as industrial centers and rapidly growing urban areas. The mismatch between energy demand and supply densities is largest between urban energy use, which is highly concentrated, and renewable energies, which are characterized by vast, but highly diffuse energy flows. (Exceptions are geothermal energy and urban [municipal] wastes, which are characterized by high energy density.)

The density of energy demand in urban areas is typically between 10 W/m<sup>2</sup> and 100 W/m<sup>2</sup> and can reach some 1000 W/m<sup>2</sup> in extreme locations, such as skyscraper complexes and high-density business districts (see Figure 5.2 for an illustration of Tokyo's 23 wards [districts]). Conversely, renewable energies have typical energy supply densities of a few W/m<sup>2</sup> under ideal conditions (assuming all land can be devoted to harnessing renewable energy flows). Under practical conditions (considering competing land-uses for agriculture and human settlements) renewable energies can yield typically between 0.1 W/m<sup>2</sup> and 0.5 W/m<sup>2</sup> (see also GEA Chapter 18; Grubler et al., 2012b). As a result, locally harvested renewable energies in densely populated areas such as cities can only provide a very small fraction (some one percent) of urban energy demand. Therefore, renewable energies also have to be harvested in locations where land and favorable renewable resource potentials are available, and need then to be transported over longer distances to urban centers with their high energy demand densities.

## 6 Production, Trade, and Conversions

### 6.1 Introduction

The energy system consists of an intricate web of energy conversion processes linking primary energy resources to the provision of energy services. A first overview of energy conversion, therefore, can be gained by looking at the associated energy flows (see Figure 2.8 above). Due to the associated conversion losses, the energy flows get larger the further upstream the energy system one moves, which is the reason why global primary energy flows (496 EJ) are about three times larger than useful energy flows (169 EJ) in 2005.

As the geographical location of energy resources and “downstream” components of the energy system are distributed very unevenly, this section begins by describing major global primary energy flows from production, use, and trade of energy.

### 6.2 Production, Use, and Trade

The sheer size of global energy flows, that dwarf energy storage capacities, implies a fundamental energy market identity: production of energy flows needs to equal demand, and vice versa. As energy demand and production capacities are distributed unevenly geographically, this basic market identity translates into vast flows of energy trade. Energy is traded in three forms:

- direct energy flows of primary energy (coal, crude oil, and natural gas) and secondary energy (primarily refined oil products); and
- indirect (embodied) energy flows, in which energy is traded in the form of (energy-intensive) commodities (aluminum, steel, etc.) and products (fertilizer, steel rails, cars, etc.).

The following sections summarize the status of primary energy production, trade, and use (defined as “Total Primary Energy Supply” – or TPES – in energy balances) for fossil fuels, as they are the dominant form of current global energy use (some 80% of primary energy) and of international energy trade flows.<sup>14</sup> Figure 6.1 complements this fossil fuel dominated picture by showing the regional distribution of non-fossil energy production, where there is little international trade.

#### 6.2.1 Direct Energy

Table 6.1 summarizes primary energy production, trade, and use<sup>15</sup> for nine regions and the world in 2005. From the TPES of some 390 EJ of fossil fuels in 2005, some 230 EJ (or close to 60%) are represented by energy imports. The share of traded energy (direct primary and secondary energy trade) in TPES is markedly different for different fuels: it is lowest for coal (18%), followed by natural gas (30%), and reaches 80% for crude oil. Including trade in refined oil products (secondary energy), oil-related energy trade flows (172 EJ) actually exceed the global TPES of oil products (167 EJ). This apparent paradox results from the fact that large importers of crude oil have corresponding large refining capacities, becoming in turn large exporters of refined petroleum products. The international

<sup>14</sup> Renewables are dominated by traditional biomass use that is harvested and used locally without international trade. Modern renewables such as hydropower, solar, or wind, or for that matter also nuclear power, enter the energy system as secondary energy carriers (predominantly electricity, with some direct heat), which are generally not traded internationally. International trade in biofuels remains comparatively modest at some 0.2 EJ in 2005. International trade in electricity is also small: slightly above 2 EJ in 2005.

<sup>15</sup> Production – Exports + Imports +/- Stock changes = TPES, or primary energy use. Due to space limitations this total is not shown in Table 6.1.

division of labor in energy means that a barrel of crude oil can be traded various times and in various forms across national boundaries (not to mention the multiple “virtual” trades of the same barrel on speculative and futures markets). A good (even if extreme) illustration is provided in the case of Singapore: total fossil fuel imports equal a staggering 880 GJ/capita, of which 210 GJ/capita are used as primary energy input to the Singapore economy (with 120 GJ/capita final energy use), 450 GJ/capita are re-exported as oil products, and an additional 220 GJ/capita exported as bunker fuels for international shipping and aviation (Schulz, 2010). In addition, Singapore’s energy trade is also characterized by vast energy flows embodied in exported products (petrochemicals) as well as in goods imported into this city state (see the discussion below).

The largest annual international trade flows (from aggregate country imports or exports) in 2005 were crude oil, with some 135 EJ, followed by oil products (40 EJ), natural gas (30 EJ), and coal (20 EJ).

In terms of regions, the largest<sup>16</sup> exporters for crude oil were the Middle East (MEA) region (some 50 EJ), the former Soviet Union (14 EJ), and Latin America and the Caribbean (LAC – 11 EJ), balanced from the oil import side with imports to Europe (27 EJ), the United States (24 EJ), and developing economies in Asia, excluding China, with 18 EJ. For gas trade, only exports from the former Soviet Union (10 EJ) and imports to Europe (13 EJ) are beyond the 10 EJ reporting threshold level adopted here. Inter-regional coal trade is comparatively small (with largest regional exports and imports of 8 EJ (Australia) and Europe (6 EJ), respectively).

Perhaps the least known aspect of international energy trade is the significant exports and imports of petroleum products. Europe, while a main crude oil importer (27 EJ), nonetheless exports 11 EJ of oil products, in order to import in turn a further 13 EJ of oil products. The trade in oil products to/from other regions is much smaller. The picture emerging from the international energy trade is thus less one of directed “source–sink” energy resource flows, but rather one of an increasingly complex “foodweb” in which energy is traded in primary and secondary forms across multiple boundaries.

As mentioned above, international trade in non-fossil energy is still very small compared to fossil fuels, but production especially of “new renewables” is expanding at high growth rates, albeit from a very low starting base. Figure 6.1 summarizes the regional breakdown of non-fossil fuel production for the year 2005 (“new renewables” include wind, solar, and geothermal).

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<sup>16</sup> Flows below 10 EJ are not discussed separately. Details are given in Table 6.1.

Table 6.1. World trade flows between regions (in EJ) for 2005. Source: data from IEA, 2007a and 2007b.

	Coal				Crude Oil				Oil Products				Natural Gas			
	Prod.	Exp.	Imp.	Stock Changes	Prod.	Exp.	Imp.	Stock Changes	Prod.	Exp.	Imp.	Stock Changes	Prod.	Exp.	Imp.	Stock Changes
Asia w/o China	14.4	-3.9	5.5	-0.2	7.6	-3.1	17.5	0.1	0.0	-6.9	6.8	0.1	9.4	-3.1	2.3	0.0
China	48.0	-2.3	0.9	-0.7	7.6	-0.3	5.3	0.0	0.0	-0.8	2.4	0.0	1.8	-0.1	0.1	0.0
EU27	8.5	-1.2	6.4	-0.1	5.4	-3.0	26.7	0.0	0.1	-11.9	13.2	-0.3	7.9	-2.5	13.3	0.0
Japan	0.0	0.0	4.7	0.0	0.0	0.0	9.0	0.0	0.0	-0.4	2.2	-0.1	0.1	0.0	2.8	0.0
LAC	2.2	-1.7	0.8	0.0	23.6	-11.0	3.0	0.0	0.2	-4.3	3.0	0.0	6.2	-1.1	1.0	0.0
MAF	6.0	-2.0	0.6	0.0	72.3	-52.1	2.6	0.0	0.0	-8.4	3.7	0.0	17.1	-5.5	0.4	0.0
rest-OECD	11.0	-7.5	1.0	0.1	12.2	-8.7	4.2	-0.1	0.8	-2.2	2.2	0.0	11.2	-7.1	1.4	0.3
REF w/o EU	10.3	-2.9	0.9	-0.1	24.1	-13.6	2.0	0.0	0.0	-4.9	0.5	0.0	27.7	-9.7	4.0	-0.1
USA	23.9	-1.2	0.8	0.1	13.3	-0.2	23.7	-0.2	0.2	-2.3	6.3	0.0	17.6	-0.7	4.2	0.1
World trade between regions	124.3	-22.8	21.7	-1.0	166.3	-92.1	94.0	-0.2	1.2	-42.0	40.3	-0.2	99.1	-29.8	29.5	0.2
World trade between countries (IEA data)	121.8	-21.6	21.8	0.1	167.8	-133.8	133.9	-0.5	–	-40.7	37.6	–	99.3	-30.0	29.4	0.3

Note: the five GEA regions have been expanded to nine to better represent international trade flows. These nine regions represent well the major international energy trade flows obtained from aggregating inter-country trade flows based on IEA statistics. Only for crude oil, the inter-regional trade flows cover only 70% of the true international trade in crude oil (the difference is intra-regional trade – e.g., within the EU27 countries, or within Latin America (LAC) countries).



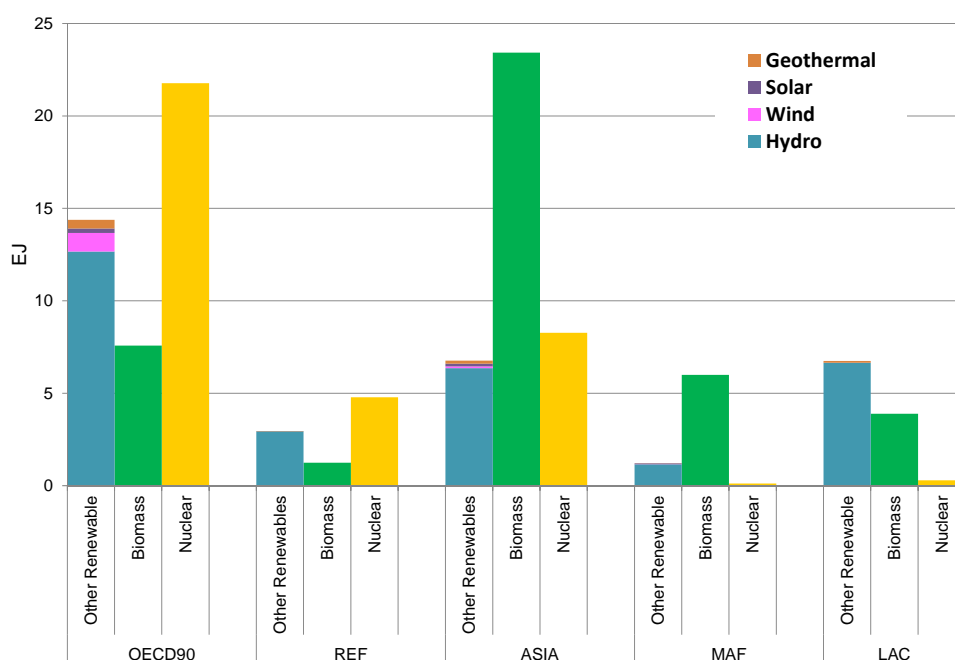


Figure 6.1. Production of non-fossil primary energy (GEA primary energy accounting, see Appendix A) by major world region for the year 2005. Source: adapted from IEA, 2007a, and 2007b.

Nuclear energy contributes about 28 EJ or 6% of global primary energy in 2005.<sup>17</sup> Its production is dominated by a few countries of the OECD90 and REF regions, particularly the US, Japan, Russia and Europe (Figure 6.1). Most of the new nuclear capacities of the recent years were installed in Asia. Particularly China is building at the moment about 40 GW of new capacity and is planning to expand nuclear to 15% of its power generation or to about 80 GW of nuclear capacity by 2020 (present global nuclear capacities are around 390 GW).

Renewables contribute more than 70 EJ (or 14%) to global primary energy use. About 25 EJ of this total stems, however, from the traditional use of biomass in developing countries, and illustrate a widespread lack of access to modern and clean energy carriers (particularly in Asia and Africa). Traditional biomass is predominantly used for cooking and heating and is the major source of energy-related health impacts (see Section 7 below). The substitution of traditional biomass use in households needs thus to be one of the central objectives for any future energy transition.

The development of modern renewables (hydro, and the “new renewables” wind, solar, and geothermal) has been particularly dynamic over the recent years. They contributed in 2005 about 6% of total global primary energy. The major source is hydro (30 EJ) and to some extent wind (>1 EJ). Other renewables (mainly solar and geothermal) contributed about another 1.2 EJ primary energy in 2005. About half of the generation of modern renewable is located in the

<sup>17</sup> Primary energy use based on GEA primary energy (substitution equivalent) accounting standard (see Appendix A).

OECD90 region with another 20% of generation in the LAC as well as ASIA regions (Figure 6.1).

### 6.2.2 Embodied Energy

The literature and statistical basis of embodied energy flows is thin, as existing studies almost invariably focus on embodied CO<sub>2</sub> emissions in international trade, without disclosing the underlying energy data. Notable exceptions are studies on embodied energy in the international trade of Brazil (Machado, 2000), China (Liu et al., 2010), and Singapore (Schulz, 2010). Current energy accounting and balances report direct energy flows, whereas embodied energy trade is quite under-researched and not reported systematically.

The only data source available for estimating embodied energy flows is the GTAP7 (Narayanan et al., 2008) database that contains data suitable for estimating the fossil fuel energy embodied in international trade flows by input-output analysis (Table 6.2). Important limitations and intricate methodological issues need to be considered when trying to estimate the energy embodied in internationally traded commodities and products based on multi-regional input-output tables. The flows summarized in Table 6.2, therefore, need to be considered as order of magnitude estimates that await further analytical and empirical refinements. Nonetheless, even these “rough” data help to get a sense of proportion. GTAP7 estimates that (fossil) energy embodied in international trade amounts to some 100 EJ – i.e., some 20% of global primary energy use – compared to direct energy trade flows of some 190 EJ in 2005 when using the same regional aggregation<sup>18</sup> as reported in Table 6.1.

Table 6.2. Trade in embodied energy between major regions (in EJ, only fossil primary energy) as derived from the GTAP7 multi-regional input-output tables for 2005. Source: Narayanan et al., 2008.

	EU	US	Japan	REF	Rest-OECD	Asia w/o China	China	LAC	Africa	Sum of Exports
EU		3.5	0.6	1.1	2.2	2.1	0.9	0.8	1.2	12.4
US	3.3		0.9	0.1	2.8	1.5	0.9	2.8	0.3	12.6
Japan	0.7	0.9		0	0.2	1.2	1.2	0.1	0.1	4.4
REF	6.1	1.3	0.3		1.1	1.5	1	0.4	0.3	12
Rest-OECD	2.4	4.1	0.4	0.2		1	0.5	0.2	0.2	9
Asia w/o China	5.1	3.6	3.5	0.3	1.3		4.9	0.7	1.1	20.5
China	5.1	5.4	3	0.4	1.3	4.8		1	0.5	21.5
LAC	1.4	4.1	0.2	0.1	0.4	0.5	0.4		0.2	7.3
Africa	2.4	0.9	0.2	0	0.3	0.6	0.3	0.2		4.9
Sum of imports	26.5	23.8	9.1	2.2	9.6	13.2	10.1	6.2	3.9	104.6

World embodied energy trade

<sup>18</sup> The difference between the 190 EJ intra-regional trade (nine regions) and the 230 EJ reported as international energy trade reflects the energy trade between countries within a given region (e.g., between Germany and France in the EU region, or between Indonesia and Bangladesh in the Asia-sans-China region) which is not counted in the regional trade flows but included in the global total trade numbers (summed from national statistics).

In other words, at least half of global primary energy use is traded among regions in either direct or indirect (embodied) form, which illustrates the multitude of interdependencies at play in the global energy system that go far beyond traditional concerns of oil import dependency. Assuming that the relative proportions of intra-regional to international trade flows hold for embodied energy flows in a similar way, as in the case of direct energy trade flows, then direct and embodied energy trade flows (of perhaps 400 EJ) approach the level of world primary energy use in the year 2005 (500 EJ). Evidently, these numbers must not be interpreted through the traditional lens of (additive) “net” energy trade flows. The nature of the international division of labor is precisely that a Joule of energy can be traded many times, hence the trade numbers discussed above include multiple double-counting. Consider two examples: Iran is a major oil producer and exporter but lacks sufficient domestic refining capacity. A barrel of oil exported to Singapore may be re-exported back to Iran in the form of gasoline, or it may be re-exported back in the form of plastic or chemical products. The same physical energy thus ends up being counted twice as an international energy trade flow. China is a major steel producer, Australia a major exporter of metallurgical coal (used in the steel industry), and Germany a major car manufacturer. In our example, coal is exported from Australia to China, where it serves to produce steel, and this steel is exported from China to Germany, where manufacturers use it to produce German cars for export to China. Direct energy trade (coal) becomes embodied energy trade (steel), which in turn becomes embodied energy trade again (cars), with a physical Joule energy counted three times as international energy trade. This example also illustrates the great difficulties in comprehensive accounting of energy (or GHG emission flows) through multiple exchanges and trade flows. Who ultimately “owns” the corresponding energy or GHG “footprint”: the Australian coal producer, the Chinese steel manufacturer, the German car company, or the Chinese consumer (car buyer)?

### **6.2.3 Energy Trade Flows**

Figure 6.2 summarizes all direct (primary and secondary) and indirect fossil fuel-related international trade flows in the form of a map to demonstrate the high degree of energy interdependence worldwide. The term interdependence suggests that the energy system is much more integrated than conventional wisdom or energy security concerns would suggest. Not only do many countries critically depend on oil exports from the Middle East, the Middle East also depends on numerous other countries for its supply of food, consumer products, and investment goods that all embody (part of) the region’s previous energy exports.

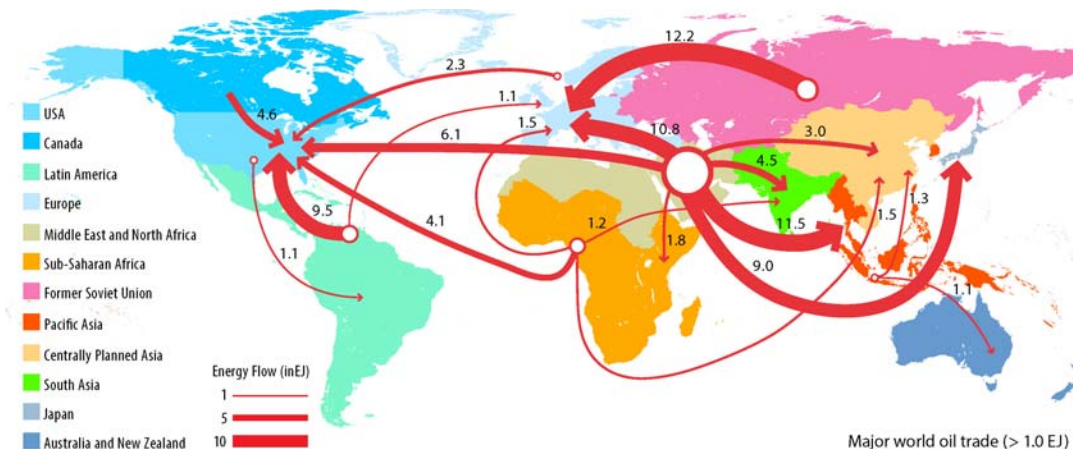
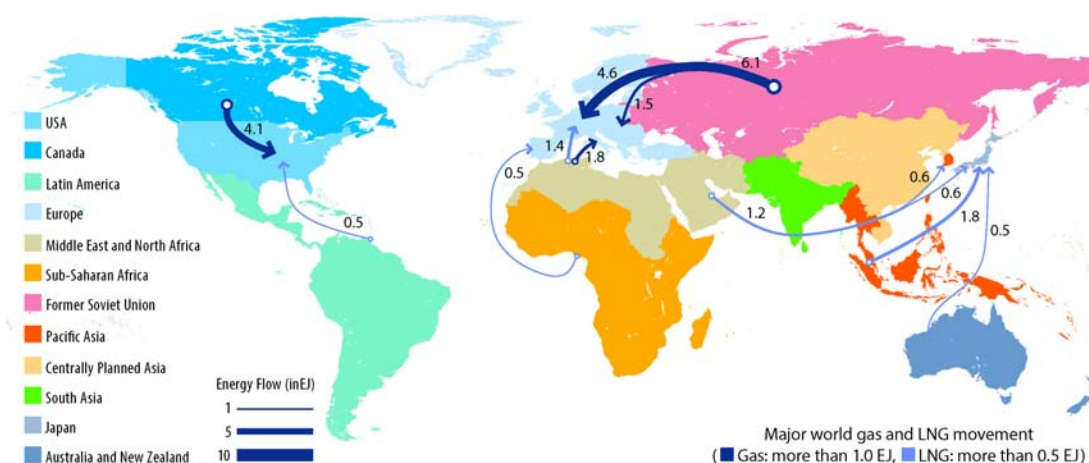
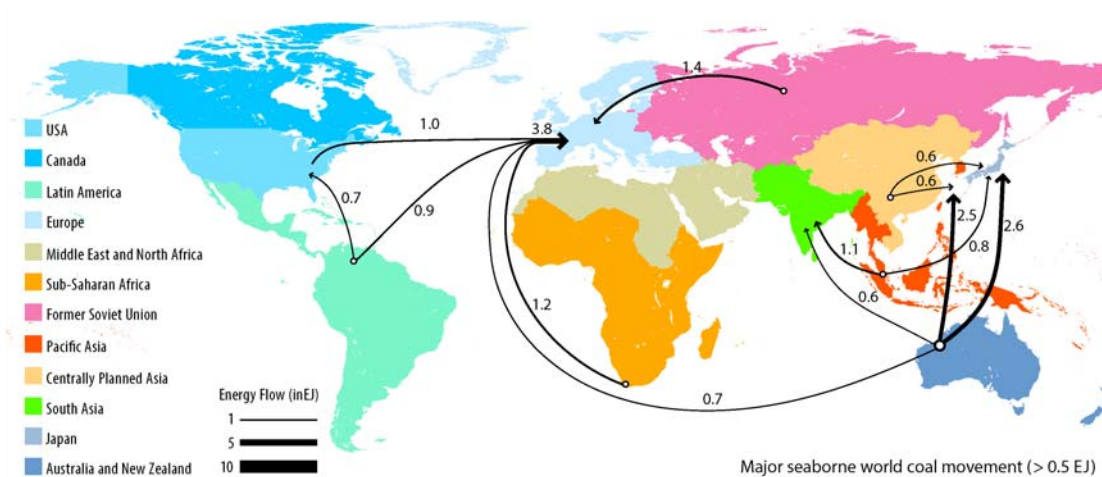
**Crude oil and oil products****Gas by pipeline and LNG****Coal**

Figure 6.2a. World energy trade of fossil fuels: direct primary and secondary energy coal (black), oil and oil products (red) and gas (LNG light blue, pipeline gas: dark blue), in EJ. Source: Oil/gas energy trade for 2005 (BP, 2007), coal trade for 2008 (WCI, 2009).

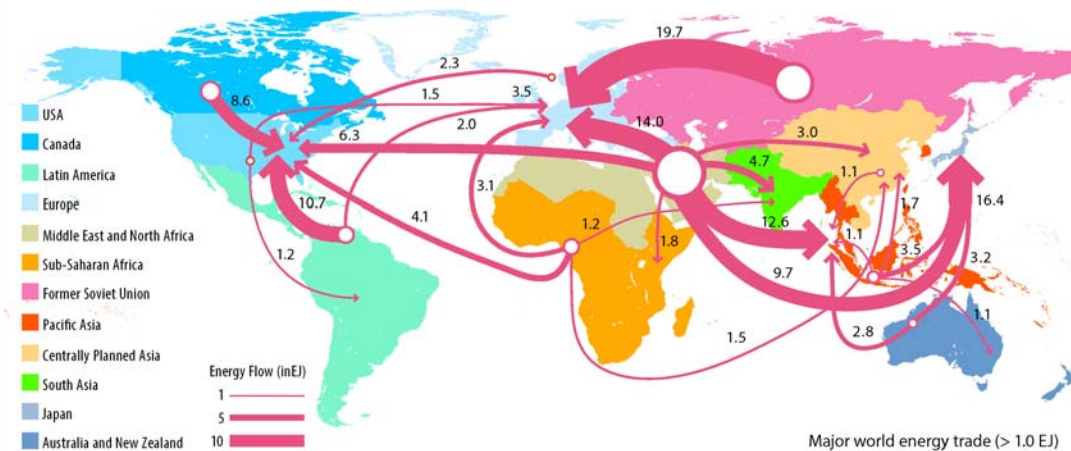
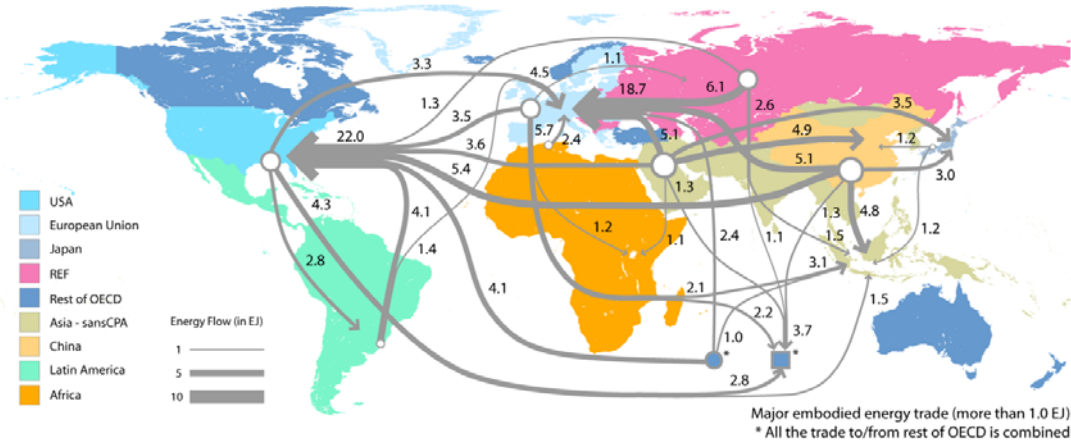
**Direct energy trade****Embodied energy trade**

Figure 6.2b. World energy trade of total direct energy (pink) as well as embodied energy in goods traded (grey), in EJ. Sources: Embodied energy trade for 2004 (GTAP7 database, 2010), direct energy trade for 2005 (BP, 2007) except coal (2008 trade, WCI, 2009).

## 6.3 Conversions

### 6.3.1 Introduction and Overview

One way of looking at energy conversion processes is to consider the associated energy conversion capacity, which is a proxy of the aggregated size of energy conversion technologies and hence an indicator of the magnitude of technological change and capital replacement required for improving energy efficiency through the application of more efficient processes and technologies. Unlike the picture that emerges when looking at energy flows, the scale of energy conversion technologies portrays a different pattern in which energy end-use conversions dominate. Although global numbers are not available, this pattern of an increasing scale of energy conversion processes and devices revealed by the long-term history of the US energy system (Table 6.3) is quite characteristic of the global picture as well.



Table 6.3. Installed capacity of energy conversion technologies (in GW) for the United States, 1850 to 2000. Source: Wilson and Grubler, 2011.

GW (rounded)		1850	1900	1950	2000
stationary end-use	thermal (furnaces/boilers)	300	900	1900	2700
	mechanical (prime movers)	1	10	70	300
	electrical (drives, appliances)	0	20	200	2200
mobile end-use	animals/ships/trains/aircraft	5	30	120	260
	automobiles	0	0	3300	25000
stationary supply	thermal (power plant boilers)	0	10	260	2600
	mechanical (prime movers)	0	3	70	800
	chemical (refineries)	0	8	520	1280
TOTAL		306	981	6440	35140

For instance, in 2000 the total installed capacity of all US energy conversion devices equaled a staggering 35 TW (that compares to a global energy flow of some 16 TWyr/yr).<sup>19</sup> Energy supply-related conversion processes account for some 5 TW, with 30 TW in energy end-use, most notably in the form of automobiles (25 TW). Assuming all cars ran on zero-emission hydrogen fuel cells, the installed capacity of the existing car fleet would be about ten times larger than that of all electricity-generating power plants and could easily substitute the traditional utility-dominated centralized electricity-generation model by an entirely decentralized generation system, powered by cars during their ample idle times. Such drastic transformations in electricity generation have been proposed (e.g., Lovins et al., 1996), especially as a means of accommodating vastly increased contributions from intermittent renewables such as wind, solar thermal, or photovoltaic systems without the need for centralized energy storage. Even if currently futuristic, such daring visions of technology are a useful reminder that the analysis of energy systems needs to look beyond energy flows only and to always consider both major components of energy systems: energy supply and energy end-use.

### 6.3.2 Electricity Generation

Electricity is growing faster as a share of energy end-uses than other direct-combustion uses of fuels. Between 1971 and 2008, world electricity production almost quadrupled from 19 EJ to 73 EJ of secondary energy (see Figure 6.3) – an absolute increase of 54 EJ. Some 60% of this growth (32 EJ) was in countries outside the Organisation for Economic Co-operation and Development (OECD).

Figure 6.3 depicts the fuel share in global electricity production. About 68% of global electricity is generated from the combustion of fossil fuels, with coal accounting for more than 40% of total production. The share of oil in power production has decreased considerably from 23% to 6% since the first oil crisis in 1973. On the other hand, the share of natural gas has increased from 12% to 21%. Renewable energy sources contribute about 18%, with hydropower

<sup>19</sup> In other words, if all US energy conversion devices operated 24 hours a day, 7 days a week, they would transform energy flows twice as large as the entire world energy use. The fact that US primary energy of 100 EJ is equal to 20% of global primary energy use illustrates the comparatively low aggregate capacity utilization of energy conversion devices, particularly in energy end use. (Transportation surveys suggest, for instance, that on average a car is used only one hour per day).



accounting for more than 85% of this. Following a rapid expansion in the 1970s and 1980s, nuclear electricity generation has seen little growth since.

Figure 6.3 also shows electricity production for the GEA regions for the base year 2005. Fuel mixes vary widely, primarily reflecting the availability of local energy resources and to some extent also reflecting past technical and financial capacity to invest in advanced technologies such as nuclear. Coal for electricity generation is most prominent in Asia, accounting for almost 70% of production. OECD and Africa also have significant shares of coal-based power generation. Nuclear energy is primarily used in OECD countries as well as in Eastern Europe and the countries of the former Soviet Union. It makes only a minor contribution in developing countries, except China, which currently has the most nuclear power under construction in the world. Hydropower is unevenly used, providing 66% of electricity in Latin America and the Caribbean. Non-hydro renewable energy in electricity production is low in all regions. However, as a result of various policy support mechanisms in a rapidly increasing number of countries, about half of current investments in power generation are in renewable generation.

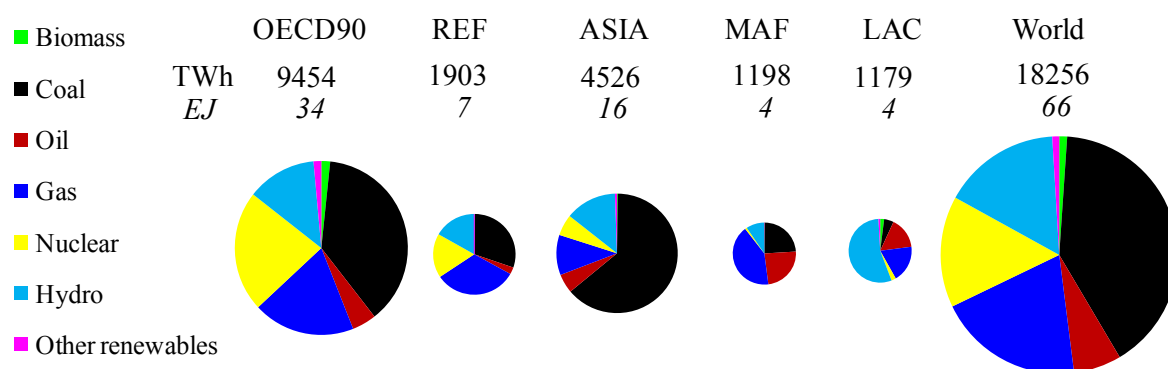


Figure 6.3. Electricity output by generating source in 2005: World and five GEA Regions in TWh and EJ (in italics). Source: IEA, 2007a and 2007b. Note: Circle areas are proportional to electricity generated.

Figure 6.4 shows regional trends in electricity output: growth trends are across heterogeneous regions. Most additional electricity production since 1971 was actually in the OECD countries (+22 EJ), slightly larger than in the Asia region (+20 EJ/yr). More recent growth trends, however, change this picture dramatically. Since 1990, growth in electricity generation has focused heavily on Asia (most notably in China, an additional 16 EJ of electricity generated), followed by the OECD (+9 EJ) and all other developing countries combined (6 EJ). The REF region even experienced a slight drop in electricity output in the aftermath of its economic restructuring.

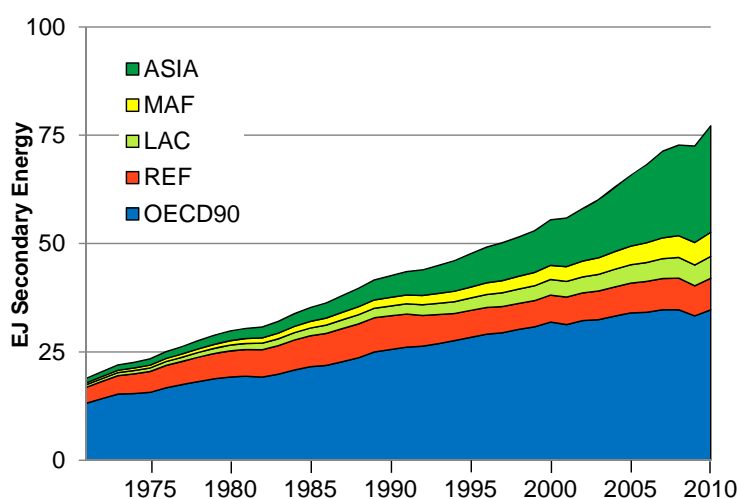


Figure 6.4. World electricity generation by five GEA Regions, cumulative total (in EJ of secondary energy generated per year). Source: derived from IEA, 2010.

## 7 Energy impact on the Human and Natural Environment

### 7.1 Introduction

Energy extraction, conversion, and use have major impacts on the environment. It is important to recall that the term *environment* includes both the human as well as the natural environment and that energy systems affect both. Whereas energy systems impacts on the human environment can be assessed in terms of their impact on human health and longevity, a similar comparable overall metric of energy systems impact on the natural environment is not possible. Too many different types of impacts and the diversity of ecosystems affected (land, water, air) preclude their aggregation into a simple overall impact metric. Therefore the discussion below focuses on summarizing major energy sources of pollutants with a particular emphasis on air pollutants for which global pollutant inventory data are available.

As illustration for the impacts of energy on the human environment consider that the largest single source of human health impacts of energy is associated with household air pollution resulting from the use of traditional biomass in open fires or inefficient cookstoves by the poor in developing countries. Its direct human health impacts are estimated by GEA to result in more than 2 million premature deaths plus a significant proportion of health impacts from outdoor air pollution (that total close to 3 million premature death per year). The health impacts from biomass-fueled cookstoves include respiratory, cardiovascular, and other diseases, with the greatest risk for women and children, making access to culturally acceptable, clean, and efficient cooking a priority policy concern.

Impacts on the natural environment can be regrouped into two broad categories: the use of natural resources in the form of energy resources (fossil fuels and renewables) and in the form of land and water; as well as pollutants that affect soil, water, and air. None of these environmental impacts can be looked at in isolation: pollutants need to be considered in relation to the absorptive capacity of the environment and many pollutants have multiple effects across different spatial scales (local, regional to global) and across different environmental compartments. The natural resource requirements of energy systems need to be differentiated

whether they are consumptive in the sense that they either deplete a natural stock (like fossil resources) or exclude an alternative use of the same natural resource (e.g., the area covered by a power plant is no longer available for alternative uses for human settlements or agriculture) or whether resource use is non-consumptive as either using a renewable resource (e.g., sunlight) or allowing the subsequent use of the resource for other human activities (e.g., riverwater exiting a hydropower plant).

## 7.2 Human Health Impacts of Energy

Energy systems negatively affect global health in major ways today, causing directly perhaps as many as 5 million premature deaths annually — and more than 5% of all ill-health (measured as lost healthy life years). (Methods and metrics used for estimating health impacts from air pollution are discussed in Box 2). Air pollution from incomplete combustion of fossil fuels and biomass fuels is by far the single major reason that energy systems negatively affect global health, although ash, sulfur, mercury, and other contaminants in fossil fuels also play a role. Second in importance are worker risks in energy industries, such as coal and oil extraction.

The largest exposures to energy-related air pollution occur in and around households, particularly in developing countries where unprocessed biomass (wood and agricultural wastes) and coal is used for cooking and heating in simple appliances. The health impact of climate change, which is largely driven by energy use, is not large yet, but is growing. Table 7.1 summarizes current health impacts from energy systems, showing that much bigger impacts are found in poor countries. As explained in Box 2, this is due both to higher exposures to the pollutants and higher vulnerability, as indicated by higher background disease rates.

Unless major policy interventions are undertaken, human use of energy is expected to continue contributing significantly to the global burden of disease for years to come.

Table 7.1: Outdoor and household health impacts by world region and global for the year 2005 (in millions of DALYs – disability adjusted life-years lost).

Region	Outdoor ( <i>impacts from solid fuel use in households</i> )*	Household
World	22.6 (4.5-6)	41.6
OECD	2.4	
REFS	1.9	
Middle East and N. Africa	0.6	
South Asia	7.0 (2.1 -2.7)	13.8
Pacific Asia	1.1 (0.2-0.3)	3.9
Sub-Saharan Africa	0.9 (0.2-0.4)	18.6
Centrally Planned Asia	8.4 (2-2.6)	4.6
Latin America and the Caribbean	0.3 (0.02-0.05)	0.8

\* Indicated in parenthesis are estimated outdoor health impacts attributable to use of solid fuels (biomass and coal) in households. Note that these estimates are based on interpolations between scenarios and are only indicative. Range represents the inherent uncertainty in calculating these impacts.

*Household air pollution:* Estimates for 2005 put the burden of disease caused by household air pollution at about 2.2 million premature deaths and at 42 million DALYs annually (GEA, Chapters 4 and 17, Smith et al., 2012; Riahi et al., 2012). These deaths occur mainly among women and young children in developing countries because they receive the highest exposures to household air pollution from cooking and heating with solid fuels.

Although the fraction of households relying on solid fuels is slowly declining, the absolute numbers globally are still rising among the world's poorest populations.

The only way to ameliorate this health risk is through encouraging as many households as possible to use cooking fuels such as electricity (e.g., in high efficiency induction cookstoves), clean-burning gases and liquids made from biomass or petroleum fuels while initiating widespread promotion of new generations of advanced combustion biomass stoves. These stoves reduce biomass emissions to nearly the level of emissions from clean fuels, by using small blowers and other technical innovations.

*Outdoor air pollution:* Outdoor air pollution from incomplete combustion and other emissions from fuel use is also an important health risk factor globally. The GEA assessment (Chapters 4 and 17, Smith et al., 2012; Riahi et al., 2012) estimates that in 2005 it was responsible for some 2.7 million premature deaths and some 23 million DALYs annually (including between 4.6 to 5 million DALYs from outdoor air pollution caused by household solid fuel use, which are thus additive to the household [indoor] air pollution impacts of 42 million DALYs presented in Table 7.1). Outdoor air pollution affects not only urban areas, but many regions between cities, due to long-range transport of pollutants. Poor household fuel combustion is also a significant contributor to outdoor pollution in many parts of the world, for example South Asia and China, which means that the goals for clean household and general ambient air pollution are linked.

*Occupational health impacts:* Occupational injuries and illnesses, particularly in biomass and coal harvesting and processing (such as coal mining and transport), are the next most important impact on health from energy systems. Only strict adherence to international norms for worker health and safety can blunt this impact. Despite substantial gains over the past 50 years at some energy-related workplaces, health and safety systems do not exhibit best practices in many countries. The advent of novel nano- and other engineered materials for advance solar and other energy systems potentially pose risks to workers and the public that need to be carefully investigated before widespread deployment to avert health impacts before they occur.

*Nuclear power impacts:* Unlike biomass and fossil fuels, nuclear power systems are not a significant source of routine health impacts, although they often garner considerable public and policy concern. Average radiation doses to workers in nuclear power industries have generally declined over the past two decades. For nuclear power facilities, as with large hydroelectric facilities, the major health risks lie mostly with high-consequence but low-probability accidents. These risks are difficult to compare to the impacts that occur day to day. Even considering accidents such as Chernobyl and Fukushima, however, the health effects of these low-probability risks do not seem to be large, on average, compared to current routine impacts of fossil and biomass fuels. Nevertheless the few accidents that have occurred make clear that nuclear power systems can cause considerable stress, disruption, fear, and anger among affected populations, which in turn creates real impacts on health.

*Energy efficiency and health:* Although energy efficiency is usually found to be the best overall first strategy to improve the sustainability of energy systems, there can also be downsides if done without care. This has been seen, for example, in programs to improve the energy efficiency of buildings without considering the impacts on indoor air quality of reducing ventilation or use of improper materials. Forced ventilation systems (often coupled with heat recovery of exhaust air) are the option of choice combining energy efficient homes with indoor air quality.

*Climate change, energy, and health:* Climate change to date, to which energy systems are a significant contributor, is starting to have an important impact on health, probably exceeding 200 thousand premature deaths annually by 2005, more than 90% among the poorest populations in the world. It is expected, however, that both the health burden and the percent due to energy systems will rise under current projections of GHG emissions and background health conditions in vulnerable populations, which are largely in developing countries. Well over 20 million people along the vulnerable coastal regions of Bangladesh, Egypt, and Nigeria are estimated to be at risk of inundation from a one-meter sea level rise, not accounting for inevitable population growth. Other health impacts from climate change include the effects of heat waves, malnutrition, spreading infectious diseases, and resource-related conflicts (see Box 3).

*Co-benefits of protecting the climate system and improving health:* There are a number of opportunities to reduce the current burden of disease while also reducing the pressure on global climate. Some relate simply to reducing energy use and its associated health and climate impacts through efficiency improvements. Others, however, take advantage of the relatively high health and climate risk per unit emission posed by targeting specific short-lived greenhouse pollutants produced by energy systems, in particular black carbon and the precursors to ozone such as methane. Some of the energy-associated and health-damaging pollutants, such as sulfate and organic carbon particles, however, have cooling characteristics that create potential trade-offs between health and climate goals when controlling certain sources.

*Overarching concepts:* Per unit useful energy, the health and climate benefits of emission reduction interventions rise with the fraction of incomplete combustion; and, also per unit useful energy, the health benefits of emission reduction interventions rise as the combustion is closer to the population, increasing the proportion of emissions inhaled by someone. This is called intake fraction (see Box 4).

From a health standpoint, in addition to reducing risk factors such as air pollution and climate change, there is equal importance to reducing vulnerability by improving background health conditions, particularly among the world's poor. Meeting the UN Millennium Development Goals (MDGs) as soon as possible will be critical and bringing modern energy services to the world's poor is a necessary, if not sufficient, condition in doing so.

#### Box 2: Air Pollution Health Impacts

To quantify the health impacts of air pollution, the most reliable results derive from epidemiological studies of human populations, although some insight can be gained from laboratory studies of animals. Basically, the disease patterns and pollution levels experienced by populations living in different conditions are compared using statistical models to estimate the portion of the difference in disease that is due to the difference in air pollution exposure and not to other factors, such as differences in nutrition, age distribution, smoking, etc. The results are expressed in relative risk, i.e., the excess risk for a particular disease due to a specific increase in air pollution exposure. The best health data are available for small particle air pollution; usually in terms of PM<sub>2.5</sub> or PM<sub>10</sub> (particles less than 2.5 or 10 microns in size, small enough to penetrate deep into the lungs). Ozone exposures are also thought to cause ill-health separately from particles.

Relative risks of air pollution exposures vary by disease category and age, for example for lung cancer in adults and pneumonia in children. Some are very well understood, heart disease for example, while risks for other diseases are less clear, tuberculosis for example.

In recent years, a new type of analysis has become possible that creates what are called Integrated Exposure Response (IER) relationships. These combine results from studies of combustion particles across a wide range of exposure conditions: outdoor air pollution, secondhand tobacco smoke, household air pollution, and active smoking. Although the actual exposures, represented by amount of particles inhaled, vary by factors of a 1000 or more between, for example, outdoor air pollution and active smoking, the relationship between exposure and disease is consistent. Of course, larger exposures cause more ill-health than smaller ones, but in a steadily rising fashion with exposure. This adds additional evidence for the overall relationship between combustion particles and ill health.

To convert relative risks to actual health impacts requires an additional step, consideration of the background disease rate in the population. Put simply, if a certain amount of air pollution causes a 20% increase in a particular disease, but the background rate of this disease is low, there will be relatively little actual health burden on the population. In another population, however, with a higher background disease rate, the same pollution exposure and relative risk will cause a much bigger burden. This is one reason why pollution exposures tend to cause more health burden in poor compared to rich countries. Another reason, of course, is that exposures tend to be higher.

Premature mortality is one metric used to compare the burdens of risk factors like air pollution, but has limitations because it does not account for the age of death or for morbidity, i.e., illnesses and injuries that affect health but do not lead directly to death. In international health comparisons, therefore, the DALY (disability-adjusted life year) is often preferred. It accounts for the age of death and the time spent with an illness or injury and presumes that all people have the potential to live equally long. The degree that people do not reach their full life expectancy, therefore, is a measure of the impact of the risk factors that they are exposed to, including air pollution. Thus a death of an 8-year old creates more lost DALYs than the death of an 88-year old. In Table 7.1, health impacts are indicated in lost DALYs.

In common with other modern health burden assessments of risk factors, therefore, the GEA estimates have three primary inputs: 1) background disease rates; 2) the size of the population exposed to each level of risk 3) and the relative risks, i.e., how much each disease is increased by the exposure for each population group. It is easy to understand, therefore, how the overall results might vary somewhat between assessments by different groups, which often start with somewhat different estimates of these three factors, which are often not well documented, particularly in poor populations. The relative scale across risk factors, however, tends to be preserved within all assessments.

The GEA is the only major published attempt to group risk factors into those related to energy systems. The most authoritative burden of disease assessment overall, the Comparative Risk Assessment (CRA) of the Global Burden of Disease Project, examined more than 60 risk factors, including many not directly associated with energy. It treats all risk factors in an equivalent fashion giving policy makers the fairest comparisons of the relative impacts of different risk factors and potential health benefits of interventions across sectors. The first CRA (for 2000) was published in 2004, and the latest one for 2010 (Lim et al. 2012) is available also at <http://www.healthdata.org/gbd>. It includes estimates for household air pollution, occupational



risks, and outdoor air pollution, but does not specify which portion is due to specifically to energy systems.

### Box 3: Climate Change Health Impacts

The health impacts of climate change are thought to be of three types:

- *Direct impacts*, such as those due to heat stress and severe weather events
- *Impacts mediated through the environment*, such as shifts in the location and activity of disease-carrying mosquitoes and waterborne disease organisms
- *Impacts mediated through human-managed systems*, such as reduced agricultural yields, forced migrations of populations, and loss of income in poor populations.

It is the last category that is thought to pose the greatest potential human health risk, although also being the most difficult to predict. This difficulty is primarily because the impact will depend not only on the degree of climate change, but also on society's response. Thus, the world has plenty of total food today, but nevertheless malnutrition is the single biggest cause of ill-health. With climate change, food availability will be even less and, if nothing changes in society, malnutrition will rise. On the other hand, if society acts in a concerted way, malnutrition could be eliminated even under conditions of severe climate change.

In general, for the next decades climate change will not create any new diseases, but exacerbate existing ones. Thus, it has its biggest health impact among the most vulnerable populations, which are already most at risk. Indeed, the only published estimate of the burden of disease from climate change show more than 90% of the impact in poor countries, particularly in South Asia and Sub-Saharan Africa, and nearly 95% of that impact in children under five years, who are already at most risk from malaria, malnutrition, diarrhea, and other conditions thought to be enhanced by climate change (McMichael, et al., 2004).

As with most other important impacts from climate change, however, the largest, but most difficult to determine, health impacts will occur after mid-century if current trends continue. To head them off, however, requires starting to make big changes several decades in advance to the world energy system and other sources of greenhouse emissions because of the inertia built into the energy and climate systems.

The latest (2014) IPCC report (Chapter 11 of Working Group II, Smith et al., 2014) on health effects and co-benefits can be found at <http://www.ipcc-wg2.gov/>

### Box 4: Intake Fraction

Health impacts of airborne and other pollutants depend on the exposure to the population of concern, which in turn depends not only on the amount and toxicity of emissions, but also their location with regard to the population. Thus, if no one is downwind to breathe it, a pollutant released far from populations may not affect health significantly, while a pollutant released in the direct proximity of people can have a major effect, even if released in relatively small amounts. The metric used to compare such situations is called "intake fraction" (iF) which for airborne pollutants is simply the amount inhaled by the population divided by the amount released (Bennett et al. 2002). The difference between major categories of pollution can be several orders of magnitude as illustrated by Figure 7.1 below.

Such differences in intake fraction explain how a relatively small amount of pollution released from household cookstoves, which is emitted right in the breathing zones of the family, can have more impact than much more pollution released from, for example, a large power plant.

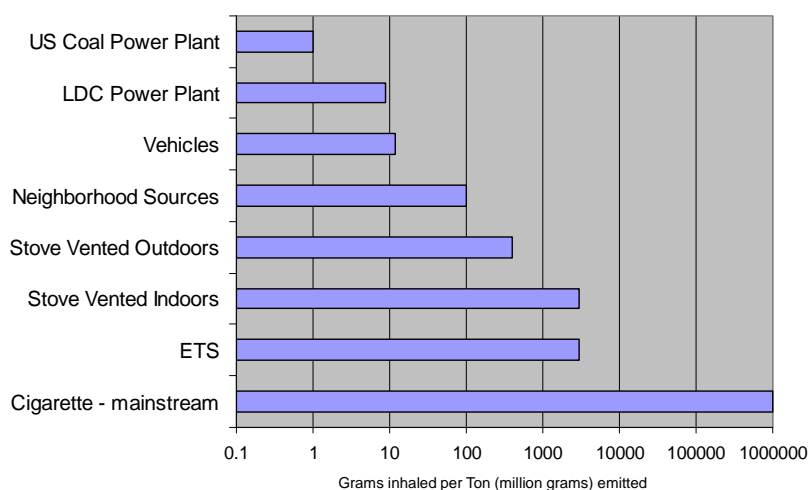


Figure 7.1. Illustrative examples of intake fractions for typical sources of air pollution expressed as grams breathed in per ton emitted (Smith 1993).

## 7.3 Impacts on the Natural Environment

### 7.3.1 Overview of Environmental Impacts

Table 7.2 presents a qualitative overview of impacts on the natural environment by major component affected and type of impact and also lists the dominant<sup>20</sup> anthropogenic source.

It is noteworthy that energy constitutes the dominant source of environmental impacts in 9 out of 18 environmental stressors summarized in Table 7.2. Equally important is to realize that any particular pollutant can have multiple impacts. Emissions of CO<sub>2</sub> lead to increases in CO<sub>2</sub> concentration that in turn affect climate and cause ocean acidification as well. Sulfur emissions impact the environment at multiple scales: at the local scale they affect human health, plant life, and can cause corrosion of buildings and structures, at the regional scale they contribute to acidic deposition (“acid rain”) causing acidification of soils and water bodies, and at the regional and global scale sulfate aerosols exercise an important impact on climate (cooling effect that masks part of the global warming signal arising from increasing greenhouse gas concentrations). It is beyond the scope of this Primer to review in detail the multitude of

<sup>20</sup> An anthropogenic activity is classified as dominant here if it either accounts for more than 50% of the total or constitutes the single largest source. This categorization can be very time dependent. For instance, industrial sources had dominated mercury emissions in the 1992 and 2004. With successful policy induced emission reductions from industrial sources, now coal combustion is the single largest source of anthropogenic mercury emissions (UNEP, 2008).

environmental impacts. Instead, below Section summarizes the major source categories of pollution where energy plays a dominant role: air pollutants.<sup>21</sup>

Table 7.2. Overview of major environmental impacts on the natural environment, major components affected and dominant anthropogenic source for the situation around the year 2005. Source: adapted/updated from Holdren, 1992; WEA, 2004; Emberson et al., 2011.

Source: adapted/updated from Holdren, 1992; Wern, 2001; Emerson et al., 2011.								
		impacting:						
environmental stressor	caused mainly by:	resources	biodiversity	land	soil	water	air	climate
Resource use:								
extraction of fossil fuels	Energy	X	X	X	X	X	X	X
extraction of minerals	Industry	X	X	X	X	X	X	
land use	Agriculture		X	X	X	X		
water use	Agriculture					X		
Nutrient cycles and impacts on land and water:								
nitrogen fixation	Agriculture				X	X		X
phosphorous cycle	Agriculture				X	X		
Pollutant emissions:								
Oil spills	Energy					X		
Cadmium	Industry				X	X		
Mercury	Energy				X	X		
Lead	Industry				X	X		
Sulfur	Energy				X (1)	X (1)	X	X
Nitrogen (NOx)	Energy				X (1)	X (1)	X	X
Carbon (BC/OC/CO)	Energy						X	X
var. chemicals (VOCs)	Energy						X	X
Particulates	Energy						X	
Greenhouse gases:								
CO2	Energy					X (2)		X
CH4	Agriculture							X
N2O	Agriculture							X
(1) acidic deposition								
(2) ocean acidification								

### 7.3.2 Air Pollutants

Table 7.3 summarizes the major sources of global GHGs and selected pollutant emissions. The main pollutants emitted in the combustion of fossil fuels are sulfur and nitrogen oxides, carbon monoxide, and black and organic carbon, including suspended particulate matter. In addition, fossil fuel combustion in the energy sector produces more CO<sub>2</sub> than any other human activity, and contributes to about 30% of global methane (CH<sub>4</sub>) emissions. Altogether, the energy sector is thus the biggest source of anthropogenic GHG emissions that are changing the composition of the atmosphere.

<sup>21</sup> This Primer does not suggest that other pollutants and emissions sources are not important, but rather that their assessment is beyond the scope of this energy focused précis.

Table 7.3. Global GHG and pollutant emissions by source for the year 2005. Sources: data from Lamarque et al., 2010; Smith et al., 2011; IPCC-RCP database (<http://www.iiasa.ac.at/web-apps/tnt/RcpDb>); Houghton, 2008; GEA Chapter 17, Riahi et al., 2012.

	Pollutant Emissions							Main Greenhouse Gases		
	Sulfur TgSO <sub>2</sub>	NO <sub>x</sub> TgNO <sub>2</sub>	BC Tg	OC Tg	CO Tg	VOC Tg	PM2.5 Tg	CO <sub>2</sub> PgCO <sub>2</sub>	CH <sub>4</sub> Tg	N <sub>2</sub> O Tg
<b>Energy &amp; Industry</b>	110.0	106.5	5.1	12.2	561.0	131.1	34.6	26.5	105.2	-
international shipping	13.1	18.8	0.1	0.1	1.3	3.1	-	-	0.5	-
transport	3.4	34.6	1.2	1.3	162.0	28.5	2.9	-	1.0	-
industry	27.0	17.2	1.6	2.3	115.3	31.8	13.2	-	0.9	-
residential & commercial	8.8	9.6	2.1	8.2	261.3	38.6	15.7	-	14.3	-
energy Conversion	57.7	26.3	0.1	0.3	21.1	29.1	2.8	-	88.5	-
<b>Non-Energy</b>	4.1	20.8	1.6	23.6	475.3	81.8	32.2	6.8	233.4	-
agriculture (animals, rice, soil)	-	2.3	-	-	-	0.8	-	-	134.4	-
waste (landfills, wastewater, incineration)	0.1	0.3	-	-	4.1	1.5	-	-	72.6	-
waste (agricultural burning on field)	0.2	0.6	0.1	0.7	19.9	2.7	-	-	1.5	-
savannah burning	1.6	11.6	1.5	10.9	222.0	35.1	-	-	8.9	-
forest fires	2.2	6.0	-	12	229.3	41.7	-	-	16.0	-
<b>TOTAL</b>	114.1	127.3	6.7	35.8	1036.3	212.9	66.8	33.3	338.6	12.1

### 7.3.2.1 CO<sub>2</sub> and other GHGs

CO<sub>2</sub> emissions from fossil energy use in 2005 are estimated at 7.2 PgC or 26.4 PgCO<sub>2</sub> (Boden et al., 2010). This represents 80% of all anthropogenic sources of CO<sub>2</sub> in that year, with the remainder associated with land-use changes (deforestation) (Houghton, 2008).

Figure 7.2 shows the historical development of fossil energy CO<sub>2</sub> emissions by major world regions (compared to global non-energy-related sources of CO<sub>2</sub>). Today's industrialized countries contribute most to the present global CO<sub>2</sub> emissions and have also emitted most of the historical emissions associated with the observed increase in atmospheric CO<sub>2</sub> concentrations. Although they are presently at lower absolute levels, emissions are growing more rapidly in developing countries. The largest source of energy-related carbon emissions are coal and oil (including oil products for feedstocks), with each about a 40% share, followed by natural gas, which represents about 20% of carbon emissions from the energy sector.

CH<sub>4</sub> is the second largest GHG contributing to anthropogenic global warming. Energy-related sources include coal production (where it is a major safety hazard), oil production (from associated natural gas), and natural gas production, transport, and distribution (leaks). Municipal solid waste, animal manure, rice cultivation, wastewater, and crop residue burning are the major non-energy-related sources of CH<sub>4</sub> emissions. While CH<sub>4</sub> emissions from energy accounted for only 30% of total CH<sub>4</sub> emissions in 2005, the relative share of the energy sector has been continuously increasing due to the rise of fossil fuel use throughout the 20th century (see Figure 7.2).

Other GHGs include nitrous oxide (N<sub>2</sub>O), tetrafluoromethane (CF<sub>4</sub>), sulfur hexafluoride (SF<sub>6</sub>), and different types of ozone-depleting hydro-fluoro-carbons (HFCs). These gases are predominantly emitted from non-energy sectors. N<sub>2</sub>O is the largest contributor to global

warming among these other GHGs (IPCC, 2001). Important sources of  $N_2O$  include agricultural soil, animal manure, sewage, industry, automobiles, and biomass burning, with energy contributing about 5% to total  $N_2O$  emissions.  $CF_4$ ,  $SF_6$ , and HFCs are predominantly emitted by various industrial sources, with only minor contributions from the energy sector (and are, therefore, not reported separately here).

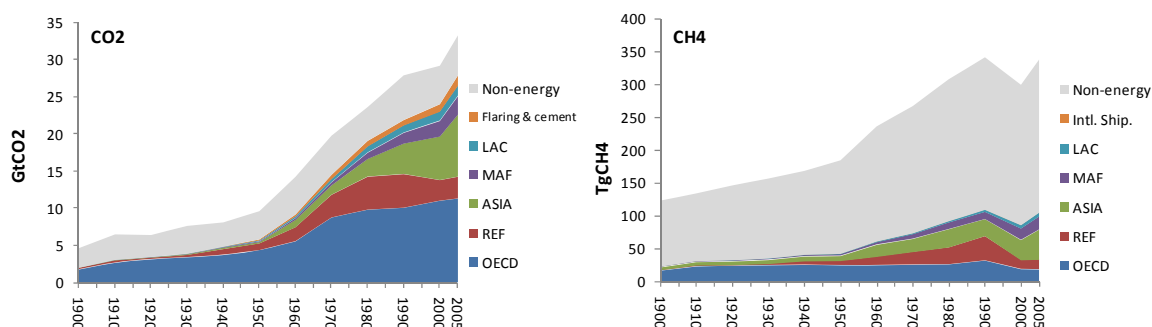


Figure 7.2. Development of energy-related  $CO_2$  and  $CH_4$  emissions by region (compared to global non-energy sources) from 1900 to 2005 in Pg ( $CO_2$ ) and Tg ( $CH_4$ ). Source: data from Boden et al., 2010; Houghton, 2008; IPCC-RCP database [www.iiasa.ac.at/web-apps/tnt/RcpDb](http://www.iiasa.ac.at/web-apps/tnt/RcpDb).

### 7.3.2.2 Traditional Pollutants ( $SO_x$ , $NO_x$ , Particulates, etc.)

Energy-related air pollution is responsible for a number of health effects including increased mortality and morbidity from cardio-respiratory diseases (Brunekreef and Holgate, 2002 and Section 7.2 above). Developing countries in particular face the greatest burden of impacts from air pollution, both outdoor and indoor. They tend to have high long-term levels of exposure from pollution sources such as forest fires, biomass burning, coal-fired power plants, vehicles, and industrial facilities, thus implying relatively high health impacts. In addition, indoor air pollution due to the lack of access to clean cooking fuels adds to exposure to air pollution, particularly in large parts of Asia and Africa. According to the World Health Report 2002, indoor air pollution is the second largest environmental contributor to ill health, behind unsafe water and sanitation (WHO, 2002).

Figure 7.3 shows the historical development of selected pollutant emissions by major world regions (compared to global non-energy-related sources). It builds upon the collaboration of major inventory experts (Lamarque et al., 2010; Smith et al., 2011).

Unfortunately for some important pollutants, such as lead or particulate matter, comparable global inventories with historical trends do not exist. Information for these pollutants is usually summarized at the regional, national, or city level only. Below, the trends for various pollutants are summarized, starting with those that are dominated by emissions from the energy sector.

Anthropogenic sulfur emissions have resulted in greatly increased sulfur deposition and atmospheric sulfate loadings and acidic deposition in and around most industrialized areas (Smith et al., 2011). High levels of ambient sulfur concentrations impact human health and cause corrosion. Sulfuric acid deposition can be detrimental to ecosystems, harming aquatic animals and plants, and is also damaging a wide range of terrestrial plant life. In addition, sulfur dioxide forms sulfate aerosols that have a significant effect on global and regional climates. The effect on global climate change of sulfate aerosols may be second only to that caused by  $CO_2$ ,

albeit in the opposite direction (Forster et al., 2007). Stratospheric sulfate aerosols back-scatter incoming solar radiation, producing (regional) cooling effects that mask the global warming signal from increased atmospheric concentration of GHGs. Sulfur is ubiquitous in the biosphere and often occurs in relatively high concentrations in fossil fuels, with coal and crude oil deposits commonly containing 1–2% sulfur by weight (and much higher in some deposits). The widespread combustion of fossil fuels from the energy sector has, therefore, greatly increased sulfur emissions into the atmosphere, with the anthropogenic component now substantially greater than natural emissions on a global basis (Smith et al., 2001; 2011). More than 90% of present sulfur emissions are released from the energy sector. Historically, global emissions peaked in the early 1970s due to the tightening of air pollution legislation particularly in industrialized countries and were decreasing until 2000. Sulfur emissions have resurged since (see Figure 7.3), with increased coal-related emissions in China, international shipping (using heavy fuel or “bunker” oil that has a particularly high sulfur content), and developing countries in general (Smith et al., 2011).

Emissions from nitrogen oxides ( $\text{NO}_x$  – predominantly nitrogen dioxide and nitric oxide) contribute to a wide variety of health and environmental problems (respiratory diseases such as asthma, emphysema, and bronchitis; heart disease; damage to lung tissue; acid rain).  $\text{NO}_x$  is also a main component of ground-level ozone and smog and thus contributes to global warming. Similar to sulfur,  $\text{NO}_x$  emissions are dominated by the energy sector, which accounts for more than 80% of total anthropogenic  $\text{NO}_x$  emissions. Emissions from  $\text{NO}_x$  have continuously been increasing with the use of fossil fuels at the global level. Emissions trends differ significantly, however, at the regional level. While control measures in industrialized countries have resulted in improved air quality and decreasing  $\text{NO}_x$  emissions since the early 1980s, the rapid increase in  $\text{NO}_x$  emissions in Asia and from international shipping have more than compensated for improvements elsewhere, leading to an overall global increase in emissions (see Figure 7.3).

The incomplete combustion of carbon-containing fuels (fossil as well as biomass) causes emissions of carbon monoxide and other pollutants, including particulate matter, black carbon, and organic carbon.<sup>22</sup> In addition, black carbon strongly absorbs solar radiation and is contributing to climate warming (although its net aggregated effect is subject to uncertainty), and its deposition is a significant contributor to Arctic ice-melt. In 2005, combustion from the energy sector contributed about 75% of the total anthropogenic emissions of black carbon, with forest fires and savannah burning accounting for the remainder. Due to relatively higher emissions coefficients of organic carbon and carbon monoxide from vegetation fires, the contribution of the energy sector is between 35% and 50% and thus smaller than for black carbon (see Table 7.3 above). Historically, industrialized countries were once the primary source of emissions from incomplete combustion. However, emissions of black carbon and organic carbon in the industrialized world have been declining since the 1920s, as have those of carbon monoxide since the 1980s. Major drivers of this trend are improved technology and the introduction of air quality legislation. Today, the majority of energy-related emissions from incomplete combustion occur in developing countries (see Figure 7.3), resulting in significant health risks, particularly from household combustion of solid fuels (mostly biomass) that affect

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<sup>22</sup> Black carbon: pure carbon (soot) emitted (“black smoke”) from the combustion of fossil fuels, biofuels and other biomass (vegetation burning). It absorbs sunlight and reradiates heat into the atmosphere, thus producing a climate warming effect. Organic carbon: carbon combined with oxygen/hydrogen atoms (organic radicals) mainly arising from the incomplete combustion (“brown” or “white smoke”) of biomass. Organic carbon aerosols (fine particles suspended in the atmosphere) tend to back-scatter sunlight, producing a cooling effect on climate.



between half and three-quarters of the population in most poor countries, particularly in rural areas.

Volatile Organic Compounds (VOCs) are emitted by a variety of sources, including industrial processes (solvents), on-road vehicles, refineries, vegetation fires, and residential wood burning, as well as emanations from a wide array of household products. Total global anthropogenic VOC emissions are estimated at about 220 Tg in 2005, with the energy and industry sectors accounting for about 60% of the total. VOCs contribute to the formation of ground-level ozone and include a variety of chemicals, some of which have short- and long-term adverse health effects. As for other pollutants, the energy and industrial emissions have been increasing substantially, and in the recent decades the major sources of VOCs have moved from the industrialized world to developing countries, which contribute about 75% of present energy and industrial VOC emissions.

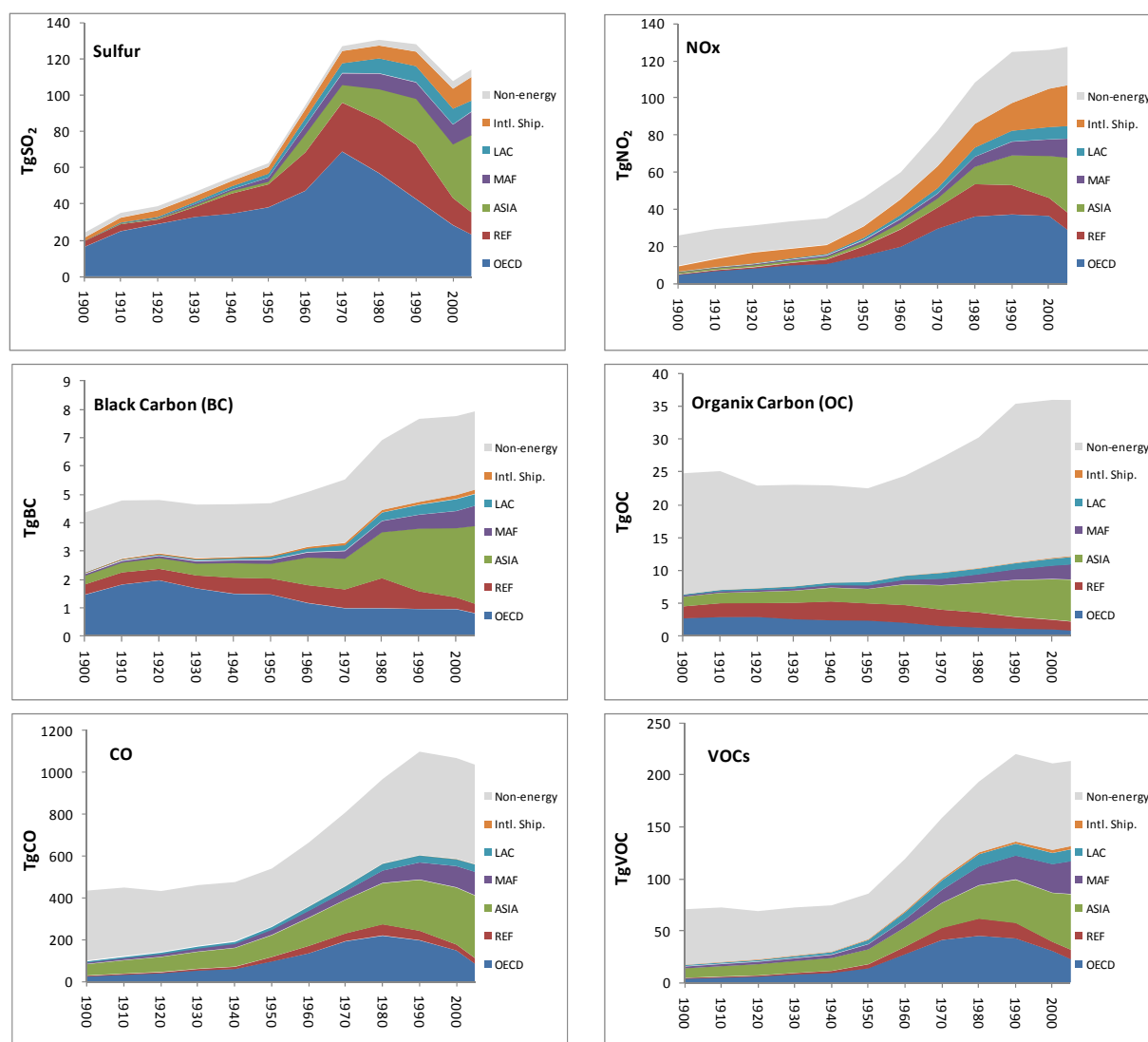


Figure 7.3. Development of energy-related pollutant emissions in Tg: sulfur (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), black carbon (BC), organic carbon (OC), carbon monoxide (CO), and volatile

organic compounds (VOCs) by region (colors), compared to global non-energy sources (grey) from 1900 to 2005.

## 8 Heterogeneity in Energy Use

In addition to the temporal variations in energy use described above, there is a wide degree of heterogeneity in energy use across the globe: between countries, between industries, and between energy users. While aggregate energy statistics are insightful for describing the energy system globally, regionally, or nationally, they often mask large disparities in energy use both across and within national and regional boundaries. Heterogeneities are evident both in the quantities of energy used and in the structure of energy use across different nations and sub-populations. These disparities stem, for the most part, from differences in incomes, production and consumption activities, and different lifestyles. A small part of these variations reflect also differences in climatic conditions and thus energy service needs across regions (e.g., heating/cooling energy demands). Differences also exist in the types of energy carriers that are predominantly used and the levels of access to these across countries and populations.

### 8.1 Heterogeneity in Energy Use across Nations

Akin to the uneven development of economies around the world, energy use and services provision vary significantly across countries. In 2005, the total final energy use was about 330 EJ globally, with the average per capita final energy use about 50 GJ. However, this global average conceals enormous differences in final energy use per capita across nations. The starkest disparity in average national final energy use per capita can be found by comparing Qatar, the country with the highest average in 2005 (445 GJ/capita), with Eritrea, that with the lowest (<5 GJ/capita), a difference of a factor of close to 100. The OECD countries, with less than a sixth of the world's population, account for over 45% of total final energy use (see Figure 8.1). Developing countries, with about four-fifths of the world's population, account for just under 40% of final energy use. OECD countries on average consume over 16 times as much final energy per capita than developing countries in South Asia and Africa.

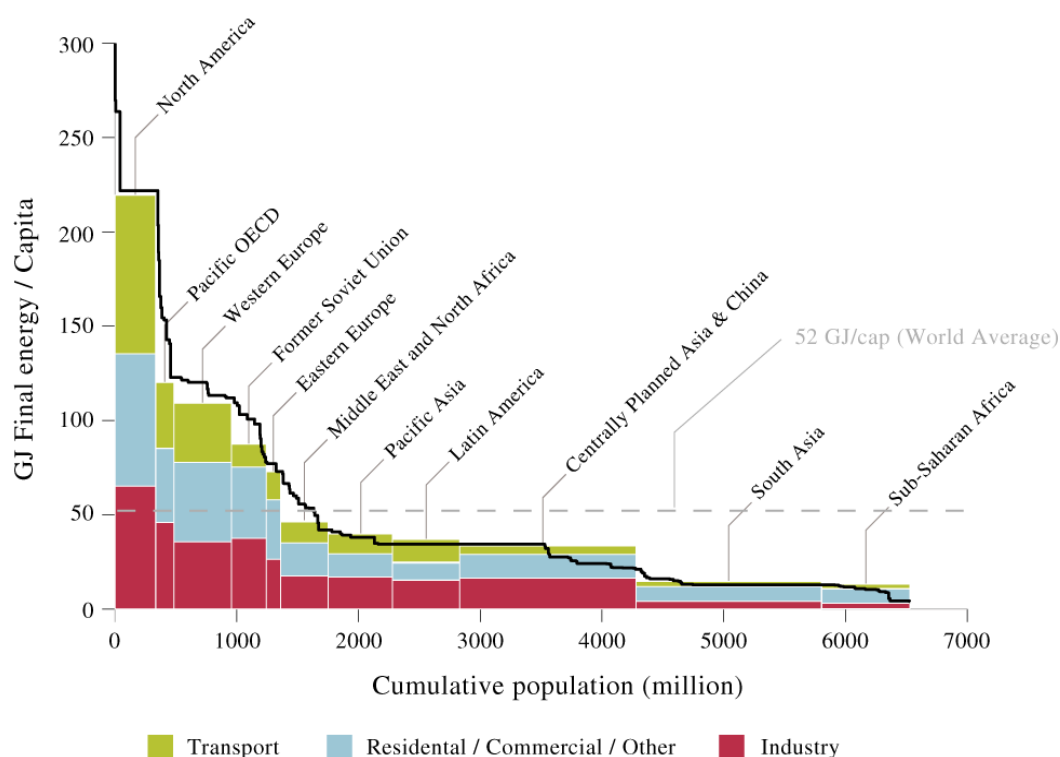


Figure 8.1. World final energy (GJ) per capita versus cumulative population for 11 GEA regions sorted by declining per capita energy use (with final energy use disaggregated by sector and total, color bars); and total per capita final energy use for 137 countries in 2005 (black, solid line).

Dashed horizontal line shows the average global final energy use per capita. Source: data from IEA, 2010.

Differences in the amounts of final energy use per capita are mirrored in variations in the structure of energy use across regions and nations. In general, countries with higher levels of energy use per capita also use a larger proportion of their total final energy for transportation. For instance, the OECD countries use over a third of their final energy for transport. In contrast, in Africa and Asia, over 40% of final energy is for residential and commercial uses with typically only 15-20% for transport. Finally, in addition to variations in the levels and purposes of energy use across nations, countries also exhibit very divergent patterns in the forms of energy used. Nearly a third of all final energy use in developing countries is unprocessed biomass, with this fraction being close to 90% for some least-developed countries. In addition, about 20% of the population in developing countries lack access to, and so do not use, any electricity. In developed OECD countries, almost all final energy use is in the form of electricity or oil/gas products. These differences in patterns have implications for the level of energy services available across nations, as some carriers like traditional biomass used in traditional end-use devices like open-fire cookstoves have very low efficiencies, and are associated with high emissions and social externalities.

## 8.2 Heterogeneity in Energy Use within Nations

Often the variance in energy use within nations can be of the same or greater order of magnitude as that across nations. In such instances, aggregate national indicators disguise intra-national

disparities, sometimes significantly. Within nations, substantial differences in energy use exist across geographical regions, rural versus urban residents, and among other socio-economic and demographic sub-groups of the population. Spatial patterns of economic development and industrial activity are reflected in variations in quantities and structures of energy use within countries. In many developing countries, one can find evidence of a dual economy with substantial disparities in quantities and types of energy use between rural hinterlands, with poor infrastructure and low levels of economic development, and urban metropolitan areas that are the centers of industrial production and economic activity. Thus, for instance, as shown in Figure 8.2, the poorest 20% of the rural population in India have per capita energy use levels comparable to those estimated for the pre-agrarian European population some 10,000 years ago. Even the richest 20% of the rural population in India use only about half as much energy per capita as the richest 20% of India's urban population, with their energy use levels comparable to the estimates for China in 100 B.C. Some of this difference in the quantity of energy used can be explained by disparities in income levels across rural and urban regions. However, large disparities in the structure of energy use are also evident, both in terms of uses of energy and the types of energy used, which largely reflects differences in access to modern energy forms and infrastructures.

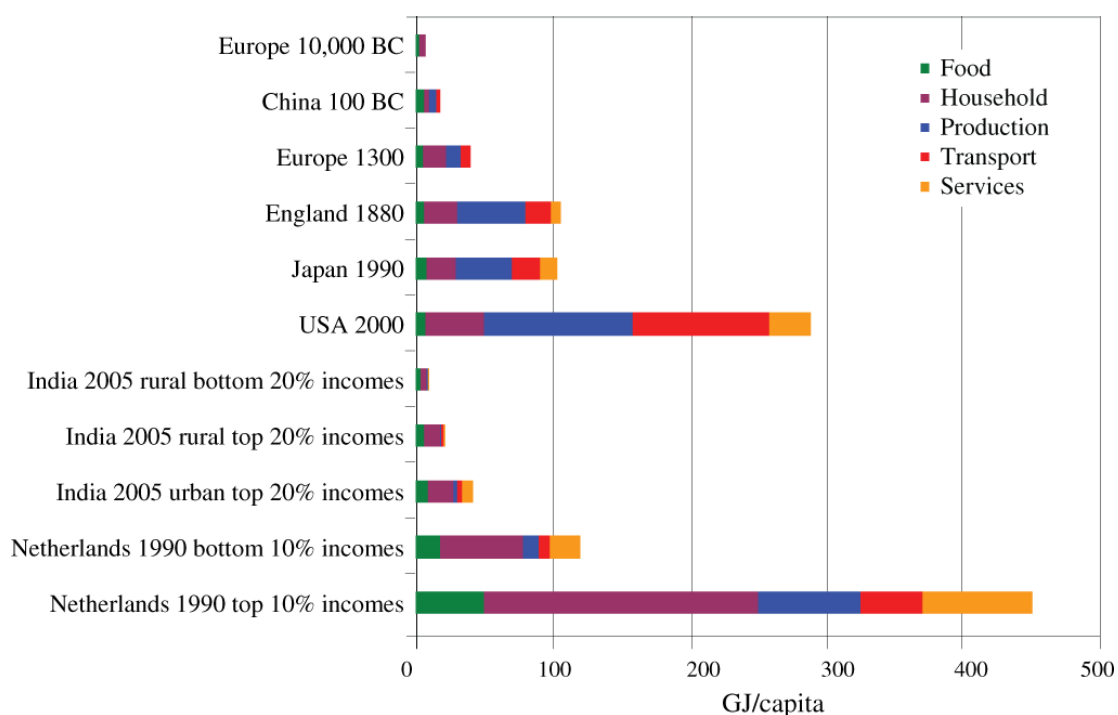


Figure 8.2. Per capita primary energy use by service category over time and across different populations. Sources: historical estimates: Smil, 1991; Japan, United States: IEA, 2010; India: Pachauri, 2007; Netherlands: Vringer and Block, 1995.

The starkest disparities in energy use within (and between) nations are those between rich and poor people. Thus, as Figure 8.2 illustrates, the richest decile (top 10% in terms of income) of the Dutch population uses almost four times as much energy per capita as the poorest decile, which is about the same order of difference as between the richest and poorest urban Indian quintiles (lowest 20% in terms of income). The richest 20% of urban Indians use only a third as much of the energy used by the poorest 10% of the Dutch, albeit the richest 20% in India will

include many examples of very wealthy individuals whose energy use vastly surpasses that of the Dutch top 10% income class. As such, these illustrative numbers reflect the wide disparities in incomes and development levels across and within nations. The richest Dutch also use almost three times as much energy for food on average as their poorest compatriots. This, of course, does not imply that rich people eat three times as much as poor people in the Netherlands. However, the food habits and types of provisions consumed do differ. For instance, the rich Dutch eat more exotic fruits and vegetables (e.g., Kiwi fruit flown in from New Zealand) than the poor which explain their much larger food-related (embodied) energy use. The biggest differences in the structure of energy use between rich and poor people, both within and across nations, is the substantially larger share of energy used for transport and for the consumption of products and services. Poor people, by contrast, use the largest proportion of energy for basic necessities such as food and household fuels (cooking and hygiene). These differences illustrate the substantial variations in lifestyles and growing consumerism evident with rising incomes and retail market sophistication.

As an illustration of differences in living standards, consumption patterns, energy access and what this implies both in terms of energy use and the services that this quantity of energy delivers for two very disparate population groups, Box 4 compares an average poor (bottom 25% income) rural Indian with a top decile Dutch citizen. The population in the poorest rural quintile in India consumes 50 times less total energy per capita on average than the top decile of the Dutch population. This comparison is in terms of primary energy use i.e., it is inclusive of all direct and embodied energy used by these two respective groups. For the poor rural Indian about half of the total energy is used directly for household lighting and cooking, while about 40% is energy embodied in food consumption and the remaining 10% is the energy embodied in all other non-food household consumption. For the rich Dutch, about a third of the total energy is used directly for purposes such as lighting, cooking, heating and to run home appliances, whereas only about 10% is energy embodied in food consumption and over 50% is energy embodied in other non-food consumption.

Box 5: Contrasting the Energy Use and Services Available to the Poorest Rural Indian and Richest Dutch Citizens

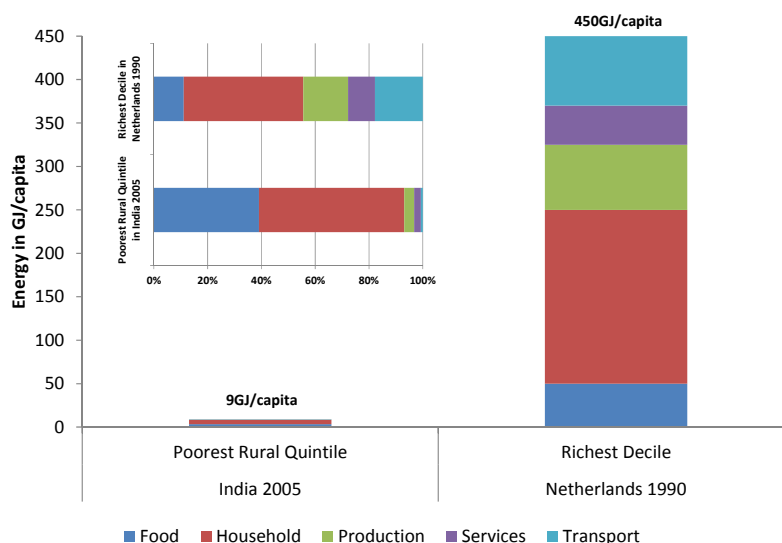


Figure 8.3. Structure of per capita primary energy use by service category (direct and embodied energy) for the bottom rural Indian income quintile (bottom 25%) and top Dutch decile (top 10%) in absolute amounts (GJ/year/capita) and in structure (percent, insert). Sources: Figure 8.2, India: Pachauri, 2007; Netherlands: Vringer and Blok, 1995.

Table 8.1. Characterization of the consumption patterns and lifestyles of the poorest Indian and richest Dutch.

Service Category	Per capita consumption/use within the poorest rural Indian quintile 2005	Per capita consumption/use within the richest Dutch decile 1990
<b>Food</b>	A diet comprising of largely cereals (< 70kg of rice and <50kg of wheat) and lentils (<8kg), with very limited self-grown seasonally available fresh vegetables and fruits or dairy products (<5kg of fruits and vegetables). No, or rare meat and fish consumption to celebrate special occasions (<3kg annually). Nutrient and calorie intake often below recommended dietary standards. Over half of the population in this group have a calorie intake less than 80% below recommended standards and are considered under or malnourished.	The Dutch consumes a diet of plenty with a large proportion of glasshouse or imported exotic fruits and vegetables, frozen and processed foods, meats, dairy and fats. On average about 80 liters of beer, 22 liters of wine, 810 cigarettes, about 130L soda and juice, about 120kg of dairy products, 87kg of meat, 60kg fresh vegetables, 75kg fresh fruit, about 80kg potatoes, over 10kg of sugar and candy, about 180 eggs, about 60kg bread, about 44kg wheat flour, 20kg snacks, about 16kg fats are consumed annually. About 10% of the Dutch are obese and have a food intake above recommended norms.
<b>Household</b>	A thatched clay and brick semi-permanent dwelling with an average living space of <6 square meters per capita. No sanitation facilities or piped water supply in house. One hot meal a day on average cooked on an open fire or artisan made traditional stove using about 1 kg of biomass per capita a day for fuel. 2-3 hours of poor quality lighting from candles and a primitive kerosene lantern consuming 0.5 liters of fuel per capita per month. Almost no appliances other than a small transistor radio run on batteries.	A brick house or wooden frame house with a tiled roof. A nationwide, average of 139m <sup>2</sup> of dwelling surface (in terms of terrain so not taking into account different layers). Among the rich living space per capita exceeds 50m <sup>2</sup> . An average of 1-1.5 hot meals a day, prepared in a fully equipped kitchen with a gas or electric range, no constraints on lighting, all modern electronics. In the highest income quintile, most people own their house and an additional holiday home. Average electricity consumption of 5600 kWh, natural gas 3250m
<b>Production</b>	Few personal effects and furniture – ownerships of few clothing and footwear, some bedding, some kitchen utensils, a few rudimentary household tools, and agricultural implements. Perhaps a bicycle.	More than 1.5 cars on average for the upper income quintile. A fully equipped kitchen, plenty of clothes, tools, televisions, music systems, computers, refrigerators, washing machines and other home appliances and equipment.
<b>Services</b>	No banking, a primary school in the village, secondary school and public health facilities at a distance of <5km for only 65% of Indian villages. One public telephone (landline) service in the village. No entertainment services other than singing and dancing by the locals on festivals and celebrations. If the village has an electricity connection, the local landlord may have a television which the other inhabitants get to view.	Banking available virtually everywhere. Schools within an average distance of 0.6km for primary education, 2.4-3.2km for secondary education. All medical, groceries, convenience, recreational facilities and local railway station within a distance of 5km or less.
<b>Transport</b>	An average distance of <5km per capita per day traveled either on foot or by bicycle. Occasional longer distance travel to local markets or public health facilities either by bus (if roads and public bus service available) or bullock cart or renting space on a tractor.	Nationwide, the Dutch travel on average 32.58km per capita per day by all means (little by foot). The rich make two-thirds of their trips by car. Persons in the top income decile take 2.32 short and 2.26 long holidays per year often traveled by flight or train.

Source: Data for India from NSSO 2007; for the Netherlands from <http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=37154&D1=a&D2=0-1,11,21,31,41,51,61,71,91-110&HDR=G1&STB=T&VW=T>



The income differences between these two groups are even starker, with the poor rural Indian earning about \$300<sub>2005PPP</sub> (i.e., less than the \$1 per day) and the rich Dutch earning about \$48,445<sub>2005PPP</sub>. Globally, about 1.4 billion people were estimated to be living on less than \$1.25 a day in 2005. Over 70% of them live in sub-Saharan Africa and South Asia and have a lifestyle similar to that of a poor rural Indian. By contrast, about 200 million people globally, most of whom live in OECD countries, are in the income bracket of the top 10% Dutch (Pinkovskiy and Sala-i-Martin 2009) and live a similar lifestyle.

### 8.3 Disparities in Energy Use

While fairness and equity are normative, ethical concepts, several methodologies and metrics exist to measure dispersions and distributions which help to describe disparities in energy use. Lorenz curves and Gini indices or coefficients are widely used to measure inequalities in income and wealth. The Lorenz curve is a graphical representation of a cumulative distribution function, often with a ranked cumulative distribution of population on the x-axis against a ranked distribution of cumulative value of a given variable such as income, wealth, or energy on the y-axis. A perfectly equal distribution is described by a straight line where  $y = x$  along the diagonal or along 45 degrees, where every given percentage of the population consumes or owns an equal percentage of the variable in question (e.g., energy, wealth, etc.). The greater the distance of the Lorenz curve from this diagonal, the greater the degree of inequality it represents. The Gini coefficient, also used as a measure of inequality, is mathematically represented as the ratio of the area between a Lorenz curve and the diagonal (or line of perfect equality) to the total area under the diagonal. The Gini coefficient can range from 0 to 1, with a value closer to 0 representing a more equal distribution. In addition to Lorenz curves and Gini coefficients, other measures of inequality commonly in use are ratios of percentiles, deciles, quintiles, or quartiles of the population.

Figure 8.4 illustrates inequality across nations by depicting the Lorenz curves for important energy and economic variables for the year 2005. The x-axis depicts the ranked cumulative distribution of population by nation, while the cumulative disposal of income (in PPP terms), final energy, and electricity are shown on the y-axis.

In terms of income and final energy use, the poorest 40% of the world's population only disposes of some 10% of global income and final energy use; the richest third disposes of two-thirds of global income and final energy. It is noteworthy that final energy use mirrors prevailing (vast) income inequalities closely. Energy and economic poverty and wealth thus go hand in hand. Access to electricity is even more inequitable. In 2005, some 23% of the world's population (1.4 billion people) had no access to electricity at all.

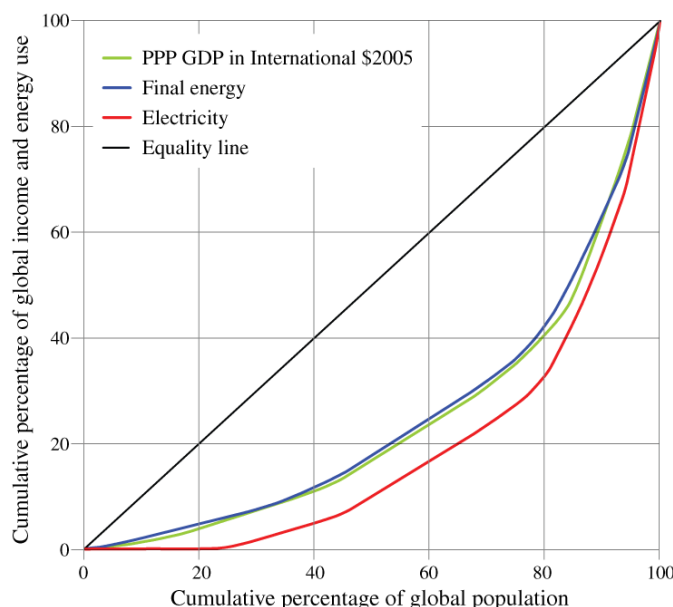


Figure 8.4. Lorenz curves of energy inequality, measuring cumulative global population (in percent) disposing of corresponding fraction of cumulative income (in percent of PPP\$ (green), final energy (blue), and electricity use (red) (in percent of Joules energy used) for the Year 2005. Due to data limitations, the figure is based on national statistics and therefore does not account for inequalities within countries, therefore underestimate global inequality. Sources: national data from IEA, 2010 and UNDP and WHO, 2009.

#### 8.4 Changes in Energy Use with Rising Incomes and Improved Energy Access

As incomes rise, people consume more of the same goods and services and shift towards consuming also higher quality goods and services. The same trend is evident in the case of energy services too. Higher quality energy carriers or fuels provide more economic value per unit energy consumed as they can be converted more efficiently into energy services. They are also more flexible and convenient to use, producing less local pollution. This is a primary reason for the observed energy transitions towards more high quality processed fuels (liquids, gases, and electricity) that have occurred historically in most industrialized nations (Grubler 2008). Evidence of this transition is present even today, particularly when we examine the share of primary biomass for the poor nations of today and the historical trends in already developed or newly emerging economies over the last century. Figure 8.5 depicts the share of biomass in final energy for the world as a whole and a select group of nations plotted against their national GDP (in 1990GK\$)<sup>23</sup> covering the period between 1870 and 2010. While there has been an overall decline in the share of biomass in final energy with development, low incomes and the lack of access to alternative fuels explain the continuing high share of biomass in some nations even today. Globally, the share of biomass has hovered at around 12% over the last 3-4 decades.

<sup>23</sup> The Geary-Khamis dollar (GK\$), more commonly known as the international dollar, is a hypothetical unit of currency that has the same purchasing power that the U.S. dollar had in the United States at a given point in time. It is widely used in economics to compare monetary values across nations using the purchasing power parity (PPP) concept. (See also the discussion in Section 3.3 above).

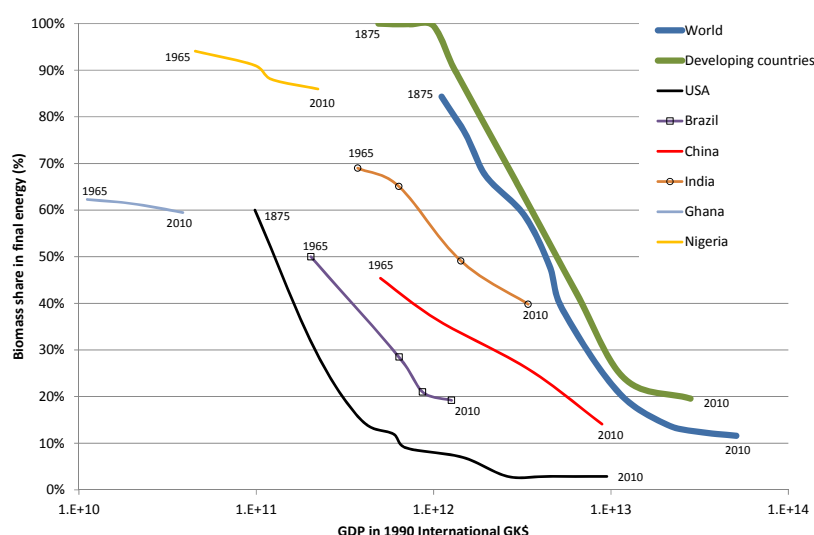


Figure 8.5. Share of biomass in primary energy mix for select nations and for the World between 1870 and 2010. Sources: Grubler, 2008, IEA, 2010, Maddison, 2008 and Victor and Victor, 2002.

Access to higher quality energy carriers is one factor responsible for the decline in the share of lower quality fuels (like solid biomass) with development, but this in turn is also a function of income. Historically, all nations have accorded high priority to providing universal access to electricity and access has improved with growth and rising income levels. Yet, many of today's poor nations have to provide access to much larger populations and starting from much lower average per capita income levels than did most industrialized nations in the past (see Figure 8.6). About a fifth of the global population still lacks access to any electricity. While some nations like China and Egypt, through committed national policies, have been successful in achieving almost universal access to electricity, other nations like India and South Africa still need to electrify between a quarter and a third of their populations. The situation in many sub-Saharan African nations is of special concern, where only 10% of the rural population is electrified even today. While the challenge is significant, the financial resources required to achieve universal access by 2030, at a global scale, are moderate (see Box 6 below).

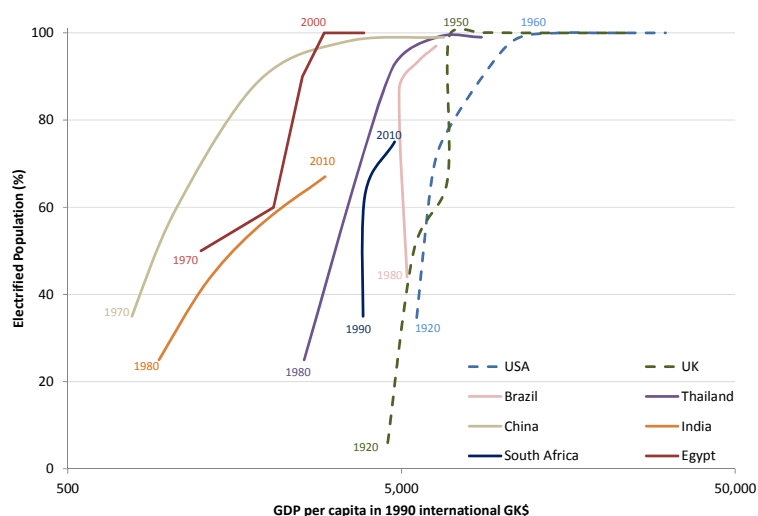


Figure 8.6. Trends in electrification for select countries (percent of population with access to electricity) between 1910 and 2010. Sources: Pachauri et al., 2012 and Maddison, 2008.

Differences in the patterns of energy use, both in terms of the types and quantities of energy used, are clearly evident when examining cross-sectional data as well (see Figure 8.7). In particular, for households in developing countries, the concept of an “energy fuel ladder” has often been used to explain how households select fuels and energy technologies (Leach, 1992; Barnes and Floor, 1996; Smith, et al., 1994) with rising incomes. According to this concept, as incomes rise, households metaphorically ascend a ladder because modern energy carriers are preferred for their higher levels of efficiency, cleanliness, and convenience of storage and use relative to crop residues, dung, firewood and other traditional solid fuels as well as coal. However, many recent empirical studies suggest that household energy transitions do not take place as a series of simple discrete steps (Masera et al., 2000; Farsi et al., 2007; Pachauri and Jiang, 2008). Multiple fuel use arises for several reasons. First, households may have significant capital invested in “traditional” technologies (e.g., wood-burning stoves) and may not have the spare capital to purchase new energy-consuming appliances immediately upon gaining access to new energy sources (Saghir, 2004). Second, modern energy sources are usually expensive and thus used sparingly and for unique services. Thus, traditional fuels and technologies tend to exit more slowly than new ones arrive. Finally, multiple fuels can provide a sense of energy security. Complete dependence on commercially-traded fuels leaves households vulnerable to variable prices and often unreliable service (Pachauri and Spreng, 2012). The traditional concept of the “energy fuel ladder” thus simplifies the household energy transition process. Households demand energy services that require both fuels and equipment, and which deliver a certain quality of service. With increasing income, households may therefore prefer to choose biomass-based fuels (e.g., pellets) rather than gas, if these can be used in efficient stoves that provide the same level of performance and convenience as gas stoves.

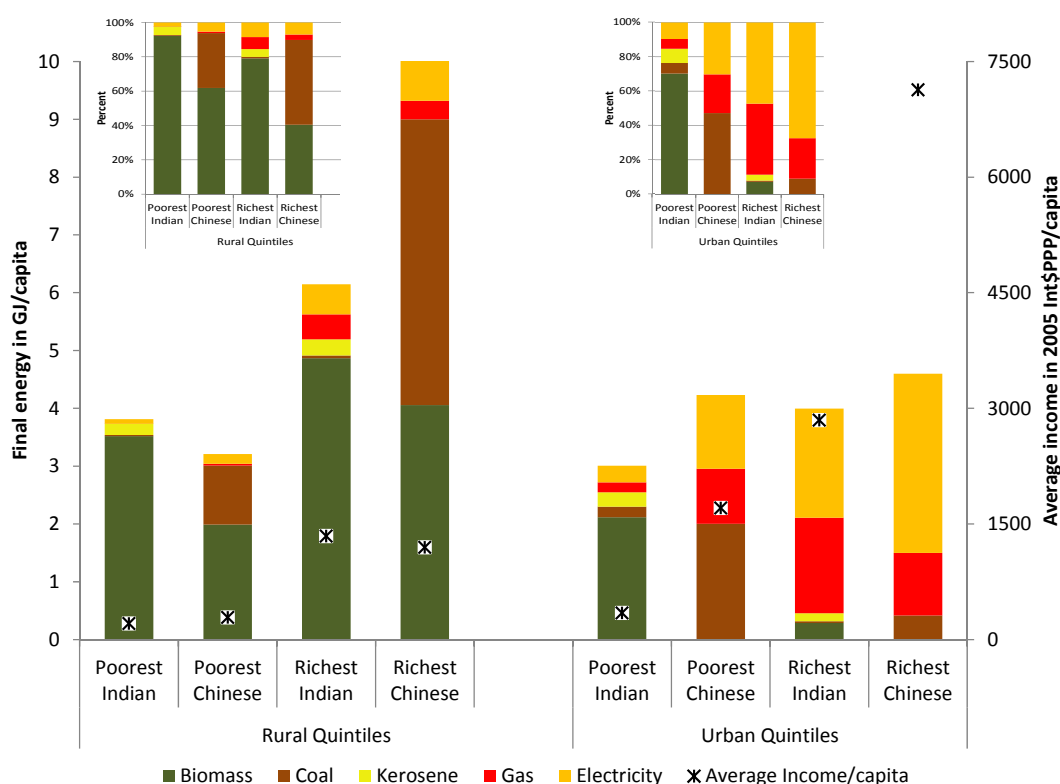


Figure 8.7. Patterns of direct household final energy use in India and China for rural (left panels) and urban (right panels) households and per income category (income quintiles) in GJ/capita final energy use (bars) and 2005PPP\$ income per year (stars). Small inserts show the same data, but as percent distribution. Sources: Riahi et al., 2012; Mainali et al., 2012; Ekholm et al., 2010.

There is also growing recognition that non-market factors (other than income and prices) can often be important in explaining energy choices, especially in rural and poor households. In particular, how households value the inconveniences associated with collecting and using traditional solid fuels is an important determinant of fuel choice (Ekholm et al., 2010; Riahi et al., 2012; Mainali et al., 2012, see also Section 9 below). Inconvenience costs capture the disutility to consumers associated with collecting and using traditional solid fuels and are reflected in the premium households are willing to pay to avoid this disutility. In general, richer households place a higher value on their time and are willing to pay a larger premium for using more convenient and efficient fuels that are however, more expensive to purchase. Hence they associate higher inconvenience costs for traditional fuels compared to poorer households. Similarly, urban households, who have higher incomes on average than rural households and more non-farm employment opportunities, are also likely to pay higher premiums on average to avoid the disutility or inconveniences associated with using traditional solid fuels. The implicit discount rates<sup>24</sup> that households use when deciding on the purchase of new equipment are also

<sup>24</sup> Implicit discount rates reflect the marginal rate of time preference that households use when discounting investment costs over the life span of technologies. It represents the trade-off to consumers between immediate consumption (partly foregone with an investment) and future consumption.

income dependent and an important factor influencing the speed of transition to modern fuels in poorer households. For many cash-strapped poor rural households, implicit discount rates can be extremely high (over 70%; see Ekholm et al., 2010). Thus, for these households, the first or upfront capital cost of purchasing new equipment can become a significant barrier to transitioning to more efficient and convenient fuels. Designing appropriate policies to accelerate a transition to modern fuels and devices among households in developing nations requires recognizing the factors that affect energy choices for these populations (see Box 6 for a brief description of the challenge of meeting a universal modern energy access goal by 2030 and the policies and costs for attaining this).

#### Box 6: Challenges and Pathways to Achieving Universal Access to Modern Energy by 2030

About 20% of humanity today still lives without access to any electricity and 40% still depends on solid fuels such as unprocessed biomass, coal, or charcoal for cooking and space heating. While many developing nations have made significant strides in improving access to modern energy, close to 90% of rural sub-Saharan Africans lack access to electricity and an equivalent percentage still rely on solid fuels. Even in emerging nations, like China and India, 75% of the rural population still uses solid fuels. Solid fuel use in households accounted for 2.2 million premature deaths in 2005, and more than 41.6 million lost Disability Adjusted Life Years due to elevated levels of household air pollution and resulting respiratory diseases, mainly affecting women and children.

The Global Energy Assessment estimates that in the absence of new policies by 2030 about 2.4 billion people in sub-Saharan Africa, South Asia and Pacific Asia will still be relying on solid fuels in their homes, and over 800 million rural inhabitants would lack electricity access. In such a scenario, over 90% of rural sub-Saharan Africans and over 80% of rural South Asians would still rely on solid fuels. Over 70% of rural sub-Saharan Africans would also continue to remain without electricity.

Access to electricity and to modern cooking energy, such as advanced low-emissions biomass cookstoves and LPG, contributes to economic development and to reducing income poverty and hunger, improving education, health, gender equality, and water and sanitation conditions for the poorest segments of society. Increased access to electricity and mechanical power enables an increase in agricultural productivity and the transformation of agrarian economies to industry-based economies. Access to mechanical power can play a vital role in enhancing income and food security, and fostering agricultural growth, small-scale enterprises and manufacturing processes in rural areas.

Improving access to modern cooking fuels alone has the potential to avert between 0.6 million and 1.8 million premature deaths, on average, every year until 2030, including between 0.4 million and 0.6 million deaths per year of children below the age of five in sub-Saharan Africa, South Asia, and Pacific Asia.

From a technical and economic perspective, providing almost universal access to electricity and modern cooking fuels is achievable by 2030. This will require global investments of US\$36-41 billion annually till 2030, which is approximately 3% of total energy infrastructure investments today. At the high end of this estimate, about half will need to be spent on electricity access and the rest on improving access to modern cooking fuels and stoves, with the most investments needed in sub-Saharan Africa.

Achieving this goal will have a negligible or even negative impact on greenhouse gas (GHG) emissions, even when a shift to fossil-based alternatives occurs. This is due to the vast



efficiency gains reaped by replacing inefficient biomass use with modern cooking fuels and kerosene for lighting with electricity. Current technologies that use traditional biomass are associated with significant emissions of greenhouse gases and aerosols due to incomplete combustion.

Supporting policies that provide a combination of subsidies and microfinance are likely to be most successful and cost-effective in achieving universal access. In addition, government-supported investments towards energy access will need to be considerably ramped up, and targeted to rural and remote areas and poor urban communities. Increasing private sector involvement will also be crucial to reach the level of scale-up in access efforts required over the next decades (Pachauri et al., 2012; Riahi et al., 2012).

## 9 Basic Energy Economics

### 9.1 Introduction

The Economist's Dictionary of Economics defines economics as “The study of the production, distribution and consumption of wealth in human society.” Energy economics is the sub discipline that studies the demand for, and the supply of, energy services, the interactions between the energy system and the overall economy as well as various levels of the environment. It analyses the roles of costs and prices, incentives, policies, market structures, among others on the ways and quantities our societies demand and use energy services and their distribution and affordability.

Energy economics complements the physical and thermodynamic aspects of energy by adding monetary values (\$) to fuels, technologies and infrastructures required to provide energy services. Thermodynamics deals with the conversion of energy (or rather energy's potential to do useful work), and with the laws governing such conversions. The first law is about energy conservation, i.e., energy cannot be created (produced) or consumed - only converted into usable and unusable parts which together amount to the original energy input to the conversion process. In essence, the first law holds that conversion efficiencies cannot exceed 100% (you cannot win). The second law reflects the simple fact that heat always flows from a hot body to a cold body but never from cold to hot. It thus places a limit on the conversion of energy into useful work (you even cannot break-even). For example, the conversion of chemical energy in coal to heat and subsequently to electricity inevitably also generates low temperature waste heat and combustion products - energy conversion also interacts with the environment.

Energy economics deals with these scarcity and waste issues predominately through costs and prices as a way to reflect resource limitations, to balance demand and supply and to increasingly internalize “externalities”, i.e., costs associated with the conversion of energy and use of energy services but not yet included in energy prices such as the degradation of common goods.

### 9.2 Costs and Prices

Unlike wine or a meal in a fancy restaurant, energy is not purchased for pleasing one's palate (or “utility” in economics speak). Energy is not an end in itself but an *intermediary good* for the provision of goods and services we actually want - food, shelter, conditioned living space, transportation, information, health care, etc. All goods and services produced, sold and consumed in an economy embody varying amounts of energy and the associated energy costs

are included in the prices we pay for goods and services. In addition, we also pay hard earned dollars for energy purchases - at the gas pump to fill up the car or on monthly electricity bills. The price of energy purchased, e.g., gasoline at the pump comprises a wide range of cost components ranging from upstream (e.g., oil exploration, production, and shipment to refineries) and downstream (e.g., refining, marketing and distribution, product sales) energy supply activities as well as taxes (which in some jurisdictions can be larger than the actual pre-tax fuel costs).

But expenditures for gasoline or electricity are only one component of the cost of the energy service getting home from work or illumination at home to read a novel. For getting home we need automobiles, roads, traffic control, etc. all of which incur costs (some costs are already paid for at the pump via the gasoline tax). To the consumer, the cost of the energy service “getting home”, therefore, is the sum of gasoline (energy) costs plus the costs of purchasing and maintaining the end use device converting energy (gasoline) into energy services (mobility), i.e., an automobile. Likewise, the costs of the energy service illumination is made up from the electricity price that covers all generation, transmission and distribution costs of electricity and the costs for a light fixture and light bulb.

To put expenditures for transportation fuels into perspective: on average American households spend 4% of annual disposable income on fuel purchases but 10.5% on other car related expenditures such as depreciation, maintenance, insurance costs, etc. Thus energy costs (gasoline) represent only about one third of the costs of providing the energy service individual automobile mobility.

In summary, any provision of an energy service requires energy (fuels) plus one or more end-use conversion devices and related infrastructures which complicates the quantification of the cost or price of an energy service as it involves both durable (a car) and non-durable (gasoline) components. Obviously, driving the car home from the workplace only once would make it an outrageously expensive service. The true service costs are also determined how often the automobile is used during its lifetime. But most importantly, the price paid at the pump is no way close to the full cost of the energy service.

So far the terms costs and prices for energy services have been used interchangeably. Indeed, cost and price are identical for an individual paying for, and also consuming, energy services. For the service provider, the price received should be larger than the cost incurred for the provision of the service. Otherwise the business is unprofitable.

### 9.3 Energy Demand

#### 9.3.1 *Basic Concepts*

The demand for fuels (energy) is a function of the quantity of energy services desired by societies, i.e., affordability - the combination of income and service prices - and the performance of energy service or end-use technologies. Using the example of providing transportation services for individual mobility, at a given level of affordability (proxy used here is the gasoline price  $p_0$  and an income of  $Y_0$  \$/yr) a person who just bought herself a second-hand car, expects to drive it 15,000 km per year commuting between the home and the workplace. The amount of fuel demand per year is then the conversion efficiency of the engine and drivetrain of the vehicle (the specific fuel use of a car in liters per km multiplied by the km driven). The car's specific fuel use is also influenced by the driving style, payload and occupancy rate.

Now let's assume the gasoline price increases to  $p_1$  with no change in income. Motorists not willing to pay the higher price (and sacrificing other amenities to stay within their respective budgets), have several options to respond to the price change. In the short run these typically include:

- Driving less by reducing unessential travels which does not reduce the need to commute;
- Car sharing along the way to work which improves the car's occupancy rate or usage efficiency; or
- Switching to other transportation modes such public transit or biking.

In the longer run, the short-term options are supplemented by changing the service technology, a.k.a. the car, to a more efficient one with a lower specific fuel use, relocating to a home closer to the workplace or vice versa. These options require time and incur investment cost. The person in our example had just bought a second-hand car using up all her savings and cannot afford the additional costs for a higher efficiency vehicle although this would allow her to resume to the pre-price increase pattern of driving at similar costs for the service (the lower specific fuel use compensates for both the higher gasoline prices and the higher service technology costs).

Figure 9.1 depicts the short-term impact of increasing the usage efficiency  $\mu$  (higher payload) and the longer-term impact of technology change (a more efficient car, i.e., technological efficiency  $\eta$ ) on fuel demand  $E$ . At  $p_0$  and  $\mu_0$ , fuel demand amounts to  $E_0^i$ . In this example, as the technology car and the economic budget for fuel remain unchanged and consumers are unwilling to lower their demand (i.e., drive less), the price increase to  $p_1$  can only be compensated by higher usage efficiency, i.e., filling up the car with additional passengers (who leave their cars in the garage). This lowers the aggregate fuel demand along the solid curve  $T_i$  from  $E_0^i$  to  $E_1^i$ .

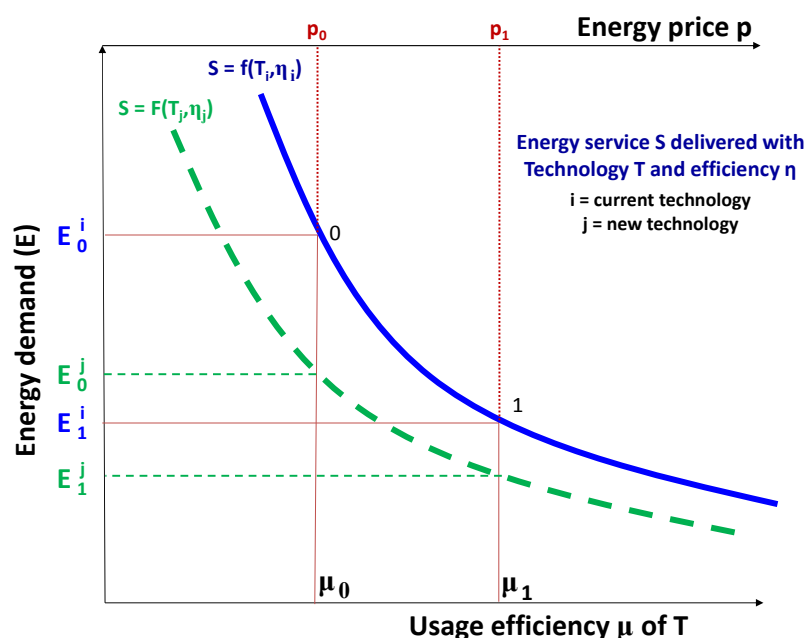


Figure 9.1. Energy demand ( $E$ ) as a function of usage efficiency ( $\mu$ ) and Technology  $T$  with technological (conversion) efficiency ( $\eta$ ) in delivering a service demand  $S$ . Note both short- and longer-term demand responses when energy prices increase from  $p_0$  to  $p_1$ : short-term response: increasing usage efficiency (from  $\mu_0$  to  $\mu_1$ ) of existing technology  $T_i$  (blue) leads to an energy demand reduction from  $E_0^i$  to  $E_1^i$ . Longer-term: use of a new conversion technology  $T_j$  (green) with improved conversion efficiency  $\eta$  leads to a demand reduction to  $E_0^j$  or  $E_1^j$  for the two original and modified usage efficiencies  $\mu_0$  and  $\mu_1$  respectively.

In the longer run, our person purchases a new, more efficient car. The solid curve now becomes the dashed technology curve  $T_j$  in Figure 9.1 and represents a new fuel demand to usage efficiency relationship where the previous usage of  $\mu_0$  without car sharing, can be obtained at the lower fuel demand  $E_0^j$ . The ultimate impact on energy demand now depends not only on the fuel efficiency of the new car  $T_j$  but also on the usage efficiency  $\mu_j$ , i.e., whether or not car sharing continues with the new, more efficient car. Important to remember is that (a) the difference between  $E_0^i$  and  $E_1^i$  is the result of a change in occupancy rate (a behavioral change) and (b) the difference between  $E_0^j$  and  $E_1^j$  reflects the impact of improved technological efficiency (a technological change). The distinction between usage and technological efficiencies also explains why the response to price changes differs between the short-term (changing usage efficiency) and longer-term (also changing technological efficiency) (see the discussion on elasticity below).

### 9.3.2 Energy Demand and Elasticities

What are the essential drivers of energy demand? Assuming for simplicity, no population growth, a given set of energy supply infrastructures and end-use technologies, energy demand is essentially determined by two economic drivers: income and energy prices. Generally, income is positively and prices are negatively correlated with energy demand: Rising incomes tend to increase energy demand, while increasing prices tend to lower energy demand. The dynamic response of demand to these economic drivers is captured in the concept of elasticity, i.e., the

responsiveness of demand to changes in its drivers or in the case of energy demand (E) to changes in income (Y) and energy prices (p) and mathematically represented as

$$E = c Y^{\alpha} p^{-\beta}$$

where  $\alpha$  and  $\beta$  denote the income and price elasticities respectively (the negative sign for the price elasticity  $\beta$  indicates its negative effect in energy demand, and the positive sign of the income elasticity  $\alpha$  indicates its positive effect in energy demand) and  $c$  is a constant reflecting the fact that even at zero income subsistence needs require some form of energy.

Examples of the responsiveness demand to different price elasticities and income levels are shown in Figure 9.2. For an income elasticity of 0.7 and constant  $c$  assumed to be 1, a doubling of income increases energy demand by  $2^{0.7}$  or by a factor of 1.6; a five-fold increase in income raises energy demand by  $5^{0.7}$  or by a factor of 3.1 (left hand axis). Likewise for any given income level, a doubling of prices with a price elasticity of -1 results in a decline of energy demand by 50% ( $2^{-1.0}$ ); a ten-fold reduces demand by 90% ( $10^{-1.0}$ ). For a price elasticity of -0.3, the demand reductions caused by a doubling of prices are 19% ( $2^{-0.3}$ ) and a ten-fold increase 50% ( $10^{-0.3}$ ), respectively. Figure 9.2 illustrates the demand responsiveness to several levels of incomes and prices in combination with a set of illustrative elasticity assumptions.

Income and price elasticities observed in the real world vary considerably over time and across different types of energy demands, economic sectors, social groups and countries (Dargay and Gately, 1999; Ajanovic et al., 2012). Yet there appears to be a common aspect across all these groupings: Higher incomes lead to *higher* energy demand but at the same time demand becomes less sensitive to price changes. Affordability cushions price effects.

As discussed above, demand responses to price changes vary significantly between the short-term and the long-term. In the short-run price elasticities are low reflecting the longevity of energy infrastructures and conversion technologies which limits demand-side responses (essentially to behavioral adjustments). In the longer run as aging technologies and infrastructures become obsolete and are progressively replaced with more efficient technologies higher price elasticities are possible. However, the time lag between the short and the long run may introduce some kind of irreversibility: When prices fall again after a price peak, demand does not respond correspondingly (different price elasticity as when price rose) – due to the previously induced improvements in technological efficiency (Walker and Wirl, 1993). Put differently, our driver from the example above will not sell the new, more efficient car and buy back the old clunker just because gasoline prices dropped back to earlier levels.

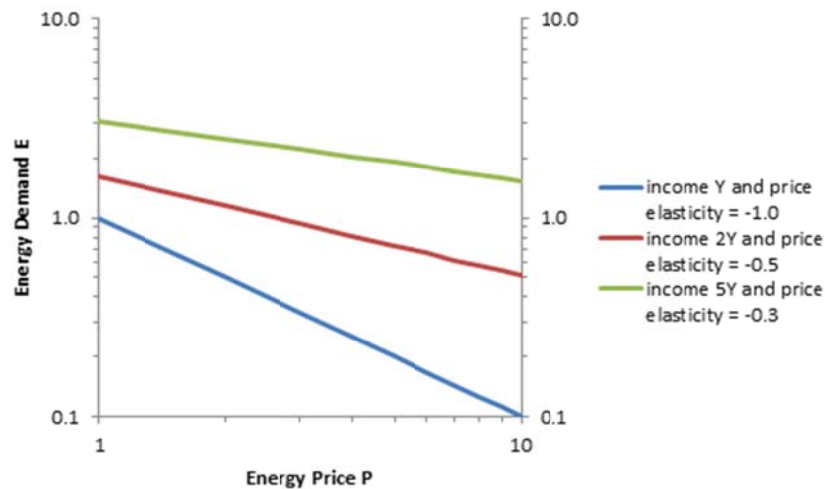


Figure 9.2. Illustrative price elasticities  $\beta = -1.0$  (blue),  $-0.5$  (red), and  $-0.3$  (green) for three different income levels  $Y$ ,  $2Y$ , and  $5Y$  with an assumed income elasticity of  $+0.7$ . Note the double logarithmic scale where the exponentially declining energy demand with increasing prices shows up as straight line.

However, the higher fuel efficiency of the new vehicle and lower gasoline prices reduce the owner's annual gasoline bill. These savings allow the owner either to drive more than before or to purchase additional goods and services all of which entail embodied energy and result in increasing energy demand. This consumer response is referred to as "take back" or "rebound" effect. The extent of the "take back" effect depends on the type of product or service considered: small when the 'fuel bill savings' are spent on a meal in a fancy restaurant; large when money is spent on an additional leisure travels. This effect was first postulated by William Stanley Jevons in 1865 (and hence is referred to also as "Jevons Paradox," see also Binswanger, 2001). Empirical studies suggest that in high-income countries the take-back effect can be anywhere between 0% and 40% (see the 2000 special issue of *Energy Policy* 28(6-7) and the review in Sorell et al., 2009). If absolute reductions of energy use are on the policy agenda, compensating for take-back effects leads to increases in energy prices via taxes. Studies in developing countries (Roy, 2000) – e.g., on compact fluorescent lighting – suggest that take-back effects can approach 100%. In this case, the effect of energy efficiency improvements are less in reductions of total energy use and rather in vastly increased human welfare.

Irrespective of these effects, what matters is that in the long run, potentials for efficiency improvements can be very large both through adoption of existing, more efficient end-use conversion technologies as well as through continued innovation and technological change, implying much larger demand responses and elasticities in the long run than in the short-run.

### 9.3.3 Substitution

Most energy services can be provided by different combinations of energy resources, energy conversion technologies and fuels. Thus different energy carriers (fuels) can therefore be substitutable, providing identical energy services (Sweeney, 2005). Homes can be heated using electricity, natural gas, oil, or wood, as each fuel can be converted to thermal energy (heat). Cooking can use electricity, natural gas, propane, wood, or charcoal. Base load electricity can be generated by coal, natural gas, nuclear, wind or hydropower. Thus, different fuels are economic substitutes for one another: the demand for a particular fuel is – among others- also a



function of the relative prices of all other fuels. This substitutability of energy is made possible, but also is limited, by the available set and vintage of energy conversion technologies. Typically, many conversion technologies can only be used in combination with a particular (single) fuel. Switching from one fuel to another then requires a change in conversion technology - in essence replacing previous devices and technologies with new ones (see our earlier automobile example).

Because energy conversion equipment and infrastructures are inherently long lived, interfuel substitution generally does not occur overnight but slowly over time at the rate by which aging conversion technologies are replaced by new ones. Short-run substitution can be possible when energy conversion technologies have multi-fuel capability, e.g., a furnace can be operated on both oil and natural gas, or several conversion devices are simultaneously available, e.g., homes that are equipped with a central natural gas heating system plus portable electric heaters. “Flexfuel” cars in Brazil that can operate on any combination of pure ethanol to gasoline only (and in some cases also compressed natural gas (CNG)), is an example where innovative end-use conversion technologies specifically designed for fuel flexibility can substantially increase short-term fuel substitution rates. Without such “flex” technologies, various fuels are best viewed as “imperfect” substitutes for one another, with much greater substitutability via technology replacement/substitution in the long run than in the short run.

While prices can be an important driver for fuel substitution, there are other important drivers that can have a more pronounced effect on fuel substitution than prices. These include the quality of energy service delivered, ease of use (convenience) or side-effects associated with the energy conversion such as adverse health impact caused by indoor air pollution from the combustion of traditional biomass in inefficient open-fire cookstoves. The concept of an “energy ladder” of household cooking fuels is a good illustration (see also the discussion in Section 8 above). With rising incomes consumer preferences shift to more convenient and clean cooking fuels (from animal dung and fuelwood, to kerosene, LPG or gas, even electricity) despite these cleaner fuels enjoy a price premium. The qualitative characteristics (convenience and cleanliness) of fuels are “priced in” (e.g., willingness to pay) by consumers, reflecting an “inconvenience cost” associated with cheap, but inconvenient and polluting traditional cooking fuels (Pachauri et al., 2013). Likewise the time saved by avoiding labor-intensive fuel wood collection and using this time for more productive purposes or leisure activities are reasons for not always adopting the fuel with the lowest - at face value - costs.

#### 9.4 Energy Supply

A core concept of economics is that transactions in the market place are governed by prices that clear the market (balance demand and supply). Put differently, the “willingness to pay” of consumers for a particular good or service must match suppliers’ “willingness to sell”. The economic drivers of energy demand have already been discussed. We now also need to consider economics from the perspective of energy suppliers. Three basic features characterize the economics of energy supply: a) no supplier will be “willing to sell” at a loss; b) the costs of energy supply are very heterogeneous among different suppliers or between different energy conversion facilities (e.g., power plants); and c) energy supply typically relies on very capital intensive, large scale technologies and infrastructures, which tend to involve what economists call “natural monopolies” (see below).

a) Energy supply industries extract and convert primary energy into secondary energy and transport and distribute secondary energy to the point of retail (final energy). In order to be economically viable, industry must be able to sell their products at a price higher than the sum

of their fuel input costs, capital costs (amortization of the capital expenditures and finance costs of their energy conversion facilities and distribution infrastructures) non-fuel operating and maintenance costs (labor, repairs, insurance, consumables, etc.) plus a fair margin of returns on investment to plant owners (shareholders)

b) The costs of energy supply vary considerably from location to location. Producing a barrel of oil from a giant oil field in the Saudi Arabian desert is considerably cheaper than producing a barrel of oil from a small offshore field in the hostile environment of the North Sea. The costs of wind generated electricity vary significantly as a function of the quality of the wind resource available (wind speed and regularity of the wind blowing). Electricity generating costs are very different between old coal fired power plants (whose capital expenses have already been amortized) and new, high efficient “super-critical” coal power plants (not to mention new nuclear builds or large scale renewables). The different costs of supply options and of different suppliers in a given market are typically ranked by an ordered, upwards sloping “supply curve” that represents the energy supply costs from the cheapest to the most expensive supplier/conversion technology (Figure 9.3). Thus a given level of energy demand can only be satisfied as long as the most expensive supplier can still recover supply costs. Otherwise there would be no “willingness to sell” and demand could not be satisfied. In other words, the energy price that balances supply with demand is determined at the margin of the most expensive supplier/supply option, or in economic terms by the marginal energy supply costs. This yields a substantial “producer surplus” for low cost energy suppliers/options (Figure 9.3).

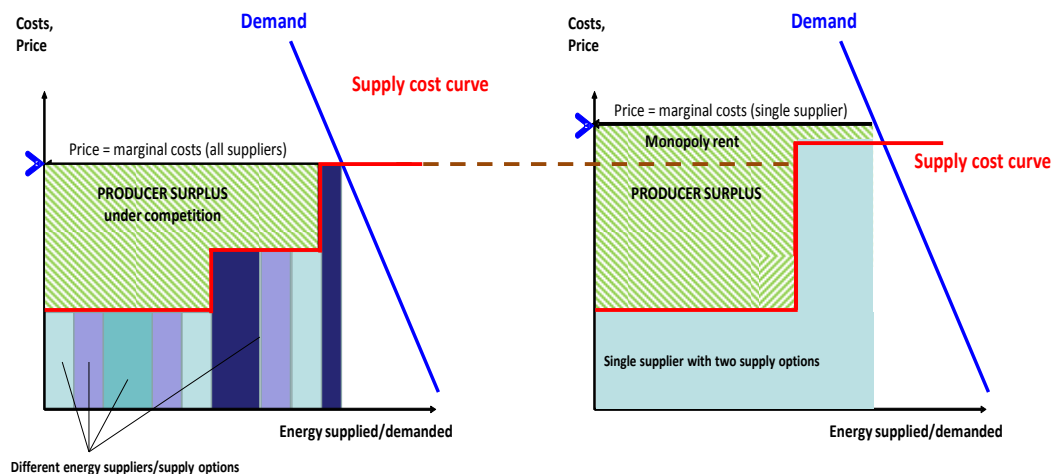


Figure 9.3. Energy demand and supply with producer surplus under competition (left panel) and under monopoly (right panel).

c) Energy supply is a business characterized by long-lived and capital intensive conversion technologies (refineries, power plants) and large-scale transport and distribution infrastructures that exhibit significant economies of scale (Definition: Unit energy costs fall with increasing scale of provision. For example, a large 1000 MW power plant has lower costs per kWh produced compared to 10 power plants at 100 MW, as the fixed plant costs [labor, equipment] can be spread over much larger production volumes.) The energy system has historically evolved towards ever larger scales in conversion technologies and infrastructures with large upfront investment costs which firms were only willing to commit in exchange for some longer-

term market security to recover their investment costs. Moreover, the infrastructure costs for gas pipelines or electricity grids are so high that it would be uneconomical to build several, parallel systems owned and operated by different entities (as is possible with relatively cheap cell phone towers). Instead utilities have been awarded “natural monopolies” or markets void of real competition but usually under supervision of a regulator.

Natural monopolies are characteristic for many capital intensive infrastructures: gas, electricity, water supply and sewage systems. Natural monopolies also tend to embrace “vertical integration”<sup>25</sup> of supply conversion, transmission and distribution which can (and has) resulted in an accumulation of substantial “producer surplus” due to a lack of competition. As a result, monopoly break-ups<sup>26</sup> and “unbundling” of energy conversion, e.g., electricity generation, from the delivery infrastructure have been and continue to be high on the policy agenda of governments.<sup>27</sup>

### 9.5 Cost Components of Energy Services and Energy Carriers

In one way or another, energy services carry a price tag. The price a consumer pays for a particular energy service, e.g., electric lighting, is made up by the energy costs (electricity demand times electricity price) themselves plus the costs of energy service delivery (light fixture and light bulb for instance). In turn, electricity prices are determined by a variety of components, the most important of which are generating costs, systems costs, rents, profits, taxes, subsidies, and, if included in the price, previous externalities.

Energy and energy service provision costs are not only a key component determining the price of a service but also a central decision criterion for investment and operating decisions alike; they consist of three major components: capital costs, fuel costs, and non-fuel operating and maintenance (O&M) costs. Capital costs are the costs associated with the construction/acquisition/purchase as well as finance of a power plant, refinery, or home furnace. Fuel costs are the expenditures associated with the fuel supply for plant operation or purchasing home heating fuel. O&M costs cover labor costs, insurance, consumables other than fuel, repairs, etc. More recently, capital and/or costs may also include decommissioning expenditures at the end of a plant’s service life, while fuel costs or O&M costs may include waste disposal costs.

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<sup>25</sup> Vertical market integration: an energy company covers all activities from primary energy extraction, conversion, all the way up to final distribution. Horizontal integration: markets are organized along distinct steps in the energy delivery chain with companies focusing exclusively on extraction, conversion, or transport and distribution of energy respectively.

<sup>26</sup> The break-up of the Standard Oil Trust Company in the US in 1911 that led to the emergence of the “seven sisters” of major international oil companies is one out of many examples of governmental regulation of the energy industry.

<sup>27</sup> “Fearful that an unregulated monopoly would exercise market power and overprice energy for consumers, most governments have chosen to tightly control or even nationalize their energy industries” (Sweeney, 2005). Taking the example of electricity, an electric utility sells two classes of products: electricity delivery services (wires) and electricity proper (kWh). Although these two classes of products have been traditionally bundled together into a single price per kilowatt hour of electricity, these two classes can also be (and actually have been) “unbundled” and sold by separate companies (and are billed separately to consumers). Electricity delivery services are characterized by substantial increasing returns to scale, while prospects for electricity generation are more limited. “Therefore the possibility is open for competitive market structure to sell electricity to consumers, separately from the electricity delivery services” (Sweeney, 2005).

While fuel and O&M costs are largely incurred on a per-use basis, capital or investment costs occur upfront – for some technologies spread over several years of plant construction – before earning revenue or providing energy services for the investor. Because of lifetimes of energy plant and equipment of up to several decades, capital costs must be allocated over the lifetime of the investment. As well, wear and tear of the plant and expected capital outlays for periodical plant refurbishment must be accounted for.

This raises the question how to compare the generating costs of plants with different technical life times, unit sizes, plant factors, capital costs, using different fuels, etc. in order to make informed investment or policy decisions?

The levelized cost of electricity (LCOE) is a widely used tool for comparing the provision costs of different technologies producing quasi undistinguishable products such as kWhs of electricity.<sup>28</sup> Two levelized cost definitions and calculation methods dominate the literature (see Appendix A-6 for more detail). One method calculates the levelized unit costs of generating one kWh of electricity by dividing the sum of annualized capital costs plus fuel and maintenance costs over the year by the annual kWh output. The other method uses a net present value (NPV) approach and LCOE is defined as ‘the ratio of total lifetime expenses versus total expected outputs, expressed in terms of their present value equivalent’. Both methods have strengths and weaknesses (see Appendix A.6). In the following paragraphs the first LCOE approach is used to compare electricity generation costs of different technologies and fuels.

A key feature of the first LCOE approach is that it spreads the capital costs (including the finance costs) uniformly over the lifetime of an investment. It further accounts for the fuel and O&M costs, and calculates the specific costs per unit of energy delivered.<sup>29</sup> A critical parameter in the LCOE approach is the discount rate, which reflects the interest rate on capital (cost of capital or return) for an investor in the absence of specific market or technology risks. The discount rate also accounts for the changing time value of money as well as opportunity costs.

The relative structure of the various generating cost components varies significantly per unit of output for different generating options (see Figure 9.4 and Table 9.1, based on a real annual discount rate of 5%). The variation indicates the inherent risks associated with a particular option. For example, gas combined cycle technology (CCGT) has the lowest capital costs but the highest fuel costs of the options. Consequently, CCGT generating costs are almost all fuel costs. Any change in natural gas prices thus greatly impacts its generating costs and the economics of gas-fired electricity generation are thus highly vulnerable to gas price volatility. Conversely, nuclear power generation is dominated by high capital costs (>70%), with fuel cycle and O&M costs assuming approximately equal shares of the remaining costs.<sup>30</sup> The high share of capital costs exposes nuclear power projects to financial risks associated with rising interest rates and accrued interest during construction (IDC) caused by construction delays due to technological complexity or public opposition (or both). Adding carbon capture and storage (CCS) to fossil generation can also increase costs substantially: typically adding some

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<sup>28</sup> For a review see Anderson, 2007. For a review quantitative cost estimates for electricity generation see Heptonstall, 2007 and NREL, 2010.

<sup>29</sup> Note: LCOE assumes perfect knowledge about future fuel prices and interest rates several decades into the future. Scenarios of different price trajectories are commonly used to reflect uncertainty.

<sup>30</sup> Unlike natural gas or coal-fired generation, the fuel cost of nuclear power generation is not dominated by the resource (uranium) input price but by enrichment and fuel fabrication costs. Uranium accounts for approximately 25% of fuel costs only.

50\$/MWh levelized costs to pulverized coal fired power plants (and 20-30 \$/MWh for IGCC or natural gas electricity generation), see GEA Chapter 12, Larson et al., 2012.

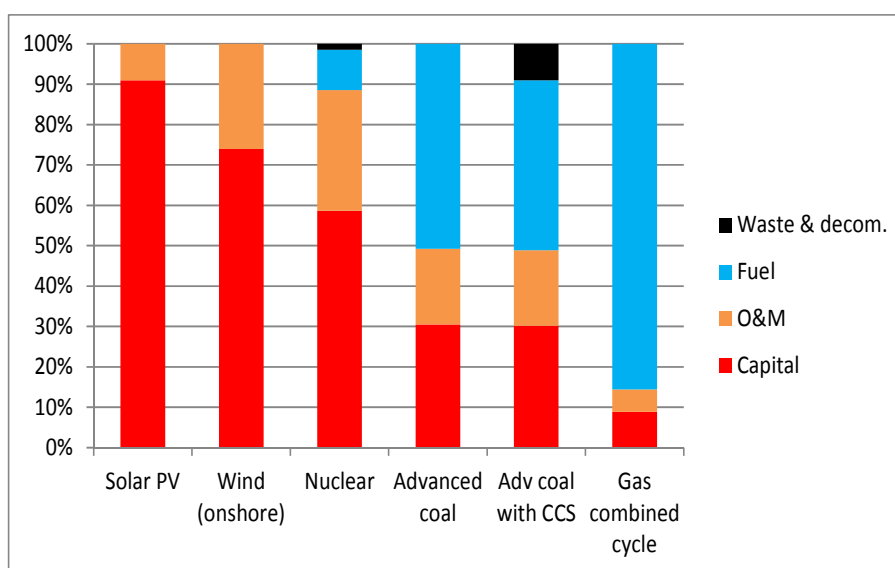


Figure 9.4. Structure of levelized generation costs of different electricity generation technologies (in percent based on a 5% discount rate) and representative cost ranges for 2030 as used in GEA Chapter 17, Riahi et al., 2012, for capital costs, operation and maintenance (O&M), fuel costs, as well as waste disposal costs for nuclear and advanced coal with carbon capture and sequestration (CCS). Values derived from the representative cost ranges presented in Table 9.1. Note: (a) Includes decommissioning costs for nuclear power and costs for transport and disposal of 90% of CO<sub>2</sub> emissions for advanced coal power plants with carbon capture and storage (CCS).

Table 9.1. Total levelized costs of different electricity generation technologies (using a 5% discount rate) and representative cost ranges in US\$2005/MWh as used in GEA for a time frame to 2030. Note: These are direct energy costs only, i.e., excluding externality costs (see Section 9.6 below). Waste and decommissioning costs include decommissioning costs for nuclear power and costs for transport and disposal of 90% of CO<sub>2</sub> emissions for advanced coal power plants with carbon capture and storage (CCS).

		Solar PV	Wind (onshore)	Nuclear	Advanced coal	Adv coal with CCS	Gas combined cycle
Capital	\$/kWe	900 - 2800	900 - 1300	4000 - 6200	1100 - 1600	1700 - 2400	400 - 500
O&M	\$/kWe	6 - 18	19 - 30	118 - 180	46 - 65	69 - 96	16 - 20
Fuel	\$/GJ	-	-	0.7 - 0.9	1.3 - 2.8	1.3 - 2.8	2.6 - 6.5
Waste & decom.	\$/MWh	-	-	1 - 2	-	6	-
Generating cost	\$/MWh	27 - 151	21 - 131	53 - 100	27 - 46	44 - 69	24 - 49

In addition to the generating costs, the price of electricity for consumers then includes transmission and distribution (T&D) costs plus taxes or subsidies.<sup>31</sup> Taxes and subsidies are policy instruments to influence consumer or producer behavior. Taxes can be used to discourage politically undesirable behavior patterns, while subsidies provide incentives to adopt a more desirable investment or consumption pattern. They can also cause unwanted market distortion. Subsidized electricity or gasoline prices are also an instrument for extending access to energy services to low-income families, supporting small rural business developments, or connecting rural areas to markets.

Figure 9.5 compares gasoline prices with and without taxes for a variety of countries. Road transportation fuels are almost invariably the most heavily taxed fuels worldwide. While prices without taxes vary by a factor of two, this doubles to a factor of four when taxes are included. The taxes imposed by countries reflect national policy objectives, e.g., revenue needs, trade balances, etc., and not necessarily the countries' endowment with oil resources. For example, oil-exporting Norway features the second highest gasoline taxes in this comparison (equivalent to a carbon tax of US\$576/tonne of CO<sub>2</sub>), while oil-importing US has the second lowest gasoline taxation (equivalent to US\$56/tonne of CO<sub>2</sub>). Other oil-exporting countries such as Kuwait (not shown in Figure 9.5) even subsidize domestic gasoline use.

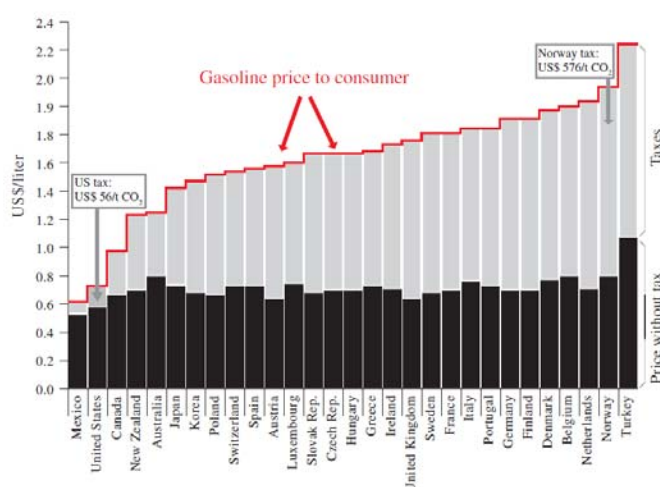


Figure 9.5. Gasoline prices with and without taxes in US\$/liter and implied price of carbon (US\$/tCO<sub>2</sub>) for 1<sup>st</sup> quarter of 2010. Source: data from IEA, 2011.

<sup>31</sup> In the most general definition, an energy subsidy is represented by the difference between (low) local and prevailing (high) world market prices (without taxes). When the local gasoline price is below the marginal costs of producing and refining crude oil, this represents a direct financial transfer/subsidy from energy producers (usually nationalized industries – i.e., from the government) to energy consumers (households, taxi companies). Beyond that, any difference between local and world market prices is best conceptualized as opportunity costs associated with foregone potential export revenues, and also classified as energy subsidy. The marginal costs of producing a barrel of crude oil in many oil-exporting countries can be as low as US\$5/bbl. The difference to a world market price of say US\$100/bbl (in economic theory determined by the global marginal [i.e., highest] production costs plus profits) is referred to in economics as “scarcity rent,” leading to vast financial transfers and wealth to energy producers, which may, however, not always have only beneficial effects (the so-called “resource curse,” Humphreys et al., 2007).



Finally there are cost elements caused by the conversion and use of energy and energy services which – although real – are not included in the price paid by the consumer but paid by society at large. Examples of such costs, called “externalities,” are health and environmental damage costs resulting from air and water pollution from fossil fuel combustion or lower property values due to the proximity of a nuclear power plant or noise from wind converters. Ignoring externalities masks the true costs of energy and sends the wrong signal to the market place. Charges or taxes on carbon emissions or investment in carbon capture and storage (CCS) technology are ways to internalize externalities caused by GHG emissions. They also change the merit order of electricity generation favoring low-GHG emission technologies.

While investment decisions are guided by LCOE considerations, operating decisions and dispatch of an existing fleet of power stations are based on short-term marginal costs – in essence, fuel costs and possibly emission charges. Capital costs are no longer a decision criterion, as these are “sunk.”

Figure 9.6 explains the inherent substitutability between capital and fuel costs using the example of providing heat for cooking. Higher-efficiency stoves are more capital-intensive but reduce fuel costs, which in a rural developing country context often mean time spent collecting fuel wood. Switching to more capital-intensive stoves (and higher-quality fuels) reduces the time spent on fuel wood collection and at the same time improves indoor air quality through lower combustion-related emissions. The time released from gathering fuel is then available for more productive uses. This freed time, lower pollution exposure, and improved human health are important examples of positive externalities of moving to cleaner household fuels.

A transition to clean cooking services can occur in two ways as shown in Figure 9.6. A simple shift or substitution to higher-quality fuels (e.g., from firewood to liquefied petroleum gas – LPG) will result in higher combustion efficiency, lower combustion-related emissions, lower time costs associated with fuel collection, but higher capital costs for stoves (and cash expenditure for LPG). Improvements in cooking services can also be achieved through the use of more capital-intensive but improved technologies that continue to use traditional fuels (e.g., firewood and residues) but more efficiently (e.g., via biogasifiers).

Further cost components related to Figure 9.6 are “inconvenience” or “opportunity” costs. Depending on the levelized costs of the heat for cooking, it might well be that using traditional fuel wood in an inefficient stove is the cheapest way to produce the required heat. However, factoring in alternative uses of the time spent for wood collection – for example, for other productive uses or just leisure activities – turns wood collection into an inconvenient task. Estimate for rural households in South Asia suggest that perceived inconvenience costs of traditional biomass cooking fuels can double the costs of biomass fuels for higher income households making cleaner alternatives like LPG competitive (Pachauri et al., 2013). A more efficient stove using commercial fuels reduces pollution and time spent gathering fuel wood, and hence reduces inconvenience costs. However, the capital spent on a more efficient stove may not be available for other investments – say, a pump for irrigation – and thus represents an opportunity cost.

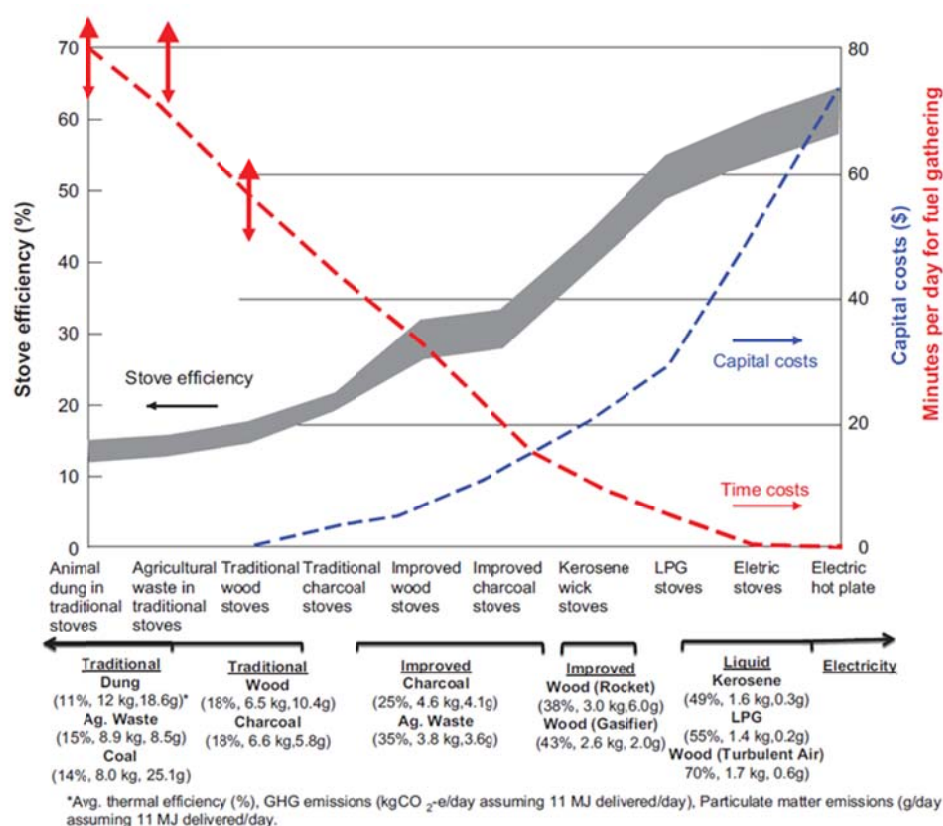


Figure 9.6 Different costs of energy service provision. Example: cooking in developing countries. Notes: Red arrows show uncertainty ranges in time costs. GHG emissions are illustrative estimates and include all greenhouse gases and other emissions that affect radiative forcing. Emissions from fuel production and renewability of charcoal, wood, and agricultural residues are not included. Source: Adapted from OTA, 1991 and GEA Chapter 3, Emberson et al., 2012.

## 9.6 Externalities

### 9.6.1 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, i.e., the price (money) they pay for the goods and services they consume - 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 paying monetary costs.

Opportunity costs represent the value of alternative uses of investments, labor, materials, etc. if used for other economic purposes instead 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, e.g., agricultural output or recreation.

Health and environmental costs include the deaths, injuries and illnesses suffered by the workers in the 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, etc.; climate change, overloading the carrying capacities of ecosystems, 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 pattern 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 socio-political costs. In so far these are not incorporated into the monetary costs, there are termed “externalities”.

### **9.6.2 Externalities**

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 and 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 electricity (“internalization”) would necessarily result in higher prices. It would send correct pricing signals to the market place thus change the merit order of investment and operating decisions as well as reducing 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, eco-systems services). To reduce negative externalities 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 for the quantification of hidden costs and assessing the effectiveness of policy instruments for the internalization of 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. “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, 2010).

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

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 is included and what is not) to the valuation of loss of human life. Externalities attributed to emissions from energy production and use have been assessed using the impact pathway approach (IPA), i.e., the pathway from emission through dispersion, exposure, physical impact and damage to monetization of the damage costs to individuals or society at large (see Figure 9.7) (Rabl and Spadaro, 1999; Ricci, 2010). Controversy usually emerges in the last steps of this chain.

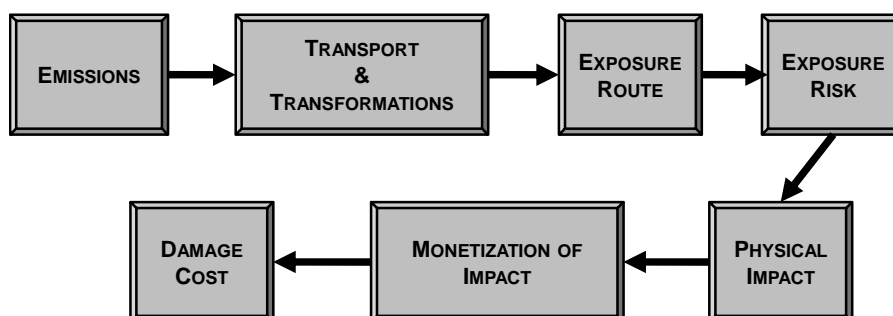


Figure 9.7. Impact pathways approach (IPA) for deriving externality costs. Source: Adapted from Rabl and Spadaro (1999).

Other methodologies include the willingness to pay (WTP)/willingness to accept (WTA) approach (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 motorist staying on the regular roads that now are less congested). Accepting a higher wage for a risky construction job is an example for WTA.

Climate change damage costs are particularly uncertain to value. Key uncertainties arise from the yet insufficient scientific knowledge about the physical phenomena associated with climate change, the monetary value of subsequent physical impacts (health effects, impacts on crops and ecosystems, impacts of extreme weather events, rising seawater level, increased needs of air conditioning or lower demand for heating). Moreover, the very long temporal scope of climate change effects and the subsequent very high sensitivity to the future evolution of welfare, individual preferences, discount rates etc. add complexity and controversy (Ricci, 2010).

### 9.6.3 Some Results of External Cost Estimation Studies

Several studies have attempted to quantify externalities most of which focus on electricity generation (EU, 2003; NRC, 2009; Ricci, 2010). The latest systematic analysis of external costs of various electricity supply technologies and their associated chains is available from European Commission's CASES project (Markandya et al., 2011). Figure 9.8 below shows the summary results for the 27 countries of the European Union (EU27), estimated for the period 2005-2010.

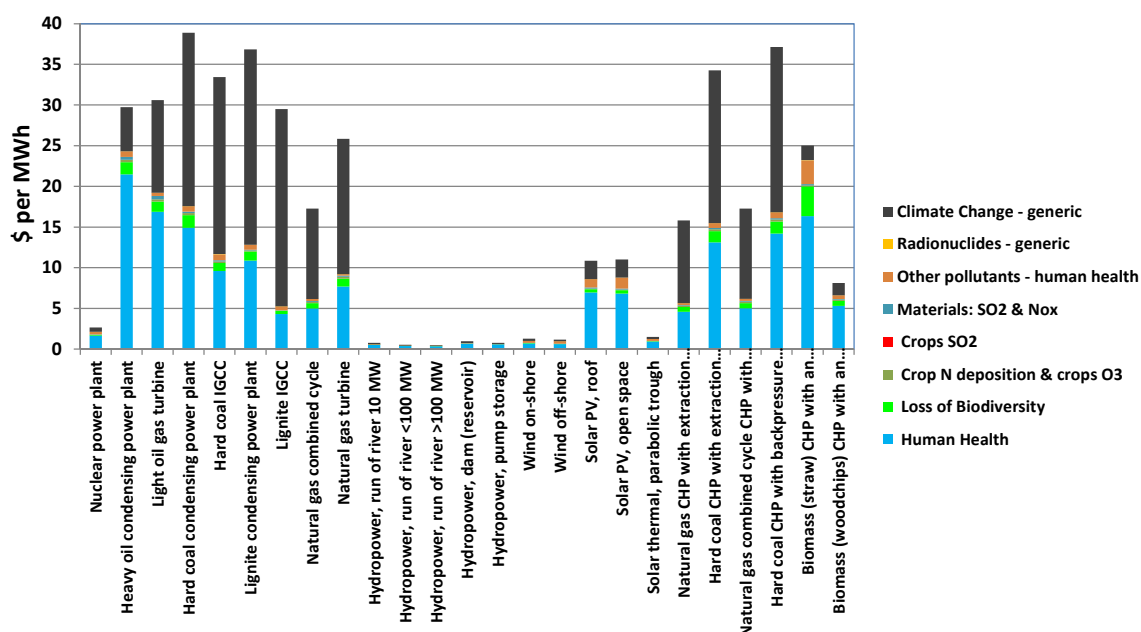


Figure 9.8 Average estimated external costs for electricity generation the European Union (EU27) in 2005-2010, in US\$2005 per MWh (converted from 2005 Euros with an exchange rate of 1.24 \$/Euro). Data source: EU CASES Project (Markandya et al., 2011).

Human health impacts due to classic air pollutant emissions (such as  $\text{NH}_3$ , NMVOC,  $\text{NO}_x$ ,  $\text{SO}_2$  and particulate matter) and the adverse consequences from greenhouse gas emissions dominate the external cost estimates across all technologies from the EU study. The magnitude of external costs associated with electricity generation approaches the levelized generating costs of electricity summarized in Table 9.1 above. Available recent estimates (Muller, Mendelsohn, and Nordhaus, 2011) for the US that have focused on air pollution induced human health impacts from electricity generation confirm the orders of magnitude illustrated in Figure 9.8 above. Externality costs of US coal electricity generation are estimated to total some 53 billion US\$ annually due to human health impacts alone, which is more than twice as large as the entire value added of that industry. This translates into some 28\$/MWh external cost from human health impacts from US coal electricity generation, a number that would increase to some 47\$/MWh when the social costs of carbon would be included as well (Muller, Mendelsohn, and Nordhaus, 2011). Thus, for fossil-based electricity generation, internalization of externalities would at least double electricity prices, but by themselves do not justify investment into expensive energy options such as high costs solar PV systems with LCOE of up to some 150\$/MWh (Table 9.1), which therefore require continued innovation efforts to drive down costs further.

On a life-cycle basis, renewables and nuclear power emit no traditional air pollutants and only a few grams of greenhouse gases (GHG) per kWh. 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).

Due to the higher amount of GHG emissions and air pollutants throughout the fuel chain, fossil-based electricity generation followed by biomass-sourced technologies have considerably higher external costs than renewables and nuclear power.



For the nuclear power, most externalities are internalized (hence the low value shown in Figure 9.8 above) except the costs of severe nuclear accidents. Although damage costs of such events may be tens to hundreds of billions of €, given the low probability of such events results in very small expected damage costs. However, as witnessed by Chernobyl and Fukushima events such accidents do happen and the resulting damages could be as high as 5-10 € cents per kWh or more. Some costs arising from severe accidents are compensated, i.e., internalized through operator payments and insurances. According to the European Commission's New Ext project (Friedrich et al., 2004) which analyzed accident related external costs using the comprehensive accident database (1969-2000) maintained by the Paul Scherrer Institute (PSI), monetary damages of the Chernobyl reactor accident were estimated, though speculative and highly uncertain, at 370 billion US dollar (in 2000 prices). This was two orders of magnitude higher than any other accident. Second biggest damages were from the Three Mile Island reactor accident in the US and estimated at 6 billion US dollar. The most costly of the non-nuclear accidents in the PSI accident database was the Exxon Valdez oil spill in 1989, estimated at 2.8 billion US dollars. The initial costs estimates for the BP oil spill in the Gulf of Mexico in 2010 suggest that the damage costs may amount to 40-100 billion dollar.

In the event of accidents, fatality and injury may occur among workers and residents. Evacuation and resettlements of residents also may take place. With a coal chain, mining accidents are the major component of the accident related external costs. According to the PSI database, over 25,000 fatalities with severe coal-related accidents have been reported. With the oil and natural gas chains, fatalities related to severe accidents at the transport and distribution stage are the major component of the accident related external costs. Over 20,000 fatalities for oil chain and nearly 2,000 for the natural gas chain in the severe accidents are reported. For hydropower, a single event, the Banqiao/Shimantan dam failure in China, accounted for 26,000 fatalities. Total fatalities from hydro chain amount to nearly 30,000 and this makes the hydro chain to have the highest accident related external costs among all the fuel chains. At the time of analysis, there were two severe nuclear accidents, Chernobyl and Three Mile Island. For Three Mile Island no fatality or injuries are reported. For Chernobyl, 31 immediate fatalities and injury of 370 persons occurred. Including longer-term health impacts the accident may ultimately cause premature death between cumulative 4,000 to 10,000 people, mostly from cancer. "Coal plants are much deadlier: the fine-particulate air pollution they produce kills about 10,000 people each year in the United States alone" (von Hippel, 2011).

The steady and strong market penetration of intermittent renewable energy technology has created some intriguing electricity system externalities. Electricity is difficult and costly to store (currently largely restricted to pumped hydro storage) and demand and supply need to be balanced instantly all the time. The intermittency of wind or solar photovoltaics adds further complexity and stress on the ability to balance the system (IEA, 2010) and requires fossil or nuclear power plants to provide the necessary reserve and backup capacity (in essence an externality of wind and PV) or, at times of ample wind, reduce their output and operate at below optimum efficiencies (and increased per kWh CO<sub>2</sub> emissions).

Transportation is another energy use creating significant externalities. Next to air pollution and climate change externalities, transport systems, contrary to routine operations of energy supply systems, exert a high toll on human health (death and injuries) from traffic accidents, a significant social externality. According to the Global Burden of Disease assessment Lim et al., 2012, see Section 7 above) 1.4 million people were killed in traffic accidents in 2010, including 1.3 million in road accidents with a total impact of 75 million DALYs (82 million DALYs for all traffic accidents).



Figure 9.9 from the ExternE study (EU, 2003) illustrates the costs of goods transport using different modes broken down in externalities associated with accidents, air pollution, up- and downstream (fuel supply, vehicle manufacturing, infrastructure provision, etc.), congestion, climate change and noise. In this comparison, road transport by trucks causes the highest externalities, especially from accidents and air pollution. While accidents and noise contribute little to the externalities of water transport via containerships and barges, NO<sub>x</sub> emissions are chiefly responsible for their high air pollution cost but also climate change costs. Electric freight train in the ExternE study causes comparably low externalities dominated in almost equal parts by the external costs from electricity generation (included in the up- and downstream category), climate change, noise and accidents.

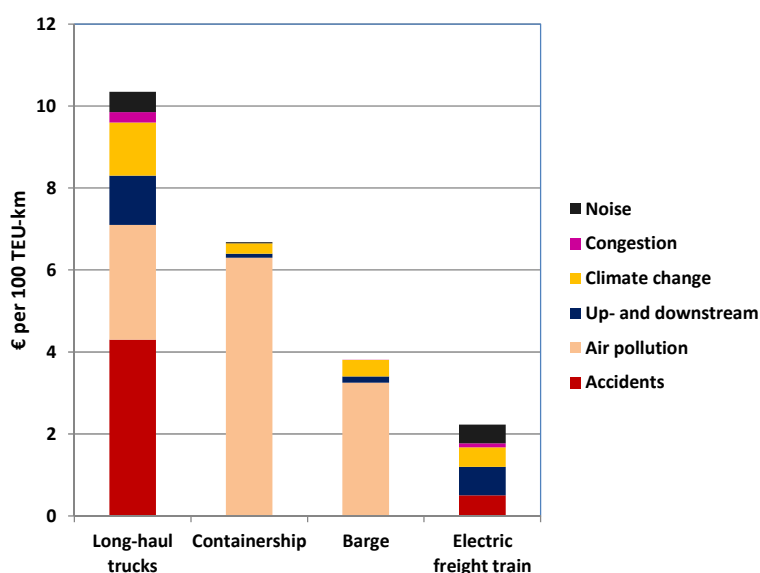


Figure 9.9 External costs due to goods transport in Europe for the year 2000, in Euro per TEU-km (twenty-foot container equivalent volume transported over one km). Source: Adapted from EU (2003)

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 non-linear. Technology change affects the overall economic and environmental performance of energy conversion technologies (higher efficiency, better abatement equipment, etc.). Pollution reductions often result from capital turn-over of retired plant and equipment by new technology. externality costs are also highly non-linear 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, e.g., depending on population density, geography, land-use patterns, wind speeds and direction, regulation, etc. As well, the boundaries of assessments are often not clearly defined, i.e., which cost factors are included and which are not (not everything that is measurable is also important).

Lastly, external cost estimation methods and their resulting ranking of energy technology options are as classical risk<sup>32</sup> assessment methods often highly controversial in the public discourse about benefits and disbenefits of technology options. This is because probabilistic risk estimations differ significantly from subjective perceptions of risks (Slovic, 1987). While car driving in probabilistic risk terms is highly risky, most people consider it (“I’m a safe driver”) much less risky than it actually is. For nuclear power, the exact opposite holds true. This difference between probabilistic and subjective risk assessment also highlights yet another critical issue: addressing technological risks and other externalities from energy production and use always needs to consider distributional aspects: who imposes risks and who is exposed to it.

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<sup>32</sup> The canonical definition of **risk** is the product of the **probability** of occurrence of an event **times** its **consequence** (e.g., damage).

## Appendix A: Accounting for Energy

### A.1 Introduction

The discussion of energy systems above described how primary energy occurs in different forms embodied in resources as they exist in nature, such as chemical energy embodied in fossils or biomass, the potential kinetic energy of water drawn from a reservoir, the electromagnetic energy of solar radiation, or the energy released in nuclear reactions. A logical question is, therefore, how to compare and assess the potential substitutability of these energy “apples and oranges.” This is the objective of this more technical section.

The primary energy of fossil energy sources and biomass is defined in terms of the heating value (enthalpy<sup>33</sup>) of combustion. Together, combustibles account for about 90% of current primary energy in the world, corresponding to some 440 EJ in 2005. There are two different definitions of the heat of combustion, the higher (HHV) and lower heating values (LHV – see the discussion below), but otherwise the determination of apple-to-apple primary energy comparisons among combustible energy sources is relatively straightforward.

The situation is more complicated for non-combustible primary energy sources such as nuclear energy and renewables other than biomass. In these cases, primary energy is not used directly but is converted and transformed into secondary energy (energy carriers) such as electricity as in the case of modern wind or photovoltaic power plants. The measurable energy flow is the secondary energy, whereas the primary energy input needed to generate electricity needs to be estimated. In the two examples of wind and solar photovoltaics, primary energy estimates of the kinetic energy of wind and the electromagnetic energy of solar radiation are needed to determine primary energy equivalences to other energy sources. There are various conventions that specify the appropriate conversion from different renewable energy forms based on the generated electricity. For these conventions, the type of energy flow and its technological characteristics – such as the efficiency of the wind converters or photovoltaic cells – are needed. These various important accounting issues are dealt with below, starting with units and heating values.

### A.2 Energy Units, Scale, and Heating Values (HHV/LHV)

Energy is defined as the capacity to do work and is measured in joules (J), where 1 joule is the work done when a force of 1 newton ( $1 \text{ N} = 1 \text{ kg m/s}^2$ ) is applied over a distance of 1 meter. Power is the rate at which energy is transferred and is commonly measured in watts (W), where 1 watt is 1 joule/second. Newton, joule, and watt are defined as basic units in the International System of Units (SI).<sup>34</sup>

There is a wide variety of energy units which can be converted into each other. Figure 2.3 in Section 2.1 above, gives an overview of the most commonly used energy units and also indicates typical (rounded) conversion factors (see also Appendix B). Typically, the choice of

<sup>33</sup> Enthalpy – from the Greek “to warm/heat” – is the product of the mass of a fuel times its specific enthalpy, which is defined as the sum of its internal energy (from combustion) plus pressure times volume. Heating values per unit mass of a fuel are, therefore, defined for standardized pressure/volume conditions.

<sup>34</sup> International System of Units – *SI* from the French *le Système international d'unités*.

an energy unit depends on various factors such as the type of the energy carrier itself, the respective energy sector, as well as geographical and historical contexts. Next to the internationally standardized SI units, the most common energy unit used for electricity is the kilowatt-hour (kWh), which is derived from the joule (one kWh (1000 Watt-hours) being equivalent to 3600 kilo-Watt-seconds, or 3.6 MJ). In many international energy statistics (e.g., IEA and OECD) tonnes of oil equivalent (1 toe equals  $41.87 \times 10^9$  J) is used as a core energy unit, but it is not included in the SI system. Certain energy subsectors often use units that apply best to their respective energy carrier. For example, the oil industry uses barrels of oil equivalent (1 boe equals  $5.71 \times 10^9$  J or about 1/7 of a toe), the coal industry tonnes of coal equivalent (1 tce equals  $29.31 \times 10^9$  J), whereas the gas industry uses cubic meters of gas at a normalized pressure (1 m<sup>3</sup> of methane equals 34 MJ – all numbers refer to LHV; see the discussion below). Some countries such as the US use the imperial system of units, which include British Thermal Units (1 BTU equals 1055 J) as a unit for energy, cubic feet (for natural gas, one ft<sup>3</sup> equals about 1000 BTU, or 1 MJ), and barrels as volumetric energy units (bbl is another name for boe).

The calorific value or heating value of a fuel expresses the heat obtained from combustion of one unit of the fuel. It is important to distinguish between the higher heating value (HHV or gross calorific value) and the lower heating value (LHV or net calorific value). Most combustible fuels consist of hydrocarbon compounds that are primarily mixtures of carbon and hydrogen. When the hydrogen combines with oxygen, it forms water in a gaseous state, which is typically carried away with the other products of combustion in the exhaust gases. Similarly, any moisture present in the fuel will typically also evaporate. When the exhaust gases cool, this water will condense into a liquid state and release heat, known as latent heat, which can be captured and utilized for low-temperature heating purposes.

The HHV of a fuel includes the latent heat recovered from condensing water vapor from combustion. Modern condensing natural gas or oil boilers can capture this latent heat.<sup>35</sup> The LHV excludes the latent heat of the water formed during combustion.

The differences between LHV and HHV are typically about 5–6% of the HHV for solid and liquid fuels, and about 10% for natural gas (IEA, 2005). Typically, the LHV is used in energy balances, since most current energy conversion devices are still not able to recover latent heat. The distinction between HHV and LHV becomes important when comparing international energy statistics and balances (usually based on LHV, as in IEA or UN statistics) with national ones that can sometimes be based on HHV (as in case of the US Energy Information Administration, EIA). Care is also required when applying fuel-specific emission factors – for example, for CO<sub>2</sub> – that are specified separately per HHV or LHV to the corresponding heating value of the fuel as defined in the underlying energy statistics but not always spelled out prominently. As a precautionary measure to avoid accounting errors, literature sources on emission factors and energy use numbers that do not specify their underlying heating value concept definition should be avoided. In this publication both definitions are used, but the LHV is the default, as in most international energy statistics (e.g., UN or IEA).

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<sup>35</sup> Commercial advertisements often inappropriately refer to furnaces as “more than 100% efficient,” which is thermodynamically impossible. The seeming paradox simply results from comparing apples and oranges in the form of LHV fuel energy inputs but HHV combustion energy releases.

### A.3 Accounting for Primary Energy

As discussed above, the determination of the primary energy equivalent of combustible fuels (all fossils as well as biomass) is straightforward (only a consistent HHV or LHV reporting format needs to be adopted). For non-combustible energies (modern renewables such as wind or solar photovoltaics, geothermal, hydropower, and nuclear), there are different conventions that specify the appropriate conversion factors to account for primary energy equivalents: the substitution, the direct equivalent, and the physical energy content method (which is a hybrid combination of the substitution and direct equivalent methods). The share of non-combustible energy sources in total primary energy supply will appear to be very different depending on the method used (Lightfoot, 2007; Macknick, 2009):

The (partial) substitution method estimates the primary energy from non-combustible sources as being equivalent to the LHV or HHV of combustible fuels that would have been required in conventional thermal power plants to substitute the generated electricity or some other secondary energy form. Basically, this means that some average or representative efficiency of thermal power plants is applied to calculate the equivalent primary energy from the generated electricity from nuclear and renewables outside biomass.<sup>36</sup> This method is used, for example, by BP (2010a) and WEC (1993) and as the default method in the GEA to maintain a consistent accounting framework across different energy options.<sup>37</sup> Throughout the GEA there is always a clear indication if another method is used. The difficulties with this method include choosing an appropriate thermal power generating efficiency factor and the fact that the method displays “hypothetical” transformation losses in energy balances which end up as reported primary energy use, but which do not have any physical basis.

The (direct) equivalent method counts one unit of secondary energy such as generated electricity from non-combustible sources as one unit of primary energy. This method is also often used in the literature – for example, by UN Statistics (2010) and in multiple IPCC reports that deal with long-term energy and emission scenarios (Watson et al., 1995; Nakicenovic and Swart, 2000; Morita et al., 2001; Fisher et al., 2007). The difficulties with this method are twofold: (i) an increase in the share of non-combustible energy sources results in the apparent efficiency improvement of the whole energy system because ever higher shares of primary energy have a definitional 100% “efficiency” of conversion into secondary forms, and (ii) actual conversion efficiencies even for these non-combustible sources of primary energy are substantially lower than 100% – for instance, the theoretical maximum efficiency (under optimal conditions) of converting wind kinetic energy into electricity is about 59%, but actual machines today achieve at best 47%.

The (physical) energy content method adopts a hybrid approach, using the direct equivalent approach for all energy sources other than those where primary energy is heat, such as nuclear, solar thermal, and geothermal energy sources. Thermal energy generated in a nuclear, geothermal, or solar power plant is considered primary energy equivalent. For example, in the case of nuclear energy, the heat released by fission is taken as primary energy, even though two-

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<sup>36</sup> Note, however, that different variants of the substitution method use somewhat different conversion factors. For example, BP applies 38% conversion efficiency to electricity generated from nuclear and hydro (BP, 2010a; 2010b), whereas the World Energy Council uses 38.6% for nuclear and non-combustible renewables.

<sup>37</sup> In the GEA a uniform primary accounting equivalent of 35% conversion efficiency for electricity from non-combustible sources (equivalent to the global average of fossil-fuel power generation in 2005) and of 85% conversion efficiency for heat is applied.

thirds are dissipated<sup>38</sup> to the environment through the turbine's condenser and the reactor cooling system and only one-third is actually delivered as electricity. This approach is identical to the case of fossil energy, for which the heat of combustion is taken as primary energy. In effect, the hybrid system leads to the following assumed primary energy accounting: (i) substitution method for heat from nuclear, geothermal, and solar thermal, and (ii) direct equivalent method for electricity from hydropower, wind, tide, wave, and solar photovoltaic energy. This hybrid method is used by the OECD, the International Energy Agency and Eurostat (IEA, 2005). The difficulty with this method is that it can result in confusion, as some energy forms such as hydropower are accounted for by the direct equivalent method, while for others such as nuclear conversion efficiencies are applied. Even though they both generate about the same electricity in the world, nuclear's primary energy equivalent is counted as three times larger than that of hydropower.<sup>39</sup>

A detailed overview of differences in primary energy accounting from different energy statistics is described in Macknick (2009); see also Figure A.2 below (the paper also contains a link to a data base where users can specify their own standardized accounting convention applied to the main international energy statistical data sources).

Table A.1 compares the differences across the primary energy accounting methods for the world by energy source using the GEA primary substitution equivalent (see GEA Technical Guidelines, Annex 1 (GEA, 2012)), the direct equivalent, and the physical energy content methods for the year 2005 based on IEA data (IEA, 2010). As is to be expected, the main differences in absolute terms across the methods are for nuclear, hydropower, and other renewables (except biomass). Great care is, therefore, advised when using and comparing reported primary energy across different statistical sources in general and in comparing the numbers reported in the GEA in particular.

Table A.1. Comparison of global primary energy supply in 2005 using three different accounting methods for primary energy. Source: data from IEA, 2010.

	GEA Substitution Method		Direct Equivalent Method		Physical Energy Content Method	
	EJ	%	EJ	%	EJ	%
Fossil fuels	389	78	389	85	389	81
Biomass	46	9	46	10	46	10
Nuclear	28	6	10	2	30	6
Hydro	30	6	11	2	11	2
Other Renewables	< 3	1	1	<1	3	1
Total	496	100	457	100	479	100

#### A.4 Limitations of Primary Energy Accounting

The alternative primary energy accounting methods outlined above show significant differences in how non-combustible energy sources are presented in energy statistics. As the differences are

<sup>38</sup> In principle such waste heat could be "recycled" but would require a close co-location of nuclear power plants with main energy uses such as major cities, which raises issues of safety and public risk perception.

<sup>39</sup>For example, in IEA/OECD (2005) the assumed conversion efficiency factor for hydropower, solar electricity, and wind is 100%, for nuclear power it is 33%, and for geothermal electricity it is 10%.



significant for nuclear and renewables, the accounting method chosen has an impact on how the primary energy structure is interpreted. This in itself is an important limitation of the concept of primary energy. It is also a cause of considerable confusion in comparing different statistics, data sources, and analyses (and the ensuing emphasis on the importance of different energy options).

The differences of applying the three accounting methods to current energy use levels are relatively modest compared to those in scenarios of possible future major energy transformations where the structure of the global energy system changes significantly. The accounting gap between the different methods tends to become bigger over time as the share of combustible energy sources declines. The very concept of a statistically defined primary energy that has no real physical equivalence is thus becoming more limited as more radical future energy systems depart from current ones.

Figure A.1 illustrates this growing divergence across the three primary energy accounting methods for an otherwise identical scenario in terms of final and useful energy demand (based on the intermediary GEA-M set of pathways; see GEA Chapter 17, Riahi et al., 2012). As the structure of the global energy system changes, different accounting methods differ by more than a factor of two in terms of implied primary energy growth. No such significant accounting ambiguities affect secondary and final energy, which are thus preferable descriptors for radical, transformative changes in energy systems.

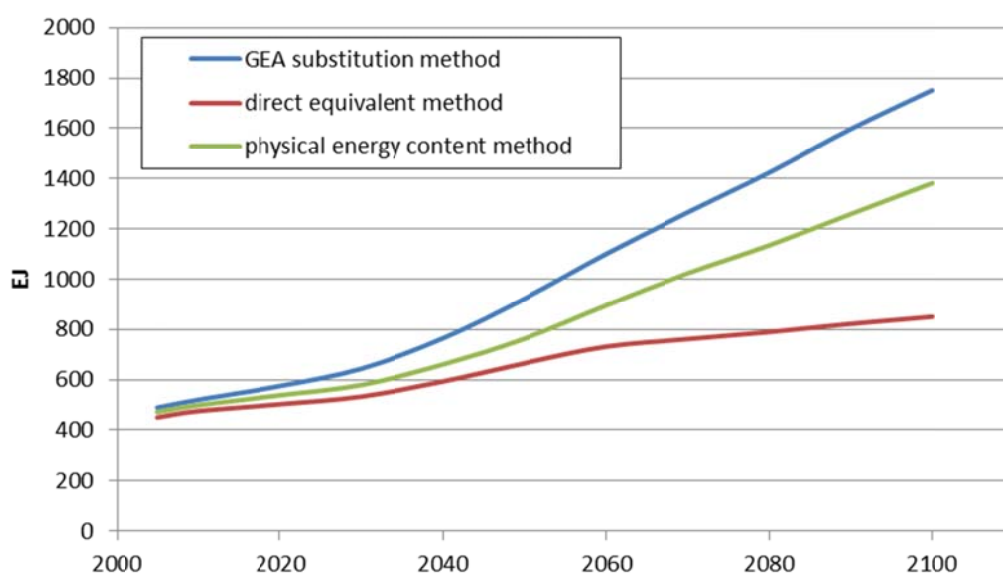


Figure A.1. Comparison of global total primary energy supply between 2005 and 2100 using three different primary energy accounting methods based on identical useful energy demands as quantified in the illustrative GEA-M set of pathways (see GEA Chapter 17, Riahi et al., 2012).

## A.5 Main Energy Statistics and Data Sources

Four institutions regularly publish globally comprehensive statistics on energy use: British Petroleum (BP), the US Energy Information Administration (EIA), the International Energy Agency (IEA), and the United Nations (UN). As Table A.2 shows, these energy statistics differ

in terms of energy coverage ranging from primary energy (PE), primary and secondary energy (EIA, IEA, UN), to primary, secondary, and final energy (IEA).

Table A.2. Overview of the four major data sources for Global Energy Statistics.

	BP	EIA	IEA	UN
Primary energy	X	X	X	X
Secondary energy		X	X	X
Final energy			X	- <sup>1</sup>
New renewables <sup>2</sup>		X	X	X
Traditional biomass <sup>3</sup>			X	X
Electronic availability	Online free	Online free	Online subscription (\$)	Offline tape order (\$)

<sup>1</sup> Not reported directly by UN but can be calculated from full data base statistics.

<sup>2</sup> New renewable refers to solar, wind, modern bioenergy, and geothermal.

<sup>3</sup> Traditional biomass refers to fuelwood, dung, and agricultural residues.

Data are mainly collected through questionnaires and exchanges between the organizations as well as with others, including but not limited to publications from the Statistical Office of the European Communities (Eurostat), the International Atomic Energy Agency (IAEA), the Organization of the Petroleum Exporting Countries (OPEC), the Organización Latinoamericana de Energía (OLADE), etc.

Statistics differ in the extent to which they include non-commercial energy (use of traditional biomass), which is fully covered in the IEA statistics (all sources) and partially in UN (mainly fuel wood), as well as modern renewables (outside hydropower), with only IEA and UN providing (near) full coverage (with BP reporting selected modern renewables). Different reporting organizations also use different methods for expressing the primary energy equivalent of non-combustible energies (see Section A.3 on Primary Energy Accounting above) and in their use of heating values (see the discussion above). LHV are used by the UN and IEA (and unless otherwise specified in this report). HHV are used in US EIA statistics (which therefore tend to report systematically higher energy use compared to other data sources), with BP using a hybrid approach which is closer to UN/IEA statistical values).

Both the UN and IEA provide comprehensive energy statistics on the production, trade, conversion, and use of primary and secondary, conventional and non-conventional, and new and renewable sources of energy covering the period from 1970 onwards (UN, 2010; IEA, 2010).<sup>40</sup> IEA's energy balances represent convenient aggregates of all energy flows in a common (non-SI) energy metric in tonnes of oil equivalent, summarized from IEA's energy statistics and for global and regional aggregates as well as for individual countries. The IEA statistics cover approximately 130 countries (of 192 UN Member countries), which represent about 98% of worldwide energy use (IPCC, 2006). BP statistics focus on commercial and conventional energy carriers and exclude fuels such as wood, peat, and animal waste and energy flows of other

<sup>40</sup> Electronic data need to be purchased from the UN and processed with appropriate data base software tools as few aggregates are contained in the statistics. For instance final energy use is not reported directly by the UN, but can be calculated from a multitude of individual energy flows reported. The UN data portal allows free electronic access to statistics of individual energy flows as well as few aggregate energy indicators (primary energy use, electricity generation) from 1990 onwards. Full IEA energy balances, by energy flow, use, and sector since 1971 are available online to subscribers (including many universities) of the OECD iLibrary online publication and statistical query service: The statistics of the EIA and BP are available online free of charge but provide a somewhat more limited coverage as well as adopt differing accounting conventions to UN and IEA.

renewables such as wind, geothermal, and solar power generation<sup>41</sup> (BP, 2010a). Its statistics cover the period since 1965, are updated regularly,<sup>42</sup> and are available free of charge on the Internet. Cumulative installed renewable power capacity data are provided in BP's full workbook of historical statistical data from 1965–2009 (BP, 2010b). US EIA energy statistics, which are also freely available online, cover primary and secondary energy use by fuel category and per country since 1980, using the (non-SI) BTU as a common energy metric and based on HHV, which is different than other energy statistics.

As a result of differences in data collection sources, boundary conditions, methodologies, and heating values used in different statistics, global primary energy use numbers reported by these four organizations differ from 442 EJ (BP) to 487 EJ (EIA), or by some 10%, for the GEA base year 2005 and throughout their entire reporting horizon (see Figure A.2). Adjusting<sup>43</sup> the different primary accounting conventions to the GEA standard and completing non-reported energies (non-commercial, traditional biomass using the IEA numbers) reduces this data uncertainty to a range from 495 EJ (IEA and BP) to 528 EJ (EIA<sup>44</sup>), or some 7%, with the UN statistics taking an intermediary position (506 EJ) for the GEA base year 2005 (see Figure A.2). This GEA assessment adopted a value of 495 EJ for the level of world primary energy use in the year 2005.

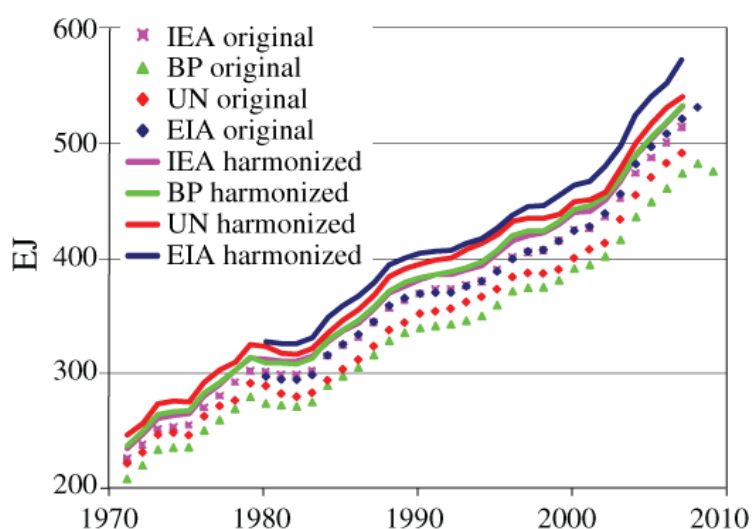


Figure A.2. World primary energy (in EJ). Original data by four reporting agencies (dots) and harmonized primary energy equivalences (lines). Source: data from Macknick, 2009.

<sup>41</sup> With exception of ethanol, only installed capacity data for geothermal, wind, and solar are reported by BP.

<sup>42</sup> Updates are fastest among all energy statistics and available by September each year for the preceding year.

<sup>43</sup> A software tool performing data comparison and adjustments to consistent and comparable accounting conventions for the 20 largest energy-using countries worldwide as well as the global total has been developed by Macknick (2009) and is available online:

[www.iiasa.ac.at/Research/TNT/WEB/Publications/Energy\\_Carbon\\_DataBase/](http://www.iiasa.ac.at/Research/TNT/WEB/Publications/Energy_Carbon_DataBase/).

<sup>44</sup> Due to the use of HHV in the EIA statistics.

## A.6 Levelized Costs Definition

The notion of levelized costs of electricity (LCOE) is an ex ante planning and analysis tool for comparative assessments of different investment options producing a quasi identical output. LCOE has been widely used for decades in the electric utility industry for comparing the generating costs of different technology and fuel combinations over their respective economic life for the purpose of identifying least-cost power plant capacity expansion plans. As well, policy makers and market regulators have used the concept for rate setting purposes and pricing policies (Anderson, 2007).

Two levelized cost definitions dominate the literature. The first calculates the levelized unit costs of generating one kWh of electricity by dividing the sum of annualized capital costs plus fuel and maintenance costs over the year by the annual kWh output. This approach requires at least the following information:

- Investment costs per kW of installed capacity, \$/kW<sub>e</sub> (INV)
- Decommissioning costs per kW of installed capacity, \$/kW<sub>e</sub> (DECOM)
- Fixed operating and maintenance costs (O&M) per year (FOM), \$/kW<sub>e</sub>
- Variable operating costs including emission charges per kWh, \$/kWh (VOM)
- Fuel price per kWh, in \$/kWh input (P<sub>FUEL</sub>)
- Plant factor, i.e., full load hours of plant operation per year, fraction of year (PLF)
- Plant life time, years (PLT)
- Plant thermal efficiency, in % (η)
- Discount rate, in % (i)
- LCOE, in \$/kWh of electricity output

$$LCOE = \left( \frac{INV \times CRF + FOM}{PLF} \right) / 8760 + VOM + \frac{P_{FUEL}}{\eta} + \left( \frac{DECOM}{PLF} \times (1 + i)^{-(PLT+T)} \right) / 8760$$

$$CRF = \frac{i (1 + i)^{PLT}}{(1 + i)^{PLT} - 1}$$

The annuity or capital recovery factor (CRF) distributes the up-front investment costs of the plant at equal installments per year over the lifetime of the plant. Generally, the discount rate reflects the time value of money. In LCOE calculations it represents the cost of capital, usually as the weighted average of the interest on loans and expected return on equity in the absence of specific market or technology risks (IEA, 2010).

The investment component as well as the fix O&M costs are divided by the plant factor so as to account for the actual utilization of the plant over the year and to arrive at a comparable “service quality” of the output (a proxy for equal reliability of generating the same firm kWh over the full 8760 hours per year). The decommissioning cost are incurred when the plant is taken out of service and the term T represents the additional time before decommissioning can begin (for plants that need extra time before safe decommissioning can commence, e.g., nuclear power plants).

Using the illustrative economic data of Table 9.1 above (upper range) for the advanced coal power plant with carbon capture and storage and assuming:

- Thermal conversion efficiency (η) of 35 per cent

- O&M costs of \$ 96 per kW<sub>e</sub> per year, split into FOM of \$ 60 per kW<sub>e</sub> per year and VOM of \$ 2.97 per MWh
- Variable CCS cost of \$ 2.50 per MWh
- 5 per cent real discount rate (i)
- Plant lifetime (PLT) 40 years
- Load factor (PLF) of 80 per cent
- No decommissioning costs (DECOM)
- No inflation

leads to a CRF of 0.0583 and LCOE of \$ 64 per MWh.

$$CRF = \frac{0.05 (1 + 0.05)^{40}}{(1 + 0.05)^{40} - 1} = 0.0583$$

$$LCOE = \frac{0.8}{0.8} / 8760 + \left( \frac{2.97 + 2.5}{1000} \right) + \frac{2.8 / 278^{45}}{0.35} = 0.064 \frac{\$}{kWh} \text{ or } 64 \frac{\$}{MWh}$$

Alternatively LCOE are defined as ‘the ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent’ (IEA, 2005). This approach accounts for the full lifetime expenditures of a generating station as incurred and allocates these costs over the lifetime revenues generated by the plant, with both future expenditures and revenues discounted to present values. LCOE then is equal to the price for the electricity. Here, information about the price at which the electricity can be sold over the lifetime of the plant in the market place (i.e. the revenue to an investor) is another input requirement. The plant factor is reflected through the annual electricity generation.

$$\sum_t [ELE_t \times P_{Ele} \times (1 + i)^{-t}] = \sum_t [INV_t \times VOM_t \times DECOM \times (1 + i)^{-(PLT+T)}]$$

$$P_{Ele} = \frac{\sum_t [INV_t \times VOM_t \times DECOM \times (1 + i)^{-(PLT+T)}]}{\sum_t [ELE_t \times (1 + i)^{-t}]} = LCOE$$

Note: Discounting physical entities appears counterintuitive as physical units neither change magnitude over time, nor do they pay interest. However, from a utility’s or investor’s perspective, the economic function of electricity generation is to produce a revenue stream that generates future revenues. From today’s point of view a MWh produced this year thus does not have the same economic value as does a MWh produced next year, it has a higher value. What is discounted is the value of output, i.e., the physical production times its price, in the above formula, and not output itself. It is only after mathematical transformation that it appears as if physical production was discounted (IEA, 2010).

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<sup>45</sup> Conversion of GJ to kW<sub>th</sub> (1 GJ = 278 kW<sub>th</sub>)

There are several limitations associated with LCOE that do not include:

- Diurnal, weekly and seasonal fluctuations in demand
- Price uncertainty of both fuel input prices and electricity rates
- Market and technology investment risks
- System costs, i.e. the impact of a power plant on the electricity system such as grid integration
- Externalities

The absence of market and technology risks results in a gap between LCOE and true financial costs of an investor operating in real electricity markets. LCOE is closer to the real cost in regulated monopoly electricity markets with loan guarantees and regulated prices rather than to the real costs of investments in competitive markets with variable prices (IEA, 2010).

Verification of ex-ante LCOE estimates with actual ex-post real costs is inherently difficult as actual generating cost information in liberalized markets reside with the utilities which treat this as commercially sensitive information. Also often certain common costs are shared by several plants making plant specific cost data either too restrictive or affected by cost allocation uncertainties (Heptonstall, 2007).

In principle, it is possible to incorporate some of these omitted factors in LCOE analyses, e.g. by expanding the number of cost factors, adjusting current ones, or redefining individual cost elements but generally at the cost of introducing additional assumptions and uncertainty and potential loss of transparency.

Given these limitations, LCOE are usually used for a first order assessment of generating costs at the plant level or for comparative assessments of different new generating options and identification of the least cost option among alternatives. Other applications include the impact of variations of key cost factors but also policy changes (e.g., carbon prices) on the cost structure of generation and thus the merit order of alternatives. Comparative assessments of various alternative technologies based on the LCOE methodology could be significantly enriched if they are included in a full energy systems context, e.g., by a comprehensive modeling approach with proper consideration of load curves, transmission and distribution networks, and integration and balancing costs associated with each generation technology.



## Appendix B: Conversion Tables

Table B.1. Conversion factors. Source: Nakicenovic et al., 1998.

TO->													
FROM	MJ	TCE	btu	toe	boe	kWyr	kcal	TJ	Gcal	Mtoe	Mbtu	GWh	GWyr
MJ	1	3.4121E-05	947.8134	2.39E-05	0.000175	3.171E-05	238.8459	0.000001	0.00023885	2.3885E-11	0.00094781	2.7778E-07	3.171E-11
TCE	29307.6	1	27778140	0.7	5.131	0.9293379	7000000	0.0293076	7	0.0000007	27.77814	0.008141	9.2934E-07
btu	0.00105506	3.6E-08	1	2.52E-08	1.85E-07	3.346E-08	0.2519968	1.0551E-09	2.52E-07	2.52E-14	0.000001	2.9307E-10	3.3456E-14
toe	41868	1.428571	39683050	1	7.33	1.327626	10000000	0.041868	10	0.000001	39.68305	0.01163	1.3276E-06
boe	5711.869031	0.19489378	5413784.9	0.136426	1	0.1811222	1364256	0.00571187	1.364256	1.3643E-07	5.413786	0.00158663	1.8112E-07
kWyr	31536	1.07603488	29890240	0.753224	5.521135	1	7532244	0.031536	7.532244	7.5322E-07	29.89024	0.00876	0.000001
kcal	0.0041868	1.4286E-07	3.968305	1E-07	7.33E-07	1.328E-07	1	4.1868E-09	0.000001	1E-13	3.9683E-06	1.163E-09	1.3276E-13
TJ	1000000	34.12084	947813400	23.88459	175.074	31.70979	238845900	1	238.8459	2.3885E-05	947.8134	0.27777778	3.171E-05
Gcal	4186.8	0.14285714	3968305	0.1	0.733	0.1327626	1000000	0.0041868	1	0.0000001	3.968305	0.001163	1.3276E-07
Mtoe	41868000000	1428571	3.968E+13	1000000	7330000	1327626	1E+13	41868	10000000	1	39683050	11630.0004	1.327626
Mbtu	1055.06	0.03599953	1000000	0.0252	0.184714	0.0334557	251996.8	0.00105506	0.2519968	2.52E-08	1	0.00029307	3.3456E-08
GWh	3600000	122.835	3.412E+09	85.98452	630.2666	114.1553	859845200	3.6	859.8452	8.5985E-05	3412.128	1	0.00011416
GWyr	31536000000	1076034.88	2.989E+13	753224.4	5521135	1000000	7.5374E+12	31536	7532244	0.7532244	29910720	8759.99625	1

Table B.2a. Typical calorific values of solid energy carriers. Source: IEA/OECD/Eurostat, 2005.

	Gross calorific value	Net calorific value
	HHV [MJ/kg]	LHV [MJ/kg]
Anthracite	29.65 – 30.35	28.95 – 30.35
Cooking coals	27.80 – 30.80	26.60 – 29.80
Other bituminous	23.85 – 26.75	22.60 – 25.50
Metallurgical coke	27.90	27.45
Gas coke	28.35	27.9
Low-temperature coke	26.30	25.4
Petroleum coke	30.5 – 35.8	30.0 – 35.3
Wood	15 – 19	-

Note: Detailed information on energy and chemical characteristics for a wide range of biomass fuels can be found at IEA Task 32 biomass database: <http://www.ieabcc.nl>; Phyllis biomass database: <http://www.ecn.nl/phyllis>; TU Vienna biomass database: <http://www.vt.tuwien.ac.at/biobib>.

Table B.2b. Typical calorific values of liquid energy carriers. Source: IEA/OECD/Eurostat, 2005; IEA, 2009b; Agarwal, 2007.

	Gross calorific value	Net calorific value
	HHV [GJ/tonne]	LHV [GJ/tonne]
Ethane	51.90	47.51
Propane	50.32	46.33
Butane	49.51	45.72
LPG	50.08	46.15
Naphtha	47.73	45.34
Aviation gasoline	47.40	45.03
Motor gasoline	41.10	44.75
Aviation turbine fuel	46.23	43.92
Other kerosene	46.23	43.92
Gas/diesel oil	45.66	43.38
Fuel oil, low sulphur	44.40	42.18
Fuel oil, high sulphur	43.76	41.57
Biodiesel	-	36.8 – 40.9
Biogasoline	-	24.0 – 37.4
Ethanol	29.4	26.87
Methanol	22.36	19.99
Dimethyl ether	30.75	28.62

Table B.2c. Typical calorific values of gaseous energy carriers, per kg and m3. Source: IEA/OECD/Eurostat, 2005; IEA, 2009

	Gross calorific value	Net calorific value	Gross calorific value	Net calorific value
	HHV [MJ/kg]	LHV [MJ/kg]	HHV [MJ/m3]	LHV [MJ/m3]
Methane	55.52	50.03	37.652	33.939
Natural gas (Norway)	-	-	39.668	-
Natural gas (Netherlands)	-	-	33.339	-
Natural gas (Russia)	-	-	37.578	-
Natural gas (Algeria)	-	-	42.000	-
Natural gas (United States)	-	-	38.341	-

Table B.3. CO<sub>2</sub> emission factors on a net calorific basis. Source: IPCC, 2006.

Fuel type	IPCC default [kg/GJ]	Range from [kg/GJ]	to [kg/GJ]
Crude Oil	73.3	71.1	75.5
Motor Gasoline	69.3	67.5	73.0
Jet Gasoline	70.0	67.5	73.0
Jet Kerosene	71.5	69.7	74.4
Kerosene	71.9	70.8	73.7
Gas / Diesel Oil	74.1	72.6	74.8
Residual Fuel Oil	77.4	75.5	78.8
Liquefied Petroleum Gases	63.1	61.6	65.6
Ethane	61.6	56.5	68.6
Naphtha	73.3	69.3	76.3
Petroleum Coke	97.5	82.9	115.0
Anthracite	98.3	94.6	101.0
Coking Coal	94.6	87.3	101.0
Lignite	101.0	90.9	115.0
Oil Shale and Tar Sands	107.0	90.2	125.0
Brown Coal Briquettes	97.5	87.3	109.0
Natural Gas	56.1	54.3	58.3
Compressed Natural Gas	56.1	54.3	58.3
Liquefied Natural Gas	56.1	54.3	58.3
Municipal Wastes (non-biomass fraction)	91.7	73.3	121.0
Municipal Wastes (biomass fraction)	100.0	84.7	117.0
Industrial Wastes	143.0	110.0	183.0
Waste Oils	73.3	72.2	74.4
Peat	106.0	100.0	108.0
Wood / Wood Waste	112.0	95.0	132.0
Sulphite lyes (Black Liquor)	95.3	80.7	110.0
Other Primary Solid Biomass	100.0	84.7	117.0
Charcoal	112.0	95.0	132.0
Biogasoline	70.8	59.8	84.3
Biodiesels	70.8	59.8	84.3
Other liquid biofuels	79.6	67.1	95.3
Landfill Gas	54.6	46.2	66.0
Sludge Gas	54.6	46.2	66.0
Other Biogas	54.6	46.2	66.0

Note: Values represent CO<sub>2</sub> emissions that arise with 100% oxidation of fuel carbon content at the point of combustion. Life-cycle CO<sub>2</sub> emissions for various fuels can be higher or lower, due to emissions in the supply chain of the fuel and due to carbon absorbed during the growth phase of biomass feedstock.

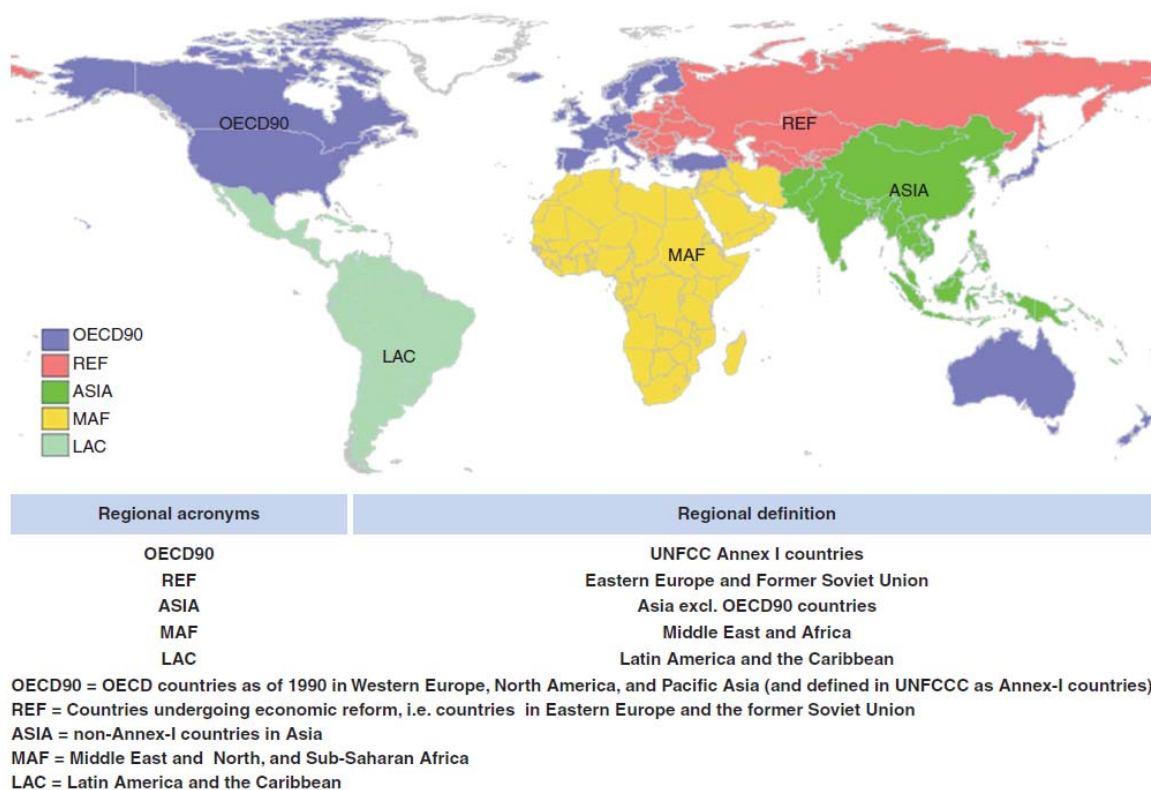


Figure B.1. Definition of GEA world regions used in the Energy Primer. For country listings and finer resolution regional definitions see GEA Technical Guidelines Annex-II.  
[http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA\\_Annex\\_II.pdf](http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Annex_II.pdf)

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