1 Energy Primer

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1.1 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 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. Energy extraction, conversion, and use always 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[1] 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 from challenges and options to *integrated* solutions, as done in the different chapters of the Global Energy Assessment (GEA). Different chapters will quite naturally emphasize different aspects and components of the global energy system, but they all share this basic common understanding of the importance of *integrating* all aspects related to energy into a common systems framework. Given the focus on assessing *current* energy systems as well as possible transformation pathways into *future* energy systems throughout this publication, the Energy Primer also aims at providing historical context that helps to understand how current energy systems have emerged and what characteristic rates of change are in these large-scale systems.

After an introduction and roadmap to Chapter 1 (Section 1.1), Section 1.2 introduces the fundamental concepts and terms used to describe global energy systems (Section 1.2.1) and then proceeds with an overview of the fundamental driver: the demand for *energy services* (Section 1.2.2), which is key in this assessment. Section 1.2.3 then summarizes the major links between energy services and primary energy resources at the global level for the year 2005. The section also contains a summary of major energy units and scales (with technical details given in Appendix 1.A).

Section 1.3 then turns to a historical perspective on energy transitions, covering both energy end-use demand and services (Section 1.3.1), as well as energy supply (Section 1.3.2), and concludes with a brief introduction into the relationship between energy and economic growth (Section 1.3.3). 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 1.4 then discusses the central aspect of energy efficiency, summarizing key concepts and measures of energy efficiency (Section 1.4.1), and estimates of global energy efficiencies based on the first (Section 1.4.2) and second law of thermodynamics (Section 1.4.3), as well as energy intensities (Section 1.4.4).

Section 1.5 provides a summary of key concepts (Section 1.5.1) and numbers of global *energy resources* that provide both key inputs and key limitations for energy systems. Fossil, fissile (Section 1.5.2), and renewable resources (Section 1.5.3) are covered comprehensively along with a basic introduction to energy densities, which are particularly critical for renewable energy (Section 1.5.4).

Section 1.6 provides a summary of major energy flows associated with production, use, and trade of energy (Section 1.6.2) and energy conversions (Section 1.6.3) that link energy resources to final energy demands. After an introduction and overview (Section 1.6.1), production, use, and trade of both direct (Section 1.6.2.1) and indirect "embodied" energy, (Section 1.6.2.2) are discussed, and all energy trade flows summarized in Section 1.6.2.3. The discussion of energy conversions is short, as it is dealt with in detail in the various chapters of this publication. After an introductory overview (Section 1.6.3.1), the electricity sector is briefly highlighted (Section 1.6.3.2).

Section 1.7 summarizes the main impacts of global energy systems on the environment in terms of emissions, including greenhouse gases (Section 1.7.2) and other pollutants where the energy sector plays an important role (Section 1.7.3). Emissions are central environmental externalities associated with all energy conversions.

Section 1.8 then complements the global synthesis of Chapter 1 by highlighting the vast heterogeneities in levels, patterns, and structure of energy use, by first introducing basic concepts and measures (Section 1.8.1), before addressing the heterogeneity across nations (Section 1.8.2), within nations (Section 1.8.3), as well as energy disparities (Section 1.8.4). This short section is of critical importance, especially in terms of a global assessment, as the inevitable top-down perspective involving Gigatonnes and Terawatts often glosses over differences in time, social strata, incomes, lifestyles, and human aspirations.

Section 1.9 provides a primer on basic economic concepts related to energy end-use and energy supply, using cooking in developing countries and electricity generation options as illustrative examples.

1 This text draws on, extends, and updates earlier publications by the authors including: Goldemberg et al., 1988; Nakicenovic et al., 1996b; 1998; Rogner and Popescu, 2000; Grubler, 2004; and WEA (World Energy Assessment), 2004.

Lastly, Section 1.10 leads into the full GEA, by providing an overview roadmap to the structure of GEA and its chapters.

Appendix 1.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 to achieve consistency and comparability across the different chapters. This is especially important in the energy field, that to date continues to use a plethora of vernacular units and accounting methods.

Appendix 1.B provides convenient summary tables of conversion and emission factors, and summarizes the various levels of regional aggregations used throughout GEA.

1.2 The Global Energy System

1.2.1 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*[2] (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 final *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 1.1 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., 1996b).

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., 1996b).

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 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 measured[3] 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

2 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). In this assessment, the term energy carrier is used throughout. A concise compendium of energy-related concepts and terms is given in Cleveland and Morris, 2006.

3 Useful energy can be defined as the last measurable energy flow before the delivery of energy services.

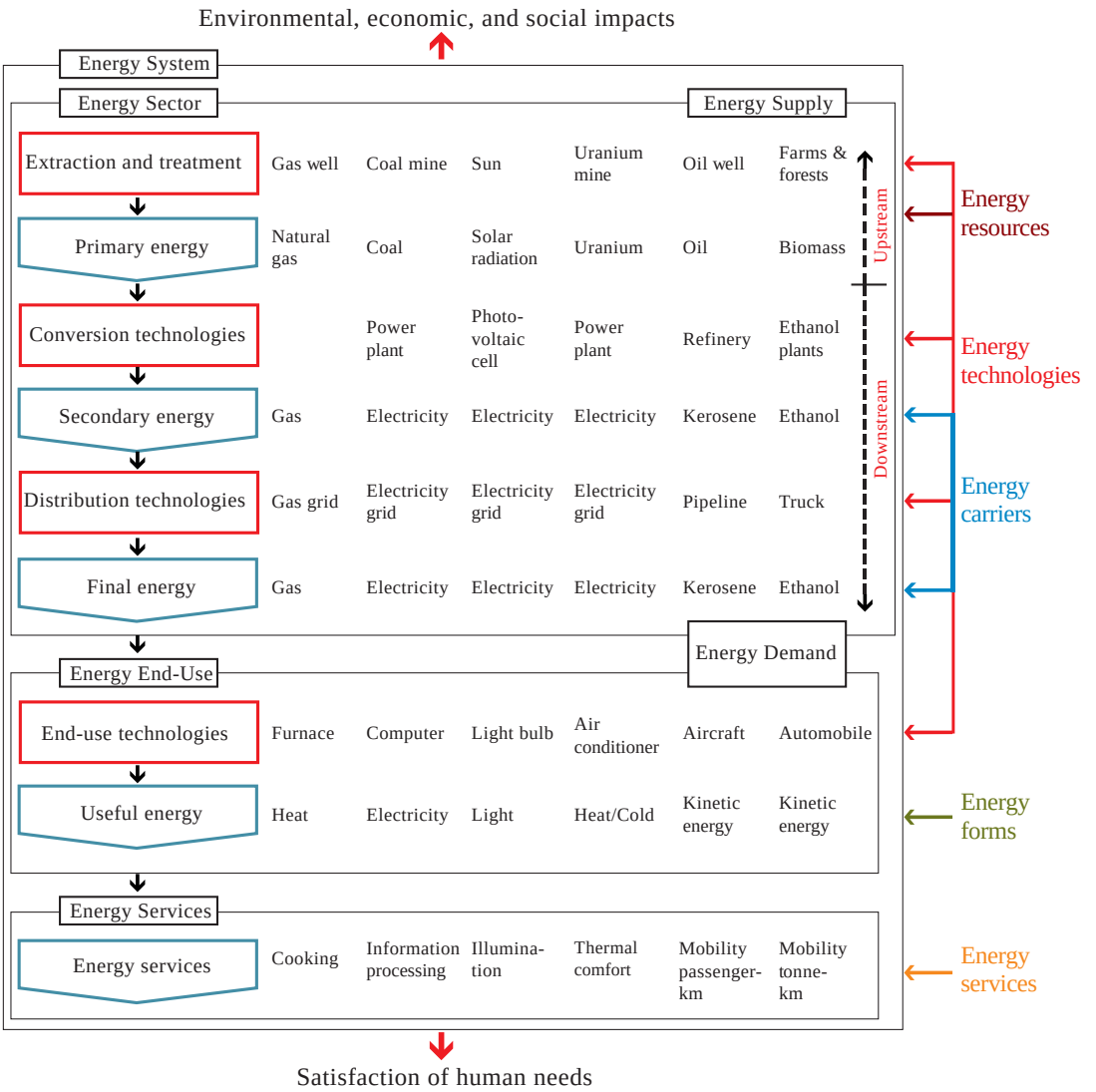


Figure 1.1 | The energy system: schematic diagram with some illustrative examples of the energy sector and energy end use and services. The energy sector includes energy extraction, treatment, conversion, and distribution of final energy. The list is not exhaustive and the links shown between stages 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., 1996b.

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., 1996b).

Figure 1.2 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 1.1 below and Appendix 1.A.

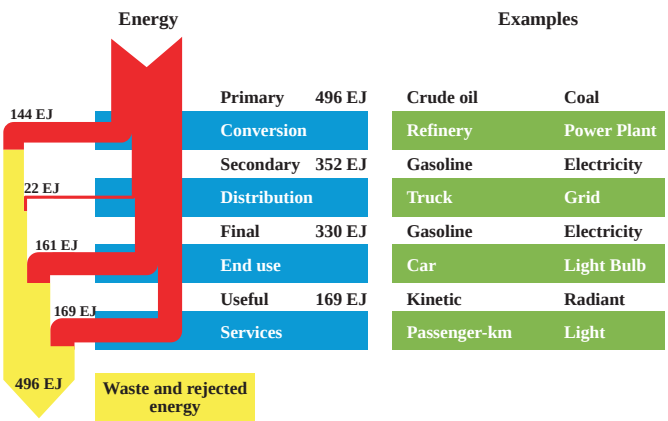


Figure 1.2 | Global energy flows of primary to useful energy, including conversion losses (waste and rejected energy), in EJ for 2005. Source: adapted from Nakicenovic et al., 1998, based on IEA, 2007a; 2007b; 2010.

Box 1.1 | 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 N=1 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).[4]

Figure 1.3 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 kilo-Watt-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 x 10^9 J) are used. Some national energy statistics (e.g., in China and India) report tonnes of coal equivalent (1 *tce* equals 29.31 x 10^9 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 1.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.

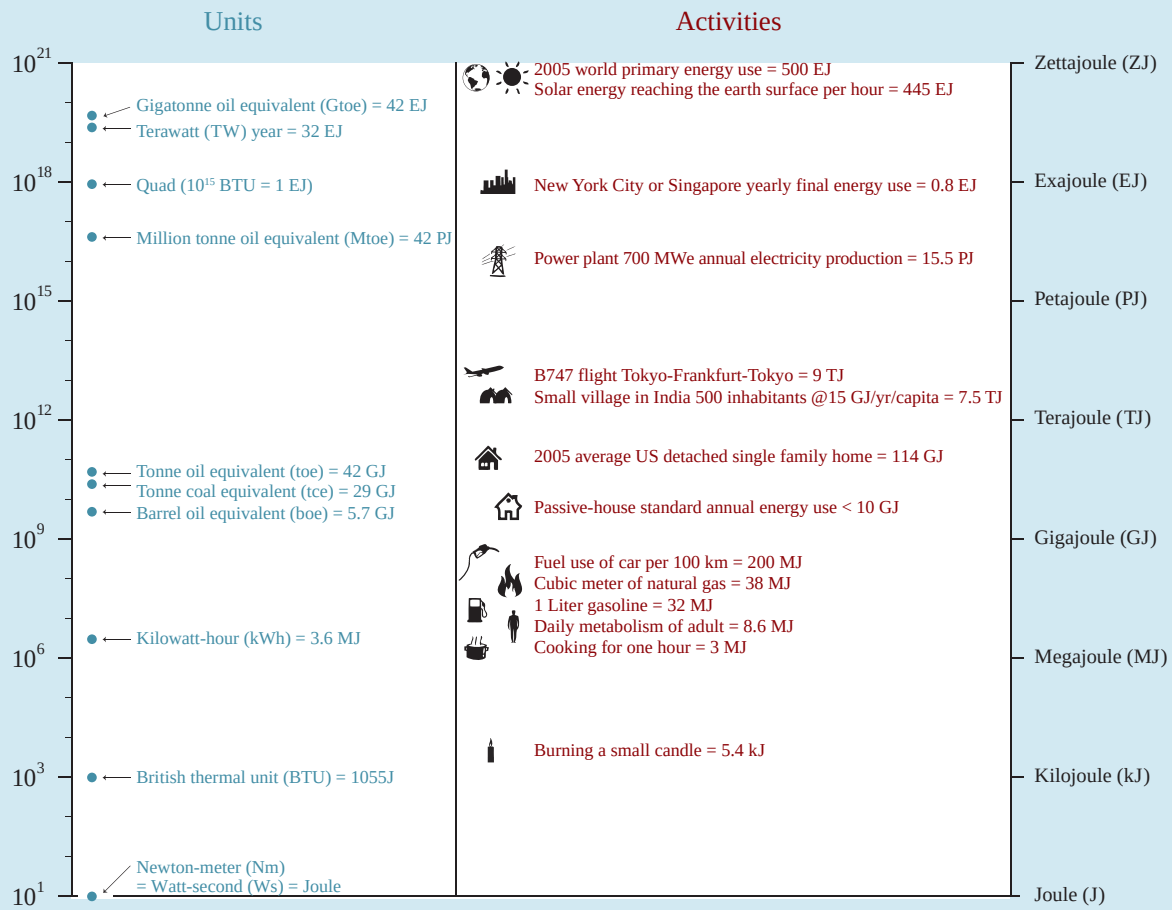


Figure 1.3 | Illustrative examples of energy units and scales used in the GEA.

4 International System of Units, *SI* from the French *le Système international d'unités*

1.2.2 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 1.1 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 1.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 assessed in separate chapters in this publication: Industry (Chapter 8), Transportation (Chapter 9), and Buildings (Chapter 10), which are the physical structures in which the remainder of energy services are provided.

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 1.8 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 1.1 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/year, or more than 9 tonnes/year 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 m^2 (including some 116 billion m^2 residential and 37 billion m^2 commercial floorspace, see Chapter 10) which corresponds to approximately 20 m^2 per person on average.

Table 1.1 | Estimated levels of energy services and corresponding shares in primary energy per service type for the year 2005.

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

* The original passenger transport data have been corrected by adding non-reported categories provided in Chapter 9.

Source: adapted from Cullen and Allwood, 2010.

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. Chapter 1 has, therefore, produced corresponding 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). This method has some drawbacks, as the available energy balances are based on an economic sectoral perspective, which does not always perfectly correspond with

Table 1.2 | 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 5).

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*

Source: final energy: data from IEA, 2007a and 2007b; useful energy: Chapter 1 estimation.

particular energy service types.[5] It needs 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 1.2 (see also Figure 1.5 below), with regional details given in Figure 1.6 below.

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 1.1 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 (see the discussion below) 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 1971 for different energy service categories and in measuring final energy inputs are shown in Figure 1.4.

1.2.3 From Energy Services to Primary Energy

Figure 1.5 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

5 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.

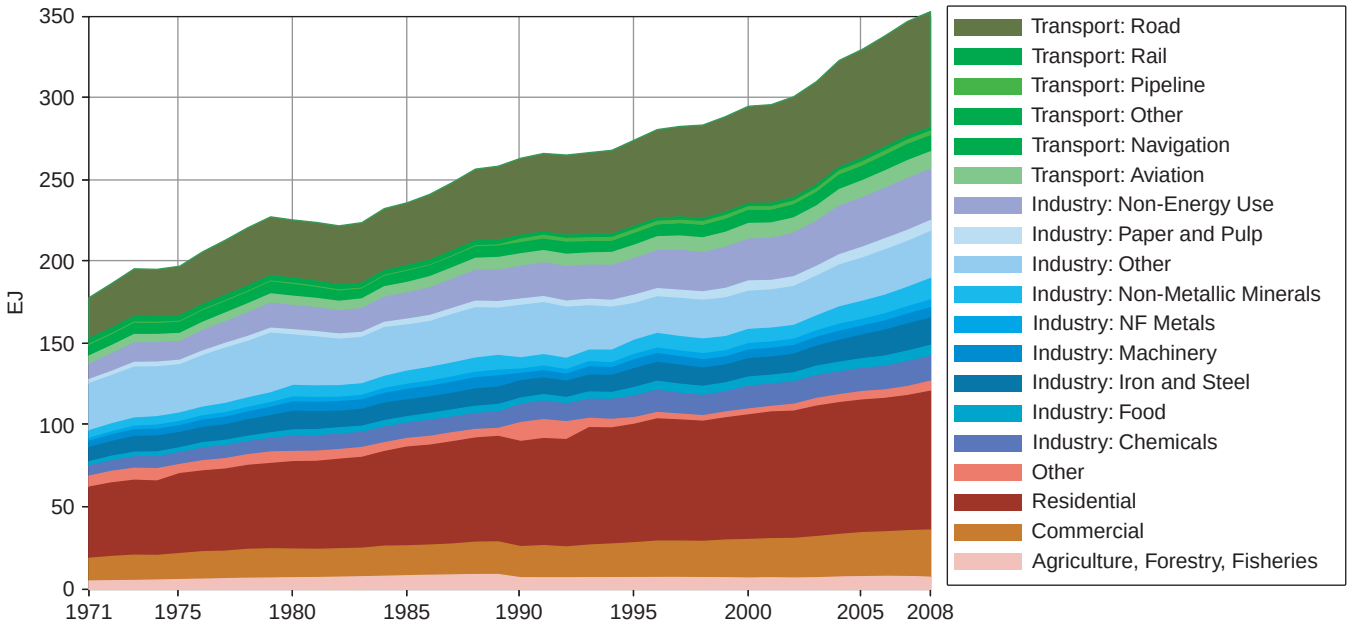


Figure 1.4 | Global final energy input into different energy services categories since 1971 (in EJ), by major energy service category. Source: adapted from IEA, 2010.

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 waste heat from electricity generation for industrial and residential customers, a scheme known as *cogeneration* or combined heat and power production (CHP).

From an energy systems perspective, the electricity sector assumes a special role (also the reason why it is discussed in greater depth in Section 1.6.3 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 1.5, 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.[6]

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. These differences are summarized at the level of useful, final, and primary energy respectively for the 5 GEA regions and the world in Figure 1.6.

1.3 Historic Energy Transitions

1.3.1 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

6 The 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.

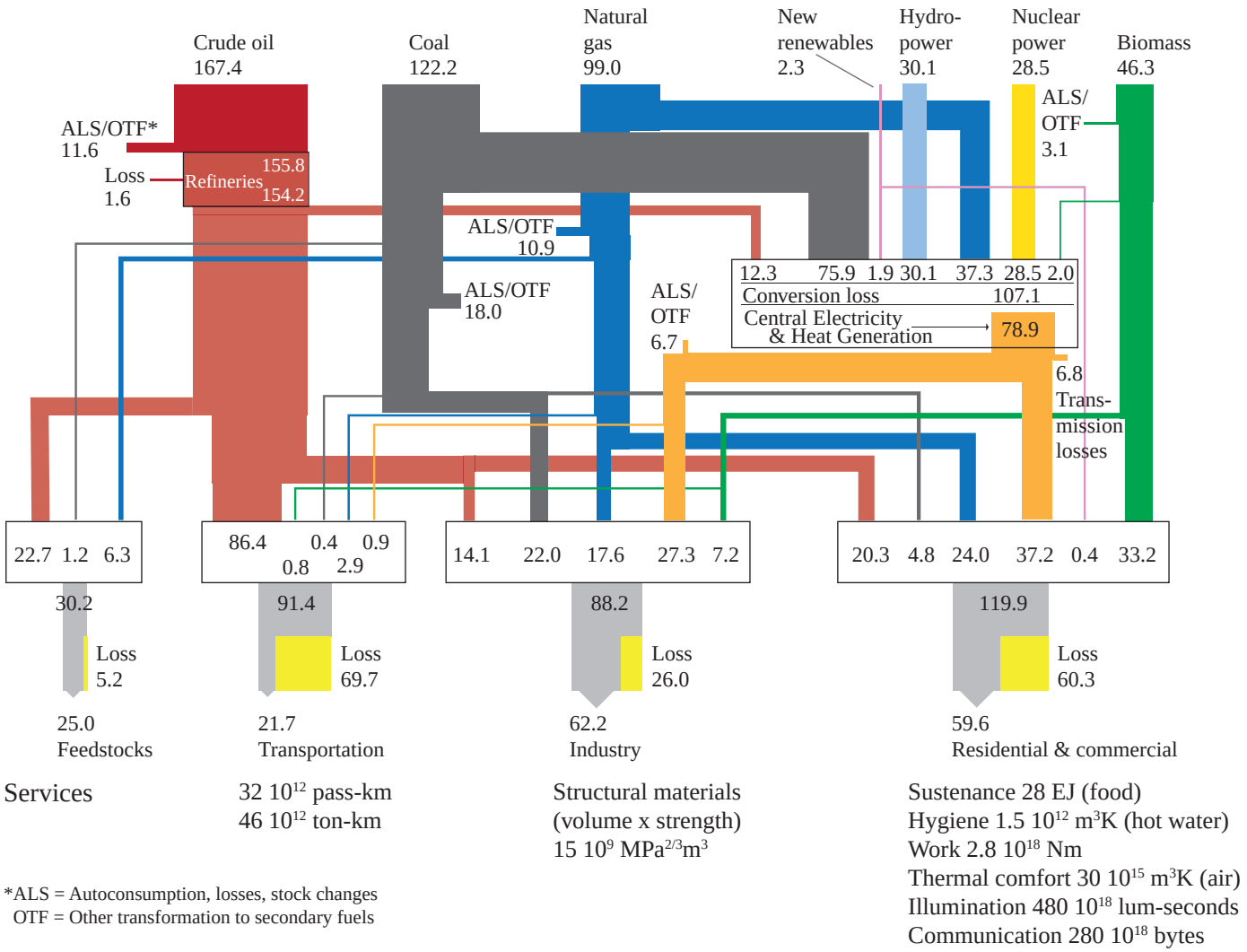


Figure 1.5 | Global energy flows (in EJ) from primary to useful energy by primary resource input, energy carriers (fuels) and end-use sector applications in 2005. Source: data from IEA, 2007a; b[7] (corrected for GEA primary energy accounting standard), and Cullen and Allwood, 2010.

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 1.7 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:

7 Readers should note some small differences (1–5%) between the 2005 base year energy flows reported in Chapter 1 and the ones derived from Chapter's 17 scenario modeling and reported in the GEA Scenario Data Base. Whereas Chapter 1 is based exclusively on statistics as reported by the International Energy Agency (IEA), Chapter 17 and the GEA Scenario data base also include data revisions and draw at times different system boundaries for the accounting of energy flows, in line with standard energy modeling practices.

The largest global differences are for final energy (330 vs. 315 EJ in Chapters 1 and 17 respectively) related to: (a) new improved estimates of non-commercial energy use based on household surveys that have revised downwards the IEA statistics on residential, traditional biomass use; and (b) different accounting of energy use for pipeline transportation, and bunker fuels for international shipping which are accounted in Chapter 17 as energy-sector auto-consumption and at the international level only whereas in Chapter 1 they are accounted at the national and regional levels as final transport energy use. Differences in global primary energy are smaller (496 vs. 489 EJ between Chapters 1 and 17 respectively, for the same reasons as outlined above).

These small energy accounting differences are within the inevitable uncertainty range of international energy statistics (for a review see Appendix 1.A) and do not diminish the coherence of this Assessment.

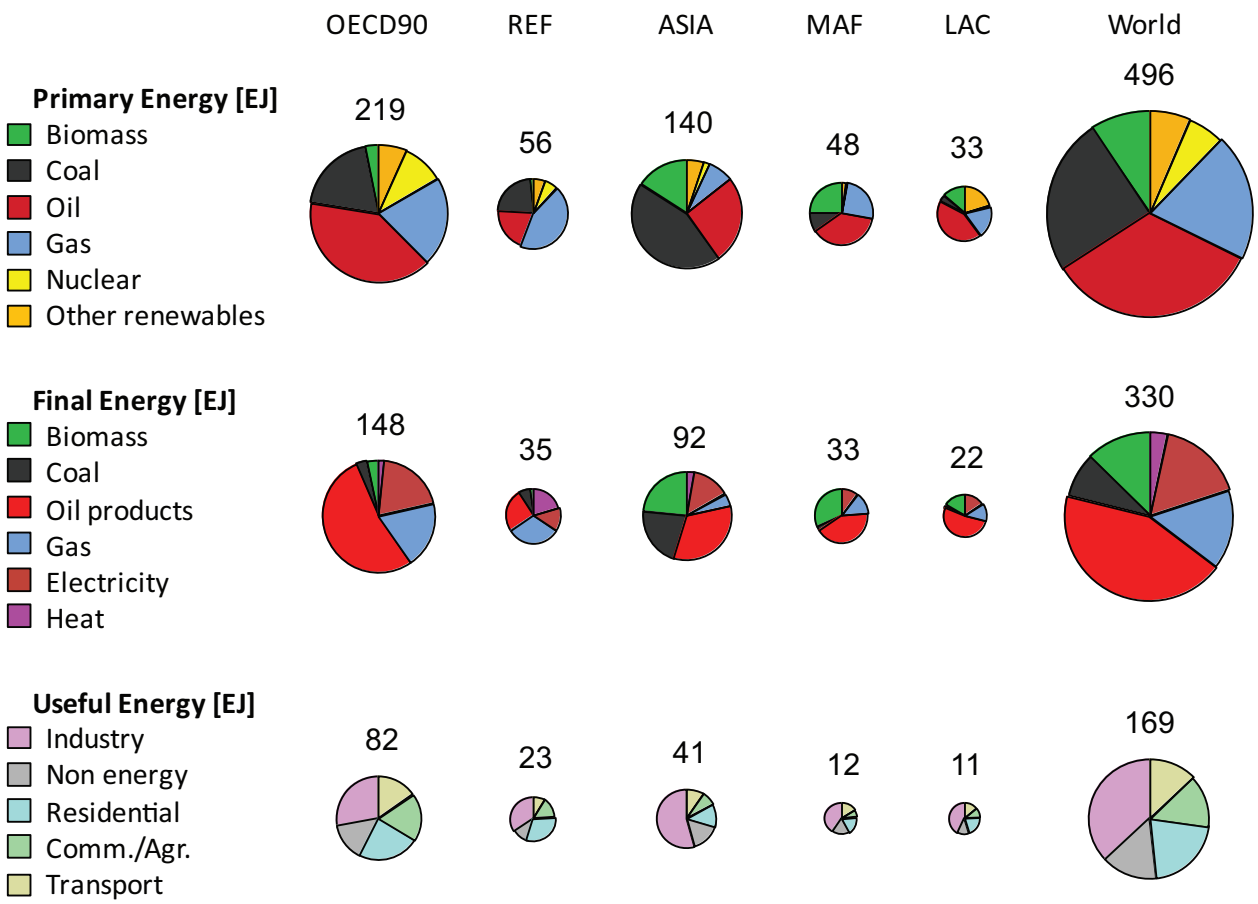


Figure 1.6 | World energy use: primary energy (by fuel), final energy (by energy carrier), and useful energy (by sector/type of energy service) for the world and five GEA regions for 2005 (in EJ). Source: based on IEA, 2007a and 2007b (corrected for GEA primary accounting standard, see also Footnote 5, above). For a definition of the GEA regions, see Appendix 1.B.

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).

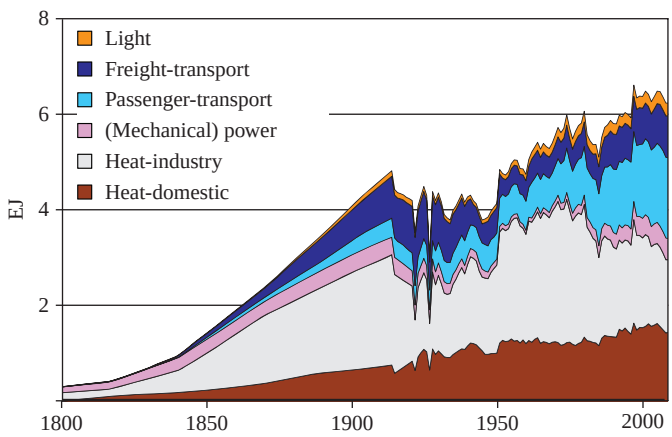


Figure 1.7 | Growth in energy service demand (measured by final energy inputs) United Kingdom since 1800, in EJ. Source: data from Fouquet, 2008. Updates after 2000 and data revisions courtesy of Roger Fouquet, Basque Centre for Climate Change, Bilbao, Spain.

At present, levels of energy services appear saturated at a level of above 6 GJ, or 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.

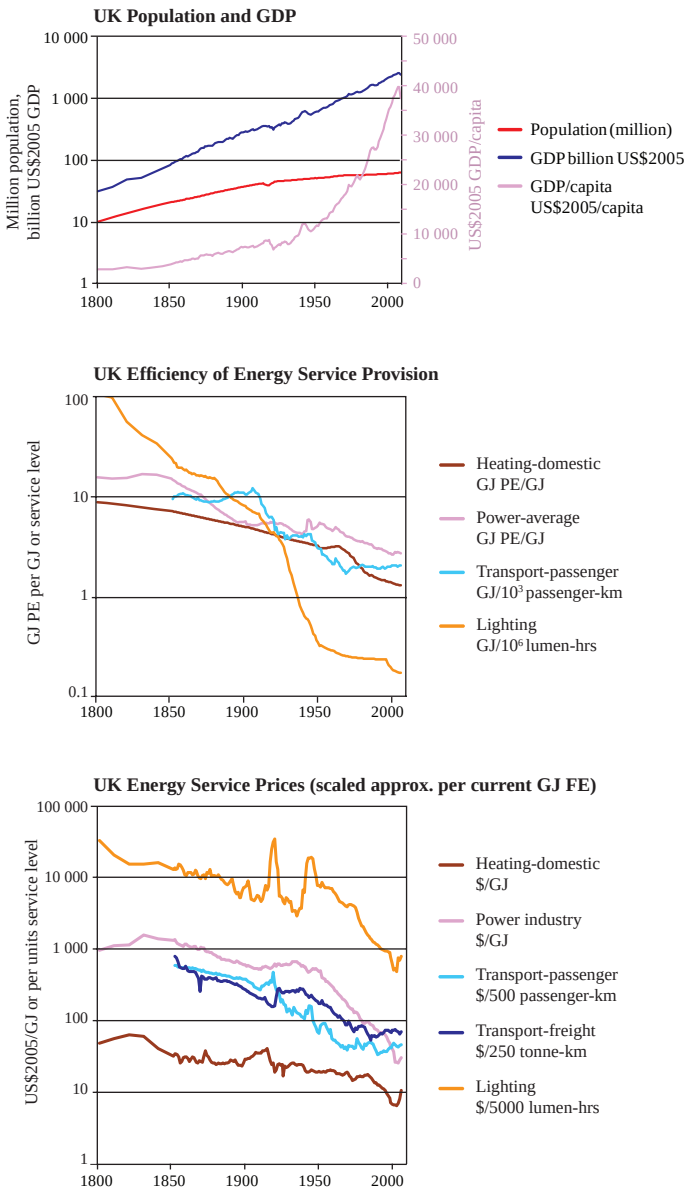


Figure 1.8 | Drivers of UK energy service demand growth: population, GDP and income per capita (panel 1); efficiency of energy service provision (per GJ service demand or service activity level – panel 2); and prices of energy services (per GJ service demand or activity level, activity level units have 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.

Figure 1.8 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[8] and the purchasing power of the population to afford traditional, as well as novel energy services.

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"[9] 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).

1.3.2 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,

8 There are both direct as well as indirect 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.

9 The "take-back" (or "rebound") effect describes a situation where an improvement in energy efficiency leads to lower energy costs and hence consumer savings, which are often spent on (energy-intensive) consumption activities. Part of the energy savings is thus "taken back" by changed consumer expenditures. For example, a new, more energy-efficient car, with lowered fuel costs, can lead to driving more, or alternatively to spending the saved fuel bill on additional recreational air travel. 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 but rather in vastly increased human welfare.

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, domestic fuel wood became increasingly scarce and expensive as forests were overexploited without sufficient replanting or other conservation measures (Ponting, 1992).[10]

The fuel crisis was eventually overcome through a radical technological end-use innovation: the steam engine powered by coal.[11] 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[12] throughout Europe, the United States and the world. Characteristic primary energy use levels during the "steam age," (the mid-19th century in England), were about 100 GJ/year 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 1.9 shows the exponential growth of global energy use at a rate close to 2%/yr since the advent of the Industrial Revolution. Figure 1.10 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 global primary energy.

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. Figure 1.10 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

10 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.

11 Note, however, that the fuel wood crises 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).

12 Quantitative historical accounts for major industrial countries are given in Gales et al., 2007, Kander et al., 2008, and Warr et al., 2010.

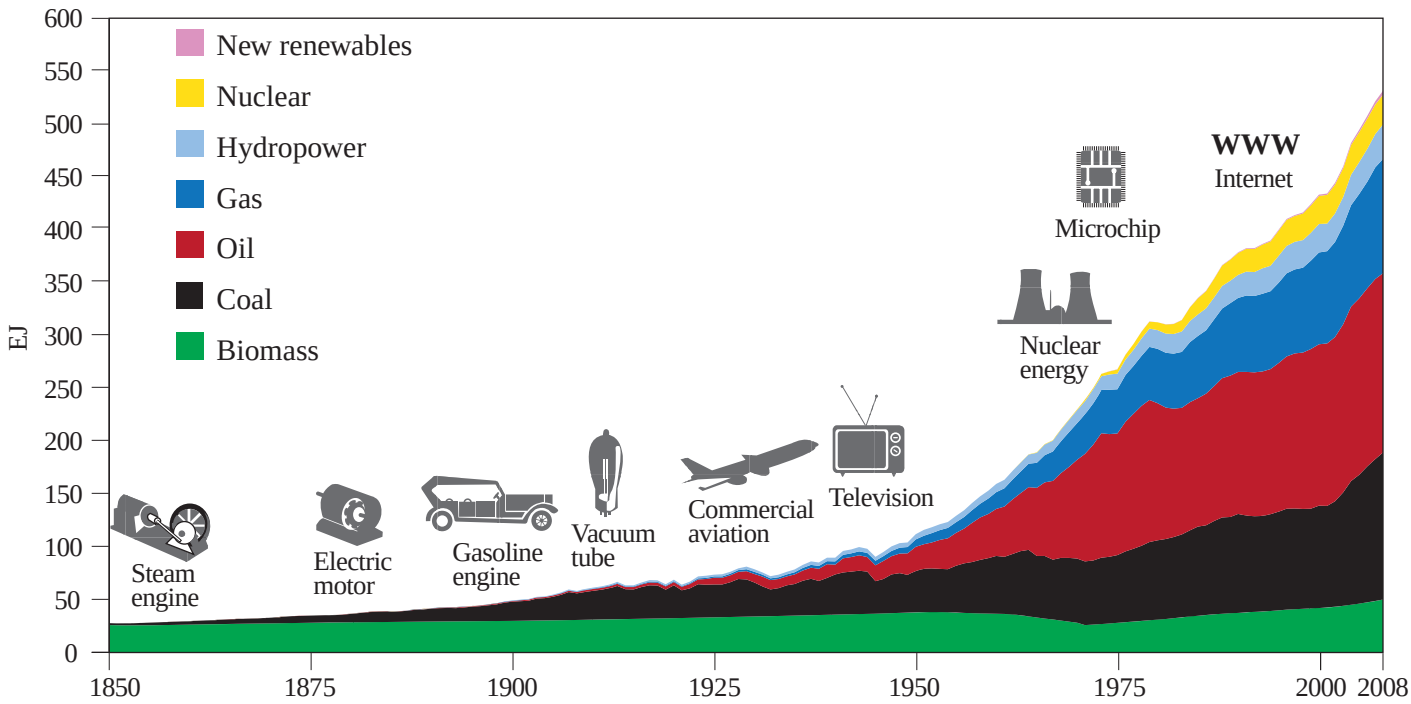


Figure 1.9 | History of world primary energy use, by Source (in EJ). Source: updated from Nakicenovic et al., 1998 and Grubler, 2008.

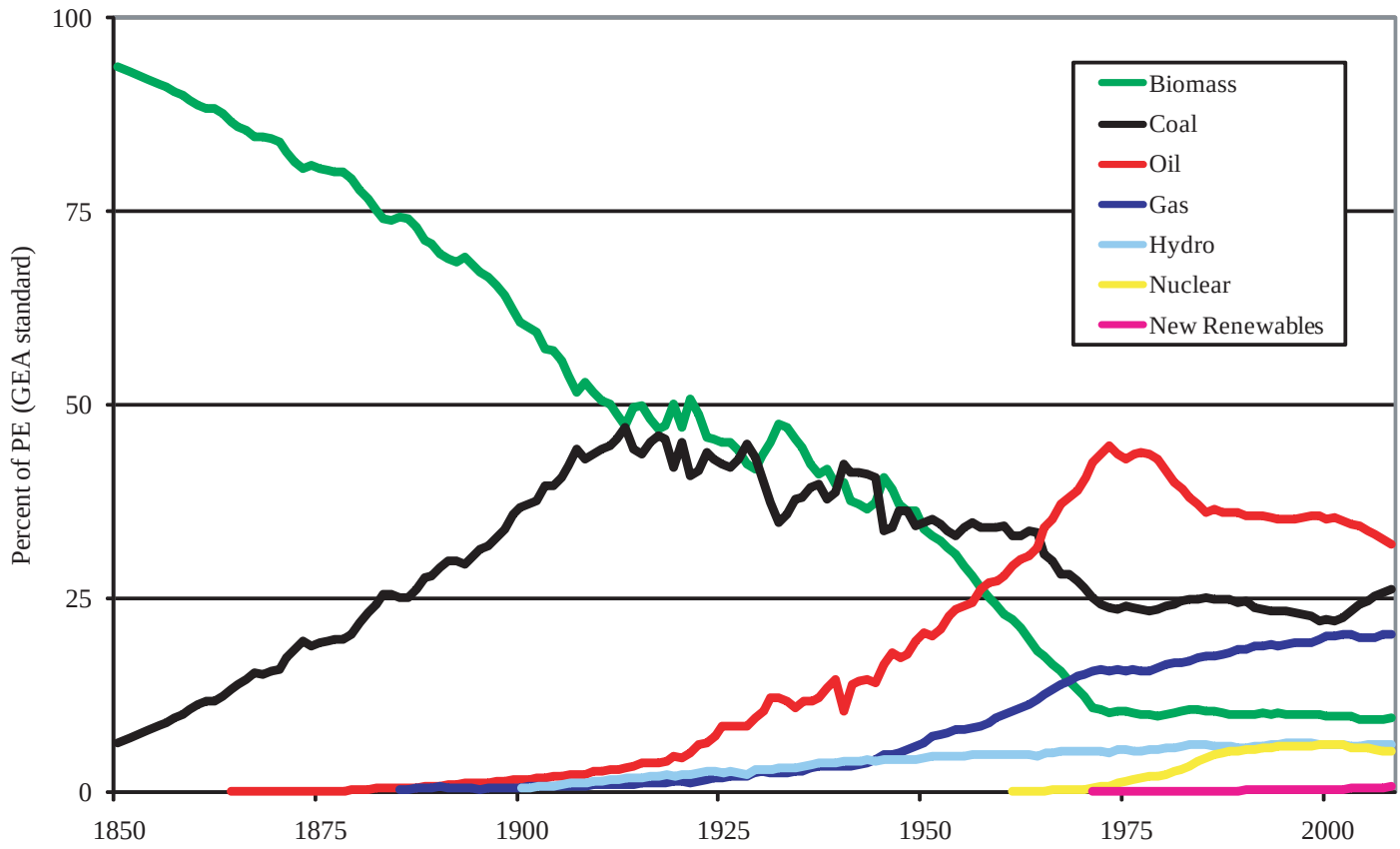


Figure 1.10 | Structural change in world primary energy (in percent). Source: updated from Nakicenovic et al., 1998 and Grubler, 2008.

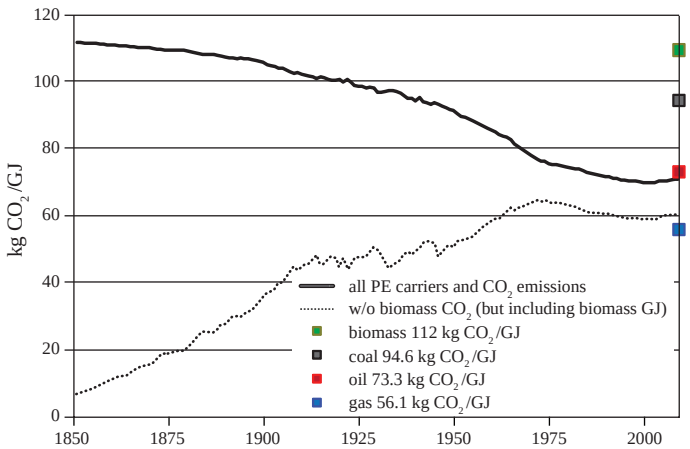


Figure 1.11 | Decarbonization of primary energy (PE) use worldwide since 1850 (kg of CO_2 emitted per GJ burned). Note: For comparison, the specific emission factors (OECD/IPCC default emission factors, LHV basis) for biomass (wood fuel), coal, crude oil, and natural gas are also shown (colored squares). See also discussion in text. Source: updated from Grubler and Nakicenovic, 1996.

and 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_2) per unit of energy. Phrased slightly differently, it refers to the decrease in the carbon intensity of primary or any other energy form. Figure 1.11 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_2 emissions, assuming they have all been taken up by the biosphere under a sustainable harvesting regime (biomass regrowth absorbing the CO_2 released from biomass burning). Historically, emissions related to land-use changes (deforestation) have far exceeded[13] carbon releases from energy-related biomass burning, which suggests that in the past, biomass, like fossil fuels, has also contributed significantly to increases in atmospheric concentrations of CO_2.

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 continues to develop. Depending on the rate of energy efficiency improvement,[14] this mostly leads to higher primary energy requirements in the future. As long as decarbonization rates do not significantly accelerate, this means higher carbon emissions compared to historical experience.

1.3.3 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)[15] condition for economic growth. In turn, economic growth increases the demand for energy services and the corresponding upstream energy conversions and resource use.

Figure 1.12 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)[16] 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).

13 Cumulative emissions of fossil fuels between 1800 and 2000 are estimated to have released some 290 GtC (gigatonnes of elemental carbon – to obtain CO_2 multiply by 44/12, yielding 1060 $GtCO_2$), 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 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.

14 The growth in 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 = Population x GDP/capita x Energy/GDP x CO_2/Energy (proposed by Holdren and Ehrlich, 1971, and applied for CO_2 by Kaya, 1990). Due to spatial heterogeneity in trends and variable interdependence, caution is advised in interpreting component growth rates of this identity.

15 Human (education) and social (functioning institutions and markets) capital as well as technology (innovation) are recognized as important determinants of economic growth (see Barro, 1997).

16 The most direct link between energy and economic activity is revealed at the level of final energy use. However, historical data are mostly available for primary energy use. For the United Kingdom, both primary and final energy (see Figure 1.7 above) are shown.

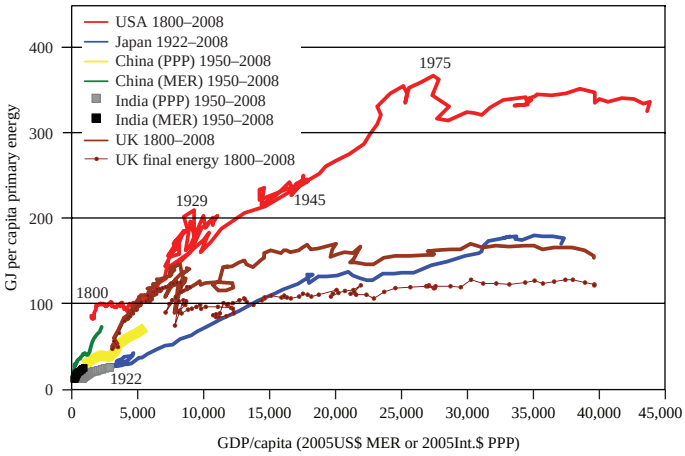


Figure 1.12 | Primary energy use (GJ) versus GDP (at market exchange rates (MER) in 2005US$) per capita. Source: USA, Japan: updated from Grubler, 1998, UK: Fouquet, 2008, India and China: IEA (2010) and World Bank (2010). Note: Data are for the United States (1800–2008), United Kingdom (primary and final energy, 1800–2008), Japan (1922–2008), China (1950–2008), and India (1950–2008). For China and India, also GDP at purchasing power parities (PPP, in 2005International$) are shown.

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.

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 1.12) 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.[17]

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 1.12). 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 1.4.4 below).

17 Based on MER. Using PPP, Japan's GDP per capita in 1885 is estimated to have been well above $4000 (in 2005International$).

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.

1.4 Energy Efficiency and Intensity

1.4.1 Introduction

Energy is conserved in every conversion process or device. It can neither be created nor destroyed, but it can be converted from one 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 calorific value of the natural gas entering the furnace. This definition of energy efficiency is sometimes called *first-law efficiency* (Nakicenovic et al., 1996b).

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., 1996b). 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 1.13 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 high-quality electricity comes along with the production of a significant amount of low-grade heat as a by-product of the process. Idle losses[18] 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.

In this example, abundant opportunities for improving efficiency exist at every link in the energy chain. They include shifting to more efficient fuels (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 first-law fuel efficiency 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.

18 Similar concepts are captured by the term "load factor" referring to the capacity utilization of plant and equipment. 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.

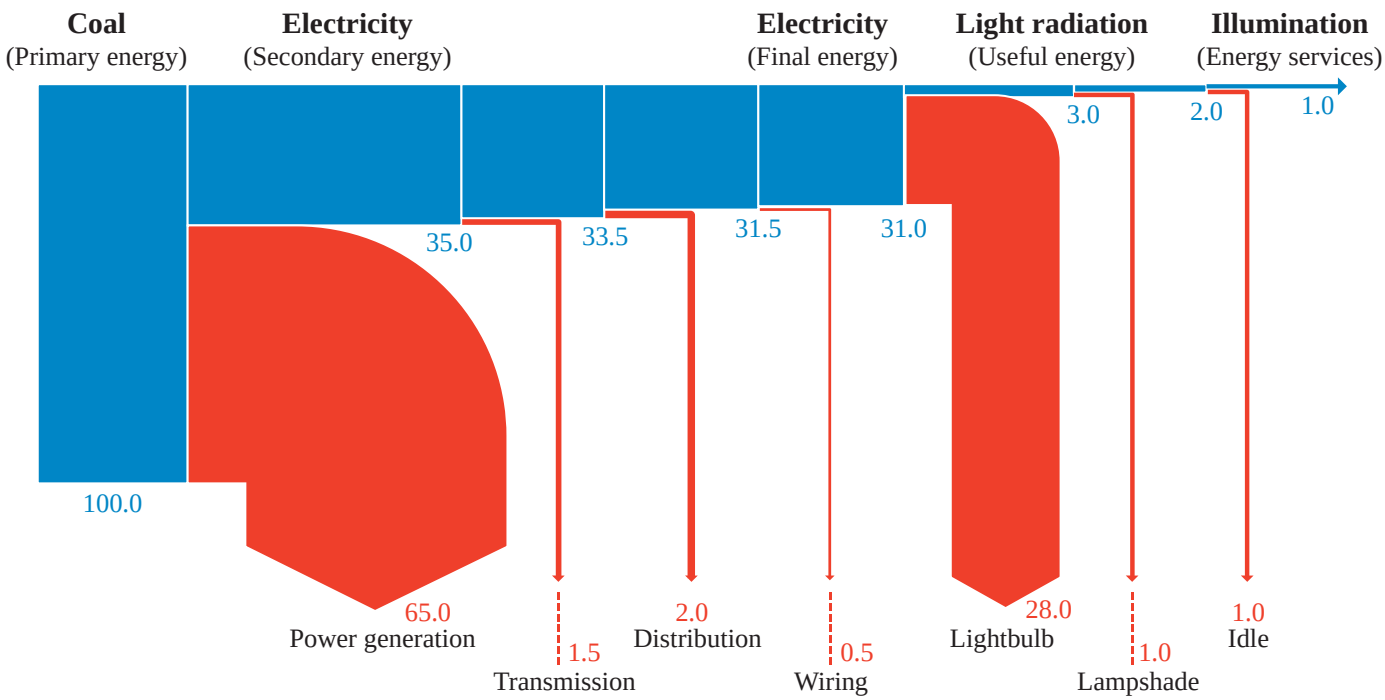


Figure 1.13 | Illustrative example of the compound First-Law efficiency of an entire energy chain to provide the energy service of illumination. Index: primary energy entering system = 100%.

1.4.2 First-Law 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 1.2). 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"). The ultimate efficiency of the energy system in the provision of energy services cannot be determined by calculations based on the First Law of Thermodynamics but requires an extension of the discussion to the Second Law of Thermodynamics.

1.4.3 Second-Law Efficiencies and Exergy

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, the fuel, including the way the fuel is supplied, and the surroundings, infrastructures, and organizations that provide the energy service. 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.[19]

Here the concept that something may get lost or destroyed in every energy 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."[20]

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

19 This section updates and expands on material that was first published in Nakicenovic et al. (1996b).

20 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 or *second-law efficiency* (based on the Second Law of Thermodynamics). See also Wall, 2006.

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 comfort) is very limited. In fact, the initial potential of the fuel or its exergy has been largely destroyed.[21] Although energy is conserved, exergy is destroyed in all real-life energy conversion processes. This is what the Second Law of Thermodynamics says.

Another, more technical, example should help clarify the difference between the first-law (energy) and second-law (exergy) efficiencies. Furnaces used to heat buildings are typically 70% to 80% efficient, with the latest best-performing condensing furnaces operating at efficiencies greater than 90%. This may suggest that minimal energy savings should be possible, considering the high first-law efficiencies of furnaces. Such a conclusion is incorrect. The quoted efficiency is based on the specific process being used to operate the furnace – combustion of fossil fuel to produce heat. Since the combustion temperatures in a furnace are significantly higher than those desired for the energy service of space heating, the service is not well matched to the source and the result is an inefficient application of the device and fuel. Rather than focusing on the efficiency of a given technique for the provision of the energy service of space heating, one needs to investigate the theoretical limits of the efficiency of supplying heat to a building based on the actual temperature regime between the desired room temperature, and the heat supplied by a technology. The ratio of theoretical minimum energy use for a particular task to the actual energy use for the same task is called exergy or *second-law efficiency.*

Consider the following case. To provide a temperature of 30°C to a building while the outdoor temperature is 4°C requires a theoretical minimum of one unit of energy input for every 12 units of heat energy delivered to the indoors. To provide 12 units of heat with an 80% efficient furnace, however, requires 12/0.8, or 15 units of heat. The corresponding second-law efficiency is the ratio of theoretical minimum to actual energy use – i.e., 1/15 or 7%.

The first-law efficiency of 80% gives a misleading impression that only modest improvements are possible. The second-law efficiency of 7% says that a 15-fold reduction in final heating energy is theoretically possible by changing technologies and practices.[22] In practice, theoretical maxima cannot be achieved. More realistic improvement potentials might be in the range of half of the theoretical limit. In addition, further improvements in the efficiency of supplying *services* are possible by task changes – for instance, in reducing the thermal heat losses of the building to be heated via better insulation of walls and windows.

What is the implication of the Second Law of Thermodynamics for energy efficiencies? First of all, it is not sufficient to account for energy-in versus energy-out ratios without due regard for the quality difference – i.e., the exergy destroyed in the process. Minimum exergy destruction means an optimal match between the energy service demanded and the energy source. Although a natural gas heating furnace may have a (First-Law) energy efficiency of close to 100%, the exergy destruction may be very high depending on the temperature difference between the desired room temperature and the temperature of the environment. The Second-Law efficiency, defined as exergy-out over exergy-in, in this natural gas home heating furnace example is some 7% – i.e., 93% of the original potential of doing useful work (exergy) of the natural gas entering the furnace is destroyed. Here we have a gross mismatch between the natural gas potential to do useful work, and the low temperature nature of the energy service space conditioning.

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 (1996b). Estimates of global and regional primary-to-service exergy efficiencies vary typically from about 10 to as low as a few percent of the thermodynamically maximum feasible (see also Ayres, 1989, Gilli et al., 1996, and Nakicenovic et al., 1996a).

The theoretical potential for efficiency improvements is thus very large, and current energy systems are nowhere close to the maximum levels suggested by the Second Law of Thermodynamics. However, the full realization of this potential is impossible to achieve. First of all, friction, resistance, and similar losses can never be totally avoided. In addition, there are numerous barriers and inertias to be overcome, such as social behavior, vintage structures, financing of capital costs, lack of information and know-how, and insufficient policy incentives.

The principal advantage of second-law efficiency is that it relates actual efficiency to the theoretical (ideal) maximum. Although this theoretical maximum can never be reached, low 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. A second advantage of exergy efficiency is that the concept can be transferred to the assessment of energy service provision, which is not possible in first-law 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

21 Alternative example: In terms of energy, 1 kWh of electricity and the heat contained in 5 kg of 20°C (raised from 0°C) water are equal, i.e. 3.6 MJ. At ambient conditions, it is obvious that 1 kWh of electricity has a much larger potential to do work (e.g., to turn a shaft, provide light, or allow to run a computer) than the 5 kg of 20°C water that cannot perform any useful work.

22 For example, instead of combusting a fossil fuel, Goldemberg et al. (1988) give the example of a heat pump that extracts heat from a local environment (outdoor air, indoor exhaust air, ground water) and delivers it into the building. A heat pump operating on electricity can supply 12 units of heat for three to four units of electrical energy. The second-law efficiency then improves to 25–33% for this particular task – still considerably below the theoretical maximum efficiency. Not accounted for in this example, however, are the energy losses during electricity generation. Assuming a modern gas-fired combined cycle power plant with 50% efficiency, the overall efficiency gain is still higher by a factor of two compared to a gas furnace heating system.

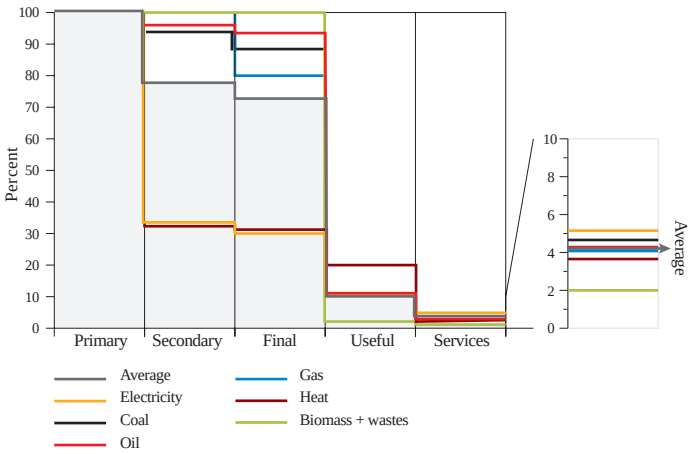


Figure 1.14 | Estimated exergy efficiencies (average for OECD countries) from primary exergy (= 100%) to useful exergy and to services by energy carrier (fuel). Source: adapted from Nakicenovic, 1993.

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 1.14).

1.4.4 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 in this publication). 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).[23] 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 Myers, 1992; Nakicenovic et al., 1996b; Greening et al., 1997; Schäfer, 2005; Baksi 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 1.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 1.3.3 above).

Figure 1.15 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).

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

23 Like energy, GDP is a *flow* variable and, therefore, does not measure wealth or welfare (which are *stock* variables).

The measurement of GDP through market transactions (sales/purchases of goods and services) is at the same time a strength (measurability by statistical offices) and a weakness of the concept, as excluding non-market transactions (such as household and voluntary work that should increase GDP if valued monetarily) as well as environmental externalities (the negative impacts of pollution, congestion, etc. that would lower GDP).

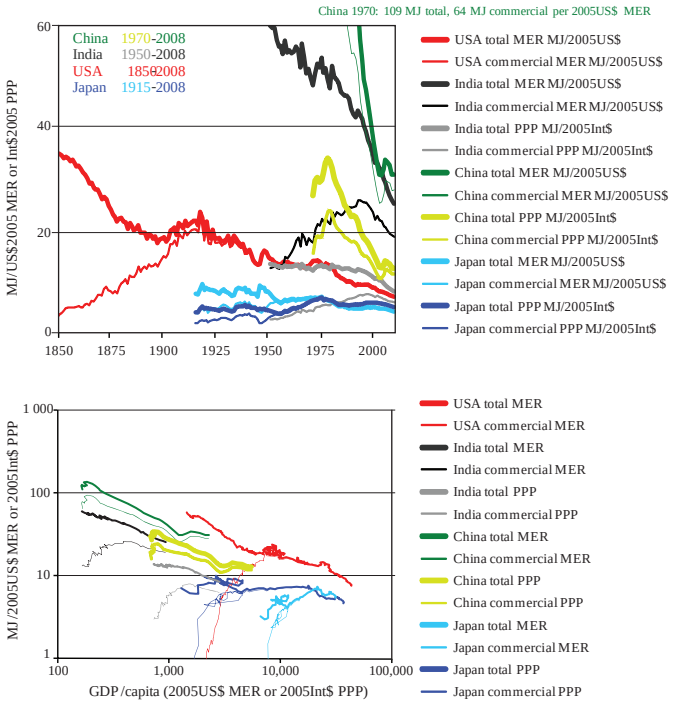


Figure 1.15 | Energy intensity improvements over time (top) and against per capita income (bottom) US (1800–2008), Japan (1885–2008), India (1950–2008), and China (1970–2008). Source: see Figure 1.12. Note: Energy intensities (in MJ per $) are always shown for total primary energy (bold lines) and commercial primary energy only (thin lines) and per unit of GDP expressed at market exchange rates (MER in 2005US$) and for China, India, and Japan also at purchasing power parities (PPP in 2005International$). For the United States, MER and PPP are identical.

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 trend toward overall lower *total* energy (including also non-commercial energy) intensities over time and across all countries.

Figure 1.15 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 that 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$2005 for MER, with an average historical reduction rate of 3.3%/year since 1971, compared with about 14 MJ per 2005International$ for PPP for the same year and an improvement rate of 1.9%/year. Since 1971, China's per capita GDP in terms of MER has grown by some 7%/year, whereas the estimated per capita GDP in PPP terms has grown by some 5%/year, compared to a growth rate of per capita primary energy use of some 3%/year (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 1.15).[24]

Adding traditional (non-commercial) energy[25] 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 1.15. 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%/year (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%/year for PPP- and MER-based energy intensities, respectively. Energy intensities in India have improved by 0.8%/year (PPP-based) to 1.5%/year (MER-based) over the period from 1970 to 2005. The much higher improvement rates of China compared to India reflects both a

24 As by definition an International$ used for PPP accounting is equal to one US$, no distinction is made between PPP- and MER-based intensities in the case of the US in Figure 1.15.

25 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.

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 1.15).

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,[26] 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.

1.5 Energy Resources

1.5.1 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 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?[27]

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.

26 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.

27 This section updates and expands on material that was first published in Rogner et al. (2000).

Occurences 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.[28]

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 1.16): decreasing geological certainty of occurrence and decreasing techno-economic recoverability (Nakicenovic et al., 1996b). 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

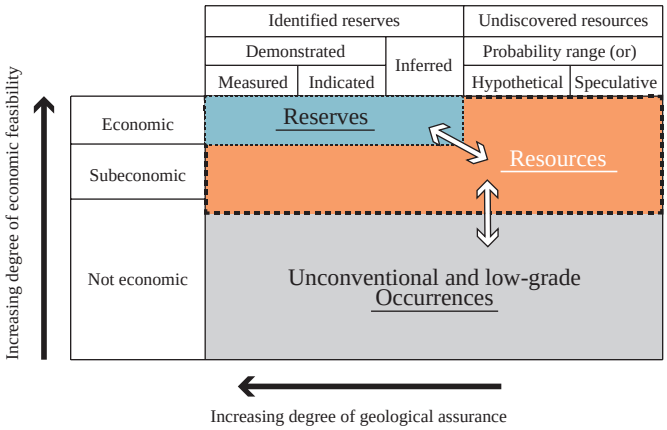


Figure 1.16 | Principles of resource classification, illustrating the definition of the three fundamental concepts: reserves, resources, and occurrences. Source: adapted from McKelvey, 1967.

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).

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

28 Physical and economic limitations of the *rates* of extraction do not enter the estimations of these stock variables.

Table 1.3 | Fossil and uranium reserves, resources and occurrences (in EJ).

	Historical production through 2005	Production 2005	Cumulative extraction GEA scenarios 2005–2100 [EJ]	Reserves	Resources	Additional Occurrences
	[EJ]	[EJ]		[EJ]	[EJ]	[EJ]
Conventional oil	6 069	147.9	6 600–10 000	4 900–7 610	4 170–6 150	
Unconventional oil	513	20.2	2–470	3 750–5 600	11 280–14 800	> 40 000
Conventional gas	3 087	89.8	7 900–11 900	5 000–7 100	7 200–8 900	
Unconventional gas	113	9.6	180–8 500	20 100–67 100	40 200–121 900	> 1 000 000
Coal	6 712	123.8	3 300–16 500	17 300–21 000	291 000–435 000	
Conventional uranium[b]	1 218	24.7	1 520–28 500	2 400	7 400	
Unconventional uranium[c]	n.a.	–			4 100	> 2 600 000

(a) 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.
(b) 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.
(c) Unconvential uranium occurrences include uranium dissolved in seawater

Source: Chapter 7.

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 analyses (see Chapter 17) are compared with their annual flows.

1.5.2 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 – 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.

Table 1.3 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.

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.

1.5.3 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

Table 1.4 | Renewable energy flows, potential, and utilization in EJ of energy inputs provided by nature.

	Primary Energy Equivalent in 2005	Utilization GEA pathways	Technical potential	Annual flows
	[EJ]	[EJ/yr]	[EJ/yr]	[EJ/yr]
Biomass, MSW, etc.	46	125–220	160–270	2200
Geothermal	1	1–22	810–1545	1500
Hydro	30	27–39	50–60	200
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 potential of some 3000 EJ/yr of ocean energy in ocean thermal energy conversion (OTEC) would result in an electricity output of about 100 EJ/yr.

Source: Chapter 7 (see also Chapter 11 and IPCC, 2011 for a discussion of renewable resource inventories and their differences). Note: MSW = municipal (and other) solid wastes.

energy densities and supply intermittencies, and to convert them into usable fuels (see Section 1.5.4 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, presented in Chapter 17, utilize up to 1500 EJ/yr of solar radiation (see Table 1.4). Note: The flows, potential, and utilization rates in Table 1.4 are given in terms of energy input – not as outputs (secondary energy or using any accounting scheme for equivalent primary energy – see Appendix 1.A). The production and utilization data, therefore, differ from the presentation in Chapter 17.

The energy carried by wind flows around the globe is estimated at about 110,000 EJ/yr,[29] of which some 1550 EJ/yr to 2250 EJ/yr are suitable for the generation of mechanical energy. 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 200 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.

1.5.4 Energy Densities

The concept of energy density refers to the amount of energy generated or used per unit of land. The customary unit for energy densities is Watts per square meter (W/m^2), 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 1.17.

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.[30] The density of energy demand in urban areas is typically between 10 W/m^2 and 100

29 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.

30 Exceptions are geothermal energy and urban (municipal) wastes, which are characterized by high energy density.

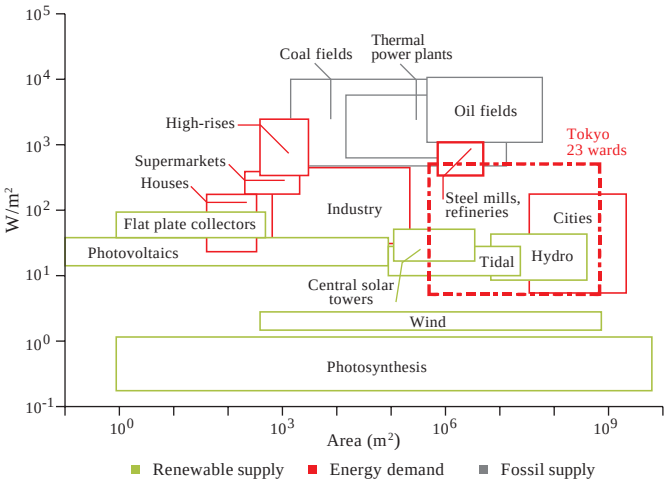


Figure 1.17 | Energy densities of fossil (grey) and renewable (green) energy supply and demand (red). Source: modified and adapted from Smil, 1991.

W/m² and can reach some 1000 W/m² in extreme locations, such as skyscraper complexes and high-density business districts (see Figure 1.17 for an illustration of Tokyo's 23 wards [districts]). Conversely, renewable energies have typical energy supply densities of a few W/m² 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/m² and 0.5 W/m² (see Chapter 18). 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.

1.6 Production, Trade, and Conversions

1.6.1 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 1.5 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).

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.

1.6.2 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 trade flows.[31]

1.6.2.1 Direct Energy

Table 1.5 summarizes primary energy production, trade, and use 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 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

31 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.

Table 1.5 | World trade flows between regions (in EJ) for 2005.

	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.

Source: data from IEA, 2007a and 2007b.

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[32] 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.

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_2 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 1.6). Important limitations and intricate methodological issues need to be considered when trying to estimate the energy embodied in internationally traded commodities

32 Flows below 10 EJ are not discussed separately. Details are given in Table 1.5. All data refer to the year 2005.

Table 1.6 | 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.

	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**

Source: Narayanan et al., 2008.

and products based on multi-regional input-output tables. The flows summarized in Table 1.6, 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. GTAP 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[33] as reported in Table 1.6.

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)?

1.6.2.3 Energy Trade Flows

Figure 1.18 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.

1.6.3 Conversions

1.6.3.1 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

33 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).

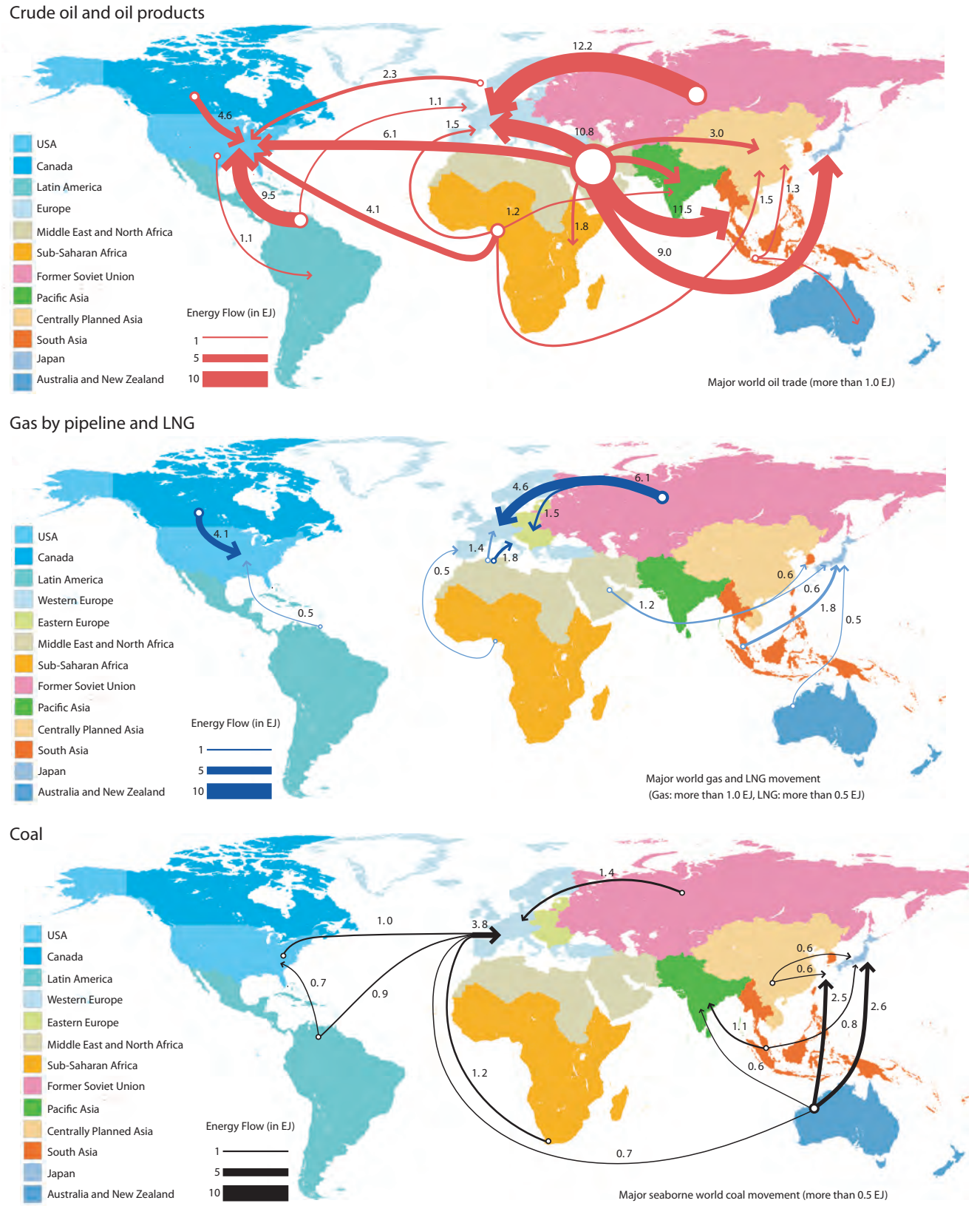


Figure 1.18a | World energy trade of fossil fuels: direct primary and secondary energy coal (black), oil and oil products (red) and gas (LNG light blue, pipeline gas: dark blue), in EJ. Source: Oil/gas energy trade for 2005 (BP, 2007), coal trade for 2008 (WCI, 2009).

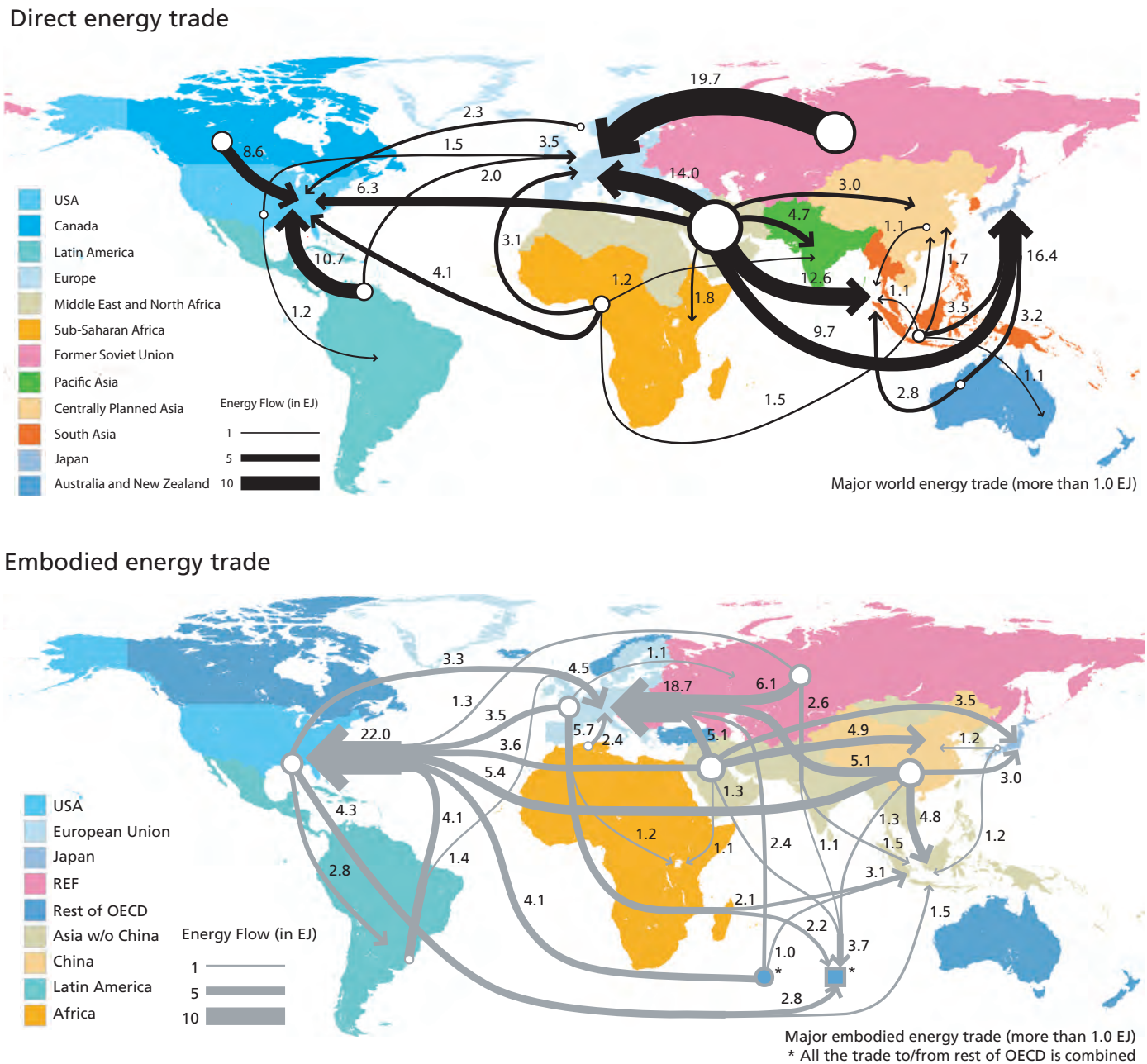


Figure 1.18b | World energy trade of total direct energy (black) as well as embodied energy in goods traded (grey), in EJ. Source: Embodied energy trade for 2004 (GTAP database, 2010), direct energy trade (BP, 2007; WCI, 2009).

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 1.7) is quite characteristic of the global picture as well.

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 TW-yr).[34] 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

34 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).

Table 1.7 | Installed capacity of energy conversion technologies (in GW) for the United States, 1850 to 2000.

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	25,000
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**	**35,140**

Source: Chapter 24 case studies, Appendix 24.B.

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.

1.6.3.2 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 1.19 below) – 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 1.19 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 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 1.19 also shows electricity production for the GEA regions for the base year 2005. Fuel mixes vary widely, primarily reflecting the

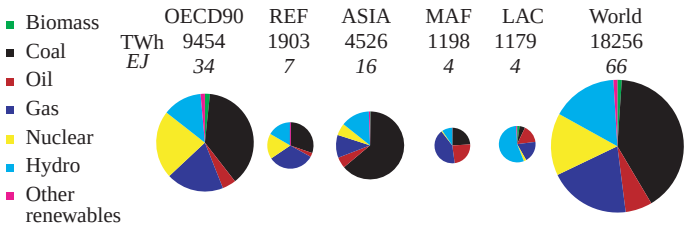


Figure 1.19 | Electricity output by generating source in 2005: World and five GEA Regions in TWh and EJ (in italics). Source: IEA, 2007a and 2007b. Note: Circle areas are proportional to electricity generated.

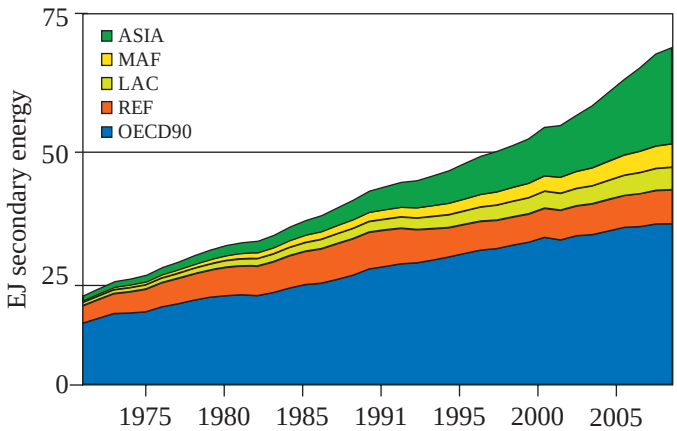


Figure 1.20 | World electricity generation by five GEA Regions, cumulative total (in EJ of secondary energy generated per year). Source: data from IEA, 2010.

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 (see Chapter 11), about half of current investments in power generation are in renewable generation.

Figure 1.20 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[35] (+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

35 For the definition of GEA regions, see Appendix 1.B.

Table 1.8 | Global GHG and pollutant emissions by source for the year 2005.

	Pollutant Emissions							Main Greenhouse Gases		
	Sulfur	NOx	BC	OC	CO	VOC	PM2.5	CO_2	CH_4	N_2O
	$TgSO_2$	$TgNO_2$	Tg	Tg	Tg	Tg	Tg	$PgCO_2$	Tg	Tg
Energy & Industry	**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	-
Non-Energy	**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	-
TOTAL	**114.1**	**127.3**	**6.7**	**35.8**	**1036.3**	**212.9**	**66.8**	**33.3**	**338.6**	**12.1**

Sources: data from Lamarque et al., 2010; Smith et al., 2011; IPCC-RCP database[38] Houghton, 2008; GEA Chapter 17.

(+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.

1.7 Environmental Impacts (Emissions)

1.7.1 Introduction

Energy extraction, conversion, and use are major contributors to GHG emissions and thus global warming. In addition, a host of energy-linked pollutant emissions, including suspended fine particles and precursors of acid deposition, contribute to local and regional air pollution and ecosystem degradation. Energy-related pollutants also result in adverse effects for human health. The largest single source of health impacts of energy is associated with indoor air pollution resulting from the use of traditional biomass in open fires or inefficient cooking stoves by poor people in developing countries. Its human health impacts are estimated to result in about 2 million premature deaths, or about 42 million person-years of life (DALYs[36]) lost per year, due to respiratory and other diseases, affecting particularly women and children, making access to culturally acceptable, clean, and efficient cooking fuels a priority policy concern.

Table 1.8 summarizes the major sources of global GHGs and selected[37] 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_2 than any other human activity, and contributes to about 30% of global methane (CH_4) emissions. Altogether, the energy sector is thus the biggest source of anthropogenic GHG emissions that are changing the composition of the atmosphere.

1.7.2 CO_2 and other GHGs

CO_2 emissions from fossil energy use in 2005 are estimated at 7.2 Pg C or 26.4 Pg CO_2 (Boden et al., 2010). This represents 80% of all anthropogenic sources of CO_2 in that year, with the remainder associated with land-use changes (deforestation) (Houghton, 2008).

36 Thus, on average, each premature death is associated with close to 20 life-years lost. Estimates for the health impact of outdoor air pollution suggest close to 3 million pre-mature deaths/year and some 23 million DALYS. The health impacts of indoor and outdoor air pollution are not additive. See Chapters 4 and 17 for a more detailed discussion. Note: DALYS: "Disability-adjusted Life Years are units for measuring the global burden of disease and the effectiveness of health interventions and changes in living conditions. DALYs are calculated as the present value of future years of disability-free life that are lost as a result of premature death or disability occurring in a particular year. DALY is a summary measure of population health and includes two components, years of life lost due to premature mortality and years lost due to disability" (WHO, 2011).

37 Only emissions of pollutants where energy plays an important role are highlighted here. As such, Chapter 1 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.

38 See www.iiasa.ac.at/web-apps/tnt/RcpDb.

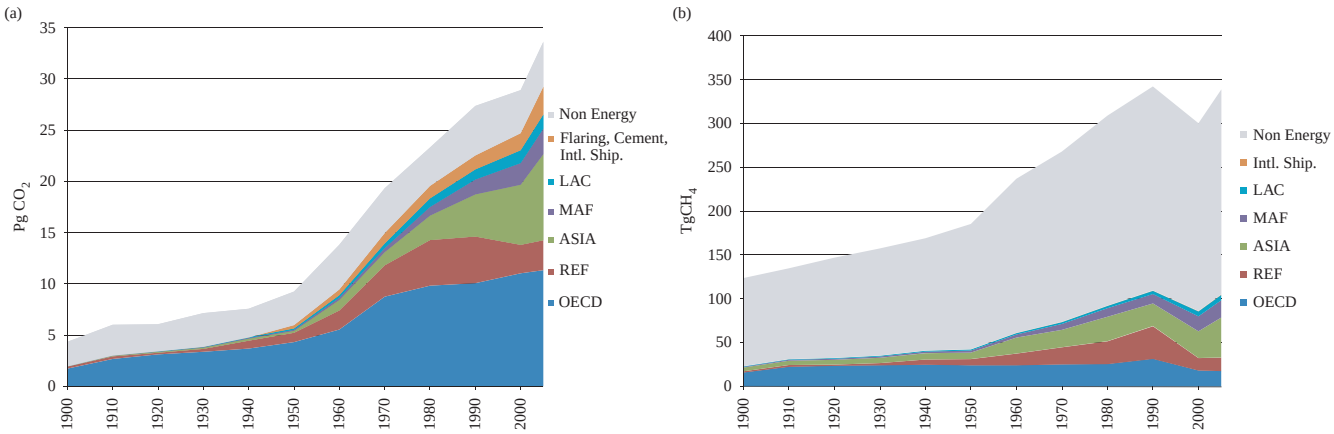


Figure 1.21 | Development of annual energy-related (a) CO_2 and (b) CH_4 emissions by region (compared to global non-energy sources) from 1900 to 2005 in Pg (Gt)(CO_2) and Tg (CH_4). Source: data from Boden et al., 2010; Houghton, 2008; IPCC-RCP database.[39]

Figure 1.21 shows the historical development of fossil energy CO_2 emissions by major world regions (compared to global non-energy-related sources of CO_2). Today's industrialized countries contribute most to the present global CO_2 emissions and have also emitted most of the historical emissions associated with the observed increase in atmospheric CO_2 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_4 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_4 emissions. While CH_4 emissions from energy accounted for only 30% of total CH_4 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 1.21).

Other GHGs include nitrous oxide (N_2O), tetrafluoromethane (CF_4), sulfur hexafluoride (SF_6), and different types of ozone-depleting hydro-fluorocarbons (HFCs). These gases are predominantly emitted from non-energy sectors. N_2O 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).

39 See www.iiasa.ac.at/web-apps/tnt/RcpDb.

1.7.3 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). 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 1.22 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

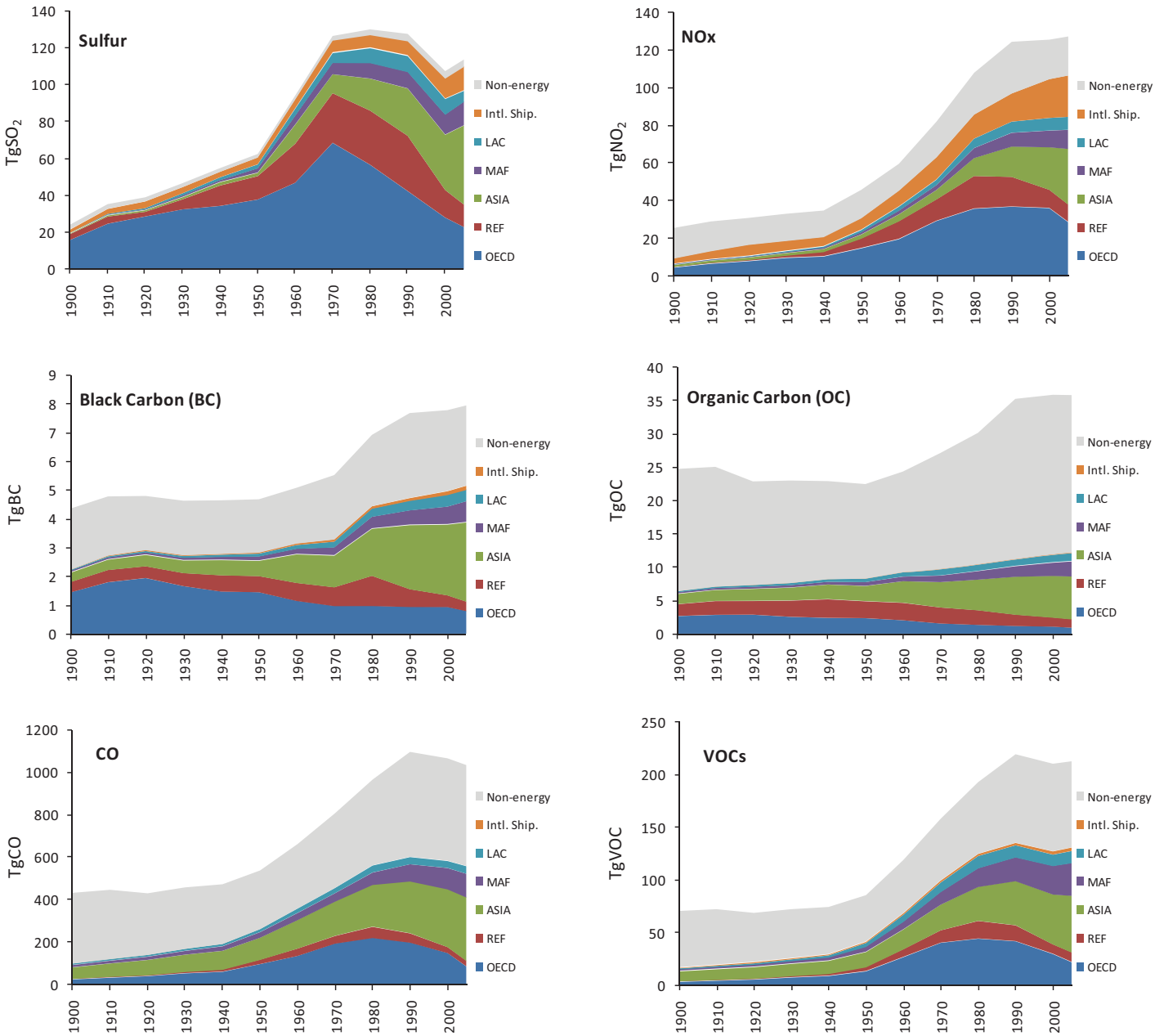


Figure 1.22 | Development of annual energy-related pollutant emissions in Tg: sulfur (SO_2), nitrogen oxides (NO_x), black carbon (BC), organic carbon (OC), carbon monoxide (CO), and volatile organic compounds (VOCs) by annual region (compared to global non-energy sources) from 1900 to 2005.

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 1.22), 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 (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). NO_x is also a main component of ground-level ozone and smog and thus contributes to global warming. Similar to sulfur, NO_x emissions are dominated by the energy sector, which accounts for more than 80% of total anthropogenic NO_x emissions. Emissions from 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 NO_x emissions since the early 1980s, the rapid increase in 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 1.22).

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.*[40] 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 1.8 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 1.22), resulting in significant health risks, particularly from household combustion of solid fuels (mostly biomass) that affect 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.

40 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.

1.8 Heterogeneity in Energy Use

1.8.1 Introduction

In addition to the temporal variations in global energy use described in earlier sections, there is a huge degree of cross-sectional heterogeneity in energy use evident across the globe today. While aggregate energy statistics are insightful for describing the energy system globally, regionally, or nationally, they often mask the 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 use across different nations and sub-populations. These disparities stem, for the most part, from differences in incomes or levels of economic affluence, production and consumption activities, and lifestyles. Yet a small part of the variations might also be on account of differences in climatic conditions and thus energy service needs across regions (e.g., heating/cooling). Differences also exist in the types of energy carriers that are predominantly used and the levels of access to these across countries and populations.

1.8.2 Heterogeneity in Energy Use across Nations

Akin to the uneven development of economies around the world, energy use and service varies 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 about 94. The OECD countries, with less than a sixth of the world's population, account for over 45% of total final energy use (see Figure 1.23). Developing countries, with about four-fifths of the world's population, account for just under 40% of this total. OECD countries on average consume over 16 times as much energy per capita than developing countries in South Asia and Africa.

Differences in the amounts of final energy use per capita are mirrored in variations in the structure of energy use across nations and regions. In general, countries with higher levels of energy use per capita also use a larger proportion of their total final energy for transport uses. 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. Finally, in addition to variations

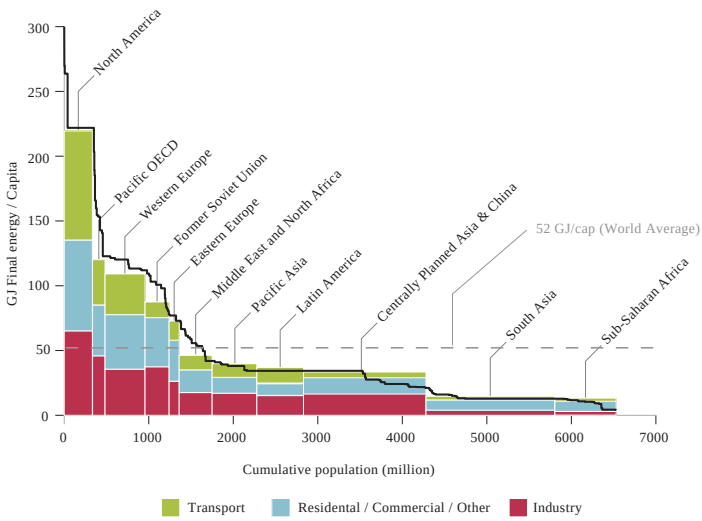


Figure 1.23 | World final energy (GJ) per capita versus cumulative population for 11 GEA regions sorted by declining per capita energy use (with final energy use disaggregated by sector and total, color bars); and total per capita final energy use for 137 countries in 2005 (black, solid line). Dashed horizontal line shows the average global final energy use per capita. Source: data from IEA, 2010.

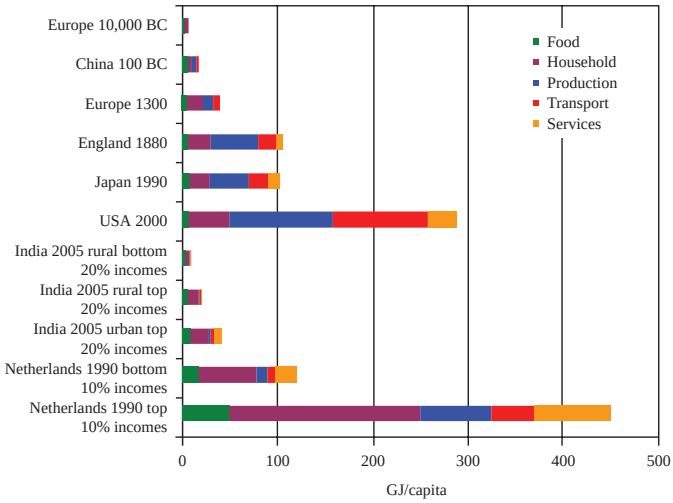


Figure 1.24 | Per capita primary energy use by service category over time and across different populations. Source: historical estimates: Smil, 1991; Japan, United States: IEA, 2010; India: Pachauri, 2007; Netherlands: Vringer and Block, 1995.

in the levels and purposes of energy use across nations, countries also exhibit very divergent patterns of energy use. 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 30% of the population in developing countries lack access to, and so do not use, any electricity. In developed OECD countries, however, 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 across nations, as some carriers like traditional biomass used in traditional end-use devices have very low efficiencies, and are associated with high emissions, and social externalities.

1.8.3 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 grievously. 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 between regions. 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 formal development, and urban metropolitan areas that are the centers of industrial production and economic activity. Thus, for instance, as shown in Figure 1.24, 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 uses only about half as much energy per capita as the richest 20% of the 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.

The starkest disparities in energy use within (and between) nations are those between rich and poor people. Thus, as Figure 1.24 illustrates, the richest decile 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. 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 average 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.

1.8.4 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 versus 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.

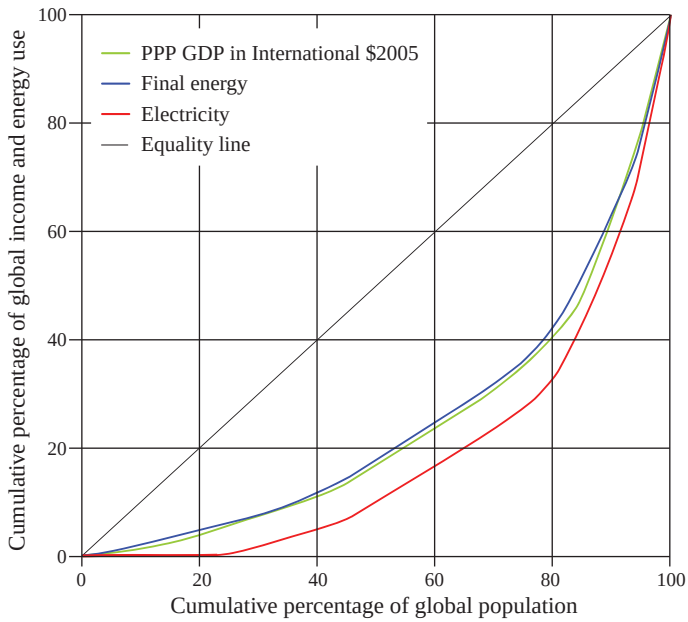


Figure 1.25 | Lorenz curves of energy inequality, measuring cumulative global population (in percent) disposing of corresponding fraction of cumulative income (in percent of PPP$ (green), final energy (blue), and electricity use (red) (in percent of Joules energy used) for the Year 2000. Source: IEA, 2010 and UNDP and WHO, 2009.

Figure 1.25 illustrates inequality across nations by depicting the Lorenz curves for important energy and economic variables for the year 2000. 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.

1.9 The Costs of Energy

1.9.1 Accounting Frameworks and Different Types of Costs

In one way or another, energy services carry a price tag. The price a consumer pays for a particular energy service based, for example, on electricity use is made up by a variety of components, the most important of which are generating costs, systems costs, rents, profits, taxes, subsidies, and externalities.

Generating 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. Generating costs 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 of a power plant, refinery, or home furnace. Fuel costs are the expenditures associated with the fuel supply for plant operation or service provision. O&M costs cover labor costs, insurance, consumables other than fuel, repairs, etc. More recently, capital costs also include decommissioning expenditures at the end of a plant's service life, while O&M costs may include waste disposal costs.

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. Capital costs must be recovered over the lifetime of the investment, reflecting the wear and tear of the plant (the investment) over its economic lifetime.

The levelized cost[41] of electricity (LCOE) is a widely used tool in policy analysis for comparing the generating costs of different technologies over their economic life. 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. LCOE spreads the capital costs (including the finance costs) uniformly over the lifetime of an investment, accounts for the fuel and O&M costs, and calculates the specific costs per unit of energy delivered.[42]

41 For a review see Anderson, 2007. For a review quantitative cost estimates for electricity generation see Heptonstall, 2007 and NREL, 2010.

42 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.

Table 1.9 | Total levelized costs of different electricity generation technologies (in percent using a 5% discount rate) and representative cost ranges in 2005US$/MWh as used in GEA. Note: These are direct energy (electricity generating) costs only, i.e. excluding externality costs; Data source: Chapters 12 and 17, and IPCC, 2011.

		Solar PV	Wind (onshore)	Nuclear[a]	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	0	0.7–0.9	1.3–2.8	1.3–2.8	2.6–6.5
Waste	$/MWh	0	0	1–2	0	6	0
Total generating costs	$/MWh	27–151	21–131	53–100	27–46	44–69	24–49

(a) Current (pre-2010) nuclear investment costs under construction in several developing countries range between 1800 and 2500 $/kWe.

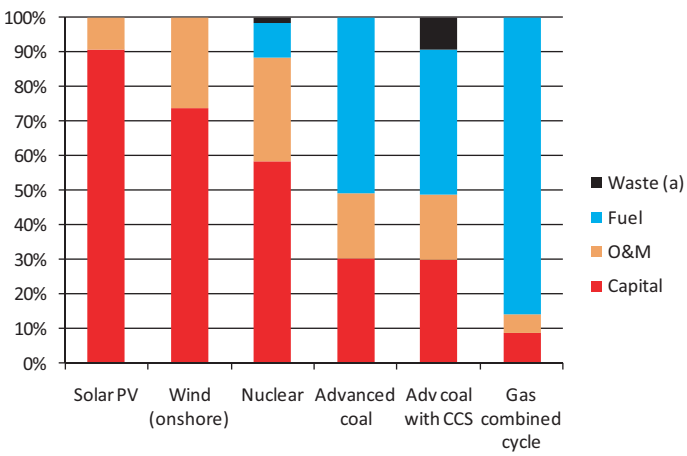


Figure 1.26 | Structure of total levelized costs of different electricity generation technologies (in percent using a 5% discount rate) and representative cost ranges for 2030 as used in the GEA pathways (cf. Chapter 17) for capital costs, operation and maintenance (O&M), fuel costs, as well as waste disposal costs for nuclear and advanced coal with carbon capture and sequestration (CCS). All values are given in 2005US$ and are shown in Table 1.9. Note: (a) Includes decommissioning costs for nuclear power and costs for transport and disposal of 90% of CO_2 emissions for advanced coal power plants with carbon capture and storage (CCS).

The relative structure of the various generating cost components varies significantly per unit of output for different generating options (see Figure 1.26 and Table 1.9, using a real annual discount rate of 5%), and 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 shown in Figure 1.26 and Table 1.9. Consequently, CCGT generating costs are almost all fuel costs. Any change in natural gas prices thus impacts its generating costs greatly. 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.[43] The high share of capital costs exposes nuclear power projects to financial risks associated with rising interest rates and to cost escalation caused by delays in construction completion. Adding carbon capture and storage (CCS) can also increase costs substantially: typically adding some 50 $/MWh levelized costs to pulverized coal fired power plants (and 20–30 $/MWh for IGCC or natural gas electricity generation), see Chapter 12.

In addition to the generating costs, the price of electricity for consumers then includes transmission and distribution (T&D) costs and taxes or subsidies. Taxes and subsidies are policy instruments to influence consumer behavior. Taxes can be used to discourage politically undesirable behavior patterns, while subsidies provide incentives to adopt a more desirable investment or consumption pattern. 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 1.27 compares gasoline prices with and without taxes for a variety of countries. 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_2), while oil-importing US has the second lowest gasoline taxation (equivalent to US$56/tonne of CO_2). Other oil-exporting countries such as Kuwait (not shown in Figure 1.27) even subsidize[44] domestic gasoline use.

43 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.

44 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).

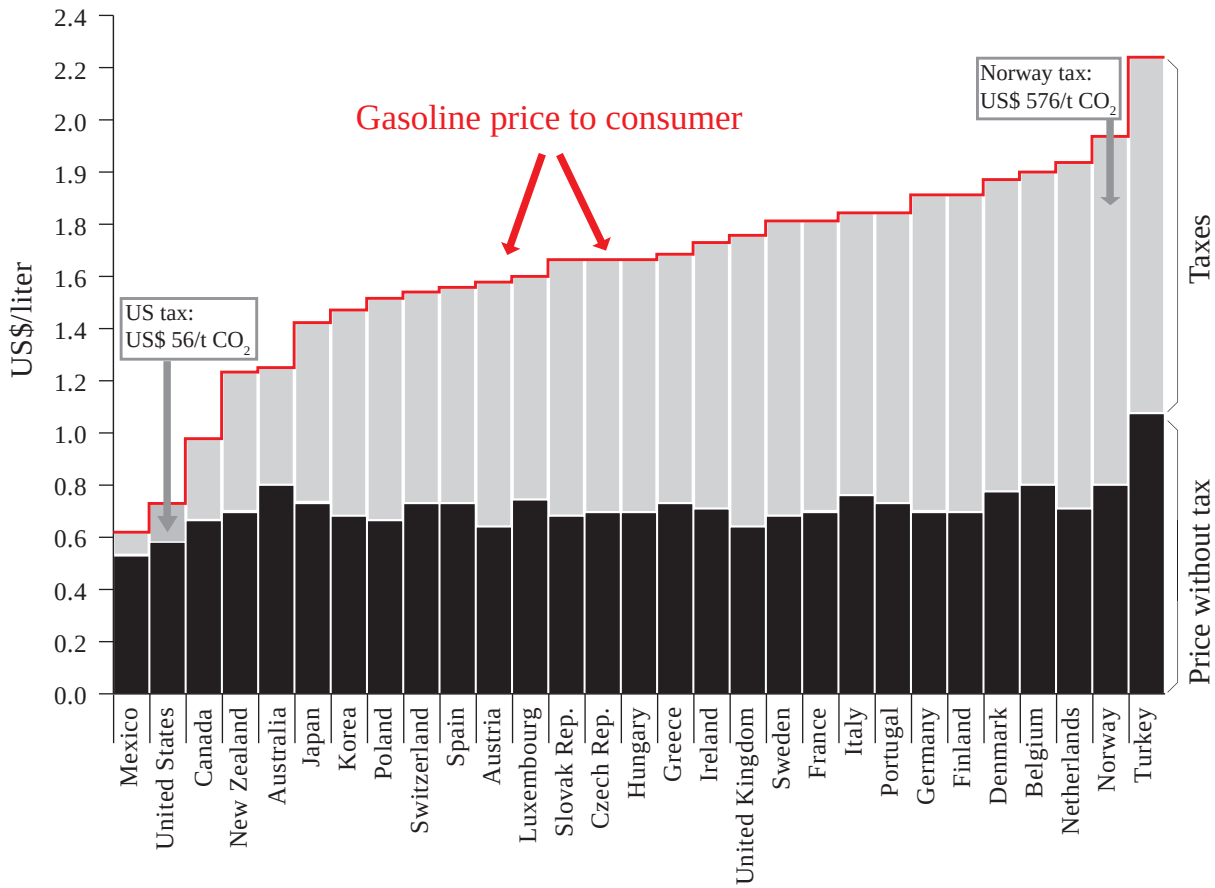


Figure 1.27 | Gasoline prices with and without taxes in US$/liter and implied price of carbon (US$/t$CO_2$) for 1st quarter of 2010. Source: data from IEA, 2011.

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 1.28 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 wood for fuel. Shifting to more capital-intensive stoves (and higher-exergy fuels) reduces the time spent on fuel supply 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 an improved cooking service can occur in one of two ways, as shown in Figure 1.28. A simple shift or substitution to higher-exergy energy carriers (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 commercial fuels). On the other hand, improvements in cooking services can also be achieved through the use of more

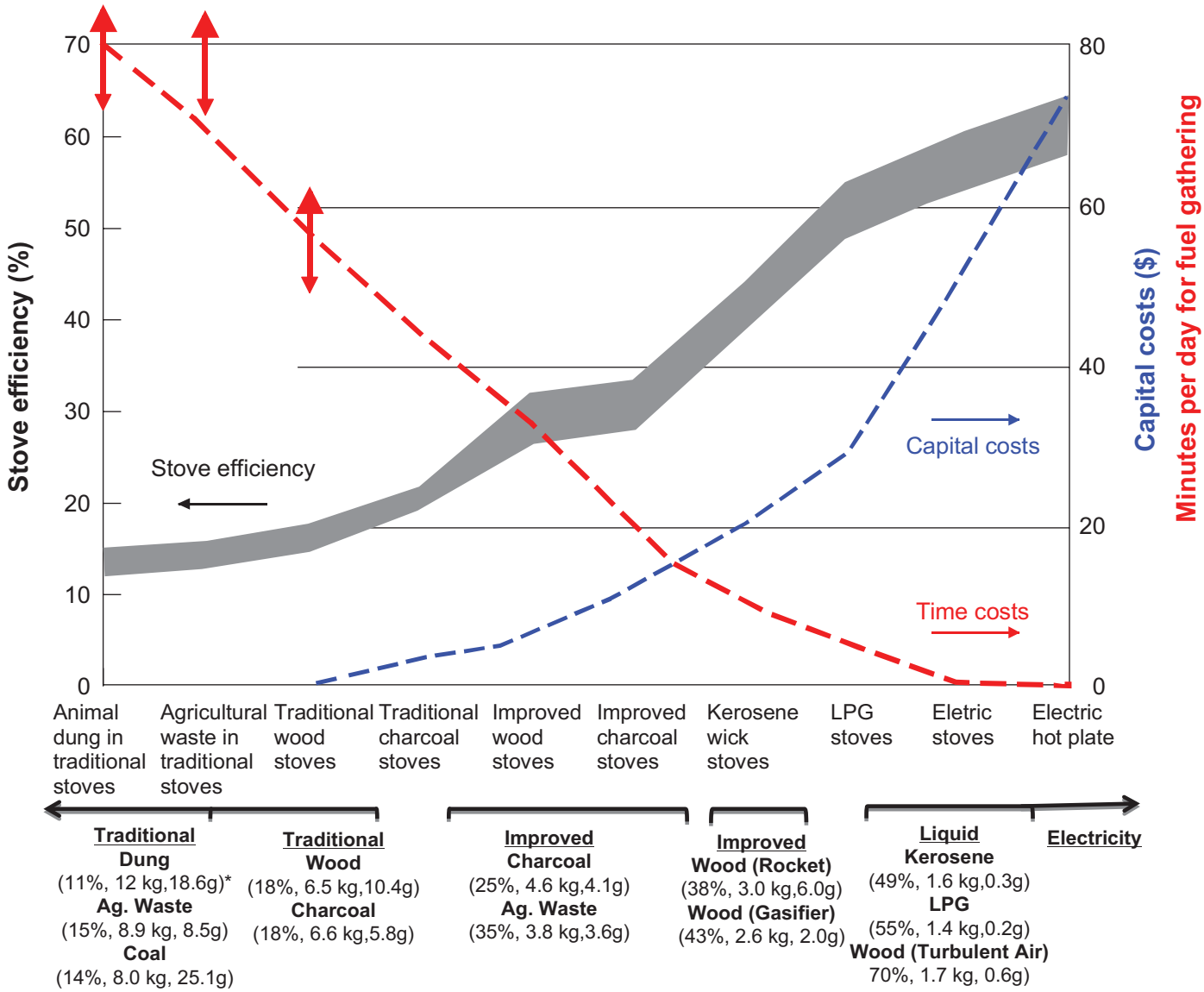


Figure 1.28 | Different costs of energy service provision. Example: cooking in developing countries. Notes: Red arrows show uncertainty ranges in time costs. GHG emissions are illustrative estimates and include all greenhouse gases and other emissions that affect radiative forcing. Emissions from fuel production and renewability of charcoal, wood, and agricultural residues are not included. Source: adapted from OTA, 1991 and Chapter 3.

capital-intensive improved technologies that continue to use traditional fuels (e.g., firewood and residues) but more efficiently (e.g., biogasifiers).

Further cost components related to Figure 1.28 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. A more efficient stove using commercial fuels reduces pollution and time spent gathering fuel wood, and hence reduces *inconvenience* costs. Likewise, 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.

1.10 Roadmap to the Chapters of the GEA

Earlier transitions of the world's energy system, from biomass to coal, to oil, and now to a mix of coal, oil, and natural gas as the dominating energy carriers were all driven by convenience and cost reductions. Coming energy transitions will occur in a world that has changed through the "great acceleration" (Chapter 3) that started in the 1950s and is still ongoing. The next transitions will have to consider these changes that in

fact create demands on the performance of the coming energy systems in order for the world to develop in a sustainable manner.

The 25 chapters of the GEA are divided into four clusters.

Cluster I sets out to describe and assess the nature and magnitude of energy system changes required from a key set of conditions and concerns. Chapter 2 evaluates the role of energy in poverty alleviation and socio-economic growth and what will be required from the energy systems to make poverty a condition of the past, especially in terms of access to electricity and clean cooking fuels and practices. Chapter 3 reviews the environmental impacts of energy systems and what changes would be required, especially in terms of emissions reductions, to protect the environment as it is now known, including mitigating climate change. Chapter 4 addresses the health impacts of energy systems, especially indoor and outdoor air pollution, and health impacts of climate change. Chapter 5 analyzes energy security from several points of view, and Chapter 6 reviews the demands for energy services from a growing global population with increased standards of living, especially for the poorer parts of the world. Together, indicators defined and quantified for the purpose of the GEA in these five areas are used to define a "sustainable" state of the world from an energy systems perspective by 2050.

Cluster II reviews the resources and energy technologies available, or on the horizon, to address the energy sustainability challenges. Chapter 7 evaluates reserves and resources of fossil fuels, fissile material, and renewable energy flows. Chapters 8 through 10 deal with energy end-use in industry, transport, and buildings, respectively, and Chapters 11 through 16 review energy supply-side options, including renewable energy technologies, fossil fuel technologies, carbon capture and storage, nuclear energy, energy systems operation, and transitions to new energy systems.

Cluster III then explores how the elements of Cluster II can be combined into *systems* that address all the concerns identified in Cluster I, all at the same time. Chapter 17 presents this back-casting (normative scenario) analysis and identifies a number of conceivable energy systems that would meet the goals from Cluster I. Special attention is then given to urbanization (Chapter 18), energy access for development (Chapter 19), trade-offs in land and water use (Chapter 20) and life-styles (Chapter 21).

Cluster IV deals with policies and institutions to bring about the sustainable energy systems that were identified in Cluster III. Chapter 22 reviews the overall implementation situation, Chapter 23 the implementation of options for access to modern energy carriers and clean cooking fuels, Chapter 24 technology innovation systems, and Chapter 25 the capacity development required in terms of policies, institutions, and people that will be the agents of change to make the next energy transition toward sustainability happen.

Appendix 1.A Accounting for Energy

1.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[45]) 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.

1.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 N=1 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).[46]

There is a wide variety of energy units which can be converted into each other. Figure 1.3 in Section 1.2.1 above, gives an overview of the most commonly used energy units and also indicates typical (rounded) conversion factors (see also Appendix 1.B). Typically, the choice of 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 x 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 x 10^9 J or about 1/7 of a *toe*), the coal industry tonnes of coal equivalent (1 *tce* equals 29.31 x 10^9 J), whereas the gas industry uses cubic meters of gas at a normalized pressure (1 m^3 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^3 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.[47] The *LHV* excludes the latent heat of the water formed during combustion.

45 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.

46 International System of Units – *SI* from the French *le Système international d'unités.*

47 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.

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_2 – 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).

1.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.[48] This method is used, for example, by BP (2010a) and WEC (1993) and as the default method in the GEA (see Annex-II Technical Guidelines) to maintain a consistent accounting framework across different energy options.[49] 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-thirds are dissipated[50] 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.[51]

48 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, 2010), whereas the World Energy Council uses 38.6% for nuclear and non-combustible renewables.

49 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.

50 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.

51 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%.

Table 1.A.1 | Comparison of global primary energy supply in 2005 using three different accounting methods for primary energy.

	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

Source: data from IEA, 2010.

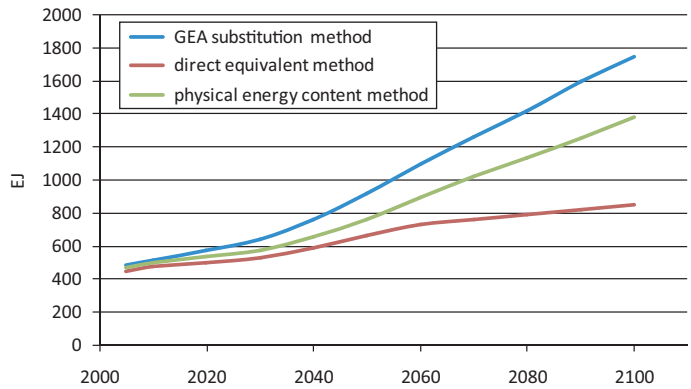


Figure 1.A.1. | Comparison of global total primary energy supply between 2005 and 2100 using three different primary energy accounting methods based on identical useful energy demands as quantified in the illustrative GEA-M set of pathways (see Chapter 17).

A detailed overview of differences in primary energy accounting from different energy statistics is described in Macknick (2009); see also Figure 1.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 1.A.1 compares the differences across the primary energy accounting methods for the world by energy source using the GEA primary substitution equivalent (see Technical Guidelines, Annex-II), 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.

1.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 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 (see Chapter 17). 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 1.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 Chapter 17). 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.

1.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 1.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).

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

Table 1.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	–[1]
New renewables[2]		X	X	X
Traditional biomass[3]			X	X
Electronic availability	Online free	Online free	Online subscription ($)	Offline tape order ($)

[1] Not reported directly by UN but can be calculated from full data base statistics.
[2] New renewable refers to solar, wind, modern bioenergy, and geothermal.
[3] Traditional biomass refers to fuel wood, dung, and agricultural residues.

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 1.11.3 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).[52] 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 renewables such as wind, geothermal, and solar power generation[53] (BP, 2010a). Its statistics cover the period since 1965, are updated regularly,[54] 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 1.A.2). Adjusting[55] 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[56]), or some 7%, with the UN statistics taking an intermediary position (506 EJ) for the GEA base year 2005 (see Figure 1.A.2). This assessment adopts a value of 495 EJ for the level of world primary energy use in the year 2005.

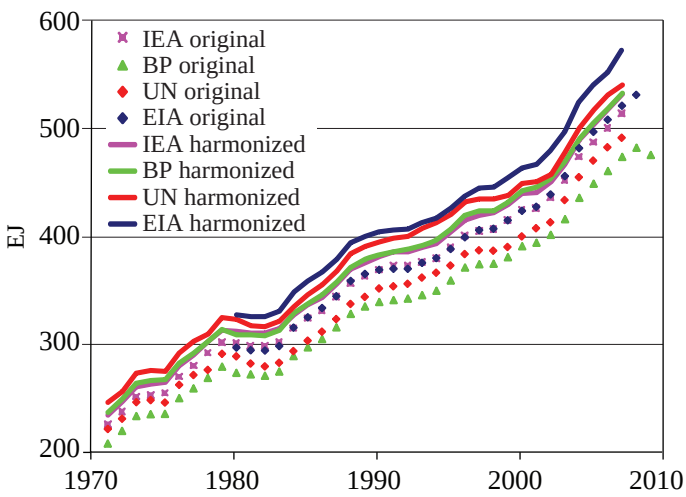


Figure 1.A.2. | World primary energy. Original data by four reporting agencies and harmonized primary energy equivalences. Source: data from Macknick, 2009.

52 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.

53 With exception of ethanol, only installed capacity data for geothermal, wind, and solar are reported by BP.

54 Updates are fastest among all energy statistics and available by September each year for the preceding year.

55 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/.

56 Due to the use of HHV in the EIA statistics.

Appendix 1.B Conversion Tables and GEA Regional Definitions

Table 1.B.1 | Conversion factors.

FROM	TO->												
	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

Source: Nakicenovic et al., 1998.

Table 1.B.2a | Typical calorific values of solid energy carriers.

	Gross calorific value HHV [MJ/kg]	Net calorific value 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.

Source: IEA/OECD/Eurostat, 2005.

Table 1.B.2b | Typical calorific values of liquid energy carriers.

	Gross calorific value HHV [GJ/tonne]	Net calorific value 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

Source: IEA/OECD/Eurostat, 2005; Agarwal, 2007; IEA, 2009b.

Table 1.B.2c | Typical calorific values of gaseous energy carriers per kg and m³.

	Gross calorific value HHV [MJ/kg]	Net calorific value LHV [MJ/kg]	Gross calorific value HHV [MJ/m³]	Net calorific value 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	–

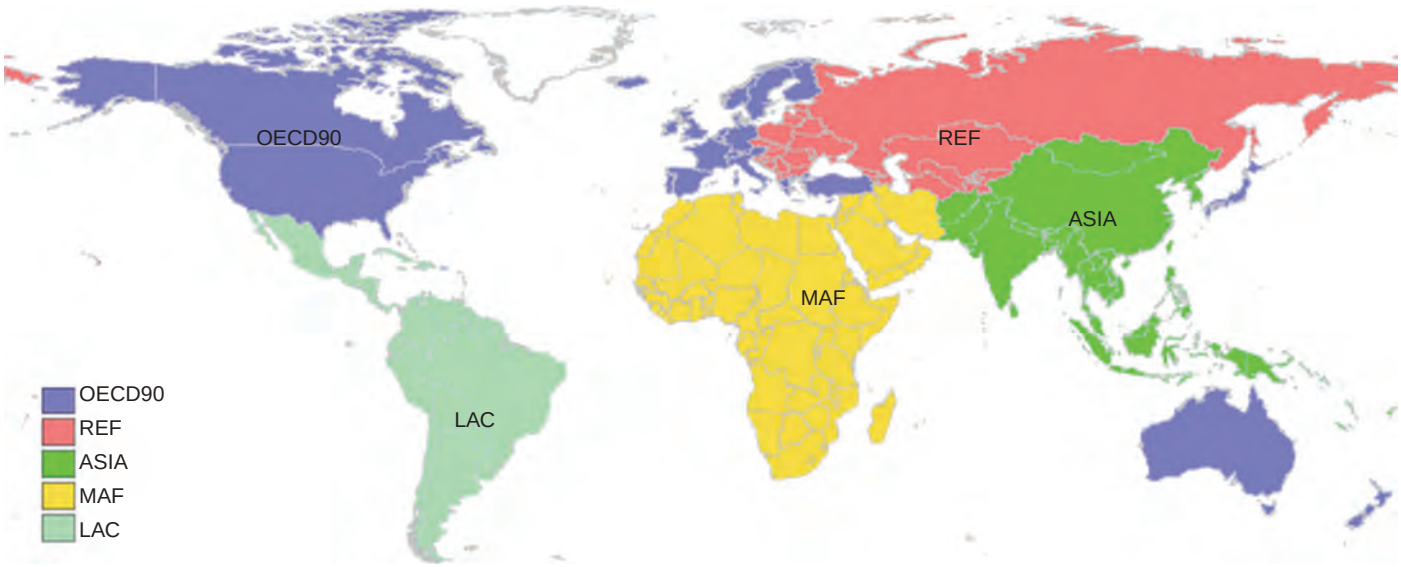
Source: IEA/OECD/Eurostat, 2005 ; IEA, 2009a.

Table 1.B.3 | CO_2 emission factors on a net calorific basis.

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_2 emissions that arise with 100 percent oxidation of fuel carbon content at the point of combustion. Life-cycle CO_2 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.

Source: IPCC, 2006.



Regional acronyms	Regional definition
OECD90	UNFCC Annex I countries
REF	Eastern Europe and Former Soviet Union
ASIA	Asia excl. OECD90 countries
MAF	Middle East and Africa
LAC	Latin America and the Caribbean

OECD90 = OECD countries as of 1990 in Western Europe, North America, and Pacific Asia (and defined in UNFCCC as Annex-I countries)
REF = Countries undergoing economic reform, i.e. countries in Eastern Europe and the former Soviet Union
ASIA = non-Annex-I countries in Asia
MAF = Middle East and North, and Sub-Saharan Africa
LAC = Latin America and the Caribbean

For country listings and finer-resolution regional definitions see Annex-II.

Figure 1.B.1. | Definition of GEA regions, see also Annex-II Technical guidelines.

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