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Stocks, Flows, and Prospects of Energy

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Abstract

Analyses of future energy systems have typically focused on energy sufficiency and climate change issues. While the potential supply of energy services will probably not constrain us in the immediate future, there are limits imposed on the energy system by climate change considerations, which, in turn, are inextricably bound up with land, water, and nonrenewable mineral resources issues. These could pose constraints to energy systems that may not have been fully accounted for in current analyses. There is a pressing lack of knowledge on the boundaries that will impact a sustainable energy system. A more integrated view of energy sustainability is necessary to ensure the well-being of current and future generations. This chapter proposes a set of measures related to sustainability within the context of selected energy scenarios and develops a methodology to define and measure relevant quantities and important links to other resource areas.

Introduction

Analyses of future energy systems have typically focused on energy sufficiency and climate change issues. Although the potential supply of energy services will probably not constrain us in the immediate future, there are limits imposed on the energy system by climate change considerations, which, in turn, are inextricably connected to land and water issues. Linkages to water, land, and nonrenewable mineral resources could pose constraints to energy systems and may not have been fully accounted for in analyses currently available. From our point of view, there is a pressing lack of knowledge with regard to these boundaries, which will impact a sustainable energy system. A more integrated

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[1] Views expressed by the authors do not necessarily reflect those of the companies or organizations they represent.

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view of energy sustainability is necessary to ensure the well-being of current and future generations.

Very roughly, sustainability of the energy system can be defined as providing for the ability of future generations to supply a set (or basket) of energy services to meet their demands without diminishing the potential for future environmental, economic, and social well-being. Our approach for assessing energy sustainability balances retrospective and prospective views. It is important to start with our current situation and analyze retrospectively how we got to this point. Based on this, we can then address the question of where we are going. We make use of scenarios as a way of thinking about future states of the world. The scenarios show a range of potential outcomes around which we construct our references. Because it is not possible to define a single, complete, and detailed energy scenario that would capture the full range of possible futures, we have selected several scenarios that embody a variety of assumptions about the future to illustrate our approach. The use of several scenarios provides increased flexibility in assessing the impacts. The scenarios range from the relatively unconstrained world, as we have now, to a significantly more environmentally constrained world.

We are convinced that it is possible to develop measures of sustainability in the energy system and to propose a set of measures related to sustainability within the context of the identified scenarios (Greene 2009). We develop a methodology to define and measure relevant quantities and the important links to other systems. In addition to the measures regularly used to describe our energy system (e.g., the quantity of energy sources and services by type), additional measures must be taken into account when assessing the sustainability of the energy system. Energy is used to supply a wide array of energy services that provide for human well-being (Worrell, this volume). Thus, the key to a sustainable energy system is to supply these services without diminishing the environmental, economic, and social well-being of future generations. Also important are energy constraints related to climate change. Finally, we are convinced that more specific details of the links between the energy system and other resource areas are crucial for an encompassing assessment of energy system sustainability (e.g., land and water requirements for growing and processing bioenergy crops). We identify some of the relevant connections between these areas and address some important, more complex issues for the energy system: how we conceive energy services, how we think about costs, and how we address substitutability (i.e., the diversity, reliability, flexibility, and geographical distribution of supply).

Our proposed methodology for making reasonable estimates is a first step and will clearly need improvement and elaboration. Our goal is to initiate an active debate about measuring energy sustainability in a broader sense and to stimulate others to pursue these issues, especially the exploration of linkages to other critical resource systems. Measurement plays an important role: if something is not measured, it is difficult to exact an improvement. What is measured

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might ultimately get done. We acknowledge the complex nature of these tasks and their limits. However, as Rayner (this volume) rightly concludes: “If it is worth doing, it is worth doing badly!” Thus, we begin by describing a simple approach which, although in need of considerable elaboration and refinement, we believe to be fundamentally sound.

Methodology

We describe the energy system as consisting of resources that are converted through various means to provide energy services. We include geological (i.e., nonrenewable fossil fuels and radioactive minerals) and renewable (solar insolation, wind, geothermal, water power, and biomass) resources. Principal conversion mechanisms include:

- Electricity generation by coal, oil, gas, and biomass combustion, nuclear fission, wind turbines, solar photovoltaic, concentrating solar thermal, geothermal, ocean energy, and hydroelectric power.
- Heating from fossil fuels, solar thermal, geothermal, and biomass combustion.
- Fuel production from oil refining as well as production of liquids from coal, natural gas, or biomass, and production of hydrogen via hydrocarbon reforming or water splitting.

Energy services are extensive, ranging from transportation to lighting, heating, communications, agricultural production, water purification and distribution, and the production of basic commodities, such as concrete and steel. The mix of energy services supplied is an integral part of the metric of the sustainability of the energy system. Similar to the use of purchasing power parities in economics, a mix or basket of energy services can be devised as an indicator of supplied energy services for human well-being.

We want to define the specific measurements that connect the elements of the energy system to the land, water, and nonrenewable minerals systems. Many of these measures include traditional quantities, such as amount of energy resource and energy service demand by type, as well as the efficiency of conversion of energy resource to energy service. An *energy service* is any use of energy in response to a demand. Familiar examples include lighting, heating, cooling, cooking, transportation, electronic communication and computing, and industrial processes (e.g., steel manufacturing). Energy services are made possible through the conversion of energy resources into a carrier such as electricity, fuel, or heat which is then used to provide the desired service. The amount of primary energy needed to produce a unit of energy service is expressed as the specific energy consumption (SEC). Energy efficiency is increased by reducing the SEC while providing the same energy service. New

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forms of *energy services* are constantly being developed in response to innovations to meet human needs or demands (e.g., in manufacturing processes, electronics, and home appliances).

Methods of measuring energy costs, as well as the level of supply diversity, reliability, flexibility, and distribution are also included and relate directly to the issue of substitutability. Substitutability, as well as the inherent transition barriers involved, poses many challenges to energy alternatives, including:

- Time-scale issues: penetration rates of new vehicles into the car fleet, turnover intervals, and build rate for new buildings, power plants, and transmission and distribution systems.
- Location: geographical mismatch between renewable resources and power load centers.
- Geographical scale and related infrastructure needs: energy storage for stationary and transportation applications, power transmission and distribution capacity, fuel distribution and dispensing capacity.
- Physical state: electrons vs. gaseous vs. liquid fuels.
- Quality: baseload vs. intermittent power, low grade vs. high temperature heat.
- Geopolitics: reduced or challenged access to oil and gas in certain countries.
- Sufficiency of human resources/capital/knowledge to develop and operate advanced energy systems: looming energy sector labor shortage in Western world.
- Institutional responsiveness, capacity, and sophistication: lagging regulatory and legal frameworks to implement renewables, financial incentives that may favor certain technologies over others.

Consider the set of critical linkages between systems (Figure 22.1). The basic transactions that connect the energy system to other systems are depicted by the gray arrows. In the case of the linkages between the energy and water systems, the basic transactions are water per unit of energy output (H_2O/Unit E) and energy required per unit of water output (E/Unit H_2O).

In addition to these linkages, each system inherently embodies constraints that may be relevant to the sustainability of both itself and the other systems (Figure 22.2). These impacts and constraints suggest new measurements including:

- An expanded definition of environmental impact that includes CO_2 as well as non-greenhouse gas air pollutants, regionally specific impacts of land use (e.g., for biofuels production and coal and bitumen mining), water demand of the energy system, and nonrenewable mineral resource demands of the energy system.
- Safety and health impacts of energy supply conversion and energy service use.

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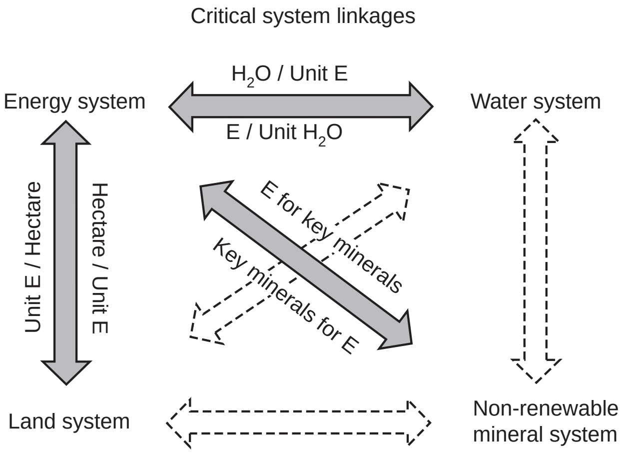

Figure 22.1 Critical system linkages between energy, land, water and nonrenewable minerals.

- Purchasing power parity for energy services.
- Accessibility of and ability to develop energy resources fully, regardless of geopolitical and/or social constraints.

Our analysis begins with a description of stocks and flows of the energy resources currently in use and their recent history.

Geologically Based (Nonrenewable) Fuels

Every year, since the end of World War II, between 91% and 93% of the world's energy supply has come from geologically based fuels: coal, oil, natural gas,

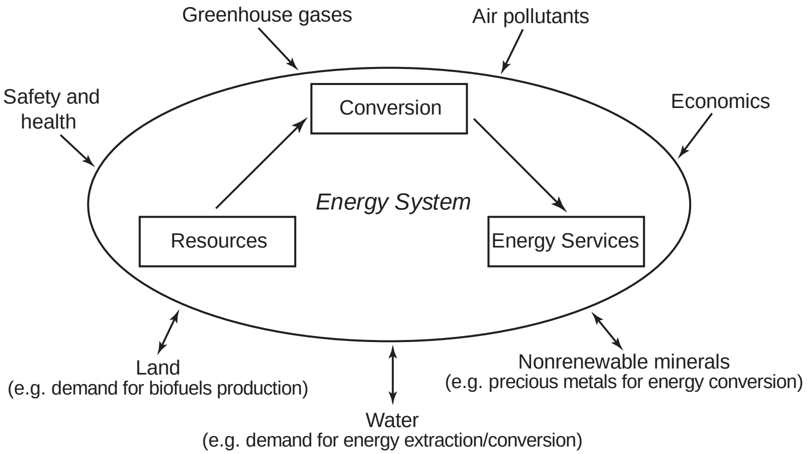

Figure 22.2 Energy system impacts and constraints.

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and uranium. In 1945, the entire human population consumed about 50 exajoules (EJ, or 10^{18} joules) or 1300 million tons oil equivalent (MTOE) of energy. By 2007, worldwide energy consumption had increased to approximately 460 EJ (11,099 MTOE). About 34% of all energy used was derived from oil or other petroleum liquids. Coal contributed approximately 26% of the primary energy supply and natural gas almost 21%. Nuclear reactors generated more than 6% and hydroelectric installations a little more than 2% of global energy. Together, geothermal, solar, and wind installations accounted for less than 1% of global energy consumption. The remaining energy was derived from other renewable sources and waste. Here, we briefly summarize the current estimates of remaining reserves, as Gautier et al. (this volume) provides an extensive discussion of trends and reserve estimates of the key nonrenewable energy resources.

With a few interruptions for warfare, economic depression, and political upheaval, global *oil* production has increased steadily since the 1860s. Approximately 180 EJ or 30 billion barrels of oil (BBO) were produced during 2007 from wells in thousands of fields in more than 100 countries. As of January 2008, the International Energy Agency estimated world reserves, excluding most heavy oil sands, to be 1332 BBO (about 8150 EJ) (IEA 2008c). All sources agree that proved reserves have increased in lockstep with rising production. For example, in January 1996, when world proved reserves were approximately 891 BBO (about 5450 EJ), annual world production was a little over 26 billion barrels (about 160 EJ). Between January 1996 and January 2008, approximately 300 BBO (about 1835 EJ) were produced, while reported proved reserves increased by nearly 350 BBO (about 2140 EJ); this suggests that almost 650 BBO (about 3980 EJ) were added to reserves during the twelve-year period. Reserves increase through two processes: (a) new-field discoveries and (b) growth of reserves in existing fields. Reserve growth refers to increases in successive estimates of oil, gas, or natural gas liquids in discovered fields, usually in fields that are already in production. In addition, significant potential exists for additions to global reserves from unconventional categories, such as heavy oil, oil sands, and oil shales. Heavy oil resources exist in many basins worldwide, but their potential contribution to world oil reserves has not been systematically evaluated.

Using BP statistics, in 2007 more than about 100 EJ or 2940 billion cubic meters (bcm) of natural gas were produced worldwide. This amount is up from 1973 levels of 1227 bcm (about 42 EJ). At the end of 1987, estimated world proved reserves of natural gas were approximately 107 trillion cubic meters (tcm) (about 3700 EJ). As of 1997, reserves had risen to approximately 146 tcm (about 5040 EJ), and at the end of 2007, world proved reserves of natural gas were estimated at approximately 177 tcm (about 6120 EJ). Exploration for natural gas has not been pursued with nearly the level of investment and intensity nor for nearly as long as has oil, and it is considered to be at a much lower level of exploitation. The median estimate of total gas (i.e., the sum of

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associated/dissolved and nonassociated gas) was that 122.6 tcm (about 4240 EJ) might be found (USGS 2000). In addition, the USGS study estimated that between 95 and 378 billion barrels of natural gas liquids (between about 386 EJ and 1536 EJ) would be discovered along with the associated/dissolved and nonassociated gas. In addition to the conventional resources, extremely large amounts of natural gas are known to exist in various so-called nonconventional reservoirs (i.e., gas in coal beds, in extremely low-permeability sandstones, and in shales). Beyond these resources are gas hydrates, which are believed to contain the largest part of organic carbon on Earth. Recent research indicates that these resources could become productive over the next decade or two.

In 2007, the combustion of coal and peat accounted for 26% of total world primary energy supply. In recent years, the rate of coal production has been expanding more rapidly than any other major energy source. Between 2000 and 2005, world coal production increased from about 95.4 EJ (90.4 Quadrillion BTU [Quads]) to more than 129 EJ (122.2 Quads), and the rate of increase is steepening. Global proved reserves of coal remain very large compared to rates of production. According to the World Energy Council, as of 2002, global proved reserves of all types of coal exceeded 900 billion tons (about 19000 EJ) (WEC 2007a). These reserve numbers are based on the numbers reported by countries and are not as thoroughly documented or independently scrutinized, as are oil or gas reserves.

In 2006, nuclear power constituted approximately 6.2% of worldwide total primary energy supply, more than 84% of which was generated in the developed countries of the OECD. Like coal, uranium is not considered in danger of geological exhaustion. Rather, the demand for uranium and the related ore pricing are the dominant forces that control uranium production rates. Recently, rises in uranium prices with the development of additional nuclear generation facilities have resulted in increasing prices for uranium.

Renewable Resources

Renewable energy resources are those that can be produced from the direct or indirect energy of the Sun or Earth: solar radiation, wind energy, biomass, geothermal energy, ocean energy, and hydropower. In theory, there is more than enough renewable energy to provide for human needs. The solar radiation that falls on the Earth's land surface each year is equivalent to ca. 10,000 times the annual global primary energy use. In practice, renewable energy makes up about 7% of total primary energy use (not including traditional biomass burning) and 18% of global electricity use today. Hydropower accounts for 16% of electric generation, whereas *together* wind, solar, and geothermal contribute another 1%. Biomass and waste energy account for about 10% of primary energy use; however, if traditional unsustainable biomass burning is not included, then biomass and waste energy accounts for only 4% (IEA 2008g).

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Scenarios developed by IEA suggest a growing role for renewable energy over the next decades (IEA 2008g).

Fossil resources are defined in terms of reserves or energy stocks, which can be depleted over time (for a description of the well-established conventions for defining fossil resources, see Gautier, this volume). In contrast, renewable energy resources are defined in terms of energy flows (e.g., energy production per year). Three types of renewable energy potential are commonly used: (a) *theoretical potential*, defined as the theoretical maximum energy flow rate; (b) *technical potential*, which is the energy that can be captured using a certain set of technology and engineering feasibility assumptions; and (c) *economic potential*, which refers to the amount of renewable resources that could be recovered and converted at an economically viable cost subject to environmental and social constraints. In addition, environmental and societal constraints can limit the potential for renewable energy deployment.

When measured in physical terms, Earth's renewable resources far exceed society's current and projected needs for primary energy. However, renewables do not generally match human needs due to a combination of intermittency, low energy density, or inconvenient locations. Addressing these challenges may result in land use conflicts, other environmental impacts, and high upfront costs (Jaccard 2005).

The global *wind resource* has been assessed in several recent reports (Archer and Jacobson 2005; De Vries et al. 2007; Grubb and Meyer 1993; GWEC 2006; Hoogwijk et al. 2004; UNDP 2000, 2004; WEC 2007a). The *physical wind resource* can be defined as the theoretical maximum energy carried by the wind. In principle, this can be estimated based on meteorological and geographic data: the time-varying distribution of wind speeds (including seasonal effects), the terrain, height above ground, elevation, and location. It has been estimated that 0.25% of the solar radiation energy reaching the lower atmosphere is transformed into wind (Grubb and Meyer 1993), an amount many times the current level of human energy consumption. Of course, only a small fraction of this energy can be captured because of technical, environmental, and societal constraints. Technical constraints include wind turbine efficiency, height, and losses due to airflow interference by adjacent turbines. Resource, environmental, and social constraints may restrict the sites of large wind turbines within cities, forests, or inaccessible mountain areas due to factors such as visual impact, noise, conflicting land uses, wildlife impact, or inaccessibility.

The amount of electrical power that can be generated from wind resources is calculated based on a wind velocity profile, turbine conversion efficiency, size, and hub height. Average annual capacity factors of up to 30–40% can be attained in high wind locations, such as ridges and offshore.

Gross wind power potential is the electrical power that might be generated, if no exclusions are imposed on siting turbines. *Practical wind power potential* imposes "first-order" constraints (no turbines in cities, forests, inaccessible

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mountain areas), and the "second-order" potential adds constraints for visual, environmental, and societal reasons.

Gross wind power potential (without exclusions) is estimated at 300,000–600,000 TWh/yr of electricity production. This is many times the current global electricity use of 19,000 TWh/yr (IEA 2008c, g) or the projected level of use in the year 2050 of 40,000–50,000 TWh/yr. With exclusions, practical wind power potential is estimated to be about 70,000–410,000 TWh/yr and economic potential at about 19,000–25,000 TWh/ yr (UNDP 2000; Jaccard 2005). These numbers suggest that wind power could play a major role in a future energy system. In addition, system integration issues could further limit how much wind power could be introduced onto the electricity grid. Often, the best wind resources are located far from a population, so that transmission capacity is a constraint. Scenario studies that account for these issues suggest that 2–12% of future electricity in 2050 could be economically produced from wind power and integrated into the grid (GWEC 2006; IEA 2008c, g).

Currently, *biomass energy* is used for heating, electricity generation, and production of liquid biofuels (e.g., ethanol and biodiesel). In 2006, the global use of biomass energy was about 50 EJ per year (IEA 2008c). About 60% of biomass energy is consumed in developing countries as traditional, noncommercial fuels (e.g., fuel wood, crop residues, dung) for home heating and cooking. Modern biomass conversion (for process heat and electricity and fuels) accounts for 19 EJ/yr.

The potential for global biomass production in the future has been estimated in several recent studies. The estimates vary widely depending on the assumptions about biomass yields, conversion efficiency to electricity or fuels, and land use restrictions

Biomass resources have been defined in various ways (Hoogwijk et al. 2005). A *theoretical upper limit for global biomass* production can be estimated, if all land were used to grow energy crops. This has been estimated at 3500 EJ/yr, far in excess of current or projected global energy use in 2050. In practice, there are many competing uses for land, so that biomass production would be much less than the theoretical potential. *Geographic potential* estimates the resource from growing biomass on available land, under constraints. *Technical potential for bioenergy production* accounts for conversion losses in producing electricity or fuels from biomass feedstocks. The economically viable potential for biomass is found by developing regional supply curves for biomass. Finally, policies and institutional constraints can impact the use of biomass (Hoogwijk et al. 2005). Concerns about the sustainability of biomass production further constrain its use. In a recent review, the IEA (2008c) estimated that the global potential for sustainable primary biomass energy production was 200–400 EJ per year.

Several issues contribute to the uncertainty in long-term contributions of biomass to the energy system. These include competition for water resources, environmental impacts from fertilizer and pesticide use for energy crops,

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biodiversity effects of energy crops, and competition for land between bioenergy crops and feed and food production.

Hydroelectricity is currently the largest renewable source for electricity generation, accounting for about 3035 TWh/yr or 16% of global electricity production. Hydroelectricity can be generated using large dams, small hydropower plants, or pumped water storage. The global hydropower resource has been assessed in several recent reports (Archer and Jacobson 2005; deVries et al. 2007; IEA 2008c; UNDP 2000, 2004; WEC 2007a). As with other renewable energy resources, several definitions exist.

Theoretical hydropower resource is defined as the theoretical maximum energy carried by water runoff on land. The world's annual water balance can be estimated, yielding a runoff from precipitation over land of 47,000 km^3 of water per year. In theory, the energy in this running water could be harnessed for hydroelectric power production. Taking into account the geographic elevation, magnitude of precipitation, and topography, the global theoretical hydropower potential has been estimated to be about 16,000–40,000 TWh of electricity per year (UNDP 2000). Much of the theoretical potential cannot be captured because of inaccessibility to the flow and other siting issues. The global *technical potential* has been estimated at up to 14,000 TWh/yr (IEA 2008c), although there is still uncertainty in the *economic potential* due to the many siting issues. Historically, about 60–70% of technical hydropower resources have been developed in industrialized regions (e.g., Europe and the United States). Using this as a guide, the global economic potential has been estimated at 6000–9000 TWh/yr (UNDP 2000; IEA 2008c, g).

Hydropower resources are distributed unevenly throughout the world. Much of the unrealized potential here lies in developing countries in Latin America, Asia, and Africa. According to recent IEA scenarios, hydropower could grow by a factor of 1.7 by 2050 (IEA 2008g), mostly in developing countries.

Two-thirds of the Earth's surface is covered by water. Almost 97% of this water fills the oceans and seas, whereas only 0.0002% flows in rivers (Gleick 1996). Although conventional hydropower has been widely tapped across the globe, ocean energy (i.e., the kinetic energy generated by waves, tidal currents, and river flows, as well as the thermal energy stored in ocean temperature gradients) has been largely underexploited. The technologies to harness these energy sources are still in various stages of development, with a handful undergoing sea trials and nearing full-scale deployment. All face, however, significant challenges, in particular, operating these devices offshore under harsh environmental conditions, intermittency, and reliability in connecting the devices to onshore electrical grids. In addition, the surface footprint of wave device arrays may affect shipping, while tidal current devices could impact sea life.

The total wave resource meeting the world's shorelines in the form of ocean waves is estimated at about 23,600–80,000 TWh/yr (IEA 2006a; Jaccard 2005; WEC 2007a), of which only about 28 TWh/yr is potentially economically recoverable (Jaccard 2005; WEC 2007a). Several different types of wave energy

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conversion devices are being tested, with a unit capacity of less than 1 MW, including oscillating water columns, overtopping devices, point absorbers, terminators, and attenuators. The average capacity factors are expected to range between 21–25% (Jacobson 2008).

The global tidal power potential in sites with good power densities is estimated at between 800–7000 TWh/yr (IEA 2006a; Jacobson 2005), of which up to 180TWh/yr may be economically converted into electricity (Jacobson 2005). Unlike waves, which have limited predictability, tidal patterns are constant, with average capacity factors of 20–35%. Currently, several in-stream tidal flow conversion devices are undergoing various stages of testing and have a unit capacity on the order of 1 MW or less. These include underwater horizontal and vertical axis turbines, venturis, and oscillatory devices. Tidal energy is able to leverage a significant amount of research from the wind industry, reflected in a narrow range of technical approaches being pursued, whereas for wave power it is still not clear what defines a winning technology, with a large number of concepts being pursued in parallel.

Technologies for harnessing energy from tides by building barrages across estuaries are well developed, but have significant impact on local ecosystems. Current installed capacity is 270 MW_e and the total resource potential is estimated at 300 TWh/yr (IEA 2006a).

Ocean thermal energy conversion (OTEC) is by far the largest ocean energy resource, estimated at up to 10,000 TWh/yr (IEA 2006a), and harnesses the constant temperature differential of up to about 20°–23ºC between tropical surface water and deep-ocean water. However, OTEC is challenged by mismatch between resource location and load, low conversion efficiencies, and the need for deep-water deployment of large amounts of hardware. Only small prototypes, 50 kW_e or less, have thus far been demonstrated. Larger systems, 10–100 MW, are being targeted if OTEC is to be commercialized. The possible benefits of integrating OTEC with other uses (e.g., aquaculture, air-conditioning, and desalination) are also being studied.

Salinity gradient technology uses the osmotic pressure differential of seawater and freshwater, which represents an equivalent of a 240 m hydraulic head. The global primary power potential is defined roughly by the volume of freshwater entering the world's oceans every year and is estimated at about 2000 TWh/yr (IEA 2006a). However, salinity power technologies are still in very early R&D stages and will likely have limited potential in the foreseeable future.

The global installed capacity from all of these emerging ocean-energy technologies is at present less than 5 MW (less than 1 TWh/yr, mostly from tidal barrages), largely from engineering prototypes and demonstration systems. Significant numbers of larger installations greater than 100 MW are not expected before 2030. IEA expects 14 TWh/yr to be generated by 2030 (IEA WEO 2008c).

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Geothermal energy projects convert the energy contained in hot rock into electricity, process heat, or space heating and/or cooling by using water to absorb heat from the rock and transport it to the Earth's surface. In conventional (hydrothermal) systems, water from high-temperature (>450°F) reservoirs is partially flashed to steam, and heat is converted to mechanical energy by passing steam through low-pressure steam turbines. In a few large reservoirs, accounting for 29% of production worldwide, dry steam is produced directly from the reservoir and separation is unnecessary. In lower temperature reservoirs, or in some cases to utilize the heat from separated brine, power is generated using a binary system, transferring the heat through a heat exchanger to a secondary working fluid to drive a turbine. This accounts for 10% of worldwide geothermal power generation. Geothermal plants are typically operated as baseload facilities with high capacity factors around 90%, and low, or in some cases zero, operational greenhouse gas emissions. Resource temperature has a strong influence on the conversion efficiency of heat to electricity such that the conversion efficiency increases from less than 5% at 212°F to more than 25% at 570°F (Armstead 1987).

New technologies are currently being developed to explore and develop unconventional geothermal systems, including: hidden systems (i.e., without surface thermal features, such as hot springs, fumaroles, or hydrothermal alteration), deeper systems (greater than 3 km deep), high temperature/supercritical systems, and enhanced (engineered) geothermal systems (EGS). In the latter, hydraulic stimulation is used to create sufficient permeability to allow fluid flow between injectors and producers (Williamson, pers. comm.). Generally, water must be introduced into the reservoir, and deep wells (e.g., 5–10 km) need to be drilled to access a sufficient heat resource. Some researchers (Pruess and Azaroual 2006) have proposed using supercritical CO_2 as the circulating fluid in EGS, instead of water, for both reservoir creation and heat extraction.[2]

It is estimated that 10^{13} EJ (2.8×10^{15} TWh) of heat energy are stored in Earth and the global rate of heat loss is estimated at 1000 EJ/yr (2.8×10^5 TWh/yr), of which 70% is lost from the oceans and 30% from the continents (Rybach et al. 2000; Pollack et al. 1993). By comparison, the total primary energy consumed by the world is roughly 491 EJ/yr (1.4×10^5 TWh/yr) (IEA 2008c). Estimates for total worldwide, technically recoverable geothermal energy for power and heat production range from 500–5000 EJ/yr (1.4×10^5 – 1.4×10^6 TWh/yr). Anywhere from 2–20 EJ/yr (556–5556 TWh/yr) may be economically recoverable (Jacobson 2008; Jaccard 2005).

Geothermal power is generated in 24 countries, with 94% of its total capacity from the following eight countries: U.S. (29%), Philippines (22%),

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[2] EGS-CO_2 systems have the potential to extract more heat from reservoir rocks, due to higher fluid mobility, and to reduce pumping losses that result from CO_2 hot/cold density differences. In addition, any CO_2 losses to formation could be considered as sequestration. Aqueous CO_2 solutions require corrosion control.

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Mexico (11%), Indonesia (9%), Italy (9%), Japan (6%), New Zealand (5%), and Iceland (2%) (Bertani 2005). Approximately 75% of the worldwide capacity is produced from 20 sites, which have more than 100 MW_e installed.

The worldwide electrical power output from geothermal sources increased from 0.0094 EJ/yr (2.6 TWh/yr) in 1960 to 0.22 EJ/yr (60 TWh/yr) in 2006, or about 0.3% of the world's electrical output (IEA 2008g), as the installed geothermal plant capacity increased from 386 MW_e in 1960 to over 10,000 MW_e in 2006 (IEA 2008g). As more fields, both conventional and unconventional, are exploited, geothermal power generation is expected to triple by 2030 (Appendix A in IEA 2008g). Direct geothermal heat for space heating accounted for over 0.1 EJ_{th} in 2006, with one-third coming from deep bore holes, and the rest from domestic ground source heat pumps. Direct use is expected to reach 0.8 EJ by 2030 (IEA 2008g).

Although Earth intercepts only a minute fraction ($\sim 5 \times 10^{-10}$) of the total power generated by the Sun, *solar energy* is the most abundant energy resource available to us (WEC 2007a). About 60% of this incoming radiation, or 3,900,000 EJ (1.1×10^9 TWh/yr), actually reaches the Earth's surface. Although this equates to about 1000 W/m^2, once weather (e.g., cloud cover, humidity), diurnal, and seasonal variations are taken into account, the average solar irradiance is about 170 W/m^2 (WEC 2007a). In one hour, approximately the same amount of solar energy hits the Earth's surface as all the energy consumed by human activities during a whole year, based on 2006 data (IEA 2008g).

Indirectly, the Sun is the source of biomass-derived, wind, and ocean energy. Commercially available applications of *direct* solar energy include passive uses (e.g., space heating, cooling via reflection, day lighting), hot water heating and cooling, process steam generation, and electricity production. The technically recoverable potential of direct solar energy ranges from 0.4×10^6 to 16×10^6 TWh/yr (Jaccard 2005; Jacobson 2008). This potential accounts for variable levels of insolation around the world, varying ability of systems to capture all the available light to service and avoid shading of solar modules, and other factors, such as dust which reduces collector efficiency. Other direct solar applications, still in very early stages of R&D, might include photoelectrolysis of water to hydrogen and photoreduction of CO_2 (and H_2O) into methanol and other liquid fuels.

People have passively harnessed solar heat since ancient times. Only recently, however, has there been a more concerted effort to integrate passive techniques into building designs. Active solar heating is, however, a relatively mature technology and generally consists of passing a heat transfer fluid through a series of pipes exposed to the Sun and then storing the thermal energy in a tank to provide hot water on demand. Because of limited daylight hours, backup gas or electric heating is typically needed. Not only is direct solar heating the most efficient use of solar energy, it is also the most common, with over 128 GW_{th} of global installed capacity, mainly in China, generating 0.08 TWh_{th}/yr in 2006 (IEA 2008e). Non-concentrating solar thermal collectors consist of unglazed

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and glazed flat panels as well as evacuated tubes that can heat water, glycol, air, or other liquids to about 100°C or slightly higher. When coupled to an absorption chiller or ejector, these systems can provide solar cooling.

Concentrating solar thermal (power) systems (CSP) involve collecting direct normal radiation with mirrors and then focusing this high temperature beam onto a heat transfer fluid, such as water, organic fluids, mineral oils, or even molten salts. Distributed collector systems (e.g., linear Fresnel reflectors and parabolic troughs) can attain temperatures up to 400°C. Heliostats that focus light onto central receiver towers can reach temperatures up to 700°C or higher. The hot working fluid can then be used to provide industrial or commercial process heat or refrigeration, or can generate electricity by driving a steam turbine. Advanced central receiver systems that heat air to fire gas turbines for power are in the early stages of R&D. Parabolic dishes, which focus sunlight to heat hydrogen or helium to drive a heat engine (e.g., Stirling engine) to produce power, is another example of a CSP technology.

Photovoltaic (PV) systems consist of arrays of cells made of semiconductor materials that can convert photons from both incident normal and diffuse/reflected light into direct electrical current. These materials consist mostly of mono- or polycrystalline silicon. However, thin film devices made of amorphous and micro-crystalline silicon, cadmium telluride, and copper indium gallium selenide are now starting to penetrate the market. PV modules can be mounted onto rooftops, integrated into building shells, or installed in ground-based arrays. Concentrating PV systems use lenses or other optical focusing techniques to focus light onto gallium arsenide cells to generate electricity. Next generation PV devices, which use nanotechnology, organic materials, and other advanced concepts, are currently in early stage R&D.

The land use area footprint for PV or CSP generation systems ranges from 1–4 ha/MW_e (~.2–.8 ha/MW_{th} for thermal systems), depending on the collection technology, whether or not they track the Sun,[3] and whether on-site thermal energy storage is used. The average annual capacity factor for solar varies from 15–35% depending on latitude, cloudiness, tilt and/or tracking, and collector efficiency.

Solar energy currently provides far less than 1% of the world's total commercial energy, but this share is expected to grow to 1–11% by 2050 (of total electricity generation, not including direct heat use) based on future scenario studies (IEA 2008g). Solar PV systems generated approximately 4 TWh/yr of electricity in 2007, while CSP generated under 1 TWh/yr (IEA 2008f, g). Most of the current installed capacity is in Europe (Germany, Spain), Japan, and the United States. Upper estimates for the total economically recoverable resource

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[3] Concentrating solar systems require tracking whereas for flat panel PV systems, it is optional. Single- or dual-axis tracking will increase PV module output at the expense of higher area footprint to avoid shading between modules.

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base for PV and CSP are, respectively, 3 × 10^6 TWh/yr and 1000–8000 TWh/yr (Jaccard 2005; Jacobson 2008).

Retrospective and Prospective Analysis

To assess energy sustainability, we use retrospective and prospective analysis methods. Both are necessary. Prospective assessment is essential because sustainability is inherently concerned with the future. However, prospective analysis is also inherently speculative. Retrospective analysis is therefore needed to serve as a reality check to reveal the path that the world has actually taken. The retrospective analysis method looks at past behavior to appraise effects on the potential well-being of future generations over a specific period of time: Have we decreased the potential well-being of future generations over, for example, the last ten years? Analysis is based on historical changes in (a) quantities of fossil resources by type, (b) cumulative flows by type, or (c) quantity of renewable energy by type, as well as (d) changes in energy efficiency of conversion processes, (e) energy efficiency of energy services (end uses), and (f) conversion efficiency of source to energy conversion for renewable energy sources by type. From these we calculate the change in the ability to produce energy services using current patterns of resource discovery, expansion (technology), use, and energy services demand.

The prospective method analyzes where we are going by using energy scenarios up to 2050 to define alternative, yet plausible futures of services demand, efficiencies of energy technologies, and resources. We can calculate changes in energy resource availability based on resource flows and resource expansion, and assess our ability to produce energy services using conversion and end-use efficiencies. Key data on reserves, resources, production, and their changes over time are listed in Table 22.1.

The Role of Scenarios

Scenarios provide a way of thinking about alternative plausible future states of the world. We selected three scenarios that reflect different dominant approaches to managing energy: a laissez-faire approach, a managed transition to low carbon, and a tightly carbon (environmentally) constrained scenario. Each scenario is rooted in alternative ways of organizing human behavior and the different values that uphold those organizational commitments; namely, the competitive market, the hierarchical state, and egalitarian cooperation, each of which corresponds to one of the three management strategies. Each way of organizing takes different views of nature and the economy. Market-based organization views nature as robust and forgiving, but worries that the economy can be easily upset by intervention. Egalitarian organization tends

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Table 22.1 Reserves and production of energy resources. All numbers are from IEA (2008c), unless otherwise noted. IEA average conversion factors assume: 1 MTOE (million tonnes of oil equivalent) = 1.98 × 10^6 tonnes coal = 0.0209 10^6 BOEPD (barrels of oil equivalent per day) = 1.21 BCM gas (billion cubic meters) = 1.21 × 10^{-3} TCM gas (trillion cubic meters).

Fossil and nuclear energy sources	Proved recoverable reserves (2005)	Annual production 2005	BASE-2050	ACT Map-2050	BLUE Map-2050
Coal (10^9 tonnes)	847 × 10^9 (a)	5.7	12.4	4.9	4.5
Conventional oil (10^6 BOEPD)	1332	84	94	84	58
Shale oil (10^6 BOEPD)		0	10	0	0
Oil sands (10^6 BOEPD)		1	16	6	2
Arctic and ultra-deep oil (10^6 BOEPD)		0	15	4	1
Total oil production (10^6 BOEPD)		85	131.3	91.8	59.4
Natural gas (TCM)	177 (a)	2.8	5.6	4.8	3.6
Uranium/nuclear energy (ktonnes) (b)	3297	42	NA	NA	NA
Nuclear electric generation (TWh/yr)		2771 (370 GWe)	3884	7336	9857

Renewable energy source	Economically recoverable resource (2005)	Annual production 2005	BASE 2050	ACT Map-2050	BLUE Map-2050
Geothermal electricity (TWh/yr)	5560 (c)	53	348	934	1059
Geothermal electricity (GW_e)		9	60	180	220
Wind electricity (TWh/yr)	19,000–25,020,(d)	111	1208	3607	5174
Wind electricity (GW_e)		57	400	1350	2000
Hydropower electricity (TWh/yr)	6000–9000 (c, d)	2922	4590	5037	5260
Hydropower electricity (GW_e)		867 (e)	1380 (f)	1510 (f)	1580 (f)
Solar heat (TWh_{th}/yr)	NA	77 (g)	390 (f)	900 (f)	1800 (f)
Solar heat (GW_{th})		128 GW_{th} (g)	650	1500	3000

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Renewable energy source	Economically recoverable resource (2005)	Annual production 2005	 BASE 2050	 ACT Map-2050	 BLUE Map-2050
Solar electricity (TWh/yr)	PV: $<3 \times 10^{6,}$ (h) CSP: 1050–7800 (h), 8340 (j)	PV: 3 (i) CSP: 1 (i)	167 (PV+CSP)	2319 (PV+CSP)	4754 (PV+CSP)
Solar electricity (GW_e)		PV: 6 (g, i) CSP: 0.4 (g)	PV ≤ 60 CSP ≤ 10	PV: 600 CSP: 380	PV: 1150 CSP: 630
Ocean energy (TWh/yr)	28 (c)	1	10	111	413
Ocean energy (GW_e)		0.3	3 (f)	37 (f)	136 (f)
Commercial biomass electricity (TWh/yr)	33,360 (c)	231	1682	1980	2452
Biomass feedstock max. production (10^9 tonnes/yr)			6.6	8.8	11.0
Biomass feedstock max. production (EJ/yr) (j)		~50	90	120	150
Biofuel production (10^6 BOEPD)		.4 (k)	≤1.5	12	15

(a) Gautier et al. (this volume)
(b) WEC (2007)
(c) Jaccard (2005)
(d) UNDP (2000)
(e) IEA (2007).
(f) Annual energy use values estimated based on 2005 capacity factor.
(g) IEA (2008e); shows only 2006 data.
(h) Jacobson (2008)
(i) IEA (2008g); see also Appendix 3 (this volume)
(j) Includes traditional biomass.
(k) IEA WEO (2007), Appendix 3 (this volume)

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to see nature as fragile and the economy as capable of absorbing the costs of environmental protection without harm. Hierarchical organization views both nature and the economy as resilient within limits that must not be transgressed, and thus tends to be preoccupied with technical analysis of the state of both nature and the economy (for elaboration, see Thompson and Rayner 1998). The driving concerns are also different under each strategy: in the hierarchical state, the concern is on system maintenance; in the competitive market, it is about staying ahead; under the egalitarian approach, it is about limiting demand. Energy supply is characterized by large infrastructure in the hierarchical approach, it is opportunistic in competitive markets, and it is based on distributed resources in the egalitarian world. The diagrammatic mapping of scenarios onto the integrated social science description of viewpoints is shown in Figure 22.3. To ensure that our analysis was robust across all three of these world views required that we identify a set of energy scenarios that exhibited corresponding diversity.

The IEA Energy Technology Perspectives (ETP) 2008 energy scenarios, the most recent comprehensive set of global energy projections, were selected to help examine the potential linkages and sustainability constraints of such value sets on future energy systems (IEA 2008c). The IEA ETP includes detailed assumptions about technology and energy uses for power, transportation, and end use. Three scenarios were chosen: Baseline, ACT Map and BLUE Map.

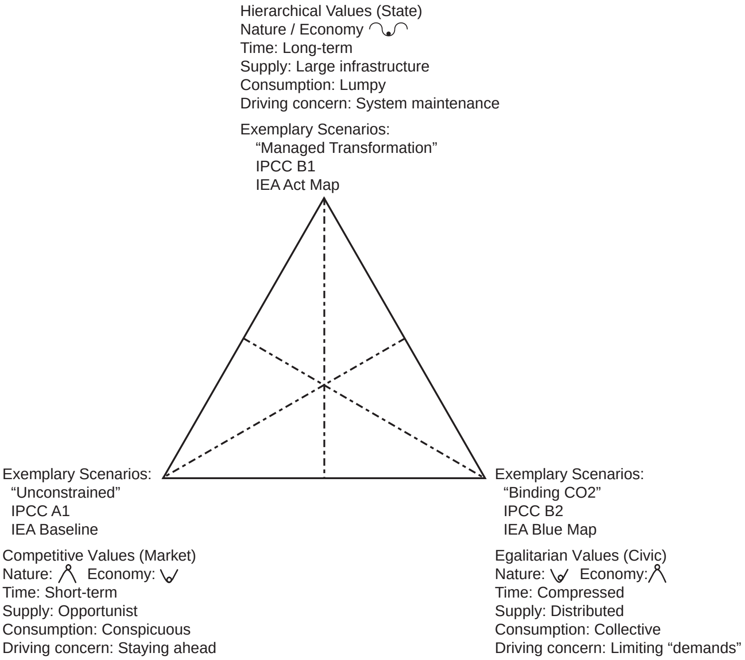

Figure 22.3 Scenario diagram.

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The average economic growth amounts to 3.3% per year in all IEA scenarios. Hence, GDP quadruples between 2005 and 2050. Demand for energy services is the same in all scenarios. There is no change in lifestyles, but the energy technology mix is radically different in each scenario. ETP explores different policy options concerning energy supply (e.g., nuclear, CO_2 capture and storage, renewables) and end-use efficiency.

The IEA Baseline is the laissez-faire scenario, characterized by increasing economic growth but slowing population growth after 2030 to reach a total world population of 9 billion in 2050. Automobile travel and freight transport increase more than threefold, and global CO_2 emissions increase by more than 130% above 2005 levels, even with enactment of all climate policies currently under consideration.

The IEA ACT scenario looks at policies to bring CO_2 emissions back to 2005 levels in 2050. This implies increased end-use efficiency and a virtually CO_2-free power sector with significant fuel switching.

The IEA BLUE scenario has the goal of halving CO_2 emissions by 2050. In addition to the options in the IEA ACT scenario, the BLUE scenario considers CO_2 capture and storage (CCS) in end-use sectors and reduced emissions from transport. Oil demand falls below current levels. With respect to specific technologies, the IEA BLUE scenario assumes 1250 GW maximum nuclear capacity, 18 thousand large wind turbines, 215 million m^2 of solar panels, nearly a billion electric or hydrogen fuel cell vehicles, and the provision of just over 19,000 TWh/yr through renewable power in 2050 (Figures 22.4–22.6).

Our approach has been to use an integrated social science framework in selecting these scenarios and then exploit a more traditional "stocks and flows" framework to understand the impacts on the energy system (see Figure 22.3).

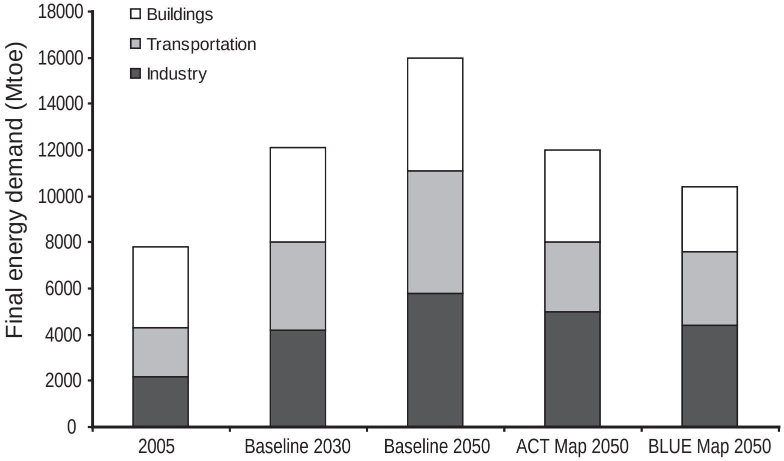

Figure 22.4 Final energy use by sector in the Baseline, ACT, and BLUE scenarios (IEA 2008g). Reprinted with permission.

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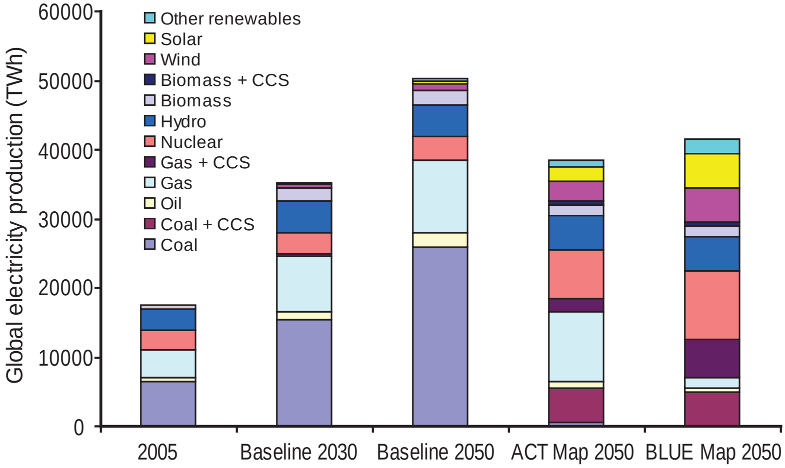

Figure 22.5 Annual global electricity production by fuel in the Baseline, ACT, and BLUE scenarios (IEA 2008g). Reprinted with permission.

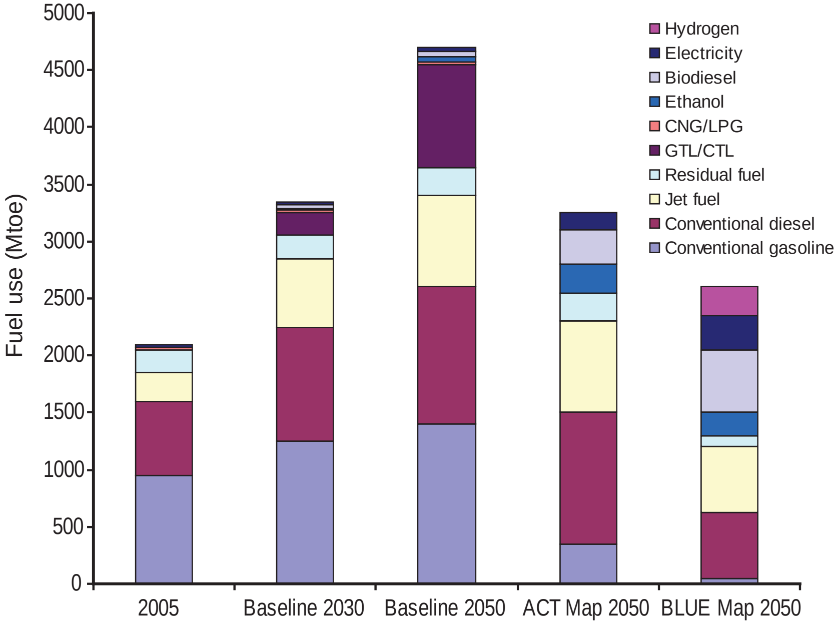

Figure 22.6 Transport energy use in the Baseline, ACT, and BLUE scenarios (IEA 2008g). Reprinted with permission.

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Measurement Framework

Before exemplifying this approach, we derive general equations for measuring sustainability. Sustainability specifies a relation between the "opportunities" available to current generations and those that are passed on to future generations. If we take energy resources, broadly defined, to be synonymous with energy opportunities, then each generation must pass on to the next an equal or greater endowment of energy resources (or the ability to provide energy services) in order for the energy system to be sustainable. This is a strong energy sustainability requirement, since it does not admit that other factors may be substituted for energy to produce an equivalent level of well-being. We will return to this issue shortly.

By "broadly defined," we do not mean energy resources measured simply in joules, but rather energy resources measured by their ability to be transformed into energy services that contribute to human well-being. This concept of sustainable energy cannot be reduced to a single equation. Nonetheless, equations are an invaluable tool for representing relationships between variables that can be measured. In that spirit, we seek to define the energy sustainability relationship between generations in mathematical form. To do this, it is useful to work at a high level of generality and abstraction, while bearing in mind that to be useful the equation must be applicable to specific, real energy resource estimates.

The difficulty in the parameterization is to define a basket or set of energy services to describe human well-being. The definition of human well-being will vary across cultures and time. Still, in economics, attempts have been undertaken to define a set of human activities and services to enable a comparison of "human well-being" between countries, the so-called *purchasing power parity*. Although by definition incomplete, the adaptation of a similar approach to determine and define a basket of energy services could provide an indicator for our exercise and proposed metric for the sustainability of the energy system.

Energy resources can be found in the form of *stocks of nonrenewable resources* that may be consumed over time (e.g., such as oil, coal, uranium, or natural gas) or in the form of *flows of renewable energy resources* (e.g., solar insolation, wind velocity, or mass of available biomass). Let the total quantity of energy resources from *stocks* at time t, measured in joules, be Q_t. There are many forms of energy resource *stocks* which must be treated individually. However, for the sake of simplicity, we assume that all forms of energy resource *stocks* can be measured in joules. Let e_t be the energy intensity of the conversion of energy resource *stocks* into energy services in time t, with units of joules per unit of energy service. The total amount of energy services available in the form of stocks is Q_t/e_t. Let the annual *flow* of energy in joules per year from all renewable sources be q_t and assume—although the conversion efficiency for renewables is in many cases much lower than for fossil

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fuels (e.g., solar to electricity is only 5–20%, geothermal 10–25% vs. gas or coal plans which range from 30–55%)—that renewable energy has the same conversion to service efficiency as energy stocks, e_t. It is important to note that neither Q_t nor q_t represent all the energy potentially available but rather those portions that are technically feasible and economically practical to produce given existing technological, economic, environmental, and social conditions.

The total stock of nonrenewable energy is Q_t/e_t, but what is the stock of renewable energy? We know that the total flow of renewable energy handed forward to future generations is $q_t/\mathrm{e}_\mathrm{t}$ per year, but how much nonrenewable energy is available each year? With these definitions, stocks and flows cannot be combined to obtain total energy resources; one is expressed in joules, the other in joules per year. One solution to this dilemma—converting fossil energy resources into a flow—can be deduced from the definition of sustainability. Let the use of fossil energy per year be g_t, then $N_t = Q_t/g_t$ is a measure of the number of years of fossil resources available relative to current use. Sustainability implies that the current generation should not leave the next generation with less energy relative to current use than it inherited. Finally, since the total needs of future generations may be expected to grow with population, P_t, it seems necessary that the endowment of energy resources should be expressed on a per capita basis.

The current per capita endowment of energy resources expressed as an annual flow of energy services is:

$$\frac{\left[\left(\frac{Q_0}{e_0}\right)\left(\frac{1}{N_0}\right)+\left(\frac{q_0}{e_0}\right)\right]}{P_0}. \tag{22.1}$$

The minimal endowment that must be left to future generations at time t is:

$$\frac{\left[\left(\frac{Q_t}{e_t}\right)\left(\frac{1}{N_0}\right)+\left(\frac{q_t}{e_t}\right)\right]}{P_t}. \tag{22.2}$$

Thus far we have addressed energy services. However, future generations may not use energy services to create human well-being in the same way that current generations do. For example, suppose that more efficient urban designs are created that allow access to opportunity with less mobility. Consumption in the future may favor less energy-intensive goods and services. Thus, we need one more term, namely the ratio between human well-being and energy services. Again, there are many forms of energy services, but for the sake of simplicity we represent only one composite energy service. Let k_t be the ratio of human well-being to energy service at time t. The equation for energy sustainability is, therefore,

$$\frac{k_t\left(\frac{1}{N_t}\frac{Q_t}{e_t}+\frac{q_t}{e_t}\right)}{P_t}\geq\frac{k_0\left(\frac{1}{N_0}\frac{Q_0}{e_0}+\frac{q_0}{e_0}\right)}{P_0}, \tag{22.3}$$

where Q_t = stock (joules) of *fossil* energy at time *t*,
g_t = flow of *fossil* energy at time *t* (joules/yr),
q_t = potential flow of *renewable* energy at time *t* (joules or TWh/yr),
e_t = energy intensity of conversion to energy service at time *t* (reciprocal of conversion efficiency),
P_t = population at time *t*,
k_t = ratio of human welfare ("well-being") to energy service to time *t*,
N_t = the number of years of fossil resources available relative to current use.

In its present form, however, the well-being coefficient conflates two potential policy mechanisms that ought to be separated: (a) the possibility of changing people's utility functions so that they get the same utility from a different level of energy service; and (b) the possibility of achieving a given level of utility by using nonenergy-service means. An example of the first is enlightening and educating people to consume less; examples of the second include using daylight instead of electric lighting, walking instead of driving, and passive solar heating instead of gas or electric heating. To separate changes in the utility functions from movements within utility functions, the sustainability equation is modified as follows. First, a term called *services from nonenergy sources*, which represents the provision of utility (happiness, welfare) by nonenergy substitutes for energy services, is added. This term is most conveniently expressed in terms of the amount of actual energy services (in joule) displaced, as a fraction of total actual energy services. Second, the well-being coefficient k_t is replaced with a constant-utility demand-modification term, which represents the possibility of achieving a given level of welfare with less total energy and nonenergy services. These new parameters might be expressed in terms of change with respect to the present or baseline situation. For convenience, we have assumed exponential growth. The equation for energy sustainability is then:

$$\frac{\exp^{k_d\cdot t}\left(\frac{1}{N_0}\cdot\frac{Q_t}{e_t}+\frac{q_t}{e_t}\right)\left(1+\hat{E}_0\cdot\exp^{k_{\hat{E}}\cdot t}\right)}{P_t}\geq\frac{\left(\frac{1}{N_0}\cdot\frac{Q_0}{e_0}+\frac{q_0}{e_0}\right)\left(1+\hat{E}_0\right)}{P_0} \tag{22.4}$$

where $\hat{E}_0$ = the joule-equivalent of services provided by nonenergy means at time *0*, as a fraction of total joules provided by energy services at time *0* (a reasonable value might be 10%),
k_d = the rate of change in constant-utility demand for energy-related services (pure demand changes), starting from time *0* (a reasonable

value might be between 0.02 and –0.02), and

$k_{\hat{E}}$ = the rate of change in the joule-equivalent of services provided by nonenergy means relative to total joules provided by energy services.

This equation states that the current generation must leave to the next one a sum of energy services produced from nonrenewable resources, scaled by their size relative to the current generation's relative rate of consumption of nonrenewable resources, plus energy services from renewable resources. The sum of the two must be translated into their ability to produce well-being that is just as great as that available to the current generation. This can be accomplished by (a) expanding nonrenewable resources (e.g., by inventing technology that increases recovery rates at equal or lower cost, energy levels, and environmental impacts), (b) expanding the flow of renewable energy that it is technically feasible, economically viable, and environmentally as well as socially acceptable to access, (c) reducing the constant-utility demand for energy-related services via demand modification, (d) increasing utility (happiness, welfare) by nonenergy substitutes for energy services, or, most likely, (e) combinations of all four. Thus, by this definition it is perfectly acceptable to "use up" nonrenewable resources provided that the potential flow of technically feasible, economically viable, and socially and environmentally acceptable renewable resources is sufficiently increased at the same time. It also asserts that changes in the relationship between the consumption of energy services and human well-being by future generations can increase or decrease energy sustainability, irrespective of actions by the current generation.

From an economic perspective, increased prices signal scarcity. It follows, therefore, that if current generations bequeath higher energy prices to future generations that this may also indicate unsustainability. Energy price indices can be constructed for energy and for energy services. While this is a useful exercise, since the early 1970s, energy prices have been highly volatile due principally to the actions of the OPEC cartel. This makes it difficult to distinguish long-term trends due to depletion or deterioration of energy resources from short-term fluctuations driven by monopoly behavior and energy market speculation. Thus, while it is essential, from a sustainability perspective, to monitor energy price trends, their correct interpretation will require distinguishing long-term technological and resource trends from short-term market manipulations. It is possible that one critical aspect in defining human well-being would be the reduction of uncertainty concerning future energy prices. Effectively reducing geopolitical tensions and their ensuing energy price uncertainties is one way for governments and policy makers to contribute to human well-being. Formulating effective policies to attain meaningful energy independence goals is another.

Price indices measuring the cost of energy and energy services should be calculated for both retrospective and prospective analyses. For example,

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Equation 22.5 is an energy flow-weighted price index, p_t, for primary energy. Nonrenewable energy resources are indexed $i = 1$ to n, while renewables are indexed $j = 1$ to m.

$$p_t = \frac{\sum_{i=1}^{n} g_{it} p_{it} + \sum_{j=1}^{m} q_{jt} p_{jt}}{\sum_{i=1}^{n} g_{it} + \sum_{j=1}^{m} q_{jt}}. \tag{22.5}$$

Equation 22.6, p_t^*, is an energy flow-weighted price index for energy services. The problems caused by energy price volatility have been noted above and will make interpretation of retrospective trends difficult. Prospective trends, although speculative, will be based on model output, which will almost certainly be more readily interpretable.

$$p_t^* = \frac{\sum_{i=1}^{n} \frac{1}{e_{it}} g_{it} p_{it} + \sum_{j=1}^{m} \frac{1}{e_{jt}} q_{jt} p_{jt}}{\sum_{i=1}^{n} \frac{1}{e_{it}} g_{it} + \sum_{j=1}^{m} \frac{1}{e_{jt}} q_{it}}. \tag{22.6}$$

Most energy services can, in principle, be produced from a variety of energy resources. This suggests using production functions to represent the creation of energy services, rather than simple energy efficiency coefficients. Instead of estimating the energy services produced from each energy resource, one would estimate an array of energy services produced from various energy resources. Under this approach, the total quantity of energy resources available would represent a constraint on the production functions. The first question is whether the energy resources left to future generations will enable them to produce greater or lesser energy services than the resources available to the current generation. The second, and more important question, is whether those energy services could lead to a greater or lesser quality of life. The production function approach, however, raises a number of additional issues which we cannot resolve here.

Exemplification

Using this framework, we can exemplify each part of the analysis. Contributions include current stocks and flows; retrospective stocks and flows; indices such as energy production and consumption per unit of GDP, and energy per human development index (HDI); and energy costs in terms of annual, energy weighted price of energy use (retrospective).

As the noted indices may be of limited utility, we are also looking for units of well-being. Specifically, what is needed are social welfare measures that

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relate energy resources to social welfare, taking into account constraints beyond CO_2; namely, land, water, and nonrenewable mineral resources (for the links between social welfare and sustainability, see Hamilton and Ruta 2006). We have developed an "Impact Matrix," which describes qualitatively the CO_2, air, land, water, and nonrenewable mineral resource impacts of energy supply and services specified in the three scenarios (Table 22.2).

We have identified three specific impacts to analyze in detail, which illustrate the approach to be used in converting this matrix to a quantitative form: land impacts from biofuel production, water impacts from biofuel production, and nonrenewable minerals impacts from fuel cell vehicle (FCV) production.

Land and Water Impacts from Biofuel Production

Per unit of energy produced, biofuels require orders of magnitude more land and water than do petroleum transportation fuels (King and Webber 2008; California Air Resources Board 2009). This raises the issue of whether there is enough land and freshwater available to sustain large-scale production of biofuels.

With estimates of the land and water requirements per unit of biofuel-cellulosic feedstock produced (Walsh et al. 2003; Lemus et al. 2002; Berndes 2002; Gerbens-Leenes et al. 2009), and of total available land and freshwater (Gleick 2009; FAO 2003 ; FAO 2009b), we can make rough estimates of the land and water requirements of the biofuel consumption levels projected by the IEA in its BLUE Map 2050 scenario, relative to available global resources. The

Table 22.2 Energy supply impact matrix. Examples of qualitative global impacts of elements of the IEA ETP scenarios on the world's environment and resource base (IEA 2008c).

Energy source/ service	Baseline		ACT Map		BLUE Map	
	Item A[a]	Item B[b]	Item A[c]	Item B[d]	Item A[e]	Item B[f]
Resource impact	H[g]	M	M[h]	L	M	
CO_2	H	L	M	L–M	L (~10%)	M[i]
Air	M	L	L	L	L	L
Land	M	M[j]	M	H	H[k]	L
Water	M	L	M	L–M	L	M[i]
Nonrenewable minerals	M	L	M–H	L	L	M/H[l]

(a) 70% + oil demand
(b) Nuclear power plants
(c) Carbon capture and sequestration
(d) Increased biofuels production (see below)
(e) Wind onshore (+1600 GW/yr over baseline)
(f) Deployment of FCVs in transportation
(g) e.g., tar sands, shale
(h) More coal extraction & conversion; 16% of power generation
(i) H_2 mainly from natural gas reforming
(j) U mining
(k) ~11 T hectares
(l) Pt for FCVs

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BLUE Map 2050 case, which has the highest level of biofuel consumption out of all the IEA scenarios, requires 6% of current global permanent pasture land, 16% of current global arable land, 6% of global renewable freshwater, 117% of current global water use by agriculture, and 82% of current total global water use.

It is useful to express the land and water requirements relative to the percent of energy demand satisfied by biofuels. For every 10% of the IEA-projected global ground transportation energy demand satisfied by cellulosic biofuels, the requirements are 2% of current global permanent pasture land, 6% of current global arable land, 2% of global renewable freshwater, 44% of current global water use by agriculture, and 31% of current total global water use.

Note that these percentages are calculated with respect to the current situation and do not reflect increases in demand for land and water in other sectors, particularly agriculture. Several studies project that total global water withdrawals could increase by more than 20% by 2025, leading to severe water stresses in several regions of the world (e.g., Seckler et al. 1999). However, even if future freshwater withdrawals for all uses other than biofuel feedstock production were to double by 2050, the addition of the water demand estimated for the IEA BLUE Map 2050 scenario still would result in a total water withdrawal of just under 20% of the total global renewable freshwater resource. Alcamo and Henrichs (2002) assume that when withdrawals are less than 20% of the available resource, there is low stress on water resources.

Thus, even though the land and water requirements of biofuels are very large with respect to both the requirements of current transportation energy systems and agricultural systems, at the *global* level there will be no obvious water and (pasture) land resource constraint on the development of bioenergy for several decades, unless the requirements of other sectors have been vastly underestimated. Water and arable land are not, however, distributed uniformly across the globe with respect to population or energy demand; thus, there can be severe constraints at the regional level on land and water availability. In parts of China, South Asia, West Asia, and Africa, current demands are already stressing water supplies, and this trend is expected to increase dramatically over the coming decades (Shah et al. 2000; Seckler et al. 1999; Serageldin 1995). Development of biofuel feedstocks in these areas could place intolerable stresses on water supplies.

Assuming that biofuels can be traded globally, the way petroleum fuels are, regional constraints on land and water need not impede the development of biofuels. FAO data (http://faostat.fao.org/faostat/) and the analysis of Berndes (2002) indicate that there are large regions of the world with ample land and water to produce biofuels: vast areas of North America, South America, Russia, Indonesia, and parts of Sub-Saharan Africa. If biofuel feedstocks can

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be grown in these resource-rich regions at reasonable cost and with minimal environmental impact,[4] and if future demands for land and water by other sectors do not dramatically exceed present expectations—issues not examined here—then biofuel production need not be constrained by the global availability of land and freshwater. (For a similar, more detailed analysis and conclusion, see Berndes 2002.)

Nonrenewable Minerals Impacts from FCV Production

It is clear that the production of millions of FCVs using platinum catalysts would increase demand for Pt substantially. Indeed, the production of 20 million 50-kW FCVs annually might require on the order of 250,000 kg of Pt—more than the total current world annual production of about 200,000 kg in 2008 (Yang 2009; USGS 2009, p. 123). How long this output can be sustained, and at what platinum prices, depends on at least three factors: (a) the technological, economic, and institutional ability of the major supply countries to respond to changes in demand; (b) the ratio of recoverable reserves to total production; and (c) the cost of recycling as a function of quantity recycled. Regarding the second factor, Spiegel (2004:364) writes that the International Platinum Association concludes that "there are sufficient available reserves to increase supplies by up to 5–6% per year for the next 50 years," but does not indicate what the impact on prices might be. Gordon et al. (2006:1213) estimate that 29 million kg of platinum group metals are available for future use, and state that "geologists consider it unlikely that significant new platinum resources will be found." This will sustain annual production of at least 20 million FCVs (with 12.5 g Pt per vehicle), plus production of conventional catalyst-equipped vehicles, plus all other current nonautomotive uses, for less than 100 years, without any recycling of Pt catalysts. Thus, the prospects for very long-term use and price behavior of platinum depend in large part on the prospects for recycling.

The prospects for economical recycling are difficult to quantify. In 1998, 10 metric tons of Pt were available from recycling automobile catalysts (USGS 1999). Carlson and Thijssen (2002) report that recycling of automotive catalysts is between only 10% and 20%, but they note that economic theory predicts that recycling will increase as demand increases. Spiegel (2004:360) states that "technology exists to profitably recover 90% of the platinum from catalytic converters," and in his own analysis of the impact of FCV platinum on world platinum production (but not price), he assumes that 98% of the Pt in FCVs will be recoverable. However, Gordon et al. (2006) assume that only 45% of the Pt in FCVs will be recovered. Our belief is that enough platinum

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[4] In this respect, note that the estimates of water requirements presented here *do* account, roughly, for the extra water needed to dilute polluted agricultural water to acceptable levels; for further discussion, see Dabrowski et al. (2009).

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will be recycled to supply a large FCV market, until new, less costly, more abundant catalysts or fuel cell technologies are found. Indeed, catalysts based on inexpensive, abundant materials may be available relatively soon. Lefèvre et al. (2009) report that a microporous carbon-supported iron-based catalyst is able to produce a current density equal to that of a platinum-based catalyst with 0.4 mg Pt/cm^2 at the cathode. They note, however, that further work is needed to improve the stability and other aspects of iron-based catalysts; still, this research suggests that a worldwide FCV market will not have to rely indefinitely on precious metal catalysts.

Summary and Recommendations

Perhaps the most challenging aspect of measuring sustainability is to develop an operational definition of sustainability itself. Our experience here suggests that the detailed definition of sustainability emerges out of the scenarios and from the unique perspective that each represents. Nonetheless, an overarching characteristic that reappeared throughout our discussions was that sustainability concerns itself with the assurance of the well-being of current and future generations. Our recognition and response to the constraints imposed by ourselves and natural systems combine to limit the range of strategies by which we might achieve a particular degree of well-being.

Effectively managing the inevitable transitions in resource utilization depends on our ability to measure critical system characteristics related to those constraints. This approach can lead to specific strategies for anticipating the need for developing social, economic, and technical mechanisms to manage these transitions. Our goal is to avoid catastrophic transitions. This requires us to understand the evolution of supply systems, demand for services, technology approaches, and the full life-cycle environmental impact on land, water, air and nonrenewable mineral resources. Perhaps, most critically, we must recognize the need to develop approaches that are resonant with the world views suggested by integrated social science. A failure to find the common ground that exists at the intersection of these diverse viewpoints will almost certainly lead to suboptimal or even counterproductive responses. The premise is that if we can see a transition on the horizon, then we can take steps to mitigate its impacts. These could include alternative investment strategies, particularly in R&D, moderating economic dislocations, avoiding suboptimal, short-term supply decisions, developing mechanisms to enhance the rate of energy intensity improvement, and provide more effective feedback on the consequences of our choices of energy services.

Our experience indicates that improvements are needed in many measurement domains, including data acquisition as well as cost and impact analysis. We recognize that there may be other resource systems (e.g., human resources) and other critical constraints (e.g., restrictions on access and geopolitical

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concerns) that need to be taken into account as well. Geopolitical concerns, for example, include energy security (Greene 2009). The foregoing analysis highlights both the high degree of complexity and uncertainty in analyzing energy system sustainability. One source of this complexity is that the constraints imposed within the various systems interact. For example, land use practices designed to produce fuels with a reduced CO_2 impact in the energy system can result in increased CO_2 impacts in the land resource system.

The following recommendations are intended to assist in developing more robust strategies that address this complexity, in an effort to reduce some of the uncertainty associated with specific constraints. This list is not exhaustive and will evolve over time as implementation is attempted:

- Complete the detailed evaluation of the impact matrix: this would help identify resource constraints in the domain bounded by the three scenarios.
- Examine the reciprocal impacts on energy resulting from resource use in land, water, and nonrenewable minerals: this would help identify energy resource and CO_2 (and air quality) constraints.
- Improve our understanding of how to measure the links between various energy services and well-being.
- Identify and elaborate additional resource linkages (e.g., human resources).
- Identify and elaborate additional constraint systems (e.g., access, geopolitical concerns).

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