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Measuring Energy Sustainability

David L. Greene

Abstract

For the purpose of measurement, energy sustainability is defined as ensuring that future generations have energy resources that enable them to achieve a level of well-being at least as good as that of the current generation. It is recognized that there are valid, more comprehensive understandings of sustainability and that energy sustainability as defined here is only meaningful when placed in a broader context. Still, measuring energy sustainability is important to society because the rates of consumption of some fossil resources are now substantial in relation to measures of ultimate resources, and because conflicts between fossil energy use and environmental sustainability are intensifying. Starting from the definition, an equation for energy sustainability is derived that reconciles renewable flows and nonrenewable stocks, includes the transformation of energy into energy services, incorporates technological change and, at least notionally, allows for changes in the relationship between energy services and societal well-being. Energy sustainability must be measured retrospectively as well as prospectively, and methods for doing each are discussed. Connections to the sustainability of other resources are also critical. The framework presented is merely a starting point; much remains to be done to make it operational.

Introduction

> Energy is the only universal currency: one of its many forms must be transformed to another in order for stars to shine, planets to rotate, plants to grow, and civilizations to evolve (Smil 1998:10).

As Solow (1992) has pointed out, "the duty imposed by sustainability is to bequeath to posterity not any particular thing," but to ensure that future generations have the opportunity to "achieve a standard of living at least as good as our own."[1] Solow's interpretation of sustainability differs from the seminal

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[1] This idea is borrowed from Sen (2000).

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statement by the Brundtland Commission (WCED 1987) in one key respect: The Brundtland definition requires that the current generation not diminish the ability of future generations to meet their "needs" rather than requiring that they be ensured the opportunity to achieve at least as good a standard of living. If needs are defined as only the most basic requisites for survival, then the two definitions are far apart. However, if a need is defined as, "a lack of something requisite, *desirable*, or useful" [emphasis added], as per Merriam-Webster's, then it is possible to argue that the two definitions intend the same meaning. The position taken in this chapter is that sustainability should be interpreted as ensuring that future generations have the opportunity to achieve a level of well-being[2] at least as good as that of the current generation. Our objective for energy is that of this Forum as a whole:

> To measure the stocks, rates of use, interconnections, and potential for change of critical resources on the planet, and to arrive at a synthesis of the scientific approaches to sustainability.

This is quite different from measuring energy for sustainable development, which has been addressed in depth elsewhere (e.g., Goldemberg and Johansson 2004). Sustainable development is concerned with simultaneously achieving economic growth, social progress, and environmental protection. Its objectives are most clearly articulated by the Millenium Development Goals enunciated by the Millenium Summit held in 2000 at the United Nations General Assembly. By comparison, our goals are more limited, yet extremely challenging.

By focusing on energy sustainability, we do not mean to imply that there are no opportunities to substitute other factors for energy in order to maintain or increase human well-being. However, energy is so fundamental to society that opportunities for substitution are limited. Most such opportunities arise from the fact that societies are not interested in using energy per se, but rather in the services that energy can provide.

> The objective of an energy system is to deliver to consumers the benefits that energy use offers. The term energy services is used to describe these benefits, which for households include illumination, cooked food, comfortable indoor temperatures, refrigeration, telecommunications, education and transportation (Goldemberg and Johansson 2004:25).

Sustainability is more about rates of change than it is about stocks. To measure energy sustainability, one must measure the extent, rate of use, and rate of creation and expansion of the ability to produce energy services and, ultimately, the ability of energy services to produce human well-being. Therefore, one must also measure the extent to which energy use affects environmental quality, security, water availability, mineral resource availability, food supply,

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[2] Webster's 11th Collegiate Dictionary defines well-being as "the state of being happy, healthy, or prosperous: WELFARE." The consensus of our discussion group at this Forum was that "well-being" is appropriately broader and more flexible than "standard of living" or "needs."

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and so on. It *is* possible to run out of resources. However, it is also possible to create new resources where there were none before. Moreover, resource creation is not only a matter of technological change; individual, economic, and institutional changes all have important roles.

Energy sustainability is not just about energy. It is also about the interrelationships between energy and other factors that affect human well-being. Humans' use of energy affects the environment, the supply of water, agriculture and food production, indeed every facet of society. Measuring the critical interrelationships is also necessary to measuring energy sustainability. In a report on scenarios of sustainable energy futures, the IEA (2003) identified two principal components of energy unsustainability: increasing greenhouse gas emissions and the security of energy supply. These are not the only sustainability issues linked to energy use. There are important linkages to water resources, agricultural land and natural habitats, as well as to minerals essential for catalysis and other critical uses.

In addition, energy sustainability must be measured retrospectively as well as prospectively. Sustainability is fundamentally about the future, about the obligation of current generations to future generations. However, the future is unknown. Löschel et al. (this volume) propose using scenario analyses to explore the sustainability of alternative future pathways. Identifying measures and estimating energy sustainability in alternative energy futures seems essential to formulating plans and strategies for achieving sustainability. Yet measuring sustainability in future scenarios is inherently speculative because scenarios, even if plausible, are inherently hypothetical. Retrospective analysis using equivalent measures provides a needed empirical test. We may be able to envision sustainable energy futures, but are we on a sustainable trajectory today? Have we been creating energy resources for future generations as fast as we are consuming stocks of energy resources? It seems essential to be able to measure both whether we have been sustainable in the recent past and whether we can envision a trajectory that could lead to a sustainable future.

Thirty five years ago, the book *Limits to Growth* had an important impact on how people thought about global society's relationship to the environment (Meadows et al. 1972). The book simulated many doomsday scenarios in which the world's economies either ran out of fundamental resources or polluted the environment so severely that it could no longer sustain human life on a large scale. The fact that none of the doomsday scenarios came to pass is often cited as proof that all such dire predictions will always be wrong. It is certainly true that the computer modeling on which the book was based underappreciated the roles of markets and innovation. However, *Limits to Growth* contained one very different scenario that is too often overlooked. In that scenario, rapid technological change, together with what may have seemed at the time to be draconian environmental regulation, permitted sustained growth of the global economy and population. Of course, it is precisely that scenario in which we live today. For example, thanks to innovation and regulation, today's automobiles emit 1% (or less) of the pollution than vehicles built over forty years ago. Pollution of air and water resources is now extensively regulated around the world, and international treaties protect certain key global resources, such as the stratospheric ozone layer.

Despite this remarkable progress, the world faces daunting environmental and resource challenges. Among these is providing sufficient energy for the world's growing economies without doing serious damage to the global climate system or inciting international conflicts over energy resources. Just as food is essential to living organisms, energy is essential to human society. Unlike food, which has been and continues to be a renewable resource, fossil energy has been a staple of human economies since the industrial revolution. For most of the past two centuries, the quantities of fossil energy resources extant in Earth's crust were vast in comparison to their rates of use by humans. Today, however, the rate of use of fossil resources is a matter of serious concern. In 1995, cumulative production of conventional petroleum amounted to 710 billion barrels,[3] a significant fraction of the World Petroleum Assessment (WPA-2000) of ultimately recoverable resources of 3 trillion barrels (USGS 2000). By 2005, cumulative consumption exceeded 1 trillion barrels (Figure 20.1). Approximately one-fourth of all oil consumed throughout human history had been consumed in the last ten years. While the USGS and Colin Campbell (2005) disagree about the measurement of ultimately recoverable oil resources, by either measure the current rate of consumption is large relative to what remains. Moreover, the rate of use has been accelerating. The US National Petroleum Council (NPC) estimated that if trends continued, another trillion barrels of oil would be used up in the twenty-five years from 2005–2030 (NPC 2007). By any standard, such a rate of consumption must be considered large in relation to what we know of conventional oil resources. It is only prudent to ask whether such a rate is sustainable.

Yet, energy sustainability is not about running out of energy. As Holdren (2000) points out, the world is not in imminent danger of running out of energy altogether. However, the world's use of energy is running into conflicts with other things we value: environmental protection, economic growth, and equity, especially equity of access to energy, which affects equity of opportunity. This brings us back to Solow's definition. Energy sustainability is about ensuring that we leave future generations with an equal opportunity to use energy services to provide for their well-being. It seems likely that this will require an enormous amount of energy. What energy resources can provide the energy services needed in ways that maintain or enhance the sustainability of Earth's other critical resources?

To make progress in measuring the sustainability of energy resources, it is important to avoid unnecessary semantic confusion. The discourse must not be

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[3] Customarily, industrial convention quantifies oil in terms of barrels, where 1 barrel of crude oil = 0.15853 kilo liters; billions = one thousand million, or 10^9.

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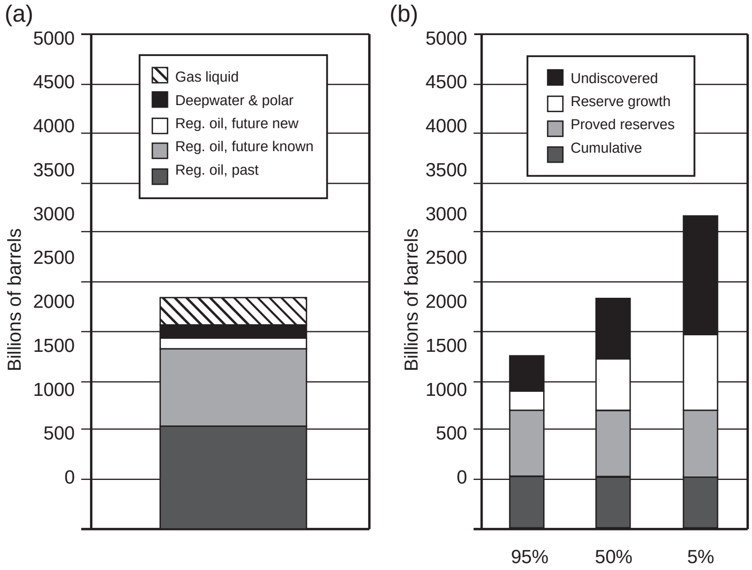

Figure 20.1 Alternative estimates of world ultimate resources of conventional oil. (a) Estimated petroleum production until 2100 (Colin Campbell, 26.09.2005). (b) Estimated conventional oil and natural gas liquid reserves until 2030 (USGS 2000).

allowed to degenerate into a debate over whether we are running out of energy or whether seemingly infinite capacities of human ingenuity and human institutions will always find alternatives. The view that we must inevitably run out of apparently finite resources runs counter to human history, which is full of examples of increased knowledge and innovation overcoming apparent limitations. Nevertheless, the assertion that because solutions seem always to have been found in the past they will always be found in the future can too easily lead to complacency. We may fail to anticipate, plan, regulate, and research; that is, we may fail to do the very things that have often led to acceptable solutions in the past.

Measuring the sustainability of energy resources *is* about measuring whether we are expanding or creating energy resources fast enough to be confident that we are not reducing the opportunities for future generations to achieve a level of well-being at least as good as our own. This requires measuring the extent of energy resource stocks, measuring their rates of use, measuring the rates at which existing resources are being expanded and new resources are being created, measuring our ability to transform energy into energy services, and, perhaps most difficult of all, measuring the ability of energy services to contribute to human well-being. This chapter considers how progress might begin to be made toward an integrated measurement of the energy sustainability of human society.

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Starting with the Basics: What to Measure?

Global energy resources comprise both stocks and flows. Stocks of energy exist in the form of potential chemical and atomic energy in fossil resources.[4] Flows exist, for example, in the form of insolation, winds, tides, and hydro and geothermal energy. Finding a way to measure both stocks and flows in comparable units constitutes the first major challenge.

In any case, it is not enough to measure energy stocks and flows. What defines an energy resource is its ability to be transformed into an energy service. Energy services created by energy use, rather than simply energy use per se, contribute to human well-being. The value to future generations of a particular physical energy resource, such as a ton of coal, is proportional to the efficiency with which it can be transformed into an energy service, such as lighting. Therefore, it is not enough to measure energy resources. We must also measure the rate at which they can be transformed into energy services; that is, we must measure energy efficiency.

In this volume, Worrell points out that improvements in energy efficiency allow less energy to be converted to more energy services, thereby effectively expanding the utility of existing energy resources to society. In addition, as Wilbanks (this volume) demonstrates, the use of energy is interdependent with other key resources necessary for human well-being. For example, burning fossil fuels produces greenhouse gases and other environmental pollutants. Substituting biomass for fossil energy at a scale meaningful to the global energy supply competes with the global food supply.

As Worrell points out, methods of decomposition analysis, such as divisia, can be used to measure trends in energy use and related human activities. In general, the ratio of energy to gross domestic product has been declining over time as energy efficiencies improve and as economies shift from more to less energy-intensive activities (Figure 20.2). These measures of energy intensity illustrate how physical measures of energy resources could be rescaled over time to better reflect their ability to provide for the needs of future generations.

In many ways, GDP is an inadequate measure of human well-being, in that it omits such fundamentally important factors as environmental services. Fortunately, more comprehensive GDP measures have been developed and could be applied just as readily for measuring the sustainability of energy resources. For example, Goldemberg and Johansson (2004) have shown how the human development index (HDI) relates to per-capita energy use in a very nonlinear way; wealthy people use more energy per income (Figure 20.3). While energy use generally increases with increasing income, the HDI indicates that equal levels of well-being can be achieved with very different levels of energy use, especially for the world's wealthier economies. How societies

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[4] Here I arguably include uranium among fossil resources despite its very different origin from hydrocarbon fossil fuels.

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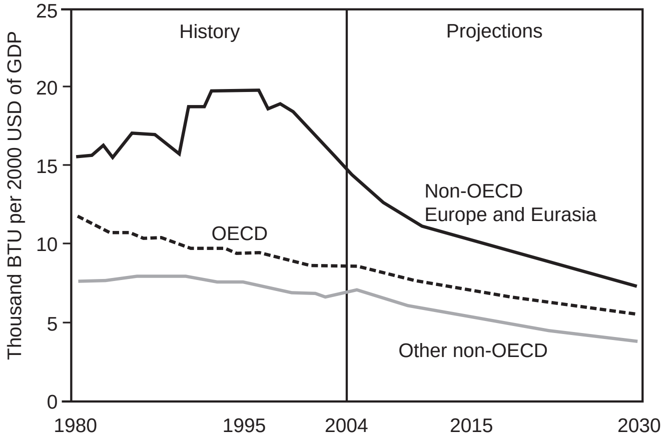

Figure 20.2 Trends in energy intensity of GDP by region (after Fig. 24 in EIA 2007). Note: 1 BTU = 1055.05585262 joules.

organize themselves, what they choose to consume, and what they choose to value can have at least as great an impact on human welfare as their use of energy. Unfortunately, not all unintended interdependencies of energy use can be analyzed in such a straightforward way.

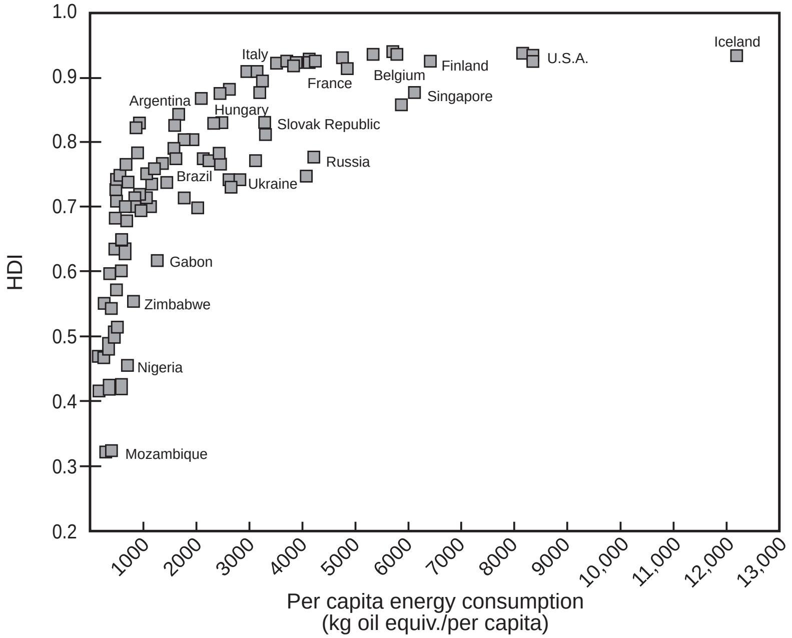

Figure 20.3 Relationship between human development index (HDI) and per-capita energy use 1999/2000 (Goldemberg and Johansson 2004).

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Stocks: Measuring the Resource Endowment

Gautier et al. (this volume) review what is known about the stocks of energy resources, comprising all potentially recoverable fossil energy, including coal, conventional oil and natural gas, unconventional oil (e.g., tar sands, oil shale, and extra heavy oil), unconventional natural gas (e.g., in shale, tight sands, geo-pressurized aquifers, and coal beds) (Nakićenović et al. 1998). Energy stocks also include uranium for producing nuclear energy. Renewable energy sources are part of the resource base but are more appropriately characterized as flows. Energy stocks are not constant but constantly changing.

> Therefore, petroleum resources are periodically reassessed, not just because new data become available and better geologic models are developed, but also because many non-geologic factors such as technological advances, accessibility to markets, and geographic or societal constraints determine which part of the crustal abundance of petroleum will be economic and acceptable throughout some foreseeable future (Ahlbrandt et al. 2005:5).

Stocks of energy resources are not a fixed number, but are perpetually changing as technology and economics redefine resources. Geologists have developed the concept of the resource pyramid as a way of illustrating how the quantity of resources relates to their physical properties, cost of extraction, and extent (Figure 20.4). The highest quality and most easily accessible energy resources are extracted first because their costs are lowest. However, lower quality, more costly resources are generally more plentiful. As technology progresses and energy prices rise, the more costly resources become economical. Geologists and energy resource specialists have also developed standardized approaches to measuring and reporting energy resource stocks according to the economics of their extraction and the certainty with which their extent is known (e.g., Rogner 1997). Of course, there are important issues concerning the consistency with which these methods are applied and their accuracy. Solow's definition of sustainability, cited above, implicitly requires that not only the quantity of

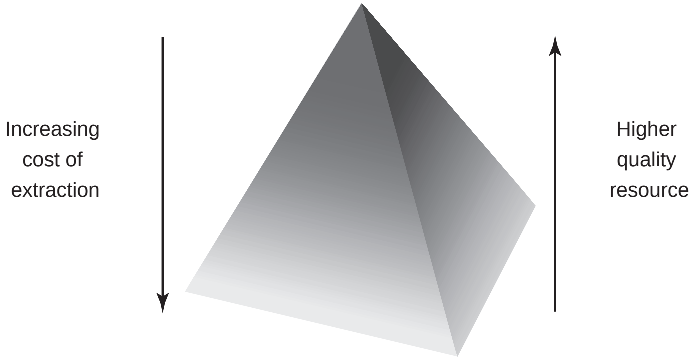

Figure 20.4 The resource pyramid (after McCabe 2007).

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energy resources but their costs be measured. While existing approaches take cost into account, they do so in a very approximate way. It seems likely that a more rigorous treatment of costs will eventually be needed for measuring the sustainability of energy resources.

Measurement of the extent of current energy resources is hindered by incomplete knowledge of the physical world, lack of agreement on or adherence to consistent definitions of energy resources, the difficulty of predicting future economic conditions, and the relative novelty of measuring resource expansion (USGS reserve expansion, EIA Canadian Oil Sands redefinition) and even more so creation. Still, geologists and other scientists and engineers have made significant advances in refining definitions and the methodologies of their estimates, such that existing data are reasonably adequate to assess sustainability (WEC 2007a). Much more is known today about the structure and composition of Earth's crust than 50 or 100 years ago thanks to more extensive exploration and the application of advanced techniques, such as 3D seismic imaging, for exploring Earth's crust.

Over one hundred estimates of the world's ultimate resources of conventional petroleum and natural gas made over the last half century and collected by Ahlbrandt et al. (2005) are shown in Figure 20.5. Note that three of the more recent estimates include unconventional resources, such as oil shale or tight gas formations. Over the first thirty years there is a clear upward trend in the estimates. The 1980s showed a strong downward revision, which has been followed by a less pronounced upward trend.

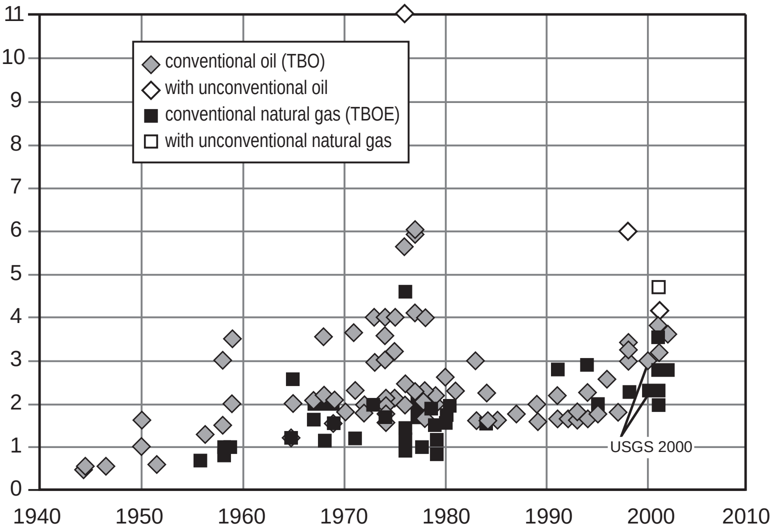

Figure 20.5 Various estimates of the world's ultimately recoverable conventional oil resources (after Ahlbrandt et al. 2005).

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No energy resource is measured perfectly. For example, the quantity of conventional petroleum resources is intensely debated and even the WPA-2000 assessment recognized a range of uncertainty of ±50% of the mean estimate as a 90% confidence interval (USGS 2000; Ahlbrandt et al. 2005). Still, nearly all of the world's energy resources have been measured well enough to support an initial retrospective assessment of sustainability.

Measuring Energy Resource Expansion and Creation

Energy resources are not only fungible but can be expanded and even created. Recent estimates of fossil energy stocks, such as the WPA-2000 estimates of global petroleum resources, attempt to quantify yet-to-be-discovered resources, as well as the likely expansion of known deposits as they are exploited. In the WPA-2000 estimate of the world's ultimately recoverable resources, remaining proved reserves, reserve growth and undiscovered resources are all comparable in size, as shown in Table 20.1.

> Undiscovered conventional petroleum resources, the first component of the USGS (2000), were assessed on the basis of geology and exploration and discovery history (Ahlbrandt et al. 2005:5).

Reserve growth is estimated by statistical methods calibrated to experience with fields whose history of development is well documented and then extrapolated to the rest of the world (Klett 2005). Critics argue that this method is flawed because of inconsistent definitions of proved reserves in different countries, especially members of OPEC (Bentley 2002). They argue that if one uses petroleum geologists' original estimates of proved plus probable reserves, reserve growth is negligible. Proponents of the method counter that recent experience since the method was first applied show that, if anything, their estimates have been conservative. Clearly, this is an area in need of additional research and better data, especially from OPEC states.

The WPA-2000 assessment also explicitly measured uncertainty, providing 95th, 50th and 5th percentile estimates in addition to mean estimates (Table 20.1). Some of the uncertainty is a consequence of lack of knowledge about what lies beneath Earth's surface, and some is due to uncertainty about future technology and economic conditions. Expansion and creation of other fossil resources have been less thoroughly studied but enough useful information exists to make a start in measuring sustainability, as Gautier et al. (this volume) demonstrate.

In addition, energy resources can be created when technological advances reduce the cost of using renewable resources. Technological advances and learning-by-doing have significantly reduced the costs of solar photovoltaics, biofuels (especially from sugarcane), and wind energy over the past two or three decades (e.g., Goldemberg and Johansson 2004:51). In 2007, geothermal,

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Table 20.1 WPA-2000 estimates of ultimate world oil resources recoverable by 2025 (USGS 2000; Ahlbrandt et al. 2005).

	Oil (billion barrels)			
	95th	50th	5th	Mean
Undiscovered	400	700	1211	732
Reserve growth	192	612	1031	688
Remaining reserves				891
Cumulative production				710
Total				3021

wind, and solar energy accounted for only about 1.5% of global electricity generation, but their rates of growth are among the highest of all forms of energy (BP 2008). Measuring the expansion of economical renewable energy is a major challenge for measuring energy sustainability.

Flows: Measuring Energy Resource Use

Energy flows (i.e., the rates of use of energy resources) are perhaps the best measured component of the sustainability equation. This is not to say that there is no room for improvement. The International Energy Agency, which was established during the first oil crisis of 1973–1974 by OECD nations to share information, coordinate energy policies, and harmonize the use of petroleum stockpiles, has made major contributions to measuring energy flows in the global economy (e.g., IEA 2008a, b). The United Nations (2008) has also been measuring global energy use and selected environmental impacts for decades.

While such factors as the total quantity of solar radiation reaching Earth's surfaces are well understood, what fraction of this energy can be feasibly exploited for producing energy services is less well known. The total quantity of solar energy intercepted by Earth is on the order of 10,000 times the total energy use by human beings (Nakićenović et al. 1998:55). Though far smaller, wind energy resources are also very large relative to global energy use. The question is how much of the enormous quantities of renewable energy resources are economically, technologically, and socially useful? Not only are there questions of economics and the performance of technologies but also issues about site selection and integration with the rest of the energy system. Solar energy is inherently intermittent on a diurnal cycle. Wind energy is also intermittent to a greater or lesser extent depending on location. Biomass energy production can be affected by weather and changing climatic conditions, and must also be integrated with the global agricultural system in a sustainable way. To address these difficult questions, the IPCC (2008b) has approved a study of global renewable energy resources that will be a valuable new source of data for measuring the sustainability of the world's energy system.

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Measuring Linkages

The scale of energy use by humans is so large that it has far-reaching impacts on every aspect of the environment and on every area of human activity. Fossil fuel combustion emits the precursors of ozone pollution, particulates, acid rain, and toxic chemicals. Exploration, development, transformation, transport, and storage of fossil fuels have some degree of negative impact on the environment. Nuclear energy creates radioactive wastes that given current technology must be safely stored for tens of thousands of years. Even renewable fuels are not free from unintended environmental consequences and will impose significant demands on water resources and arable land (Fargione et al. 2008). New energy conversion technologies (e.g., fuel cells) will demand significant quantities of mineral resources. Fortunately, measurement of these consequences has been a subject of serious research and analysis for over forty years. Inventories of pollutant emissions from energy use are far from perfect but useful, meaningful data for measuring and monitoring the impact of energy use on the environment are available in nearly every area.

The IPCC (2006) has developed comprehensive methods for nations to use in measuring their emissions of greenhouse gases due to energy use. Rigorous models have been developed for assessing well-to-end use emissions due to energy use (e.g., Delucchi 2003; Burnham et al. 2006) but substantial methodological challenges remain. For example, there is presently a very serious controversy over the full greenhouse gas impacts of biofuels (e.g., Fargione et al. 2008).

The complexity of linkages between critical resources is potentially enormous. If the energy (and other resource sectors) were represented by matrices with resource types comprising the rows and energy processes the columns, then every cell in the matrix would be potentially linked to every other cell (see Figure 25.2, this volume). The key is to identify the important linkages, the linkages that are likely to pose sustainability issues for the entire system. The task of doing so will be most difficult for prospective sustainability analysis. Several of these are explored by Löschel et al. (this volume), who illustrate that the linkages can be made, albeit imperfectly.

Measuring Energy Security

Upon first glance, energy security may not appear to be an issue of sustainability. Yet the security of energy supplies has important implications for the well-being of future generations, both in terms of the cost of energy and the potential for conflicts over access to energy.

> *Longer term risks to energy security are also set to grow….*OPEC's global market share increases in all scenarios….The greater the increase in the call on oil and gas from these regions, the more likely it will be that they will seek to extract

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> a higher rent from their exports and to impose higher prices in the longer term by deferring investment and constraining production. Higher prices would be especially burdensome for developing countries still seeking to protect their consumers through subsidies (IEA 2007:49).

Measuring energy security is by no means a simple task. The meaning of energy security differs from nation to nation. Greene (2009) recommends measuring U.S. energy security in terms of the economic costs of oil dependence, arguing that the actual and potential economic costs are the core problem and that national security concerns which have led to conflicts in the past are derivative of the threat of dire economic consequences. This approach might be appropriate for the United States at present, but it is not universally applicable. Other nations might be more concerned about the security of natural gas supplies, while others worry about the security of their electricity grid. It may be that energy security is too parochial a concern to be rigorously addressed in an assessment of global energy sustainability. Yet bequeathing future generations a world with greater conflicts over energy seems inconsistent with a mandate of sustainability.

Measuring Energy Equity

Sustainability is inherently about equity. Its essence is an assertion about equity across generations. There is no escaping this fact, yet it appears to raise difficult questions for scientific measurement. If sustainability asserts a requirement for intergenerational equity, can it ignore intragenerational equity? The UN estimates that more than two billion people do not have access to affordable energy services today (Goldemberg and Johansson 2004:11). Is it possible to assert a moral imperative about the just treatment of future generations, human beings who do not yet exist, but deny the same moral imperative applied to existing human beings? The question is not rhetorical. If sustainability is strictly about preserving the species in a biological sense, then the concept might not have intragenerational implications. However, if the concept is to be interpreted in a consistent ethical framework, then it must incorporate intragenerational considerations.

If one accepts that the same moral imperative must apply to the current generation, then one must include within the concept of sustainability at least the necessity of ensuring that the current society is not diminishing the ability of any of its members to meet their needs and, more likely, the imperative to strive to raise the standard of living of its less fortunate members to an appropriate level (i.e., to ensure the opportunity to achieve an acceptable level of well-being). Although this chapter will not attempt to address energy equity in a meaningful way, others have done so in the context of sustainable development, and the urgency and importance of the issue must be stressed (e.g., Goldemberg and Johansson 2004).

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Energy Substitutability and Integrated Assessment

Energy resources are more or less substitutable, which means that assessments of energy sustainability must integrate across different forms of energy. It may, for example, be sustainable to be using up coal resources faster than new coal resources are being discovered or existing exploitable resources expanded when the cost and practicality of solar energy is improving. Thus, while it is essential to know whether petroleum production is nearing a peak, truly useful conclusions about sustainability can only be drawn when an integrated assessment determines whether the net effect is to reduce or expand the energy services available to future generations.

Forms of energy are not perfectly substitutable, however. Problems can arise when large quantities of energy must be stored to meet patterns of demand or because forms of energy have very different properties (Nakićenović et al. 1998). This is especially the case with some forms of renewable energy, such as solar or wind. Substitution of other forms of energy for petroleum in the transportation sector has so far proven to be difficult, and successes are few and far between. For example, electricity, coal, and natural gas are not yet useful to power commercial air transport, which continues to rely on high energy density, easily stored distillate fuel. However, the chemical processes for making distillate fuel from coal, oil shale, natural gas, and even biomass are well known. These resources could be considered substitutes for petroleum when the conversion processes are economical.

Over time, human societies have increasingly demanded higher forms of energy, such as fossil fuels with higher hydrogen contents and electricity. Grübler (2007) points out that in general, such energy transitions are driven by technology changing the nature of demand for energy services. The internal combustion engine largely created the market for petroleum, and inventions such as the light bulb, electric motor, radio, and computer created the market for electricity. Measuring sustainability does not require that such changes be accurately predicted. It does require, however, that sustainable pathways be envisioned and analyzed and that past changes be observed and measured.

Retrospective and Prospective Sustainability

It appears that sustainability must be measured both retrospectively and prospectively. At the outset of this chapter, sustainability was defined as a steady state: creating and expanding energy resources as fast as they are used up. Such assessments must out of necessity be made retrospectively. Resources were later defined in terms of their ability to produce energy services, so that sustainability subsumed energy efficiency. Interactions with other determinants of human well-being were added to the equation, so that the sustainability of energy resources included more broadly the maintenance or improvement of

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well-being. The steady-state concept of sustainability is strictly consistent with the Brundtland Commission's definition, yet prudent behavior requires anticipating and planning. Thus, sustainability in practice will require assessing the future. Predictive modeling can play a useful role, but predictive modeling is most often based on an extrapolation of past trends (i.e., business as usual). If business as usual does not appear to be sustainable, alternative futures must be envisioned and analyzed via scenario analysis. It is for this reason that sustainability must be measured prospectively, as well as retrospectively.

How Can We Make Progress?

Energy is so fundamental to and so pervasive in modern human society that the full ramifications of energy sustainability are complex in the extreme. To begin by measuring in a completely satisfactory way all aspects of energy sustainability seems too daunting a task. In his contribution to this volume, Rayner concludes with the admonishment that what is worth doing is worth doing badly. In this spirit, let us begin with an approach that is undoubtedly too simple and work to improve it. Let us consider measuring rigorously the following key factors:

1. Quantities of energy resources, by type.
2. Rates of use of energy resources, by type and end use.
3. Efficiencies with which energy resources are converted into energy services by type and end use.
4. Rates of expansion and creation of energy resources.
5. Rates of change in energy efficiency.
6. Market costs and full social costs of energy services.
7. Key linkages between the energy system and other critical global resources.

Given the present state of knowledge, it should be possible to make an initial assessment of the sustainability of the world's energy system. Over the last forty years, substantial progress has been made in measuring all of these factors.

There is sufficient international data to attempt a retrospective evaluation of the ability of energy stocks to provide energy services, as described very generally by Equation 20.1, below, in which Q represents a stock of energy resources measured in joules (or other comparable units), i indexes forms of energy resource stocks, j indexes energy end uses, t indexes time periods, e is energy intensity (energy per unit of energy service, potentially measured in monetary units), σ represents the share of energy form i going to end use j. The inequality in Equation 20.1 can be satisfied if the quantity of newly discovered energy stocks or the expansion of energy stocks due to technological advances between time t and the previous time period exceeds consumption. It can also be satisfied by decreasing energy intensities or shifting energy resources to

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produce less energy intensive energy services. Time periods might be 5 or 10 years long in order to allow time for meaningful changes to occur and for data to be updated.

$$\sum_{i=1}^{N} Q_{it-1} \sum_{j=1}^{M} \frac{\sigma_{ijt-1}}{e_{ijt-1}} \le \sum_{i=1}^{N} Q_{it} \sum_{j=1}^{M} \frac{\sigma_{ijt}}{e_{ijt}}. \qquad (20.1)$$

In Equation 20.1, the quantities of energy resources would be assessed as they have been traditionally, based on a criterion of economic recoverability. Equation 20.1 accounts only for energy resource stocks and not energy resource flows in the form of renewable energy. A more complete formulation is suggested below.

From the above discussion it should be obvious that the concept of sustainable energy cannot be reduced to a single equation. Yet for representing relationships between variables that can be measured, equations are often an invaluable tool. In that spirit, we attempt 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 capable of application to specific real energy resource estimates.

Energy resources can be found in the form of stocks that may be consumed over time, such as oil, coal, uranium, or natural gas occurrences, or in the form of flows of renewable energy, such as insolation, wind, biomass, or geothermal energy. Let the total quantity of energy resources from stocks at time t, measured in joules, be Q_t. In reality, and as shown in Equation 20.1, there are many forms of energy resources which must be treated individually. However, for the sake of simplicity of exposition, let us assume that all forms of energy resources can be measured in joules. Let e_t be the energy intensity of the conversion of energy resources into energy services in time t, with units of joules per unit of energy service. Again, to simplify the exposition, a single energy intensity is assumed. The total amount of energy services available in the form of stocks is Q_t/e_t. Let the annual flow of energy from all renewable sources be q_t and, again for the sake of simplicity of exposition, assume that renewable energy has the same conversion efficiency as energy stocks, e_t. Neither Q_t nor q_t represent all of the energy potentially available, but rather those portions that are technically feasible and economically practical to produce given current technological, economic, and social conditions.

The total flow of renewable energy handed forward to future generations is q_t/e_t per year, but how much nonrenewable energy is available each year? It appears that stocks and flows cannot be directly added together to obtain total energy resources; one is joules, the other joules per year. A solution to this dilemma 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 quantity of resources available relative to current use. Sustainability implies that the

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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 the growth of population, P_t, it seems necessary that the endowment of energy resources should be expressed on a per-capita basis.

The current ($t = 0$) per-capita endowment of energy resources, expressed as an annual flow of energy services, is given as:

$$\frac{\left[\left(\frac{Q_0}{e_0}\right)\left(\frac{1}{N_0}\right)+\left(\frac{q_0}{e_0}\right)\right]}{P_0}. \tag{20.2}$$

The minimal endowment that must be left to future generations at time t is shown by Equation 20.3. N_0 rather than N_t is used so that energy stocks are converted into flows using the current generation's rather than the future generation's relative rate of use. This ensures that future generations are entitled to use energy stocks at a rate at least equal to the rate at which current generations use them.

$$\frac{\left[\left(\frac{Q_t}{e_t}\right)\left(\frac{1}{N_0}\right)+\left(\frac{q_t}{e_t}\right)\right]}{P_t}. \tag{20.3}$$

Thus far we have addressed energy services. However, future generations may not use energy services to create well-being in the same ways that current generations do.[5] For example, suppose that more efficient urban designs are created that allow equal or improved access to opportunities with less mobility. Consumption in the future may well favor less energy-intensive goods and services. Thus, we need one more term, namely the ratio between human well-being and energy services. Let k_t be the ratio of human well-being to energy service in time t. The basic equation for energy sustainability then becomes:

$$\frac{k_t\left[\left(\frac{Q_t}{e_t}\right)\left(\frac{1}{N_0}\right)+\frac{q_t}{e_t}\right]}{P_t} \geq \frac{k_0\left[\left(\frac{Q_0}{e_0}\right)\left(\frac{1}{N_0}\right)+\frac{q_0}{e_0}\right]}{P_0}. \tag{20.4}$$

Equation 20.4 states that the current generation must leave to the next 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 that is at least as great as what it had. Further, the sum of the two must be translated into their ability to produce well-being that is at least as good as that of the current generation. This could be accomplished by expanding nonrenewable resources or

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[5] I am grateful to Mark Delucchi for suggesting this addition.

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by expanding the flow of renewable energy. By this definition it is perfectly acceptable to “use up” nonrenewable resources provided that the potential flow of technically feasible, economically practical and socially acceptable renewable resources is sufficiently increased at the same time. Equation 20.4 can be expanded to recognize different forms of energy, as in Equation 20.5 where *i* indexes nonrenewable forms and j renewable forms.

$$\frac{k_t\left(\sum_{i=1}^{n}\frac{1}{N_{i0}}\frac{Q_{it}}{e_{it}}+\sum_{j=1}^{m}\frac{q_{jt}}{e_{jt}}\right)}{P_t}\geq\frac{k_0\left(\sum_{i=1}^{n}\frac{1}{N_{i0}}\frac{Q_{i0}}{e_{i0}}+\sum\frac{q_{j0}}{e_{j0}}\right)}{P_0}. \qquad (20.5)$$

However, different energy services can 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. In fact, this will almost certainly best be accomplished using energy models similar to the MARKAL model (IEA 2008d). Rather than estimating the energy services produced from each energy resource, one would estimate the energy services producible from different quantities of energy resources.

From an economic perspective, increased prices signal scarcity. It follows, therefore, that if current generations bequeath higher energy prices to future generations, this, too, may indicate unsustainability. Energy price indices can be constructed for energy (Equation 20.6a) and for energy services (Equation 20.6b). Let p_{it} be the price of energy type *i* (or *j*, if renewable) in time *t*, and let g_{it} be the use of nonrenewable energy. The simplest energy price index would take the form:

$$p_t=\frac{\sum_{i=1}^{n}g_{it}p_{it}+\sum_{j=1}^{m}q_{jt}p_{jt}}{\sum_{i=1}^{n}g_{it}+\sum_{j=1}^{m}q_{it}}, \qquad (20.6a)$$

$$p_t=\frac{\sum_{i=1}^{n}\frac{1}{e_{it}}g_{it}p_{it}+\sum_{j=1}^{m}\frac{1}{e_{jt}}q_{jt}p_{jt}}{\sum_{i=1}^{n}\frac{1}{e_{it}}g_{it}+\sum_{j=1}^{m}\frac{1}{e_{jt}}q_{it}}. \qquad (20.6b)$$

Ideally, one would estimate the quantity of energy services available to future generations at the same cost as the current generation must pay. This would imply holding the economic criterion for defining an energy resource constant at a certain price per joule. It is unlikely that the agencies with responsibility for quantifying energy resources will adopt this practice so precisely. More likely, these agencies will continue to use fuzzy economic criteria for defining energy resources. Therefore, it will probably be necessary to monitor separately the

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cost of energy resources, both private and social. In this regard, it might be useful to begin by dividing the full costs of energy use into direct economic costs and external costs and to measure the two separately. Serious studies of the full social costs of energy use have been undertaken in Europe (EC 1995) and North America (ORNL 1992–1998), and a new study by the U.S. National Academy of Sciences is just beginning. However, to date, the assessments have been characterized by a high degree of uncertainty and complexity.

Linkages must also be quantified. As an initial starting point, one can estimate the greenhouse gas emissions from energy use, the demands of bioenergy production on land resources, the water requirements of the energy system, and the consumption of critical mineral resources, such as platinum. This would increase the probability for successful measurement, albeit for a limited set of factors. Given the widespread recognition of climate change as the principal unresolved environmental challenge facing the global energy system, and the availability of data to describe the relationships between energy and greenhouse gas emissions, this would seem like a promising strategy for beginning the measurement of the sustainability of the global energy system.

Measuring energy sustainability is a daunting task. It is also one that must be attempted in order for current generations to act responsibly toward their descendants. Fortunately, much valuable work has already been done in collecting necessary data and constructing useful analytical frameworks. Even if we must begin by measuring energy sustainability badly, it seems clear that we can and must begin.

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