1

The Energy System

> Normative economics and the art of economics … cannot be independent of positive economics. Any policy conclusion necessarily rests on a prediction about the consequences of doing one thing rather than another, a prediction that must be based—implicitly or explicitly—on positive economics.
>
> —Milton Friedman (1966)[1]

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This chapter asks basic questions about why and how the exploration of the energy system is important. Having a clear sense of the answers to these questions will help guide this exploration, even as the discoveries along the way continue to raise more varied and interesting questions.

As this book is grounded in the concept of systems, defining precisely what is meant by a system and how it works is important. Conceptualizing how a system transforms something, in this case energy, as it moves through the system helps to create a dynamic platform for understanding the motivations of and opportunities available to various stakeholders within that system. Understanding both individual and overall system behavior and the constraints they face helps to explain the trajectories and forces driving the system and provide insight on potential future outcomes—and ultimately this comprehensive insight can also provide avenues for well-designed intervention to alter those outcomes.

A. Why Does Energy Matter?

It is nearly impossible to overstate the role of energy in modern society. Everything observed in the modern world has been enabled by access to incredible amounts of energy, far beyond the endowments of humans to create with their own hands. All forms of energy, from basic animal power and agriculture to modern fossil fuels and renewables have combined to empower the building of previously unimaginable societies and technologies over the last few hundred years since the start of the Industrial Revolution.

1. Energy, Output, Income, and Welfare

One of the most telling aspects of the importance of energy is its centrality in our economic and industrial consciousness despite not being inherently useful in its own right. Unlike other basic resources, such as food or water or air, energy itself is almost never the goal but rather serves as an intermediate step in pursuit of some higher fulfillment that improves the ability, reach, or satisfaction of people. Energy expert Amory Lovins has written that “customers don't want kilowatt-hours; they want services such as hot showers, cold beer, lit rooms, and spinning shafts.”[2] Yet, somehow, energy is at the very center of human existence, and the continued procurement of these **energy services** it provides is vital to modern well-being.

It is this primacy that requires examining energy as the analytical point of departure and treating it as its own field of study. However, such an examination quickly reveals that energy touches every aspect of the economy, society, and prospects for the future, and so understanding the role of energy requires understanding how it is linked to all of these aspects of the surrounding world.

a) Growth in Energy Is (Approximately) Growth in Wealth and Welfare

To begin the study of energy, it is first important to understand what energy is and what it does. As mentioned, energy is fundamentally an enabler of the ability to accomplish other tasks, leveraging the human capabilities to heat, light, manipulate, and move things. From the dawn of humankind, traditional forms of energy—including basic biomass combustion and animal power—have been used to provide these services much easier than if humans had to perform this work alone.

This relationship is, in fact, definitional. One physics definition of useful energy is often interpreted as "the ability to perform work" and describes an entire class of physical phenomena, including light, heat, sound, motion, and electricity. These are precisely the types of energy harnessed to achieve the outcomes desired, such as providing the ability to move machines, power vehicles, and perform work far beyond the basic endowments of humans.[3]

This basic understanding of the energy system as the enabler of work links elegantly to the understanding of societies and economies through the mechanism of gross product or, specifically, **gross domestic product** (**GDP**) in the case of a specific country's territory. GDP is a measure of the production of a society, which can be calculated by adding up all of the goods and services produced in a given period. (Economic theory defines final output to be the same as the total income in the economy, and both terms will be used interchangeably to describe the economic product unless otherwise noted.)

By extension, all of the work that gets done in an economy is through the efforts of humans amplified by the energy they can command to perform work on their behalf. This implies that energy is the foundational concept of economic activity, and economic activity cannot be divorced from the energy required to perform it, though the efficiency with which that conversion takes place must also be considered.

The highest correlation of energy to economic activity is seen in the growth of the use of modern forms of energy. From the start of the Industrial Revolution (around 1770), the world economy has grown more than 100 times in terms of output, or work performed.[4] As shown in Figure 1.1 for the US over that period and mirrored in other countries the amount of energy consumed has grown similarly and through the use of a progression of fuel sources—first coal, then petroleum, natural gas, hydropower, and nuclear—that have collectively enabled this growth in global economic activity.

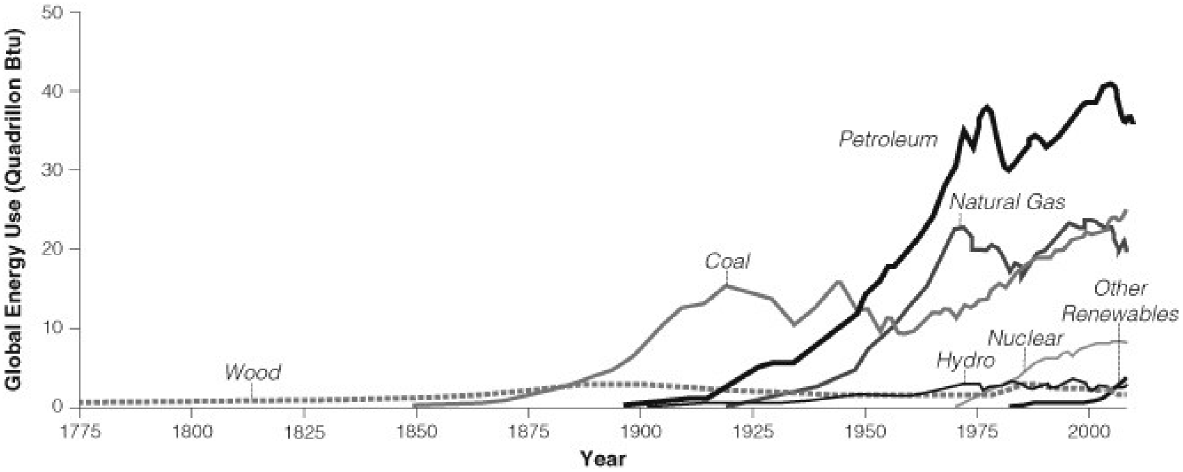

Figure 1.1 US Energy Use by Fuel since 1775
Source: "History of Energy Consumption in the United States, 1775–2009," eia.gov, http://www.eia.gov/todayinenergy/detail.cfm?id=10.

Human intuition about energy and use of it far predates the formal study of energy. Though the term *energy* is attributed originally to Aristotle in the fourth century BCE, it did not enter scientific use until the early 1800s and did not enter the popular lexicon until the latter half of that century.[5] By then, the foundation of the modern energy-driven economy had already been deeply established.

The reason that humans have intuitively sought out these forms of energy is simply because they made life better. Wealth and income, not unlike energy, are intermediate means to what is actually desired, which is welfare. Welfare, as defined by economists, refers to prosperity and living standards as measured by the notion of "utility." Merely being richer or having more access to modern forms of energy does not necessarily make a person happier or better off. Even the originator of the calculus of

GDP, Simon Kuznets, expressed concern over the imperfect relationship of wealth to welfare.[6] A complete calculus of the benefits, costs, risks, allocations within a population (also called **distribution**), and prospects for society's future relationship to welfare and energy would be required to understand the welfare impacts of energy choices.

However, over the last few centuries more access to modern forms of energy has strongly correlated with greater welfare in many observable ways. Besides GDP growth, many other indicators, such as health, literacy, and other measures of satisfaction, have tended to rise across societies in the last few centuries as access to energy grew.[7] At the same time, other measures of welfare have diminished in line with rising energy use, including many forms of natural resource degradation or pollution. A robust debate of these tradeoffs should be included for a complete understanding of the relationship between society and energy.

b) Risks in the Energy System Are (Precisely) Risks to Wealth and Welfare

Once the powerful relationship between energy and economic activity is revealed, it is easy to see why the energy system is considered a bedrock of modern economic activity. Consequently, any threat to the continued functioning of the energy system constitutes a threat to modern economic activity and the welfare that it creates. While more energy may not always improve welfare, less or riskier energy will almost certainly make it worse off.

These risks can come from loss of physical access to necessary supplies through depletion or supply chain disruption (**physical risks**). Running out of easily procurable energy, whether in the form of food or fuel, can compel people to forgo higher order economic activity until additional energy supplies can be obtained. In longer supply chains, particularly those that cross jurisdictional boundaries, potential disruptions of supply can be powerful political leverage tools and can even compel preemptive protective behavior by those who are exposed.

Such risks can also come from dramatic changes in the cost to produce or the price to procure these energy resources (**economic risks**). Because of the fundamental nature of energy as an economic input, changes in the cost of production often are passed to the consumer either in redistribution of available spending or in reduction in potential work output. In places where import of energy is required, external events that raise the import price can have damaging economic effects. Conversely, nations that are significant energy exporters are constantly vulnerable to a drop in the price they can obtain for their natural resource endowments.

The realization of any of these physical or economic risks has the potential to be incredibly costly and disruptive in direct proportion to how dependent an economy is on these modern energies and how long it takes for the economy to make the necessary adaptations and investments to accommodate changing circumstances. Due to the potential impact on a nation's income and livelihood, access to energy is among the most fiercely protected and vital interests for everyone from households to whole societies.

B. How Much Energy Is Needed?

If energy is positively related to welfare, then the quickest answer to “How much energy is needed?” is simply “more.” From the discussion above, with all other things being equal—or **ceteris paribus** in economic terms—it seems obvious that more energy creates more economic output, thereby increasing welfare while also protecting from the risks of loss of access. However, that answer is too trite, and the relationships among energy, income, and welfare are much more complex and require making important tradeoffs within scarce and constrained circumstances.

A starting point for analysis of the energy system is to understand the components that determine how much energy is actually used, as well as the metrics of how each of these components is measured (see the Metrics Sidebar). Then, understanding how each of these components varies over different circumstances and changes over time gives a clear pathway to begin an analytical exploration.

Metrics Sidebar: What Is a Metric?

The word *metric* is often used in this textbook, and how metrics are constructed is fundamental to understanding the statistics and analytics constructed to explain what goes on in the energy industry.

At its root, a **metric** is a quantifiable and standard unit of measure. It is far more than a unit, though. Because it is standardized using a common convention, a metric represents a benchmark, a standard of measure that enables easy comparison across different items that can be defined using the same metric. Dollars per pound ($/lb), pounds per square inch (lb/in^2), and miles per gallon (mpg) are all metrics that enable a useful comparison of similar things to determine relative cost or performance.

This section describes three different metrics—population (P), GDP, and energy (E)—and then formulates how they are definitionally related to one another, using additional metrics that combine them, including GDP/P and E/GDP. Each of these variables has a unit of measurement; when they are used for comparative purposes, however, they become a metric.

Misusing metrics is easy. Not understanding how they are constructed, and therefore precisely what they are measuring, leads to many errors of conclusion, which can be a source of great frustration among both users and consumers of metrics in decision-making. For example, this section and its elaboration in Chapter 19 describe some of the difficulties in understanding the true meaning of GDP as a metric and relying on it for certain comparisons or decisions.

In addition, single metrics are relatively useless by themselves. To be used correctly, all metrics should be compared either against similarly constructed metrics (**cross-sectionally**) or over time against itself (as a **time series**).

1. Determining Energy Requirements

As energy leverages human capability to create output, or income, then what determines how much energy needed is based on the number of people and how much output they each want to produce, or GDP as it is defined. Precisely, energy use (E) can be factored into the number of people (or population, P) and the energy use per person (E/P).

$$E = P * (E/P)$$

Then, E/P can be further factored into the amount of energy required to create each unit of economic output (E/GDP) and how much economic output is produced by each person (GDP/P) on average. The point of this analysis is to disaggregate energy needs into component parts that can be understood (and even potentially forecast) separately.

$$E = P * (E/GDP) * (GDP/P)$$

This most basic definition becomes the foundation of understanding the three primary components of energy needed, each of which will be discussed in detail below. For now, it is not important what the metrics or units of measurement are for either the energy components (Btu, joules, or kWh) or the output ($ or ¥ or €). It is merely important to understand the definitional relationship among the component parts.

2. Population (P)

The population of people on the planet has grown from about 1 billion in 1800 to over 7 billion today (Figure 1.2). Increased access to medicine, health-care services, sanitation, and reliable supplies of food and clean water has enabled dramatic growth in population from preindustrial levels. This growth in global population has been a primary driver of increases in the energy required by the global economy, independent of the simultaneous increase in global living standards experienced over the same period.

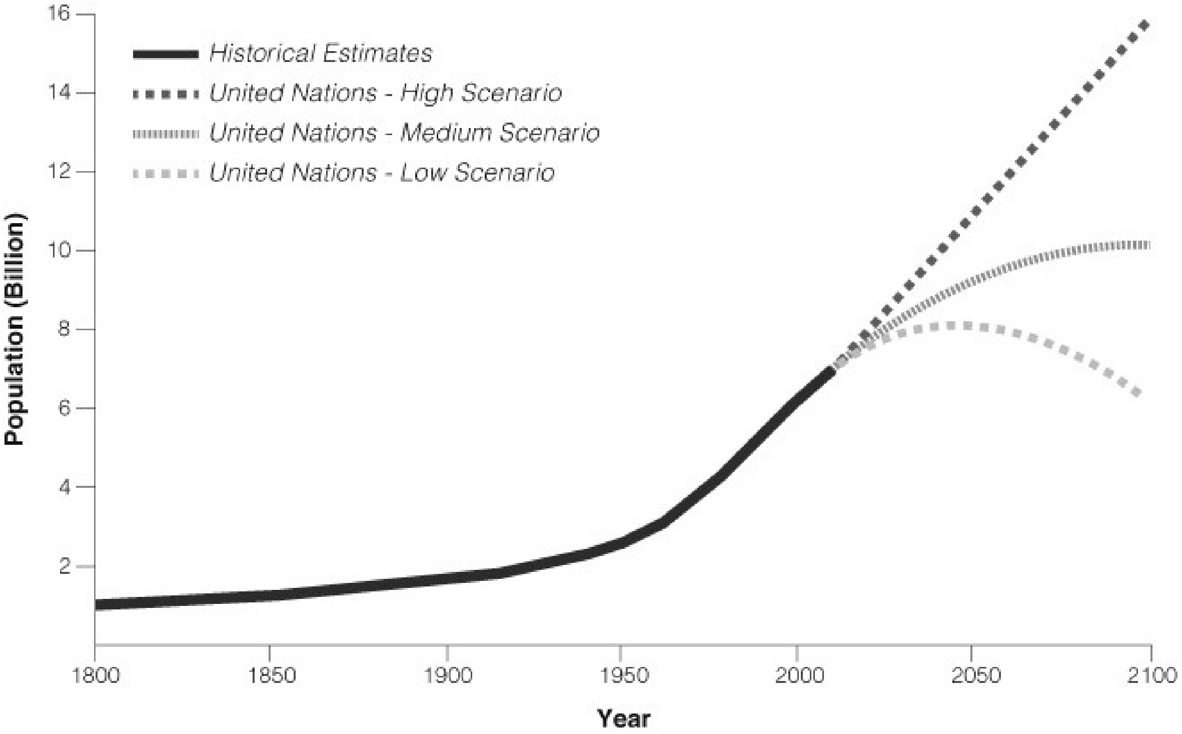

Figure 1.2 Population from 1800 to Present and Three Scenarios for the Future

Source: "World Population Prospects, the 2015 Revision," UN Department of Economic and Social Affairs, Population Division, https://esa.un.org/unpd/wpp/Graphs/DemographicProfiles/.

The direct relationship between population and energy needs begs the question of how much population growth can occur before the scarce energy resources of the planet are overwhelmed. The original economic formulation of this argument came from Thomas Malthus, considered to be one of the founders of modern economics alongside Adam Smith. Malthus postulated in his *An Essay on the Principle of Population* (1798) that rising prosperity would lead to rising population growth until physical limits or resource availability were reached and then would collapse through disease or a self-inflicted famine.[8] While Malthus's conclusions are hotly debated and are still foundational to some schools of economic thought, the efficiency of resource use has also improved over time and has, thus far, largely limited the impacts of resource constraints on population and economic growth.

Regardless, population growth continues to be a major determinant of total energy use, and understanding the future population trajectory is necessary to project society's energy requirements. Figure 1.2 presents three scenarios developed by the UN for population growth through 2100 to help assess the possible future states of the world. These three scenarios diverge dramatically in their outcomes, with one scenario peaking by midcentury at 8 billion people and then falling, one stabilizing by the end of the century at 10 billion, and the third continuing to grow unabated. Obviously, each of these scenarios would result in a very different outcome for society's energy (and other resource) requirements.[9]

In some countries, population growth has already slowed dramatically. China, Central Asia, Russia, and much of Europe have seen population growth rates fall to or below zero. Conversely, other countries, including much of Africa and Southeast Asia, continue to see high population growth rates.[10] In aggregate, global population growth rates have slowed in the last few decades but still remain high in some of the poorest areas of the world.

A related concept that can be used to analyze the trends in population growth is the **fertility rate**. This calculation of live births per female can explain the rate of population replacement in a country or region. The **replacement fertility rate**, accounting for child and premature adult mortality, is usually benchmarked at 2.1 live births per female in industrialized countries and higher in developing countries. The replacement rate globally is currently estimated to be around 2.33 and dropping.[11] The historical figures from Figure 1.2 reflect a substantial fall in the actual global fertility rate from 4.97 in the early 1950s to about 2.53 through 2010.[12]

The change in these developing countries' population growth rates will therefore determine the overall growth rate of the global population, but they will be further affected by a mathematical phenomenon known as the **population momentum effect**.[13] This effect causes the age distribution in a currently fast-growing population to be disproportionately young, such as in many poor and developing nations. This means that these younger populations continue to reproduce faster than older populations, growing until the natural death rate equals the fertility rate, thereby equilibrating younger and older members of the society. This effect can also occur in the opposite direction with declining population and a disproportionately elderly population, a situation in Japan, for instance, and in an increasing number of European countries.

Because of the long average lifetimes and momentum effects in population growth, understanding global population trajectories must take a very long view, and even small changes in the fertility rate can have a dramatic impact on global population over a time span of centuries. While current trajectories of slowing growth rates and fertility rate stabilization suggest that global population may be entering a more stable pattern (or perhaps eventually even declining), only time will tell how the population dynamics work out. Regardless of how many people eventually inhabit the planet, figuring out how to provide vital energy services to them will also be a function of the quality of life they can expect and the efficiency with which energy can provide it.

3. Per Capita Income (GDP/P)

In addition to knowing the level and growth rates of population, it is important to understand how much economic output each of those people creates, and expects to consume, on average. This measure of output per capita is calculated by dividing GDP by the population, or GDP/P. Macroeconomists rely heavily on this statistic to evaluate the relative economic activity level across countries, or some subset of the population within countries. As described above, it is important to note that GDP is not a precise measure of welfare, though it is often conflated with it by economists and financial theorists.

The complete relationship of energy and the macroeconomy is explored in Chapter 19. For now, it is enough to note that the relationship between GDP per capita and both welfare and energy use, though correlated, is very noisy and imprecise. Figure 1.3 shows the relationship of energy use to GDP across a number of economies, and the fitted line suggests a positive relationship, even if individual points vary wildly from the average. This suggests that if society intends to continue increasing its growth in economic income (GDP/P), then more energy inputs—to a greater or lesser extent, depending on other variables—will be needed to support that growth.

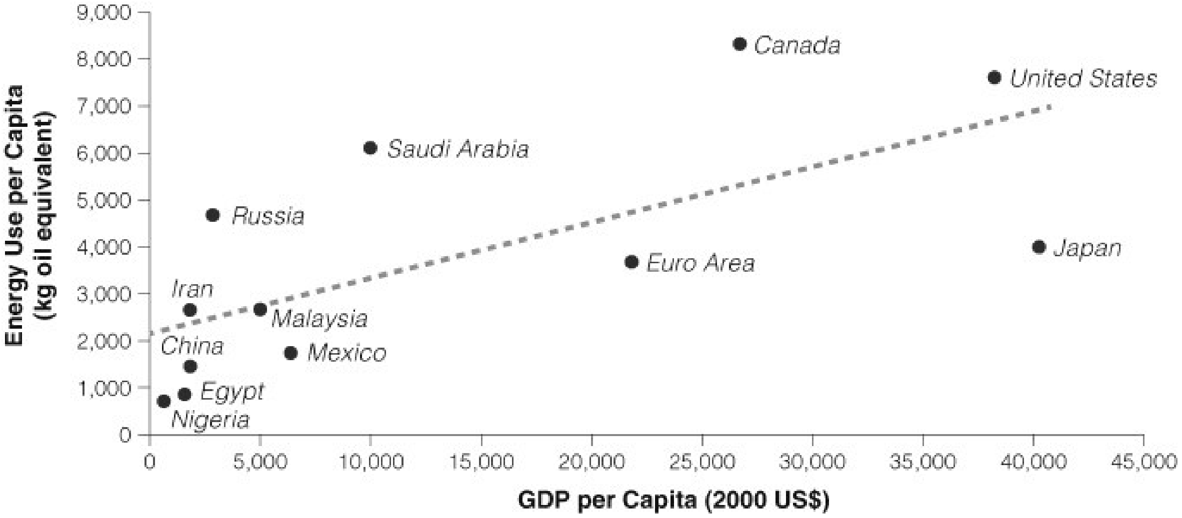

Figure 1.3 Energy per Capita vs. GDP per Capita
Source: Glada Lahn and Paul Stevens, "Burning Oil to Keep Cool," in *The Hidden Energy Crisis in Saudi Arabia* (London: Chatham House, 2011), fig. 5b.

4. Energy Intensity (E/GDP)

Finally, the amount of energy needed is also determined by how much output can be created with each unit of that energy. The third factor of the energy calculus is energy (E) per unit of GDP, or **energy intensity**. As shown in Figure 1.4, average energy intensity has been falling worldwide for the last few decades. Such a trend is not universally true for all countries at all times. Countries undergoing rapid industrialization, such as what occurred in Japan in the pre– and post–World War II era and in China more recently, experience a period of increasing energy use per unit of GDP. This effect, however, tends to mitigate itself quickly as industry and economies find benefit in becoming more efficient in their use of energy to create economic output. Figure 1.4 shows this experience for many current industrialized nations.[14]

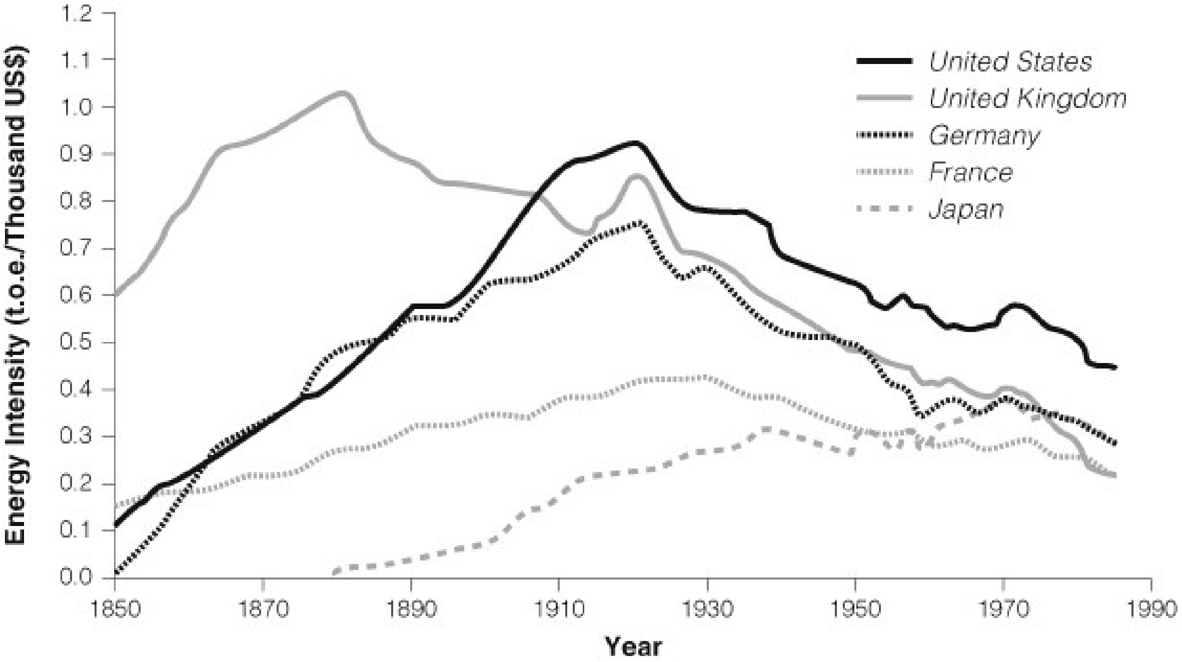

Figure 1.4 Energy Intensity of Industrialized Economies, 1850–1985

Source: José Goldemberg, "Leapfrog Energy Technologies," *Energy Policy* 26, no. 10 (1998): 729–41.

In aggregate, though, global energy intensity has fallen, making each unit of GDP less costly in terms of the volume of energy required. This correlates with the idea of becoming more efficient in energy use over time, at least in terms of ability to create GDP, and is often explained through the concept of technology improvement and learning. Other proposals suggest that the structure of the global economy is evolving to include increasing levels of services and knowledge, which require less energy in creating units of GDP. Either way, creating GDP is clearly less energy intensive over time except in rare and constrained circumstances.

Note that this metric for energy intensity uses a physics notion of energy in the numerator and a financial notion of economic output in the denominator. This construction is a radical simplification used to make the basic relationships of the energy system easily explainable. However, it has the potential to create misleading conclusions, as the cost of each physical unit of energy can and does change, and sometimes quite dramatically. This difference between **energy consumption** (the quantity of physical units of energy used) and **energy expenditures** (the currency required to procure those energy volumes) is shown in

Figure 1.5. It is important to remember that just because energy intensity generally improves from a consumption perspective does not mean it will from an expenditure perspective—or put simply, using less energy does not always mean paying less for it.

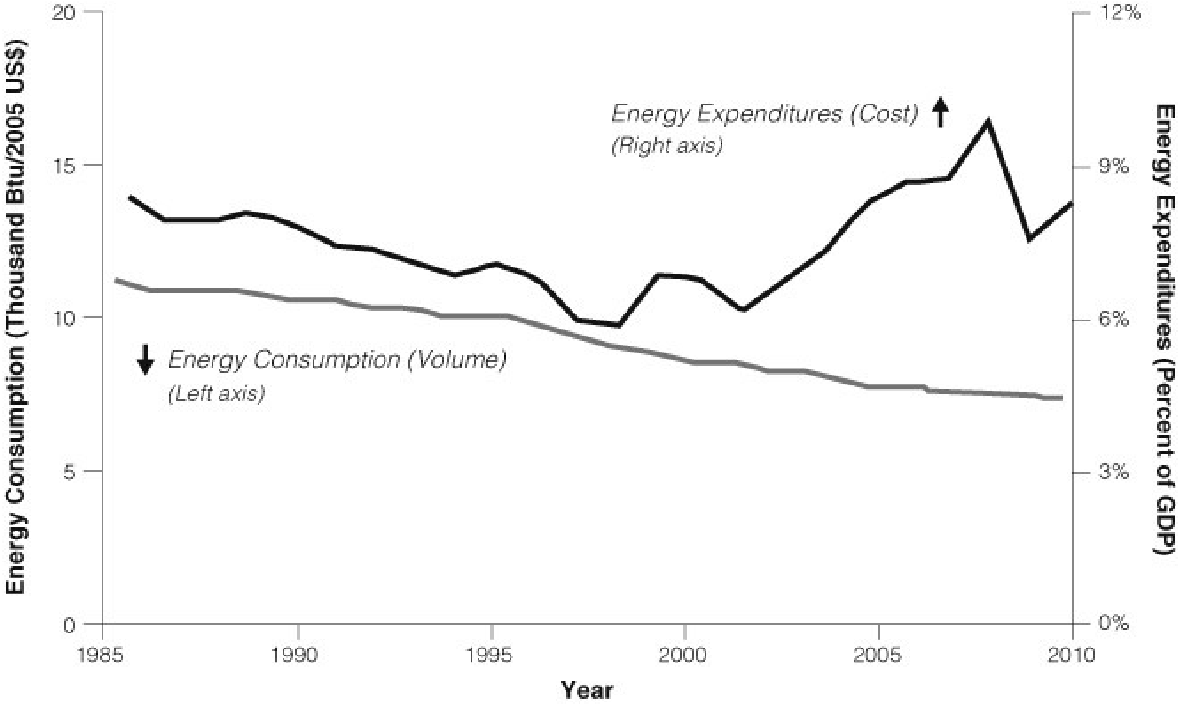

Figure 1.5 Historical Energy Consumption per Dollar vs. per Unit of GDP

Source: *Annual Energy Outlook 2015* (Washington: DOE/EIA, 2015).

Finally, the concept of energy intensity is closely related to **energy productivity** (GDP/E), its inverse. It reframes GDP as a function of energy, and it is often used as a measure of comparative productivity across countries. This metric, like energy intensity, can be misleading to compare across countries because of major differences in (1) the structure of the economy and the relative proportion of GDP from manufacturing vs. service sectors, (2) which goods are primarily manufactured, (3) weather, and (4) availability of local energy resources. One of the countries with the lowest energy productivity in the world is Iceland, which is endowed with both cold weather and ample supplies of hydropower and geothermal energy; among other structural changes, these ample energy supplies have allowed the development of an energy-intensive metals industry.[15] Clearly, comparisons across countries should be conducted carefully and with an eye to their underlying heterogeneity in sources and uses of energy.

5. Aggregating Energy Needs and Impacts

The deconstruction of aggregate energy needs into these basic components introduces the elements of a complete, if simplified, analysis. It scopes out the basic relationship among population, output, and efficiency and how each contributes to overall energy demand.

Figure 1.6 highlights how some of these components have and are anticipated to change during the period from 2005 to 2040 in both the richest nations (those in the Organisation for Economic Co-operation and Development, the OECD), and the economically developing ones. While total energy consumption (E) worldwide has grown dramatically, along with total GDP, energy use per capita (E/P) has grown much less so, mostly due to increasing per capita income (GDP/P) being offset by a steady reduction in energy intensity (E/GDP). Each of these trends tells a different aspect of the energy story, and understanding the relationships among them allows anticipating system dynamics.

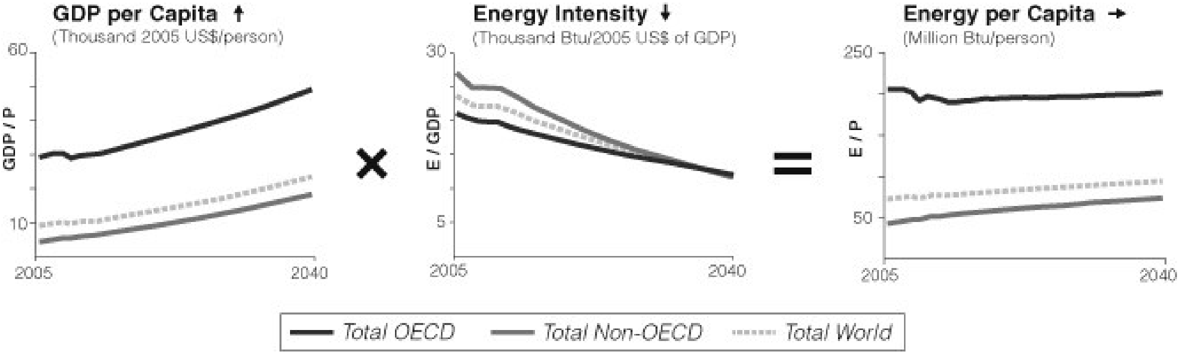

Figure 1.6 Projected World Energy and GDP Factors, OECD and Non-OECD

Source: David Peterson, *Future World Energy Demand Driven by Trends in Developing Countries*, eia.gov, http://www.eia.gov/todayinenergy/detail.cfm?id=14011.

Similar frameworks have been developed to explain not just energy use but also its impacts on other variables of interest, including environmental or social outcomes. One of these is characterized in the **IPAT framework**, originally proposed by John Holdren and Paul Ehrlich.[16] This framework is a general form of thinking about measuring the impact of various elements on the environment, and is designed with the form:

$$IPAT \rightarrow Impact = Population * Affluence * Technology$$

Impact, in this case, is defined more broadly than just energy use and can measure almost any aspect of resource absorption or its effects and is often used to measure the environmental impact of society's industrial choices. It suggests that limiting the impact of energy resource choices (such as pollution or resource absorption) across a fixed population can only be achieved through either dramatically improved technology or an eventual loss of affluence.

This relationship is identical to the one that determines society's relationship to the amount of energy it consumes. Thinking about impact as the amount of energy needed, or the amount that can be procured, presents the same type of structural limit. Society's ability to get richer is limited by the amount of energy that can be captured and the efficiency (i.e., the technology) with which it is used to create economic output. If there is a limit to the amount of energy procured and technology does not improve to efficiently convert that into income generation or production, that limits the amount of affluence that can be expected.

Though conceptually useful as a starting point, these simple frameworks fail to provide the machinery to fully appreciate the complex relationship of the volume of energy required to meet growing needs and their economic and societal costs and benefits. Unpacking those questions will require a more complete analytic toolkit.

C. What Are the Key Questions to Examine in the Energy System?

Given how vital the human relationship to energy is, a comprehensive treatment of the energy sector remains elusive. At best, the models used to explain it are incomplete and insights only partially formed. At worst, what is presented as analysis can be unintentionally, or even intentionally, biased.

The problem of analysis and developing insights about energy is initially complicated by a lack of common language across sectors