Energy Quality, Net Energy, and the Coming Energy Transition

Cutler J. Cleveland

Department of Geography and Center for Energy and Environmental Studies, Boston University, 675 Commonwealth Ave., Boston, MA 02215, phone: (617) 353-3083, fax: (617) 353-5986; email: cutler@bu.edu

Abstract

Global oil production will peak in the coming decades, followed by natural gas and coal. These turning points constitute an unprecedented watershed in human history. This paper focuses on some of the critical challenges we face in the transition from conventional fossil fuels to alternative sources, particularly solar energy. Conventional wisdom holds that technical improvements in the efficiency of energy end use and the shift towards a dot-com economy will de-couple energy use and economic well-being. But the relationship is much more complex than this simple formulation. Most analyses underestimate the important quality differences between fossil fuels and solar energy and their economic implications. Quality in this case is measured by the amount of economic output generated per unit of energy input. The lower quality nature of solar energy is reflected in part by its energy density, and its lower energy return on investment, the amount of energy delivered by a system compared to the energy used in the delivery process. When quality differences are accounted for, the relationship between energy use and economic activity is very strong.

Acknowledgements

The author gratefully acknowledges the comments from many of the participants at the Sixth Annual Energy Conference "The Future of Oil as an Energy Source," sponsored by the Emirates Center for Strategic Studies and Research, 7-8 October, 2000 in Abu Dhabi, United Arab Emirates.

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Introduction

Global oil production will peak in the coming decades, followed by natural gas and coal. These turning points constitute an unprecedented watershed in human history. This paper focuses on some of the critical challenges we face in the transition from conventional fossil fuels to alternative sources, particularly solar energy. Foremost is the capacity for renewable fuels to develop into the functional equivalent of fossil fuels, i.e., to have a similar capacity to generate goods and services per unit of energy input. The cost of many renewable energy systems have declined in the past two decades, but significant challenges remain. This paper describes the nature of some of those challenges, especially in regards to the prospects for overcoming the spatially diffuse nature of many renewable energy systems. It also explores the relationship between energy use and economic growth, and the factors that determine the strength of that relationship.

Energy Transitions in the Past

The level of health, food security and especially material standard of living that exists today throughout the world is made possible by the expansive use of fossil fuels. While many take this affluence for granted, a long run view illustrates that the fossil fuel era is relatively new and will last for a relatively short period of time (Figure 1). For thousands of years prior to the Industrial Revolution, human societies were powered by the products of photosynthesis, principally fuelwood and charcoal. Widespread use of coal did not develop until the 18^{th} century, oil and gas not until the late 19^{th} century.

The history of energy use in the United States illustrates these transitions (Figure 2). In 1800, the nation was fueled by animal feed, which powered the draft animals on farms, and wood fuel, which was used for domestic heating and cooking and by early industry. The Industrial Revolution transformed the nation's energy picture, substituting coal for renewable fuels on a massive scale. By the time of the first World War, coal accounted for nearly three quarters of the nation's energy use. Wood and animal feed were rapidly disappearing, the latter due to the introduction of the first tractor in 1911.

But coal's place as the dominant fuel was fleeting. Oil and natural gas quickly replaced coal, just as coal had replaced wood. By the 1960s, oil and gas together accounted for more than 70 percent of total energy use; coal had dropped to less than 20 percent. Primary electricity ha splayed a small but steadily growing role. Primary electricity refers to electricity generated by hydroelectric, nuclear, geothermal, solar, and other so-called "primary sources. The increase in the share of primary electricity towards the end of the period is due to the rise in nuclear generating capacity.

Energy Return on Investment

This long run view of energy raises an important question: what guided these transitions in the past, and to what extent can such information inform us about the impending transition from fossil to renewable fuels? The transition from one major energy system to the next is driven by a combination of energetic, economic, technological and institutional factors. The energy-related forces stem from the tremendous economic and social opportunities that new fuels, and their associated energy converters, offered compared to earlier ones.

A key aspect of an energy delivery system is its energy return on investment (EROI) (Gever et al., 1986; Hall et al., 1986). The EROI is the ratio of the gross energy extracted to the energy used in the extraction process itself (Figure 3). A related term is net energy or energy surplus, which is equal to the gross energy extracted minus the energy used in the extraction process. Thus, the EROI is a ratio reflecting the return on energy investment, while energy surplus is a quantity of energy delivered to the rest of a system after the energy cost of obtaining it has been paid.

The concepts were developed in ecology to describe the critical role energy plays in nature. All organisms must use energy to perform a number of life-sustaining tasks such as growth, reproduction, and defense from predators. The most fundamental task of all is using energy to obtain more energy from the environment. When energy is used to do useful work, energy is degraded from a useful, high quality state to a less useful low quality state. This means that all systems must continuously replace that energy they use, and to do so takes energy. This fundamental reality means that EROI and net energy are used to explain the foraging behavior of organisms, the distribution and abundance of organisms (Hall et al., 1992) and the structure and functioning of ecosystems (Odum, 1957).

While human society is driven by a much more than simple energetic imperatives, the concept of net energy and EROI help explain the dramatic energy transitions of the past. For the overwhelming majority of their existence, humans obtained energy from the environment by hunting and gathering. The EROI for food capture is the caloric value of the food capture to the expenditure of energy in the capture or gathering process. The EROI for energy dense roots is 30 to 40; a reasonable average for all gathering is 10 to 20 (Table 1) (Smil, 1991). The shift to agriculture represented a fundamental shift in the way humans obtained food energy from the environment. Agriculture required greater inputs of energy compared to hunting and gathering. The forest had to be cut or the wetland had to be drained to free the land for cultivation. The land had to be prepared for planting, the crop had to be planted, cared for and ultimately harvested. All of these activities required substantial inputs of energy. As a result, the EROI for agriculture often times was less than or about equal to that for hunting and gathering (Table 1).

From an energy perspective, then, why, did agriculture replace hunting and gathering? The answer lies with the size of the energy surplus delivered by agriculture. Although the EROI for agriculture may have been lower, the energy inputs increased faster than the EROI declined, such that the surplus food energy increased. The greater surplus vastly increased human carrying capacity of the environment and offered new economic, social, and cultural opportunities. Natural ecosystems produce enough edible food energy to support hunter-gatherers at densities no greater than one person per square kilometer. Traditional agricultural societies support hundreds of people square kilometer, enabling permanent settlements to grow in size and number. The greater surplus released labor from the land, creating the potential for people to move to urban areas and work in manufacturing and industry.

Energy Converters

Coincident with a change in the types of energy used was a change in the machines used to convert that energy into useful work. The economic usefulness of an energy converter is determined in part by its power, the rate at which it converts energy to do useful work. In economic terms useful work refers to the use of energy to produce goods and services.

Animate energy converters (humans and draft animals) convert energy to work at low power outputs. The energetic limits of people and draft animals set very definite economic and social limits. The Industrial Revolution erased these limits with the introduction of the steam engine, which had a power output that dwarfed that of animate sources. The higher power output of the steam engine enabled it to deliver a much large energy surplus than human labor or draft animals. The higher energy surplus expanded economic opportunities just as agriculture had done compared to hunting and gathering, only on a much grander scale.

Given the economic advantage offered by heat engines powered by fossil fuels, it is no surprise that labor and draft animals we rapidly replaced by heat engines once they became available. The United States' economy illustrates this transition. In 1850, more than 90 percent of thew work done in the economy was accomplished by human labor and draft animals. Over the next half-century, engines powered by wood and then coal rapidly displaced the animate converters. By the 1950s, labor and animals had almost been completely displaced.

Of the economic changes driven by the new fuels and machines, one of the most dramatic was the effect on labor productivity. In agriculture, for example, the productivity of labor increased more than 100-fold relative to rates possible prior to the Industrial Revolution. As mentioned above, this increase in labor productivity reduce the need for labor in the agricultural sector, and thus providing a potential supply for burgeoning industrial sectors. The same increase in labor productivity occurred in other sectors of the economy where the efforts of human labor were subsidized by more energy and more powerful energy converters. Indeed, labor productivity in general is related tot the amount of energy used per laborer (Hall et al., 1986).

Energy and Economic Growth

How strong is the connection between energy use and economic growth? There are quite divergent views on this subject. One hypothesis is that the link is weak, that the production of goods and services can be de-coupled from energy inputs. There are several forces that might achieve this. First, it generally is assumed that as fossil fuels become scarcer, their price will rise, which in turn will trigger technological changes and substitutions that improve energy efficiency. Indeed, many believe that the price shocks in 1973-74 and 1979-80 led to the adoption of many new energy efficient technologies. Second, the shift to a service-oriented, dot-com economy will de-couple energy use from economic activity. A dollar's worth of steel requires 93,000 Btu to produce in the United States; a dollar's worth of financial services uses 9,500 Btu. Thus, it stands to reason that a shift towards less-energy intensive activities will reduce the need for energy. Third, growing environmental imperatives will create new incentives to de-couple energy use from economic output. In particular, concern over climate change is increasing the need to de-carbonize the economy. Improving the efficiency of energy use is one way to do this.

International comparisons of energy use seem to lend support to the hypothesis that energy use and economic growth. Aggregate energy efficiency frequently is measured by the energy/real GDP (E/GDP) ratio. This is the quantity of commercial energy use compared to the quantity of GDP produced. By this measure, many industrial nations have become more energy efficient in the last few decades (Figure 4). The E/GDP ratio declined even faster after the energy price shocks, lending support to the argument that the price increases triggered energy-saving technological change. Note also that the level of energy efficiency varies significantly among nations. This suggests that nations such as the United States have the potential to improve their energy efficiency while maintaining the same level of output.

Energy Quality and the Energy/GDP Ratio

A second hypothesis is that the connection between energy use and economic output is strong. A key concept in understanding this argument is energy quality. From an economic perspective, the value of a heat equivalent of fuel is determined by its price. The value marginal product of a fuel in production is the marginal increase in the quantity of a good or service produced by the use of one additional heat unit of fuel multiplied by the price of that good or service (Cleveland et al., 2000).

The marginal product of a fuel is determined in part by a complex set of attributes unique to each fuel such as physical scarcity, capacity to do useful work, energy density, cleanliness, amenability to storage, safety, flexibility of use, cost of conversion, and so on. But the marginal product is not uniquely fixed by these attributes. Rather, the energy vector's marginal product varies according to the activities in which it is used, how much and what form of capital, labor, and materials it is used in conjunction with, and how much energy is used in each application. As the price rises due to changes on the supply-side, users can reduce their use of that form of energy in each activity, increase the amount and sophistication of capital or labor used in conjunction with the fuel, or stop using that form of energy for lower value activities. All these actions raise the marginal productivity of the fuel. When capital stocks have to be adjusted, this response may be somewhat sluggish and lead to lags between price changes and changes in the value marginal product.

The heat equivalent of a fuel is just one of the attributes of the fuel and ignores the context in which the fuel is used, and thus cannot explain, for example, why a thermal equivalent of oil is more useful in many tasks than is a heat equivalent of coal (Adams and Miovic, 1968). In addition to attributes of the fuel, marginal product also depends on the state of technology, the level of other inputs, and other factors. According to neoclassical theory, the price per heat equivalent of fuel should equal its value marginal product, and, therefore, represent its economic usefulness. In theory, the market price of a fuel reflects the myriad factors that determine the economic usefulness of a fuel from the perspective of the end-user.

Consistent with this perspective, the price per heat equivalent of fuel varies substantially among fuel types (Table 2). The different prices demonstrate that end-users are concerned with attributes other than heat content. As Berndt (1978) states:

> Because of [the] variation in attributes among energy types, the various fuels and electricity are less than perfectly substitutable - either in production or consumption. For example, from the point of view of the end-user, a Btu of coal is not perfectly substitutable with a Btu of electricity; since the electricity is cleaner, lighter, and of higher quality, most end-users are willing to pay a premium price per Btu of electricity. However, coal and electricity are substitutable to a limited extent, since if the premium price for electricity were too high, a substantial number of industrial users might switch to coal. Alternatively, if only heat content mattered and if all energy types were then perfectly substitutable, the market would tend to price all energy types at the same price per Btu (p. 242).

Do market signals (i.e. prices) accurately reflect the marginal product of inputs? Kaufmann (1994) investigates this question in an empirical analysis of the relation between relative marginal product and price in US energy markets. To do so, he estimates a reduced form of a production function that represents how the fraction of total energy use from coal, oil, natural gas, and primary electricity (electricity from hydro and nuclear sources) affects the quantity of energy required to produce a given level of output. The partial derivatives of the production function with respect to each of the fuels gives the marginal product of individual fuels, in which marginal product is defined as the change in economic output given a change in the use of a heat unit of an individual fuel. The equations are used to calculate the marginal product for each fuel type for each year between 1955 and 1992. The time series for marginal products are compared among fuels, and these ratios are related to relative prices using a partial adjustment model. The results indicate that there is a long run relation between relative marginal product and relative price, and that several years of adjustment are needed to bring this relation into equilibrium. This suggests that over time prices do reflect the marginal product - and hence the economic usefulness - of fuels.

Other analysts calculate the average product of fuels, which is a close proxy for marginal products. Adams and Miovic (1968) estimate a pooled annual cross-sectional regression model of industrial output as a function of fuel use in seven European economies from 1950 to 1962. Their results indicate that petroleum is 1.6 to 2.7 times more productive than coal in producing industrial output. Electricity is 2.7 to 14.3 times more productive than coal. Using a regression model of the energy/GDP ratio in the U.S., Cleveland et al. (1984) find that the quality factors of petroleum and electricity relative to coal were 1.9 and 18.3, respectively.

Energy quality is important to account for in the assessment of E/GDP ratios (Stern, 1993; Kaufmann, 1992). When energy use is calculated in the standard heat equivalents, energy use and GDP diverge in the United States, seemingly consistent with the de-linking hypothesis. Figure 5 also shows energy use represented in with Divisia index, a method for aggregating heat equivalents by their relative prices. This quality-corrected measure of energy use shows a much stronger connection with GDP. This visual observation is corroborated by econometric analysis that confirms a strong connection between energy use and GDP when energy quality is accounted for (Stern, 1993; Cleveland et al., 2000).

International comparisons of the E/GDP relationship also demonstrate the importance of energy quality. Econometric analysis of the E/GDP in the United States, Japan, the UK and France from since 1950 indicates that changes in energy quality explain much of the variation (Kaufmann, 1992). Declines in the E/GDP ratio are associated with the general shift from coal to oil, gas, and primary electricity. Also important are fuel prices, the structure of economies, and household purchases of energy.

The Quality of Solar Energy

There is no shortage of energy on Earth (Table 3). Indeed the storages and flows of energy on the planet are staggering relative to human needs. Consider the following:

- The amount of solar energy intercepted by the Earth every *minute* is greater than the amount of fossil fuel the world uses every *year*.
- Tropical oceans absorb 5.3×10^{20} Btu of solar energy each year, equivalent to 1,600 times the world's annual energy use.
- The potential energy in the winds that blow across the United States each year could produce more than 4.4 trillion kWh of electricity—more than one and one-half times the electricity consumed in the United States in 2000.
- Annual photosynthesis by the vegetation in the Unites States is 4.7×10^{16} Btu, equivalent to nearly 60% of the nation's annual fossil fuel use.

In contrast to its vast *quantity*, the *quality* of solar energy is low relative to fossil fuels. Consider the energy flow in the Earth's crust. The total heat loss from the Earth's crust is

1.3×10^{18} Btu per year, equivalent to nearly 4 times the world's annual energy use. But this energy flow is spread over the entire 5.1×10^{14} square meters of the Earth's surface. This means that the amount of energy flow per unit area is 2,400 Btu per square meter, an amount equivalent to just 1/100 of a gallon of gasoline.

Consider incoming solar energy. The land area of the lower 48 United States intercepts 4.7×10^{19} Btu per year, equivalent to 500 times of the nation's annual energy use. But that energy is spread over nearly 3 million square miles of land area, so that the energy absorbed per unit area is just 1.5×10^{13} Btu per square mile per year. But plants, on average, capture only about 0.1% of the solar energy reaching the Earth. This means that the actual plant biomass production in the United States is just 1.6×10^{10} Btu per square mile per year.

These examples illustrate that heat flow from the Earth, solar energy, plant biomass and other renewable forms of energy are diffuse forms of energy, particularly when we compare them to fossil fuels. This is captured by the concept of power density. Power density combines two attributes of energy sources: the rate at which energy can be produced from the source and the geographic area covered by the source. A coal mine in China, for example, can produce upwards of 10,000 watts per square meter of the mine. As the above examples indicate most solar technologies have low power densities compared to fossil fuels,

A low energy or power density means that large amounts of capital, labor, energy and materials must be used to collect, concentrate and deliver solar energy to users. This tends to make them more expensive than fossil fuels. The difference between solar and fossil energy is best represented but their energy return on investment (EROI). The EROI for fossil fuels tends to be large while that for solar tends to be low (Figure 6). This is the principal reason that humans aggressively developed fossil fuels in the first place.

Fossil fuels have allowed us develop lifestyles that also are very energy intensive. The places that we live, work and shop have every high power densities. Supermarkets, office buildings and private residences in industrial nations demand huge amounts of energy. This very energy-intensive way of living, working, and playing have been made possible by fossil fuels sources that are equally as concentrated.

Another quality difference between renewable fuels and fossil fuels is their energy density: the quantity of energy contained per unit mass of a fuel (Table 4). For example, wood contains 15 Mj per kilogram; oil contains up to 44 Mj per kilogram. Higher energy densities also contribute to the higher EROI for fossil fuels relative to many renewable fuels.

Conclusions

Among the countless technologies humans have developed, only two have increased our power over the environment in an *essential* way. Georgescu-Roegen (1982) called these Promethean technologies. Promethean I was fire, unique because it was a qualitative conversion of energy (chemical to thermal) and because it generates a chain reaction that sustains so long as sufficient fuel is forthcoming. As Georgescu (1982) described:

> The mastery of fire enabled man not only to keep warm and cook the food, but, above all to smelt and forge metals, and to bake bricks, ceramics, and lime. No wonder that the ancient Greeks attributed to Prometheus (a demigod, not a mortal) the bringing of fire to us (p. 30).

Promethean II was the heat engine. Like fire, heat engines achieve a qualitative conversion of energy (heat into mechanical work), and they sustain a chain reaction process by supplying surplus energy. Surplus energy or (net energy) is the gross energy extracted less the energy used in the extraction process itself. The Promethean nature of fossil fuels is due to the much larger surplus, they deliver compared to animate energy converters such as draft animals and human labor. The energy surplus delivered by fossil fuel technologies is the energetic basis of the Industrial Revolution (Cottrell, 1955; Odum,. 1971; Cleveland et al., 1984; Cleveland, 1992).

Can solar energy be Promethean II? The challenge we face is to overcome the constraints imposed by the nature of solar energy and develop it in sufficient quantities to fuel not only the industrialized North, but also the developing South. This is a formidable challenge. There is no guarantee that we will escape economic hardship in the transition from fossil to solar energy, or that current lifestyles can be supported in an all-solar economy. But great strides are being made in many solar technologies, progress fueled by the growing awareness of the role fossil fuels play in climate change and other pressing environmental problems.

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Biography

Cutler Cleveland is Director and Professor of the Center for Energy and Environmental Studies at Boston University. He holds a B.S. in Ecology and Systematics from Cornell University, a M.S. in Marine Science from Louisiana State University, and Ph D. in Geography from the University of Illinois at Urbana-Champaign. Dr. Cleveland is a member of the Scientific Planning Committee for the Human Dimensions of Global Environmental Change/Industrial Transformation Programme. He has been a consultant to numerous private and public organizations, including the Asian Development Bank, the Technical Research Centre of Finland, the U.S. Department of Energy, and the U.S. Environmental Protection Agency. Dr. Cleveland's research focuses on the ecological-economic analysis of how energy and materials are used to meet human needs. His research employs the use of econometric and systems dynamics models of oil supply, natural resource scarcity, and the relation between the use of energy and natural resources and economic systems.