The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

Energy Transitions Past and Future

Posted by Nate Hagens on August 8, 2007 - 8:30am
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This is a guest post from Cutler Cleveland. It provides an excellent big picture overview of what variables we need to consider as we transition away from fossil fuels. Professor Cleveland previously wrote "Energy From Wind - A Discussion of the EROI Research", and "Ten Fundamental Principles of Net Energy" posted on theoildrum.com. Cutler Cleveland is a Professor at Boston University and has been researching and writing on energy issues for over 20 years. He is Editor-in-Chief of the Encyclopedia of Earth, Editor-in-Chief of the Encyclopedia of Energy, the Dictionary of Energy and the Journal of Ecological Economics

Prometheus chained to Mount Caucasus. Source: Pieter Paul Rubens: "Prometheus Bound," 1611-1612, Oil on canvas, 95 7/8" x 82 1/2". (Philadelphia Museum of Art: The W.P. Wilstach Collection) *Click to Enlarge*

This is a guest post from Cutler Cleveland. It provides an excellent big picture overview of what variables we need to consider as we transition away from an extreme fossil fuel subsidy. Professor Cleveland previously wrote "Energy From Wind - A Discussion of the EROI Research", and "Ten Fundamental Principles of Net Energy" posted on theoildrum.com. Cutler Cleveland is a Professor at Boston University and has been researching and writing on energy issues for over 20 years. He is Editor-in-Chief of the Encyclopedia of Earth, Editor-in-Chief of the Encyclopedia of Energy, the Dictionary of Energy and the Journal of Ecological Economics

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INTRODUCTION

In Greek mythology, Prometheus defied the will of Zeus by stealing fire and giving it to the mortal race of men in their dark caves. Zeus was enraged by Prometheus' deceit, so he had Prometheus carried to Mount Caucasus, where an eagle would pick at his liver; it would grow back each day and the eagle would eat it again. Fire transformed mortal life by providing light, warmth, cooking, healing and ultimately the ability to smelt and forge metals, and to bake bricks, ceramics, and lime. Fire became the basis for the Greek culture and ultimately all Western culture. It is no wonder, therefore, that the Greeks attributed fire not to a mortal origin, but to a Titan, one of the godlike giants who were considered to be the personifications of the forces of nature.

If fire was the first Promethean energy technology, then Promethean II was the heat engine, powered first by wood and coal, and then by oil and natural gas. 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 changes wrought by fossil fuels exceeded even those produced by the introduction of fire. The rapid expansion of the human population and its material living standard over the past 200 years could not have been produced by direct solar energy and wood being converted by plants, humans and draft animals. Advances in every human sphere — commerce, agriculture, transportation, the military, science and technology, household life, health care, public utilities —were driven directly or indirectly by the changes in society's underlying energy systems.

In the coming decades, world oil production will peak and then begin to decline, followed by natural gas and eventually coal production. There is considerable debate about when these peaks will occur because such information would greatly aid energy companies, policy makers, and the general public. But at another level, the timing of peak fossil fuel production doesn't really matter. A more fundamental issue is the magnitude and nature of the energy transition that will eventually occur. The next energy transition undoubtedly will have far reaching impacts just as fire and fossil fuels did. However, the next energy transition will occur under a very different set of conditions, which are the subject of the rest of this discussion.

The Magnitude of the Shift

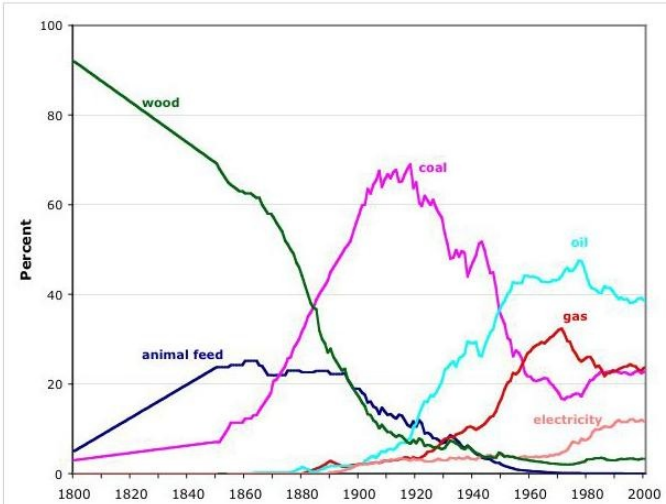

Figure 2. Composition of U.S. energy use. (Source: Cutler Cleveland) *Click to Enlarge*

The last major transition occurred in the late 19th century when coal replaced wood as the dominant fuel. Figure 2 illustrates this transition for the United States, a period often referred to as the second Industrial Revolution (the first being the widespread replacement of manual labor by machines that began in Britain in the 18th century, and the resultant shift from a largely rural and agrarian population to a town-centered society engaged increasingly in factory manufacture). Wood and animal feed suppled more than 95% of the energy used in the United States in 1800. The population of the nation stood at just 5.3 million people, per capita GDP was about $1,200 (in real US$2000), dominant energy converters were human labor and draft animals (horses), and the population was overwhelmingly rural and concentrated near the eastern seaboard.

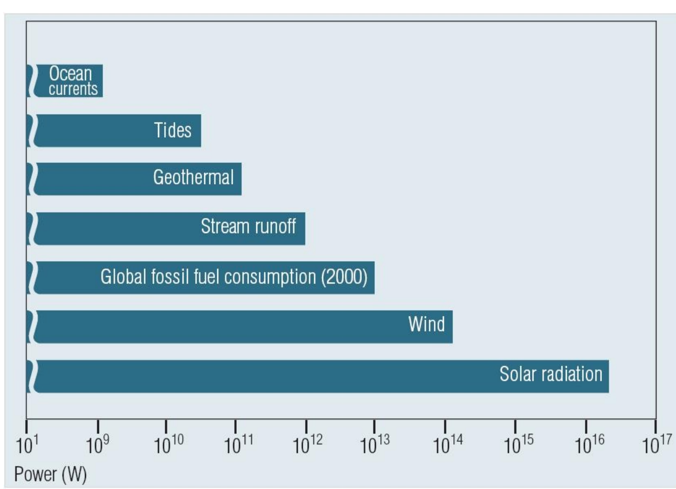

Figure 3. The global flux of fossil and renewable fuels. (Source: Smil, V. 2006. "21st century energy: Some sobering thoughts." OECD Observer 258/59: 22-23.)

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energy: Some sobering thoughts." OECD Observer 258/59: 22-23.)*Click to Enlarge*

The nation was completely transformed by World War I. Coal had replaced wood as the dominant fuel, meeting 70% of the nation's energy needs, with hydropower and newcomers oil and natural gas combining for an additional 15%. Steam engines and turbines had replaced people and draft animals as the dominant energy converters. The population had soared to more than 100 million, per capita GDP had increased by a factor of five to $6,000, more than half of the nation's population lived in cities, and manufacturing and services accounted for most of the nation's economic output. Thus, the transition from wood to fossil fuels, and its associated shift in the energy-using capital stock, produced as fundamental a transition in human existence as did the transition from hunting and gathering to agriculture.

How much renewable energy is needed if it were to replace fossil fuels in the same pattern as coal replaced wood? The United States first consumed as much coal as wood in about 1885. Total energy use then was about 5.6 quadrillion BTU (1 quadrillion = 1015), equal to about 0.19 TW (Terawatts or 1012 watts). Consider what it would take today to replace even just one-half of U.S. fossil fuel use with renewable energy: we would need to displace coal and petroleum energy flows of 2.9 TW, or 32 times the amount of coal used in 1885. Current global fossil fuel use is about 13 TW, so we need more than 6 TW of renewable energies to replace 50% of all fossil fuels. This is a staggering shift.

Is renewable energy up to this challenge? There are physical, economic, technical, environmental, and social components to this question. Figure 3 depicts one slice of the picture: pure physical availability as measured by the global annual flow of various energies. The only renewable energy that exceeds annual global fossil fuel use is direct solar radiation, which is several orders of magnitudes larger than fossil fuel use. To date however, the delivery of electricity (photovoltaics) or heat (solar thermal) directly from solar energy represents a tiny fraction of our energy portfolio due to economic and technical constraints. Most other renewable energy flows could not meet current energy needs even if they were fully utilized. More importantly, there are important qualitative aspects to solar, wind, and biomass energy that pose unique challenges to their widespread utilization.

ENERGY QUALITY

Most discussions of energy require the aggregation of different forms and types of energy. The notion of "total energy use" in Figures 2 and 3 indicates that various physical amounts of energy —coal, oil, gas, uranium, kilowatt-hours (kWh), radiation—are added together. The simplest and most common form form of aggregation is to add up the individual variables according to their thermal equivalents (BTUs, joules, etc.). For example, 1 kWh is equal to 3.6x106 joules, 1 barrel of oil is equal to 6.1x109 joules, and so on.

Despite its widespread use, aggregation by heat content ignores the fact that not all joules are equal. For example, a joule of electricity can perform tasks such as illumination and spinning a CD-ROM that other forms of energy cannot do, or could do in a much more cumbersome and expensive fashion (Imagine trying to power your laptop directly with coal).

These differences among types of energy are described by the concept of energy quality, which is the difference in the ability of a unit of energy to produce goods and services for people. Energy quality is determined by a complex combination of physical, chemical, technical, economic, environmental and social attributes that are unique to each form of energy. These attributes include gravimetric and volumetric energy density, power density, emissions, cost and efficiency of conversion, financial risk, amenability to storage, risk to human health, spatial distribution, intermittency, and ease of transport.

Energy Density

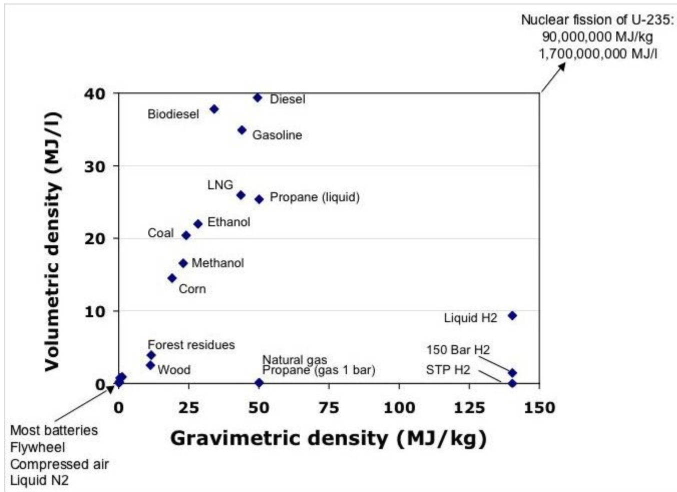

Figure 4. Energy densities for various fuels and forms of energy. (Source: Cutler Cleveland)
Click to Enlarge

Energy density refers to the quantity of energy contained in a form of energy per unit mass or volume. The units of energy density are megajoules per kilogram (MJ/kg) or megajoules per liter (MJ/l). Figure 4 illustrates a fundamental driver behind earlier energy transitions: the substitution of coal for biomass and then petroleum for coal were shifts to more concentrated forms of energy. Solid and liquid fossil fuels have much larger mass densities than biomass fuels, and and an even greater advantage in terms of volumetric densities. The preeminent position of liquid fuels derived from crude oil in terms of its combined densities is one reason why it transformed the availability, nature and impact of personal and commercial transport in society. The lower energy density of biomass (12-15 MJ/kg) compared to crude oil (42 MJ/kg) means that replacing the latter with the former will require a significantly larger infrastructure (labor, capital, materials, energy) to produce an equivalent quantity of energy.

The concept of energy density underlies many of the challenges facing the large scale utilization of hydrogen as a fuel. Hydrogen has the highest energy to weight ratio of all fuels. One kg of hydrogen contains the same amount of energy as 2.1 kg of natural gas or 2.8 kg of gasoline. The high gravimetric density of hydrogen is one reason why it is used for a fuel in the space program to power the engines that lift objects against gravity. However, hydrogen has an extremely low amount of energy per unit volume (methane has nearly 4 times more energy per liter than hydrogen). Hydrogen's low volumetric energy density poses significant technical and economic challenges to the large-scale production, transport and storage for commercial amounts of the fuel.

Power Density

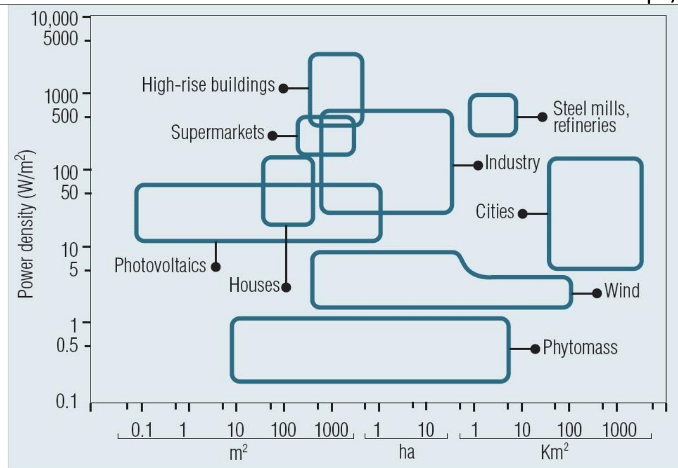

Figure 5. Power densities for fossil and renewable fuels. (Source: Smil, V. 2006. "21st century energy: Some sobering thoughts." OECD Observer 258/59: 22-23.)

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Power density is the rate of energy production per unit of the earth's area, and is usually expressed in watts per square meter (W/m2). The environmental scientist Vaclav Smil has documented the important differences between fossil and renewable energies, and their implications for the next energy transition. Due to the enormous amount of geologic energy invested in their formation, fossil fuel deposits are an extraordinarily concentrated source of high-quality energy, commonly extracted with power densities of 10^2 or 10^3 W/m2 of coal or hydrocarbon fields. This means that very small land areas are needed to supply enormous energy flows. In contrast, biomass energy production has densities well below 1 W/m2, while densities of electricity produced by water and wind are commonly below 10 W/m2. Only photovoltaic generation, a technique not yet ready for mass utilization, can deliver more than 20 W/m2 of peak power.

The high power densities of energy systems has enabled the increasing concentration of human activity. About 50% of the world's population occupies less than 3% of the inhabited land area; economic activity is similarly concentrated. Buildings, factories and cities currently use energy at power densities of one to three orders of magnitude lower than the power densities of the fuels and thermal electricity that support them. Smil observes that in order to energize the existing residential, industrial and transportation infrastructures inherited from the fossil-fueled era, a solar-based society would have to concentrate diffuse flows to bridge these large power density gaps. Mismatch between the inherently low power densities of renewable energy flows and relatively high power densities of modern final energy uses means that a solar-based system will require a profound spatial restructuring with major environmental and socioeconomic consequences. Most notably according to Smil, there would be vastly increased fixed land requirements for primary conversions, especially with all conversions relying on inherently inefficient photosynthesis whose power densities of are minuscule: the mean is about 450 mW/m2 of ice-free land, and even the most productive fuel crops or tree plantations have gross yields of less than 1 W/m2 and subsequent conversions to electricity and liquid fuels prorate to less than 0.5 W/m2.

Energy Surplus

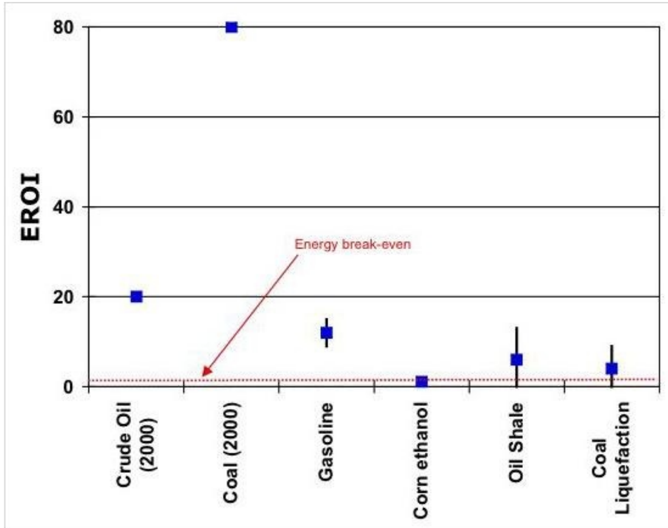

Figure 6. The energy return on investment (EROI) for various fuel sources in the U.S. (Source: Cutler Cleveland)
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Energy return on investment (EROI) is the ratio of the energy extracted or delivered by a process to the energy used directly and indirectly in that process. A common related term is energy surplus, which is the gross amount of energy extracted or delivered, minus the energy used directly and indirectly in that process. The unprecedented expansion of the human population, the global economy, and per capita living standards of the last 200 years was powered by high EROI, high energy surplus fossil fuels. The penultimate position of fossil fuels in the energy hierarchy stems from the fact that they have a high EROI and a very large energy surplus. The largest oil and gas fields, which are found early in the exploration process due to their sheer physical size, delivered energy surpluses that dwarfed any previous source (and any source developed since then). That surplus, in combination with other attributes, is what makes conventional fossil fuels unique. The long-run challenge society faces is to replace the current system with a combination of alternatives with similar attributes and a much lower carbon intensity.

Most alternatives to conventional liquid fuels have very low or unknown EROIs (Figure 6). The EROI for ethanol derived from corn grown in the U.S. is about 1.5:1, well below that for conventional motor gasoline. Ethanol from sugarcane grown in Brazil apparently has a higher EROI, perhaps as high as 8:1, due to higher yields of sugarcane compared to corn, the use of bagasse as an energy input, and significant cost reductions in ethanol production technology. Shale oil and coal liquefaction have low EROIs and high carbon intensities, although little work has been done in this area in more than 20 years. The Alberta oil sands remain an enigma from a net energy perspective. Anecdotal evidence suggests an EROI of 3:1, but these reports lack veracity. Certainly oil sands will have a lower EROI than conventional crude oil due to the more diffuse nature of the resource base and associated increase in direct and indirect processing energy costs.

Intermittency

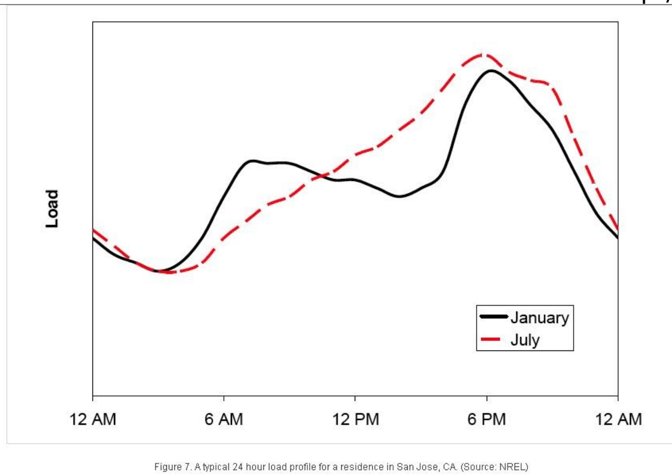

Figure 7. A typical 24 hour load profile for a residence in San Jose, CA. (Source: NREL)
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Intermittency refers to the fraction of time that an energy source is available to society. It is an essential feature of electricity generation systems that must combine power generated from multiple sources and locations to supply electricity "24/7." The wind does not blow all the time and the sun does not shine all the time, so a wind turbine and PV array sometimes stand idle. One aspect of intermittency is the load factor or capacity factor, which is the ratio of the output of a power plant compared to the maximum output it could produce. Due to the more or less continuous nature of fossil fuel extraction, thermal power plants have capacity factors of 75 to 90 percent. Typical annual average load factors for wind power are in the range of 20 to 35 percent, depending primarily on wind climate, but also wind turbine design.

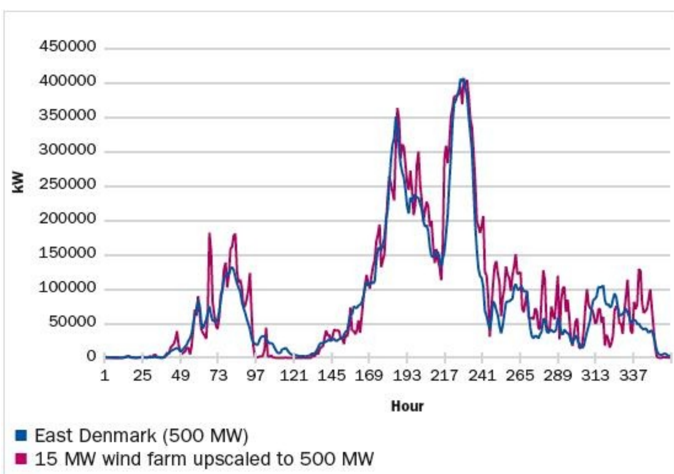

Figure 8. The variability of wind energy over a 1y day period. The figure compares the hourly output of 500 MW wind power capacity in two situations, calculated from observed data in Denmark. The red line shows the output of a single site; the blue line shows the multiple site output. Source: European Wind Energy Association, "Large scale integration of wind energy in the European power supply: analysis, issues and recommendations" (December 2005)
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Load profiles show characteristic daily and seasonal patterns (Figure 7). For example, most hourly profiles for commercial and institutional facilities rise in the middle of the day and then taper off during early morning and late evening hours. Wind and solar energy availability frequently do not match typical load profiles (Figure 8).

Such intermittency means that wind and solar power are really not “dispatchable”—you can’t necessarily start them up when you most need them. Thus, when wind or solar power is first added to a region’s grid, they do not replace an equivalent amount of existing generating capacity—i.e. the thermal generators that already existed will not immediately be shut down. This is measured by capacity credit, which is the reduction of installed power capacity at thermal power stations enabled by the addition of wind or solar power in such a way that the probability of loss of load a peak times is not increased. So, for example, 1000 MW of installed wind power with a capacity credit of 30% can avoid a 300 MW investment in conventional dispatchable power. A recent survey of U.S. utilities reveals capacity credits given to wind power in the range of 3 to 40 percent of rated wind capacity, with many falling in the 20 to 30 percent range. A large geographical spread of wind or solar power is needed to reduce variability, increase predictability and decrease the occurrences of near zero or peak output.

These and other "ancillary costs" associated with wind and solar power are small at low levels of utilization, but rise as those sources further penetrate the market. In the longer run, the impacts of these additional costs on the the deployment of wind and solar power must be compared with the effective costs of other low-carbon power sources such as nuclear power, or the costs of fossil thermal generation under strong carbon constraints (i.e., carbon capture and storage).

Spatial distribution

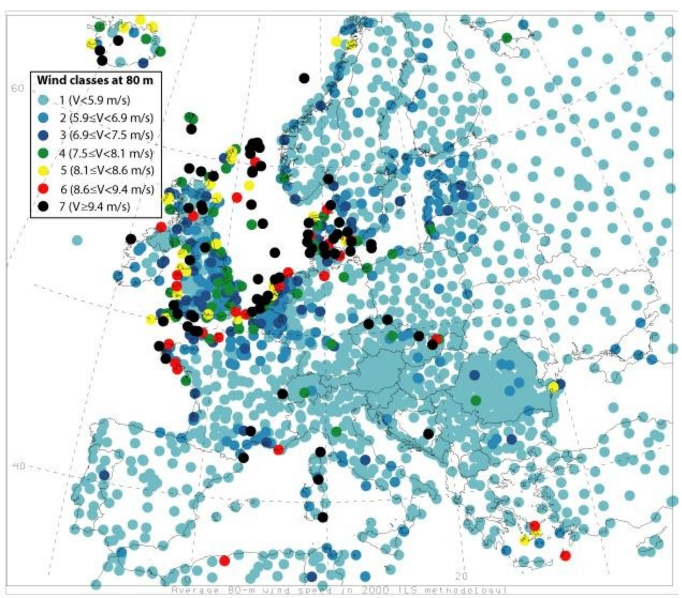

Figure 9. The distribution of wind speeds at 80 meters, the hub height of a modern turbine. (Source: Cristina L. Archer and Mark Z. Jacobson, Evaluation of global wind power)
Click to Enlarge

All natural resources show distinct geographical gradients. In the case of oil and natural gas for example, the ten largest geologic provinces contain more than 60 percent of known volumes, and half of those are in the Persian Gulf. Coal and uranium deposits also are distributed in distinct, concentrated distributions. The pattern of occurrence imposes transportation and transaction costs, and in the case of oil and strategic minerals, also imposes risk associated with economic and national security.

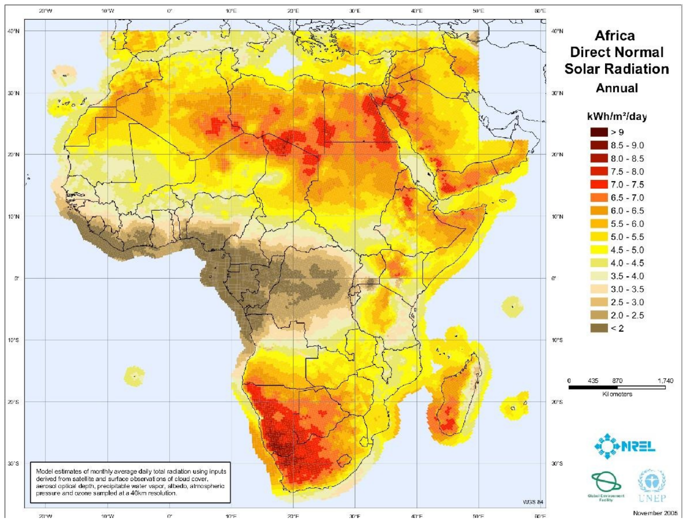

Figure 10. The distribution of solar energy exhibits a strong geographical gradient. (Source: NREL)
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Of course, renewable energy flows exhibit their own characteristic distributions (Figures 9 and 10), producing mismatches between areas of high-quality supply and demand centers. Many large urban areas are far from a high-quality source of geothermal energy, do not have high wind power potential, or have low annual rates of solar insolation. Indeed, many of the windiest and sunny regions in the world are virtually uninhabited. The spatial distribution of renewable energy flows means that significant new infrastructures will be needed to collect, concentrate and deliver useful amounts of power and energy to demand centers.

THE ENVIRONMENTAL FRONTIER IS CLOSED

The transition from wood to coal occurred when the human population was small, its affluence was modest, and its technologies were much less powerful than today. As a result, environmental impacts associated with energy had negligible global impact, although local impacts were at times quite significant. Any future energy transition will operate under a new set of environmental constraints. Environmental change has significantly impaired the health of people, economics and ecosystems at local, regional and global scales. Future energy systems must be designed and deployed with environmental constraints that were absent from the minds of the inventors of the steam engine and internal combustion engines.

Air Pollution and Climate Change

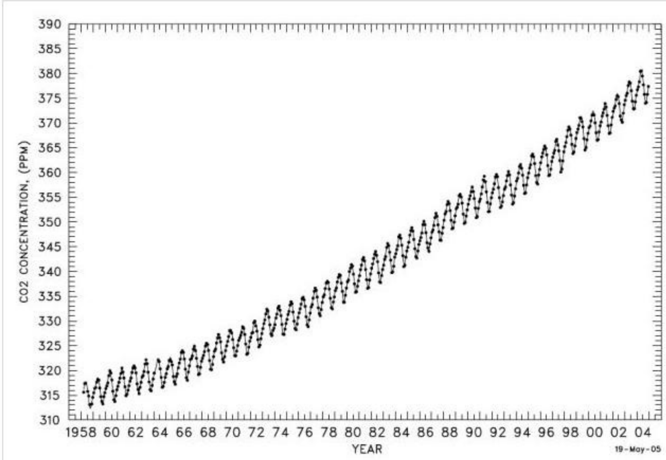

Figure 11. The Mauna Loa curve showing the rise in atmospheric carbon dioxide concentrations (Source: Keeling, C.D. and T.P. Whorf. 2005. Atmospheric CO_2 records from sites in the SIO air sampling network. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.)
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Atmospheric releases from fossil fuel energy systems comprise 64 percent of global anthropogenic carbon dioxide emissions from 1850-1990 (Figure 11), 89 percent of global anthropogenic sulfur emissions from 1850 to 1990, and 17 percent of global anthropogenic methane emissions from 1860-1994. Fossil energy combustion also releases significant quantities of nitrogen oxide; in the United States, 23 percent of such emissions are from energy use. Power generation using fossil fuels, especially coal, is a principal source of trace heavy metals such as mercury, selenium, and arsenic.

These emissions drive a range of global and regional environmental changes, including global climate change, acid deposition, and urban smog, and they pose a major health risk. According to the Health Effects Institute, the global annual burden of outdoor air pollution amounts to about 0.8 million premature deaths and 6.4 million years of life lost. This burden occurs predominantly in developing countries; 65% in Asia alone. According to the World Health Organization, in the year 2000, indoor air pollution from solid fuel use was responsible for more than 1.6 million annual deaths and 2.7% of the global burden of disease. This makes this risk factor the second biggest environmental contributor to ill health, behind unsafe water and sanitation.

Climate change may be the most far-reaching impact associated with fossil fuel use. According to the Intergovernmental Panel on Climate Change (IPCC), the global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 parts per million (ppm) to 379 ppm in 2005 (Figure 6). The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores. The primary source of the increased atmospheric concentration of carbon dioxide since the pre-industrial period results from fossil fuel use, with land use change providing another significant but smaller contribution. The increase in carbon dioxide concentrations are a principal driving force behind the observed increase in globally averaged temperatures since the mid-20th century.

Carbon intensity is an increasingly important attribute of fuel and power systems. Social and political forces to address climate change may produce another distinguishing feature of the next energy transition: environmental considerations may be a key important driver, rather then the inherent advantages of energy systems as measured by energy density, power density, net energy, and so on.

Appropriation of the products of the biosphere

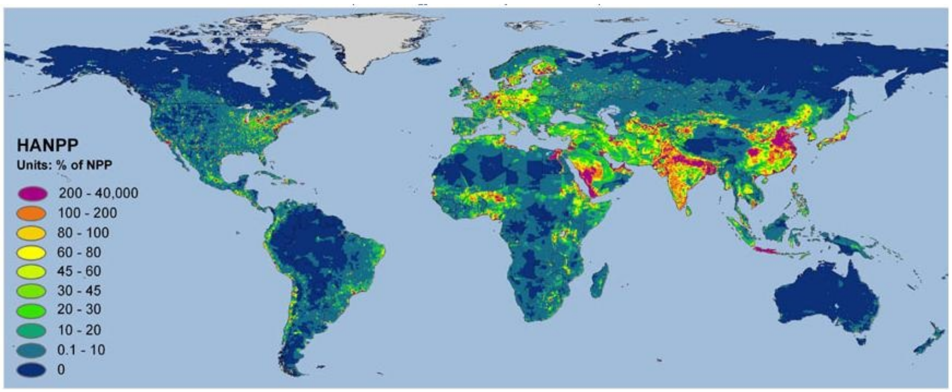

Figure 12. Human appropriation of net primary production (NPP) as a percentage of the local NPP. (Source: Imhoff, Marc L., Lahouari Bounoua, Taylor Ricketts, Colby Loucks, Robert Harriss, and William T. Lawrence. 2004. Global patterns in human consumption of net primary production. "Nature", 429, 24 June 2004: 870-873. Image retrieved from NASA)
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The low energy and power density of most renewable alternatives collides with a second global environmental imperative: human use of the Earth's plant life for food, fiber, wood and fuelwood. Satellite measurements have been used to calculate the annual net primary production (NPP) —the net amount of solar energy converted to plant organic matter through photosynthesis—on land, and then combined with models to estimate the annual percentage of NPP humans consume (Figure 12). Humans in sparsely populated areas, like the Amazon, consume a very small percentage of locally generated NPP. Large urban areas consume 300 times more than the local area produced. North Americans use almost 24 percent of the region's NPP. On a global scale, humans annually require 20 percent of global NPP.

Human appropriation of NPP, apart from leaving less for other species to use, alters the composition of the atmosphere, levels of biodiversity, energy flows within food webs, and the provision of important ecosystem services. There is strong evidence from the Millennium Ecosystem Assessment and other research that our use of NPP has seriously compromised many of the planet's basic ecosystem services. Replacing energy-dense liquid fuels from crude oil with less energy dense biomass fuels will require 1,000- to 10,000-fold increase in land area relative to the existing energy infrastructure, and thus place additional significant pressure on the planet's life support systems.

The rise of energy markets

When coal replaced wood, most energy markets were local or regional in scale, and many were informal. Energy prices were based on local economic and political forces. Most energy today is traded in formal markets, and prices often are influenced by global events. Crude oil prices drive the trends in price for most other forms of energy, and they are formed by a complex, dynamic, and often unpredictable array of economic, geologic, technological, weather, political, and strategic forces. The rise of commodity and futures markets for energy not only added volatility to energy markets, and hence energy prices, but also helped elevate energy as to a key strategic financial commodity. The sheer volume of energy bought and sold today combined with high energy prices has transformed energy corporations into powerful multinational forces. In 2006, five of the world's largest corporations were energy suppliers (Exxon Mobil, Royal Dutch Shell, BP, Chevron, and ConocoPhillips). The privatization of state-owned energy industries is also a development of historic dimensions that is transforming the global markets for oil, gas, coal and electric power.

Global market forces will thus be an important driving force behind the next energy transition. There is considerable debate about the extent to which markets can and should be relied upon to guide the choice of our future energy mix. Externalities and subsidies are pervasive across all energy systems in every nation. The external cost of greenhouse gas emissions from energy use looms as a critical aspect of energy markets and environmental policy. The distortion of market signals by subsidies and externalities suggests that government policy intervention is needed to produce the socially desirable mix of energy. The effort to regulate greenhouse gas emissions at the international level is the penultimate example of government intervention in energy markets. The political and social debate about the nature and degree of government energy policy will intensify when global crude oil supply visibly declines and as pressure mounts to act on climate change.

Energy and poverty

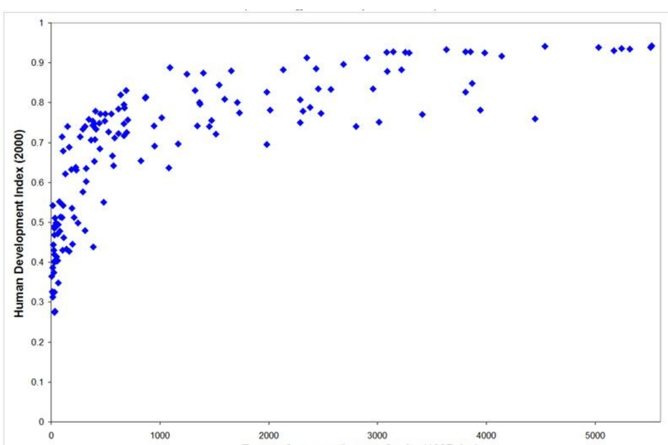

Figure 14. Energy and basic human needs. The international relationship between energy use (kilograms of oil equivalent per capita) and the Human Development Index (2000). (Source: UNDP, 2002, WRI, 2002)
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The energy transition that powered the Industrial Revolution helped create a new economic and social class by raising the incomes and changing the occupations of a large fraction of society who were then employed in rural, agrarian economies. The next energy transition will occur under fundamentally different socioeconomic conditions. Future energy systems must supply adequate energy to support the high and still growing living standards in wealthy nations, and they must supply energy sufficient to relieve the abject poverty of the world's poorest. The scale of the world's underclass is unprecedented in human history. According to the World Bank, about 1.2 billion people still live on less than $1 per day, and almost 3 billion on less than $2 per day. Nearly 110 million primary school age children are out of school, 60 percent of them girls. 31 million people are infected with HIV/AIDS. And many more live without adequate food, shelter, safe water, and sanitation.

Energy use and economic development go hand-in-hand (Figure 14), so poverty has an important energy dimension: the lack of access to high quality forms of energy. Energy poverty has been defined as the absence of sufficient choice in accessing adequate, affordable, reliable, high quality, safe and environmentally benign energy services to support economic and human development. Nearly 1.6 billion people have no access to electricity and some 2.4 billion people rely on traditional biomass—wood, agricultural residues and dung—for cooking and heating. The combustion of those traditional fuels has profound human health impacts, especially for woman and children. Access to liquid and gaseous fuels and electricity is a necessary condition for poverty reduction and improvements in human health.

CONCLUSIONS

The debate about "peak oil" aside, there are relatively abundant remaining supplies of fossil fuels. Their quality is declining, but not yet to the extent that increasing scarcity will help trigger a major energy transition like wood scarcity did in the 19th century. The costs of wind, solar and biomass have declined due to steady technical advances, but in key areas of energy quality —density, net energy, intermittancy, flexibility, and so on—they remain inferior to conventional fuels. Thus, alternative energy sources are not likely to supplant fossil fuels in the short term without substantial and concerted policy intervention. The need to restrain carbon emissions may provide the political and social pressure to accelerate the transition to wind, biomass and solar, as this is one area where they clearly trump fossil fuels. Electricity from wind and solar sources may face competition from nuclear power, the sole established low-carbon power source with significant potential for expansion. If concerns about climate change drive a transition to renewable sources, it will be the first time in human history that energetic imperatives, especially the the economic advantages of higher-quality fuels, were not the principal impetus.

FURTHER READING

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