The Economics of Renewable Energy

by David Timmons,
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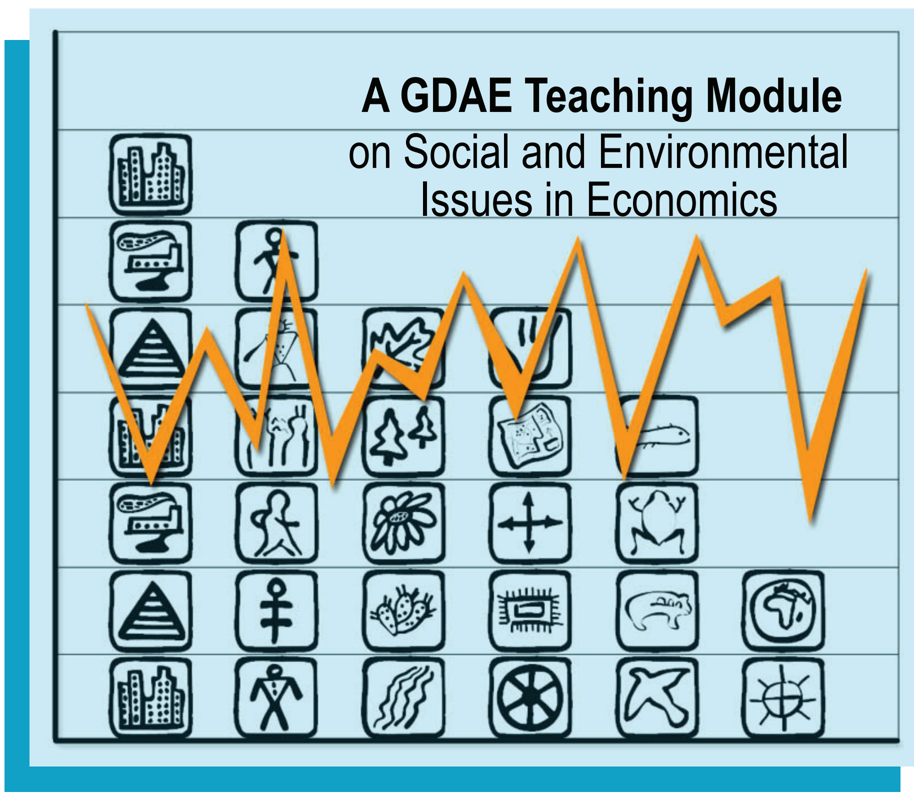

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THE ECONOMICS OF RENEWABLE ENERGY

1. ENERGY TRANSITIONS

The history of industrial civilization is a history of energy transitions. In less developed, agrarian economies, people's basic need for food calories is provided through simple forms of agriculture, which is essentially a method of capturing **solar energy** for human use. Solar energy stored in firewood or other **biomass energy** meets other basic needs for home heating and cooking.

As economies develop and become more complex, energy needs increase greatly. Historically, as supplies of firewood and other biomass energy proved insufficient to support growing economies in Europe and the United States, people turned to **hydropower** (also a form of stored solar energy), then to coal during the nineteenth century, and then to oil and natural gas during the twentieth century. In the 1950s nuclear power was introduced into the energy mix.

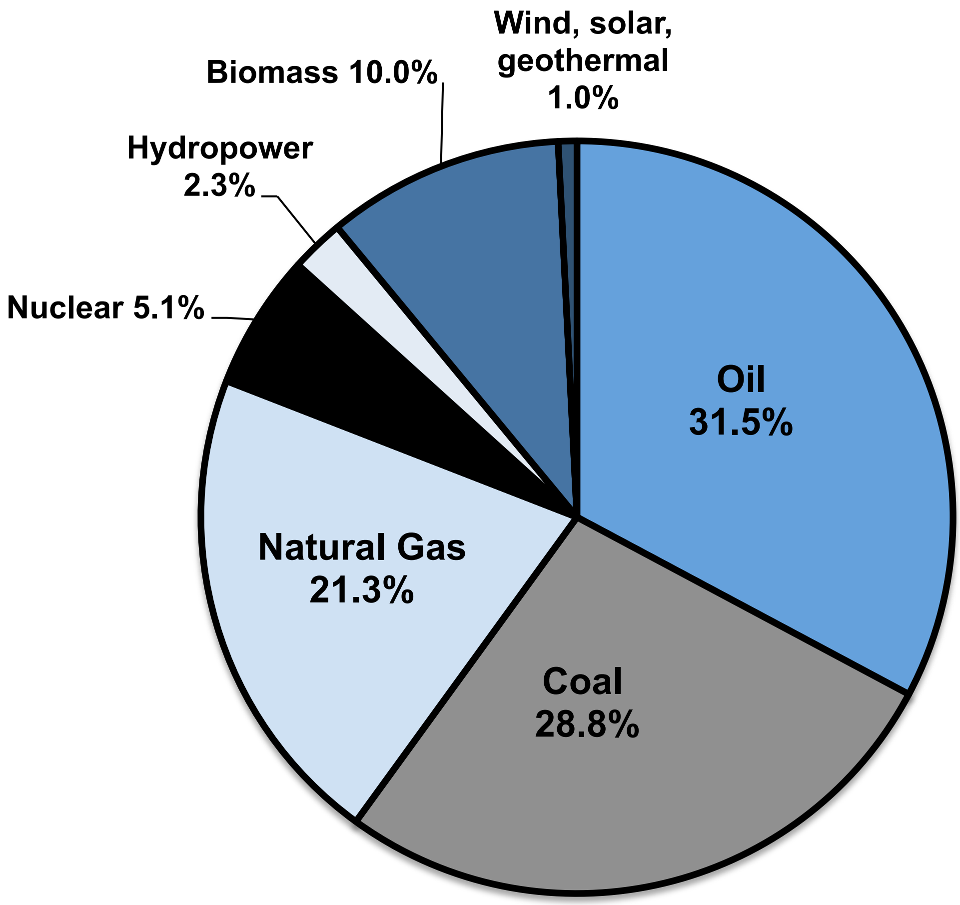
Each stage of economic development has been accompanied by a characteristic **energy transition** from one major fuel source to another. Today, fossil fuels—coal, oil and natural gas—are by far the dominant energy source in industrial economies, and the main source of energy production growth in developing economies (see Figure 1). But the twenty-first century is already seeing the start of the next great transition in energy sources—away from fossil fuels towards **renewable energy** sources. This transition is motivated by many factors, including concerns about environmental impacts (particularly **climate change**), limits on fossil fuel supplies, prices, and technological change.

Society will eventually adopt renewable energy, since fossil fuels are limited in supply and only created over geologic time. Thus the question is not whether society will shift to renewable energy, but when. Fossil fuel reserve lifetimes may be extended by new technologies for extraction, but the need to minimize the damaging effects of climate change is a more immediate problem than fossil fuel depletion. If the worst impacts of rising temperatures and climate alteration are to be avoided, society needs to switch to renewable energy sources while much fossil carbon is still safely buried in the earth's crust.

This module focuses on the outlines of the new renewable energy economy that must eventually take hold: what renewable energy sources are available, and how will optimum mixtures of renewable-energy sources be determined? How will renewable-energy mixtures vary by location? What are the direct and external costs of the new renewable energy sources likely to be? How will renewable-energy realities change the way energy is used in the economy? What kind of engineering, economic, and policy adjustments will be needed to accommodate renewable energy sources, which are somewhat different from fossil fuels?

Because so much of the **capital stock** and infrastructure of modern economic systems are based on fossil-fuel energy use, any transition away from fossil-fuel dependence will involve massive restructuring and new investment. While private markets will play a critical role in this process, major changes in government policies are necessary to foster the transition. The considerable economic implications of this justify a special focus on renewable energy use as a central economic and environmental issue.

Figure 1. Global Energy Consumption by Source, 2011



Source: International Energy Agency (IEA 2013)

2. RENEWABLE ENERGY SOURCES

In one sense, renewable energy is unlimited, as supplies are continually replenished through natural processes. The daily supply of solar energy is theoretically sufficient to meet all human energy needs for an entire year. But solar energy and other renewable energy sources are limited in the sense that their availability varies across space and time.

Some regions of the world are particularly well-suited for wind and/or solar energy. For example, solar energy potential is highest in the Southwestern United States, Northern Africa and the Middle East, and parts of Australia and South America. Some of the best regions for wind energy include Northern Europe, the southern tip of South America, and the Great Lakes region of the United States. Geothermal energy is abundant in countries such as Iceland and the Philippines. Every world region has some renewable energy resources, though availability and cost of using these vary.

Most renewable energy is ultimately solar energy. The sun's energy can be used directly for heat or electricity. Hydropower comes from falling water, which occurs because solar energy evaporates water at low elevations that later rains on high elevations. The sun also creates wind through differential heating of the earth's surface. Biomass energy comes from plant matter, produced in photosynthesis driven by the sun. Thus biomass, wind, and hydropower are just secondary sources of solar energy. Non-solar renewable energy sources include geothermal energy, which comes from the earth's core, in some combination of energy left from the origin and continued decay of nuclear materials. Tidal energy is another non-solar renewable energy source, being driven by the moon. Though nuclear power from fission is not renewable, there is great debate about whether nuclear power should be part of the post-fossil-fuel energy mix (see Box 1).

Biomass

Biomass is any fuel derived from plant matter in the recent past, and includes wood, crops, crop residues, and animal waste. Fossil fuel was also once biomass, but in the ancient past. Biomass is humanity's original energy source, in use since the discovery of fire. It still accounts for 10% of world primary energy supply and is the world's largest single renewable energy source, since much of the world's population uses wood, charcoal, straw, or animal dung as cooking fuel (IEA 2012).

Industrial economies may use biomass energy in several different forms. There is an array of biomass utilization technologies, so the literature on this subject can be confusing. In its most basic state, biomass in the form of wood pieces, chips, or sawdust can be burned. Similarly, grass and crop residues can be compressed into pellets or bricks to be burned. Biomass combustion can be used for heat (as in a wood stove), or it can generate electricity in a power plant, just like burning coal.

Box 1. Nuclear Power: Coming or Going?

Currently, nuclear power provides about 6% of the world's energy and 14% of the world's electricity. Operating externalities of nuclear energy are relatively low, as the life cycle of nuclear power generates low levels of air pollution and greenhouse gas emissions. But the potentially most significant externalities from nuclear power are the risks of a major accident and the long-term storage of nuclear wastes. These impacts are difficult to estimate in monetary terms.

The 2011 Fukushima accident, in which three of six reactors at the site melted down, leading to considerable release of radiation and continuing danger of further release, has caused many countries to reevaluate their nuclear power plans. "In Japan, the world's most catastrophic nuclear crisis since the 1986 Chernobyl disaster has other nuclear energy-dependent nations on edge. Citizens and politicians, fearful of the same tragedies in their own backyards, are calling on governments around the world to rethink their nuclear power programs" (The Citizen 2011).

Most of the world's nuclear power plants date prior to 1990. With an expected lifespan of 30 to 40 years, the decommissioning of older plants has already begun. But some prominent advocates of climate-change action support new nuclear power development (Kharecha and Hansen 2013). Of particular interest are future Generation IV reactors, which promise to have several advantages over Generation II reactors (≈1970-2010) and the current Generation III technology (Grimes and Nuttall 2010). Generation IV reactors rely more on passive measures for emergency cooling, so that unexpected power loss or failure of mechanical systems is less risky. Future reactors may also use less fuel, produce less waste, and produce shorter-lived waste than today's reactors, which create waste requiring several hundred thousand years of safe storage (Marques 2010).

But no nuclear technology can be completely safe, and many of the more-efficient nuclear cycles require isolating plutonium, an extremely toxic material that can also be used in weapons (Butler 2004). From an economic perspective, there are currently no operating examples of Generation IV reactors, so real-world costs of these reactors are unknown.

In this module we do not provide in-depth coverage of nuclear energy economics, since the characteristics of nuclear energy are quite different from the renewable energy sources discussed here. Nuclear economics hinge in part on the costs of improbable, infrequent, but extremely costly accidents, and on assumptions about nuclear waste costs, which may be incurred for millennia. The connection between peaceful and military uses of nuclear energy is another important non-economic nuclear issue. Economic tools have limited ability to evaluate such issues, some of which fall more into the ethical domain.

Chemical processes can also turn biomass into fuels like ethanol and methanol, and some crops yield vegetable oil, another fuel. Also, when biomass decomposes anaerobically (without air), methane gas is generated, which is yet another potential fuel (methane is CH_4 , the main component of natural gas). All of these energy sources are derived from biomass plant matter. Biomass for energy is normally burned in some way, which releases air pollutants, a **negative externality** of biomass use.

There are two prominent features of biomass economics. First, the solar-driven plant photosynthesis that creates biomass is a relatively inefficient way to collect solar energy, i.e. most of the available solar energy falling on plants is lost. Pimentel (2002) compared generating electricity with solar photovoltaic (PV) panels to generating electricity in a power plant fueled by forest wood chips, calculating how much land area was required to grow the trees for power-plant fuel. For each unit of electricity generated, the biomass forest required 71 times more land area than the PV panels (though the biomass electricity was still less expensive than the solar photovoltaics).

This is true for biomass in all of its forms: generating a significant amount of biomass energy requires large amounts of land. The economics of biomass energy are thus to a large extent land economics. How much land can be made available, and at what price? Using land for biomass energy production always has an **opportunity cost**, since the same land could be used to produce food or fiber, or to preserve wilderness. The effect of large-scale biomass energy use on food availability and prices is a particular concern.

The second, and related, fact about biomass is that the total quantity of biomass energy available is finite (based on available land) and small in relation to current energy consumption. One study in Massachusetts estimated that about 800,000 dry metric tons of forest biomass could be produced annually on a sustainable basis, i.e. without reducing the ability of the forest to keep producing this quantity (Kelty, D'Amato and Barten 2008). Yet even if all of this biomass were used for energy, it would replace less than 1% of 2008 Massachusetts energy consumption. Though the majority of the state is forested, biomass alone could not supply energy for current consumption levels.

This is also true for the United States as a whole and for most developed countries – biomass can provide at most a small portion of total energy needs. But there is no reason to rely on any single renewable energy source, and current consumption patterns will also be likely to change in a renewable energy economy.

Hydropower

Water power is the world's largest source of renewable electricity, generating about 16% of global electricity in 2008(IEA 2010). Where conditions are favorable, hydropower can be an inexpensive source of renewable energy, often cheaper than fossil fuels. Thus hydropower has already been extensively developed in many parts of the world.

Hydropower requires precipitation and elevation change to produce energy—wet, mountainous areas provide the best prospects for hydropower. The total energy available from hydropower depends on the volume of water available (**flow**), and its vertical drop (**head**). Head and flow are substitutes for producing hydropower: a given amount of power can be obtained with relatively low flow and high head, or with high flow and low head.

The best hydropower sites have both high head and high flow (like Niagara Falls). Such sites provide a large amount of electricity at relatively low cost. As with biomass, however, the energy potential of such sites is finite. The International Energy Agency (IEA) estimates that that in 2008, world hydropower production was 3,288 TWh, (TWh = Terawatt-hours, or trillion watt-hours, or billion **kilowatt- hours**), or about 2-3% of total global energy use in 2008, while technical potential is about five times greater at 16,400 TWh, equivalent to about 11% of 2008 global energy use . A recent U.S. Department of Energy report indicated significant additional hydropower development potential in the United States without building new dams, by developing electrical generation facilities at existing dams (http://energy.gov/articles/energy-department-report-finds-major-potential-increase-clean-hydroelectric-power)

Extent of hydropower development varies greatly by country. For example, Switzerland has developed 88% of its estimated technical potential, Mexico has developed 80%, and Norway has developed 70%. China is estimated to have developed just 24% of its technical potential, and the United States 16% (IEA 2010). Where hydropower has long historical roots, many of the best sites have already been developed, and additional development will come at higher cost. But in a renewable-energy world, energy prices may rise, which in turn would make more sites feasible for hydropower development.

The other major question in hydropower economics is external costs, particularly those attributable to dam construction. Hydropower dams have two functions: to create vertical drop or head over a short horizontal distance, and to store water to allow greater flows during times of high electricity demand. Water impoundments occupy valuable land and radically alter natural riverine ecosystems, changing habitats and provision of other **ecosystem services** (see Box 2 about the world's largest hydroelectric facility, in China). In New England, for example, the native salmon and shad populations were reduced in part by dams blocking migration routes that fish used during spawning.

Environmental externalities of hydropower can be mitigated, but at a cost. Some hydropower facilities have no dams. Water is simply piped from a higher elevation to lower one, though this may cost more than building a dam, especially if there is a long horizontal distance from the high point to the low. Generating hydropower without a dam also means forgoing water storage, which is a valuable asset for matching energy supply and demand (discussed below). Minimum and maximum alterations to natural river flow can also be established, so that a river ecosystem stays within natural flow limits. But this is likely to mean forgoing power production at times, raising the cost of generating electricity.

Box 2: Hydropower in China: the Three Gorges Dam

The world has about 45,000 dams over 15m in height and 22,000 or almost half of these are in China (compared to just 6,390 dams of this size in the United States), so China was the world's largest dam-building country even before Three Gorges (Wu et al. 2004). A dam on the Yangtze River in the Three Gorges region of south-central China was first proposed in the 1930s, with the objective of controlling devastating river flooding. For example, a 1931 Yangtze River flood killed at least 145,000 people (Stone 2008). The project was revived in 1984 by Premier Li Peng (a water engineer by training). After a long period of assessment, construction began in 2003, with the reservoir filled and power production starting in 2006.

The total area inundated by the Three Gorges Dam is 1080 km^2, with the reservoir averaging 1.1 km in width—a very long, narrow reservoir (Wu et al. 2004). The generating station has a capacity of 18.2 gigawatts (the world's largest) and is expected to produce as much as 85 billion kWh of electricity per year (Acker 2009).

There were many social and ecological concerns about building the Three Gorges Dam. An estimated 1.13 million people were displaced as their communities were destroyed by rising waters (Acker 2009), and many farms were lost as well. The Three Gorges Region is extremely biodiverse, with many rare and endangered species, a number of which are endemic to the region (Wu et al. 2004). The new reservoir both diminishes total habitat for many of these species, and fragments much of the remaining habitat. Some species are confined to newly-created islands in the reservoir. Based on such species isolation in other locations, this is expected to result in a number of extinctions, though the precise impacts are difficult to estimate (Wu et al. 2004).

Though larger and more extreme than most hydropower projects, the Three Gorges Dam represents the dilemma posed by additional hydropower development in general. Losing land to dam development is costly, environmentally damaging, and potentially unjust to those affected. Yet a large quantity of electricity can be produced at low cost, and without carbon dioxide emissions from burning fossil fuels. Using coal to produce the same amount of electricity provided by The Three Gorges Dam would require an estimated 50 million tons of coal per year (Stone 2008).

Though **tidal power** is in fact generated by lunar activity rather than solar, the physics are similar to hydropower. As with hydropower, energy is generated by a combination of water head and flow, the best sites having both high head and high flow. One method for harnessing tidal energy is to construct a dam across the mouth of an inlet. Water can flow in both directions, when the tide is coming in and going out, and energy is generated by flow in either direction. Head changes constantly with the tides, from the maximum elevation difference between high and low tide, to zero.

Compared to most hydropower sites, average tidal head is rather low, implying higher costs. In addition, building dams and generation facilities in a marine environment is more problematic and costly than in a freshwater environment. There is also great potential for environmental externalities in a marine estuary, since estuaries are some of the richest biological sites in the world. Yet in some places, tidal power may have potential as a significant and reliable source of renewable energy.

Wind power

Like biomass and hydropower, **wind power** has been used since ancient times. On the best sites, modern electricity production from wind is very close to cost parity with sources like coal and nuclear power. But there is a big difference between wind power cost on the best sites and on less suitable sites.

Wind power is generated by the energy in moving air, and available energy varies with the cube of wind velocity. Doubling wind velocity results in 2*2*2 = 8 times more potential energy; tripling wind velocity results in 3*3*3 = 27 times more energy. More potential energy generally means lower cost for a given quantity of energy. The windiest sites are thus much better than less windy sites. Generally these sites are coastal and offshore, along mountain ridges, and in vast open areas like the U.S. Great Plains.

Like biomass and hydropower, wind power potential in most regions is finite and limited by the number of sites where the energy source can be developed at reasonable cost. But if the energy output could be feasibly moved long distances, a region like the U.S. Great Plains could in theory supply much of the energy for the United States.

Not only does average wind power vary greatly by site, but power available at any particular moment also varies greatly with wind speed. Much more energy is available on windy days than on calm days. This **intermittency** characteristic is common to most renewable energy sources, but is particularly challenging with wind, given the extent to which potential energy varies with wind speed.

The **capacity factor** of an energy plant is defined as the ratio of actual energy produced to maximum energy production potential. Nuclear and coal power plants typically have very high capacity factors, sometimes exceeding 90%, meaning that over a year they can produce more than 90% of the energy they would get from running continuously at maximum output for a whole year. By contrast, a capacity factor for wind power on a good site might be 30%, with much lower factors on poor wind sites. While wind power is sometimes criticized because of its inherently low capacity factor, this is only an issue to the extent it relates to cost.

Box 3: Offshore Wind Power in Massachusetts: Cape Wind

To date most wind power development has been land-based, but **offshore wind power** has a number of advantages. Offshore winds are both stronger and more consistent than onshore. Greater wind consistency increases the wind energy capacity factor and reduces the need for energy storage. And the potential offshore wind resource capacity is enormous: according to the U.S. Energy Information Administration (EIA), U.S. coastal and Great Lakes wind energy capacity is 4.15 TW, or four times total 2009 U.S. electric generating capacity (EIA 2012).

In addition to having access to more wind energy, offshore installations do not compete with other land uses as on-shore generation sites do. Offshore there are no neighbors to be troubled by turbine noise, and installations far enough offshore can be invisible to land dwellers. Offshore turbines may ultimately be larger than on-shore turbines, since larger turbine components can be moved more easily by water.

Developing wind power offshore is also more expensive than developing wind power on land. Anchoring towers to the seafloor is one significant expense, which increases with water depth. Grid infrastructure must be extended undersea to capture the energy generated by offshore turbines. Maintenance is also more expensive offshore, as is building turbines to withstand a harsh marine environment (Snyder and Kaiser 2009).

The first offshore wind farm proposed in the United States was Cape Wind, off Cape Cod in Massachusetts. The project was first proposed in 2001, received final permits in 2011 after a lengthy permitting process, but as of 2014, construction had not yet begun. Project permits allow for the installation 130 turbines with a maximum height of 440' and capacity of 3.6 MW each, or a total of 468 MW installed capacity. Projected electricity production would provide 75% of the electricity for Cape Cod and nearby islands.

Since inception Cape Wind has been enormously controversial. Project opponents fear damage to cherished views, since at 5.6 miles offshore (closest point), the turbines would be slightly visible from shore. There could be effects on real estate values, marine and bird life, and boating. The more than 10-year long permitting process reflects both the strength of opposition to the project and lack of government jurisdictional clarity for the new offshore wind resource. Legal appeals were still in progress as of 2014.

In 2012, Cape Wind penned an agreement with National Grid for sale of electricity starting at $0.187/kWh (Ailworth 2012), considerably higher than market electricity rates in Massachusetts and more than double the cost of land-based wind power, generating still more controversy. But the success of Cape Wind would be an important step in developing what may ultimately be one of the United States' largest sources of renewable energy. In Europe, offshore wind is significantly further developed, with 64 operating offshore wind farms as of 2014.

Like all energy sources, wind power has its own externalities. The main ones of concern are aesthetic impact of the wind turbines, which are commonly over 400' in height; noise related to wind in turbine blades, which can be troublesome in close proximity to wind turbines; and bird mortality from collisions with turbine blades.

Noise and bird mortality may be mitigated by appropriate siting of wind facilities, though wind power is not completely flexible in siting, given the need to be in the windiest locations. Aesthetic impact is not easily mitigated, as wind power requires large structures that are not easily hidden. But perhaps all beauty is subjective, and some of us find wind turbines attractive, in part because of the renewable energy transition they represent. Offshore wind energy is a renewable energy resource with the potential for fewer negative externalities than onshore (see Box 3).

Wave power can be considered a secondary source of wind power, since wind generates waves. Strategies for harnessing wave power include floatation devices that rise and fall with waves, which in turn create mechanical energy, eventually being converted to electricity. While there are many conceptual designs for harnessing wave energy, there are few large-scale working examples. Cost is again the issue: while some energy is available in waves, it is expensive to turn this into useful energy for society.

Direct Solar Energy

Solar energy comes in three basic forms: 1) Low temperature solar thermal, 2) solar electric or photovoltaic (PV), and 3) high-temperature solar thermal energy.

Low-temperature solar applications include solar water heating and solar space heating. Sunshine strikes some surface, usually black for maximum solar absorption, which in turn heats air or water. A protective layer of glazing helps to retain heat captured. Solar heat can be stored in high-mass materials like water or stone. Low-temperature solar energy typically uses simple and proven technologies.

Solar water heating is already financially competitive with fossil fuels in many climates. Solar space heating is also possible, but a challenge with solar space heating economics is that monthly demand and supply are almost exactly opposite: the greatest demand is in winter, when there is the least supply of sun, and the most sunshine occurs in summer when demand for heating energy is lowest. In practice this means that solar space heating systems almost always require some supplemental heat source, since the marginal cost of gathering solar energy in the depths of winter is extremely high. Supplemental heating adds to the cost of solar heating systems.

Solar energy can also be used to produce electricity instead of heat. **Photovoltaic (PV)** cells employ semiconductor material to generate a flow of electricity when struck by sunlight. Though the technology is now well developed and reliable, it is also expensive compared to current energy sources, perhaps three times as expensive as fossil-fuel generated electricity, depending on the specific circumstances being compared. Costs of solar PV have fallen considerably, and are projected to fall further; an important issue, discussed further below, is whether and when solar costs will reach a fully competitive range.

In contrast to other renewable energy sources, solar PV is sustainably available in almost infinite quantities, and in almost any location. In the United States, National Renewable Energy Laboratory data shows annual mean available solar PV kWh per day for all locations in the United States. Available energy varies from about 6.0 kWh per day per m^2 of PV panel in most of New Mexico and Arizona, to about 4.0 kWh per day in all of New England, to as little as 3.5 kWh per day in coastal Oregon and Washington (NREL 2008). Though these availability differences translate into cost differences, solar PV can be employed almost anywhere (with the possible exception of far northern and southern latitudes). For example, though Germany is not among the world's sunniest places, Germany has been a leader in installed photovoltaic capacity.

The space required for solar PV is significant. Solar cells are typically mounted in modular panels, which are installed in arrays that can be ground, pole, or roof mounted. Arrays range in size from a few panels on a rooftop, to a roof made entirely of solar panels, to a field of many acres covered by panels. Supplying much of society's electricity from solar PV would require a considerable, though not insurmountable, amount of space (see Box 4). But solar PV is not the only renewable energy source, and energy use may decrease in a renewable-energy economy (as discussed below).

High-temperature solar energy is another means to generate electricity or to provide process heat for industrial applications. In a typical installation, the sun's rays are concentrated by a mirrored collector. The concentrated sunlight is directed at a point where energy is absorbed and passed to a transfer medium such as oil. The high-temperature oil then makes steam to generate electricity in conventional turbines. Though such systems are more complex than solar PV, with many moving parts, on a large scale they may produce electricity less expensively than PV in some locations (as indicated in Figure 2, below). Spain has been a global leader in concentrated PV, with over 2,000 megawatts installed capacity as of 2014. But since concentrating solar electric systems are not yet in widespread use, long-run costs are not well known, and estimates of future cost vary widely.

Box 4: Solar Electric Footprints

While the total quantity of solar energy reaching Earth each day from the sun is enormous, available energy at any specific point is modest. The amount of energy derived from solar panels depends on the ambient solar level as well as collector energy conversion efficiency. The angle at which collectors are installed also affects energy production and space requirements: panels arranged perpendicular to solar rays gain the most energy but require space between them to avoid shading, and panels laid horizontally gather less energy per panel but require the least amount of total space.

Since solar energy supply does not always meet demand, some solar energy may need to be stored (discussed below), and since storage is less than 100% efficient the total solar electricity generation requirement may be greater than final electricity demand.

One study looked at the space requirements to power the U.S. electric grid exclusively with solar energy (Denholm and Margolis 2008). Although this scenario is unlikely even in a 100% renewable-energy economy, it gives an idea about the space requirement for an electric supply with a large solar component. At current solar panel efficiencies, the authors find the average U.S. solar footprint is about 181 m^2 per capita, or an area about 44 feet square for each person in the United States. This value varies depending on location, angle of panel installation, and assumptions about location of industrial electricity use: much electricity used in the creation of manufactured goods represents embedded energy moved around the United States (and the world).

Nationally, generating 100% of electricity with solar PV would require an area about 235 km (146 miles) square, again depending in part on where the panels were located. This is 0.6% of U.S. land area. At the state level (if each state produced all its own electricity exclusively from PV), the percentage of land area needed ranges from a low of 0.04% in Wyoming to a high of 8.8% in New Jersey. For New Jersey, this represents about the twice the current area of state roads and roofs. Of course states need not be electricity self-sufficient and not all renewable electricity will come from PV. But the solar electric footprint will clearly be noticeable.

Geothermal Energy

Like “biomass” and “solar”, the term “**geothermal**” actually refers to a number of different technologies, distinguished primarily by the temperature of the geothermal resource. The temperature of the earth increases steadily with depth, and the core of the earth is actually molten. For geothermal energy utilization, the key questions are how high the temperature is, at what depth, and how easily the heat can be extracted.

In the most pure and most economical form of geothermal energy use, temperatures high enough to boil water are found near the surface of the earth. This occurs in places like the Philippines and Iceland, as well as in other countries near the boundaries of tectonic plates. In such places, relatively shallow wells can produce steam with high enough pressure and temperature to generate electricity in steam turbines. Though there are a number of costs of dealing with natural steam (an array of undesirable chemicals in the steam, for example), such geothermal energy is relatively low cost, and unlike other renewable energy sources discussed here, has the advantage of being able to operate continuously. But this possibility is limited to active seismic areas. Binary cycle power plants rely on boiling a non-water liquid like ammonia, operating at lower temperatures than steam turbines, and useable in many more locations.

At the next level on the thermal gradient, some areas have geothermal water too cool to generate electricity but hot enough for space heating. Again, this is common in Iceland, where about 90% of building space is heated by geothermal water (Eggertsson et al. 2010). Areas with geothermal water of sufficient temperature for heating are more common than areas with steam for generating electricity, but are still relatively unusual in the world. Hot water could of course be found in a deep enough well at any place on earth (given that the Earth's core is molten), but such wells would need to be extremely deep in most places, and the cost of drilling wells makes such energy expensive.

The term "geothermal" can also be applied to a system using groundwater **heat pumps**. In such systems, water is circulated through the ground at temperatures too low to heat buildings directly, usually around 50^{o} F. But there is still energy in 50^{o} F water, and heat pumps use refrigeration technology to concentrate this heat and bring it up to a useable temperature for heating a building (e.g. 120^{o} F). Heat pumps require electricity to run their motors, but heat output is up to five times more than electrical energy input. Thus while the heat technically comes from the earth, it is more accurate to think of groundwater heat pumps as a very efficient way to use electricity for heating.

Renewable Energy Availability

A recent study concluded that renewable energy sources, based on wind, water, and sunlight (abbreviated as WWS; not including biomass), could provide all new energy globally by 2030, and replace all current non-renewable energy sources by 2050 (Jacobson and Delucchi 2011, p. 1154). Table 1 shows estimates of the potential energy from various renewable energy sources, converted into trillions of watts.

Projected global energy demand in 2030 is 17 trillion watts. Thus we see in Table 1 that the availability of energy from wind and solar in likely-developable locations is more than sufficient to meet all the world's energy needs. The authors' analysis envisions:

> "...a world powered entirely by WWS, with zero fossil-fuel and biomass combustion. We have assumed that all end uses that feasibly can be electrified use WWS power directly, and that the remaining end uses use WWS power indirectly in the form of electrolytic hydrogen (hydrogen produced by splitting water with WWS power). The hydrogen would be produced using WWS power to split water; thus, directly or indirectly, WWS powers the world."

Table 1. Availability of Global Renewable Energy

Energy Source	Total Global Availability (trillion watts)	Availability in Likely-Developable Locations (trillion watts)
Wind	1700	40 – 85
Wave	> 2.7	0.5
Geothermal	45	0.07 – 0.14
Hydroelectric	1.9	1.6
Tidal	3.7	0.02
Solar photovoltaic	6500	340
Concentrated solar power	4600	240

Source: Jacobson and Delucchi (2011)

The authors then estimate the infrastructure that would be necessary to supply all energy worldwide from WWS in 2030. Table 2 presents their results, based on the assumption that 90% of global energy is supplied by wind and solar, and 10% by other renewables.

They also consider the land requirements for renewable energy infrastructure, including the land for appropriate spacing between wind turbines. Total land requirements amount to about 2% of the total global land area, with most of this the space between wind turbines that could be used for agriculture, grazing land, or open space. Also, wind turbines could be located offshore to reduce the land requirements.

Table 2. Infrastructure Requirements for Supplying All Global Energy in 2030 from Renewable Sources

Energy Source	Percent of 2030 Global Power Supply	Number of Plants/Devices Needed Worldwide
Wind turbines	50	3,800,000
Wave power plants	1	720,000
Geothermal plants	4	5,350
Hydroelectric plants	4	900
Tidal turbines	1	490,000
Rooftop solar PV systems	6	1.7 billion
Solar PV power plants	14	40,000
Concentrated solar power plants	20	49,000
TOTAL	100	

Source: Jacobson and Delucchi (2011)

The technology already exists to implement these renewable energy sources, and while world renewable energy is available in sufficient quantities, the issue of costs is central to the question of how rapidly an energy transition will occur. Costs include energy infrastructure investment and the day-to-day operations. In analyzing costs, we should consider both the market costs of supply and the environmental costs of various energy sources. It is to this analysis that we now turn.

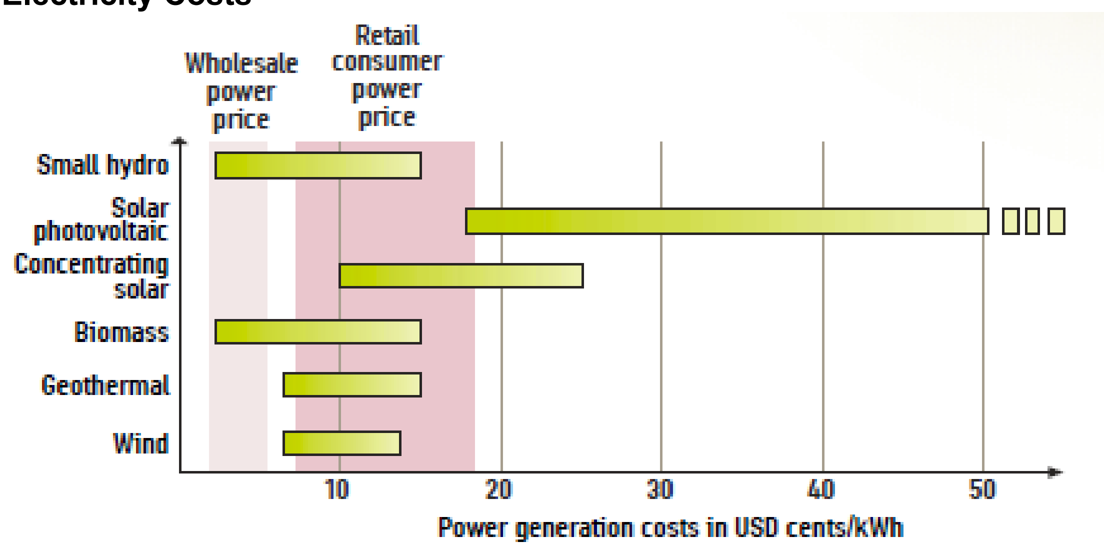
3. RENEWABLE ENERGY ECONOMICS

The world currently gets about 80% of its energy supplies from fossil fuels because these sources generally provide energy at the lowest cost. However, the cost advantage of fossil fuels over renewable energy sources has been decreasing in recent years, and certain renewables can already compete with fossil fuels solely on financial terms. Renewable energy costs are expected to decline further in the future, while fossil fuel prices will likely rise. Thus even without policies to promote a transition toward renewables, economic factors are currently moving us in that direction.

Cost comparisons between different energy sources are made by calculating the **levelized cost of energy (LCOE)**. Levelized costs represent the **present value** of building and operating a plant over an assumed lifetime, expressed in real terms to remove the effect of inflation. For energy sources that require fuel, assumptions are made about future fuel costs. The levelized construction and operations costs are then divided by the total energy obtained to allow direct comparisons across different energy sources.

Figure 2 compares the cost of renewables with traditional fossil fuel electricity costs. In order for renewables to be cost competitive, their costs generally need to fall to the wholesale electricity price, or the price at which fossil-fuel power plants sell electricity to the grid. This has already occurred for some renewables, such as hydropower and biomass. Figure 2 indicates that wind and geothermal are nearly cost competitive with traditional power sources. Solar is more costly, but since solar photovoltaics can be installed by individual consumers the price of PV only needs to fall to the retail power price that consumers pay, which is greater than the wholesale price.

Figure 2. Cost Comparison of Renewable Energy Sources to Fossil Fuel Electricity Costs

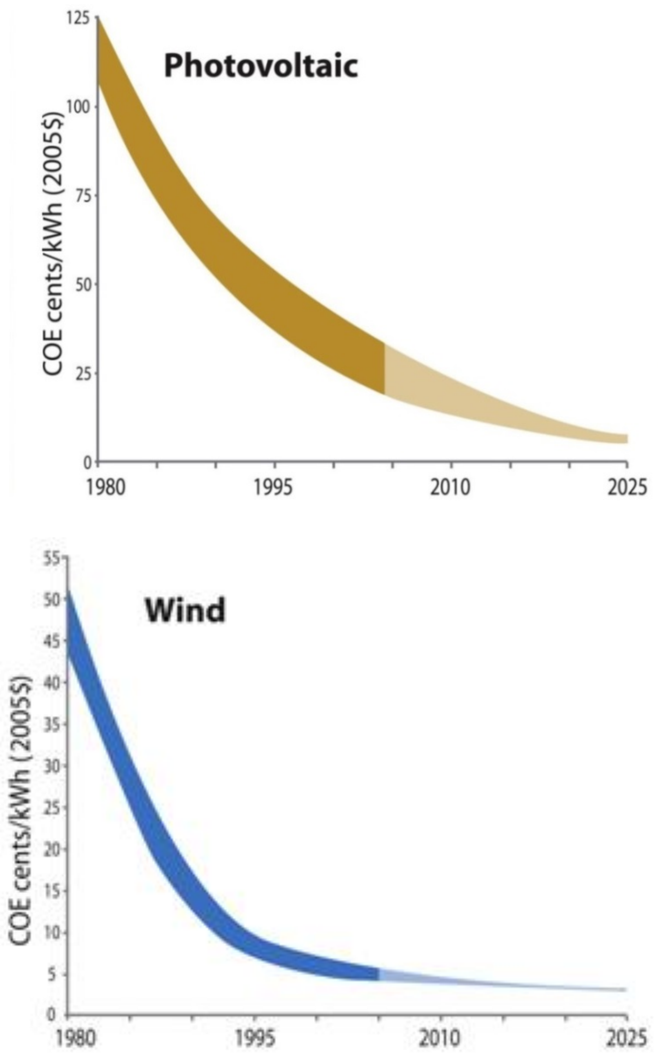


Source: International Energy Agency and Organization for Economic Cooperation and Development (IEA 2007)

Figure 3 shows past and projected cost trends for wind and solar energy. While further cost decreases are likely, the shape of the cost curves suggest that future costs will decline more slowly than in the past. Besides decreasing in cost, Figure 3 also suggests that photovoltaic and wind cost variation will decrease. Thus the future prices for renewable energy are expected to be more predictable, which is not the case for fossil fuels. According to a U.S. Department of Energy report, installed prices of U.S. PV systems fell by 5-7% per year on average from 1998-2011and by 11-14% from 2010-2011, with further price declines expected (DOE 2012).

While renewable energy costs are decreasing, future market prices for renewable energy will not necessarily be less than historic fossil fuel prices. Cost challenges for producing renewable energy include renewables' net energy, their intermittency, and their capital intensity.

Figure 3. Declining Cost of Solar and Wind Energy



Source: National Renewable Energy Laboratories (2005)

Net Energy

The fossil fuels that make up most of our current energy portfolio represent very concentrated pools of energy. For example, a gallon of gasoline contains about 37 kWh (kilowatt hours) of potential energy. An average person running for an hour burns about 0.13 kWh (Haymes and Byrnes 1993), so a person would have to run for 285 hours or almost 12 days continuously to expend the amount of potential energy in just one gallon of gasoline. A typical 3' x 6' solar PV panel can generate about 0.2 kWh in one hour of bright sunshine. The sun would need to shine on such a panel for 185 hours (about a month, assuming six hours of bright sun per day) to provide the same energy as a gallon of gasoline. The reason that gasoline and other current fossil fuel sources are so widely used is that they have large amounts of conveniently concentrated energy, readily available to perform useful work.

It takes energy to get energy, but in the past it did not take very much. For example, early oil deposits were found near the surface, avoiding the need for deep drilling and pumping the oil a great vertical distance. As time went on, the energy required to find, extract, and process crude oil increased. This energy cost of acquiring oil should be deducted from the energy obtained to reflect the net available energy.

Net energy is normally expressed a ratio of the energy available for final consumption divided by the energy required to produce it. (Another term for "net energy" is "energy return on (energy) invested", or EROI. See Cleveland 1991). A large **net energy ratio** means we get lots of useful energy for a small energy investment, as with the original oil deposits. Table 3 shows the net energy ratios for various energy sources. Net energy ratios for the same source can vary significantly, depending on specific production technology and conditions, as shown by difference in net energy ratios for various forms of biomass energy (Table 3, last four rows).

Table 3. Net Energy Ratios for Various Energy Sources

Energy Source	Net Energy Ratio	Reference
Oil (global)	35	(Yandle, Bhattarai and Vijayaraghavan 2004)
Natural gas	10	(Hall 2008)
Coal	80	(Cleveland 2005)
Shale oil	5	(Hall 2008)
Nuclear	5-15	(Lenzen 2008; Murphy and Hall 2010)
Hydropower	>100	(Hall 2008)
Wind	18	(Kubiszewski, Cleveland and Endres 2010)
Photovoltaic cells	6.8	(Battisti and Corrado 2005)
Ethanol (sugarcane)	0.8 – 10	(Hall, Cleveland and Kaufmann 1986),(Goldemberg 2007)
Ethanol (corn-based)	0.8 – 1.6	(Farrell, Pelvin and Turner 2006)
Biodiesel	1.3	(Hall, Cleveland and Kaufmann 1986)
Farmed willow chips	55	(Keoleian and Volk 2005)

Adapted from Murphy and Hall (2010)

Net energy is a physical attribute of an energy source, and one component of energy cost. For example, if better technology reduces the energy required to make a solar panel, the cost of the panel will fall, and the cost of delivered photovoltaic electricity will also fall. As shown in Table 3, renewable energy sources generally have low net energy ratios, at least compared to historic fossil fuels like oil and coal. Though there is a large quantity of solar radiation falling on the earth every day, it is dissipated over the whole earth's surface, and collecting such dispersed energy is costly.

Intermittency

By their nature, most renewable energy supplies cannot be matched to demand as easily as fossil fuels. Natural sources of energy cannot be conjured up in each moment that we need energy: some days the wind does not blow, and the sun does not shine. Hydropower may be unavailable during drought periods, and biomass crops experience crop failures (just like food crops). Most renewable energy sources have low capacity factors and are less consistent than fossil fuels, which increases cost.

The supply-demand matching problem is most extreme in the electricity market, where supply must match demand in every moment. To some extent demand is predictable, and fossil fuel plants can be scheduled to start and stop at times of anticipated demand change. Additional plants that start and stop quickly (e.g. gas turbines) can be held in reserve for unanticipated demand changes.

On the renewable side, solar and wind power do not have this character at all; energy output simply cannot be increased on demand. Hydropower may be regulated to accommodate demand, if reservoirs are adequate (and adequately replenished by rainfall). Biomass is similar to fossil fuels, available to burn on demand. Geothermal energy is the most constant of the renewable energy sources and can be started and stopped on demand. Most renewable energy portfolios will include some sources that are not available on demand, and thus most regions will have to confront energy-source intermittency. There are several approaches to this.

Energy diversity is one approach to intermittency. For example, solar energy is strongest in the summer, while in most places wind energy is strongest in the winter. A combination of the two can provide more consistent year-round electricity generation than either one individually. If this diversity of sources would be chosen in a given area anyway, there is no cost to using diversity as a way to correct intermittency.

It also is possible to store electricity. For example, remote solar houses can store electricity in batteries. Battery storage must be at least sufficient for nights, ideally with some additional storage for cloudy days and/or periods of high electricity use. This same technology could be deployed on a broader scale, with individual buildings having on-premise battery storage. Renewable energy could be taken from the grid as it was available, and used as needed. The cost of delivered energy would then be the cost of production plus the cost of battery storage.

On a grid scale, electricity storage is more frequently accomplished with **pumped water storage**. When excess electricity is available from the grid, water is pumped from a lower reservoir to a higher reservoir. When electricity is needed, the water is allowed to flow back down and generate electricity. This is the same technology used in hydroelectric plants, but with water and energy able to move in both directions. This technology has already been deployed for use with non-renewable energy sources, for example at the Northfield Mountain pumped-storage station in Massachusetts (http://www.firstlightpower.com/generation/north.asp). Again, costs of required energy storage are in addition to costs of renewable energy generation.

Energy source redundancy means building excess generation capacity. The authors of the world WWS assessment shown in Table 1 envision building significant excess wind and solar capacity, with excess power used to produce hydrogen through electrolysis. The hydrogen could then be burned for heat or for electricity generation during times of low renewable energy availability. The cost of this kind of system is in the infrastructure to produce, store, and burn hydrogen.

In combination with excess capacity, a robust national (and possibly international) electric grid is another approach to intermittency. Though the wind may not blow in a particular place at a particular time, wind is likely blowing somewhere all the time. An electric grid can be used to move energy from where it is being produced to where it is needed. But moving large amounts of electricity over long distance requires a substantial electricity grid. Policies that support grid development will likely be needed to support increased renewable energy utilization.

Finally, the marginal cost of renewable energy will clearly vary substantially depending on ambient conditions. At times of low wind, water, and solar energy availability, the marginal cost of renewable energy will be very high. **Variable electricity pricing** implemented with **smart electric meters** could charge consumers a higher price for electricity at times when the renewable electricity supply was limited. Consumers could then make choices to limit electricity use, or to program appliances to only operate at certain price points. For example, water heaters could be programmed to only operate in low-price time periods, since water in an insulated tank stays hot for many hours.

A complete transition to renewable energy is also likely to take many years (as discussed below). To the extent that fossil fuel resources continued to be used, one of their most valuable applications will be in balancing renewable energy supply with demand. Natural-gas fired electricity is particularly well suited to this purpose, as natural-gas turbines can be started and stopped quickly as needed.

Capital Intensity

Compared to fossil fuels, most renewable energy sources require large capital investments, as shown in Table 4. When burning a fossil fuel like natural gas to generate electricity, a large portion of the total electricity cost is from purchasing gas, and these gas purchases are spread out over a long period of time.

For a gas-fired plant with a 50-year lifetime, $1 of gas purchased in year 50, discounted at a 5% rate, would account for just $0.09 in present value at the time of plant construction. In addition, no money has to be borrowed to finance the purchase of gas for future years of electricity production.

Table 4. Capital Cost of Renewable and Non-Renewable Electricity Sources

	Nominal Capacity (MW)	Capital Cost ($/kW)	Assumed Capacity Factor	Capital $/Expected[1] kW
Natural gas: combined cycle	620	$917	90%	$1,019
Coal: advanced pulverized fuel	650	$3,246	90%	$3,607
Hydroelectric: conventional	500	$2,936	75%	$3,915
Nuclear: dual unit	2,234	$5,530	90%	$6,144
Wind: onshore	100	$2,213	25%	$8,852
Biomass combined cycle	20	$8,180	90%	$9,089
Wind: offshore	400	$6,230	35%	$17,800
Solar: photovoltaic	150	$3,873	20%	$19,365
Solar: thermal electric	100	$5,067	20%	$25,335

Adapted from EIA (2013)

Renewable solar and wind energy sources have low operating costs—once generating facilities are built, there is little additional cost for producing energy each year. While this is an operating advantage over fossil fuels, it comes at the cost of higher capital expenditure. Building a renewable energy plant is similar to building a fossil energy plant plus buying all the fuel that the fossil plant will use over its lifetime. Few homeowners would purchase a gas furnace and at the same time purchase all the gas the furnace would use over its life. Yet by their nature, this is what is expected for most renewable energy sources.

The high capital cost of most renewable energy sources means that renewable electricity cost is sensitive to interest rates. High interest rates make renewable sources significantly less attractive when compared to fossil fuels, while low interest rates make renewables more attractive. Changing interest rates effectively changes the cost of renewable energy, since interest rates determine the cost of borrowing for initial capital investment.

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[1] For comparing sources with different capacity factors, we define $/expected kW as ($/kW)/(capacity factor), or the capital cost to produce the same amount of electricity as one kW of capacity running continuously.

Renewable Energy Mix and Energy Conservation

If you have studied microeconomics before, you know that marginal values are an important part of the story. For example, it is generally true that we maximize net benefits when the marginal benefit (of anything) equals its marginal cost. The **marginal cost** of something is the cost of another unit, given how much we already have—if I have 5 kW solar electric array in my yard, the marginal cost is the cost of adding a sixth kW, which may be more expensive than the first 5 kW, if I have to use a less ideal location. Marginal costs of renewable energy are key to understanding the optimum mix of renewable energy resources and the balance between producing and conserving energy.

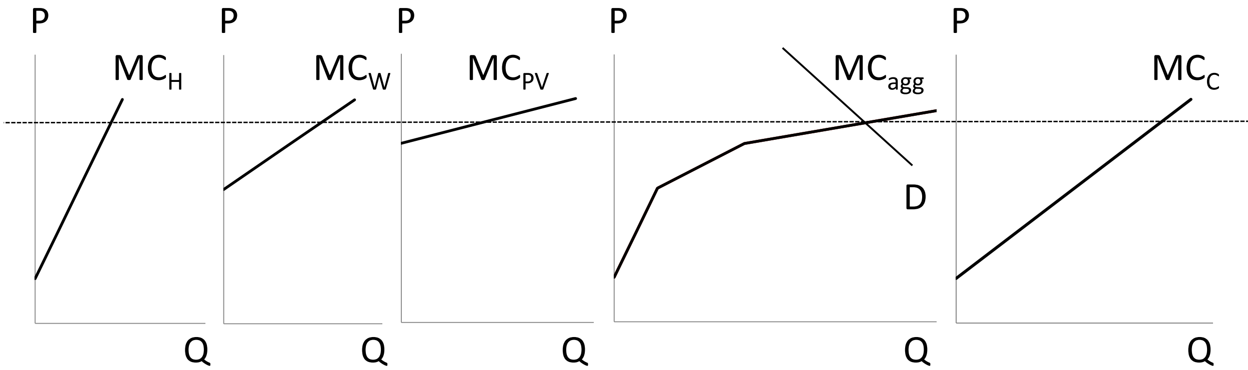
Typically we find rising marginal costs for renewable energy sources in any particular place. We build the first increments of hydropower, wind, and solar power generation in the most-accessible, least-costly, and most productive sites. Additional increments of energy come from sites that are more expensive to develop and/or yield less energy.

For economic efficiency, all energy sources within a given market should have the same marginal cost. For example, if I could get solar electricity for $0.15/kWh and wind electricity for $0.10/kWh, I should of course use the cheaper wind power (assuming no non-market externalities are involved). Having built more wind capacity, the next unit of wind energy will likely be more expensive (marginal cost is rising). But to minimize my energy cost, I should keep building wind power as long as it less expensive than solar electricity. If the marginal cost of one energy source is cheaper than another, I have not fully exploited the cheaper energy source and have not minimized my energy cost.

Thus the **equimarginal principle** is that minimum total cost occurs when all marginal costs are equal. An optimal mix of renewable energy sources would have equal marginal costs for all sources, which means each type of energy will likely include some lower-cost and higher-cost sources. For example, an optimum mix would likely include both lower-cost hydropower and higher-cost hydropower, with higher marginal cost being close to that of solar electricity.

Figure 4 demonstrates the equimarginal principle graphically, with schematic representations of marginal cost (MC) curves illustrative of a renewable energy supply in some hypothetical region (an actual supply would likely include more sources). Hydropower (panel A) is typically the least expensive renewable source, at least for initial quantities, though costs rise quickly as more difficult hydropower sites are used. Wind (panel B) is somewhat more expensive but often available in higher quantities than hydropower, especially if offshore wind is included. Solar PV energy (panel C) is currently the most expensive renewable source, but is available in virtually unlimited quantities. Panel D shows an aggregate renewable marginal cost curve, a combination of curves A-C.

Figure 4. Equality of renewable energy marginal costs (MC) and cost of conservation



A. Hydropower: low initial cost, but limited quantity	B. Wind: higher cost, higher quantity	C. Solar PV: highest cost, unlimited quantity	D. Aggregate renewable supply, and demand	E. Conservation: high quantity available at MC of solar PV

In figure 4, panel D, the intersection of the upward-sloping aggregate supply curve and downward-sloping demand curve (D) identifies how much energy our regional market will produce. The dotted horizontal line across panels A-D in Figure 4 shows that if we apply the equimarginal principle, the marginal costs of all renewable energy sources used are equal. Though initial quantities of hydropower are much less expensive than solar PV, the least-cost energy supply is provided by a combination of high-priced hydropower and wind, as well as solar (since in this example we need all three sources to provide the required quantity of energy).

The marginal cost of the most expensive energy source needed to meet demand effectively determines the marginal cost of all the energy sources we use (since marginal costs must be equal to minimize total cost). Solar PV is the most expensive but most abundant renewable energy resource in this example, as in many parts of the world. The cost of solar PV can thus have a great effect on the entire renewable energy economy. Research and development to reduce the marginal cost of solar energy is critical to widespread deployment of renewable energy technology.

The Potential for Energy Efficiency

If economic efficiency requires equality of marginal costs for all energy sources, then this is also true for energy conservation, which can effectively make more energy available by reducing its use. If it is less expensive to reduce energy use through conservation than to incur the cost of more energy, one should of course reduce use. The marginal cost of energy conservation should equal the marginal cost of renewable energy. This is shown in Figure 4, panel E. The marginal cost of energy conservation is currently very low compared to the cost of renewable energy, especially compared to the cost of solar PV, the renewable that will likely determine the marginal cost of all renewable energy. Thus a major issue in replacing fossil fuels with renewables is extensive development of energy efficiency and conservation.

In the past, residential construction in the northern United States used 4” of wall insulation; now 6” is more common, but “super-efficiency” can be achieved with even thicker insulation Windows can also be super-insulated. Cars previously traveled 15 miles per gallon of gasoline (MPG); now 25 MPG is more typical, but 50 MPG or higher is attainable with existing technology.

Since the technologies for much higher efficiency are already available, the issue is largely economic. Our current society is designed around energy prices at current levels. Walls previously had only 4” of insulation because it was cheaper to buy energy than to buy more insulation (in present value, after discounting future energy expenditures). Change the price of energy, and the optimum thickness of wall insulation changes. And this is true for every energy use in society.

If energy costs rise with depletion of fossil fuels and deployment of higher-cost renewables, efficiency becomes a more economically attractive option. This can already been seen in regions like Europe, where historically high gasoline taxes have created development patterns and transportation systems that are much less energy intensive than those in the United States. While price is not the only determinant of energy use, it is a critical factor.

Much energy conservation can be accomplished at very low cost. As the U.S. Environmental Protection Agency has noted:

> Improving energy efficiency in our homes, businesses, schools, governments, and industries—which consume more than 70 percent of the natural gas and electricity used in the country—is one of the most constructive, cost-effective ways to address the challenges of high energy prices, energy security and independence, air pollution, and global climate change (National Action Plan for Energy Efficiency 2008).

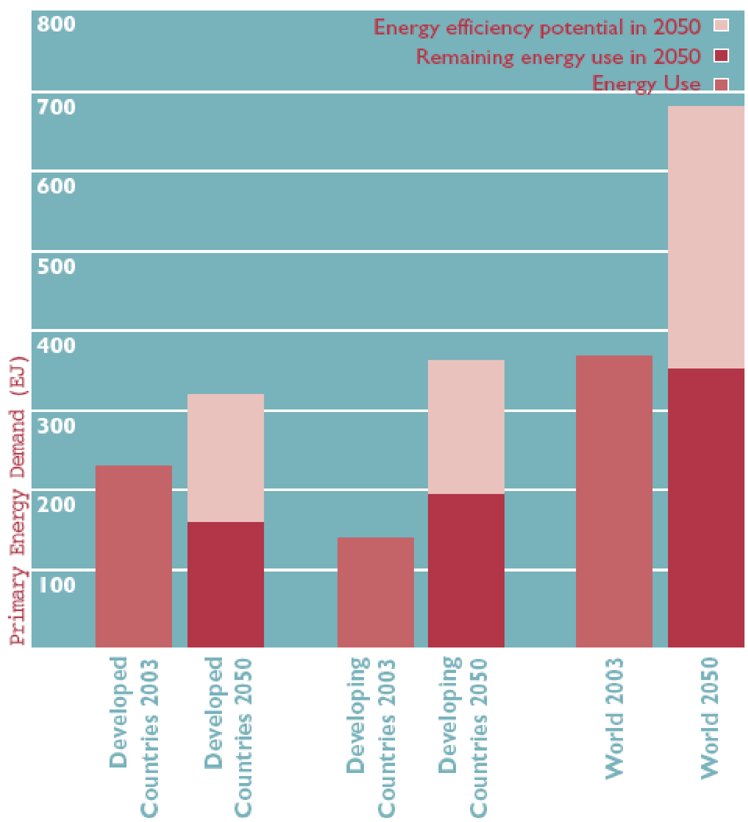
In some cases energy efficiency improvements can be obtained by technological changes, such as reducing fuel use by driving a hybrid car. In other cases, energy efficiency means changing behaviors, such as drying clothes on a clothesline instead of a clothes dryer, or allowing dishes in a dishwasher to air-dry rather than using the “heated dry” setting . The potential for demand-side management to reduce the projected growth of energy consumption is significant.

Under a business-as-usual (BAU) scenario, global energy demand is projected to nearly double between 2003 and 2050. However, based on the untapped potential for energy efficiency it has been estimated that global demand could be held steady during this time period, as shown in Figure 5. In developed countries, energy demand could actually decrease relative to current levels. In developing nations, energy consumption would still increase, but only by about 40%, instead of by 160% under a BAU scenario.

Realizing such gains from energy efficiency will require substantial investment, estimated to be about 0.2% of global GDP (Blok et al. 2008). However, investments in energy efficiency are typically much cheaper than meeting demand growth through developing new energy supplies. Well-designed energy efficiency programs currently cost an average of only about one-half the cost of providing new energy supplies (National Action Plan for Energy Efficiency 2006).

Another analysis estimates the current cost of energy efficiency at zero to 5 cents per kilowatt-hour (Lazard 2009). Comparing this estimate to the $0.20-0.50 current cost of PV electricity (Figure 2), we see the great opportunities to reduce current energy use through conservation.

Figure 5. Global Potential for Energy Efficiency



Source: Blok et al. (2008)

These figures on the potential of energy efficiency indicate that it may, in fact, be the “alternative energy source” with the greatest potential. The renewable transition may be accomplished as much by reducing energy requirements of daily living as by introducing new renewable energy sources. The renewable energy revolution will be in significant part an energy efficiency and conservation revolution.

If energy prices rose as part of the transition to renewable energy, this would create the incentive for a market response of greater efficiency. Society would respond by redesigning all systems to use less energy. But even without a significant increase in the price of energy, major progress on energy efficiency is possible, and can be promoted through the use of standards, such as the Obama administration fuel efficiency standards, announced in 2011, that would raise the average fuel efficiency of new vehicles to 54.5 mpg by 2025. Other efficiency standards that can be tightened include those for buildings, appliances, electronics, and light bulbs.

Economists point out that if efficiency standards are raised without any increase in energy prices, there is a **leakage** effect – since it is cheaper to use more efficient cars and appliances, people may respond by using them more, thus partly offsetting the energy reductions from greater efficiency. There is also a good argument that energy prices *should* rise to reflect the negative externalities of current fossil fuel use (discussed further below). Of course, higher energy prices are not popular – but from an economic view they are the best way to promote increased efficiency.

Energy Subsidies

The preceding discussion assumes an unregulated free market for energy, which is not the case in most of the world today. In particular, many forms of energy use are financially supported or subsidized by governments. Energy subsidies can take various forms, including:

- Direct payments or favorable loans: A government can pay a company a per-unit subsidy for producing particular products, or provide them a loan at below-market interest rates.
- Tax credits and deductions: A government may allow individuals and businesses to claim tax credits for actions such as installing insulation or purchasing a fuel-efficient vehicle. **Depletion allowances** are a form of tax credit widely used for oil production.
- Price supports: For example, the price that producers of renewable energy receive may be guaranteed to be at or above a certain level. **Feed-in tariffs**, commonly used in Europe, guarantee producers of solar and wind power a certain rate for sales of power to the national grid.
- Mandated purchase quotas: These include laws requiring that gasoline contain a certain percentage of ethanol, or that governments buy a certain percentage of their energy from renewable sources.

Subsidies can be justified to the extent that they support goods and services that generate **positive externalities**. All energy sources currently receive some degree of subsidy support, but as discussed in Box 5, subsidies heavily favor fossil fuels. Given that fossil fuel use tends to generate negative, rather than positive, externalities, it is difficult to justify such subsidies on the basis of economic theory. Directing the bulk of energy subsidies toward fossil fuels tilts the playing field in their favor relative to renewables.

In 2009 the G20 nations, a group of major economies including both developed and developing countries, agreed to "rationalize and phase out over the medium term inefficient fossil fuel subsidies that encourage wasteful consumption" and "adopt policies that will phase out such subsidies worldwide" (IEA 2011d). The International Energy Agency notes:

> "Energy subsidies—government measures that artificially lower the price of energy paid by consumers, raise the price received by producers or lower the cost of production—are large and pervasive. When they are well-designed, subsidies to renewables and low-carbon energy technologies can bring long-term economic and environmental benefits. However, when they are directed at fossil fuels, the costs generally outweigh the benefits. Fossil fuel subsidies encourage wasteful consumption, exacerbate energy-price volatility by blurring market signals, incentivize fuel adulteration and smuggling, and undermine the competitiveness of renewables and other low-emission energy technologies" (IEA 2011c).

Global subsidies to fossil fuels in the electricity sector amount to about $100 billion annually (Kitson, Wooders and Moerenhout 2011). Data on subsidies to nuclear power are difficult to obtain, but the limited information available suggests global nuclear subsidies of at least $10 billion.[2] Global subsidies to renewable forms of electricity amount to about $30 billion annually, but are growing faster than other subsidies.

While the majority of electricity sector subsidies go to fossil fuels, on a per-kilowatt-hour basis subsidies actually do provide a price advantage for renewables. Subsidies effectively lower the price of electricity provided by fossil fuels by about one cent per kilowatt-hour. But according to one estimate, subsidies in 2007 lowered the price per-kilowatt-hour of wind energy by 7 cents, of concentrated solar energy by 29 cents, and of solar photovoltaics by 64 cents (Badcock and Lenzen 2010). Thus electricity sector subsidies are generally encouraging a shift to renewables.

In the transportation sector, global oil subsidies averaged about $200 billion annually over the period 2007-2009 (Charles and Wooders 2011). With annual global oil consumption around 1.3 trillion gallons, this amounts to a subsidy of about $0.15 per gallon. If we assume this value is applicable for the United States, oil subsidies approximately cancel out the federal gasoline tax of 18 cents per gallon. The other major recipient of subsidies in the transportation sector is biofuels. Global subsidies to biofuels are estimated to be about $20 billion, and growing rapidly.

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[2] In addition, there are implicit subsidies to the nuclear industry involved in limiting accident liability. The Price-Anderson Act in the U.S. limits nuclear operator liability to under half a billion dollars, although the potential costs of a major accident could be much greater.

Box 5. Fossil Fuel Subsidies

According to analysis by Bloomberg New Energy Finance, global subsidies for fossil fuels are about twelve times higher than the subsidies allocated toward renewable energy. In 2009, global subsidies for renewable energy were $43 to $46 billion, mainly in the form of tax credits and feed-in tariffs. Meanwhile, the International Energy Agency estimated that governments spent about $550 billion to subsidize fossil fuels.

The G20 countries have agreed to phase out fossil fuel subsidies over “the medium term” but progress has been slow and no specific target date has been set. Meanwhile, many countries are ramping up their commitment toward renewable energy. The most expensive renewable energy subsidy in 2009 was Germany’s feed-in tariff, which cost nearly $10 billion. Other feed-in tariffs in Europe totaled another $10 billion.

The United States spent more than any other country on renewable energy subsidies, around $18 billion. China provided about $2 billion, although this figure is likely too low as it does not include the value of low-interest loans offered for renewable energy projects by state-owned banks.

Source: Morales (2010)

Environmental Externalities

In addition to subsidy reform, economic theory also supports **internalizing externalities**. The price of each energy source should reflect its full social costs. Various studies of energy externalities suggest that if the price of all energy sources included externality costs, a transition toward renewables would already be much further along.

Figure 6 provides one summary of the range of external costs associated with different electricity sources, based on European analyses. The externality cost of coal is particularly high, ranging between 2 and 15 Eurocents per kilowatt-hour. This is consistent with other research that estimates the external cost of coal electricity in the United States at about 6 cents per kilowatt-hour (Jacobson and Delucchi 2011b). The externalities associated with natural gas are lower, but still range between 1 and 4 Eurocents per kilowatt-hour, also a result that is consistent with U.S. estimates.

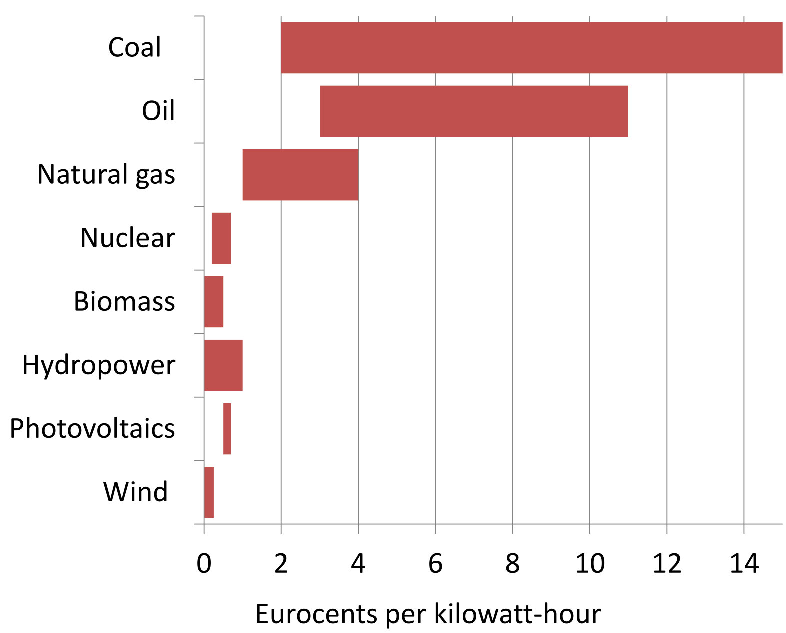
The externality costs associated with renewable energy are much lower, less than one Eurocent per kilowatt-hour. So while fossil fuels may currently have a cost advantage over renewables based solely on market prices, if externalities were included several renewables would likely become the most affordable energy sources—in particular onshore wind, geothermal, and biomass energy. Similarly, the cost advantage of oil in transportation would likely disappear if externalities were fully accounted in the price (See, for example, Odgen, Williams and Larson 2004).

The operating externalities of nuclear energy are relatively low, as the life cycle of nuclear power generates low levels of air pollution and greenhouse gas emissions. But the potentially most significant externalities from nuclear power are the risks of a major accident and the long-term storage of nuclear wastes. These impacts are difficult to estimate in monetary terms, and as a result the estimates shown in Figure 6 may understate the true negative externalities associated with nuclear power (see also Box 1 above).

Our discussion suggests that the biggest factor currently preventing a transition toward renewable energy is the failure to account for externalities. Getting the prices "right" would send a clear signal to businesses and consumers that continued reliance on fossil fuels is bad economics.

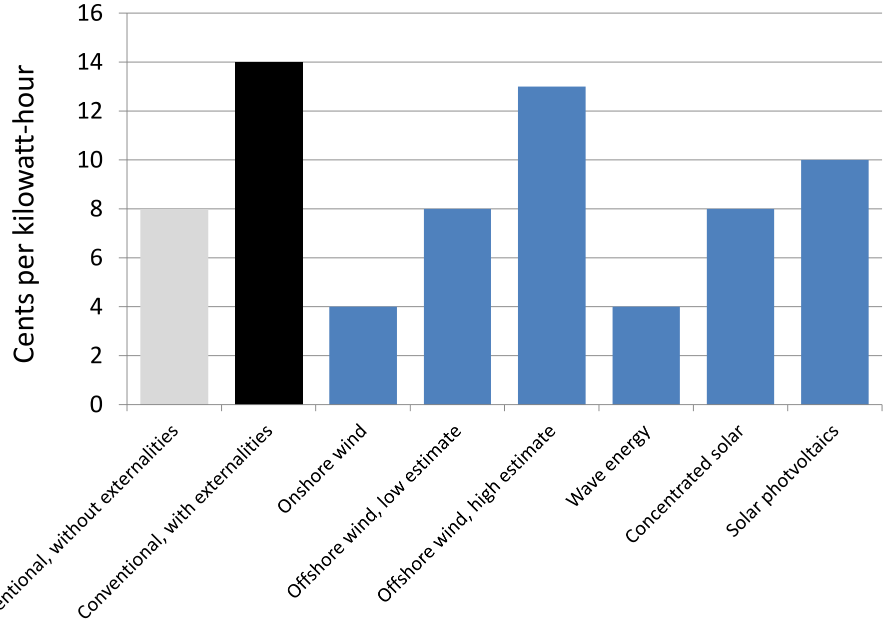
Figure 7 shows one projected comparison of the cost of electricity generation in 2020 using traditional fossil fuel methods and various renewable alternatives. Based solely on production costs, the renewable sources of onshore wind, wave energy, concentrated solar, and potentially offshore wind are all expected to be cost competitive with fossil fuels. When the impacts of externalities are included, all renewable sources become less expensive than fossil fuels. These results imply that there are good economic reasons to promote a transition towards renewables. In the final section of this module, we look more closely at the renewable energy transition.

Figure 6. Externality Cost of Various Electricity Generating Methods, European Union



Source: Owen (2006)

Figure 7. Cost of Electricity Generating Approaches, 2020



Source: Jacobson and Delucchi (2011b)

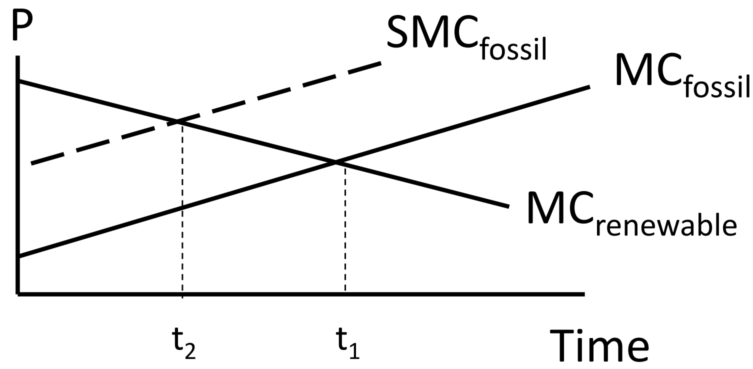
4. THE RENEWABLE ENERGY TRANSITION

In the beginning of this module we asserted that all energy will eventually be renewable. This must be true, since fossil fuels are finite and available quantities can only decrease over time. Yet there is no certainty about the time of "eventually", or about how much damage from climate change might occur before a renewable energy transition. There are three dynamics that affect the speed of the transition: rising fossil-fuel costs, declining renewable energy costs, and implementing policies to speed the transition, including policies that internalize externalities to reflect the true costs of fossil-fuels.

Rising Fossil Fuel Costs

Renewable energy will be adopted when fossil fuels have become scarce enough that they are more expensive than renewables, i.e. when fossil fuels are economically depleted. In Figure 8, increasing fossil-fuel extraction cost is indicated by the upward-sloping price path for fossil fuel (MC_{fossil}). Economic depletion of fossil fuels could take a very long time. There is still a large stock of liquid oil in the ground, and new technologies make it cheaper to extract oil from shale formations. We also have close substitutes for oil from oil wells, like oil from tar sands and synthetic oil made from coal. Greater supplies of natural gas are also available using hydraulic fracturing ("fracking") technologies, and extensive reserves of coal remain to be exploited. But many of these new technologies do involve higher costs, so an upward trend in fossil fuel prices over time is likely.

Figure 8. Renewable energy transition dynamics



Declining Renewable Energy Costs

At the same time fossil fuel prices rise, new technology will likely reduce renewable energy costs, as indicated by the downward-sloping price path for renewable energy ($MC_{renewable}$) in Figure 8. At time t_1, the supply paths for fossil fuels and renewable energy cross and costs are equal. After time t_1 renewable energy will be less expensive than fossil fuels, and market forces will then accomplish the renewable transition with little or no assistance.

Where this has already happened, renewables are prevalent. For example, in Iceland geothermal hot water is less expensive than coal or oil for heating buildings, and most buildings are now heated with geothermal water (though government assistance was necessary to develop the needed district heating systems). Similarly, hydropower is already widely employed where it is cheaper than alternatives, for example in the U.S. Pacific Northwest.

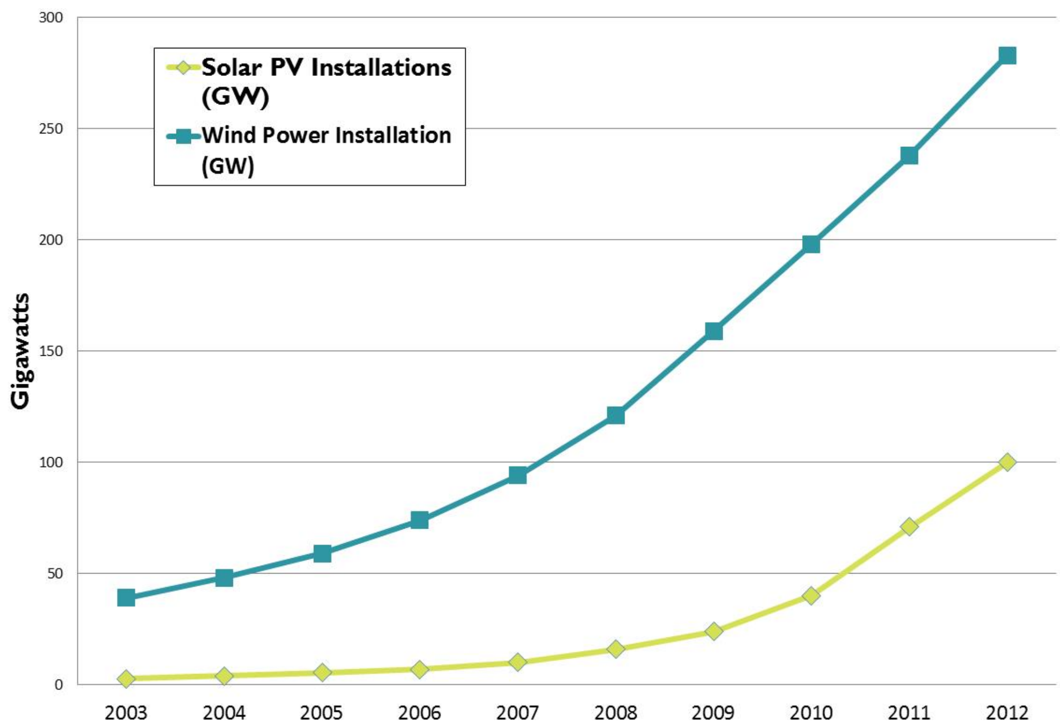
While there are success stories for renewable energy technology, the timing of improvements needed for renewables to displace fossil fuels is uncertain. For example, better ways to produce solar photovoltaic panels are lowering panel production cost, but we still have costs of daily and seasonal intermittency. Cellulosic ethanol technology allows ethanol production from switchgrass rather than corn, but land availability still places constraints on switchgrass production. Better technology can lower renewable energy costs to some extent, but cannot change fundamental characteristics of energy sources.

This is particularly obvious at the margin: while large-scale hydropower and biomass have the potential to deliver energy near current prices for fossil fuels, quantities of these energy sources are very limited compared to current usage, and are not expandable in many locations. Solar PV and offshore wind may be the only renewable sources abundant enough to displace fossil fuels. While costs of these technologies are declining, they are decreasing at a decreasing rate, as shown in Figure

3. It is unclear when solar PV and offshore wind energy prices will reach parity with fossil fuels.

As shown in Figure 9, global use of solar and wind power has grown rapidly, with accelerating growth in recent years. According to a recent report by the U.S. Department of Energy, "the installed capacity of global and U.S. photovoltaic (PV) systems has soared in recent years, driven by declining PV prices and government incentives. The U.S. Department of Energy's SunShot Initiative aims to make PV cost competitive without incentives by reducing the cost of PV-generated electricity by about 75% between 2010 and 2020." (DOE 2012)

Figure 9: Growth of Solar PV and Wind Installations (2003-2012)



Source: Worldwatch Institute (2014).

According to the 2014 report of the Intergovernmental Panel on Climate Change, since 2007 "Many renewable energy (RE) technologies have demonstrated substantial performance improvements and cost reductions, and a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale" (IPCC 2014). Innovative methods for consumer financing of solar installation are also being widely promoted (see Box 6).

Box 6: Financing Solar Installation

Declining costs for solar energy systems, combined with federal tax incentives, have brought them within reach of many consumers. But some barriers remain. Solar photovoltaic power is still not competitive at the wholesale level (see Figure 2). A huge concentrating solar power plant in the Mojave Desert of southern California opened in 2014, but despite its optimal location the prospects for future development of such plants is limited:

"The Ivanpah solar power plant stretches over more than five square miles of the Mohave Desert. Almost 350,000 mirrors the size of garage doors tilt toward the sun with an ability to energize 140,000 homes. The plant, the first electric generator of its kind, could also be the last. Since the project began, the price of rival technologies has plummeted, incentives have begun to disappear, and the appetite among investors for mammoth solar farms has waned. Although several large new projects have been coming online in recent months, experts say fewer are beginning construction and not all those under development will be completed" (Cardwell and Wald 2014).

At the same time, solar has been making great strides at the retail level. The economic advantage of installing a solar system on an individual residence or business is that distribution costs, which can be about half the final costs of electricity, are avoided.[3] This means that, as shown in Figure 2, solar PV is entering the competitive range at the retail level. Shared community solar arrays are providing a means for residential customers whose own property is not suitable for solar installation:

"Like many consumers, David Polstein had already done much to reduce energy use in his large Victorian home in Newton, Massachusetts. He replaced his appliances with energy-efficient models, installed better heating and put in new insulation. But he was unable to get a solar system to reduce his utility bill because his roof is too small and shady. . . Now, that could be changing. Mr. Polstein is considering joining a community solar garden that is one of many similar new arrangements now available in Massachusetts. Through the approach—largely pioneered in Colorado and spreading across the country—customers buy into a solar array constructed elsewhere and receive credit on their electricity bills for the power their panels produce. . . it is among the profusion of financing mechanisms meant to encourage the development of solar energy, from residential leasing programs to crowdfunding. The combination of plummeting prices for solar equipment and installation and generous federal and state incentives has widened their appeal" (Cardwell 2014).

Solar installations involves high upfront costs, but consumers are rewarded with lower—often zero—electric bills. If electric costs rise in future, either due to limits on other supply sources or policies such as carbon taxes, the installed systems would become even more beneficial in terms of avoided electric costs

[3] If residential systems are set up to sell power back to the grid during sunny periods and buy grid power at night, distribution costs are involved, but these are often offset by feed-in tariffs that provide a favorable rate to home solar systems – a form of subsidy (see section on renewable transition policies below).

Accounting for Fossil Fuel Externalities

If the only issue were fuel availability, it would not necessarily be a problem for society to take a long time transitioning to renewable energy. But of course there is another issue: combustion of fossil carbon creates carbon dioxide, which causes climate change. Most scientists believe it is already too late to avoid significant damage from climate change, and waiting until fossil fuels are exhausted to deploy renewable energy sources could be catastrophic for civilization. This creates a strong argument for internalizing the expected costs of climate change into the price of fossil fuels.

Policies to internalize the external costs of fossil fuels are shown by the fossil-fuel social marginal cost path in Figure 8 (SMC_{fossil}). The costs of climate change and other pollution from fossil fuels suggest taxing fossil fuels to reflect these pollution costs to society. A fossil-fuel tax would increase fossil-fuel prices, making prices more closely approximate the true marginal cost of using fossil fuels. In Figure 8, the SMC_{fossil} lies above the MC_{fossil} path, representing the social costs of burning fossil fuel, and the taxes that could be imposed to reflect this cost.

As shown in Figure 8, increasing the prices of fossil fuels with corrective taxes reduces the time of the transition to renewables from t_1 to t_2. Raising fossil fuel prices also provides more incentive for energy conservation, reducing the total amount of energy needed in society and accomplishing a large portion of the transition to renewable energy.

Having fossil fuel prices reflect their externality costs is likely the only way to accomplish a rapid renewable energy transition in the near future (though the required political will may be difficult to develop), and may also be the only option with potential to avoid the most disastrous effects of climate change. At the same time fossil fuels prices were increased, fossil energy prices would continue to rise due to depletion, and higher prices would in fact accelerate technology improvement, reducing renewable energy costs. All three dynamics shown in Figure 8 could work simultaneously.

Policies for the Renewable Energy Transition

Government policy can clearly affect the speed of transition to a renewable energy economy, as shown by the example of Portugal in Box 7. What kinds of government policies are most important to foster a timely and efficient transition to a shift toward renewable energy sources? As discussed, one policy goal agreed upon by many of the world's largest nations is to phase out inefficient fossil fuel subsidies. One concern is that in the short term this could lead to higher energy prices and a decrease in economic growth. But the money governments save could be invested in ways that would reduce the cost of renewable alternatives and encourage a more rapid transition away from fossil fuels.

Box 7. Portugal Gives Itself a Clean-Energy Makeover

"Five years ago, the leaders of this sun-scorched, wind-swept nation made a bet: To reduce Portugal's dependence on imported fossil fuels, they embarked on an array of ambitious renewable energy projects—primarily harnessing the country's wind and hydropower, but also its sunlight and ocean waves.

Today, Lisbon's trendy bars, Porto's factories and the Algarve's glamorous resorts are powered substantially by clean energy. Nearly 45 percent of the electricity in Portugal's grid will come from renewable sources this year, up from 17 percent just five years ago.

Land-based wind power—this year deemed 'potentially competitive' with fossil fuels by the International Energy Agency in Paris—has expanded sevenfold in that time. And Portugal expects in 2011 to become the first country to inaugurate a national network of charging stations for electric cars.

'I've seen all the smiles—you know: It's a good dream. It can't compete. It's too expensive,' said Prime Minister José Sócrates, recalling the way Silvio Berlusconi, the Italian prime minister, mockingly offered to build him an electric Ferrari. Mr. Sócrates added, 'The experience of Portugal shows that it is possible to make these changes in a very short time.'

Portugal was well poised to be a guinea pig because it has large untapped resources of wind and river power, the two most cost-effective renewable sources. Government officials say the energy transformation required no increase in taxes or public debt, precisely because the new sources of electricity, which require no fuel and produce no emissions, replaced electricity previously produced by buying and burning imported natural gas, coal and oil. By 2014 the renewable energy program will allow Portugal to fully close at least two conventional power plants and reduce the operation of others."

Source: Rosenthal (2010)

In the long run, subsidy reform would be economically beneficial:

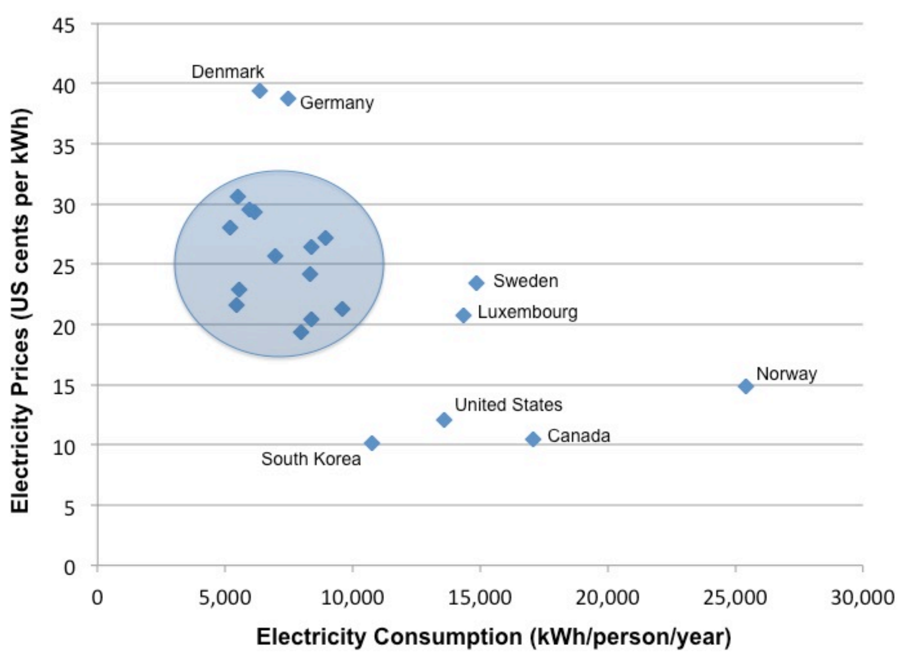
> "…fossil fuel subsidy reform would result in aggregate increases in gross domestic product (GDP) in both OECD and non-OECD countries. The expected [increase is as high as] 0.7 per cent per year to 2050…Results from a wide variety of global and single-country economic modeling studies of subsidy reform suggest that on an aggregate level, changes to GDP are likely to be positive, due to the incentives resulting from price changes leading to more efficient resource allocation." (Ellis 2010, p. 7, 26).

As discussed above, a major issue is the need to have energy prices reflect true costs of energy use to society. Taxes called **Pigovian taxes** (after economist Arthur Pigou) can be used to accomplish this. A common form is a Pigovian tax on gasoline. Even though governments may use this tax primarily to raise revenue, it serves the function of reflecting costs of society of gasoline use. While the price of crude oil is determined in a global market, the retail price of gasoline varies widely across countries due to differences in gasoline taxes. In late 2010 the price of gasoline ranged from less than $1/gallon in countries such as Venezuela, Saudi Arabia, and Kuwait, where gas is actually subsidized rather than taxed, up to $8/gallon in countries such as France, Norway, and the United Kingdom, where gas is heavily taxed.

Economic theory suggests that the "correct" tax on gas should fully account for the negative externalities. In the United States, the current federal gas tax is 18 cents per gallon (an amount that has not changed since 1993), in addition to state taxes that range from 8 to 50 cents per gallon. Virtually all economists agree that these taxes are too low, although there is disagreement about how much higher the tax should be. While some economists suggest it should be only about 60 cents higher, others suggest that gas taxes should be over $10 per gallon (International Center for Technology Assessment 1998; Parry and Small 2005)

Pigovian taxes can also be applied to the electricity sector. As we see in Figure 10, electricity prices vary across countries, primarily due to variations in tax rates. In general, higher electricity prices are associated with lower per capita consumption rates.

Figure 10. Electricity Prices and Consumption Rates



Sources:International Energy Administration. 2014. EIA Statistics, Electricity Information 2014. Paris, France.

Note: Shaded area represent price consumption data in Western European countries and Japan.

For example, the United States has relatively low electricity prices, and relatively high consumption rates. Electricity prices in Germany, Spain, and Denmark are much higher, and per capita consumption rates are about half the rate of the United States. While there are other differences between these countries, Pigovian taxes are almost always effective because they take advantage of one of the most reliable results in economics, the **law of demand**: when prices increase, quantities demanded decrease.

Beyond reducing fossil fuel subsidies and implementing Pigovian taxes, other policy options to encourage a transition to renewable energy include:

1. Energy research and development
2. Feed-in tariffs
3. Subsidies, including favorable tax provisions and loan terms
4. Renewable energy targets
5. Efficiency improvements and standards

Research and development (R&D) expenditures will speed the maturation of renewable energy technologies. Energy R&D expenditures have been increasing in recent years, up globally from $18 billion in 2004 to $122 billion in 2009. Countries investing heavily in energy R&D will likely gain a competitive advantage in this area in the future.

> Those nations—such as China, Brazil, the United Kingdom, Germany and Spain—with strong, national policies aimed at reducing global warming pollution and incentivizing the use of renewable energy are establishing stronger competitive positions in the clean energy economy. Nations seeking to compete effectively for clean energy jobs and manufacturing would do well to evaluate the array of policy mechanisms that can be employed to stimulate clean energy investment. China, for example, has set ambitious targets for wind, biomass and solar energy and, for the first time, took the top spot within the G-20 and globally for overall clean energy finance and investment in 2009. The United States slipped to second place. Relative to the size of its economy, the United States' clean energy finance and investments lag behind many of its G-20 partners. For example, in relative terms, Spain invested five times more than the United States last year, and China, Brazil and the United Kingdom invested three times more (Pew Charitable Trusts 2010).

Feed-in tariffs guarantee renewable energy producers access to electricity grids and long-term price contracts. Those taking advantage of feed-in tariffs need not be companies. For example, homeowners who install solar PV panels could sell any excess energy back to their utility at a set price. Feed-in tariff policies have been instituted by dozens of countries and several U.S. states. The most ambitious is in Germany, which has become the world's leader in installed solar PV capacity.

Feed-in tariffs are intended to be reduced over time as renewables become more cost competitive with traditional energy sources. A reduction in feed-in tariff rates has already begun in Germany. A 2008 analysis by the European Union of different approaches for expanding the share of renewables in electricity supplies found that "well-adapted feed in tariff regimes are generally the most efficient and effective support schemes for promoting renewable electricity" (Commission of the European Communities 2008, p. 3).

Subsidies can take the form of direct payments, or other favorable provisions such as tax credits or low-interest loans. As mentioned earlier, the bulk of current subsidies go toward fossil fuels. Yet subsidies make more sense for developing, rather than mature, technologies. Subsidies for renewable energy can promote economies of scale that lower production costs.

Like feed-in tariffs, output subsidies can be gradually reduced as renewables become more competitive. A disadvantage of subsidies is that they do nothing to encourage conservation, where a great deal of potential lies. Subsides may be misdirected if the immediate problem is not that we need more renewable energy, but rather that we need less fossil fuel combustion and carbon dioxide emissions. But subsidies are often easier to accomplish politically than instituting new taxes.

Renewable energy targets set goals for the percentage of total energy or electricity obtained from renewables. Over 60 countries have set renewable energy targets. The European Union has set a goal of 20% of total energy from renewables by 2020, with different goals for each member country. The 2020 targets include goals of 18% for Germany, 23% for France, 31% for Portugal, and 49% for Sweden. While the United States does not have a national renewable goal, most states have set goals. Some of the most ambitious goals include Maine (40% by 2017), Minnesota (25% by 2025), Illinois (25% by 2025), New Hampshire (24% by 2025), and Connecticut (23% by 2020) (Wiser and Barbose 2008).

Governments can promote energy efficiency by setting **energy efficiency standards**. Fuel economy standards are one example. In 2011 fuel economy standards in the United States were 30 miles per gallon (MPG) for passenger cars and 24 MPG for light trucks, a category which includes pickups, minivans, and sport utility vehicles. After about 20 years in which fuel economy standards were little changed, in 2011 the Obama Administration announced new standards that would ramp up the average fuel efficiency of new vehicles to 54.5 MPG in 2025. Compared to 2010 model year vehicles, total fuel savings for 2025 vehicles would amount to more than $8,000 over the lifetime of the vehicle. Other energy efficiency standards exist for buildings, appliances, electronics, and light bulbs.

Efficiency labeling informs consumers about the energy efficiency of various products. For example, in the United States the U.S. Environmental Protection Agency and U.S. Department of Energy manage the Energy Star program. Products that meet high-efficiency standards, above the minimum requirements, are entitled to receive the Energy Star label. About 75% of consumers who purchased an Energy Star indicated that the label was an important factor in their purchase decision. In 2011 the energy savings from Energy Star products amount to about $23 billion (EPA 2011).

Even with informative labels, many consumers do not purchase high-efficiency products because the upfront costs may be higher. For example, LED and compact fluorescent light bulbs cost more than traditional incandescent light bulbs. However, the energy savings from efficient bulbs means that the additional cost will be recovered in a relatively short time period, normally less than one year. The problem is that people often have high implicit **discount rates**, focusing on the upfront cost while discounting the long-term savings (see Box 8). Education and promoting a cultural change toward more long-run thinking will likely be needed to make consumer purchasing habits more consistent with resource conservation.

Box 8: Implicit discount rates and energy efficiency

A major problem in increasing energy efficiency of appliances arises from high implicit discount rates. Suppose that a consumer can purchase a standard refrigerator for $500, and an energy-efficient model for $800. The energy efficient model will save the consumer $15 per month in energy costs. From an economic point of view, we can say that the return on the extra $300 invested in the efficient model is $15 x 12 = $180/year, which generates a 50% internal rate of return (a metric equivalent to return on a financial asset).

Anyone who was offered a stock market investment that would bring a guaranteed 50% annual return would consider this a tremendous opportunity. But it is very likely that the refrigerator buyer will turn down the chance to make this fantastic return. The reason is that s/he will weigh more heavily the immediate decision to spend $500 versus $800, and therefore choose the cheaper model. We could say that the consumer is implicitly using a discount rate of greater than 50% to make this judgment—a consumer behavior difficult to justify economically, yet very common.

SUMMARY

Energy is a fundamental input for economic systems. Current economic activity depends overwhelmingly on fossil fuels including oil, coal, and natural gas. These fuels are non-renewable. Renewable sources such as hydroelectric, wind, and solar power currently provide less than 10% of global energy.

Many sources of renewable energy are available, and have been used for centuries. Most renewables are less available and/or have higher costs than fossil fuels used in the recent past. The costs of renewable energy resources are attributable in part to inherent characteristics, particularly their low net energy ratios, intermittent availability, and capital intensity. Development of new technology will reduce cost but may not make renewable energy cost competitive with market prices of fossil fuels in the near future unless fossil-fuel externalities are considered.

The speed of the transition to renewable energy will be highly influenced by policy choices. Reforming fossil fuel subsidies and instituting Pigovian taxes are two policies that can yield more economically efficient outcomes. Other potential policies include increasing energy research and development expenditures, feed-in tariffs, and renewable energy targets. Public policy can also aid in providing capital for renewable energy projects, and in providing a robust electricity grid for moving energy long distances. Reducing costs of solar PV and costs of energy storage devices (e.g. batteries) are two key areas for technology development that could significantly reduce renewable energy costs in the long run.

With higher energy costs, buildings, transportation networks, and manufacturing would be redesigned to use less energy. A large portion of the transition to renewable energy will likely be accomplished not by providing new energy sources, but rather by redesigning systems to consume less energy. This would be spurred by the higher costs of renewable energy, since energy conservation is optimized where the marginal cost of energy conservation equals the marginal cost of renewable energy. Solar PV energy is sustainably available in almost unlimited quantities, and the marginal cost of solar PV is an upper bound on all energy costs.

An eventual transition to renewable energy is unavoidable, so the question is how to best manage it, minimizing total cost of energy services plus cost of damages caused by energy utilization. A combination of conservation and renewable energy sources will eventually replace the current fossil-fuel dominated energy system. Addressing climate change suggests that this needs to happen sooner rather than later.

DISCUSSION QUESTIONS

1. In general, how do renewable energy sources differ from fossil fuels, i.e. what are some common characteristics of renewable energy sources that are different from characteristics of fossil fuels used in the past?

2. Explain the equimarginal principle in your own words. How would this apply to developing a portfolio of renewable energy sources in your home region?

3. Is energy conservation likely to be more important in a renewable energy economy than it has been in the past? Explain.

4. Hydropower is currently the largest source of renewably generated electricity in the world, and there is potential for expansion. In some parts of the world, a renewable energy portfolio could be based on hydropower and energy conservation alone. Yet hydropower is also controversial, chiefly because of associated negative externalities. Describe some of these. Do you think more hydropower should be developed in the world? How would you decide whether or not to develop a particular hydro project?

5. Why does public policy have such a prominent role in promoting renewable energy use, and in accelerating the transition to renewable energy? What public policy approaches do you think will be most effective?

EXERCISES

1. Energy use can be expressed in an annoying number of different units, but fortunately any energy unit can be converted to any other unit. To compare real energy costs, search the web to get typical prices, energy content, and conversion factors, and express the following costs in gross $/kWh (to get net $/kWh we would also need to consider efficiency, which would vary by application):

- electricity bought from a utility in your home region
- natural gas
- home heating oil (#2 fuel oil)
- gasoline in the United States
- gasoline in some European country

(*Hint: you may need to find energy content of the fuels in Btu, then convert Btu to kWh.* See for example http://www.onlineconversion.com/energy.htm)

2. Hydropower availability can be calculated as:

$$kW = 9.8\eta QH$$

where Q is flow in m^3/sec, H is head in meters, and η is overall system efficiency.

Also,

$$\text{Annual kWh} = \text{kW x annual operating hours}$$

If a waterfall has an average flow of 5 m^3/sec, a head of 10 meters, and overall system efficiency (η) is 0.8, how much power is available from the falls (in kW)? If the capacity factor is 0.7, how much energy can be generated in a year (in kWh)?

3. Switchgrass grown in the United States can produce about 7.5 tons of biomass per acre per year, yielding about 80 gallons of ethanol per ton, and each gallon of ethanol has about 67% of the energy in a gallon of gasoline. Find total annual U.S. gasoline consumption and the farmland area of the United States, and calculate the percentage of U.S. farmland needed to grow switchgrass to completely replace gasoline with ethanol. What economic effects might there be from getting a large portion of the U.S. fuel supply from switchgrass ethanol? (*Hint: it may be easiest to work this problem in millions of gallons and millions of acres*)

Useful websites: http://www.eia.gov/tools/faqs/faq.cfm?id=23&t=10
http://www.census.gov/compendia/statab/cats/agriculture/farms_and_farmland.html

4. For an energy source with constant energy production and no operating cost, the levelized cost of energy (LCOE) per kilowatt hour (kWh) can be calculated as:

$$\frac{\textit{annualized capital cost}}{\textit{annual kWh production}}$$

The annualized capital cost is like a mortgage payment, an annual cost that includes paying both the principle and interest (or opportunity cost of capital) over the life of a project. This can be calculated as:

$$Annualized\ capital\ cost = K\frac{r(1+r)^T}{(1+r)^T - 1}$$

where *K* is the capital cost, *r* is an interest rate, and *T* is the life of the project.

a. Find the levelized cost of electricity for a 5 kW capacity solar electric system if the system capital cost is $3,000 per kW of capacity, the interest rate is 5%, the system lasts 30 years, and the capacity factor is 0.15.

b. Find the levelized cost of energy for a 300 kW hydropower plant, if the capital cost is $5,000 per kW of capacity, the interest rate is 5%, the system lasts 40 years, the capacity factor is 0.70, and for simplicity we assume no operating costs (small-scale hydropower operating costs are typically low, but greater than zero).

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ADDITIONAL RESOURCES

1. **http://www.eia.gov/** Website for the Energy Information Administration, a division of the U.S. Department of Energy that provides a wealth of information about energy demand, supply, trends, and prices.

2. http**://www.cnie.org/nle/crsreports/energy** Access to energy reports and issue briefs published by the Congressional Research Service.

3. **http://www.nrel.gov/** The website for the National Renewable Energy Laboratory in Colorado. NRE conducts research on renewable energy technologies including solar, wind, biomass, and fuel cell energy.

4. **www.rmi.org/** Homepage for the Rocky Mountain Institute, a non-profit organization that "fosters the efficient and restorative use of resources to create a more secure, prosperous, and life-sustaining world." RMI's main focus has been promoting increased energy efficiency in industry and households.

5. **http://www.eren.doe.gov/** Website for the Energy Efficiency and Renewable Energy Network within the U.S. Department of Energy. The site includes a large amount of information on energy efficiency and renewable energy sources as well as hundreds of publications/.

6. **http://www.iea.org/** Website of the International Energy Agency, an "autonomous organisation which works to ensure reliable, affordable and clean energy for its 28 member countries and beyond." While some data are available only to subscribers, other data are available for free, as well access to informative publications such as the "Key World Energy Statistics" annual report.

7. **http://www.energystar.gov/** Website for the Energy Star program, including information about which products meet guidelines for energy efficiency.

GLOSSARY

biomass energy: energy derived from biological sources such as trees, crops, and animal waste, which may be used for heating, for conversion to liquid fuels, or for generating electricity.

capacity factor: for an electricity generating plant or device, the ratio of actual energy produced in a period of time to maximum energy production potential in that time period. A capacity factor is usually less than one, since most electricity generating plants do not operate at full power continuously given lack of source energy (e.g. from solar or wind), required maintenance time, lack of demand, etc.

capital stock: an existing quantity of productive assets, which can include manufactured, human, and natural capital.

climate change: changes in global climate, including temperature, precipitation, and storm frequency and intensity, that arise from changes in the concentrations of greenhouse gases in the atmosphere.

depletion allowance: a tax deduction for extracting natural resources such as fossil fuels.

discount rate: the annual rate at which future benefits or costs are discounted (or reduced) relative to benefits or costs in the present. A discount rate reflects the difference in value between getting something now and having to wait to get the same thing in the future.

ecosystem services: beneficial services provided freely by nature such as flood protection, water purification, and soil formation.

efficiency label: a product label that indicates energy efficiency relative to similar products, such as a label on a home appliance showing annual energy use.

energy efficiency standard: an environmental regulation approach that sets a minimum standard for efficiency, such electricity use for a household appliance or fuel use for a vehicle.

energy source redundancy: extra or backup energy production capacity for use when other generating sources are unavailable, for example natural-gas-fired generators used when wind power is unavailable or insufficient.

energy transition: an overall change in the energy sources used by society, for example in the past from wood to fossil fuels, and now from fossil fuels to renewable energy sources.

equimarginal principle: the economic principle that total production cost is minimized when the marginal costs of different production options are equal. If marginal costs of different options were not equal, it would be possible to reduce total cost by switching some production to a lower-cost alternative.

feed-in tariff: a policy to provide renewable energy producers long-term contracts to purchase energy at a set price, normally based on the cost of production plus an additional incentive.

flow: in a hydropower context, the quantity of water in a river or stream moving past a given point over a specific period of time, usually measured in cubic meters per second or cubic feet per second.

geothermal energy: energy derived from heat in the earth, which may be used for heating or electricity production.

head: in a hydropower context, the vertical distance that water falls, usually measured in meters or feet.

heat pump: a device that uses mechanical energy and refrigeration technology to move heat from a colder area to a warmer area (the opposite of natural heat flow), usually for heating buildings and domestic water.

hydropower: energy derived from falling water, usually in the form of electricity.

intermittency: a characteristic of energy sources such as wind and solar, which are available in different amounts at different times.

internalizing externalities: using policies such as taxes or fees to add external costs to market prices.

kilowatt (kW): an energy flow of 1000 watts.

kilowatt hour (kWh): an energy quantity equal to a flow of 1 **kilowatt** (kW) for 1 hour, or 2 kW for ½ hour, or 0.5 kW for 2 hours, etc.

law of demand: the economic principle that when the price of a good or service rises, the quantity demanded falls. The law of demand is observed for most goods and services in most markets.

leakage: (in the context of energy use) the effect of improved efficiency in promoting higher energy use as a result of lower costs, thereby cancelling out some of the reduction in energy use from the original efficiency increase.

levelized cost of energy (LCOE): the average cost of producing energy (usually electricity) from a source over the life of the source, including capital cost, fuel cost (if any), and all other operating costs.

marginal cost: the cost of producing one more unit of a good or service.

negative externality: negative impact of a market transaction affecting people not involved in the transaction.

net energy ratio: the ratio of useable energy obtained to energy expended in producing the energy. A useful energy source must have a net energy ratio greater than one.

offshore wind power: wind power derived from wind turbines placed in the ocean or another large body of water.

opportunity cost: an economic term for the value of the best alternative given up in order to get something.

photovoltaic energy (PV): one form of solar energy, where electricity is produced by sunlight falling on silicon semiconductor cells.

Pigovian tax: a per-unit tax set equal to the external damage caused by an activity, such as a tax per ton of pollution emitted equal to the external damage of a ton of pollution.

positive externality: positive impact of a market transaction affecting people not involved in the transaction.

present value: the current value of a future cost or benefit, or a stream of future costs and benefits. A discount rate is used to convert future value to present value.

pumped water storage: a method of storing energy where energy is first used to pump water to a higher elevation (for example in a high lake) and the energy is later recovered when the water is allowed to fall to its original level. Pumped water storage is based on hydropower technology.

renewable energy: any energy that comes from an inexhaustible source. The main examples are solar, wind, hydropower, geothermal, and biomass energy.

renewable energy targets: regulations that set minimum percentages of energy to be obtained from renewable energy sources.

smart electric meters: electricity measurement devices that record total electricity usage and also collect data like electricity usage over time. Smart electric meters may also have communication capabilities and have the ability to control loads, i.e. to turn off low-priority electric appliances at times when electricity is expensive or unavailable.

solar energy: energy derived from the sun directly or indirectly (e.g. through production of plant biomass), usually as heat or electricity.

tidal power: energy derived from incoming and outgoing tidal water flows, usually in the form of electricity.

variable electricity pricing: having different electricity rates for different times of day or for times when energy is more or less available, for example to reflect changing demand or renewable-energy supply conditions.

wind power: energy derived from moving air. Wind power is often in the form of electricity, though it may also be used to pump water or generate heat.