Global Development Policy Center
Economics in Context Initiative

The Economics of Renewable Energy

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An ECI Teaching Module on Social and Environmental Issues in Economics

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NOTE – terms denoted in bold face are defined in the KEY TERMS AND CONCEPTS section at the end of the module.

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1. RENEWABLE ENERGY TRANSITION

Until a few centuries ago, humans obtained all their energy from renewable resources: food from plant and animal sources, wood for cooking and heating fires, and later **hydropower** and **wind power** for simple tasks like grinding grain and pumping water. As technology developed, humans harnessed fossil fuels for extracting and smelting metal, for manufacturing, and for high-speed transportation around the globe. It is no exaggeration to say that the wealth of modern civilization is built on the combustion of fossil fuels, including coal, oil, and gas.

Within the last few decades it has become clear that widespread use of fossil fuels also has a cost in disrupting the global climate, and that this cost increases steadily as carbon emissions from fossil fuel burning accumulate in the atmosphere. Carbon dioxide (CO_2)—a byproduct of burning any fossil fuel—is the main **greenhouse gas** responsible for **climate change**.

Global emissions of CO_2, which were about 5 million tons per year in 1950, reached 35 million tons per year by 2020. Methane, another major greenhouse gas, is emitted as a result of leakage or incomplete combustion of natural gas, and as a byproduct of coal mining. The Intergovernmental Panel on Climate Change (IPCC) estimates that stabilizing the climate will require reducing world emissions by about 80% from 2020 levels by 2050, and achieving near-zero emissions by 2100 (IPCC 2023).

Since burning fossil fuels is responsible for the majority of global CO_2 emissions, achieving near-zero CO_2 emissions requires another major **energy transition**, from fossil to **renewable energy**, including both traditional forms and new options. Fortunately, technology that has been developed during the fossil-fuel era makes this possible. An important economic question is how to satisfy society's energy needs from renewable sources at the least cost, which we consider in this module.

Regardless of the climate change problem, society will eventually have to 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 outlines the renewable energy economy that must eventually take hold:

- What renewable energy sources are available, and why do most renewable energy scenarios involve extensive electrification?
- How will optimum mixtures of renewable energy sources be determined?
- What is the role of supporting technologies including energy transmission and storage?
- What kind of engineering, economic, and policy approaches are needed to accommodate renewable energy sources?

The economic implications of a worldwide transition to renewable energy are huge, and the transition has already begun. We will discuss how it can continue and accelerate, and what its impacts are likely to be in terms of economic costs and benefits.

2. RENEWABLE ENERGY SOURCES

In one sense, renewable energy is unlimited, as supplies are continually replenished through natural processes. 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.

BOX 1: ENERGY UNITS

Many different units are used to measure energy, for example, watt hours (Wh) or **kilowatt hours** (kWh), joules, calories, and barrels of oil equivalent. In the United States, we also use some measurement units that are not widely used in the rest of the world, for example, British thermal units (Btu) and therms. Some units are more commonly associated with specific forms of energy. For example, electrical energy is normally measured in kWh and heat energy is normally measured in Btu (in the United States), though the reverse is also possible. Fortunately, any energy unit can be converted to any other unit. For simplicity, in this module we work primarily with kilowatt hours and their multiples (as described below).

Solar Energy

Solar energy comes in three basic forms:

1) low temperature solar thermal
2) solar photovoltaic energy (PV)
3) high temperature concentrating solar power (CSP) to generate thermal electricity or heat.

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

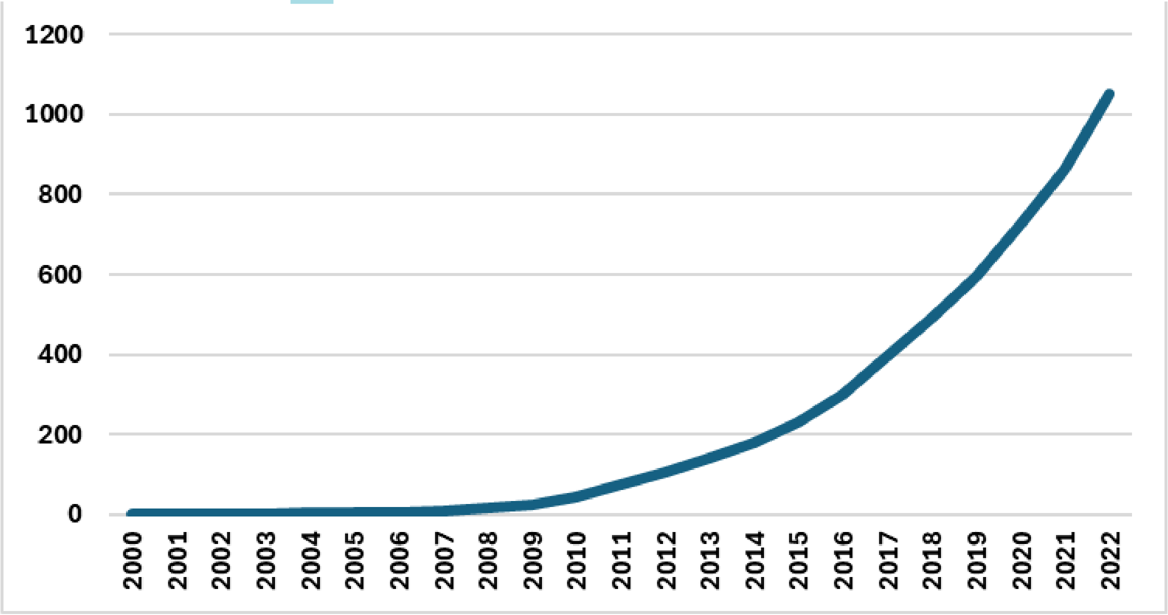
A challenge with solar space heating economics is that monthly demand and supply are almost exactly opposite: the greatest demand is in winter, when there is the least supply of sun, and the most sunshine occurs in summer when demand for heating energy is lowest. Nonetheless, efficiently designed “passive solar” systems can significantly reduce the need for other heat energy sources even in cold climates.

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. 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, 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 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.

High temperature concentrating solar power (CSP) 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, on a large scale they may produce electricity less expensively than PV, at least in the sunniest locations.

Solar installations have increased rapidly in the U.S. and worldwide, with cumulative U.S. solar capacity reaching over 100 megawatts in 2022. In 2023, the U.S. added more solar capacity than ever before, at 32.4 gigawatts; this added capacity exceeded any other energy source in 2023, marking the first time a renewable energy source outpaced fossil fuels since World War II. According to the International Energy Agency (IEA), global solar PV generation increased by a record 270 trillion watt-hours (TWh) in 2022, reaching almost 1300 TWh, with especially rapid growth in China. (See Figure 1).

Figure 1. *World Solar PV Capacity, GW 2000-2022*



Source: Data from International Renewable Energy Agency, 2023.

Wind power

Wind power has been used since ancient times. Wind power is generated by the energy in moving air, and the windiest sites provide much more energy than typical locations. These sites are often coastal and offshore, along mountain ridges, and in vast open areas like the U.S. Great Plains.

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

Like all energy sources, wind power has **negative externalities**. The main ones of concern are aesthetic impact of the wind turbines, which can be over 500 feet 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.

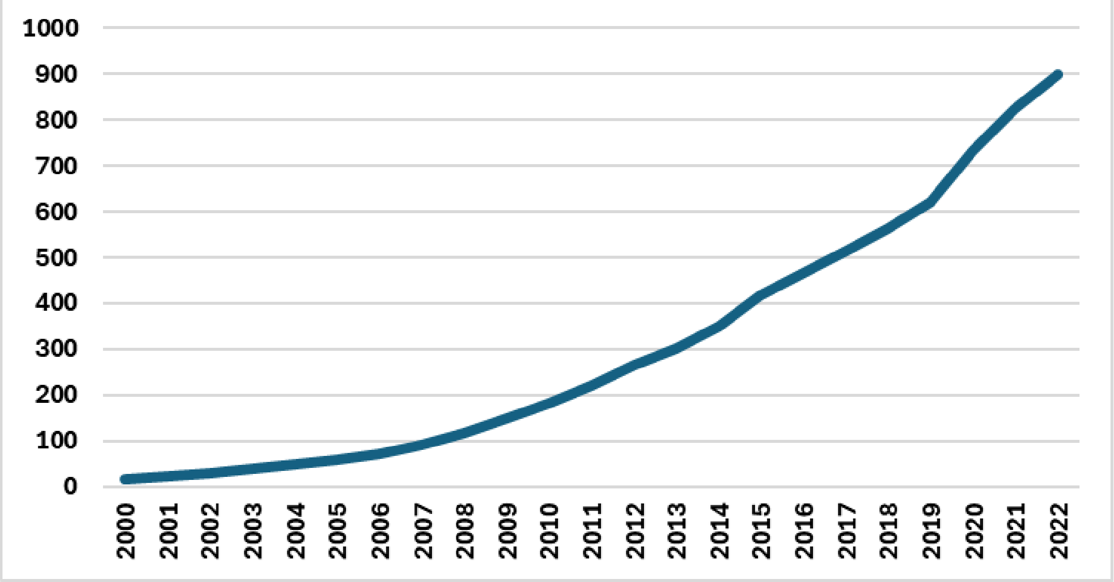
Early wind power development was land-based, but **offshore wind power** has several advantages. Offshore winds are both stronger and more consistent than onshore. And the potential offshore wind resource capacity is enormous: according to a 2022 study by the National Renewable Energy Laboratory (NREL), U.S. coastal and Great Lakes wind energy could produce three times as much electricity as the country now consumes each year. In 2024, offshore wind farms started providing power to the electric grid in New York State and Massachusetts.

In addition to having access to more wind energy, offshore installations do not compete with other land uses as onshore 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 can be larger than onshore turbines, since larger turbine components can be transported more easily over 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 more expensive offshore, as is building turbines to withstand a harsh marine environment. In 2023, U.S. offshore wind energy was more than twice as expensive as onshore wind (Lazard 2023).

Overall, wind energy has continued to develop rapidly in the United States and worldwide, accounting for 22% of new capacity installed in the U.S. in 2022, second only to solar power. According to the U.S. Department of Energy, wind power is "poised for further rapid growth." (DOE, 2023). In 2022, global installed wind capacity grew to 906 Gigawatts, representing 9% year-on-year growth (Global Wind Energy Council, 2023) (See Figure 2.)

Figure 2. *Global Wind Capacity, GW, 2000-2022*



Source: Data from International Renewable Energy Agency, 2023.

Hydropower

Until recently, waterpower has provided the world's largest source of renewable electricity, generating about 17% of global electricity in 2020 (IEA 2020). Where conditions are favorable, hydropower can be the least expensive source of renewable energy. Hydropower has thus been extensively developed in many parts of the world, but the potential for further hydropower development is limited.

Hydropower requires precipitation and elevation change to produce energy—wet, mountainous areas provide the best prospects for hydropower. Energy availability depends on the volume of water available (**flow**), and its vertical drop (**head**). The best hydropower sites have both high head and high flow (like Niagara Falls).

The International Energy Agency (IEA 2020) estimates that that in 2020, world hydropower production was 4,444 TWh, (TWh = Terawatt-hours, or trillion watt-hours, or billion kilowatt-hours), or about 2-3% of total global energy use in 2020. Theoretically, global hydropower capacity could be scaled up by a factor of five, but practical limits mean that even optimistic projections for 2050 are only about 50% above current levels.

Hydropower also has negative externalities, particularly those attributable to dam construction (see Box 2). Water impoundments cover valuable land and radically alter natural riverine ecosystems, changing habitats and provision of other **ecosystem services.** 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. Dams are also a source of methane emissions from decaying submerged vegetation.

Best practices can mitigate at least some of the negative externalities of hydropower development. The ability of hydropower to be dispatched on demand (unlike wind and solar energy) has value in fully renewable energy systems Though in most places hydropower is insufficient to supply all energy needs, new and existing hydropower might be used differently in a renewable energy system, providing energy mostly when there is no wind or sun rather than on a steady basis.

BOX 2: HYDROPPOWER IN CHINA: THE THREE GORGES DAM

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. The project was revived in 1984; 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 22.5 gigawatts (the world’s largest) and produces as much as 100 billion kWh of electricity per year.

There were many social and ecological concerns about building the Three Gorges Dam. An estimated 1.3 million people were displaced and “1711 villages, 356 communes, 116 towns, and 20 cites were submerged under the rising waters of the reservoir” (Carney 2021). Multiple changes in riverine habitat have been documented, including changes in water temperature, average and peak water flows, and changes to downstream habitat. A number of species have been affected, some of which were already endangered for a variety of reasons, and at least two of which are now thought to be extinct (Zwahlen 2022).

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 the dispatchable electricity may be valuable for backing up more variable solar and wind generating resources without the use of fossil fuels.

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. Traditional biomass—mostly cooking fuels—is declining as an energy source, accounting for about 7% of world primary energy supply in 2022, while modern biomass for electricity generation and heating is expanding, reaching over 6% of global energy supply in 2023 according to the International Energy Agency (IEA 2023).

Industrial economies may use **biomass energy** in several different forms. 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.

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 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.

The solar-driven plant photosynthesis that creates biomass is a relatively inefficient way to collect solar energy for human use, 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 and found that the forest biomass option required 71 times more land area.

Biomass also releases CO_2 when burned, like any other hydrocarbon fuel. But because biomass carbon is part of the active biological carbon cycle (unlike fossil-fuel carbon), carbon effects are complicated as well as controversial (Timmons, Buchholz, and Veeneman, 2016; Sterman et al., 2022). Simple rules are 1) that biomass combustion is preferable to fossil-fuel combustion, but less preferred than noncombustion alternatives; and 2) high-efficiency uses of biomass like heating buildings are preferred to low-efficiency uses like generating electricity.

There are many types of biomass: woody biomass can in principle be sustainably harvested from forests (harvesting no more than growth), which can also provide many ecosystem services when properly managed. But current large-scale woody biomass burning is often associated with significant deforestation. Crops developed specifically for biomass production provide more yield per acre than forests, as well as shorter carbon cycles: For annual crops, carbon released in combustion is reabsorbed by new growth in less than one year. But biomass crops may compete with food crops and other land uses, and may have the same negative externalities as other crops from use of fertilizers, herbicides, etc.

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 (Kelty, D'Amato and Barten 2008). Yet this quantity of biomass would have replaced less than 1% of Massachusetts energy consumption at the time. This is also true for the United States as a whole and for most high-income 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 like hydropower, the availability of biomass energy to be dispatched on demand has value in complementing variable renewable energy sources.

Geothermal Energy

Geothermal energy comes from the earth's core, in some combination of energy left from the origin of the planet and continued decay of nuclear materials. Like "biomass" and "solar", the term "**geothermal energy**" 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 its core 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 purest 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, where magma is close to the earth's surface. In such places, relatively shallow wells can produce steam with high enough pressure and temperature to generate electricity in steam turbines. Such geothermal energy is relatively low cost, and 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 are useable in more locations.

At the next level on the thermal gradient, some areas have geothermal water 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). Hot water could 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** (see Box 3). This type of geothermal energy has the advantage that it can be deployed widely, without the need for subsurface hot water. In most temperate climates, below-ground temperatures remain at about 50^{o} F year-round, and so geothermal systems can be used both for heating in winter and cooling in summer. Heat pumps are growing in popularity; in 2024 , and they currently provide heat for 2/3 of households in Norway.

BOX 3: HEAT PUMPS

A key technology for retiring fossil fuels used for heating buildings in cold climates is heat pumps, which use refrigeration technology to move heat from one place to another rather than creating new heat, just as a window air conditioner moves heat from a hot room to the outside. Room heat boils a special refrigerant compound, and in changing from liquid to gas, the refrigerant absorbs heat from its surroundings (the hot room). Then on the outside, the refrigerant is compressed and forced to condense to liquid again, releasing the heat it absorbed in becoming a gas. A heat pump works the same way, except it removes heat from the outside and transfers it to the inside of a building. Most heat pumps provide both heating and cooling, since these are just different sides of the same process.

Air-source heat pumps work as described above, transferring heat from outside air to inside air, or the reverse. Ground-source heat pumps (also known as geothermal heat pumps) use the same technology but move heat from the ground rather than the air. In such systems, water is circulated through the ground at temperatures too low to heat buildings directly, usually about 50° F. But there is still energy in 50° F water, and heat pumps concentrate this heat and bring it up to a usable temperature for heating a building (e.g. 120° F). In summer, the process can be used in reverse to cool buildings.

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 outside air, from the earth, or from water bodies, it is more accurate to think of heat pumps as a very efficient way to use electricity for heating and cooling. Since they save so much energy as compared to using electricity to heat buildings directly, heat pumps are expected to play an important role in building electrification and energy-system decarbonization.

Other Low-Carbon Energy Sources

A number of other technologies can be used to capture renewable energy from the ambient environment. For example, **tidal power** harnesses the energy of water flowing in and out of a tidal basin (similar to hydropower). Various devices have been used to capture **wave energy**, an indirect form of wind power (waves being created by wind). **Ocean thermal energy conversion** is driven by temperature differences between warm surface waters and the cold, deep ocean. As of 2024, none of these technologies are sufficiently developed to have reliable cost estimates, or even to know whether they may eventually be competitive with the more proven biomass, hydro, wind, solar, and geothermal resources.

Mitigating the climate-change damages of fossil fuels may be possible with **carbon capture and storage**. Fuels can be combusted in a conventional way, with carbon dioxide emissions captured directly at an exhaust stack or later with **direct air capture** technology, which could be employed anywhere on earth (Fasihi, Efimova, and Breyer, 2019). The captured carbon dioxide is then injected into the ground to react with bedrock or to be stored under pressure as a liquid. Many questions remain about the cost and likelihood of large-scale carbon capture and storage (Sekera and Goodwin, 2021). But if the cost of renewable energy is to be compared to the cost of fossil fuels, a relevant comparison is to the cost of fossil fuels plus carbon capture and storage, i.e. a comparison to a carbon-neutral alternative.

In this module we do not provide detailed coverage of **nuclear energy** economics; see discussion of current nuclear fission issues in Box 4. While nuclear fusion is often touted as a potential energy source, in 2024 a controlled fusion reaction has not yet provided net energy, i.e. in laboratory experiments it has always required more energy to generate a fusion reaction than the reaction itself produces. Thus nuclear fusion cannot be considered an energy source at this time.

BOX 4: NUCLEAR POWER: COMING OR GOING?

Currently, nuclear power provides about 10% of the world's electricity and 19% of U.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. Because of these low emissions and because nuclear power is a proven technology, there is debate about whether the transition away from fossil-fuel energy should include new nuclear power. Significant externalities from nuclear power include the risks of major accidents and the long-term storage of nuclear wastes. These impacts are difficult to estimate in monetary terms.

The 2011 Fukushima, Japan accident, in which three of six reactors at the site melted down, leading to considerable release of radiation and continuing management of contaminated wastes and groundwater, including wastewater release into the ocean, caused many countries to reevaluate their nuclear power plans. In the aftermath of Fukushima, Germany decided to shut down its nuclear plants, Switzerland and Spain committed to no new nuclear energy, and many other countries have affirmed decisions to remain nuclear free.

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 is in progress. But some prominent advocates of climate-change action support new nuclear power development. Of particular interest are future Generation IV reactors and small modular reactors (SMR), which promise to have several advantages over Generation II reactors (≈1970-2010) and the current Generation III technology. 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.

But no nuclear technology can be completely safe, and some 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, the only operating example of a Generation IV reactor is the HTR-PM demonstration plant in China. The ultimate cost of energy from these reactors is 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. And many studies now show that nuclear power is not needed to retire fossil fuels (Breyer et al. 2022).

Renewable Energy and Land Use

In total, there is plenty of renewable energy to satisfy human needs. Earth receives about 173 PW from the sun continuously, or more than 10,000 times world energy use (and additional geothermal energy is also available). Although the sun’s energy is free, collecting this energy is not. Another cost of gathering renewable energy is land for solar panels, wind turbines, etc.—more land than fossil fuel and nuclear resources required. To a large extent, renewable energy economics are influenced by land economics. How much land can be made available, and at what price?

As mentioned above, land requirements are greatest for biomass energy. 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 crop production on food availability and prices is a particular concern.

After biomass, solar energy development is likely to consume the most land in a renewable energy system, with solar farms ranging to thousands of acres of panels. The value of land varies greatly, from relatively unproductive desert to prime farmland and highly valued urban lots. Various ways of utilizing otherwise unused space for solar panels have been employed, including installation on rooftops, over roads and parking, etc., though in 2024 these approaches are 3-5 times more expensive than utility-scale ground-mounted solar installations. The value of land must be weighed against the cost of structures that avoid using new land for energy production. There has also been some success combining solar panels with agricultural land use, especially grazing.

Wind energy towers do not occupy a great deal of land—the footprint of an individual tower is small—but turbines are tall enough to be seen for many miles, and they thus affect large quantities of land, at least visually. Offshore turbines can be even taller than land-based turbines, but if they are far enough offshore, the visual impact is limited to people in boats.

Hydropower dams and reservoirs do not consume large proportions of land, but land in some fertile river valleys can be highly productive, from both environmental and social perspectives. (See Box 2 above about the Three Gorges Dam in China.)

Luderer et al. (2022) estimate global land requirements for a renewable energy development scenario that would curtail most fossil-fuel use and limit climate change to 1.5 ˚C. They estimate a need for about 205 million hectares (791,506 sq mi) of land, representing about 1.4% of the global total, or an area a bit larger than Mexico. In this scenario, about 61% of the energy-producing land is used for bioenergy, though bioenergy supplies only about 8% of total energy, highlighting the large land requirement for this energy source. Acquiring the needed land resources represents a significant challenge and cost in a renewable energy system.

BOX 5: POWER AND ENERGY

In energy economics, there is an important distinction between power and energy. Power is measured in Watts, and is an instantaneous flow. For example, a 15 W lightbulb consumes a flow of 15 W whenever it is on, and a 5000 W generator can produce 5000 W when it runs.

A watt hour (Wh) measures energy, an accumulation equal to 1 watt for 1 hour. For example, a 15 W bulb that runs for 1 hour consumes 15 Wh of energy; running for 2 hours it consumes 30 Wh.

To calculate Wh we literally multiply watts by hours:

$$(15\text{ W})(2\text{ h}) = 30\text{ Wh}$$

A 5000-watt generator running at full output for half an hour produces:

$$(5000\text{ W})(0.5\text{ h}) = 2500\text{ Wh} = 2.5\text{ kWh}$$

Power is measured in watts, and energy is measured in watt hours.

Because quantities of power and energy vary greatly depending on context, we use standard international multiples of watts and watt hours. For example, 1 kWh = 1000 Wh. The most common prefixes for power and energy are:

Prefix	Abbrev-iation	Multiplier	Power of ten	Power unit	Energy unit
kilo-	k	thousand	10^3	kW	kWh
mega-	M	million	10^6	MW	MWh
giga-	G	billion	10^9	GW	GWh
tera-	T	trillion	10^{12}	TW	TWh

3. A SYSTEMS APPROACH TO RENEWABLE ENERGY

Our current global energy system is dominated by fossil fuels because they have historically provided reliable energy at the lowest cost. But a global transition is now underway toward a future energy system dominated by renewable energy, motivated by concerns about climate change. Rather than replacing fossil fuels with any one of the individual energy sources described previously, in most cases an energy system will include multiple sources. The economic question is which combination of renewable sources and energy storage can provide reliable energy at the minimum cost, while keeping environmental impacts at an acceptable level.

For example, the main wind and solar technologies are both variable in output; the wind does not always blow, and the sun does not always shine. But in much of the world, wind and solar energy are complementary, i.e. it tends to be sunnier when there is no wind, and the reverse (Weschenfelder et al. 2020). A combination of wind and solar can thus provide more consistent and lower cost energy than either alone. In this section we consider such characteristics of renewable energy systems.

Electrification

For a renewable energy system, converting most energy demands to electricity is a key strategy. For example, rather than running on gasoline or diesel fuel, cars can be powered by electric batteries, and homes now heated by natural gas can shift to electric heat pumps. There are similar examples throughout the economy.

Electrification is important for two main reasons. First, most of the renewable energy sources described in Section 2—including the main wind, water, and solar technologies—produce energy in the form of electricity (biomass and geothermal energy being exceptions that produce heat). If energy is produced as electricity, it is usually more efficient and less expensive to use the electricity directly rather than convert it to a form such as hydrogen energy (Hydrogen is sometimes referred to as an energy carrier, since producing hydrogen to be burned elsewhere is a way of transporting energy, and burning hydrogen generates only water vapor as emissions).

Second, in many applications electric energy can be used much more efficiently than combustion fuels. For example, a gasoline engine powering a car is only about 20% efficient, meaning that only this portion of the potential energy in gasoline can be converted to kinetic energy to move the car. An electric motor in a vehicle is up to 91% efficient (Westbrook, 2022).

Similarly, the most efficient natural gas furnaces for home heating are around 90% efficient, while electric heat pumps produce 3-5 times more heat than the electricity consumed, for an effective efficiency of 300%-500% (this is possible because heat pumps draw energy from the surrounding air or ground). Using electricity can thus require much less total energy to power the economy.

While electric cars, trucks, and trains are feasible in a renewable energy system, applications such as long-range aircraft are not as easily electrified, since the weight of batteries limits aircraft range (though there are now examples of short-range electric aircraft). Other hard-to-electrify applications include shipping and steel production. Yet renewable energy can also be used in these more challenging applications. For example, synthetic fuel for long-range aviation can be made with renewable electricity, using carbon drawn from the atmosphere and hydrogen split from water through electrolysis (Timmons and Terwel 2022). Electrification is thus not the only option, but it is usually the preferred approach when it is possible.

Accommodating Renewable Energy Variability

By their nature, most renewable energy supplies cannot be matched to demand as easily as fossil fuels. Renewable sources of energy cannot be conjured up in each moment that we need energy:

the wind may not blow, the sun may not shine, droughts may limit hydropower, and biomass crops can fail. Since many renewable energy sources cannot run continuously, they often have lower **capacity factors** than fossil-fuel and nuclear sources (see explanation in Box 6 below), though this is not necessarily a problem except in how it affects energy cost; a source with a low capacity factor could still be attractive if it was inexpensive enough.

The energy supply-demand matching problem is most extreme in the electricity grid, where supply must match demand at every moment. To some extent demand is predictable, and fossil fuel plants have typically been scheduled to start and stop at times of anticipated demand change. Additional plants that start and stop quickly (e.g. gas turbines) have often been held in reserve for unanticipated demand changes. Renewable sources such as solar and wind power do not have this flexibility, as energy output cannot be increased on demand. There are several ways to address this limitation.

Energy diversity is one approach to variability. **Dispatchable** renewable sources include hydropower, biomass, and geothermal energy, all of which can be made available on demand. Energy systems that include these sources can use them when wind and/or solar are not available in sufficient amounts.

Overbuilding generation capacity and curtailing production as necessary is another approach to assuring adequate supply in a renewable energy system. For example, on days with low wind and sun conditions, more energy can be produced in these less-than-ideal conditions by simply adding more wind turbines and solar panels. Then on days with abundant wind and sun, some generation may need to be curtailed to match supply with demand. Though this means leaving some energy capacity unused on the best generation days, it can be the least expensive approach to assuring a reliable supply (Perez et al. 2019). Most current renewable energy systems include at least some overbuilding and **curtailment**. In Australia and California, for example, renewable energy sometimes provides more than 100% of total power demand, requiring some curtailment.

Energy can also be stored as electricity in batteries. Just as a cell phone uses a small battery for energy storage, large battery systems can be deployed at the scale of an electric grid. Renewable energy can then be taken from variable sources such as wind and solar when it is available and used as needed. Batteries are usually the least expensive form of short-term electricity storage (e.g. a few hours), and rapid progress in battery technology is making longer-term battery storage cost-competitive (McFarlane and Twidale, 2023). In California, for example, battery storage for solar power increased tenfold between 2020 and 2023.

Longer-term electricity storage can be more cost effective with **pumped hydroelectric storage** (PHES), a technology that goes back to at least 1929 (Evans et al. 2012). When excess electricity is available from the grid, it is used to pump water from a lower reservoir to a higher reservoir. When power is needed, the water is allowed to flow back down and generate electricity. PHES uses the same technology as hydroelectric plants, but with water and energy able to move in both directions. This technology has already been in use for many years, for example at the Northfield Mountain pumped-storage station in Massachusetts.

Compressed air storage is another promising technology with a similar principle. Use of these and other grid-scale electricity storage technologies may be needed to support large amounts of wind and solar energy production.

Though as noted above, it is usually less expensive to use electricity directly when possible, limited electricity conversion can be an effective approach to variability. The term **power-to-X** refers to converting electricity into energy forms that are more easily stored; making synthetic aviation fuel as described above is one example.

A similar approach is using renewable electricity to separate hydrogen from water. The hydrogen can then be stored and used as needed for heating, transportation fuel, or making electricity with a hydrogen fuel cell. Though this may represent expensive energy—including the cost of the original electricity, the equipment to convert it to hydrogen, hydrogen storage, and the cost of energy losses in conversion—for times when other energy is unavailable, energy stored as hydrogen may be the best choice. In 2024, most hydrogen is made from natural gas, though there are a few examples of "green" hydrogen (produced from renewable electricity) projects being developed in the United States and around the world.

Another power-to-X example is converting renewable electricity to thermal energy for heating or cooling. This may be done with electric heat pumps or chillers, or with simple electric resistance heating. Energy for heating buildings or domestic hot water can be stored in large tanks of water, sand, or special phase-change materials that store more energy in less space. Cooling energy is typically stored as ice. The attraction of such approaches is that thermal energy can be stored for as little as one tenth of the cost of storing energy as electricity (Lund et al. 2016). It would not necessarily make sense to store electricity in batteries for running electric heat pumps on a cold winter day; it is much less expensive to store the heat.

BOX 6: CAPACITY AND CAPACITY FACTOR

Capacity describes the size of an energy-producing facility, and is given by maximum power output in watts, **kilowatts**, megawatts, etc. For example, a 250 W solar panel produces this power level in bright sunshine, and 3 MW wind turbine produces a maximum of 3 million watts in windy conditions. Actual output is of course often less than the maximum.

Capacity factor (CF) is the portion of maximum energy production obtained over a period of time, always less than or equal to 1. Capacity factor in any period of time (often 1 year) is calculated as:

$$CF = \frac{actual\ enegy\ production}{maximum\ energy\ production}$$

For example, suppose that a solar panel with 250 W capacity produces at full power for an average of four hours per day. Energy produced is:

$$(250\ W)(4\ h) = 1000\ Wh = 1\ kWh$$

Maximum energy production for this panel in a day is (in the theoretical case of 24 hours of bright sunshine):

$$(250\ W)(24\ h) = 6000\ Wh = 6\ kWh$$

Capacity factor for this day is then:

$$CF = \frac{1\ kWh}{6\ kWh} = 0.17$$

This is a typical CF for a solar panel in a northern climate. While this may seem like a problem compared to a nuclear power plant that may have a CF of 0.9 or more, the bottom line is how much an energy system costs to build and operate (see discussion of levelized cost of energy (LCOE) in Box 7 below). Capacity factor is only one of several determinants of the cost of an energy system, and energy sources should not be accepted or rejected based on capacity factor alone.

The Electric Grid

While much of the world already has **electric grids** for transmission and distribution, the role of the electric grid is somewhat different in a renewable energy system. For example, grids historically transmitted electricity in only one direction: from generator to user. But with home generation from solar panels or other sources, consumers (sometimes called **prosumers**, who both produce and consume) can also send electricity back to the grid, so the grid must be able to accommodate electricity flows in two directions. And in general, renewable energy generation is more widely distributed on the landscape than legacy fossil fuel sources, which requires the electric grid to have greater long-distance transmission capacity.

Having robust national (and possibly international) electric grids is also an approach to variability. Though the wind may not blow in a particular place at a particular time, wind is 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. Studies of renewable energy systems consistently show that cost falls as the area served grows, due to this greater diversity of weather conditions across a larger area.

The electric grid in the 48 contiguous U.S. states is currently not really one grid, but three: the Eastern Interconnection, Western Interconnection, and Texas Interconnection (the former two including parts of Canada). These wide-area synchronous grids are managed by a number of regional balancing authorities which assure that electricity supply always meets demand.

For example, ISO-New England (ISO for independent system operator) is the balancing authority for that region. The grid regions have some connections, but to a large extent function autonomously. The National Renewable Energy Laboratory undertook the Interconnections Seam Study to estimate the benefits of increasing connectivity between the current grids, creating a truly national grid. The study found net cost savings for increasing grid connectivity in all of 32 scenarios studied (4 grid construction scenarios with 8 generation scenarios), with the greatest savings in scenarios that included the most generation from variable renewable energy sources (e.g. solar and wind).

More specific regional studies also support the benefits of grid expansion. For example, a study of benefits from increasing the grid connection between the U.S. Northeast and the Canadian province of Quebec found potential net benefits for both regions (Dimanchev et. al 2020).

The Northeast has lower-cost solar and wind energy resources than Quebec. Meanwhile, electricity generation in Quebec is mostly from hydropower with reservoirs—a dispatchable energy source. The Northeast could export wind and solar energy to Canada when there is an excess, and Quebec could return hydropower when this is needed, reducing cost of decarbonization in both regions. What prevents this is lack of sufficient grid connections, and these have not proven easy to build. As of 2024, Massachusetts has attempted to establish new grid connections to Quebec on several routes, with none yet completed. New grid connections that are underground on existing rights of way or underwater have faced less public opposition, and appear more likely to be built.

A national grid could also exploit the timing of peak demands in different population centers. For example, peak summer demands often occur in the late afternoon when cooling demand is greatest, businesses are still open, and consumers are returning home. But this occurs three hours later on the U.S. West Coast than on the East Coast, and some of the same generation equipment could thus serve both coasts if there were sufficient long-distance transmission capacity. Facilitating grid expansion is a key need for increasing renewable energy use, decreasing its cost, and also for supporting electrification of transportation, home heating, and other sectors.

Optimizing Renewable Energy Systems

As suggested by the previous discussion, fully renewable energy systems should typically include multiple sources of energy as well as provisions for energy storage. Some sources, like wind and solar, tend to be complementary in time, and a combination of the two provides more consistent generation. Dispatchable sources including hydropower, biomass, and geothermal can fill in at times when wind and solar sources are insufficient to meet demand. And energy storage such as batteries or hydrogen effectively moves energy from one time to another.

Designing a renewable energy system is clearly a **dynamic problem**, or one in which time is a significant variable. Given this variability in time, how would we decide how much of which energy and storage infrastructure to include in a renewable energy system? This section describes an economic approach to answering this question.

From an economic perspective, a primary criterion is minimizing cost. Because of the need to curtail the fossil-fuel emissions driving climate change, we assume that the sources of energy must be renewable. We thus do not require that the system be less expensive than burning fossil fuels (though it would be helpful if it were), but given a menu of renewable sources and storage, the system should utilize the least expensive combination of technologies that meets energy demand. In economics, this is called a **constrained optimization** problem: optimum because we seek the minimum total cost, and constrained by the availability of wind, sun, and other energy sources in each time period, as well as the requirement to meet energy demand at every point in time.

To solve this constrained optimization problem, we must first establish a relationship between **capital and operating costs**. Capital costs are those initial investments required to build infrastructure, and operating costs are incurred in running a plant. For example, wind power requires a large capital investment in a turbine that will last for 25 years or so, but costs almost nothing to operate after it is built (with just some maintenance costs). By contrast, a biomass plant has less capital cost than wind, but much greater operating costs for fuel, which must be purchased continuously.

One method to compare one-time capital costs and ongoing operating costs is to annualize (or amortize) capital costs. This reveals how much of an initial capital cost for a source like a wind turbine can be assigned to each year of the turbine's life. The annualized capital cost can be added to annual operating cost to get total annual cost, which is then comparable for different energy sources with varying capital and operating cost characteristics. This is known as the **levelized cost of energy** (LCOE; see Box 7 for a description of the math behind this).

Environmental and ecological economists are also concerned about monetary and nonmonetary costs of **environmental externalities**, or unintended environmental effects of energy systems. Fossil fuels have high externality costs, including ground-level pollution as well as climate impacts (Gregory, 2023). Renewable energy sources also have externality costs. For example, hydropower dams may reduce the market value of fish and/or reduce nonmarket values of biodiversity, recreation, or aesthetics.

There are several methods that can be used to assign dollar values to these negative externalities (Dunford et al., 2018). Where possible, the monetized externality values can be included as costs in a constrained optimization problem. In cases where it is not possible to assign a monetary value, for example if a certain area proposed as an energy production site is considered sacred in indigenous traditions, these other considerations of a social or ethical nature must be weighed against economic benefits and costs.

Given the number of variables (e.g. potential energy sources) and constraints (e.g. solar and wind availability in each hour of a year), a computer optimization program is usually the only practical way to identify an optimum portfolio of renewable energy sources and storage. Inputs to an energy optimization program include the annualized capital and operating costs of each potential energy and storage technology, the possible capacity factor of each source in each time period (e.g. in each hour of a model year, given wind and solar conditions in each hour), and the demand for energy in each time period.

This input data describes how much it would cost to build a renewable energy source such as a wind turbine, how much energy it would generate in each time period, and how this generation potential compares to energy demand in each time period. Computer software using **linear programming** or some similar optimization method can then find the lowest-cost combination of generating and storage technologies that satisfies energy demand in each time period.

Table 1 shows results for a computer optimized world energy system based almost exclusively on renewable sources in the year 2050 (Bogdanov et al. 2021). In this study the world was divided into 145 regional energy systems, with demand projections from the International Energy Agency, including a 30% growth in primary energy demand that reflects population increases, greater energy use with rising incomes in some parts of the world, and efficiency improvements. Enough generation and storage are provided in each region to meet demand in each hour of a model year.

Table 1. *World Energy Optimum Sources and Storage in 2050*

Electricity Generation, TWh			**Heat Generation, TWh**			**Energy Storage, TWh**		
Solar	104,468	76.1%	Solar	3,009	5.3%	Batteries	27,522	44%
Wind	27,307	19.9%	Geothermal	791	1.4%	Pumped hydro	668	1%
Hydro	4,192	3.1%	Biomass	5,830	10.3%	Compressed air	2,404	4%
Biomass	330	0.2%	Methane	6,573	11.6%	Thermal	9,300	15%
Geothermal	381	0.3%	Waste	665	1.2%	Synthetic methane	9,531	15%
Fossil fuels	37	0.0%	Electric	39,614	70.1%	Hydrogen	13,311	21%
Nuclear	26	0.1%	Fossil fuels	-	-	**Total**	**62,736**	**100%**
Other	436	0.3%	**Total**	**56,482**	**100%**			
Total	**137,277**	**100%**						

Source: Bogdanov et al. (2021)

In this example, solar provides the largest share of energy, with most of the remaining energy coming from wind. Batteries and hydropower storage provide most of the backup capacity for times of little wind and sun. Biomass is quite limited in availability compared to energy demand, and is used mostly for generating heat rather than electricity.

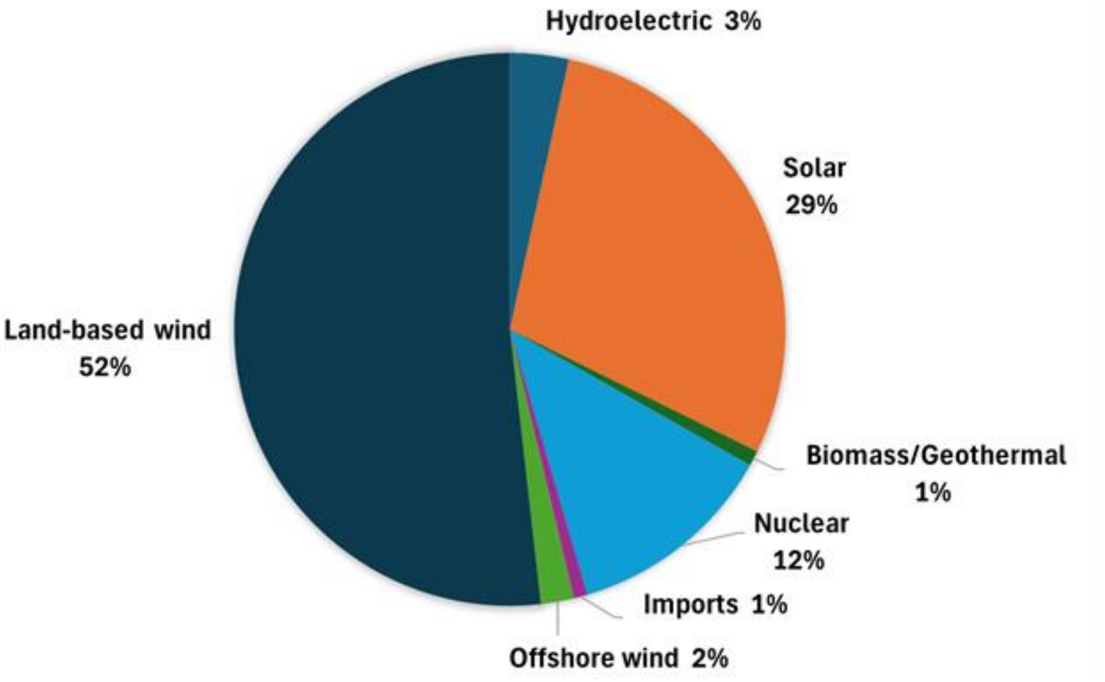
Most of the heat generation is provided by electric heat pumps (which in turn are powered mostly by solar and wind). In addition to batteries and hydropower, thermal energy storage as well synthetic methane and hydrogen (produced from renewable electricity) provide energy storage. In this study, approximately 3.5% of the generation was curtailed, i.e. available but not needed when generated. Solar is the most widely distributed renewable energy source, though wind energy is more prominent in northern latitudes and sources such as hydropower and geothermal energy are important in some regions.

In the study shown in Table 1, the authors estimate steep cost reductions for the core solar and battery technologies by 2050, with prices falling 74% for solar and 76% for batteries by 2050 as compared to 2023 prices. Since the computer optimization program identifies the lowest-cost combination of energy sources that always meets demand, it is not surprising that solar coupled with nighttime battery storage will dominate energy production if prices fall as far as expected in the study.

Other studies that assume lesser price reductions for solar and battery technology have found larger roles for wind energy, pumped hydro storage, and other technologies. The National Renewable Energy Laboratory (NREL 2022) conducted a similar study of the U.S. electric grid (not including other U.S. energy demands), finding that it is technically feasible to have a decarbonized grid by 2035.

Figure 3 shows the least-cost combination of generating sources for a scenario that does not include any fossil fuels. Generation is dominated by onshore wind, followed by solar, with small contributions from other generating sources. Energy storage, mostly in the form of hydrogen, serves to meet demand at all times.

Figure 3. *Generation for U.S. Electric Grid in 2035, Without Fossil Fuels*



Source: NREL (2022)

Electricity transmission would be substantially increased, especially for moving energy from the windy Great Plains to coastal areas. The study estimated that this scenario would cost $400 billion more than business as usual, but that climate change benefits totaled $1,260 billion and other human health benefits added $400 billion, with total benefits being more than four times greater than total costs.

Though specific results differ by location and future price assumptions, the general patterns seen in Table 1 and Figure 3 are typical: most of the energy comes from wind and/or sun, with some combination of dispatchable energy sources and energy storage used to ensure energy demand can always be met, and a small amount of generation overbuilding and curtailment.

BOX 7: LEVELIZED COST OF ENERGY (LCOE)

Often we want to know the cost of producing energy from a specific source, for example in dollars per kilowatt hour ($/kWh). A challenge is that most energy sources require both initial capital costs to build, as well as on-going costs to operate, but in different proportions for different sources. Levelized cost of energy (LCOE) provides an answer to this problem: it is the average cost per unit of energy over the life of a generating source or system.

A method for calculating LCOE that is appropriate when there is little or no change in annual costs or output is:

$$LCOE = \frac{K\alpha + C}{E}$$

where K is capital cost, C is annual operating cost, E is annual energy production, and α is a capital recovery factor given by:

$$\alpha = \left(\frac{r(1+r)^T}{(1+r)^T - 1}\right)$$

where r is an annual interest rate, and T is number of years in the project.

For example, consider a 5 kW residential solar electric system that costs $15,000 to install, produces 7000 kWh per year, has zero operating cost, and lasts for 25 years, with an interest rate of 5%. First calculate capital recovery factor (α):

$$\alpha = \left(\frac{0.05(1+0.05)^{25}}{(1+0.05)^{25} - 1}\right) = \left(\frac{0.05(3.39)}{(3.39) - 1}\right) = \left(\frac{0.17}{2.39}\right) = (0.07)$$

Using the capital recovery factor (α), we can then calculate LCOE:

$$LCOE = \frac{[\$15{,}000(.07)+0]}{7000\ kWh} = \frac{\$1050}{7000\ kWh} = \frac{\$0.15}{kWh}$$

Over the life of the solar energy project, the average cost of electricity production is $0.15/kWh. This can be compared directly to the cost of electricity from other sources, e.g. wind, hydropower, or biomass electricity. But as discussed in the text, renewable energy availability varies over time, so the average cost of a source is not necessarily the most useful metric. The main goal is to minimize the LCOE of an entire energy system, where we justify spending more for some sources than others because they are available when we need them. Finding system LCOE ($LCOE_S$) is similar to the method above, except that we include all energy sources:

$$LCOE_S = \frac{annualized\ cost\ all\ sources}{total\ demand} = \frac{\sum_{i=1}^{I}(K_i\alpha_i + C_i)}{kWh_S}$$

where K, α, and C are as defined above, i represents an individual energy or storage source, and kWh_S represents all energy utilized in a system (which may be less than total energy generated, if there is curtailment of wind and solar sources). Minimizing LCOE_S is a typical goal for energy system optimization, subject to a given energy demand and to the availability of individual sources through time.

Energy efficiency

So far we have only discussed energy production options. But better technology can often deliver the same energy services with less energy consumption, thereby improving energy efficiency. Efficiency options often require an initial capital expense to generate a stream of energy benefits over time, just like investing in an energy source. Since reducing energy consumption has exactly the same effect on total energy supply/demand balance as increasing production, efficiency and generation are in fact substitutes. In this section we consider the potential for increasing efficiency instead of, or in addition to, expanding renewable energy production.

Energy efficiency improvements and energy conservation are related but different approaches. Energy efficiency uses better technology to provide the same service with less energy. For example, the light from an LED bulb can equal the light of an incandescent bulb (can provide the same energy service) with about 15% of the electricity consumed—an efficiency improvement, which has led to LEDs largely replacing incandescent.

On the other hand, conservation is reducing consumption by giving up an energy-related service. For example, winter heating energy can be reduced by lowering a thermostat setting, but a cool house does not represent the same energy service as a warm house.

Conservation does not necessarily mean sacrifice – for example, turning off lights and appliances when not needed conserves energy while not affecting comfort or convenience. Some techniques have aspects of both efficiency and conservation, for example a low-flow showerhead which conserves water and energy while providing a similar (but not identical) service. This section focuses on energy efficiency, but includes comments at the end of the section about the potential role of energy conservation in a renewable energy system.

Building energy efficiency options are numerous, and include better building envelopes with less air leakage and more insulation, recovery of heating/cooling energy from ventilation air, more efficient lighting (as in the LED example above), variable speed motors that consume less electricity, controls to prevent using energy when it is not needed, etc. Beyond buildings, sectors including transportation and industry also hold many potential efficiency improvements.

Efficiency improvements typically have decreasing **marginal benefits**, i.e. each additional efficiency measure provides less benefit than the previous one. For example, doubling the amount of attic insulation cuts heat loss in half. Another doubling of insulation thickness halves heat loss again, but the reduction is now half of half the original, or one quarter of the original heat loss. And the improvements have increasing **marginal cost**: doubling insulation the second time requires twice as much insulation.

Though much greater efficiency is physically possible, from an economic perspective, the question is when efficiency improvements are worthwhile, e.g. when should we stop adding attic insulation? A common financial metric has been the simple payback period, or the capital cost of an efficiency improvement divided by its annual benefit.

Simple payback has many problems as a metric, including that it does not reflect an interest rate (time value of money) and that there is no consistent criterion for how many years of payback is acceptable. Instead, economists usually recommend calculating the cost of conserved energy (CCE), a less common metric that more accurately expresses efficiency benefit in value per unit of energy saved (e.g. $/kWh). (Note that despite the term “conserved energy”, this really refers to energy efficiency, not conservation as we have defined it above). This can be compared directly to the cost of energy, which is appropriate, since energy and efficiency are substitutes. See Box 8 for a description of calculating CCE.

For example, a student group at the University of Massachusetts Amherst did a complete assessment of one classroom building, and identified potential improvements including air sealing, wall cavity insulation, door replacement, better windows, and thermostat upgrades. Given the capital cost and projected energy savings, CCE was calculated at $0.02/kWh (of heat energy). Since this was less than the cost of purchasing energy, the proposed improvements were found to be worthwhile (Timmons and Weil, 2022). If curtailing fossil fuel use is a goal, in this case it would be less expensive to invest in efficiency than to invest in renewable energy.

While using CCE as a metric improves the economic analysis of efficiency measures, it is still a static analysis if we compare CCE to an unchanging cost of energy. As discussed above, in a renewable energy system the marginal cost of energy changes over time. Given this, real-time electric rates may become more common— implemented with **smart electric meters**—which complicates a CCE comparison. And as with energy generating sources, the only way to know with certainty that an efficiency improvement is (or is not) worthwhile for society is to include efficiency options along with generating options in an optimization model that minimizes total cost of energy and efficiency investments (Timmons and Weil, 2022).

Similarly, energy conservation (behavior changes) at specific times may have very high marginal value, for example, during hot midday periods when air conditioning demand tends to peak. Deferring energy-intensive processes like washing clothes or charging electric vehicles to a period with lower overall demand would be very beneficial, and could be incentivized through variable real-time electricity costs (Timmons et al. 2022).

Investments in renewable energy must be accompanied by investments in energy efficiency if the world is to meet its energy challenges. A 2017 analysis by the International Renewable Energy Agency (IRENA) found that successful decarbonization of the world’s energy system by 2050 to limit warming to 2°C could be accomplished with 50% of the carbon reduction coming from a transition to renewable energy and 45% from energy efficiency gains (with the remaining reduction being reduced emissions from remaining fossil fuel sources; IRENA 2017). The electrification of the world's energy systems will produce a large portion of the efficiency gains, as electric products are generally more efficient than their fossil fuel counterparts (e.g., electric vehicle drivetrains are more efficient than internal combustion engines).

The IRENA report emphasizes the synergistic benefits between renewable energy and energy efficiency – when countries focus primarily on only one approach the economic and environmental benefits are not nearly as significant. Another finding is that low- and middle-income countries (LMIC) stand to gain the most from energy efficiency investments, as they currently tend to have the least efficient energy systems. A 2020 analysis concludes that energy efficiency investments in LMIC not only produce cost savings, but also foster expanded output of goods and services to reduce poverty (UK Aid et al. 2020).

The potential for energy efficiency indicates 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 as by introducing new renewable energy sources. In effect, it may be possible to "squeeze out" fossil fuels by "lowering the ceiling" of total energy demand while "raising the floor" of renewable energy supply. The renewable energy revolution is in significant part an energy efficiency revolution.

BOX 8: COST OF CONSERVED ENERGY

For energy efficiency, cost of conserved energy (CCE) is a metric similar to LCOE that can be used to calculate the value of energy efficiency investments. In this case we are calculating how much it costs (in \$/kWh) to *not use* energy, which has the same effect as producing energy:

$$CCE = \frac{K\alpha + C}{\Delta E}$$

where K, α, and C are the same as in Box 7 above, and ΔE is the energy conserved (change in energy) as compared to a base case without the efficiency measure. If CCE is less than the cost of purchasing or producing energy, an energy efficiency project is desirable.

Consider an energy efficiency investment that costs \$105, lasts 3 years, has no operating cost, and saves 400 kWh per year, with an interest rate of 5%.

The capital recovery factor (α) is:

$$\alpha = \left(\frac{0.05(1.05)^3}{(1.05)^3 - 1}\right) = \left(\frac{0.05(1.16)}{(1.16) - 1}\right) = \left(\frac{0.06}{0.16}\right) = (0.38)$$

And CCE is:

$$CCE = \frac{\$105(0.38) + 0}{400\ kWh} = \frac{\$40}{400\ kWh} = \frac{\$0.10}{kWh}$$

If the levelized cost of electricity is more than $0.10/kWh, reducing electricity use is less expensive than producing it, and we should invest in the improvement.

4. POLICIES TO SUPPORT RENEWABLE ENERGY

In the beginning of this module we asserted that all energy will eventually be renewable, since fossil fuels are finite in supply. Yet there is no certainty about the time of “eventually”, or about how much damage from climate change will occur before fossil fuels are retired. Government policy clearly affects renewable energy use. What kinds of government policies are most important and most effective? In this section, we consider various government policy options for supporting renewable energy.

Renewable Energy Portfolio Policies

Renewable portfolio standards (RPS) and **clean electricity standards** (CES) require a percentage of total energy or electricity to be obtained from renewable sources. A portfolio policy might start, for example, with a requirement that 20% of energy come from renewable resources, with that percentage increasing over time. Many countries, regions, and states have set renewable portfolio standards; in 2023, 29 U.S. states had RPS and/or CES. For example, Massachusetts’ original RPS requires 40% of electricity to be renewable by 2030 (increasing 1% annually thereafter), along with a variety of other specific regulations on energy sources.

Though there are various ways to implement RPS and CES, all represent direct government requirements to use some minimum amount of renewable energy. This is perhaps the most direct way for governments to promote renewable energy.

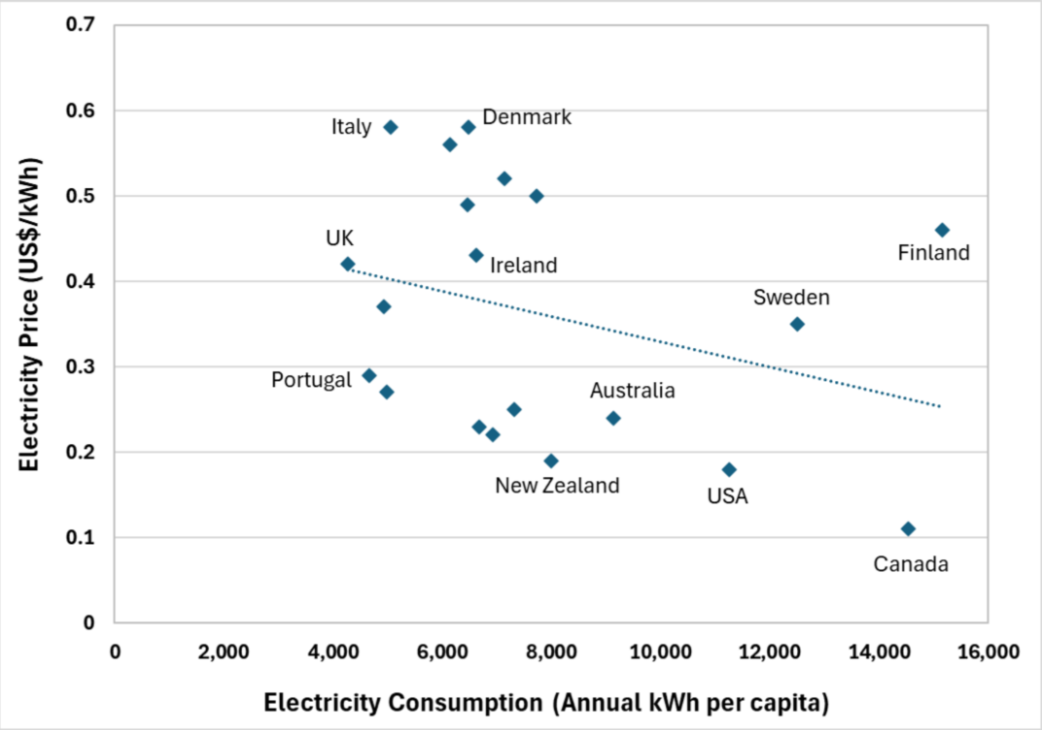
To limit fossil fuel use, governments could in principle enact direct restrictions on producing fossil fuels. Such policies are not common today, though ecological economist Herman Daly long advocated production caps on resource use to ensure sustainability: “Caps are physical quotas, limits to the throughput of basic resources, especially fossil fuels. The quota usually should be applied at the input end because depletion is more spatially concentrated than pollution and hence easier to monitor” (Daly, 2013). Perhaps as climate change worsens, restricting fossil fuel production will become a more acceptable option.

Externalities and Carbon Taxes

Environmental economics teaches us that resource prices should reflect their true costs to society. Fossil fuels are rarely priced “correctly” given their significant climate and pollution costs. Taxes on such negative externalities (called **Pigovian taxes** after economist Arthur Pigou) can be used to accomplish this, such as a Pigovian tax on gasoline. Even though governments may use this tax primarily to raise revenue, it ensures that gasoline buyers and sellers pay the true costs of gasoline use. While nearly all economists agree that current fossil fuel taxes are too low, there is disagreement about how much higher taxes should be.

Pigovian taxes can also be applied to the electricity sector. As we see in Figure 4, electricity prices vary across countries (largely due to variations in electricity taxes), and in general, higher electricity prices are associated with lower per-capita consumption rates (as shown by the trend line in Figure 4).

Figure 4. *Electricity Prices and Consumption Rates*



Source: Consumption (2021 data): U.S. Energy Information Administration, *International Data, Electricity; Prices* (2022 data): World Population Review, *Cost of Electricity by Country.*

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.

Though not as a direct a method of encouraging renewable energy use as renewable portfolio standards, Pigovian taxes on fossil fuels are a reliable policy for reducing use of fossil fuel and encouraging renewable energy adoption.

With **cap-and-trade** policies the government enacts a limit on emissions of a pollutant, for example, carbon. The government allocates emissions permits giving the right to emit a certain amount of a pollutant (such as a ton of carbon), either giving the permits away freely or auctioning them to the highest bidders. Permits can then be bought and sold between different consumers of fossil fuels. Since the number of permits is fixed, the price of permits rises with increased demand. While total pollution is unknown in advance with a Pigovian tax, total emissions are known with cap-and-trade—equal to the number of permits.

Energy Subsidies

In economics, **subsidies** can be thought of as reverse taxes. Instead of the government causing something to be more expensive and thus less used (e.g. fossil fuels), the government makes the alternative (e.g. renewable energy) less expensive through providing subsidies. 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 with 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 solar panels, increasing insulation, or purchasing an electric vehicle.
- Price supports: 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. For example, homeowners who install solar PV panels can sell any excess energy back to their utility at a set price.

Subsidies can be justified to the extent that they support goods and services that generate **positive externalities**, i.e. benefits to society that are not reflected in market prices (though fossil fuels have often received subsidies, despite their negative externalities). In the early stages of technology adoption, subsidies can promote economies of scale that lower production costs, i.e. they may be important for allowing new industries to become competitive, and can be gradually reduced as technologies becomes more mature.

A disadvantage of energy subsidies is that they do not encourage energy efficiency, 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.

An example of the use of subsides to promote renewable energy development is the Biden Administration's Inflation Reduction Act of 2022. This legislation provided for tax credits for investments in wind, solar, energy storage, and other renewable energy projects including home solar energy installation, and battery storage, as well as energy efficiency.

Efficiency Policies

Governments can promote energy efficiency by setting **energy efficiency standards**. For example, in 2022 the United States adopted light-bulb efficiency standards that effectively phased out old-style incandescent light bulbs (invented by Thomas Edison in 1879) and required the use of LED lighting. Other energy efficiency standards exist for buildings, appliances, electronics, and vehicles. Like renewable portfolio standards, efficiency standards are an example of government taking a direct role in regulating the efficiency of products available in the market.

Efficiency labeling is a different approach that 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 product indicated that the label was an important factor in their purchase decision. Since the program inception in 1992, the savings from Energy Star products amount to over $500 billion.

Even with informative labels, many consumers do not purchase high-efficiency products because the upfront costs may be higher. For example, more-efficient refrigerators cost more than less-efficient ones. However, the energy savings from efficient refrigerators means that the additional cost will be recovered in a relatively short time period. The problem is that people often have high implicit **discount rates**, focusing on the upfront cost while discounting the long-term savings (see Box 9). Rebates on efficient products can reduce this problem. Education and promoting a cultural change toward more long-run thinking will likely be needed to make consumer purchasing habits more consistent with energy efficiency.

Economists point out that if efficiency is raised without any increase in energy prices, there is a **leakage** or **rebound 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. Gillingham et al. (2016) find that the magnitude of rebound effects estimated in different studies varies greatly, but most results fall in the range of 5%-25%, i.e. this proportion of the energy reduction from efficiency is lost due to greater usage.

As mentioned earlier, from an economic theory point of view energy prices *should* rise to reflect the negative externalities of fossil fuel use. Higher energy prices could prevent rebound effects. Of course, higher energy prices are not popular – but from an economic point of view they are a reliable way to promote increased efficiency.

BOX 9: 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 60% internal rate of return (a metric equivalent to return on a financial asset) over a 15-year refrigerator life.

Anyone who was offered a stock market investment that would bring a guaranteed 60% 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 they 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 60% to make this judgment—a consumer behavior difficult to justify economically, yet very common.

Capital Intensity and Interest Rates

Most renewable energy technologies, such as wind and solar, are **capital intensive**. For these energy sources, annual operating costs account for only a small portion of total costs, relative to the large initial capital costs. Given this capital intensity, the levelized costs of renewable energy (see Box 7) are very sensitive to interest rates. (Exercise 4 at the end of the module asks you to calculate LCOE with low and high interest rates). Lower interest rates imply a lower cost of capital and thus lower costs for renewable energy, while higher rates have the opposite effect.

Government policy affects interest rates, particularly the rates set by central banks to regulate the macroeconomy. Targeted policies can also provide lower-interest loans for specific technologies such as renewable energy to encourage adoption. Such policies are particularly important where interest rates are high, for example, in lower-income countries where interest rates can be double those found in higher-income countries.

Removing Regulatory Barriers

Finally, government policies can affect renewable energy adoption by addressing regulatory hurdles to deploying renewables. For example, siting wind turbines is easy in some government jurisdictions, and almost impossible in others. Permitting processes may require environmental reviews that can last for years. A process designed to allow a reasonable level of public information and participation can be abused by a small number of people who wish to block a project, regardless of its level of public support or net environmental benefits.

In the United States, building new electric transmission lines—critical for the cost and reliability of a renewable energy system, as discussed above—has been particularly stymied by regulatory processes that were not designed to address the urgent problem of climate change (though this may be changing: in early 2024, the Federal Energy Regulatory Commission approved a new rule to speed up the process of connecting new sources to the power grid, especially benefitting the considerable backlog of new wind and solar projects.

Governments thus have a role to play in hastening and smoothing the adoption of renewable energy through reconsideration of its own procedures. Governments must provide the right balance of necessary regulation, appropriate public participation, and concrete action to address the crisis of climate change through transformation of the global energy system.

Renewable Energy in Low and Middle-Income Countries (LMICs)

The economic and policy principles governing renewable energy systems as described in this module are intended to be nearly universal, i.e. to apply to countries and regions regardless of their economic, environmental, and social characteristics. Yet several aspects of renewable energy development may differ in low- and middle-income countries (LMICs).

The term "leapfrogging" is often used to describe a technology development path that uses the most current technology without ever adopting its historical antecedents. For example, countries that never installed universal landline telephone service can now move directly to mobile technology without the expense of landlines. The leapfrogging concept applies in part to renewable energy development.

The most obvious example is that LMICs without fossil-fuel infrastructure can now avoid the expense of developing this, along with the potential for **stranded capital assets** as fossil fuels are retired to mitigate climate change. Rather than building coal, oil, and gas-fired power infrastructure, LMICs can invest in solar and wind energy along with the necessary energy storage. Similarly, buildings and transportation infrastructure can be built for electricity use initially and at appropriate levels of efficiency.

On the other hand, completely avoiding the development of a hard-wired electric grid (i.e. as a parallel with communications technology) in LMIC seems unlikely. For those without electricity, small, independent energy systems can indeed provide substantial benefits at minimal cost and without an electric grid.

For example, a family without electricity could add a single solar panel and battery to supply a few lights and charge phones, greatly increasing quality of life. But larger electric loads—even a refrigerator—can be less expensively supplied by an electric grid than by an independent system. Where consumers also demand electric cooking, cooling, transportation, water pumps, etc., there is no substitute for an electric grid.

Even where most households supply their own solar energy, an electric grid may be a less expensive way to balance loads between households (and between commercial and industrial uses) than to have enough batteries for each household to be fully independent. But the characteristics of newly developed electric systems may be different, including initial use of smart-grid features, microgrids, two-way energy flows, and local energy storage not found in older electric grids. New electric grids can also be better positioned to access the best renewable energy production sites and for interregional electric transmission. In these ways new electric grid development represents a partial leapfrogging of earlier technologies.

As described above, most renewable energy sources require substantial initial investments, and their final costs (LCOE) are thus greatly dependent on interest rates. Many LMICs face much higher costs of borrowing than higher-income countries, effectively making renewable energy more expensive in LMICs. If all countries of the world are to adopt renewable energy—as needed to avoid the worst effects of climate change—LMICs are likely to need assistance in the form of lowered interest rates for renewable energy investments.

As observed above for the Bogdanov et al. (2021) study, prices for renewable energy are widely expected to decline over time, especially for the core solar and battery technologies. This expectation is based on learning that occurs as the technologies are more widely deployed and on achieving greater economies of scale in production. If prices indeed fall as expected, early adopters will thus face higher prices than later ones. A key role for higher-income countries is thus being the initial renewable energy developers, in part to mitigate climate change and in part to drive down prices, making renewable energy more affordable throughout the world.

Finally, the nature of renewable energy systems may be somewhat different in LMICs. In particular, many LMICs are in regions near the equator, where solar energy is stronger than at far northern and southern latitudes.

A 2020 report by the World Bank found that many of the world's poorest countries are also those with the highest solar potential, including Namibia, Lesotho, Afghanistan, and Sudan (World Bank 2020). Year-round equal day length at the equator also removes the seasonal solar energy storage problem. Solar energy is thus expected to be more prominent in equatorial LMICs.

Many LMICs also face freshwater shortages that can be mitigated with seawater desalination (at least in coastal areas). Desalination represents a large electric load that can be accomplished only when solar energy is available, with the resulting freshwater easily stored in reservoirs, effectively storing energy at low cost. Such reservoirs may also hold potential for pumped hydropower electricity storage. This energy-water nexus is thus likely to provide opportunities to reduce costs and increase benefits of renewable energy systems in LMICs.

5. SUMMARY

Addressing climate change requires that carbon emissions eventually approach zero, so most remaining fossil fuels must be left in the ground. A number of renewable energy technologies are available to replace fossil fuels, with many of the needed technologies being well established and cost-effective, and others, such as battery storage, rapidly improving in efficiency and capability. A renewable energy economy is technically and economically feasible.

A general plan for energy decarbonization is to use energy in the form of electricity, and then make electricity from renewable sources. In this renewable energy economy, many applications that previously used fossil fuels, e.g. transportation and home heating, can most cost effectively be powered by electricity.

An essential goal for society is minimizing the cost of a renewable energy system—a system that provides for society's energy needs at all times. Costs can be considered broadly, including any externalities of energy production.

There is now much evidence that least-cost, fully renewable energy systems should include a diversity of renewable energy sources as well as energy storage in different forms. This energy diversity includes both variable sources (wind and solar) and dispatchable sources (hydropower, biomass, geothermal, storage), taking advantage of source complementarity and making provision for occasions when variable sources are unavailable. Long-distance electricity transmission lines are also important to increase reliability and decrease cost, since wind and solar energy are more consistent over larger areas, and long-distance transmission allows generation to take place in the best (e.g. windiest, sunniest) and least expensive locations.

In addition to energy production, energy efficiency must play a central role in achieving the shift to renewable energy systems, since it can significantly reduce overall energy demand. Energy conservation (doing without energy for some purposes, at least temporarily) at critical times can also reduce the cost of a renewable energy system.

Climate change is a major externality of economic activity. As such, economic theory indicates that an unregulated free market will not respond adequately to this problem. Some level of government policy to limit fossil fuel use and promote renewable energy and energy efficiency is needed. Potential policies range from direct controls (e.g. requiring use of renewable energy) to various incentives (e.g. taxes, subsidies) to promote a transition away from fossil fuels.

While climate change is a formidable problem, technically and economically feasible solutions already exist. The challenge for our society is to organize ourselves around renewable energy use with all possible speed. Economic analysis is essential to indicate the most effective choices.

6. DISCUSSION QUESTIONS

1. What are the main reasons for promoting a transition away from fossil fuels? What are the characteristics of renewable energy sources that distinguish them, and an economic system based on renewables from fossil fuels?
2. What are some of the problems and limitations of renewable energy sources? What major solutions are available, or can be developed, to respond to these?

3. Compared to fossil fuels, biomass fuels might appear to be the easiest substitute, since in most cases biomass fuels can easily replace fossil fuels, using similar technology. Also, like fossil fuels, biomass fuels are dispatchable on demand. But what are some potential problems with moving to a more biomass-based economy?

4. Hydropower is currently the largest source of renewably generated electricity in the world, and there is potential for expansion. In a few countries, a renewable energy portfolio could be based on hydropower and energy efficiency 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? What criteria would affect a decision on whether to develop a particular hydro project?

5. In this module, we have stressed a systems approach to the renewable energy transition. Rather than considering only individual energy sources, we should consider the set of production and consumption technologies as a whole. What are some of the motivations for a systems approach, and some examples of this?

6. Why is public policy essential to promoting renewable energy use, and in accelerating the transition to renewable energy? What public policy approaches do you think will be most effective?

7. 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

(*Hints: See Box 1 on units above. You may need to find the 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)?

(Hints: See Box 5 on power and energy and Box 6 on capacity factor above.)

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
https://www.ers.usda.gov/topics/farm-economy/land-use-land-value-tenure/major-land-uses/

4a. Find the levelized cost of electricity (LCOE) 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, and for simplicity we assume no operating costs (solar PV operating costs are typically low, but greater than zero)

(*Hints: See Box 7 on LCOE and Box 6 on capacity factor above.)*

b. Repeat problem 4a. using an interest rate of 10%. How much does this change in interest rate affect the LCOE?

5. Find the system LCOEs for the simplified (but realistic) renewable energy system shown below, if the interest rate is 8.0%.

source	**capacity, kW**	**capital cost/kW**	**useful life, years**	**fixed operating cost/kW**	**energy generated, kWh**
Wind	**100**	**1400**	**25**	**35**	**210,000**
Solar	**200**	**1000**	**30**	**10**	**240,000**
Hydropower	**150**	**3000**	**50**	**60**	**150,000**
		Total system supply and demand, kWh:			**600,000**

(*Hint: See Box 7 on LCOE above.)*

6. A study of energy efficiency options for a Vermont apartment building estimated the additional capital cost of heat-recovery ventilation to be $16,000 (as compared to ventilation without heat recovery). If the heat-recovery ventilation saves 9,000 kWh per year, the equipment has a useful life of 20 years, and the discount rate is 4%, what is the cost of conserved energy (CCE)?

(*Hint: See Box 8 on CCE above.)*

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WEBSITES

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. **https://crsreports.congress.gov** 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 RMI (founded as 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.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.

6. **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.

cap and trade: an emissions control system where the government issues permits for a target emissions level (the cap), requires polluters to hold permits for their emissions, and allows polluters to buy and sell permits in a market.

capital and operating costs: costs of supply (for energy or other products), with capital costs being the initial costs of constructing facilities, and operating costs extending over the life of the facility.

capital intensive: requiring a relatively higher level of investment cost for initial establishment as compared to ongoing cost for operation.

carbon capture and storage: technology that captures carbon dioxide from an emissions stream or the atmosphere and sequesters the carbon dioxide underground in liquid form or chemically through reaction with bedrock.

clean electricity standard: a requirement that some or all of a utility's electricity sales come from sources defined as clean, for example, from sources having low or zero carbon dioxide emissions.

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.

constrained optimization: an economic method to identify a best solution subject to one or more limits or constraints. For example, constrained optimization for a renewable energy system might seek the lowest cost subject to the availability of wind and solar resources over time and to having enough generation to meet demand.

curtailment: limiting supply of energy to the grid from sources such as solar, to avoid overloading the grid at specific times

direct air capture: a version of **carbon capture and storage** that removes carbon dioxide from the atmosphere at normal atmospheric concentration (as opposed to capturing concentrated carbon dioxide in an emissions stream).

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.

dispatchable: an electricity generation source that can be started or increased when needed (not including sources like wind and solar, where the output depends on weather conditions).

dynamic problem: a problem in which conditions change over time, i.e. where time is an important variable in the problem.

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.

electric grid: the network of electric cables, transformers, controls, and other equipment that provides long-distance electricity transmission and local electricity distribution to users.

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 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.

environmental externalities: effects of market transactions on the environment, usually not considered by market participants

feed-in tariff: a policy to provide renewable energy producers with 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.

greenhouse gas: a gas whose accumulation in the atmosphere heats up the planet, just as the glass in a greenhouse heats its interior by trapping solar energy.

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.

kilowatt (kW): an energy flow of 1000 watts or 1000 Joules per second.

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 because of lower costs, thereby cancelling out some of the reduction in energy use from the original efficiency increase. See also **rebound effect**.

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.

linear programming: a method for finding the best solution to a problem with a linear objective function and linear constraints.

marginal benefit: the benefit of consuming one more unit of a good or service.

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.

nuclear energy: atomic energy that produces heat from fission, the splitting of atoms in radioactive materials, producing steam used to generate electricity with a steam turbine. Nuclear fusion would make use of heat from combining atoms, but in 2024, nuclear fusion does not yet exist as an electricity generation technology.

ocean thermal energy conversion (OTEC): a system that uses the temperature difference between relatively warm water at the surface of the ocean and cold water at great ocean depths to drive a turbine that generates electricity.

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.

power-to-X: converting electricity into energy forms such as fuels or latent heat that are needed in some applications and/or more easily stored.

prosumer: a consumer who produces all or part of the product consumed, for example, an electricity consumer who produces part of their electricity from home solar panels.

pumped hydroelectric 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.

rebound effect: the tendency of demand for a resource such as energy to increase when increased efficiency reduces costs, thereby cancelling out some of the reduction in energy use from the original efficiency increase.

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

renewable portfolio standards: 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 collect data like electricity usage over time. Smart electric meters may also have communication capabilities and can control loads, i.e. turn off low-priority electric appliances 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.

stranded capital asset: productive infrastructure that must be abandoned before the end of its useful life, for example, oil wells that may be retired to mitigate climate change.

subsidy: financial support provided usually by the government to encourage an action, sometimes in the form of reduced taxes or direct payments.

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

variability: a characteristic common to most renewable energy sources, meaning that they are more or less available at different times; variability is particularly challenging with wind energy, given the extent to which available energy varies with wind speed.

wave energy: technology that uses the rising and falling action of waves to generate energy, usually in the form of electricity.

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.