RENEWABLE ENERGY FOR A SUSTAINABLE FUTURE

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STUDY RESOURCES

Part A

Part 2
Introduction to Energy

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Page snapshot: Introduction to energy, including definition of energy and units used to measure energy, fossil fuel types and their extraction, renewable energy, and the future of energy in the United States.

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What is energy?

Energy is an interdisciplinary topic, and the concepts used to understand energy in the Earth system are fundamental to all disciplines of science. One cannot study physics or understand biomes, photosynthesis, fire, evolution, seismology, chemical reactions, or genetics without considering energy. Everything we do depends upon energy—without it there would be no civilization, no sunlight, no food, and no life. Energy moves people and goods, produces electricity, and heats our homes and businesses. It is used in manufacturing and other industrial processes.

But what is energy? Energy is power that is derived from the utilization of physical or chemical resources. Wind and solar power, fossil fuels, nuclear energy, and hydroelectricity are primary energy sources. Primary energy sources are energy sources that occur in nature. Secondary energy sources, also known as energy carriers, have been transformed into energy used directly by humans. Examples of secondary energy sources are electricity and gasoline.

For most of human history, the way we captured and used energy changed little. With very few exceptions, materials were moved by human or animal power. Heat was produced largely through the burning of wood. Exceptions include the use of sails on boats by a very small percentage of the world’s population to move people and goods. In China, people used natural gas to boil brine in the production of salt beginning roughly 2000 years ago. Nearly all the energy to power human society was, in other words, biomass; it was produced by humans, by other animals, or by burning wood.

The transition from brute force and burning wood to the production and use of various industrial sources of energy has occurred remarkably quickly, happening in the course of just a few generations. Much of the rural US was without access to electricity until the 1930s, and cars have been around for only slightly longer. Yet, many of us take these conveniences for granted today. The transition to industrial sources of energy has caused changes in virtually every aspect of human life, from transportation to economics to war to architecture. In the US, every successive generation has enjoyed the luxury of more advanced technology (e.g., the ability to travel more frequently, more quickly, and over greater distances). Especially as the global population grows and standards of living increase in some parts of the world, so too does global energy demand continue to grow.
Our energy system—how we get energy and what we use it for—is still changing remarkably quickly in some ways, while it is very resistant to change in others. The use of wind to generate electricity, for example, grew rapidly in the late 2000s and early 2010s. In 2002, wind produced less than 11 million megawatt hours (MWh) of electricity in the US, whereas in 2011, wind produced more than 120 million MWh. In contrast, we continue to rely heavily on fossil fuels like coal, oil, and natural gas to produce electricity, supply heat, and fuel transportation. Our reliance on fossil fuels is driven by a number of factors, including low upfront cost, very high energy densities, and the cost and durability of the infrastructure built to use fossil fuels.

Traffic on Interstate 95-North, Miami, in 2012. Fossil fuels are being used to power the cars. Photo by B137 (Wikimedia Commons, Creative Commons Attribution-ShareAlike 4.0 International license, photo cropped and resized).

What do different units of energy mean?

Heat is energy. Measurements of heat can be thought of as the most basic way to measure energy. The British thermal unit (abbreviated BTU or BTU) is the most commonly used unit for heat energy. By definition, one BTU is approximately the amount of heat required to raise one pound of water by one degree Fahrenheit. One BTU is also about the amount of energy released by burning a single wooden match.

A joule is the energy expended (or work done) to apply a force of one newton over a distance of one meter. Since a typical apple weighs about one newton (about 100 grams or 3.6 ounces), lifting an apple one meter requires about a joule of energy. A BTU is roughly 1055 joules. That means that one BTU—the energy contained in a wooden match—is equivalent to the total amount of energy required to lift an apple 1055 meters (about 3461 feet) or a bit over one kilometer (about 0.66 or 2/3 miles).

This comparison of the energy of heat to the energy of motion—also called kinetic energy—might be a little confusing. However, energy is transformed from one type to another all the time in our energy system. This is perhaps most obvious with electricity. Electrical energy is transformed into light, heat, or motion at the flip of a switch. Those processes can also be reversed; light, heat, and motion can all be transformed into electricity. The machines that make those transformations in either direction are always imperfect, so energy always degrades into heat when it is transformed from one form to another.

Another measure of energy, the kilowatt-hour (kWh), represents the amount of energy required to light ten 100-watt light bulbs for one hour. One kWh is about 3412 BTUs or about 3.6 million joules.
1 kilowatt-hour (3412 BTUs) will light:

OR

One 100-watt incandescent bulb (1800 lumens) for 10 hours

One 28-watt compact fluorescent bulb (1800 lumens) for 38 hours

Producing 1 kilowatt-hour requires:

One lb. of coal 7.5 cubic ft. of natural gas 8.5 oz. of gasoline

Consumption based on traditional thermal power plant production, which loses about 50% of energy as waste heat, plus electrical transmission losses of about 7%.

Examples of uses and sources of 1 kWh. 1kWh will light a 100-watt incandescent light bulb for 10 hours and one 28-watt compact fluorescent bulb for 38 hours. Producing 1kWh requires one pound of coal or 7.5 cubic feet of natural gas or 8.5 ounces of gasoline. About 50% of energy used is lost as waste and 7% is lost in transmission. Image modified from original by Jim Houghton, published in The Teacher-Friendly Guide to the Geology of the Southeastern U.S., 2nd ed., edited by Andrielle N. Swaby, Mark D. Lucas, and Robert M. Ross (published by the Paleontological Research Institution) (CC BY-NC-SA 4.0 license).

How do we look at energy in the Earth system?

The Energy Information Administration (EIA) categorizes energy as coming from one of five sources: petroleum, natural gas, coal, renewable energy (for example, wind or hydroelectric), and nuclear electric power. The EIA categorizes energy as being used in one of four energy sectors: transportation, industrial, electric power, and residential and commercial. All of the energy that powers our society comes from one of these five sources and is used in one of these four sectors.

The more we come to understand the Earth system, the more we realize that there is a finite amount of consumable energy, and that harvesting certain resources for use in energy consumption may have wide ranging and permanent effects on the planet's life. Understanding energy within the Earth system is the first step to making informed decisions about energy transitions.
Hydropower Explained: Hydropower and the Environment

US Energy Information Administration, 2022

Hydropower generators produce clean electricity, but hydropower does affect the environment

Most dams in the United States were built mainly for flood control, municipal water supply, and irrigation water. Although many of these dams have hydroelectric generators, only a small number of dams were built specifically for hydropower generation. Hydropower generators do not directly emit air pollutants. However, dams, reservoirs, and the operation of hydroelectric generators can affect the environment.

A dam that creates a reservoir (or a dam that diverts water to a run-of-river hydropower plant) may obstruct fish migration. A dam and reservoir can also change natural water temperatures, water chemistry, river flow characteristics, and silt loads. All of these changes can affect the ecology and the physical characteristics of the river. These changes may have negative effects on native plants and on animals in and around the river. Reservoirs may cover important natural areas, agricultural land, or archaeological sites. A reservoir and the operation of the dam may also result in the relocation of people. The physical impacts of a dam and reservoir, the operation of the dam, and the use of the water can change the environment over a much larger area than the area a reservoir covers.

Manufacturing the concrete and steel in hydropower dams requires equipment that may produce emissions. If fossil fuels are the energy sources for making these materials, then the emissions from the equipment could be associated with the electricity that hydropower facilities generate. However, given the long operating lifetime of a hydropower plant (50 years to 100 years) these emissions are offset by the emissions-free hydroelectricity.

Greenhouse gases (GHG) such as carbon dioxide and methane form in natural aquatic systems and in human-made water storage reservoirs as a result of the aerobic and anaerobic decomposition of biomass in the water. The exact amounts of GHG that form in and are emitted from hydropower reservoirs is uncertain and depend on many site specific and regional factors.

Fish ladders help salmon reach their spawning grounds

Hydropower turbines kill and injure some of the fish that pass through the turbine. The U.S. Department of Energy has sponsored the research and development of turbines that could reduce fish deaths to lower than 2%, in comparison with fish kills of 5% to 10% for the best existing turbines.

Many species of fish, such as salmon and shad, swim up rivers and streams from the sea to reproduce in their spawning grounds in the beds of rivers and streams. Dams can block their way. Different approaches to fixing this problem include the construction of fish ladders and elevators that help fish move around or over dams to the spawning grounds upstream.

The Safe Harbor Dam on the Susquehanna River in Pennsylvania has elevators that lift migrating shad from the base of the dam to the top of the reservoir.
Hydropower dams threaten fish habitats worldwide

New research maps impacts of hydropower dams on species critical to human livelihoods.

BY SARAH CAFASSO, STANFORD NATURAL CAPITAL PROJECT – February 3, 2020

Rivers and other ecosystems that provide essential habitats to freshwater fish are under increasing pressure from global hydropower development. While dams can provide flood protection, energy supply, and water security, they also pose a significant threat to freshwater species. Dams block fish from moving along their natural pathways between feeding and spawning grounds, causing interruptions in their life cycles that limit their abilities to reproduce. As hydropower development continues along river basins around the world, scientists are concerned about the unknown impacts to the diverse species found in freshwater habitats – many of which are critical sources of food and livelihood for humans.

"Because fisheries based on migratory species support tens of millions of people, understanding where hydropower development could negatively impact river basin connectivity – and therefore fish – is an important step in identifying solutions that deliver needed electricity while minimizing the loss of essential natural resources," said Jeff Opperman, Global Lead Freshwater Scientist for World Wildlife Fund.

Without detailed information about where exactly freshwater species feed and spawn, it has been difficult for planners to make more sustainable decisions around hydropower and river basin development. Now, researchers from the Stanford Natural Capital Project and Radboud University have mapped the impacts of past and future hydropower development on fish habitats worldwide. Their results were published Feb. 3 in Proceedings of the National Academy of Sciences.

"We’ve known that future development will impact fish species, but we didn’t have the detailed information about some of the places with the highest development pressures – like the Amazon, the Mekong, and the Congo – until now.” – RAFAEL SCHMITT, Postdoctoral Research Fellow, Natural Capital Project

Data-driven decision making

“We’ve known that future development will impact fish species, but we didn’t have the detailed information about some of the places with the highest development pressures – like the Amazon, the Mekong, and the Congo – until now,” said Rafael Schmitt, researcher at the Natural Capital Project and second author on the study. “This dataset will help decision-makers better understand impacts of land and infrastructure development on aquatic biodiversity, so they can make choices that protect it.”

The researchers used detailed spatial data for 10,000 fish species to measure impacts of dams on their habitats. They evaluated around 40,000 existing and 3,700 planned hydropower dams to create high resolution global maps. “These dams pose a real danger to the survival of species and associated human livelihoods,” said Schmitt. “Salmonids in North America were mostly wiped out by dams, and with them the livelihoods of people depending on their annual migration. Now,
similar impacts become evident in other geographies. Recently, we’ve seen how dams on the Yangtze contributed to the extinction of the Chinese paddlefish, a source of food and cultural reverence for communities along the river. If we aren’t more strategic about where and how we develop future hydropower, we can expect to see more and more examples like this one.”

**Opportunity for strategic hydropower planning**

The study shows the highest numbers of fragmented habitats from current hydropower are found in the United States, Europe, South Africa, India and China. In developing countries, though, the impacts of planned hydropower development are disproportionately high. “For example, we see that the completion of only one dam close to the outlet of Purari River in Papua New Guinea will decrease habitat connectivity by about 80 percent on average for freshwater fish in the region,” said Valerio Barbarossa, environmental researcher at Radboud University and lead author on the study.

“With these maps, we have a global picture of where fish species are already impacted by dams and where local conservation efforts should be fostered,” said Barbarossa.

The researchers hope that their results will help guide strategic decision-making around hydropower planning. “Evaluating impacts of dams is only the first step,” said Schmitt. “These data can be used to highlight the additional benefits of thoughtful, strategic river basin development to drive conservation and restoration efforts in local areas and at global scales.”

*Rafael Schmitt is a postdoctoral fellow at the Natural Capital Project and the Stanford Woods Institute for the Environment.*
U.S. Renewable Energy

Patterns of Use

While energy is essential to modern society, most primary sources are unsustainable. The current fuel mix is associated with a multitude of environmental impacts, including global climate change, acid rain, freshwater consumption, hazardous air pollution, and radioactive waste. Renewable energy has the potential to meet demand with a much smaller environmental footprint and can help to alleviate other pressing problems, such as energy security, by contributing to a distributed and diversified energy infrastructure. About 79% of the nation’s energy comes from fossil fuels, 8.4% from nuclear, and 12.5% from renewable sources. In 2019, renewables surpassed coal in the amount of energy provided to the U.S. and continued this trend in 2021. Wind and solar are the fastest growing renewable sources, but contribute just 5% of total energy used in the U.S.

U.S. Renewable Energy Consumption: Historic and Projected

U.S. Total and Renewable Energy Consumption by Source, 2021

Major Renewable Sources

Wind

- U.S. onshore wind resources have a potential capacity of almost 11,000 GW and current installed capacity of 132.7 GW. Offshore wind resources are potentially 4,120 GW, current capacity is 42 MW, and the development pipeline contained over 2.8 GW of projects in 2019.
- Over 16 GW of wind capacity was installed in the U.S. in 2020, a 83% increase from 2019.
- The federal production tax credit (PTC) significantly influences wind development, but cycles of enactment and expiration lead to year-to-year changes in investment. In 2020, the PTC was extended to allow wind projects beginning construction in 2020 or 2021 to receive PTC at 1.5¢/kWh for 10 years of electricity output.
- Based on the average U.S. electricity fuel mix, a 1.82 MW wind turbine (U.S. average in 2019) can displace 3,679 metric tons of CO₂ emissions per year. By 2050, 404 GW of wind capacity would meet an estimated 35% of U.S. electricity demand and result in 12.3 gigatonnes of avoided CO₂ emissions, a 14% reduction when compared to 2013.
- Wind turbines generate no emissions and use no water when producing electricity, but concerns include bat and bird mortality, land use, noise, and aesthetics.

Solar

- Assuming intermediate efficiency, solar photovoltaic (PV) modules covering 0.6% of U.S. land area could meet national electricity demand.
- PV module prices have declined to $0.29/Watt in residential systems. The U.S. manufactured 1% of PV cells and 1% of PV modules globally in 2020.
- In 2021, a new record high of over 23.6 GW of solar photovoltaic capacity was added in the U.S., raising total installed capacity to over 121 GW. Solar accounted for 46% of new generating capacity in 2021.
- The U.S. Department of Energy's SunShot Initiative aims to reduce the price of solar energy 50% by 2030, which is projected to lead to 33% of U.S. electricity demand met by solar and a 18% decrease in electricity sector greenhouse gas emissions by 2050.
- While solar PV modules produce no emissions during operation, toxic substances (e.g., cadmium and selenium) are used in some technologies.

Biomass

- Wood—mostly as pulp, paper, and paperboard industry waste products—accounts for 43% of total biomass energy consumption. Waste—municipal solid waste, landfill gas, sludge, tires, and agricultural by-products—accounts for an additional 9%.
- Biomass has low net CO₂ emissions compared to fossil fuels. At combustion, it releases CO₂

For Complete Set of Factsheets visit css.umich.edu
previously removed from the atmosphere. Further emissions are associated with processing and growth of biomass, which can require large areas of land. Willow biomass requires 121 acres of land to generate one GWh of electricity per year, more than other renewable sources.9

- U.S. ethanol production is projected to reach 54 million gallons per day in 2050.6

### Geothermal

- Hydrothermal resources, i.e., steam and hot water, are available primarily in the western U.S., Alaska, and Hawaii, yet geothermal heat pumps can be used almost anywhere to extract heat from shallow ground, which stays at relatively constant temperatures year-round.29
- Each year, electricity from hydrothermal sources offsets the emission of 4.1 million tons of CO₂, 80 thousand tons of nitrogen oxides, and 110 thousand tons of particulate matter from coal-powered plants.25 Some geothermal facilities produce solid waste such as salts and minerals that must be disposed of in approved sites, but some by-products can be recovered and recycled.31
- Electricity generated from geothermal power plants is projected to increase from 15.9 billion kWh in 2021 to 47.4 billion kWh in 2050. Geothermal electricity generation has the potential to exceed 500 GW, which is half of the current U.S. capacity.7-13

### Hydroelectric

- In the U.S., net electricity generation from conventional hydropower peaked in 1997 at 336 TWh/yr. Currently, the U.S. gets about 260 TWh/yr of electricity from hydropower.7
- While electricity generated from hydropower is virtually emission free, significant levels of methane and CO₂ may be emitted through the decomposition of vegetation in the reservoir.30 Other environmental concerns include fish injury and mortality, habitat degradation, and water quality impairment. “Fish-friendly” turbines and smaller dams help mitigate some of these problems.36

### Advancing Renewable Energy

#### Encourage Supportive Public Policy

- Lawrence Berkeley National Laboratory estimates that 45% of renewable energy growth in the U.S. can be attributed to state Renewable Portfolio Standards (RPS) that require a percentage of electricity be derived from renewable sources.27 Clean Energy Standards (CES) that mandate certain levels of carbon-free generation can include some non-renewables such as nuclear fuels.38 Thirty-three states, the District of Columbia, and three U.S. territories had renewable portfolio standards or goals in place as of August 2021.39 State standards are projected to support an additional 90 GW of renewable electricity projects by 2030.47
- Renewable energy growth is also driven by important federal incentives such as the Investment Tax Credit, which offsets upfront costs by 30-40%, as well as state incentives such as tax credits, grants, and rebates.21
- Eliminating subsidies for fossil and nuclear energy would encourage renewable energy. Congress allocated over $5.7 billion in tax relief to the oil and gas industries for fiscal years 2020-2024.30 Studies estimate that the Price-Anderson Act, which limits the liability of U.S. nuclear power plants in the case of an accident, amounts to a subsidy of $366 million to $3.5 billion annually.39
- Net metering enables customers to sell excess electricity to the grid, eliminates the need for on-site storage, and provides an incentive for installing renewable energy devices. Thirty-nine states, the District of Columbia, and four U.S. territories have some form of net metering program.21

#### Engage the Industrial, Residential, and Commercial Sectors

- Renewable Energy Certificates (RECs) are sold by renewable energy producers in addition to the electricity they produce; for a few cents per kilowatt hour, customers can purchase RECs to “offset” their electricity usage and help renewable energy become more cost competitive.24 Around 80 utilities in the U.S. offer consumers the option to purchase renewable energy, or “green power.”38
- Many companies purchase renewable energy as part of their environmental programs. Microsoft, Google, T-Mobile, Intel, and The Proctor & Gamble Company were the top five users of renewable energy as of April 2022.20

### Conversion Factors

- kWh = kilowatt hour. One kWh is the amount of energy required to light a 100 watt light bulb for 10 hours.
- Btu = British Thermal Unit. One Btu is the amount of energy required to raise the temperature of a pound of water by 1° Fahrenheit.
- Quad = quadrillion (10¹⁵) Btu. One Quad is equivalent to the annual energy consumption of ten million U.S. households.

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10. DSIRE (2021) "Renewable Electricity Production Tax Credit (PTC)."
33. DSIRE (2020) USA Summary Map: Net Metering.
34. NREL (2020) "Buying Green Power and Renewable Energy Certificates."
36. U.S. EPA (2021) "Green Power Partnership National Top 100.”

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Renewable Energy to Support Energy Security

Background
Renewable energy plays an important role in supporting energy security through contributing to the protection and continued provision of energy services when a disruption occurs (DOE 2017). Sources of disruption to energy services can be natural, technological, and human-caused—such as weather events, cyberattacks, and global market disturbances.

Although energy systems have always been subject to disruption, potential threats are increasing in relation to reliance on energy for economic growth; intensifying weather events; and the growing potential of large-scale cyberattacks on increasingly networked energy systems. Such evolutions give urgency to understanding trends and vulnerabilities in emerging energy technologies, planning, and practices.

Institutions and governments around the world define energy security in different ways. The International Energy Agency (IEA) defines energy security as "the uninterrupted availability of energy sources at an affordable price." IEA also makes a distinction between long-term energy security for future economic development and short-term energy security that ensures energy systems will react quickly to sudden changes in the supply-demand balance (IEA). The U.S. Department of State defines energy security as "access to diversified energy sources, routes, suppliers (in order to limit) the influence of a single dominant buyer, seller, or investor and guards against those who would use energy for coercive ends" (DOE 2017).

Energy security is vital to many sectors of the economy. Examples include, but are not limited to, the following:

**Industry:** Nearly all modern industries depend on reliable and affordable power supplies. Power outages and poor power quality can cause damage to manufacturing equipment and impact production. Unstable energy prices can impact the economics of producing goods and services.

**Food:** The globalized industrial food system is largely dependent on fossil fuels to power farming equipment, produce pesticides and fertilizer, and transport goods. To prevent food from spoiling, reliable power is needed to keep produce cool in refrigerated warehouses or transportation containers. Rising fuel and energy prices can impact food prices and affordability (Neff, Parker, Kirschenmann, Tinch, and Lawrence 2011).

**Health Care:** Interruptions to power supplies can impact medical centers and hospitals. Certain treatments or medical care protocols rely on dependable power (e.g., dialysis centers and operating rooms). Vulnerable patients can die from heat or cold exposure. The blackouts in Puerto Rico after Hurricanes Maria and Irma in 2017 greatly impacted the chronically ill who relied on electricity to power health care machines. Deaths due to chronic illness after the hurricanes surged in comparison to the same period in 2016 (Hernandez, Learning, and Murphy 2017).

**Other Critical Services:** Power is also essential in providing other critical services related to water and sanitation and telecommunications, among others. Provision of these services is especially critical in the aftermath of a disaster to avoid cascading negative impacts and enable recovery.

Threats to Energy Security
Threats to the energy sector can be natural, technological, or human-caused—and can damage, destroy, or disrupt energy systems (Resilient Energy Platform). A community that is energy-secure will incorporate resilient systems and approaches that can prevent, mitigate, or allow for adaptation to threats and changing conditions. Examples of threats to the energy sector include:

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1. It is important to note that energy security is not the same as energy sovereignty. Energy sovereignty refers to the ability of a community or nation to internally produce all necessary energy; however, energy sovereignty does not mean a community is energy secure. As an example, a jurisdiction that internally produces 100% of its energy from solar power may not be energy secure if they experience natural disasters that threaten solar photovoltaic (PV) systems.

www.resilient-energy.org | www.nrel.gov/usaid-partnership
**Natural Disasters:** Severe weather events like droughts and storms are projected to become more intense and destructive (IPCC 2012). These events can decrease or disrupt supplies and negatively impact energy infrastructure (Rudnick 2011). In the United States, severe weather is the number one cause of power outages (Executive Office of the President 2013).

**Cyberattacks:** The energy sector is becoming more automated, digitized, and interconnected. Cyberattacks are becoming more common and could pose a greater threat as the energy sector becomes more modern and connected (IEA).

**Geopolitics:** Interstate conflicts can threaten energy security. For example, the 1973 oil crisis resulted from an embargo by the Organization of Petroleum Exporting Countries on the United States (U.S. Department of State). Political instability in fuel producing nations can impact energy prices.

**Fuel Price Fluctuations:** Changes in fuel prices (e.g., related to market or other factors) can threaten energy security through impacting a nation’s or community’s ability to purchase fuels.

**Long-Term Climatic Changes:** Changing environmental conditions like air temperature, water temperature, and water availability can cause stress to energy systems.

- Rising temperatures increase the demand for air conditioning, most significantly impacting summer peak energy demands (Zamuda, Billelo, Conzelmann, Mecray, et al. 2018).
- Water is necessary for energy production. Hydroelectric systems depend on flow, and some electricity production systems need water for cooling. Reduced precipitation or increased water temperatures can impact supply by limiting power plant capacity. Snowpack melt changes (i.e., the timing of melt and runoff in the spring or summer) changes peak production for hydroelectric systems (Zamuda, Billelo, Conzelmann, Mecray, et al. 2018).
- Changes in sea levels or storm surges can impact energy infrastructure close to shorelines, due to flooding (EPA).


Energy security remains a key objective of many countries around the world. Deploying renewable energy technologies supports the goal of energy security and supports the realization of additional benefits.

**Diversifying the Generation Mix:** Renewable energy can support energy security by adding diversity to an overall electricity generation portfolio. Diversity of a power generation portfolio can relate to the spatial location, types of generation resources, and fuel sources or supply.

- Spatial diversity—A more spatially diverse generation and storage energy portfolio can better withstand shocks to the system. With more resources across different geographic locations, the system is more resilient to any individual disruption.
areas, such diversity could power infrastructure during disasters, cyberattacks, or other extreme events. Spatially diverse energy generation portfolios can also provide a smoothing effect across variable generation resources, allowing for improved reliability and integration of variable renewables (Cox, Hotchkiss, Bilello, Watson, et al. 2017).

Reducing Water Use: Technologies with high water requirements are vulnerable to drought or other climatic events. Deploying renewable energy can reduce potential fluctuations or uncertainty in power generation portfolios that depend on hydro or require significant amounts of water for generation or cooling.

Modularity and Rapid Deployment: According to Cox et al. "Modularity [of distributed renewable technologies] allows for locational flexibility and for new generation systems to be put in place at a faster pace than large-scale systems as electricity demand grows and understanding of climate risks improves." Modularity can support energy security through rapid deployment of more modular, distributed energy systems in response to changing threats. In addition, modularity can support the diversification of energy generation, as distributed systems have greater locational flexibility and can be deployed in diverse settings. Finally, when a part of a modular system is damaged or fails it is typically easier to repair than a larger system failure. In some cases, the section that is damaged can be removed while the rest of the system continues to function, or the part replacement can occur quickly.

Islanding: Renewable distributed generation technologies can be equipped with control mechanisms to support "islanding" of on-site power sources in the event of a disaster. Islanding controls can isolate a distributed power source from other systems, allowing them to continue to provide power locally even if the main grid is compromised or disrupted. Importantly, islanded distributed energy systems (especially when combined with storage) can provide power to critical facilities, such as hospitals, water treatment facilities, or vulnerable communities, in a safe manner.

Coupling with Storage: A renewable based energy system, utility-scale or distributed, can further support energy security when coupled with energy storage technologies. Storage allows for fluctuations of a generation technology (e.g., solar PV or wind), while providing power to a site through stored power (e.g., a charged battery system). In addition, storage can provide backup power in the event of an outage and potentially allow for black start recovery2 when the system is designed to do so. In alignment with energy security objectives, energy storage can also support stabilization of electricity prices, management of demand changes, and mitigation of curtailment.

Deploying renewable energy technologies supports the goal of energy security and supports the realization of additional benefits. Photo by Dennis Schroeder, NREL, 5800M

Resilient Energy Platform
The Resilient Energy Platform helps countries to address power system vulnerabilities by providing strategic resources and direct country support, enabling planning and deployment of

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2 "Black Start is the procedure [used] to restore power in the event of a total or partial shutdown of [a] national electricity transmission system" (National Grid ESO).
resilient energy solutions. This includes expertly curated reference materials, training materials, data, tools, and direct technical assistance in planning resilient, sustainable, and secure power systems. Ultimately, these resources enable decision makers to assess power sector vulnerabilities, identify resilience solutions, and make informed decisions to enhance energy sector resilience at all scales (including local, regional, and national scales). To learn more about the solutions highlighted in this fact sheet, please visit the Platform at: resilient-energy.org.

Additional Resources


References


Understanding Power System Threats and Impacts

Background
Understanding potential threats to a power system is an essential first step in supporting power sector resilience. It is important to assess both current and future threats, as well as the likelihood of these threats over time. Threats can be grouped in three categories, as highlighted below.

Natural threats resulting from acts of nature (e.g., severe weather, floods, earthquakes, hurricanes, and solar flares), as well as wildlife interactions with the power system (e.g., squirrels, snakes, or birds causing short circuits on distribution lines).

Technological threats resulting from failures of systems and structures (e.g., defects in materials or water line disruption).

Human-caused threats resulting from accidents (e.g., cutting an underground line) or from intentional actions of an adversary (e.g., cyberattacks or acts of terror).\(^1\)

Identifying Threats
Threats can be identified through stakeholder processes and expert judgement, data sets, literature, and national planning documents and resources. Key experts and stakeholders engage for threat identification and determination of likelihood of occurrence include:

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1. [https://training.fema.gov/programs/emschool/ei361toolkit/glossary.htm](https://training.fema.gov/programs/emschool/ei361toolkit/glossary.htm)
What is a Power System Threat?
Anything that can damage, destroy, or disrupt the power system is considered a threat. Threats can be natural, technological, or caused by human activity. Threats are not typically within the control of the power system planners and operators and can include wildfires, cyclones or typhoons, droughts, long-term temperature changes, cyberattacks, and many others.

ministries and offices of energy, environment, and natural resources; meteorological agencies; utilities; power systems operators; risk assessment experts; and emergency managers. Examples of resources that could be reviewed to inform threat identification are outlined below:

- Existing threat and risk assessments
- Historical data related to disasters, extreme temperatures, and grid outages. Figure 1 shows an example of historical data being used to understand risks to the energy sector in the United States related to hurricanes.
- National planning documents across sectors with information and data related to threats to water quality, river systems, floodplain management, and geology, such as landslide areas and earthquakes
- Integrated resource plans
- Emergency plans
- Maps and geographic data
- Utility information.

Box 1 presents key questions that stakeholders can consider when working to identify threats to a power system.

Likelihood of Threat Occurrence
The likelihood of threat occurrence is another important step in assessing the vulnerability of power systems. Natural threats can be given a likelihood score based on historical threat data (e.g., disasters) and climate projections. Technological and human threats, which may be more dynamic than natural threats, may be given a score based on a more qualitative stakeholder

| Box 1: Key Questions to Support Understanding of Threats to the Power System |
| 1. What natural threats exist for your power sector, and how frequently do they occur? |
| 2. How have power infrastructure systems been impacted by past threats (natural, technological, and human-caused) or system stresses? |
| 3. Has critical power sector infrastructure ever gone offline or experienced reduced operability?  |
| | - What threat caused this?  |
| | - How many hours, days, or weeks was the infrastructure offline or not operational? |
| 4. In the future, which threats and shocks are likely to increase (at the city, national, or multinational scale)? |
Connecting Threats to Possible Power System Impacts

Natural, technological, and human-caused threats can have various impacts on electricity infrastructure and systems. Both chronic (e.g., temperature change) and acute events (e.g., storms and cyberattacks) can affect the demand, supply, and delivery of electricity. Impacts are highly localized (in terms of characteristics, severity, and variability), reflecting unique combinations of environmental factors and stressors in a specific location. Table 2 presents types of threats over the near- and long-term and potential impacts on generation, transmission, distribution, and demand.

Table 1. Scoring Framework for Threat Likelihood

<table>
<thead>
<tr>
<th>Threat Likelihood Scores</th>
<th>Threshold Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Categorical</td>
<td>Numerical</td>
</tr>
<tr>
<td>High</td>
<td>9</td>
</tr>
<tr>
<td>Accidents</td>
<td></td>
</tr>
<tr>
<td>Medium-High</td>
<td>7</td>
</tr>
<tr>
<td>More likely to occur than not.</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>5</td>
</tr>
<tr>
<td>May occur.</td>
<td></td>
</tr>
<tr>
<td>Low-Medium</td>
<td>3</td>
</tr>
<tr>
<td>Slightly elevated level of occurrence. Possible, but more likely not to occur.</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>1</td>
</tr>
<tr>
<td>Very low probability of occurrence. An event has the potential to occur but is still very rare.</td>
<td></td>
</tr>
</tbody>
</table>

This fact sheet describes how natural, technological, and human-caused threats might impact the power sector across generation, transmission and distribution, and demand. In addition to direct system and infrastructure impacts, loss of power can affect other sectors (e.g., healthcare, education, and wastewater), as well as society and economic activity more broadly. While these impacts are not described in detail in this fact sheet, they are crucial in considering prioritization of resilience actions.

Power sector threats (including likelihood) and impacts assessed at the local or national level are essential inputs for performing a power-sector vulnerability assessment. A resilience action plan provides key power sector resilience actions designed to address power sector threats identified in a vulnerability assessment. 

Photo from iStockphoto, 903262322
<table>
<thead>
<tr>
<th>Threats</th>
<th>Technologies/Sectors</th>
<th>Potential Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Change</td>
<td>Generation - Biopower, Hydropower, Solar PV; Thermal technologies (coal, geothermal, natural gas, nuclear, concentrated solar power) Transmission and distribution Demand</td>
<td>Crop damage and increased irrigation demand Reduced generation capacity and operational changes Reduced generation capacity (e.g., higher heat can impact panel efficiency) Reduced generation efficiency and capacity Reduced transmission efficiency and capacity Increased demand for cooling</td>
</tr>
<tr>
<td>Water Availability and Temperature Changes</td>
<td>Generation - Biopower, Hydropower, Thermal technologies</td>
<td>Decreased crop production Reduced generation capacity and operational changes Reduced generation capacity</td>
</tr>
<tr>
<td>Wind Speed Changes</td>
<td>Generation - Wind</td>
<td>Variations in generation capacity, making investments harder to pay back or generation harder to predict long-term</td>
</tr>
<tr>
<td>Sea Level Rise</td>
<td>Generation - Bioenergy, Hydropower, Solar PV, Thermal technologies, Wind Transmission and distribution Demand</td>
<td>Physical damage to infrastructure and power disruption/loss—all generation technologies</td>
</tr>
<tr>
<td>Extreme Events (e.g., storms, short-term extreme heat events, floods, fires, and other natural disasters)</td>
<td>Generation - Bioenergy, Hydropower, Solar PV, Thermal technologies, Wind Transmission and distribution Demand</td>
<td>Physical damage to infrastructure and fuel sources, and power disruption/loss—all generation technologies Reduced transmission efficiency and capacity Unpredictable changes to peak electricity demand</td>
</tr>
<tr>
<td>Technological</td>
<td>Generation - Bioenergy, Hydropower, Solar PV, Thermal technologies, Wind Transmission and distribution Demand</td>
<td>Physical damage and power disruption/loss—all generation technologies Physical damage and reduced transmission capacity Unpredictable demand</td>
</tr>
<tr>
<td>Human caused (e.g., cyberattacks, accidents, and physical attacks/malicious events)</td>
<td>Generation - Bioenergy, Hydropower, Solar PV, Thermal technologies, Wind Transmission and distribution Demand</td>
<td>Physical damage and power disruption/loss—all generation technologies Physical damage and reduced transmission capacity Unpredictable demand</td>
</tr>
</tbody>
</table>

Box 2: Identifying Threats to the Power Sector in the Lao PDR, and Planning for Resilience

USAID and NREL partnered with the government of the Lao PDR to perform a vulnerability assessment of the power sector and develop a resilience action plan. Key threats related to potential hydrological changes (and a large dependence on hydropower), wildfires, landslides, and flooding, among others. After undertaking a full vulnerability assessment process, key power sector resilience actions were identified to address these threats and related impacts. Selected actions are highlighted below. As can be seen, actions can relate to operational changes and planning, data collection, analysis, partnership across borders, and technology implementation, as well as other areas.

- Develop standard operating procedures and continuity-of-operation plans for extreme events—including staffing plans, prioritized repowering of networks, and agreements with neighboring countries;
- Develop climate projections and geospatial data for hydropower and other generation planning, and make these maps available publicly;
- Reduce dependence on hydropower through diversification of energy mix;
- Introduce flexibility solutions into power system operation;
- Establish protocol for data collection at all hydropower dams, including data types, collection frequency, and data format for sharing; and
- Develop incentive and enforcement structures to ensure that users and areas that are upstream from hydropower dams protect watersheds located upstream.

Source: Power Sector Resilience Action Plan for Lao PDR (forthcoming)

assessment. Box 2 describes a power-sector vulnerability assessment undertaken in the Lao People's Democratic Republic (PDR), supported by the U.S. Agency for International Development (USAID) and the National Renewable Energy Laboratory (NREL), that fed into a climate resilience action plan. For a full view of how threats and impacts are integrated with broader vulnerability assessment processes and power-sector resilience action plans, see: https://resilient-energy.org/guidebook, and learn more about power sector resilience at www.resilient-energy.org.

Resilient Energy Platform

The Resilient Energy Platform helps countries address power system vulnerabilities by providing strategic resources and direct country support, enabling planning and deployment of resilient energy solutions. This includes expertly curated reference materials, training materials, data, tools, and direct technical assistance in planning resilient, sustainable, and secure power systems. Ultimately, these resources enable decision makers to assess power sector vulnerabilities, identify resilience solutions, and make informed decisions to enhance sector resilience at all scales (including local, regional, and national). To learn more about the technical solutions highlighted in this fact sheet, visit the Resilient Energy Platform at https://resilient-energy.org/.

Resources


Cronin, Jennifer, Gabriel Anandarajah, and Clivier Dessens. "Climate change impacts on the energy system: a review of trends and gaps." Climatic


Written by Sadie Cox, National Renewable Energy Laboratory

www.resilient-energy.org | www.nrel.gov/usaid-partnership

Jennifer E. Leisch, Ph.D.
USAID-NREL Partnership Manager
U.S. Agency for International Development
Tel: +1-303-813-0103 | Email: Jleisch@usaid.gov

Sadie Cox
Senior Researcher
National Renewable Energy Laboratory
Tel: +1-303-384-7391 | Email: sadie.cox@nrel.gov

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The Resilient Energy Platform provides expertly curated resources, training, tools, and technical assistance to enhance power sector resilience. The Resilient Energy Platform is supported by the U.S. Agency for International Development.

The USAID-NREL Partnership addresses critical challenges to scaling up advanced energy systems through global tools and technical assistance, including the Renewable Energy Data Explorer, Greening the Grid, the International Jobs and Economic Development Impacts tool, and the Resilient Energy Platform. More information can be found at: www.nrel.gov/usaid-partnership.