Renewable Energy Guidance for Industry: Supplemental Document

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Primary authors for this report are Ahmad Abbas, Christopher Price, Paulomi Nandy, and Thomas Wenning of ORNL, Oak Ridge, Tennessee, USA.

The efforts of the following contributors are appreciated for their review and suggestions for this guidance:

Sachin Nimbalkar, ORNL
Subodh Chaudhari, ORNL
Eli Levine, U.S. Department of Energy, Advanced Manufacturing Office
Bruce Lung, Boston Government Services, LLC
Paul Lemar, Resource Dynamics Corporation
John O'Neill, U.S. Department of Energy, Advanced Manufacturing Office
Susanna Murley, U.S. Department of Energy, Solar Energy Technologies Office
Susan Hamm, U.S. Department of Energy, Geothermal Technologies Office
Alexis McKittrick, U.S. Department of Energy, Geothermal Technologies Office
Katherine DeBrandt, BCS, LLC
Caroline Grace, U.S. Department of Energy, Geothermal Technologies Office
Jennifer Garson, U.S. Department of Energy, Water Power Technologies Office
Allison Johnson, U.S. Department of Energy, Water Power Technologies Office

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Preface

The U.S. Department of Energy's (DOE's) Better Buildings, Better Plants program (Better Plants) is a voluntary energy efficiency leadership initiative for U.S. manufacturers and water/wastewater entities. The program encourages organizations to commit to reducing the energy intensity of their U.S. operations, typically by 25% over a 10-year period. Companies joining Better Plants are recognized by DOE for their leadership in implementing energy efficiency practices and for reducing their energy intensity. Better Plants Partners are assigned to a Technical Account Manager who can help companies establish energy intensity baselines, develop energy management plans, and identify key resources and incentives from DOE, other federal agencies, states, utility companies, and other organizations that can enable them to reach their goals.

This document is a supplement to the Better Plants Renewable Energy Guidance for Industry 2022. The purpose of this document is to further explain renewable energy technologies (i.e., solar energy, wind energy, biogas, hydropower, and geothermal) and to briefly discuss fuel cells, hybrid renewable energy systems, and microgrids.

For more information on the Better Plants program, please visit:
betterbuildingssolutioncenter.energy.gov/better-plants

For more information on the Better Plants Challenge program, please visit:
https://betterbuildingssolutioncenter.energy.gov/better-plants/better-plants-challenge

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1. Renewable Energy Technologies

1.1 Introduction

Various options are available to implement renewable energy in your organization, and these options can generally be divided into self-generation (on-site or off-site) and purchasing renewable electricity. Self-generation projects can be owned or leased, and these will generate green power either on-site at your own facility (behind the meter) or at an off-site location. Renewable electricity can typically be obtained through power purchase agreements, renewable energy credits or certificates, or your utility provider. This document will discuss the available renewable energy technologies for self-generation, and the mechanism of purchasing renewable electricity with its all options is discussed in the U.S. Department of Energy's (DOE's) Better Buildings, Better Plants program (Better Plants) Renewable Energy Guidance 2021.[1]

On-site renewable generation is an evident demonstration of an organization's environmental pledge. Considering on-site power generation also provides control over electricity cost. However, under certain circumstances, organizations may prefer to own renewable electricity technologies off-site, away from their own facilities, perhaps because of limited resource availability or complicated permitting and regulations at the on-site location, or for utility and economic benefits.

Generally, there are several renewable energy technologies for on-site or off-site self-generation installations, including solar energy, wind power, biogas, hydropower, geothermal, and fuel cells that use renewable fuels. The following sections describe each of these technologies in addition to briefly introducing hybrid renewable energy systems.

1.2 Solar Energy

Various technologies are being used to convert sunlight to useful energy (electric or thermal), some of which are solar photovoltaic (PV), concentrating solar power (CSP), passive solar, solar water heating, and solar process heat. The most common technology for electricity generation is solar PV.

Solar PV

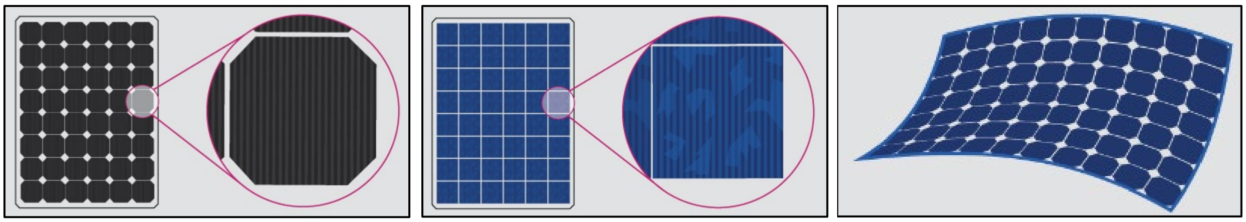
In a solar PV system, sunlight is converted into electricity through the PV effect by using a semiconducting material. Typically, multiple solar cells (usually 60, 72, or 96 cells) arrayed in a solar module (i.e., a solar panel) are used for this purpose. When multiple solar panels (modules) are connected together in series, it is called *string*, and several strings are usually connected in parallel to build a solar PV array. Commercially available solar panels have wattage ranges between 350 and 400 W, with an average top-tier module efficiency of 21%.[2]

Solar panels can be classified by type, and there are mainly three common types of solar panels: monocrystalline, polycrystalline, and thin-film (see Figure 1). The various panel types have different advantages and disadvantages. Generally, monocrystalline and polycrystalline panels have higher

[1] Abbas, A., C. Price, P. Nandy, and T. Wenning. 2022. *Renewable Energy Guidance for Industry*. ORNL/SPR-2021/2026. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[2] Svarc, J. 2022. "Top 10 Most Efficient Solar Panels." Clean Energy Reviews. Accessed at https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels.

efficiency than the thin-film panels; monocrystalline panels have the highest efficiency, and thin-film panels are the most cost-effective, followed by polycrystalline and then monocrystalline. Because of the flexibility and light weight of the thin-film panels, these can be wall-mounted (building-integrated PV). Solar panels can also be rooftop-mounted, ground-mounted, or floating. Ground-mounted systems might also have a system to track the sunlight over the day.

Solar PV systems can generate electricity while being grid-connected or in stand-alone mode (off-grid) and usually have energy storage (batteries) and another conventional (or renewable) source of generation as a backup.



(a) (b) (c)

Figure 1: Types of cells in solar PV panels: (a) monocrystalline, (b) polycrystalline, and (c) thin-film.[3]

The performance of different solar systems depends on the amount of solar radiation (insolation) delivered to the Earth, and it varies depending on the geographical location, time of day, season, landscape, and weather. The useful solar irradiance for estimating the performance of a solar PV system is the global horizontal irradiance (GHI), which is the total irradiance from the sun on a horizontal surface on Earth. GHI includes the direct normal irradiance (DNI) and the diffuse horizontal irradiance. DNI is the component of solar irradiation that reaches a surface of the Earth (normal to the direction of the sun) without any atmospheric losses caused by scattering or absorption. Diffuse horizontal irradiance is the irradiation component that reaches a horizontal Earth surface as a result of being scattered by air molecules, aerosol particles, cloud particles, or other particles. The U.S. annual solar GHI map is available in Appendix A-1. GHI is useful for estimating solar PV systems, and DNI is useful for estimating the performance of solar thermal systems (i.e., CSP, solar water heating, and solar process heat). The U.S. annual solar DNI map is available in Appendix A-2.

Concentrator PV

An advanced version of solar PV is concentrator PV, which uses curved mirrors or lenses (Fresnel lenses) to focus the sunlight (500–1,000 times sunlight reflected) on highly efficient solar cells. To guarantee higher efficiency from the concentrator PV technology, solar tracking and cooling systems are needed. This technology is not used as the conventional PV systems, but it is under further research and development to increase competitiveness and feasibility.

CSP

CSP is an electricity and heat generation technology that uses mirrors to reflect and concentrate the sunlight into a receiver to generate heat that can increase the temperature of a thermal energy carrier (i.e., heat transfer fluid) such as water, oil, or molten salt, which then can be used directly as hot water or steam, or indirectly to run a turbine and generate electricity or to heat a process. The four CSP

[3] Marsh, J. 2021. "Types of Solar Panels." EnergySage. Accessed at https://www.energysage.com/solar/101/types-solar-panels/.

technologies are parabolic trough collectors, linear Fresnel flat reflectors, power towers or central receiver systems, and dish/engine systems; parabolic trough collectors and central receiver systems are the only two commercially developed CSP technologies. For parabolic trough collectors and linear Fresnel flat reflectors, temperatures can reach up to 400°C (750°F) with conversion efficiencies from 8% to 18%. For central receiver systems, temperatures can range from 600°C to 1,200°C (1,100°F to 2,200°F); for dish/engine systems, temperatures can reach up to 800°C (1,470°F). Conversion efficiencies range from 20% to 40% for both central receiver systems and dish/engine systems. CSP systems can be used for electricity generation or industrial and agricultural processes (see Figure 2).

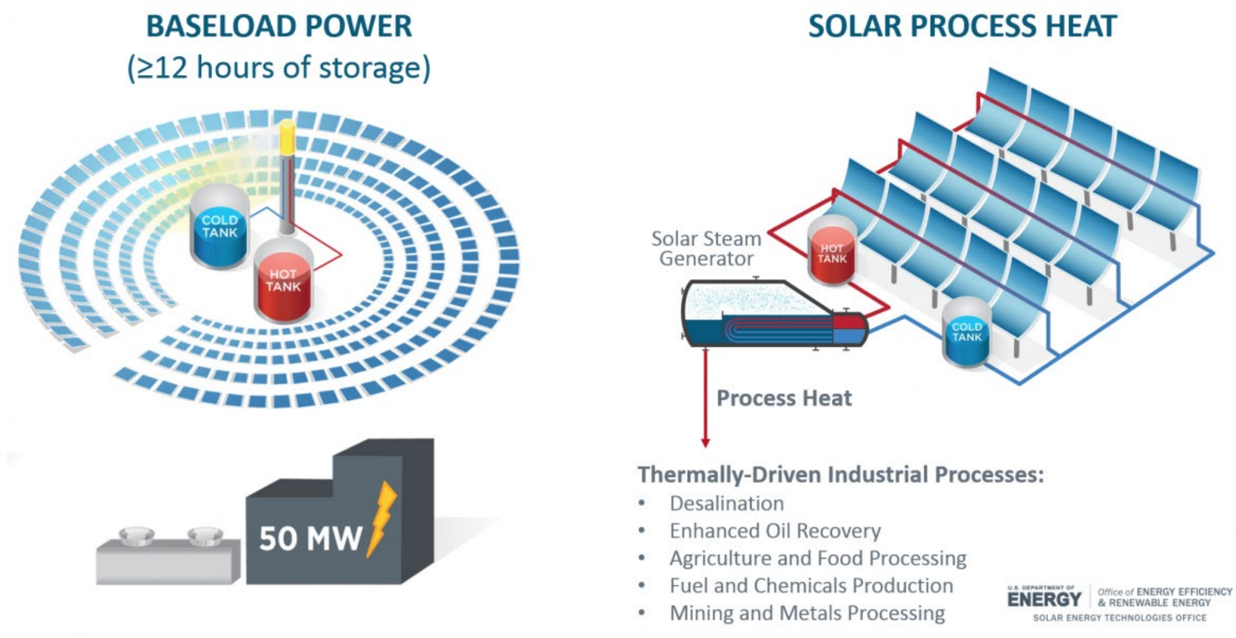


Figure 2: CSP applications.[4]

Solar Process Heat

Solar energy can provide heat to support industrial processes that serve water- or air-heating end uses. More than 50% of industrial processes require heat below 400°C (750°F),[5] and other industrial processes, such as cooking, have even lower temperature requirements. Several thermal renewable energy technologies can easily be used in low-temperature applications. Although the entire heating load may not be met by a renewable source, renewables can still supply a conventional heating process with preheating. Raising the temperature of water requires a large amount of energy when compared with heating air; even a small amount of preheating can help reduce a process's fuel consumption and increase cost-effectiveness.

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[4] US Department of Energy. "Concentrating Solar-Thermal Power." Office of Energy Efficiency & Renewable Energy. Accessed at https://www.energy.gov/eere/solar/concentrating-solar-thermal-power.

[5] US Environmental Protection Agency. "Renewable Industrial Process Heat." Accessed at https://www.epa.gov/rhc/renewable-industrial-process-heat.

Industrial processes that require warm temperatures or hot water (i.e., preheating water, pressurization, or for agricultural purposes such as warming soil or warming water for fish farming) can use flat-plate solar collectors. These collectors can deliver heat up to 80°C (176°F) with a maximum efficiency of 60%.[6,7]

When higher temperatures are needed for processes such as drying, curing, sterilization, kilning, chemical processing, and distillation, evacuated tube solar collectors can be used. An evacuated tube solar collector is defined as "a set of many double-walled, glass tubes and reflectors to heat the fluid inside the tubes. A vacuum between the two walls insulates the inner tube, retaining the heat."[8] These collectors can provide heat up to 400°C (750°F) and have an efficiency range of 70% to 80%. For applications with temperatures above 400°C (750°F), such as pressurized and superheated water or steam and fuel production, concentrating solar thermal technologies can be used.

Solar Water Heating

Generally, there are two categories of water heating systems: batch heating and on-demand heating. In batch heating, the water is heated while being stored in tank; in on-demand heating, the cold water is quickly heated while it moves to the point of use. The latter is considered more energy-efficient, but it requires higher capital cost.

Multiple types of solar technologies can supply sufficient hot water for nonresidential buildings. Even if the demand is not met or there is insufficient solar irradiation, solar heating can still preheat the water for a conventional heating unit and save energy. The most common technologies are the evacuated tube solar collectors and linear Fresnel flat reflectors because of their high temperatures and efficiency. Flat-plate solar collectors and geothermal heating can also be used. Usually, these systems are built with a pump and a heat exchanger with one or more energy storage tanks.

Solar Space Heating

Similar to solar water heating, solar space heating uses solar collectors, and it requires more collectors and larger storage. In this system, solar collectors transfer heat to a heat-transfer medium such as air, water, or other nontoxic liquids, to where the medium will circulate into the building to heat the space. Furthermore, another solar space heating technology uses transpired collectors to provide ventilation air in buildings to control indoor air quality. This technology can save energy and lower costs by preheating ventilation air for large buildings, especially in winter, when a significant amount of energy is needed to raise the outdoor ambient temperature to the level needed inside the building. This technology typically uses a collector (i.e., a transpired collector) made from thin black metal panels fixed on the wall of the building to absorb 60%–75% of the sun's heat.[9] Small holes in the perforated metal panel allow the air to pass through and then be collected and preheated between the panel and the building wall. From there and at the top of the trapped space, a fan pulls the preheated air into the building ventilation system (see Figure 3).

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[6] McMillan, C., et al. 2021. *Opportunities for Solar Industrial Process Heat in the United States*. NREL/TP-6A20-77760. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/77760.pdf.

[7] ScienceDirect. "Flat-Plate Collector." Accessed at https://www.sciencedirect.com/topics/engineering/flat-plate-collector.

[8] National Renewable Energy Laboratory. "Solar Process Heat Basics." Accessed at https://www.nrel.gov/research/re-solar-process.html.

[9] National Renewable Energy Laboratory. 1998. *Transpired Collectors (Solar Preheaters for Outdoor Ventilation Air)*. Federal Technology Alert. https://www1.eere.energy.gov/femp/pdfs/FTA_trans_coll.pdf.

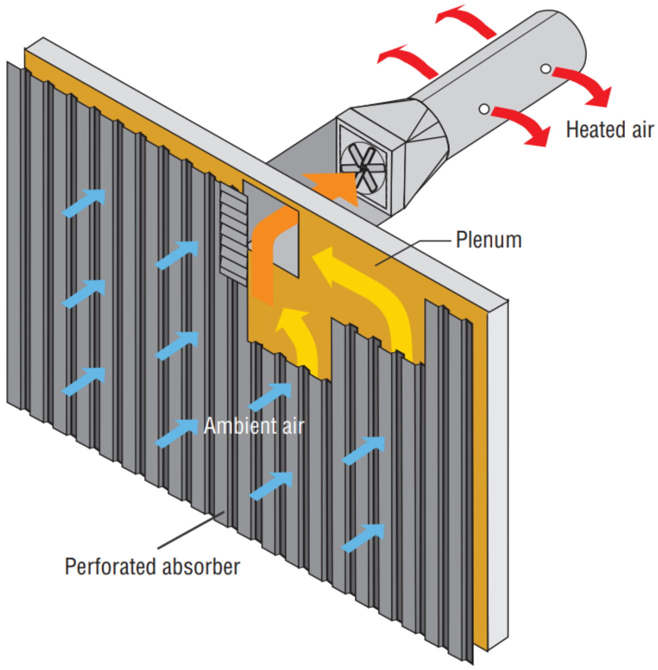

Figure 3: Solar ventilation by transpired air collectors. Credit: NREL.[10]

Solar Cooling

In solar cooling, thermally driven cooling systems use heat from the sun and convert it into cooling, which can be used for air conditioning, refrigerating products, or generating chilled water. Two common systems are used for solar cooling are absorption cooling and desiccant cooling. In the absorption cooling system, the cooling process depends on the evaporative cooling of a refrigerant; to complete the vaporization process, a source of heat is needed, and solar energy can provide heat via solar collectors. The desiccant cooling system depends on the process of dehumidification and humidification. For dehumidification, a special material or substance (i.e., desiccant) is used to absorb the water from the surroundings; then, when solar heat is available, that heat will regenerate the desiccants for the cooling cycle. Generally, thermally driven cooling systems are not prevalent because of the high initial investment and low coefficient of performance of the less than 1.0.

1.3 Wind Energy

Wind energy (or wind power) is the process of creating electricity using the wind, or airflows that occur naturally on Earth because of uneven heating of the Earth's surface by the sun. Wind power has been used to grind grain in windmills, and modern wind turbines are used to capture the kinetic energy from the wind and generate electricity. The U.S. annual average wind speed at 80 m hub height is available in Appendix A-3.

The working principle of wind turbines is such that wind (airflow) passing through the turbine's blades rotates the turbine. Thus, the kinetic energy of wind is converted into mechanical energy via a shaft connected to a gearbox, where the gearbox is needed to increase the rotational speed of the shaft that is

[10] National Renewable Energy Laboratory. 2006. *Solar Buildings: Transpired Air Collectors: Ventilation Preheating*. https://www.nrel.gov/docs/fy06osti/29913.pdf.

connected on the other side to an electric generator to generate electricity. The shaft, gearbox, generator, and other controls are all enclosed in a nacelle. Other parts include the turbine itself (usually three blades connected by a hub in the horizontal-axis wind turbines), supported by a tubular steel tower with a height of at least 80 m. Vertical-axis wind turbines are also used, such as Darrieus and Savonius wind turbines, but horizontal-axis wind turbines are more commonly used.

Wind turbines work within a certain range of wind speeds (approximately 8–55 mph or 3.5–25 m/s). In Figure 4, the minimum wind speed (i.e., cut-in speed) is the minimum wind speed needed to start the blades turning. As the speed increases, the power increases until it reaches the maximum power (i.e., rated power); then, the turbine maintains its rated power until the maximum wind speed (i.e., cut-out speed) is reached, at which the turbine needs be shut down to prevent damage to the blades; this speed may vary by turbine.

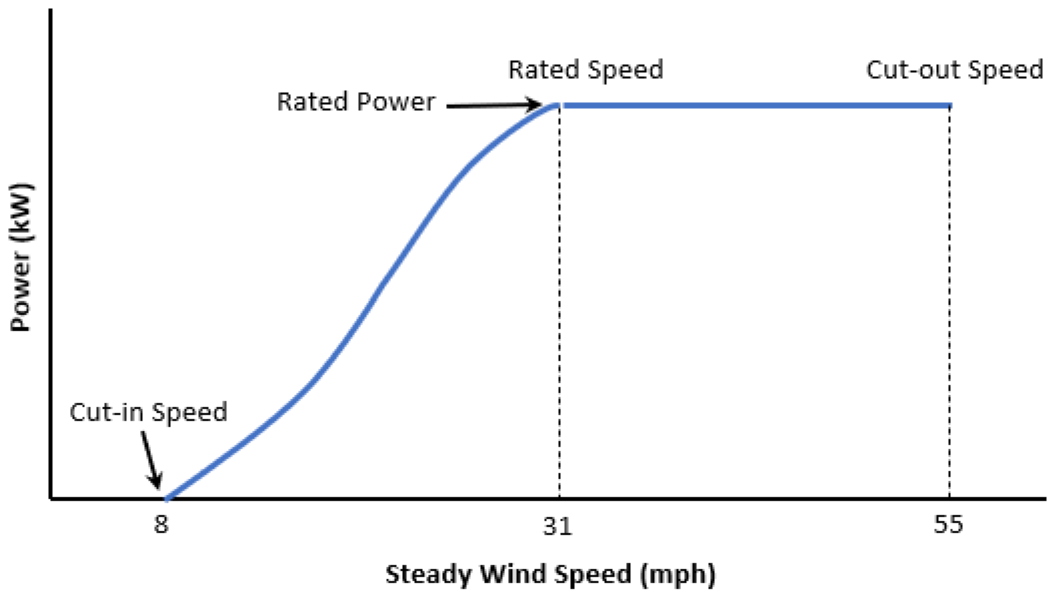

Figure 4: Typical wind turbine power with steady wind speed.

There are three main categories of wind energy:

- **Utility-scale wind—**Any wind turbine with a size over 100 kW and up to several megawatts, generating electricity by electric utility companies or power producers and then transmitting and distributing to the end user through an electricity grid
- **Distributed wind—**Wind turbines with a size below 100 kW that generate electricity at the point of use to power a home, farm, or small facility, with no need for transmission or distribution of electricity, and usually not grid-tied
- **Offshore wind—**Generally, offshore wind turbines are larger than onshore wind turbines and thus generate more power; constructed in seas or oceans near land (on the continental shelf)

Modern wind turbines can generate electricity around 90% of the time over the year. One common way to measure the performance of wind turbines is the capacity factor. Generally, the capacity factor (as a percentage) of a generation system is defined as the actual amount of electricity generated over a period of time—usually 1 year—to the system's maximum possible generated electricity (see Box 1).

Box 1: Example of a wind turbine capacity factor

A 100 kW wind turbine has a maximum theoretical output of 876,000 kWh/year (100 kW x 8,760 h/year), and the actual electricity generated is 350,470 kWh/year.

The capacity factor (CF) is calculated as

$$CF = \frac{Actual\ Electricity\ Generated\ \left(\frac{kWh}{year}\right)}{Maximum\ Theoretical\ Output\ \left(\frac{kWh}{year}\right)} = \frac{350{,}470\,\frac{kWh}{year}}{876{,}000\,\frac{kWh}{year}}$$

$$\boldsymbol{CF = 40\%}$$

Note: *CF* of 40% does not necessarily mean the turbine only generated electricity 40% of the time. Modern wind farms have capacity factors over 40%, which make them comparable to some types of coal or natural gas power plants.

Connecting wind turbines to the grid as a distributed energy resource requires interconnection approval similar to interconnection applications for solar PV to mitigate safety and power quality issues. More specific information about the interconnection requirements can usually be obtained from the local utility in your area. The main renewable energy guidance document's[11] Section 2.4.2 provides more information on interconnection requirements.

1.4 Biogas

On-Site Digestion

What is biogas?

Biogas is a renewable energy resource that is produced naturally from the decomposition of organic matter by bacteria in an oxygen-free environment. A blend of methane (50%–70%), carbon dioxide (30%–40%), and other gases is released when matter decomposes anaerobically. The high methane content of biogas makes it flammable and suitable as an energy source for heat and electricity generation.

What are the benefits of biogas?

Recovering energy from biogas has a myriad of environmental benefits. Methane has nearly 30 times the heat-trapping capability of carbon dioxide. Capturing biogas from waste streams instead of releasing it into the atmosphere as landfill gas reduces emissions. The microbes involved with anerobic digestion reduce the toxicity of waste, thus lowering the risk of groundwater pollution. Burning biogas also displaces the need for fossil fuel consumption, thus reducing the release of sequestered carbon. Finally, the remaining waste sludge can be used or sold as an organic fertilizer in agricultural industries.

There are also several financial benefits in using biogas as a renewable fuel source. Biogas can reduce natural gas consumption, thereby lowering utility bills for a facility. The breakdown of organic materials

[11] Abbas, A., C. Price, P. Nandy, and T. Wenning. 2022. *Renewable Energy Guidance for Industry*. ORNL/SPR-2021/2026. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

also reduces the quantity of waste, which saves on waste disposal costs. Finally, biogas can be used for on-demand energy to substitute for gaps in other renewable energy streams (e.g., wind, solar) or reduce grid energy demand during high price periods.

How does anaerobic digestion work?

Biogas can be created from multiple waste sources, such as livestock waste, food waste, wastewater, crop residues, and landfills. Some wastes are more difficult to break down than others; livestock waste is typically the most difficult, and food waste the least difficult. These waste streams are added to an anaerobic digester that mixes the waste and bacteria needed to convert the waste into combustible gas. There are several versions of digesters, such as mixed stream, high temperature, wet/dry, and batch/continuous. The off-gases are collected and filtered, and the remaining solid/liquid waste is removed from the digester as new material is added. The specific type of digester used depends on the kinds and quantities of waste being processed in each manufacturing facility (see Figure 5).

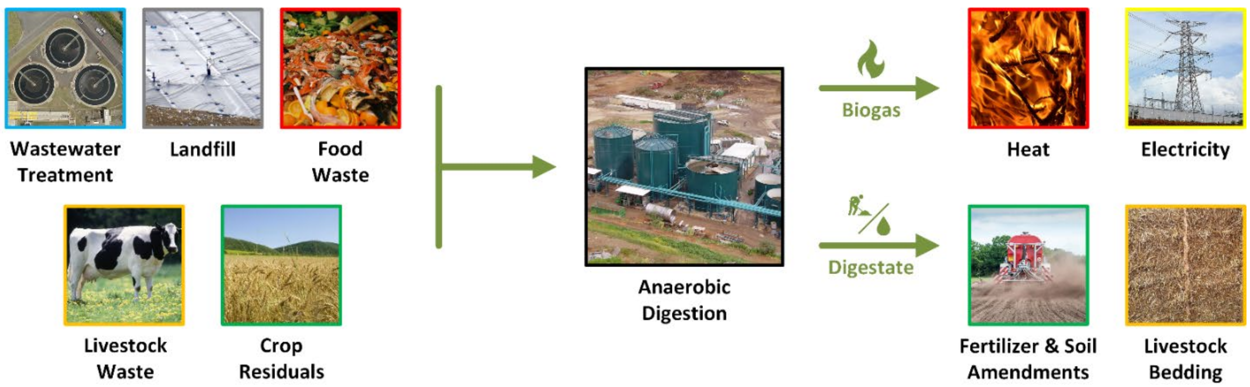

Figure 5: Biogas production can use many types of waste streams to produce heat and electricity.

Owing to the variable nature of the biogas methane content, some manufacturing facilities require blending equipment to ensure constant heat and/or power output of gas-powered equipment. Blenders will combine biogas and natural gas to maintain a consistent energy content in the biogas stream, which process allows facilities to maximize their biogas usage without affecting production. However, a biogas conditioning system may be needed to remove siloxanes, moisture, and other contaminants from the digester gas to make it suitable for use. Facilities that combine natural gas with biogas should be careful to not double-count resource consumption as some natural gas will be used in the biogas energy stream.

The use of biogas at a facility will affect the facility's energy intensity reporting to Better Plants. Unrecovered or flared biogas creates a significant opportunity to replace grid-supplied energy with on-site generated energy that has a lower site-to-source multiplier. The precise benefits will be determined by the operational efficiency of the gas turbines and/or combined heat and power (CHP) system being used. Biogas is only beneficial for reporting purposes when biogas energy can be generated more efficiently than grid energy.

Figure 6 shows the three ways to account for biogas usage at a facility. Treating biogas as free energy (Option A) has the greatest potential for energy intensity improvement but is not consistent with sound energy management principles. Burning biogas still has environmental considerations, and not tracking its use can obscure issues such as inefficient energy use or underlying issues at a facility. Measuring the energy content of fuels entering a biogas generator (Option B) treats biogas as an additional fuel source.

Although optimal, this method requires flow-measuring equipment and can actively discourage biogas use to conserve energy resources. DOE recommends Option C, measuring the electricity and heat generated from the biogas stream. This method is equivalent to treating biogas like solar or wind power and is a middle ground between the other two options.

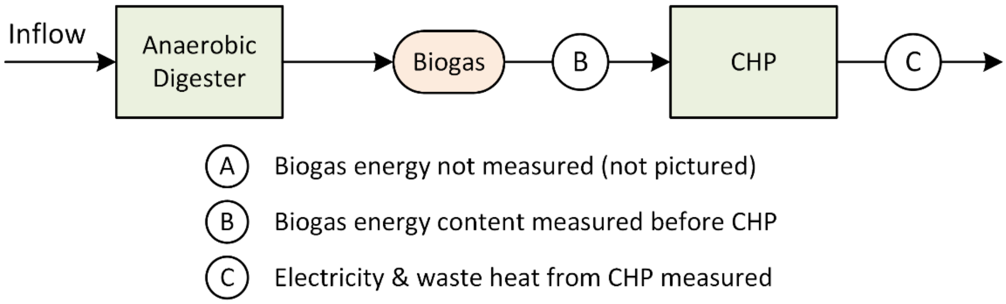

Figure 6: Options for measuring recovered energy from biogas.[12]

When using biogas, there are important subjects to focus on when reporting energy use to Better Plants. If using Option C to track biogas, facilities that blend natural gas with biogas for heat content must be careful not to double-count resource consumption. The heat content of the blended natural gas will be captured in the measurements taken after the generation equipment and therefore should be excluded from natural gas reporting. Some facilities with significant biogas availability (e.g., paper mills, wastewater treatment plants) may be able to become net-zero energy consumers through biogas use. Any energy generated in excess of what is consumed on site should be treated as an *energy product* instead of an energy resource, according to the criteria in the DOE Energy Intensity Baselining and Tracking Guidance.[13]

Renewable Natural Gas

Renewable natural gas (RNG) (i.e., biomethane) is a high-quality biogas that can be an alternative to the conventional natural gas. RNG is used as a pipeline-quality gas that can be used in natural gas vehicles or CHP systems, for example. RNG is essentially biogas produced from the decay of organic matter, but RNG must be processed to pipeline-quality gas (see Box 2).

Box 2: RNG quality requirements

RNG needs to meet the pipeline natural gas as stated in the Code of Federal Regulation of the United States of America:[14] "Pipeline natural gas contains 0.5 grains or less of total sulfur per 100 standard cubic feet. Additionally, pipeline natural gas must either be composed of at least 70 percent methane by volume or have a gross calorific value between 950 and 1100 Btu per standard cubic foot."

[12] Adapted from P. Lemar and A. de Fontaine. 2017. *Energy Data Management Manual for the Wastewater Treatment Sector.* DOE/EE-1700. Oak Ridge National Laboratory.
[13] C. Price, S. Nimbalkar, and T. Wenning. 2020. Energy Intensity Baselining and Tracking Guidance 2019. ORNL/SPR-2020/1566. Oak Ridge National Laboratory, Oak Ridge, Tennessee. Accessed at https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/Energy%20Intensity%20Baselining%20and%20Tracking%20Guidance%202020.pdf
[14] The Code of Federal Regulations of the United States of America. 72.4: 29. Accessed at https://bit.ly/3FYZWcP.

Similar to natural gas, RNG can be in the form of liquefied natural gas or compressed natural gas, and then it can be used as a transportation fuel. The Renewable Fuel Standard considers RNG as an advanced biofuel.[15] RNG can also be used in CHP systems to generate heat and electricity for power plants; in this case, it is also a purified pipeline-quality biogas that had been conditioned and cleaned to remove non-methane elements, and then it is biomethane.

Generally, processing biomass via biochemical processes (i.e., anaerobic digestion) or via thermochemical processes (i.e., gasification) will produce biogas, but with some cleanup, the biogas qualifies as a fuel for electricity and heat generation. With further cleanup and conditioning, the biogas meets the high purity standard to be used as fuel for vehicles. Such processes are needed to increase the content of methane in the raw biogas and make the RNG and biomethane comparable to the conventional natural gas. Then, these fuels can be used in applications in which a pipeline-quality gas is needed.

The Renewable Natural Gas Database,[16] developed and maintained by Argonne National Laboratory, provides a comprehensive list of projects that are upgrading gas for pipeline injection or use as fuel for vehicles.

Landfill Gas

Landfills are designated locations for disposal of waste collected from residential, industrial, and commercial entities. Landfills are the third largest source of human-related methane emissions in the United States, according to the U.S. Environmental Protection Agency. Biogas from landfills is also called *landfill gas* since the process of digestion occurs in the ground, unlike in an anaerobic digester. According to the U.S. Environmental Protection Agency and as of September 2021, approximately 548 active landfill gas projects are in the United States; the majority of these projects use biogas for electricity generation.[17] Most landfill methane projects have a generating capacity of 5–20 MW; however, some projects are as large as 50 MW.[18]

1.5 Hydropower

The primary principle of hydropower is the extraction of kinetic and potential energy from water flow in a river, such as through a dam, to convert it into mechanical energy and then to electrical power by using the head and the volume flow rate. Increasing demand for renewable energy has contributed to increased interest in further innovation, optimization, and application of hydropower systems.

Currently, hydropower energy supplies 16.8% of the global electricity. In comparison with other renewables, hydropower is the most significant contributor with a power capacity of 1,170 GW and generated power of around 4,370 TWh/year as of 2020.[19] The growth rate of hydropower is not as high

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[15] For more information about the Renewable Fuel Standard: https://afdc.energy.gov/laws/RFS. The EPA's Renewable Fuel Standard program: https://www.epa.gov/renewable-fuel-standard-program.

[16] Argonne National Laboratory. Renewable Natural Gas Database. Accessed at https://www.anl.gov/es/reference/renewable-natural-gas-database.

[17] US Environmental Protection Agency. LMOP Landfill and Project Database. Accessed at https://www.epa.gov/lmop/lmop-landfill-and-project-database

[18] Jaramillo, P., and H. S. Matthews. 2005. "Landfill-Gas-to-Energy Projects: Analysis of Net Private and Social Benefits." *Environmental Science & Technology* 39(19): 7365–7373. https://pubs.acs.org/doi/10.1021/es050633j.

[19] REN21 Secretariat. 2021. *Renewable Energy Policy Network for the 21st Century*. Accessed at https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf.

as wind and solar sources, but hydropower accounts for more than 50% of the total renewable energy sources in the world.[20,21]

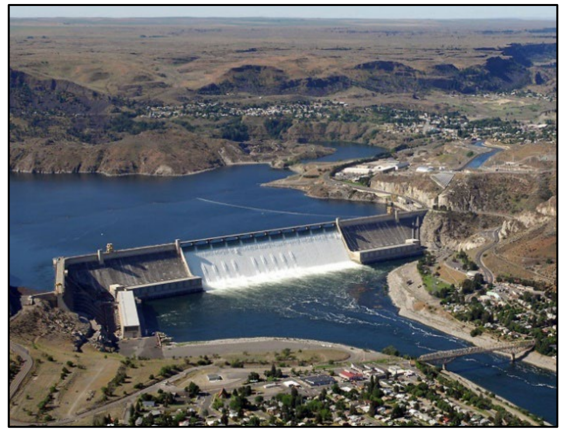
In 2019, hydropower capacity accounted for 6.7% (80.25 GW) of installed electricity generation capacity in the United States, and its generation represented 6.6% (274 TWh) of all electricity generated and 38% of electricity from renewables produced in the United States, and almost half of this capacity is located in Washington, California, and Oregon.[22] The majority of the installed hydropower plants in terms of capacities are located in the northwest United States, whereas the northeast United States has the highest number of facilities. The largest hydroelectric plant in the United States is located at the Grand Coulee Dam in Washington, with a capacity of 6,809 MW (Table 1 shows the top largest hydroelectric power stations in the United States). The first commercial hydroelectric plant (12.5 kW) was built in 1882, on the Fox River in Appleton, Wisconsin.[23] At the beginning of the 20th century, commercial power companies started to construct several small hydropower plants in mountainous regions near populated urban areas. Construction of the Hoover Dam (see Figure 7(a)) started in 1931, and when completed in 1936, it was the largest hydroelectric project in the world with 2 GW.[24] The Hoover Dam was then surpassed by the Grand Coulee Dam (6.8 GW) on the Columbia River in 1941 (see Figure 7(b)).[25] The massive power output is influenced by the higher volume of water available.

Table 1: List of largest hydroelectric power stations in the United States

	Name	Location	Year of completion	Total capacity (MW)
1	Grand Coulee	Washington	1942/1980	6,809
2	Bath County Pumped Storage Plant	Virginia	1985	3,003
3	Chief Joseph Dam	Washington	1958/1973/1979	2,620
4	Robert Moses Niagara Power Plant	New York	1961	2,515
5	John Day Dam	Oregon/ Washington	1949	2,160
6	Hoover Dam	Nevada/Arizona	1936/1961	2,080
7	The Dalles Dam	Oregon/ Washington	1957	2,038
8	Ludington Pumped Storage Plant	Michigan	1973	1,872
9	Raccoon Mountain Pumped Storage Plant	Tennessee	1978	1,652
10	Glen Canyon Dam	Arizona	1966	1,320

[20] Power Technology. 2020. "The world's most used renewable power sources." Accessed at https://www.power-technology.com/features/featurethe-worlds-most-used-renewable-power-sources-4160168/.
[21] Ritchie, H., and M. Roser. 2020. "Renewable Energy." Accessed at https://ourworldindata.org/renewable-energy.
[22] Uria-Martinez, R., M. M. Johnson, and R. Shan. 2021. "U.S. Hydropower Market Report: January 2021." Oak Ridge National Laboratory, Oak Ridge, Tennessee. Accessed at https://www.energy.gov/sites/default/files/2021/01/f82/us-hydropower-market-report-full-2021.pdf.
[23] Nelson, V., and K. Starcher. 2015. *Introduction to Renewable Energy*. Second Edition. CRC Press.
[24] Bureau of Reclamation. Hoover Dam. Accessed at https://www.usbr.gov/lc/hooverdam/index.html.
[25] Bureau of Reclamation. Grand Coulee Dam. Accessed at https://www.usbr.gov/pn/grandcoulee/index.html.

(a)



(b)

Figure 7: Aerial photo of (a) the Hoover Dam and (b) the Grand Coulee Dam.

Hydropower Technologies

Several hydropower technologies can generate electricity, including an impoundment, a diversion, or multiple reservoirs such as in pumped storage hydropower (PSH).

In an impoundment (see Figure 8), dams are used. The impoundment stores water in a reservoir and when the water is released, it flows through and spins a turbine, turning a generator that produces electricity.

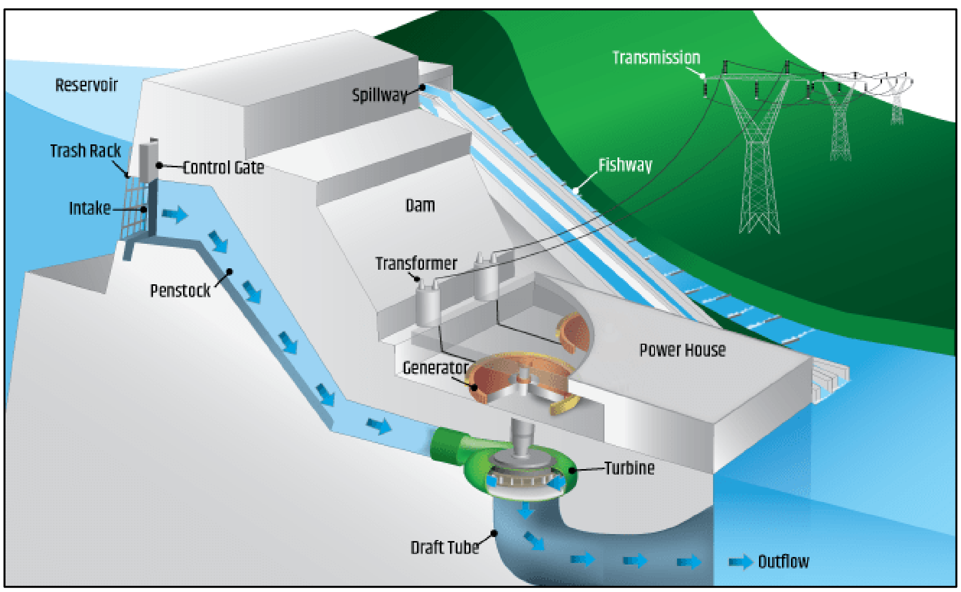


Figure 8: Impoundment facility. Credit: DOE.

A diversion, sometimes called a *run-of-river facility*, channels a portion of a river through a canal and/or a penstock to use the natural decline of the river bed elevation to produce energy (see Figure 9). A penstock is a closed conduit that channels the flow of water to turbines with water flow regulated by gates, valves, and turbines. A diversion may not require the use of a dam.

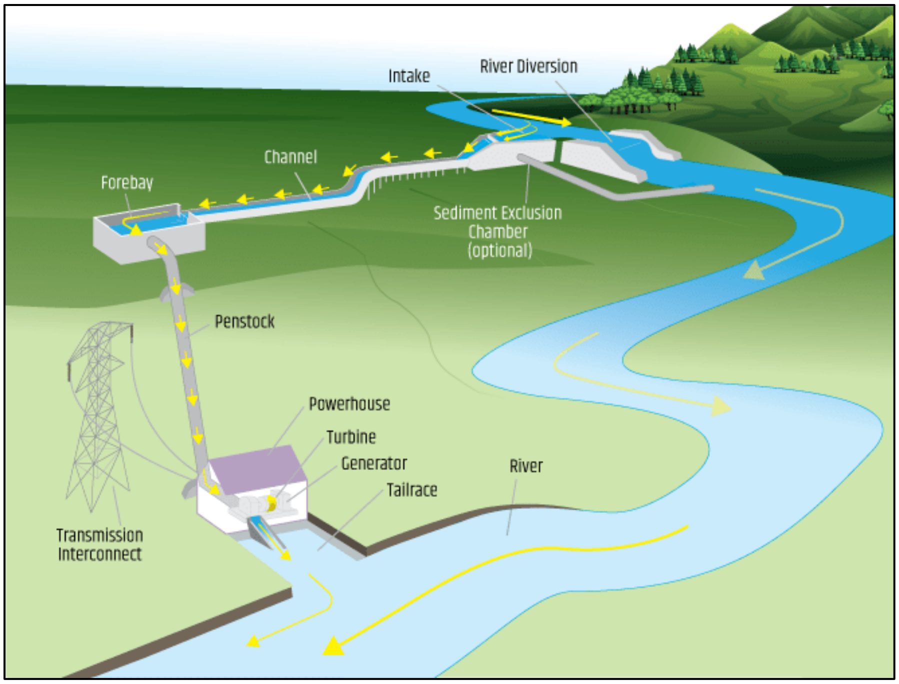


Figure 9: Diversion technology. Credit: DOE.

PSH is considered as a huge battery—the battery is charged by pumping the water back up into a reservoir during periods of low energy use (off-peak hours), and then when more power is needed during the day (on-peak hours), the water is released to produce electricity.

There are two general designs for PSH—open and closed loop (see Figure 10). An open-loop PSH facility has an ongoing hydrologic connection to a natural body of water, whereas the reservoirs in a closed loop facility are not connected to an outside body of water. Closed-loop PSH systems provide more opportunities to minimize environmental effects to aquatic and terrestrial habitats than open-loop systems. Although all PSH projects currently operating in the United States are considered open-loop, multiple permit and licensing applications have been filed in recent years for closed-loop systems, and these projects may come online soon.

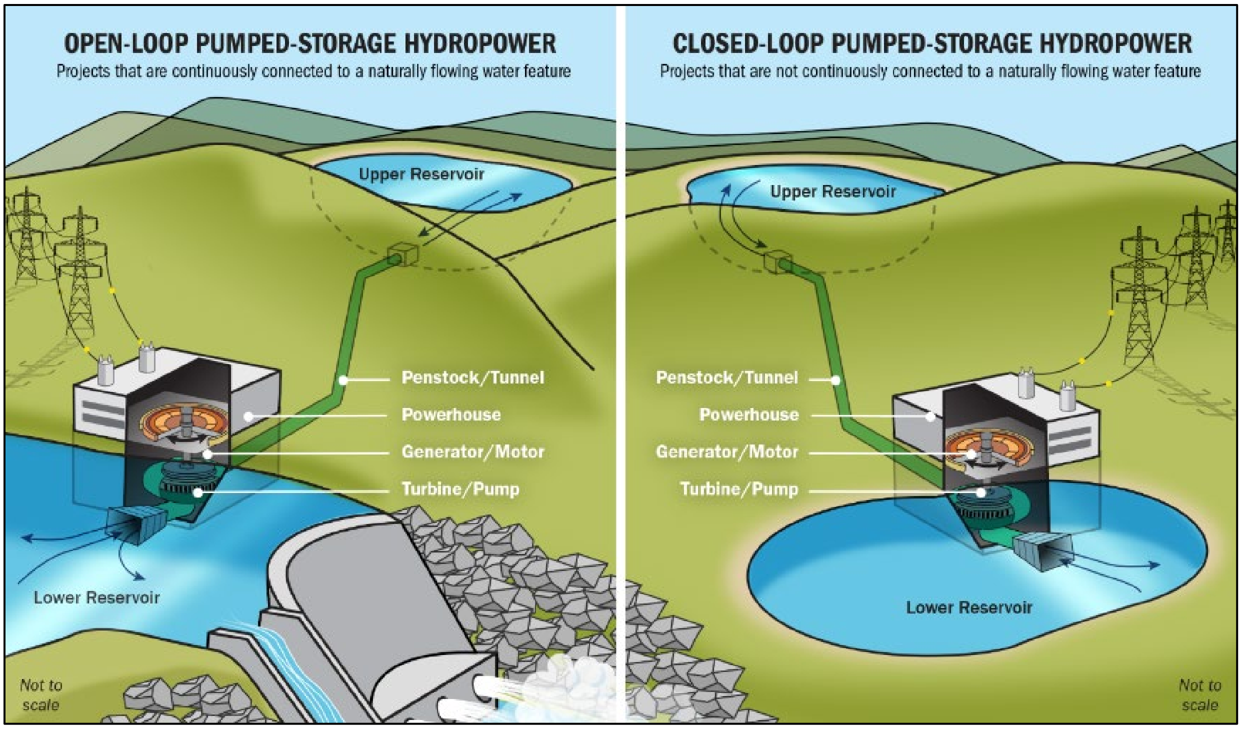


Figure 10: Open-loop and closed-loop PSH. Credit: DOE.

Conduit hydropower

There are many other ways of generating power via water. One novel technique is conduit hydropower, which generates electricity from turbines installed inside water pipelines, usually with a vertical axis configuration, and attached to an electric generator outside the pipe (see Figure 11). These turbines are designed for energy recovery applications in water supply pipelines. This technology is unique in its compact design and ease of installation, which reduce the cost of installation and allow such hydropower turbines to be installed inside facilities without the need for a large space. Conduit turbines are usually installed between flanges and can be used as pressure-reducing valves for existing structures, which can minimize the cost of new construction. These turbines can primary be used in water and wastewater facilities with output capacities of approximately 3–90 kW.

Some features and advantages of such a system are as follows:

- Compact design allowing for in-pipe installation, which minimizes space requirements
- Reduced capital cost because the compact design integrates both the turbine and the generator
- Built-in generator to reduce vibration and noise, thus lowering maintenance costs
- Designed for use with water supplies where oil pollutants are to be completely avoided
- Can be feasible at locations with large water head (effective in cases with small flow and large head)
- Can be used as a pressure-reducing valve

Figure 11: Main parts of a conduit hydroelectric turbine.[26]

Hydropower Potential

Although most of the hydropower generated in the United States comes from large plants, most of the nation's potential hydropower generation remains untapped, particularly at lower power and head levels. There is a substantial opportunity worldwide, and across the United States specifically (see Appendix A-4), to add new hydropower generating capabilities to existing dams. Only 3% of the nation's 80,000 dams currently generate electricity, and some of these sites—especially low-head sites such as non-powered dams, canals, and conduits—can be suitable for power generation. As stated in Oak Ridge National Laboratory's report,[27] there is an estimated potential hydropower capacity of 12,000 MW at the existing 80,000 unpowered dams with at least 0.91 m (3 ft) of water head available. The 2020 National Hydropower Map, which shows the current operating hydropower plants in the United States, is available in Appendix A-5.

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[26] Photo source: Agnos, C. 2019. "Portland Now Generates Electricity from Turbines Installed in City Water Pipes." Sustainable Human. Accessed at https://earthmaven.io/sustainablehuman/new-stories-1/portland-now-generates-electricity-from-turbines-installed-in-city-water-pipes.

[27] Hadjerioua, B., Y. Wei, and S. Kao. 2012. *An Assessment of Energy Potential at Non-Powered Dams in the United States*. Oak Ridge National Laboratory, Oak Ridge, Tennessee. https://www.energy.gov/sites/prod/files/2013/12/f5/npd_report_0.pdf.

1.6 Geothermal

Geothermal energy is heat derived from below the Earth's surface, which can be harnessed as a carbon-free renewable energy around the year with a small physical footprint. Geothermal energy can be used as a steady heat source for heating and cooling purposes or for electricity generation.

Geothermal is divided into three categories based on how it is used:

- Geothermal heating and cooling (e.g., district heating)
- Geothermal heat pumps
- Geothermal electricity production

Geothermal Heating and Cooling

Geothermal heating and cooling use the hot water that already exists in hot springs and geothermal reservoirs near the surface of the Earth, producing heat directly from hot water within the Earth to heat and cool buildings, homes, and communities. Lower-temperature resources can also support other geothermal direct-use applications in agriculture, recreation, and industry (e.g., food dehydration, mining, and milk pasteurizing).

Geothermal heating and cooling and other direct-use systems typically have three components:

- A production facility—usually a well—to bring hot water to the surface
- A mechanical system—piping, heat exchanger, and controls—to deliver the heat to the space or process
- A disposal system—injection well, storage pond, or river—to receive the cooled geothermal fluid (does not apply to systems with closed loops in which the fluid circulates continuously in the piping)

Direct-use geothermal systems, including geothermal heating and cooling, offer great opportunities to significantly expand the impact and reach of geothermal energy across the country and could provide a large fraction of the energy demand currently supplied by high-grade fossil fuels. According to the DOE's GeoVision study published in 2019,[28] deployment of direct-use systems could increase to as many as 17,500 district heating systems by 2050. Geothermal district-heating systems have significant economic potential in the northeast corridor of the United States, and the Appalachian region is promising for direct-use geothermal potential, as well.

Geothermal district heating and cooling systems with a variety of architectures can be designed to provide heating, cooling, and/or water heating to multiple buildings from a shared piping system. Geothermal district heating and cooling systems using geothermal heat pumps (see next section) are increasing in use in the United States. Newer systems circulate ambient-temperature water (approximately 10°C–27°C or 50°F–80°F) between buildings equipped with geothermal heat pumps. These systems can use a single pipe network to provide space heating, space cooling, and water heating to networks of buildings. Multiple

[28] US Department of Energy. "GeoVision." Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/geothermal/geovision

studies and installations have shown that these types of systems can recycle heat between different buildings with different heating needs, thereby reducing capital cost, energy use, and resultant carbon dioxide emissions. For example, buildings with high occupancy and/or many computers are often warm and thus are almost always in a cooling mode. The extracted heat from the building warms the water in the shared pipe, and then another building that needs hot water or space heating can recover that heat instead of burning natural gas. These systems are commonly combined with geothermal boreholes to absorb heat or reject heat to the ground as needed.

Geothermal Heat Pumps

Geothermal heat pumps are among the most efficient and comfortable heating and cooling technologies available because they use the Earth's natural heat to provide heating, cooling, and water heating. Although many parts of the country experience seasonal temperature extremes, a few feet below the Earth's surface, the ground remains a relatively constant temperature. The natural ground temperature is cooler than the natural air temperature in summer and warmer than the natural air temperature in winter.

Geothermal heat pumps take advantage of seasonal variation by transferring heat stored in the Earth or in groundwater into a building during the winter and transferring it out of the building and back into the ground during the summer. In other words, the ground acts as a heat source in the winter and a heat sink in the summer. The benefit of ground source heat pumps is that they concentrate naturally existing heat, rather than producing heat through the combustion of fossil fuels.

Installing a geothermal heat pump system is often the most cost-effective and energy-efficient home heating and cooling option. Residential geothermal heat pumps exist in homes in all U.S. states and territories. Geothermal heat pumps are a particularly good option for building a new home or planning a major renovation to an existing home by replacing, for example, an HVAC system.

Geothermal heat pumps come in four types of loop systems that loop the heat to or from the ground and the house. Three of these—horizontal, vertical, and pond/lake—are closed-loop systems, and the fourth type is an open-loop system. Choosing the ideal system depends on the climate, soil conditions, available land, and local installation costs at the site.

Closed-loop systems

- **Horizontal—**This type of installation is generally most cost-effective for residential installations, particularly for new construction where sufficient land is available. It requires trenches at least 1.2 m (4 ft) deep.
- **Vertical—**This type is often used for larger-scale geothermal systems (such as in commercial buildings) where land is limited, or where the soil is too shallow to bury the horizontal loops in the trenches and some form of drilling into the bedrock is necessary. Vertical loop systems can be more expensive than other systems, but they use less land and also minimize disturbance to the existing landscape.
- **Pond/lake—**If the site has an adequate water body, this system may be the least expensive option. A supply line pipe runs underground from the building to the water and coils into circles

at least 2.4 m (8 ft) under the surface to prevent freezing. The coils should only be placed in a water source that meets minimum volume, depth, and quality criteria.

Open-loop systems

This type of system uses well or surface body water as the heat exchange fluid that circulates directly through the geothermal heat pump system. Once the water has circulated through the system, it returns to the ground through the well, a recharge well, or surface discharge. This option is practical only with an adequate supply of relatively clean water and when all local codes and regulations regarding groundwater discharge are met.

Residential hot water

In addition to space conditioning, geothermal heat pumps can be used to provide domestic hot water when the system operates. Many residential systems are equipped with desuperheaters that transfer excess heat from the geothermal heat pump's compressor to the house's hot water tank. A desuperheater provides no hot water during the spring and fall when the geothermal heat pump system is not operating; however, because the geothermal heat pump is much more efficient than other means of water heating, manufacturers are beginning to offer full-demand systems that use a separate heat exchanger to meet all of a household's hot water needs. These units cost-effectively provide hot water as quickly as the competing systems.

According to the GeoVision study,[28] 28 million geothermal heat pumps could be deployed nationwide by 2050. Geothermal heat pumps help decarbonize the grid by reducing peak and average loads while creating jobs in local communities.

Geothermal Electricity Production

The United States generates the most geothermal electricity in the world: more than 3.5 GW, predominantly from the western United States. This electricity is sufficient to power approximately 3.5 million homes. A geothermal resource requires fluid, heat, and permeability to generate electricity.

- **Fluid**—Sufficient fluid must exist naturally or be pumped into the reservoir.
- **Heat**—The Earth's temperature naturally increases with depth and varies based on geographic location.
- **Permeability**—To access heat, the fluid must come into contact with the heated rock, either via natural fractures or by stimulating the rock to create fractures.

Power plants use steam produced from geothermal reservoirs to generate electricity. Three geothermal power plant technologies are used to convert hydrothermal fluids to electricity: dry steam, flash steam, and a binary cycle. The type of conversion used (selected in development) depends on the state of the fluid (steam or water) and its temperature.

- **Dry steam power plant**—Dry steam plants use hydrothermal fluids that are primarily steam. The steam travels directly to a turbine, which drives a generator that produces electricity. The steam eliminates the need to burn fossil fuels to run the turbine and also eliminates the need to transport and store fuels. These plants emit only excess steam and very minor amounts of gases.

Dry steam power plants systems were the first type of geothermal power generation plants built (they were first used at Lardarello in Italy in 1904). Steam technology is still effective today and is currently in use at The Geysers in northern California, the world's largest single source of geothermal power.

- **Flash steam power plant**—Flash steam plants are the most common type of geothermal power generation plants in operation today. Fluid at temperatures greater than 182°C (360°F) is pumped under high pressure into a tank at the surface held at a much lower pressure, causing some of the fluid to rapidly vaporize, or "flash." The vapor then drives a turbine, which drives a generator. If any liquid remains in the tank, it can be flashed again in a second tank to extract even more energy.
- **Binary-cycle power plant**—Binary-cycle geothermal power generation plants differ from dry steam and flash steam systems in that the water or steam from the geothermal reservoir never comes into contact with the turbine/generator units. Mildly to moderately heated (below 200°C or ~400°F) geothermal fluid and a secondary (hence, "binary") fluid with a much lower boiling point than water pass through a heat exchanger. Heat from the geothermal fluid causes the secondary fluid to flash to vapor, which then drives the turbines and subsequently drives the generators. Binary-cycle power plants are closed-loop systems, and virtually nothing (except water vapor) is emitted to the atmosphere. Because resources below 150°C (~300°F) represent the most common geothermal resource, a significant proportion of geothermal electricity in the future could come from binary-cycle plants.

A map showing the geothermal resources of the United Stats is available in Appendix A-6.

1.7 Fuel Cells

Fuel cells produce electricity from chemical energy because of a chemical reaction between a fuel such as hydrogen or hydrocarbons (i.e., natural gas, biogas, and alcohols/methanol) and oxygen or another oxidizing agent. Fuel cells are usually used in place of batteries; however, fuel cells require a consistent source of fuel and oxygen to produce electricity continuously.

How Fuel Cells Work

Similar to batteries, fuel cells have a positive side called *cathode* and negative side called *anode*, as well as an electrolyte that allows the electric charge to travel between the two sides. When a load is connected, electrons will move from the anode to the cathode, forming a direct current (DC) electricity. As the hydrogen is supplied as a fuel at the anode, a chemical reaction causes the electrons of hydrogen atoms to be disjoined, which causes hydrogen atoms to be ionized with positive electrical charge as DC electricity (see Figure 12). Besides electricity production, fuel cells produce heat, water, nitrogen dioxide (in some cases, based on the used fuel), and other emissions. The electric efficiency of a fuel cell is normally between 40% and 60%, and by considering recovering waste heat, efficiency can reach up to 85%.[29]

[29] U.S. Department of Energy. 2016. "Comparison of Fuel Cell Technologies." Office of Energy Efficiency & Renewable Energy. Accessed at https://www.energy.gov/sites/prod/files/2016/06/f32/fcto_fuel_cells_comparison_chart_apr2016.pdf.

Generally, fuel cells have greater efficiency than combustion-based power, and they typically use hydrogen as a fuel source with little or no pollution.

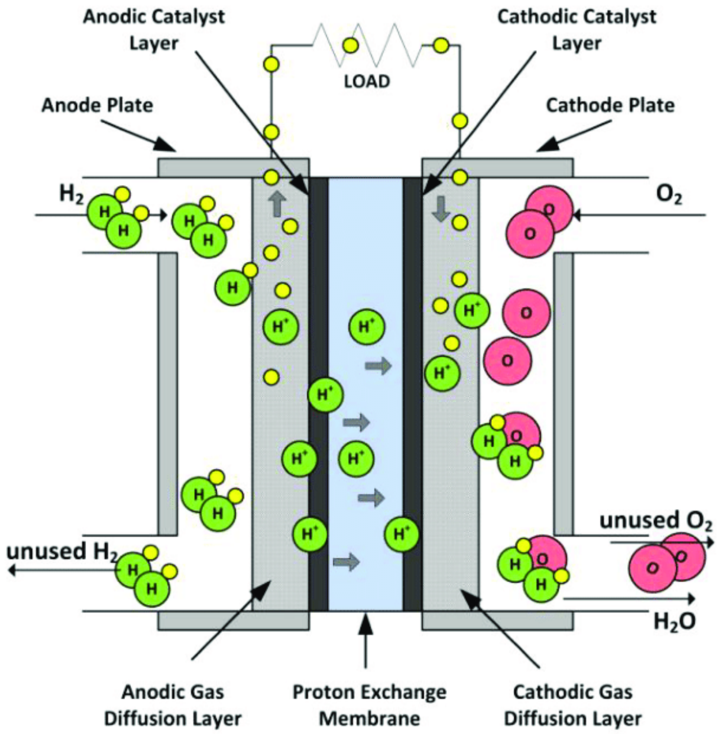


Figure 12: Working principle of fuel cells, and an example of the proton exchange membrane fuel cell.[30]

Benefits

- **Cost reduction:** The electricity is generated at high efficiency and thus uses little fuel to generate the same amount of electricity as needed from a conventional power source. In addition, the cost is predictable and can be locked in the long-term as opposed to fluctuating or continuously increasing as in utility rates.
- **Reliability and resilience:** Outages are avoided by the system being grid-independent (bypassing the vulnerabilities of conventional transmission and distribution lines), and a fault in the system will not affect the whole system because the system includes multiple independent power generation modules that can be easily swapped. An expanded definition of energy resilience, the difference between resilience and reliability, and an example are included in Box 3.
- **Sustainability:** Greenhouse gas (GHG) emissions are reduced, especially when a renewable energy source or biogas is used. In addition, fuel cells do not require water, which is needed for the operation of conventional power plants.

[30] Fărcaş, A. C., and P. Dobra. 2014. "Adaptive control of membrane conductivity of PEM fuel cell." *Procedia Technology* 12: 42–49. https://doi.org/10.1016/j.protcy.2013.12.454

Box 3: Energy Resilience

Being energy-resilient is to guarantee that a facility has a continuous and reliable supply of energy and a back-up plan in place in the case of a power failure caused by weather, natural disasters, power surges, human error, accidents, or equipment breakdown. With the grid upgrades such as moving from large centralized coal power generation plants to decentralized smaller gas-fired plants and renewable distributed generation, the supply of electricity faces stability concerns influenced by intermittency, which will negatively affect energy pricing. To avoid fluctuations in supply and pricing and to reduce operational risks, it is necessary to ensure that your company is energy-resilient.

General example from the food sector

Consider a power shutdown that takes place at a perishable products manufacturing facility; without the facility temperature being controlled, the products may being negatively affected. If these products are distributed to the market and are later recalled, the company would face a loss of sales, cost of recall, waste of materials and labor, energy and other support cost, and negative publicity.

Solution

Multiple steps could be taken to improve energy resilience and avoid the negative effects of the power shutdown:

1- Identifying and assessing the risks

2- Building in resilience where possible or at least based on the predicted cost of a power failure by reducing reliance on the grid or generating on-site power

3- Developing a plan and making sure that the concerned personnel are trained on executing it in case of a power failure

Resilience vs. reliability

Reliability is the ability of the system to consistently supply electricity or natural gas regardless of the time of the day. *Resilience* is the ability of the system to adapt to the unexpected changes in conditions and rapidly recover from interruption. Reliability and resilience are intertwined and often conflated. The North American Electric Reliability Corporation defines reliability "as a combination of sufficient resources to meet demand (adequacy) and the ability to withstand disturbances (security)," and resilience as "a more expansive concept than reliability, encompassing consequences to the electricity system and other critical infrastructure from increasingly likely high-impact external events."[31]

Since hydrogen is not available in large quantities naturally, a primary source of energy is needed to produce it on an industrial scale. Common production methods include electrolysis and steam-methane reforming. Steam-methane reforming, the leading technology for producing hydrogen in large quantities, extracts hydrogen from methane. However, this reaction releases carbon dioxide and carbon monoxide into the atmosphere, which are exogenous to the natural carbon cycle.

[31] O'Boyle, M. 2017. "Trending Topics – What "Resilience" Means in A Clean Energy Future." Energy Innovation. Accessed at https://energyinnovation.org/2017/11/30/trending-topics-resilience-means-clean-energy-future/.

In electrolysis, electricity is run through water to separate the hydrogen and oxygen atoms. This method can use wind, solar, geothermal, hydropower, fossil fuels, biomass, nuclear, and many other energy sources. Obtaining hydrogen from this process is being studied as a viable way to produce hydrogen domestically at a low cost, and it is considered clean and renewable if a renewable energy source is used. One drawback of electrolysis is that it is more energy-intensive than natural gas reformation.

Types of Fuel Cells

Fuel cells are mainly classified by the type of the employed electrolyte, which indicates the type of electrochemical reactions that occur inside the cell, the fuel required, the type of catalysts needed, the operating temperature range, and other parameters. Therefore, each fuel cell type has its own applications. Several types of fuel cells are listed as follows. A comparison of different types of fuel cells with their operating temperatures, typical sizes, electrical efficiencies, applications, advantages, and challenges is included in Appendix B.

1. Polymer electrolyte membrane (PEM) fuel cells
2. Alkaline fuel cells
3. Molten carbonate fuel cells
4. Phosphoric acid fuel cells
5. Solid oxide fuel cells

Fuel Cells Applications

There are three main markets for fuel cell technologies: stationary power, transportation power, and portable power.

Stationary power—This includes any application in which the fuel cells are operated at a fixed location for primary power plants (see Box 4), uninterruptable power supply units, or CHP. Molten carbonate, solid oxide, phosphoric acid, and PEM fuel cells are used in these applications.

Transportation power—These applications relate to the automotive industry, including fuel cell electric vehicles such as cars, buses, and trucks, specialty vehicles, forklifts, and auxiliary power units for highway and off-road vehicles. PEM fuel cells are primarily used for these applications.

Portable power—These applications represent fuel cells that are installed in portable devices or meant to not be permanently installed. Such applications are limited to electronics, fuel cell toys, and battery chargers. Because of the limited size of fuel cells, effectiveness of batteries, and low efficiency, these applications share a small portion of the fuel cells market. PEM fuel cells are primarily used for these applications.

Box 4: Example of commercial-scale distributed stationary generation

In 2012, eBay used 6 MW of solid oxide fuel cells for its Quicksilver data center in South Jordan, Utah. The installation included 30 units of 200 kW solid oxide fuel cells using biogas as a fuel. Fuel cells were used as the primary power source and the utility grid as a backup power.

Figure 13: A row of fuel cells outside the eBay data center in South Jordan, Utah. Credit: Bloom Energy.

1.8 Hybrid Systems

In many situations, benefits from sustainable projects can be maximized by combining complementary renewable technologies and providing energy storage capacity. Custom application of integrated hybrid renewable energy systems and energy storage is the next step toward decarbonization by achieving a zero-carbon future.

Hybrid power systems integrate two or more electricity generation mechanisms or use two or more fuels for the same mechanism to overcome the limitations associated with using only one mechanism or one fuel type. Hybrid power systems can be decentralized from electricity grids and can vary in size from powering a single house (few kilowatts) to large island grids (many megawatts). Generally, hybrid systems may involve the following components:

1. AC or DC diesel generators
2. AC or DC distribution system
3. Loads
4. Renewable power sources, such as wind turbines, solar PV systems, biomass, and hydroelectric generators
5. Energy storage
6. Power converters, rotary converters, coupled diesel systems, dump loads, load management, and a control system

Hybrid Energy Systems Drivers

1. Categories of limitation associated with using fuels for electrical generation

Availability—Fuel may not be available for a specific site, may be costly to transport to site, or may require supportive infrastructure.

Economic—Fuel may be too costly to purchase, have high price volatility, high storage costs, high extraction and preparation costs, or high financial risks.

Technical—Fuel may be infeasible to use, have low efficiency, or be technically inappropriate in other ways.

Regulatory mandates—Fuel may have legal requirements or limitations, permitting, inspection requirements, and so on.

Social issues—People might not want a plant to be developed because of various social issues (e.g., emissions and radiation risks).

Environmental impacts—Fuel may cause environmental damage or serious health consequences.

Security risks—Fuel may be hard to secure, protect against damage or theft, or manage supply disruptions.

2. Limitations of using some fuels and resources for electrical generation

Coal requires long periods for permitting, has high infrastructure, maintenance, and regulatory costs, has low efficiencies (35%–40%), requires site storage for fuel supply, has high fuel transportation costs, causes environmental pollution, emits GHGs, has site reclamation costs, has waste heat, has ash disposal and storage, requires high water usage, has financial risk associated with variable fuel costs, and is generally opposed by nearby residents, especially near cities.

Crude oil requires long periods for permitting, has high infrastructure, maintenance, and regulatory costs, has moderate fuel transportation costs, creates environmental pollution, emits GHGs, can cause oil spills and leaks, has low conversion-efficiencies, has high water usage, creates waste heat, has financial risk associated with variable fuel costs, has political complications with foreign fuel dependencies, and is generally opposed by nearby residents.

Natural gas requires pipelines, has high security costs, creates moderate environmental pollution, emits GHGs, creates waste heat, has high water usage, and has financial risk associated with variable fuel costs.

Nuclear fuel requires long periods for permitting, has high construction and security costs, has low efficiencies (33%–34%), has site storage of nuclear wastes, has high water usage, can have costly serious accidents (e.g., Three Mile Island, Chernobyl, Fukushima), and is generally opposed by nearby residents, especially near cities.

Hydropower requires a large scale to achieve high efficiencies, requires large land areas, might require moving people from reservoir-designated areas, and is hydrology-dependent.

Solar thermal and PV have no production at night, have low production in winter, require storage to increase capacities for baseload electricity, and have relatively low efficiencies (19%–23%); and, most modules are not made in the United States.

Wind power requires wind, which is intermittent, and requires storage to increase capacities for baseload electricity.

Geothermal has high costs for resource identification and testing (e.g., drilling for oil), has high initial construction costs (1.5 times that of a coal plant), must be near energy sources that are often not near existing transmission, and has low efficiencies with low-temperature resources.

Hydrogen requires an expensive and energy-intensive extraction process. Causes GHGs emission if it is produced by a fossil fuel.

Biofuel requires reliable feedstocks even if waste materials are being used, and it is technology-specific to feedstocks.

By their very nature, hybrid energy systems are developed to solve stand-alone generation system problems. Addressing such problems may lead to the following:

- **Site-specific solutions:**

  Remote regions, islands, and off-grid locations have been the traditional sites for hybrid power generation. Such sites often located beyond the reach of the conventional power grid and require special shipment of fuel to power generation plants. Thus, they pose a problem that can be solved with hybrid renewable energy systems. Also, the cost of extending the conventional electrical grid to these locations is typically cost-prohibitive if not impossible, which creates another opportunity for hybrid renewable energy systems.

- **Synergistic solutions:**

  Some renewable energy technologies (e.g., wind, solar, run-of-river hydropower) provide only intermittent generation. Lack of consistent and reliable power to meet consumer demand can stress utility companies, which may place limits on how much intermittent power their grid can absorb. This issue can be offset if, prior to feeding power into the utility grid, the renewable energy generation plant can combine complementary technologies to provide more consistent, dispatchable power service.

- **Environmental improvement:**

  Much of the existing, aging fossil fuel–powered generation fleet is still functional. Hybrid renewable energy strategies can be implemented to lessen the environmental impacts of existing conventional generation plants. Among these efforts is the use of renewable energy fuel to assist and augment the generation of power at a fossil fuel power plant.

- **Economic efficacy:**

  Significant cost savings can be realized if generation equipment (turbines and generators) can be shared by complementary technologies to maximize equipment usage. Furthermore, combining generation technologies is economically practical to share the cost of transmission infrastructure development. Savings in generation costs can also be offset when an energy source is used to generate power with multiple technologies where productivity can be maximized.

1.9 Microgrids

A microgrid is mainly a combination of power generation systems and interconnected loads that can be controlled to interact with the grid under defined boundaries. Microgrids have the flexibility to be either connected to or disconnected from the grid (island mode). They are also known as modern, small-scale forms of the centralized electricity system. Considering microgrids helps in achieving reliability and diversification energy sources and reducing costs and carbon emissions.

Why You Would Need a Microgrid

Microgrids are needed when there is no nearby electricity grid, and in this case, a generator is used. However, if the generator went down, an alternative source of generation or storage would be needed. If a nearby electricity supplied grid is available, then you may want to look into diversified fuel sources, which are secure, dependable, resilient, and more environmentally friendly forms of electricity generation.

There are many drivers for microgrids, which can be summarized in three main categories—primary, utility, and emerging drivers—as described in Figure 14.

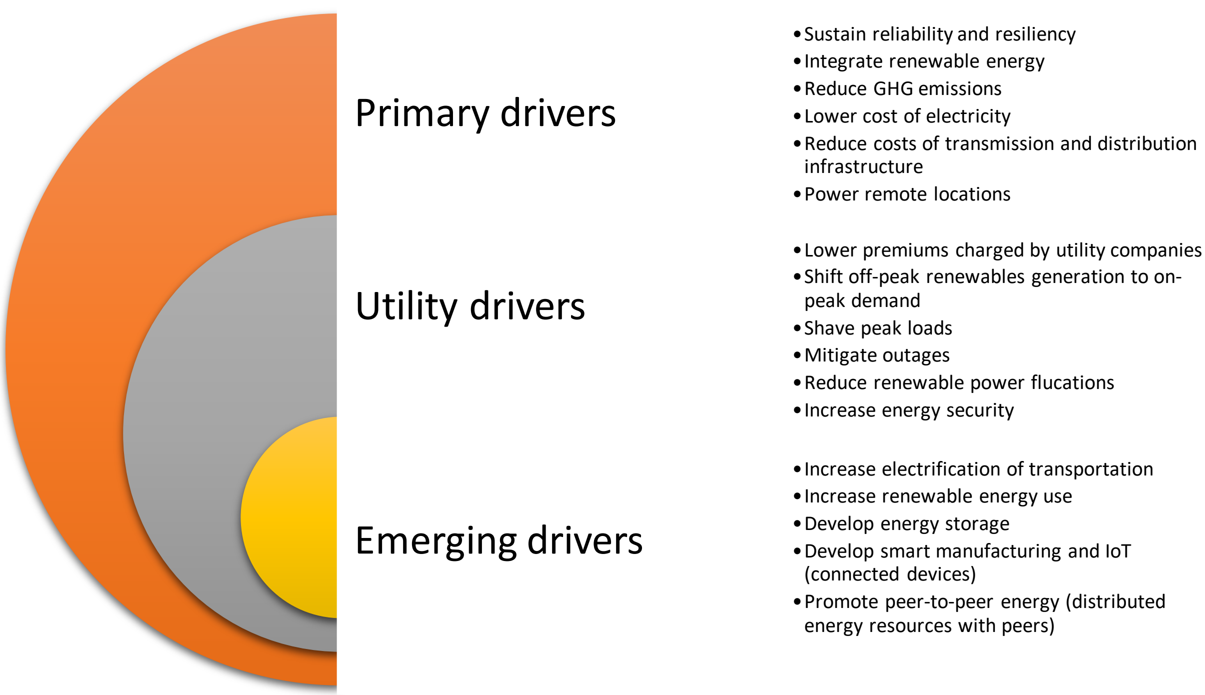


Figure 14: Main drivers for microgrids.

How Microgrids Work

Microgrids are connected to the main electricity grid via the point of common coupling to help maintain the same level of voltage as the main grid. However, if there is a problem on the grid or the grid needs to be repaired, then microgrids can operate solely without being connected to the grid; otherwise, if a microgrid is not available, then everyone on the grid will be affected by the power failure or the time needed for maintenance. Generally, microgrids operate in a grid-connected mode, but they can also operate in a grid-disconnected mode by depending on local energy generation systems in times of emergency such as natural disasters or power outages.

Basic components of microgrids

The basic components of a microgrid are shown in Figure 15 and listed as follows:

- Power generation system (PV units, wind turbines, and gas turbines)
- Energy management system
- Energy storage units
- Electrical energy consuming devices (electric vehicles and loads)
- Hardware for device connections to allow energy and information (data) flows
- Utility connection (point of common coupling)

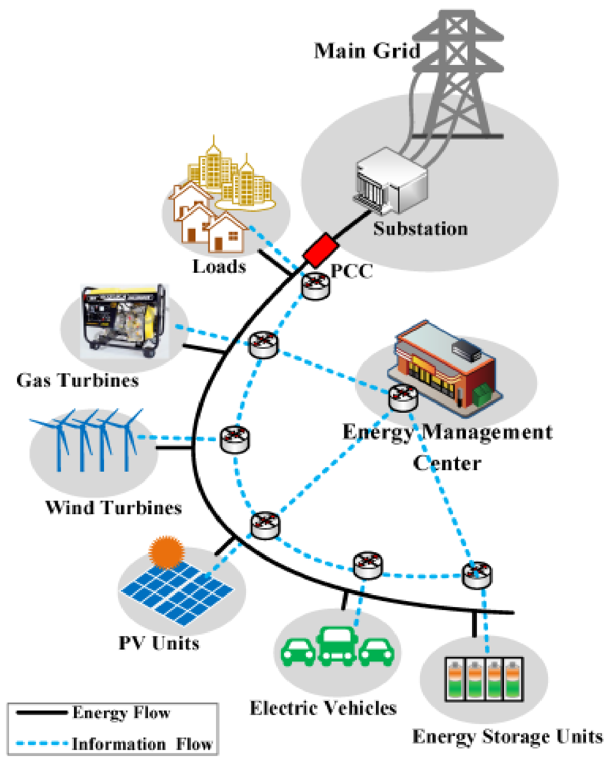
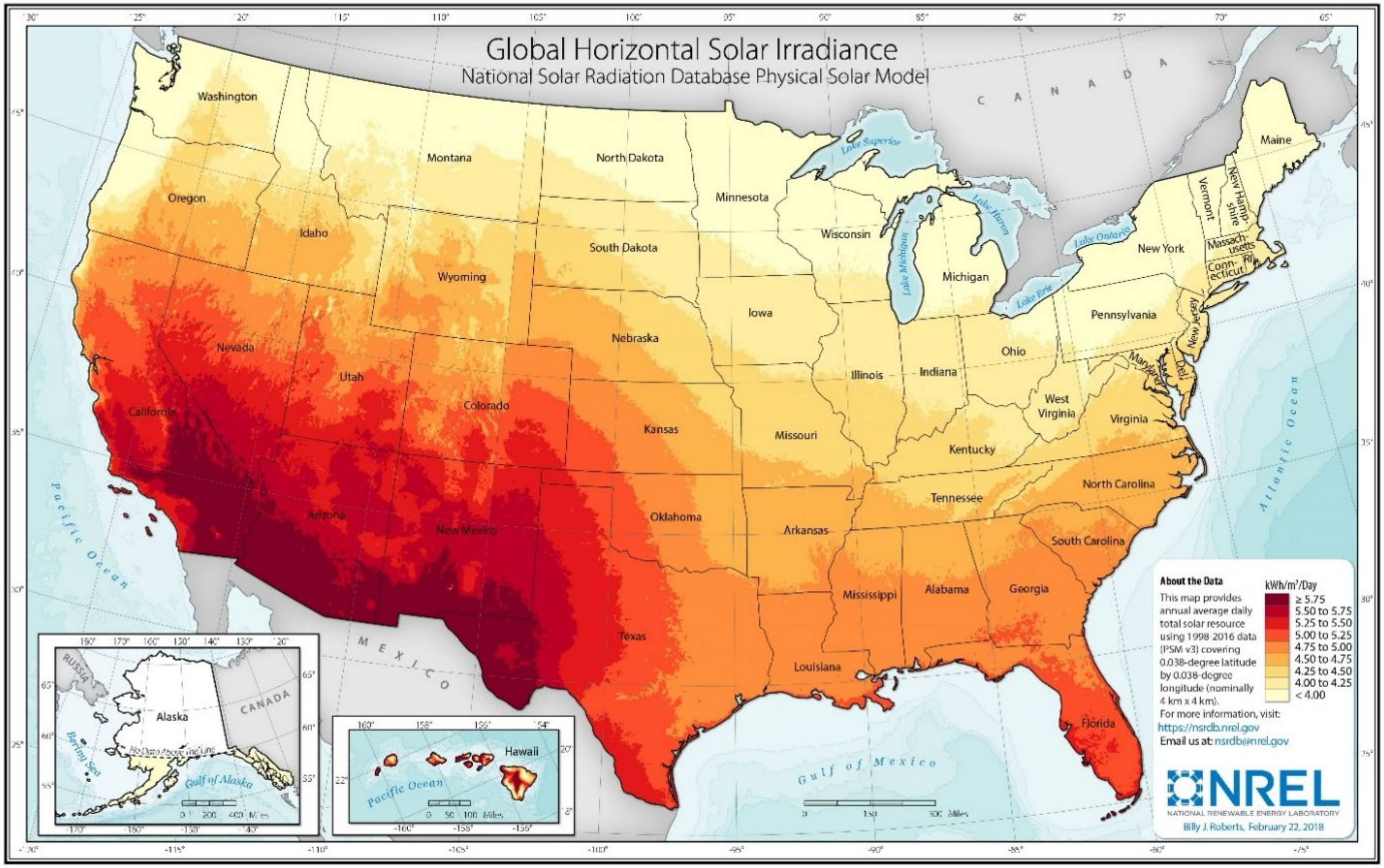


Figure 15: Basic components of a microgrid. PCC: point of common coupling.[32]

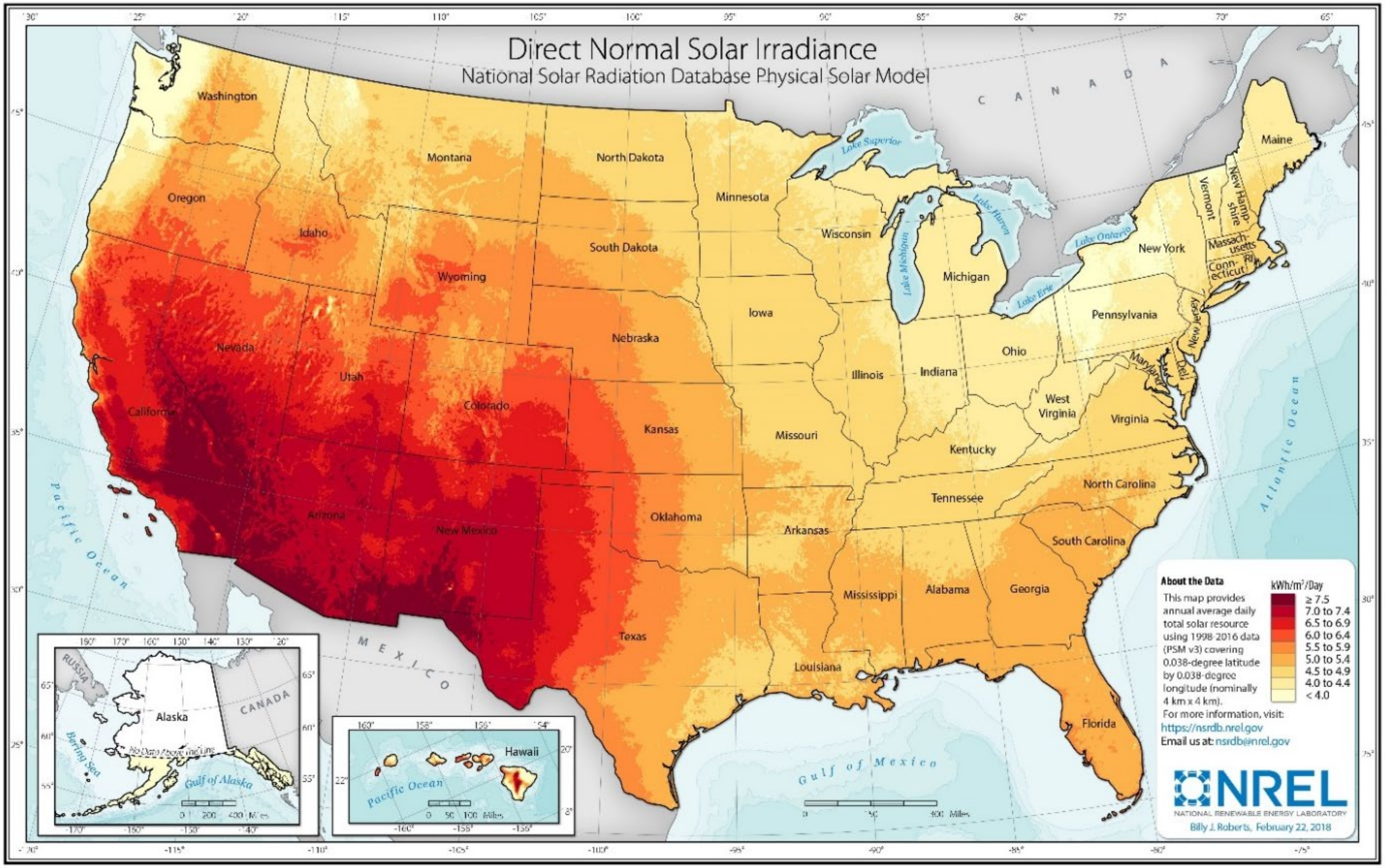
[32] Huang, C., D. Yue, S. Deng, and J. Xie. 2017. "Optimal Scheduling of Microgrid with Multiple Distributed Resources Using Interval Optimization." *Energies* 10: 339.

APPENDICES

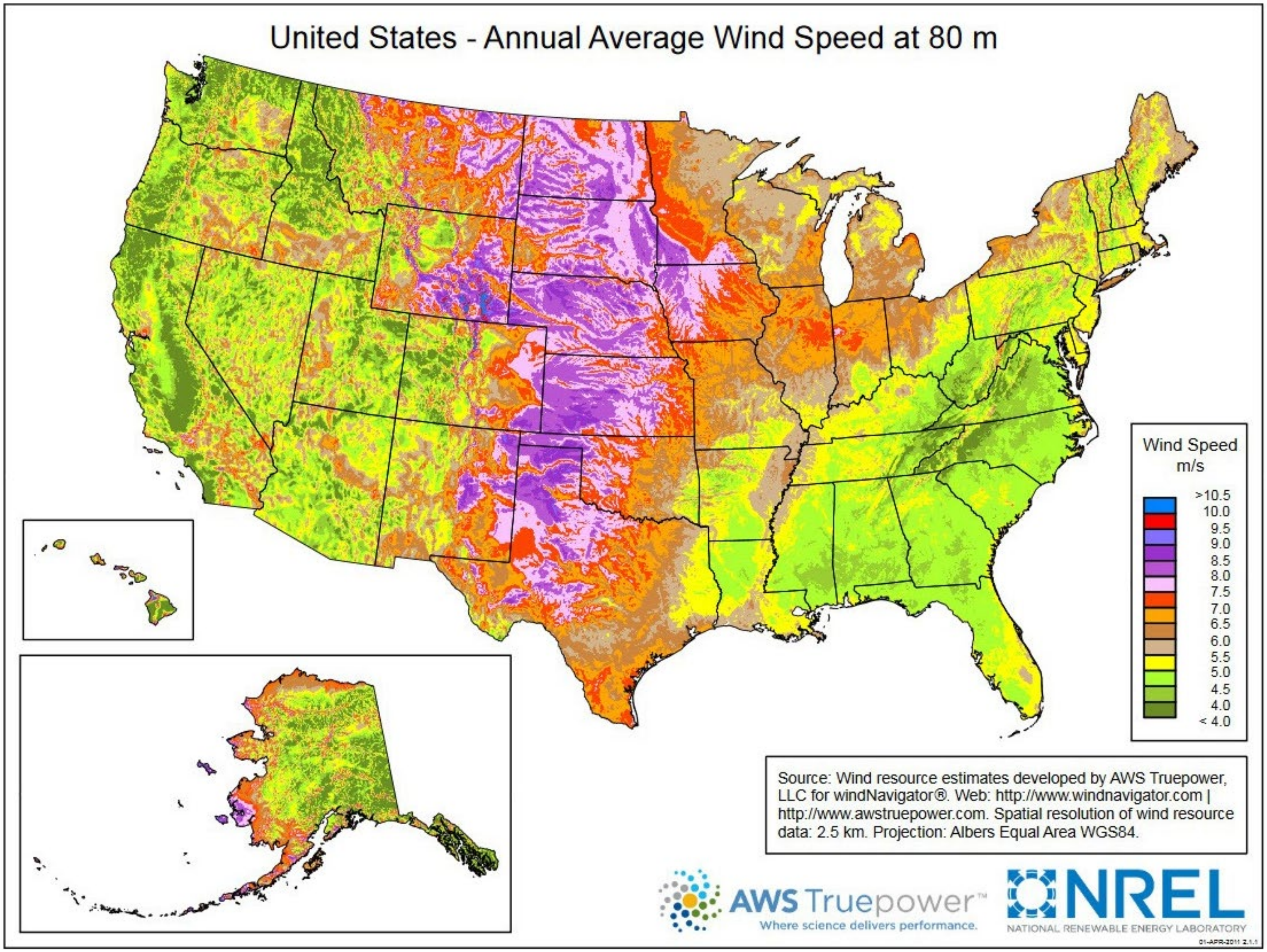
Appendix A: Maps of renewable energy resources (solar, wind, and hydropower) in the United States



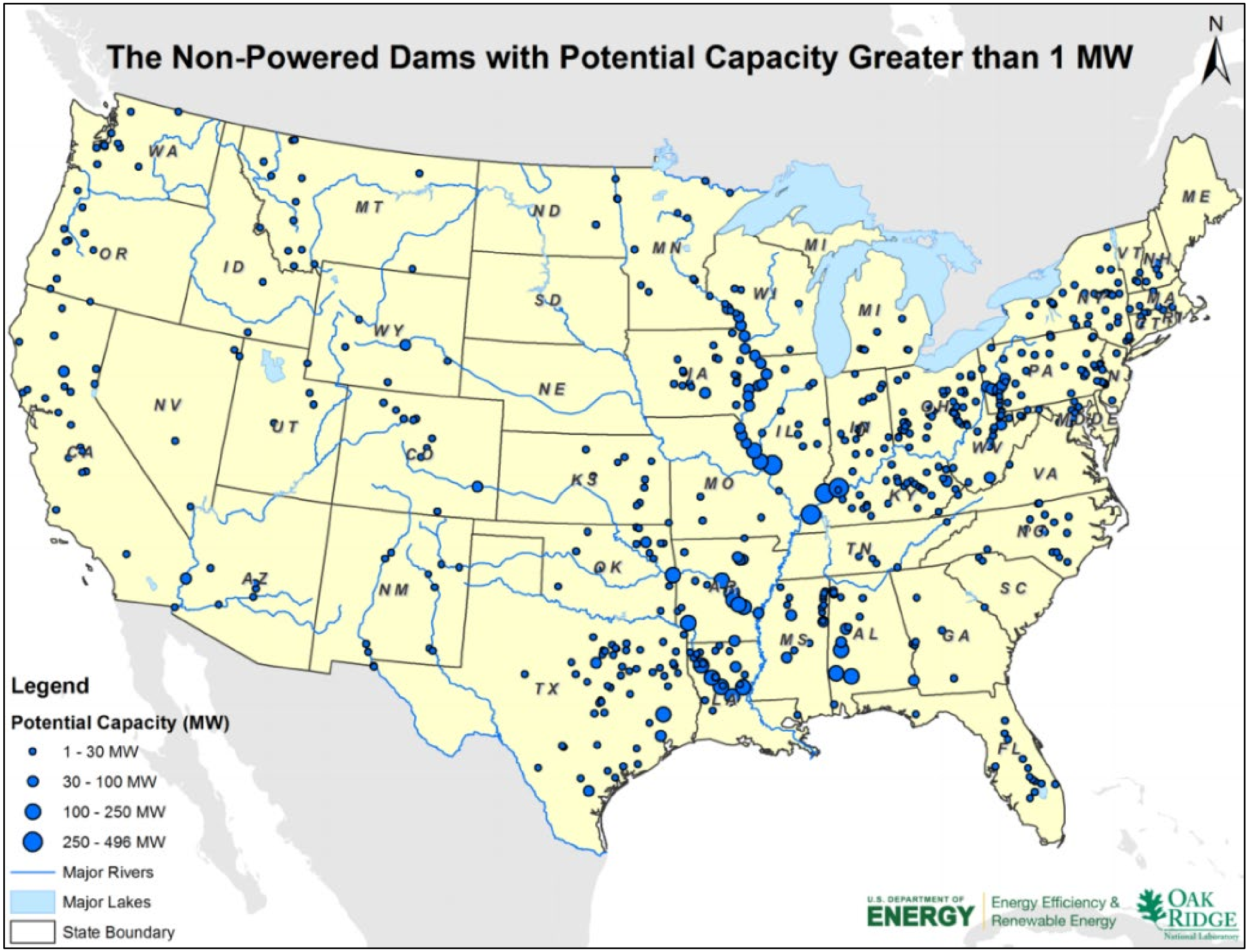
Appendix A-1: U.S. annual solar GHI.



Appendix A-2: U.S. annual solar DNI.



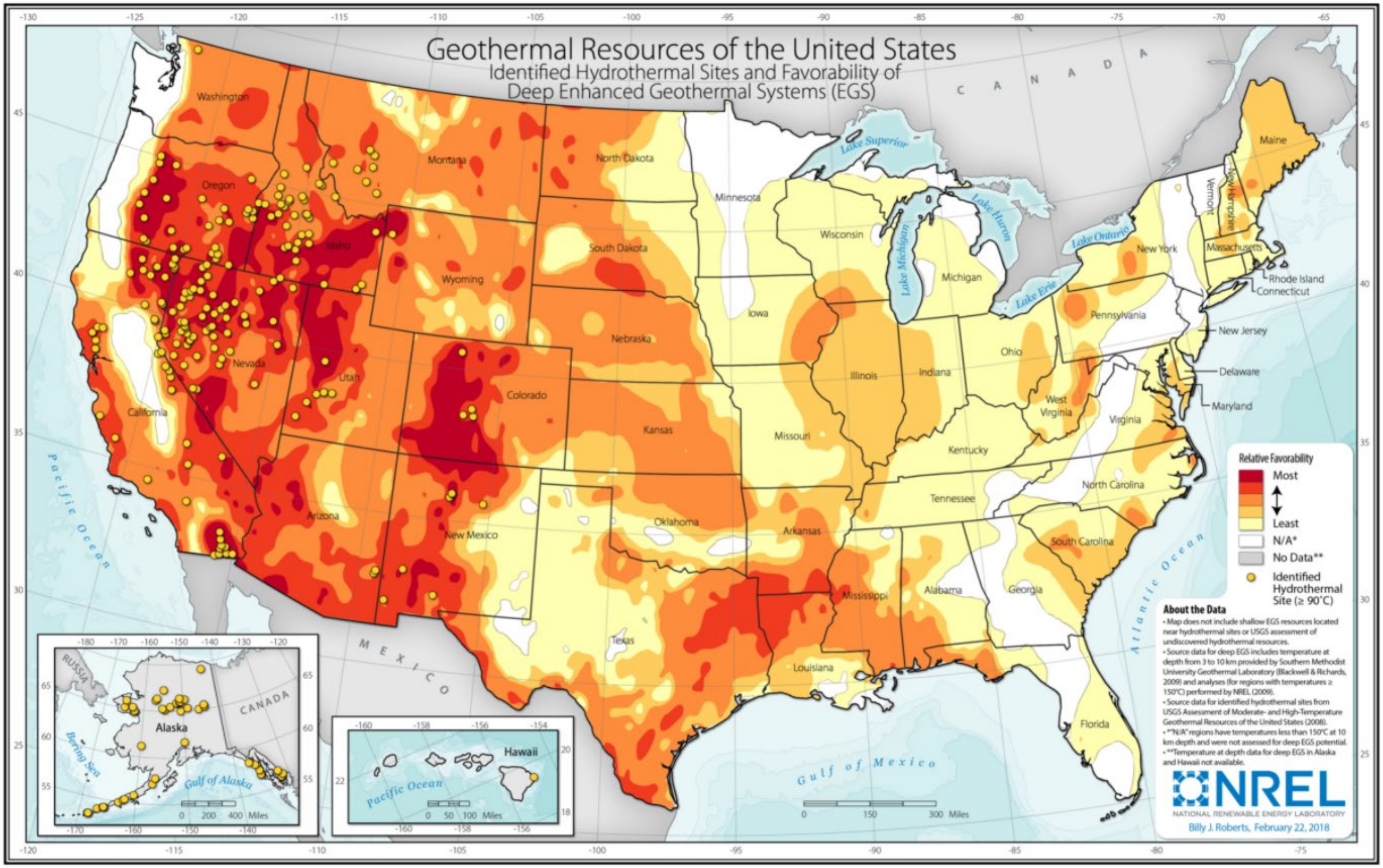
Appendix A-3: U.S. annual average wind speed at 80 m hub height.



Appendix A-4: Non-powered dams with potential capacity greater than 1 MW.

Appendix A-5: The 2020 national hydropower map. Credit: HydroSource, Oak Ridge National Laboratory.[33]

[33] Samu, N. M., D. Singh, M. Johnson, S.-C. Kao, S. Gangrade, S. Curd, and B. T. Smith. 2020. *The 2020 National Hydropower Map*. HydroSource. Oak Ridge National Laboratory, Oak Ridge, Tennessee.



Appendix A-6: Geothermal resources of the United States.

Appendix B: Comparison of Fuel Cell Technologies

Credit: U.S. DOE Fuel Cell Technologies Office[34]

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluorosulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2;[i] 40% reformed fuel[ii]	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%[iii]	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40%[iv]	• Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50%[v]	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%[vi]	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

i NREL Composite Data Product 8, "Fuel Cell System Efficiency," http://www.nrel.gov/hydrogen/docs/cdp/cdp_8.jpg
ii Panasonic Headquarters News Release, "Launch of New 'Ene-Farm' Home Fuel Cell Product More Affordable and Easier to Install," http://panasonic.co.jp/corp/news/official.data/data.dir/2013/01/en130117-5/en130117-5.html
iii G. Mulder et al., "Market-ready stationary 6 kW generator with alkaline fuel cells," ECS Transactions 12 (2008) 743-758
iv Doosan PureCell Model 400 Datasheet, http://www.doosanfuelcell.com/attach_files/link/PureCell%20Model%20400%20Datasheet.pdf
v FuelCell Energy DFC300 Product Specifications, http://www.fuelcellenergy.com/assets/DFC300-product-specifications1.pdf
vi Ceramic Fuel Cells Gennex Product Specifications, http://www.bloomenergy.com/fuel-cell/es5-data-sheet/

For More Information

More information on the Fuel Cell Technologies Office is available at http://www.hydrogenandfuelcells.energy.gov.

[34] U.S. DOE Fuel Cell Technologies Office, Comparison of Fuel Cell Technologies. https://www.energy.gov/sites/prod/files/2016/06/f32/fcto_fuel_cells_comparison_chart_apr2016.pdf

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