NCF-Envirothon 2024 New York

Current Issue Part A Study Resources

Key Topic #2: Renewable Energy and Infrastructure

7. Describe the criteria for an energy source to be renewable, and identify examples.
8. Explain how Solar, Wind, and Hydroelectric systems generate electricity, and identify the technological advancements that have made this possible.
9. Identify the environmental, social, and economic advantages and disadvantages of Solar, Wind, and Hydroelectric power, and evaluate their suitability for meeting the world's energy needs in the future. *(See also Key Topic #3)*
10. Explain the setup and design of renewable energy infrastructure and distribution systems.
11. Describe how renewable energy can contribute to energy security.

Study Resources

Resource Title	Source	Located on
Renewable Energy	*Jennifer Morris – MIT Climate Portal – February 2, 2023*	Pages 55 -56
Solar at a Glance	*National Energy Education Development, 2023*	Page 57
Wind at a Glance	*National Energy Education Development, 2023*	Page 58
Hydropower at a Glance	*National Energy Education Development, 2023*	Page 59
Geothermal at a Glance	*National Energy Education Development, 2023*	Page 60
Biomass at a Glance	*National Energy Education Development, 2023*	Page 61
Biofuel	*Kristala Jones Prather – MIT Climate, 2020*	Pages 62 - 63
Facts About Solar Energy: Solar Electricity	*Wisconsin Center for Environmental Education, 2020*	Pages 64 - 68
The Dark Side of Solar Power	*Atalay Atasu, Serasu Duran, and Luk N. Van Wassenhove – Harvard Business Review, 2021*	Pages 69 -73
Advantages and Challenges of Wind Energy	*Wind Energy Technologies Office, 2023*	Pages 74 - 75

Study Resources begin on the next page! ➡

Renewable Energy

By Jennifer Morris – MIT Climate Portal – February 2, 2023

Renewable energy is energy from sources we cannot run out of. Some types of renewable energy, like wind and solar power, come from sources that are not depleted when used. Others, like biomass, come from sources that can be replenished. Common types of renewable energy are wind, solar, hydropower, biomass and geothermal. Renewable energy has two advantages over the fossil fuels that provide most of our energy today. First, there is a limited amount of fossil fuel resources (like coal, oil and natural gas) in the world, and if we use them all we cannot get any more in our lifetimes. Second, renewable energy produces far less carbon dioxide (CO2) and other harmful greenhouse gases and pollutants. Most types of renewable energy produce no CO2 at all once they are running. For this reason, renewable energy is widely viewed as playing a central role in climate change mitigation and a clean energy transition.

Renewable vs. carbon-free

Most kinds of renewable energy are also "carbon-free": they do not emit CO2 or other greenhouse gases into the atmosphere. Because of this, and because renewables like wind and solar power are so popular in climate activism, the terms "renewable energy" and "carbon-free energy" are sometimes confused. But not all renewable energy is carbon-free, and not all carbon-free energy is renewable.

Biofuels and bioenergy are renewable: we can regrow plants that we burn for fuel. But they are not necessarily carbon-free. Growing plants absorbs CO2; burning plants releases CO2. The total impact on CO2 in the atmosphere depends on how sustainably the bioenergy is produced.

Nuclear energy is carbon-free: a nuclear power plant does not emit any CO2, or any other greenhouse gases. But it is not renewable. Nuclear reactors use uranium, and if we run out of uranium, we can never get it back.

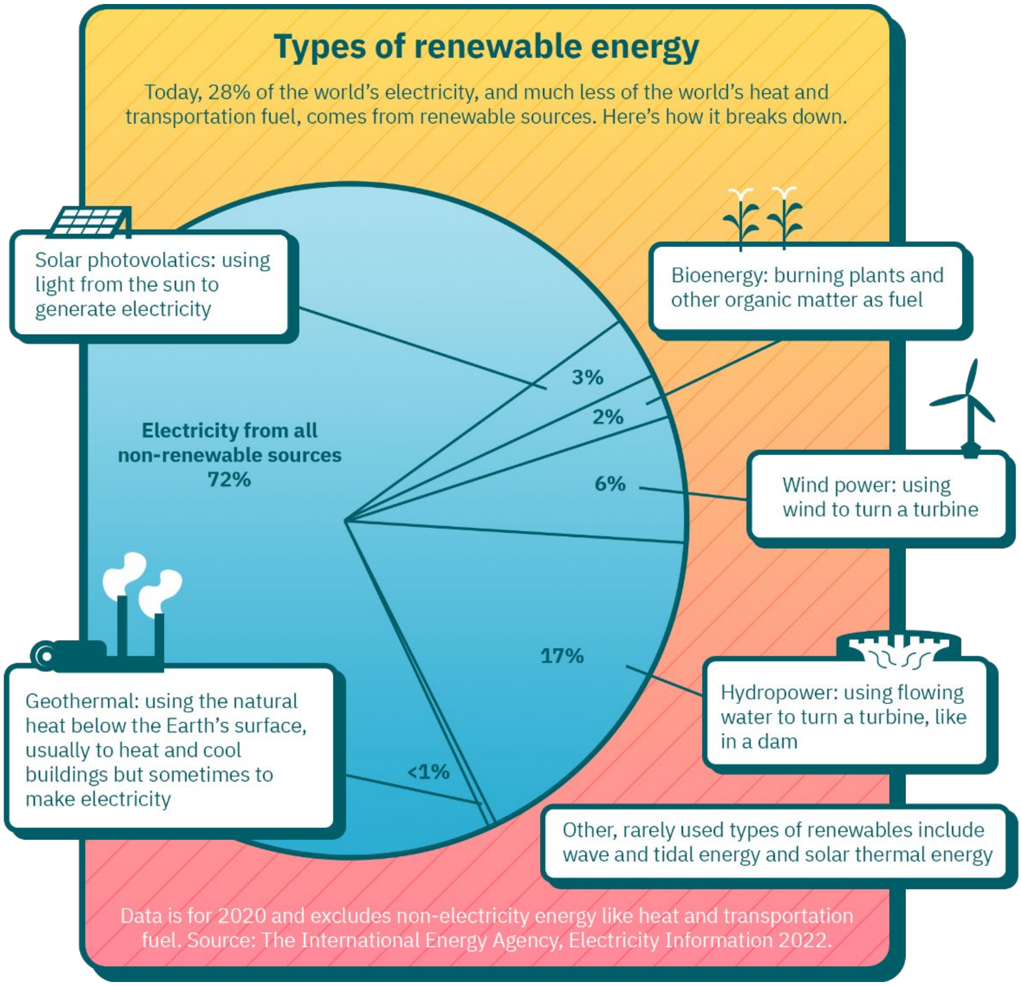
Transforming the Electric Grid

Some types of renewable energy can provide fuel for transportation (e.g. biofuels) or heating and cooling for buildings (e.g. geothermal). However, most renewable energy is used to make electricity. In 2020, renewable energy sources made up over 28% of the world's electricity, and that number is rising every year.1 Around 60% of renewable electricity worldwide comes from hydropower, which has been widely used since the invention of the electric grid, but today wind and solar power are growing fastest.

Renewable energy presents great challenges and opportunities for electricity generation. Some renewable energy sources, such as wind and solar, are "variable," meaning the amount of electricity they make changes depending on the amount of wind or sunlight available. This can cause problems for system operators, particularly when there is a mismatch between the amount of electricity demanded and the amount of wind or sun available. Another challenge is that the best places to generate renewable energy are often far away from the areas that use that electricity. For these reasons, adding much more renewable energy to our electric grid will require other changes, including more energy storage, backup generation, strategies to match electricity use with times of high power generation, and infrastructure for long-distance power transmission.

A Growing Source of Energy

Renewable energy also needs to compete with well-established and cheap fossil fuels. Renewable energy has grown quickly over the last decade, driven by policy support (tax incentives, R&D funding and mandates requiring the use of renewables) and falling costs (especially in solar photovoltaics and wind turbines). Globally, wind and solar electricity grew from just 32 terawatt-hours in 2000 to over 2,400 terawatt-hours in 2020: more than enough to power the entire country of India.1 Nonetheless, together they still only provide 9% of electricity worldwide.1 As societies work to lower their greenhouse gas emissions, renewable energy is expected to play a large role, especially if we switch more heating and transportation to run on electric power and solve the problem of affordable, large-scale energy storage. How much of our energy we ultimately get from renewables will also depend on their ability to compete with other low-carbon technologies, such as nuclear, carbon capture and storage and hydrogen.



Types of renewable energy

Today, 28% of the world's electricity, and much less of the world's heat and transportation fuel, comes from renewable sources. Here's how it breaks down.

Solar photovolatics: using light from the sun to generate electricity

Bioenergy: burning plants and other organic matter as fuel

Wind power: using wind to turn a turbine

Hydropower: using flowing water to turn a turbine, like in a dam

Geothermal: using the natural heat below the Earth's surface, usually to heat and cool buildings but sometimes to make electricity

Other, rarely used types of renewables include wave and tidal energy and solar thermal energy

Data is for 2020 and excludes non-electricity energy like heat and transportation fuel. Source: The International Energy Agency, Electricity Information 2022.

SOLAR AT A GLANCE

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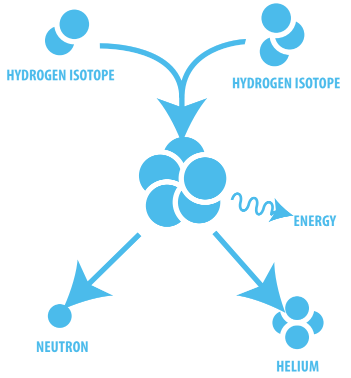
www.need.org

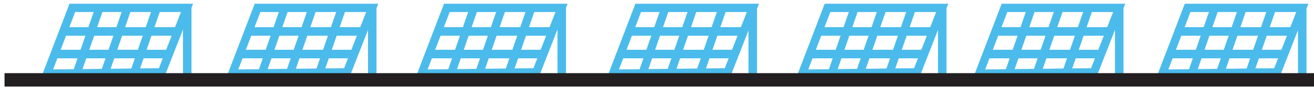
WHAT IS SOLAR?

Solar energy is radiant energy that is produced by the sun. Every day the sun radiates, or sends out, an enormous amount of energy. The sun radiates more energy in one second than people have used since the beginning of time!

NUCLEAR FUSION

The process of fusion most commonly involves hydrogen isotopes combining to form a helium atom with a transformation of matter. This matter is emitted as radiant energy.





PHOTOVOLTAIC CELLS

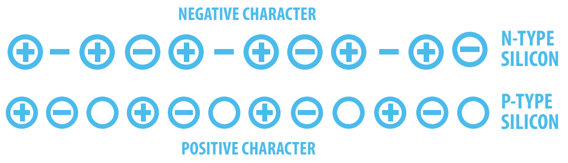
Photovoltaic comes from the words photo meaning “light” and volt, a measurement of electricity. Sometimes photovoltaic cells are called PV cells orsolar cells for short. These are the four steps that show how a PV cell is made and how it produces electricty.

⊕ PROTON – FREE ELECTRON ⊖ TIGHTLY-HELD ELECTRON ○ A LOCATION THAT CAN ACCEPT AN ELECTRON

1

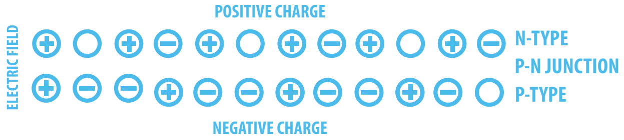
A slab (or wafer) of pure silicon is used to make a PV cell. The top of the slab is very thinly diffused with an “n” dopant such as phosphorous. On the base of the slab a small amount of a “p” dopant, typically boron, is diffused. The boron side of the slab is 1,000 times thicker than the phosphorous side.

The phosphorous has one more electron in its outer shell than silicon, and the boron has one less. These dopants help create the electric field that motivates the energetic electrons out of the cell created when light strikes the PV cell. The phosphorous gives the wafer of silicon an excess of free electrons; it has a negative character. This is called then-type silicon (n = negative). The n-type silicon is not charged—it has an equal number of protons and electrons—but some of the electrons are not held tightly to the atoms. They are free to move to different locations within the layer. The boron gives the base of the silicon a positive character, because it has a tendency to attract electrons. The base of the silicon is called p-type silicon (p = positive). The p-type silicon has an equal number of protons and electrons; it has a positive character but not a positive charge.



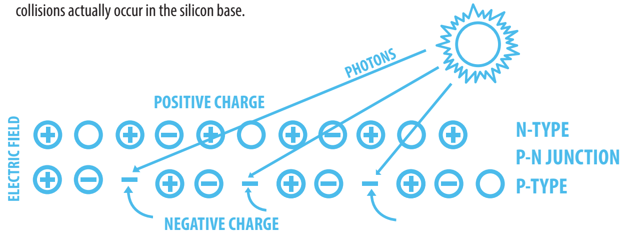
2

Where the n-type silicon and p-type silicon meet, free electrons from the n-layer flow into the p-layer for a split second, then form a barrier to prevent more electrons from moving between the two sides. This point of contact and barrier is called the p-n junction. When both sides of the silicon slab are doped, there is a negative charge in the p-type section of the junction and a positive charge in the n-type section of the junction due to movement of the electrons and “holes” at the junction of the two types of materials. This imbalance in electrical charge at the p-n junction produces an electric field between the p-type and n-type silicon



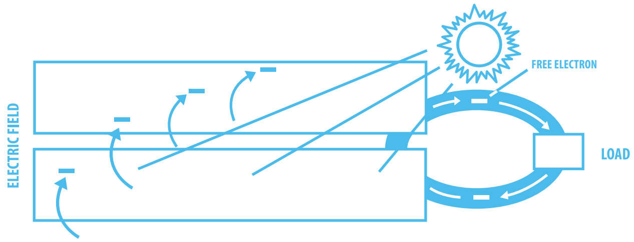
3

If the PV cell is placed in the sun, photons of light strike the electrons in the p-n junction and energize them, knocking them free of their atoms. These electrons are attracted to the positive charge in the n-type silicon and repelled by the negative charge in the p-type silicon. Most photon-electron collisions actually occur in the silicon base.



4

A conducting wire connects the p-type silicon to an electrical load, such as a light or battery, and then back to the n-type silicon, forming a complete circuit. As the free electrons are pushed into the n-type silicon they repel each other because they are of like charge. The wire provides a path for the electrons to move away from each other. This flow of electrons is an electric current that travels through the circuit from the n-type to the p-type silicon. In addition to the semi-conducting materials, solar cells consist of a top metallic grid or other electrical contact to collect electrons from the semi-conductor and transfer them to the external load, and a back contact layer to complete the electrical circuit



TOP SOLAR STATES

CALIFORNIA

TEXAS

NORTH CAROLINA

ARIZONA

FLORIDA

Data: Energy Information Administration

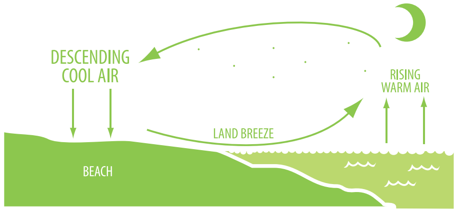
WIND AT A GLANCE

NEED
National Energy
Education Development

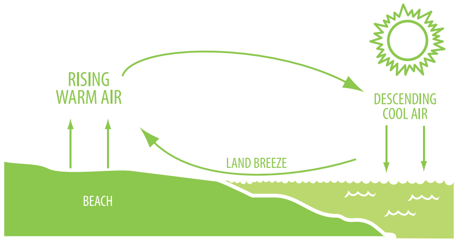
WHAT IS WIND?

Wind is simply air in motion. It is produced by the uneven heating of the Earth's surface by energy from the sun. Since the Earth's surface is made of very different types of land and water, it absorbs the sun's radiant energy at different rates. Much of this energy is converted into heat as it is absorbed by land areas, bodies of water, and the air overthese formations.

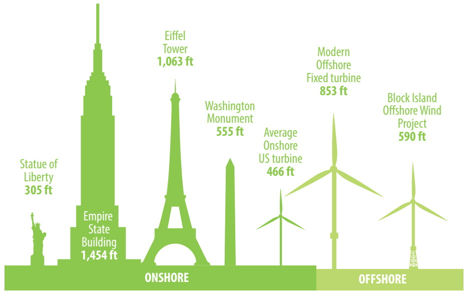
LAND BREEZE



SEA BREEZE



TURBINE SIZE



WIND TURBINES

Wind is harnessed and converted into electricty using wind turbines. They convert the wind's kinetic energy into motion energy that generates electricty. The following steps illustrate how.

1 The moving air spins the turbine blades.

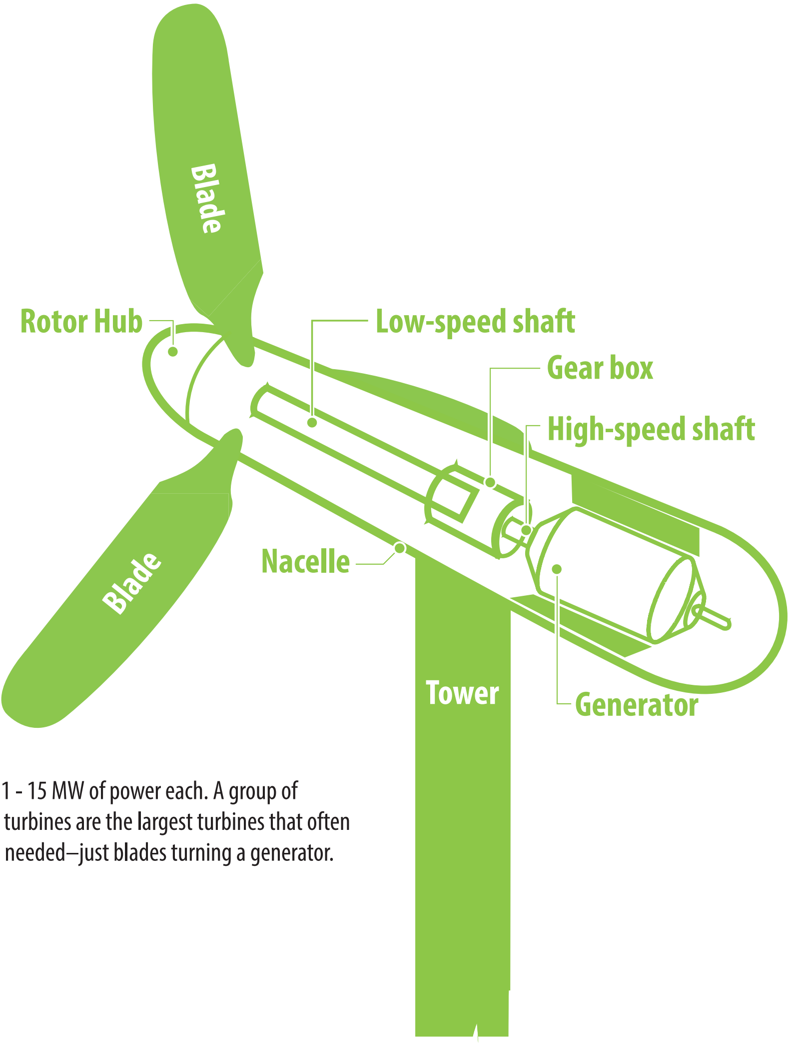
2 The blades are connected to a low-speed shaft. When the blades spin, the shaft turns.

3 The low-speed shaft is connected to a gear box. Inside, a large slow-moving gear turns a small gear quickly.

4 The small gear turns another shaft at high speed.

5 The high-speed shaft is connected to a generator. As the shaft turns the generator, it produces electricity.

6 The electric current is sent through cables down the turbine tower to a transformer that changes the voltage of the current before it is sent out on transmission lines



Large turbines can generate anywhere from 1 - 15 MW of power each. A group of turbines is called a wind farm. Offshore wind turbines are the largest turbines that often use a direct drive design where no gearbox is needed—just blades turning a generator.

TOP WIND STATES

Data: Energy Information Administration

HYDROPOWER AT A GLANCE

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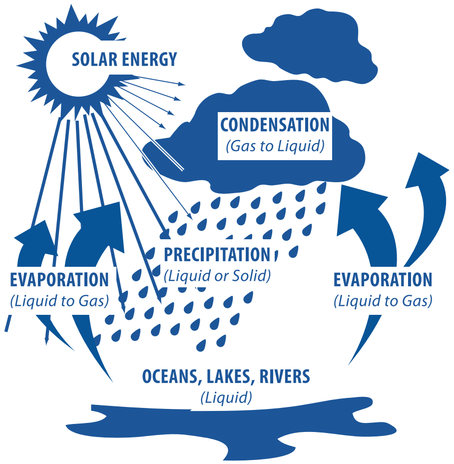
WHAT IS HYDROPOWER?

Hydropower (from the Greek word hydor, meaning water) is energy that comes from the force of moving water. The fall and movement of water is part of a continuous natural cycle called the water cycle. Energy from the sun evaporates water in the Earth's oceans and rivers and draws it upward as water vapor. When the water vapor reaches the cooler air in the atmosphere, it condenses and forms clouds. The moisture eventually falls to the Earth as rain or snow, replenishing the water in the oceans and rivers. Gravity drives the moving water, transporting it from high ground to low ground. The force of moving water can be extremely powerful.

THE WATER CYCLE



HYDROKINETICS

In the U.S., most hydropower is generated using conventional designs. Hydropower has the potential for growth by using hydrokinetic technologies: energy from moving waves, tides, and currents.

HYDROPOWER PLANT

A conventional hydropower plant is a system with three parts: a power plant where the electricity is produced; a dam that can be opened or closed to control water flow; and a reservoir (artificial lake) where water can be stored.

HEAD AND FLOW

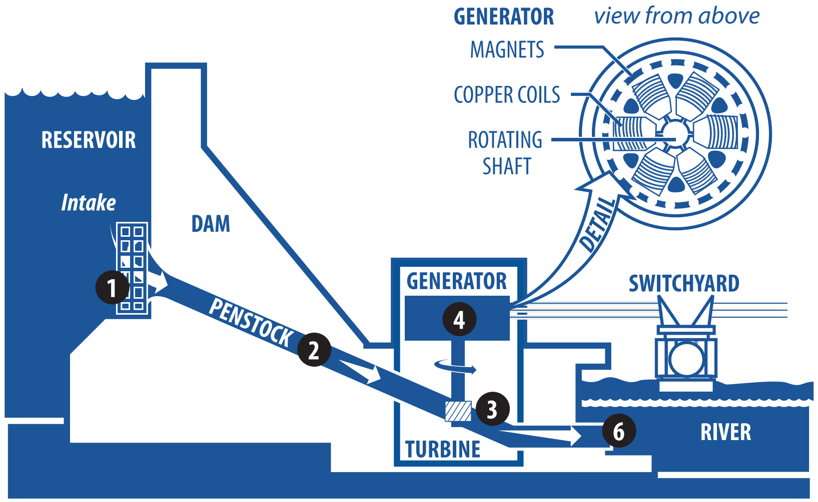
The amount of electricity that can be generated at a hydro plant is determined by two factors: head and flow. Head is how far the water drops. It is the distance from the highest level of the dammed water to the point where it goes through the power-producing turbine. Flow is how much water moves through the system—the more water that moves through a system, the higher the flow. Generally, a high-head plant needs less water flow than a low-head plant to produce the same amount of electricity. If a river has high flow rates, a reservoir may not be needed.

STORING ENERGY

One of the biggest advantages of a hydropower plant is its ability to store energy. The water in a reservoir is, after all, stored energy. Water can be stored in a reservoir and released when needed for electricity production. During the day when people use more electricity, water can flow through a plant to generate electricity. Then, during the night when people use less electricity, water can be held back in the reservoir. Storage also makes it possible to save water from winter rains for generating power during the summer, or to save water from wet years for generating electricity during dry years.

PUMPED STORAGE SYSTEMS

Some hydropower plants use pumped storage systems. A pumped storage system operates much like a public fountain does; the same water is used again and again. At a pumped storage hydropower plant, flowing water is used to make electricity and then stored in a lower pool. Depending on how much electricity is needed, the water may be pumped back to an upper pool. Pumping water to the upper pool requires electricity so hydro plants usually use pumped storage systems only when there is peak demand for electricity



1. Water in a reservoir behind a hydropower dam flows through an intake screen, which filters out large debris, but allows fish to pass through.
2. The water travels through a large pipe, called a penstock.
3. The force of the water spins a turbine at a low speed, allowing fish to pass through unharmed.
4. Inside the generator, the shaft spins coils of copper wire inside a ring of magnets. This creates an electric field, producing electricity.
5. Electricity is sent to a switchyard, where a transformer increases the voltage, allowing it to travel through the electric grid.
6. Water flows out of the penstock into the downstream river.

TOP HYDRO STATES

Data: Energy Information Administration

GEOTHERMAL AT A GLANCE

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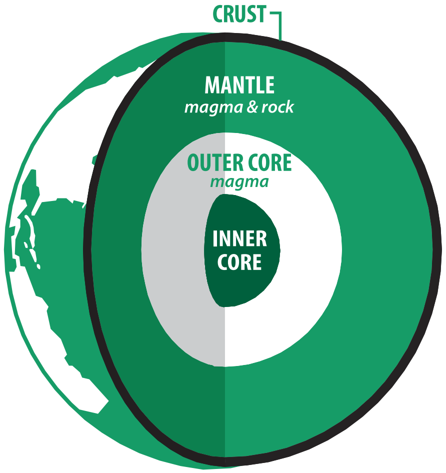
WHAT IS GEOTHERMAL?

Geothermal energy comes from the heat within the Earth. The word geothermal comes from the Greek words geo, meaning earth, and therme, meaning heat. People around the world use geothermal energy to produce electricity, to heat homes and buildings, and to provide hot water for a variety of uses.

THE EARTH'S INTERIOR

The Earth's core lies almost 4,000 miles beneath the Earth's surface. The double-layered core is made up of very hot molten iron surrounding a solid iron center. Estimates of the temperature of the core range from 5,000 to 11,000 degrees Fahrenheit. Surrounding the Earth's core is the mantle, thought to be partly rock and partly magma. The mantle is about 1,800 miles thick. The outermost layer of the Earth, the insulating crust, is not one continuous sheet of rock, like the shell of an egg, but is broken into pieces called plates. These slabs of continents and ocean floor drift apart and push against each other at the rate of about two centimeters per year in a process called plate tectonics. This process can cause the crust to become faulted (cracked), fractured, or thinned, allowing plumes of magma to rise up into the crust.



USES OF GEOTHERMAL

Today, we drill wells into geothermal reservoirs deep underground and use the steam and heat to drive turbines in electric power plants. The hot water is also used directly to heat buildings, to increase the growth rate of fish in hatcheries and crops in greenhouses, to pasteurize milk, to dry foods products and lumber, and for mineral baths.

When geothermal reservoirs are located near the surface, we can reach them by drilling wells. Exploratory wells are drilled to search for reservoirs. Once a reservoir has been found, production wells are drilled. Hot water and steam—at temperatures of 250°F to 700°F—are brought to the surface and used to generate electricity at power plants near the production wells. **THERE ARE SEVERAL DIFFERENT TYPES OF GEOTHERMAL POWER PLANTS:**

FLASH STEAM PLANTS

Most geothermal power plants are flash steam plants. Hot water from production wells flashes (explosively boils) into steam when it is released from the underground pressure of the reservoir. The force of the steam is used to spin the turbine generator. To conserve water and maintain the pressure in the reservoir, the steam is condensed into water and injected back into the reservoir to be reheated

DRY STEAM PLANTS

A few geothermal reservoirs produce mostly steam and very little water. In dry steam plants, the steam from the reservoir shoots directly through a rock-catcher into the turbine generator. The rock-catcher protects the turbine from small rocks that may be carried along with the steam from the reservoir.

BINARY CYCLE POWER PLANTS

Binary cycle power plants transfer the thermal energy from geothermal hot water to other liquids to produce electricity. The geothermal water is passed through a heat exchanger in a closed pipe system, and then reinjected into the reservoir. The heat exchanger transfers the heat to a working fluid—usually isobutane or isopentane—which boils at a lower temperature than water. The vapor from the working fluid is used to turn the turbines. Binary systems can, therefore, generate electricity from reservoirs with lower temperatures. Since the system is closed, there is little heat loss and almost no water loss, and virtually no emissions.

HYBRID POWER PLANTS

In some power plants, flash and binary systems are combined to make use of both the steam and the hot water.

USES OF GEOTHERMAL ENERGY

HEATING

The most widespread use of geothermal resources—after bathing—is to heat buildings. In the Paris basin in France, geothermal was used to heat homes 600 years ago. More than 150,000 homes in France use geothermal heat today.

INDUSTRY

The heat from geothermal water is used worldwide for dying cloth, drying fruits and vegetables, washing wool, manufacturing paper, pasteurizing milk, and drying timber products. It is also used to help extract gold and silver from ore. In Klamath Falls, OR, hot water is piped under sidewalks and bridges to keep them from freezing in winter.

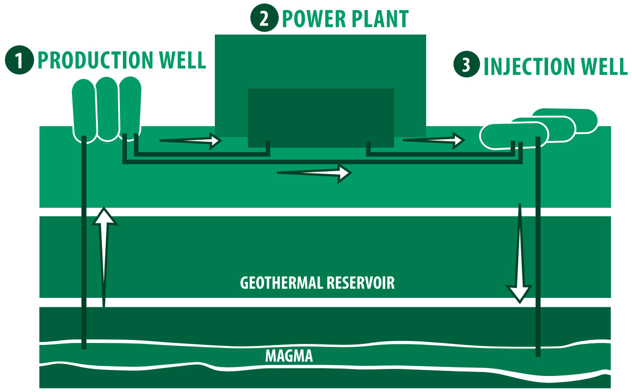
HOT SPRING BATHING AND SPAS

For centuries, people have used hot springs for cooking and bathing. The early Romans used geothermal water to treat eye and skin diseases and, at Pompeii, to heat buildings. Medieval wars were even fought over lands for their hot springs.

AGRICULTURE AND AQUACULTURE

Water from geothermal reservoirs is used in many places to warm greenhouses that grow flowers, vegetables, and other crops. Natural warm water can also speed the growth of fish, shellfish, reptiles, and amphibians.

GEOTHERMAL POWER PLANT



1. **Production Well:** Geothermal fluids, such as hot water and steam, are brought to the surface and piped into the power plant.
2. **Power Plant:** Inside the power plant, the geothermal fluid turns the turbine blades, which spins a shaft, which spins magnets inside a large coil of wire to generate electricity.
3. **Injection Well:** Used geothermal fluids are returned to the reservoir.

BIOMASS AT A GLANCE

NEED
National Energy
Education Development

WHAT IS BIOMASS?

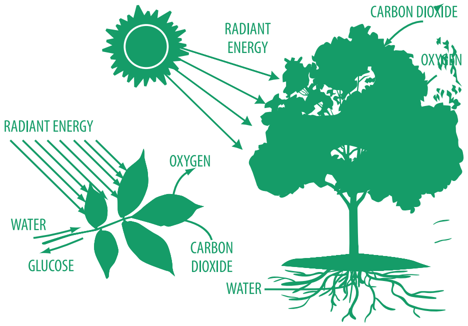
Biomass is any organic matter—wood, crops, seaweed, animal wastes—that can be used as an energy source. Biomass is probably our oldest source of energy after the sun. For thousands of years, people have burned wood to heat their homes and cook their food.

Biomass gets its energy from the sun. All organic matter contains stored energy from the sun. During a process called photosynthesis, sunlight gives plants the energy they need to convert water and carbon dioxide into oxygen and sugars. These sugars, called carbohydrates, supply plants and the animals that eat plants with energy. Foods rich in carbohydrates are a good source of energy for the human body.

Biomass is a renewable energy source because its supplies are not limited. We can always grow trees and crops, and waste will always exist.

PHOTOSYNTHESIS

In the process of photosynthesis, plants convert radiant energy from the sun into chemical energy in the form of glucose (or sugar)



water + carbon dioxide + sunlight ⟶ glucose + oxygen

$$6\,H_2O + 6\,CO_2 + \text{radiant energy} \longrightarrow C_6H_{12}O_6 + 6\,O_2$$

TYPES OF BIOMASS

We use four types of biomass today—wood and agricultural products,solid waste, landfill gas and biogas, and alcohol fuels (like Ethanol or Biodiesel).

1 WOOD AND AGRICULTURAL PRODUCTS

Most biomass used today is home grown energy. Wood—logs, chips, bark, and sawdust—accounts for just under half of biomass energy. But any organic matter can produce biomass energy. Other biomass sources can include agricultural waste products like fruit pits and corncobs.

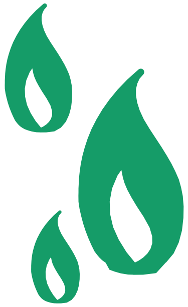
Wood and wood waste are used to generate electricity. Much of the electricity is used by the industries making the waste; it is not distributed by utilities, it is a process called cogeneration. Paper mills and saw mills use much of their waste products to generate steam and electricity for their use. However, since they use so much energy, they need to buy additional electricity from utilities.

2 SOLID WASTE

Burning trash turns waste into a usable form of energy. One ton (2,000 pounds) of garbage contains about as much heat energy as 500 pounds of coal. Garbage is not all biomass; perhaps half of its energy content comes from plastics, which are made from petroleum and natural gas. Power plants that burn garbage for energy are called waste-to-energy plants. These plants generate electricity much as coal-fired plants do, except that combustible garbage—not coal—is the fuel used to fire their boilers.

3 LANDFILL GAS AND BIOGAS

Bacteria and fungi are not picky eaters. They eat dead plants and animals, causing them to rot or decay. A fungus on a rotting log is converting cellulose to sugars to feed itself. Although this process is slowed in a landfill, a substance called methane gas is still produced as the waste decays. New regulations require landfills to collect methane gas for safety and environmental reasons. Methane gas is colorless and odorless, but it is not harmless. The gas can cause fires or explosions if it seeps into nearby homes and is ignited. Landfills can collect the methane gas, purify it, and use it as fuel. Methane can also be produced using energy from agricultural and human wastes. Biogas digesters are airtight containers or pits lined with steel or bricks. Waste put into the containers is fermented without oxygen to produce a methane-rich gas. This gas can be used to produce electricity, or for cooking and lighting.



4 ETHANOL

Ethanol is an alcohol fuel (ethyl alcohol) made by fermenting the sugars and starches found in plants and then distilling them. Any organic material containing cellulose, starch, or sugar can be made into ethanol. The majority of the ethanol produced in the United States comes from corn. New technologies are producing ethanol from cellulose in woody fibers from trees, grasses, and crop residues.

Today nearly all of the gasoline sold in the U.S. contains around 10 percent ethanol and is known as E10. In 2011, the U.S. Environmental Protection Agency (EPA) approved the introduction of E15 (15 percent ethanol, 85 percent gasoline) for use in passenger vehicles from model year 2001 and newer. Fuel containing 85 percent ethanol and 15 percent gasoline (E85) qualifies as an alternative fuel. There are about 20 million flexible fuel vehicles (FFV) on the road that can run efficiently on E85 or E10. However, a small percentage of these vehicles use E85 regularly.

BIODIESEL

Biodiesel is a fuel made by chemically reacting alcohol with vegetable oils, animal fats, or greases, such as recycled restaurant grease. Most biodiesel today is made from soybean oil. Biodiesel is most often blended with petroleum diesel in ratios of two percent (B2), five percent (B5), or 20 percent (B20). It can also be used as neat (pure) biodiesel (B100). Biodiesel fuels are compatible with and can be used in unmodified diesel engines with the existing fueling infrastructure. It is one of the fastest growing transportation fuels in the U.S.

Biodiesel contains virtually no sulfur, so it can reduce sulfur levels in the nation's diesel fuel supply, even compared with today's low sulfur fuels. While removing sulfur from petroleum-based diesel results in poor lubrication, biodiesel is a superior lubricant and can reduce the friction of diesel fuel in blends of only one or two percent. This is an important characteristic because the Environmental Protection Agency now requires that sulfur levels in diesel fuel be 97 percent lower than they were prior to 2006.

Biofuel

By Kristala Jones Prather – MIT Climate – September 3, 2020

Biofuel is any liquid fuel made from “biomass”—that is, plants and other biological matter like animal waste and leftover cooking fat. Biofuels can be used as replacements for petroleum-based fuels like gasoline and diesel. As we search for fuels that won’t contribute to the greenhouse effect and climate change, biofuels are a promising option because the carbon dioxide (CO2) they emit is recycled through the atmosphere. When the plants used to make biofuels grow, they absorb CO2 from the air, and it’s that same CO2 that goes back into the atmosphere when the fuels are burned. In theory, biofuels can be a “carbon neutral” or even “carbon negative” way to power cars, trucks and planes, meaning they take at least as much CO2 out of the atmosphere as they put back in.

A major promise of biofuels is that they can lower overall CO2 emissions without changing a lot of our infrastructure. They can work with existing vehicles, and they can be mass-produced from biomass in the same way as other biotechnology products, like chemicals and pharmaceuticals, which are already made on a large scale. In the future, we may also be able to move large amounts of biofuels through existing pipelines.

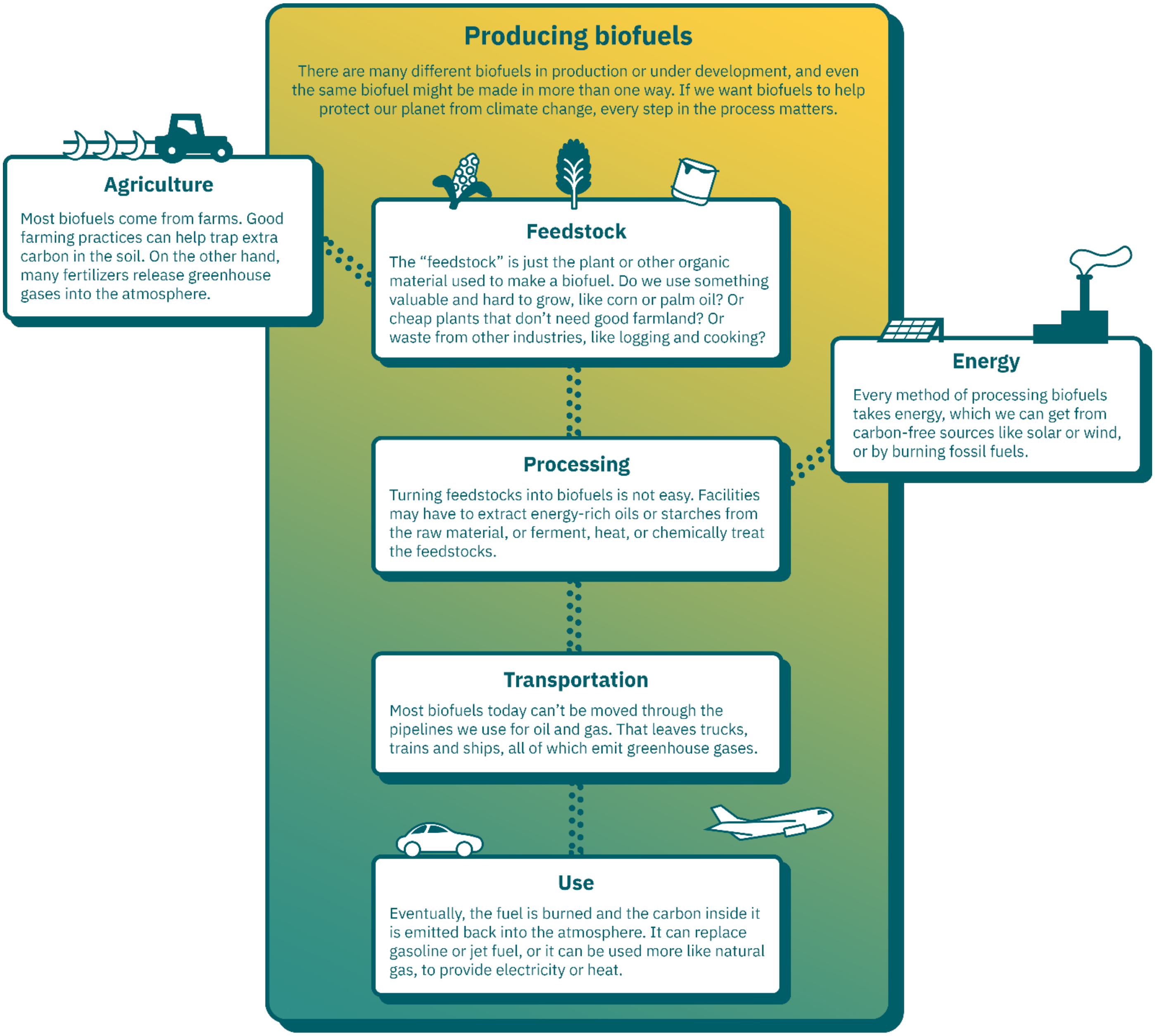
Toward advanced biofuels

Today, many different biofuels are in production, made in many different ways. The most common process is to use bacteria and yeast to ferment starchy foods like corn into ethanol, a partial replacement for gasoline. Most gasoline sold in the U.S. is mixed with 10% ethanol.

Newer research in biofuels aims to produce higher-grade fuels like jet fuel; to create cleaner-burning fuels that are better for the environment and human health; or to use less valuable biomass like algae, grasses, woody shrubs, or waste from cooking, logging and farming. While some of these “advanced biofuels” are already in production, none are being used in nearly the amounts of “first-generation” ethanol and biodiesel.

Climate challenges

There are many challenges to making biofuels that are truly carbon neutral. That’s because many steps used to create biofuels—fermentation, the energy for processing, transportation, even the fertilizers used to grow plants—may emit CO2 and other greenhouse gases even before the fuels are burned. The farmland used to grow biomass can also have its own climate impacts, especially if it takes the place of CO2-storing forests. This means that the details of how biofuels are made and used are very important for their potential as a climate solution.



Producing biofuels

There are many different biofuels in production or under development, and even the same biofuel might be made in more than one way. If we want biofuels to help protect our planet from climate change, every step in the process matters.

Agriculture

Most biofuels come from farms. Good farming practices can help trap extra carbon in the soil. On the other hand, many fertilizers release greenhouse gases into the atmosphere.

Feedstock

The "feedstock" is just the plant or other organic material used to make a biofuel. Do we use something valuable and hard to grow, like corn or palm oil? Or cheap plants that don't need good farmland? Or waste from other industries, like logging and cooking?

Energy

Every method of processing biofuels takes energy, which we can get from carbon-free sources like solar or wind, or by burning fossil fuels.

Processing

Turning feedstocks into biofuels is not easy. Facilities may have to extract energy-rich oils or starches from the raw material, or ferment, heat, or chemically treat the feedstocks.

Transportation

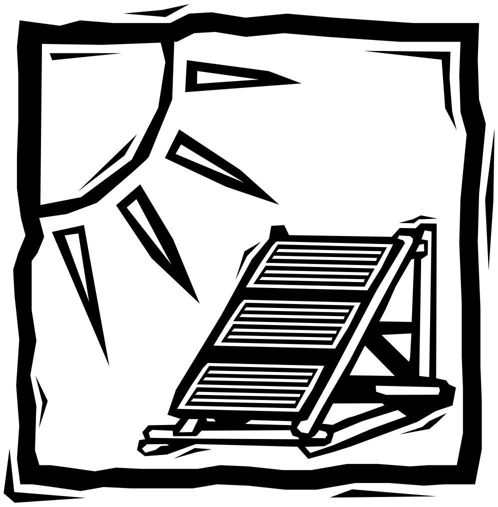
Most biofuels today can't be moved through the pipelines we use for oil and gas. That leaves trucks, trains and ships, all of which emit greenhouse gases.

Use

Eventually, the fuel is burned and the carbon inside it is emitted back into the atmosphere. It can replace gasoline or jet fuel, or it can be used more like natural gas, to provide electricity or heat.

Facts about Solar Energy: Solar Electricity

Introduction



Harnessing energy from the sun holds great promise for meeting future energy needs because solar energy is a renewable and clean energy resource. Fossil fuels will eventually run out and the future of nuclear power is uncertain. For these reasons, other energy sources need to be harnessed. Solar energy is one of these sources.

Solar energy is produced by the sun, which is essentially a gigantic nuclear fusion reactor running on hydrogen fuel. The sun converts five million tons of matter into energy every second. Solar energy reaches the Earth's surface as ultraviolet (UV) light, visible light, and infrared light. Many other electromagnetic waves are stopped in the upper parts of the atmosphere. Scientists expect that the sun will continue to provide light and heat energy for the next five billion years.

Solar Energy Potential

The amount of solar energy that strikes Earth's surface per year is about 29,000 times greater than all of the energy used in the United States. Put another way, in one hour more energy from the sun falls on the earth than is used by everyone in the world in an entire year. The solar energy falling on Wisconsin each year is roughly equal to 844 quadrillion Btu of energy, which is almost 550 times the amount of energy used in Wisconsin.

Although the amount of solar energy reaching Earth's surface is immense, it is spread out over a large area. There are also limits to how efficiently it can be collected and converted into electricity and stored. These factors, in addition to geographic location, time of day, season, local landscape, and local weather, affect the amount of solar energy that can actually be used.

Producing Solar Electricity

Solar electricity is measured like most electricity, in kilowatt-hours, a unit of energy. Solar cells convert sunlight directly into electricity, and many solar-powered devices have been in use for decades, including wrist watches and calculators. Traditional cells are made of silicon, a material that comprises 28 percent of the Earth's crust. One solar cell measuring four inches across can produce one watt of electricity on a clear, sunny day. However, its efficiency can be affected by many factors including the wavelength of light, the temperature, and reflection. To produce more electricity, cells are wired together into panels (about 40 cells), and panels are wired together to form arrays.

Solar cells are reliable and quiet, and they can be installed quickly and easily. They are also mobile and easily maintained. They provide an ideal electrical power source for satellites, outdoor lighting, navigational beacons, and water pumps in remote areas. In the United States, more than 784,000 homes and businesses have 'gone solar.'

Facts about Solar Energy: Solar Electricity

Concentrated Solar Power (CSP)

Solar energy can be used to heat a fluid to produce steam that spins a turbine connected to an electrical generator. These systems are called solar thermal electric systems. Concentrated solar power systems use mirrors to reflect and concentrate sunlight onto a small area. The concentrated sunlight heats a fluid and creates steam, which then powers a turbine generating electricity.

One type of solar thermal electric system, the solar power tower, uses mirrors to track and focus sunlight onto the top of a heat collection tower (see Fig. 1.1). An experimental 10-megawatt solar power tower called Solar Two was tested in the desert near Barstow, California. It was used to demonstrate the advantages of using molten salt for heat transfer and thermal storage. The experiment showed that this type of solar energy production was efficient in collecting and dispatching energy. The world's largest operating power tower system is the Ivanpah Solar Electric Generating System in the Mojave Desert of California. Ivanpah currently runs 69 percent below operating capacity, lacking thermal storage. It cannot compete with PV panels which have undergone a huge price reduction and can be installed on homes.

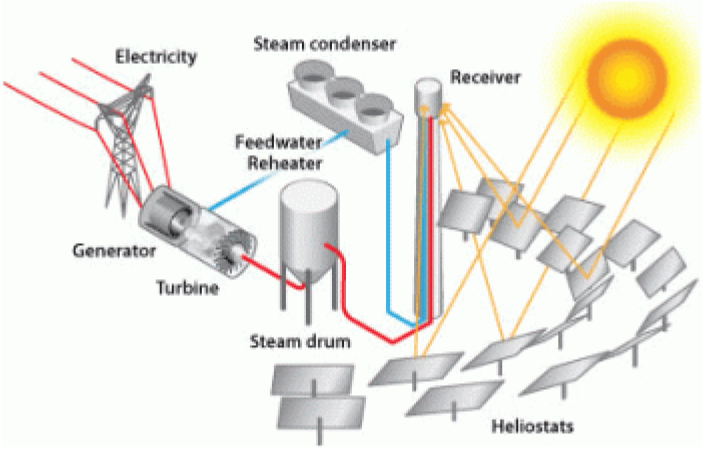


Fig. 1.1 Power Tower Power Plant
Source: energy.gov/eere/energybasics/articles/power-tower-system-concentrating-solar-power-basics

A second type of solar thermal electric system is called a parabolic trough. It is a linear concentrator system and uses curved, mirrored collectors shaped like troughs. The concentrated sunlight heats a working fluid running through the pipes that is then used as a heat source to generate electricity (see Fig 1.2). The largest system of this type is located in northern San Bernadino County in California with a capacity of 354 MW combined from three locations.

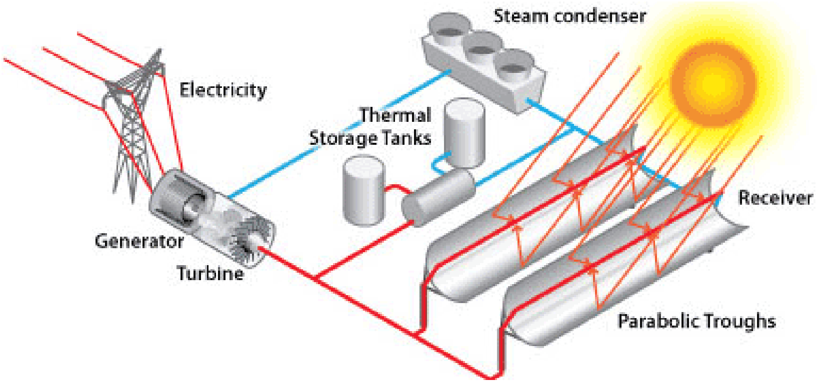


Fig. 1.2 Linear Concentrator Power Plant using Parabolic Tough Collectors
Source: energy.gov/eere/energybasics/articles/linear-concentrator-system-basics-concentrating-solar-power

Facts about Solar Energy: Solar Electricity

A third type of solar thermal electric system is an enclosed trough which use mirrors encapsulated in glass like a greenhouse to focus sunlight on a tube containing water, yielding high-pressure steam (see Fig. 1.3). This system was designed to produce heat for enhanced oil recovery.

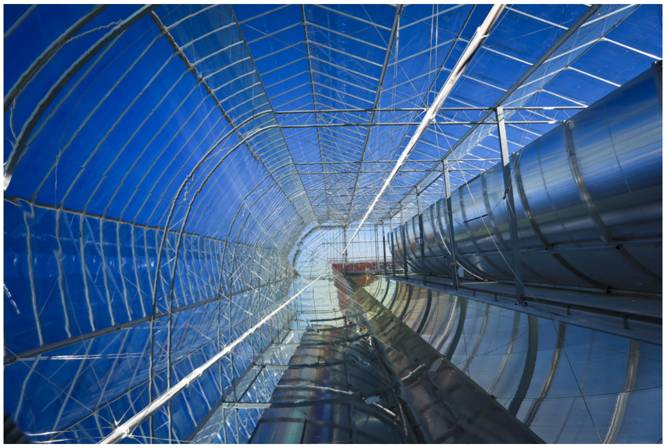


Fig. 1.3 View from inside the enclosed-trough parabolic solar mirrors, used to concentrate sun and generate steam for enhanced oil recovery (EOR).

Source: commons.wikimedia.org/wiki/File%3AInside_an_enclosed_CSP_Trough.jpg

A fourth type of solar thermal electric system is a Dish Stirling system which uses a mirrored dish similar in appearance to a satellite dish (see Fig. 1.4). This system, like the others, uses mirrors to concentrate and reflect solar energy and the heat generated is used to produce electricity by concentrating sunlight onto a receiver--located at the dish's focal point – containing a working fluid that powers a Stirling Engine.

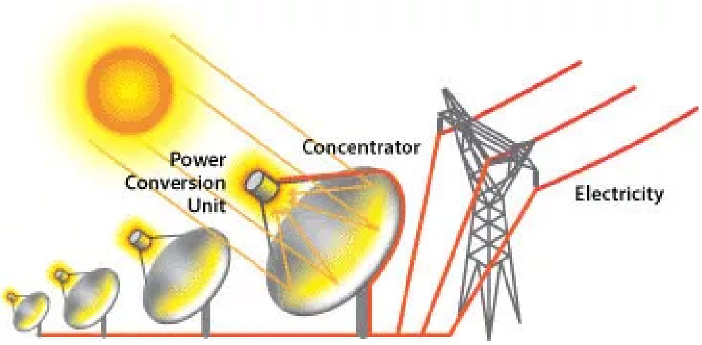


Fig. 1.4 Dish/Engine Power Plant

Source: energy.gov/eere/energybasics/articles/dishengine-system-concentrating-solar-power-basics

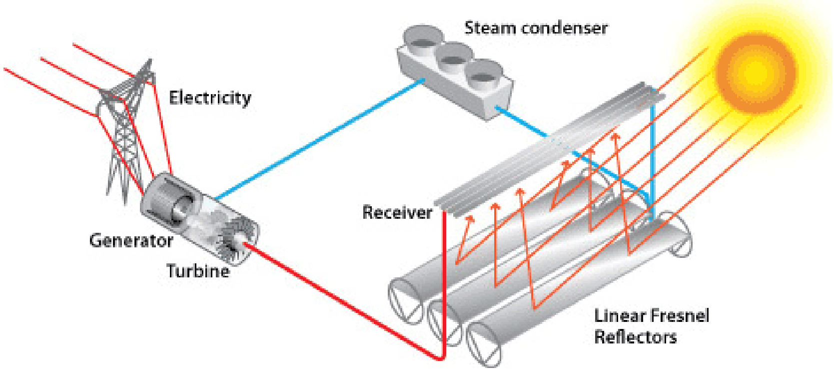


Fig. 1.5 Linear Fresnel Power Plant

Source: energy.gov/eere/sunshot/downloads/linear-fresnel-power-plant-illustration

A fifth type of solar thermal electric system called Fresnel reflectors are long, thin segments of mirrors that focus sunlight onto a fixed absorber located at a common focal point of the reflectors (see Fig. 1.5). Flat mirrors allow more reflective surface than parabolic reflectors and are much cheaper.

Facts about Solar Energy: Solar Electricity

Solar Electricity Production

Of the total electricity production in the United States, solar energy provides less than 2 percent. In Wisconsin only about 0.4 percent of total electricity production is from solar energy. A negligible amount of electricity from solar energy is currently being generated by individual homeowners and businesses.

Effects

Solar electricity has many benefits. Solar electric systems have no fuel costs, low operating and maintenance costs, produce virtually no emissions or waste while functioning, and even raise the value of homes.

Solar electric systems can be built quickly and in many sizes. They are well-suited to rural areas, developing countries, and other communities that do not have access to centrally generated electricity.

Solar electricity also has limitations. It is not available at night and is less available during cloudy days, making it necessary to store the produced electricity. Backup generators can also be used to support these systems. During the manufacturing process of photovoltaic cells, some toxic materials and chemicals are used. Some systems may use hazardous fluids to transfer heat. Adverse impacts can be experienced in areas that are cleared or used for large solar energy generating sites. Large-scale solar electric systems need large amounts of land to collect solar energy. This may cause conflicts if the land is in an environmentally sensitive area or is needed for other purposes. Deaths of birds and insects may occur if they happen to fly directly into a beam of light concentrated by a CSP.

Sometimes large-scale solar electric systems are placed in deserts or marginal lands. CSP developments are common in the southwestern United States (Colorado and Mojave Deserts); however, these locations are not without conflict either. For example, the Mojave desert tortoise is a threatened species that is in decline due to a complex array of threats including habitat loss and degradation.

Another idea is to place solar cells on rooftops, over parking lots, in yards, and along highways, and then connect the systems to an electric utility's power-line system. As the use of solar electric systems increases, laws may be needed to protect peoples' right to access the sun.

Solar Array Near Cantil, California

Source: Hanwha Q CELLS USA.

Facts about Solar Energy: Solar Electricity

Outlook

The sun is expected to remain much as it is today for another five billion years. Because we can anticipate harvesting the sun's energy for the foreseeable future, the outlook for solar energy is optimistic. Continued growth in utility-scale solar power generation is expected. The flexibility and environmental benefits of solar electricity make it an attractive alternative to fossil and nuclear fuels. Although the cost of solar panels has dropped significantly, other solar installations (such as CSP) are relatively expensive when compared to the amount of electricity they generate. Land issues and the need for electricity storage or backup systems are also obstacles, of which many experts are confident can be overcome. Incentives are increasingly offered at the utility, county, state, and federal levels. The U.S. Department of Energy's SunShot Initiative has launched an effort to make solar energy more cost-competitive with other types of energy. Incentives such as these will ultimately assist in the continued growth of solar energy.

In the near future, the use of solar electric systems will likely continue to increase in the Southern and Western parts of the United States where sunshine is plentiful. Solar energy growth in Wisconsin has been slower than that of Southern and Western states but currently has 22 MW of solar energy installed, equivalent to what is needed to power 3,000 homes. A number of homeowners and businesses in Wisconsin have already demonstrated that solar electric systems can meet their needs, and it is reasonable to expect growth of solar electric power in Wisconsin as well.

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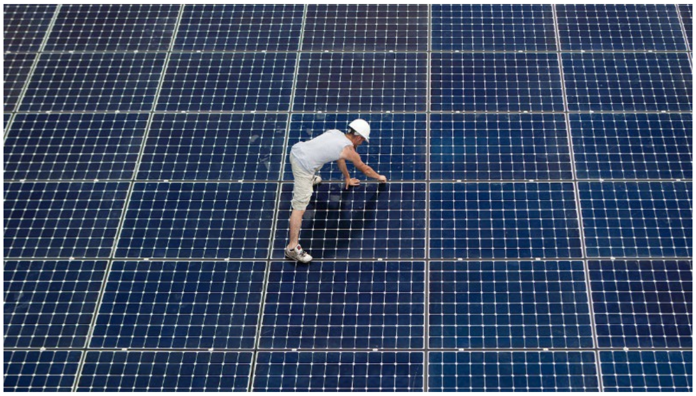
The Dark Side of Solar Power

by Atalay Atasu, Serasu Duran, and Luk N. Van Wassenhove – Harvard Business Review

June 18, 2021

Summary: Solar energy is a rapidly growing market, which should be good news for the environment. Unfortunately there's a catch. The replacement rate of solar panels is faster than expected and given the current very high recycling costs, there's a real danger that all used panels will go straight to landfill (along with equally hard-to-recycle wind turbines). Regulators and industry players need to start improving the economics and scale of recycling capabilities before the avalanche of solar panels hits.



It's sunny times for solar power. In the U.S., home installations of solar panels have fully rebounded from the Covid slump, with analysts predicting more than 19 gigawatts of total capacity installed, compared to 13 gigawatts at the close of 2019. Over the next 10 years, that number may quadruple, according to industry research data. And that's not even taking into consideration the further impact of possible new regulations and incentives launched by the green-friendly Biden administration.

Solar's pandemic-proof performance is due in large part to the Solar Investment Tax Credit, which defrays 26% of solar-related expenses for all residential and commercial customers (just down from 30% during 2006–2019). After 2023, the tax credit will step down to a permanent 10% for commercial installers and will disappear entirely for home buyers. Therefore, sales of solar will probably burn even hotter in the coming months, as buyers race to cash in while they still can.

Tax subsidies are not the only reason for the solar explosion. The conversion efficiency of panels has improved by as much as 0.5% each year for the last 10 years, even as production costs (and thus prices) have sharply declined, thanks to several waves of manufacturing innovation mostly driven by industry-dominant Chinese panel producers. For the end consumer, this amounts to far lower up-front costs per kilowatt of energy generated.

This is all great news, not just for the industry but also for anyone who acknowledges the need to transition from fossil fuels to renewable energy for the sake of our planet's future. But there's a massive caveat that very few are talking about.

Panels, Panels Everywhere

Economic incentives are rapidly aligning to encourage customers to trade their existing panels for newer, cheaper, more efficient models. In an industry where circularity solutions such as recycling remain woefully inadequate, the sheer volume of discarded panels will soon pose a risk of existentially damaging proportions.

To be sure, this is not the story one gets from official industry and government sources. The International Renewable Energy Agency (IRENA)'s official projections assert that "large amounts of annual waste are anticipated by the early 2030s" and could total 78 million tonnes by the year 2050. That's a staggering amount, undoubtedly. But with so many years to prepare, it describes a billion-dollar opportunity for recapture of valuable materials rather than a dire threat. The threat is hidden by the fact that IRENA's predictions are premised upon customers keeping their panels in place for the entirety of their 30-year life cycle. They do not account for the possibility of widespread early replacement.

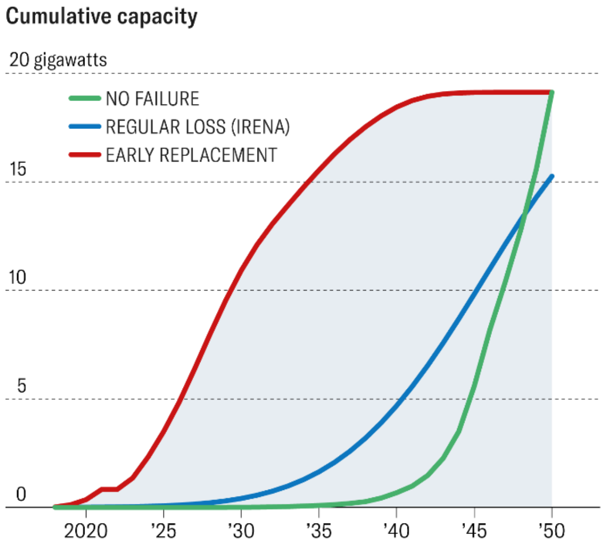
Our research does. Using real U.S. data, we modeled the incentives affecting consumers' decisions whether to replace under various scenarios. We surmised that three variables were particularly salient in determining replacement decisions: installation price, compensation rate (i.e., the going rate for solar energy sold to the grid), and module efficiency. If the cost of trading up is low enough, and the efficiency and compensation rate are high enough, we posit that rational consumers will make the switch, regardless of whether their existing panels have lived out a full 30 years.

As an example, consider a hypothetical consumer (call her "Ms. Brown") living in California who installed solar panels on her home in 2011. Theoretically, she could keep the panels in place for 30 years, i.e., until 2041. At the time of installation, the total cost was $40,800, 30% of which was tax deductible thanks to the Solar Investment Tax Credit. In 2011, Ms. Brown could expect to generate 12,000 kilowatts of energy through her solar panels, or roughly $2,100 worth of electricity. In each following year, the efficiency of her panel decreases by approximately one percent due to module degradation.

Now imagine that in the year 2026, halfway through the life cycle of her equipment, Ms. Brown starts to look at her solar options again. She's heard the latest generation of panels are cheaper and more efficient — and when she does her homework, she finds that that is very much the case. Going by actual current projections, the Ms. Brown of 2026 will find that costs associated with buying and installing solar panels have fallen by 70% from where they were in 2011. Moreover, the new-generation panels will yield $2,800 in annual revenue, $700 more than her existing setup when it was new. All told, upgrading her panels now rather than waiting another 15 years will increase the net present value (NPV) of her solar rig by more than $3,000 in 2011 dollars. If Ms. Brown is a rational actor, she will opt for early replacement. And if she were especially shrewd in money matters, she would have come to that decision even sooner — our calculations for the Ms. Brown scenario show the replacement NPV overtaking that of panel retention starting in 2021.

The Solar Trash Wave

According to our research, cumulative waste projections will rise far sooner and more sharply than most analysts expect, as the below graph shows. The green “no failure” line tracks the disposal of panels assuming that no faults occur over the 30-year life cycle; the blue line shows the official International Renewable Energy Agency (IRENA) forecast, which allows for some replacements earlier in the life cycle; and the red line represents waste projections predicted by our model.



Source: International Renewable Energy Agency, Electricity Data Browser, Global Solar Atlas

If early replacements occur as predicted by our statistical model, they can produce 50 times more waste in just four years than IRENA anticipates. That figure translates to around 315,000 metric tonnes of waste, based on an estimate of 90 tonnes per MW weight-to-power ratio.

Alarming as they are, these stats may not do full justice to the crisis, as our analysis is restricted to residential installations. With commercial and industrial panels added to the picture, the scale of replacements could be much, much larger.

The High Cost of Solar Trash

The industry’s current circular capacity is woefully unprepared for the deluge of waste that is likely to come. The financial incentive to invest in recycling has never been very strong in solar. While panels contain small amounts of valuable materials such as silver, they are mostly made of glass, an extremely low-value material. The long life span of solar panels also serves to disincentivize innovation in this area.

As a result, solar's production boom has left its recycling infrastructure in the dust. To give you some indication, First Solar is the sole U.S. panel manufacturer we know of with an up-and-running recycling initiative, which only applies to the company's own products at a global capacity of two million panels per year. With the current capacity, it costs an estimated $20–$30 to recycle one panel. Sending that same panel to a landfill would cost a mere $1–$2.

The direct cost of recycling is only part of the end-of-life burden, however. Panels are delicate, bulky pieces of equipment usually installed on rooftops in the residential context. Specialized labor is required to detach and remove them, lest they shatter to smithereens before they make it onto the truck. In addition, some governments may classify solar panels as hazardous waste, due to the small amounts of heavy metals (cadmium, lead, etc.) they contain. This classification carries with it a string of expensive restrictions — hazardous waste can only be transported at designated times and via select routes, etc.

The totality of these unforeseen costs could crush industry competitiveness. If we plot future installations according to a logistic growth curve capped at 700 GW by 2050 (NREL's estimated ceiling for the U.S. residential market) alongside the early-replacement curve, we see the volume of waste surpassing that of new installations by the year 2031. By 2035, discarded panels would outweigh new units sold by 2.56 times. In turn, this would catapult the LCOE (levelized cost of energy, a measure of the overall cost of an energy-producing asset over its lifetime) to four times the current projection. The economics of solar — so bright-seeming from the vantage point of 2021 — would darken quickly as the industry sinks under the weight of its own trash.

Who Pays the Bill?

It will almost certainly fall to regulators to decide who will bear the cleanup costs. As waste from the first wave of early replacements piles up in the next few years, the U.S. government — starting with the states, but surely escalating to the federal level — will introduce solar panel recycling legislation. Conceivably, future regulations in the U.S. will follow the model of the European Union's WEEE Directive, a legal framework for the recycling and disposal of electronic waste throughout EU member states. The U.S. states that have enacted electronics-recycling legislation have mostly cleaved to the WEEE model. (The Directive was amended in 2014 to include solar panels.) In the EU, recycling responsibilities for past (historic) waste have been apportioned to manufacturers based on current market share.

A first step to forestalling disaster may be for solar panel producers to start lobbying for similar legislation in the United States immediately, instead of waiting for solar panels to start clogging landfills. In our experience drafting and implementing the revision of the original WEEE Directive in the late 2000s, we found one of the biggest challenges in those early years was assigning responsibility for the vast amount of accumulated waste generated by companies no longer in the electronics business (so-called orphan waste).

In the case of solar, the problem is made even thornier by new rules out of Beijing that shave subsidies for solar panel producers while increasing mandatory competitive bidding for new solar projects. In an industry dominated by Chinese players, this ramps up the uncertainty factor. With reduced support from the central government, it's possible that some Chinese producers may fall out of the market. One of the reasons to push legislation now rather than later is to ensure that the responsibility for recycling the imminent first wave of waste is shared fairly by makers of the equipment concerned. If legislation comes too late, the remaining players may be forced to deal with the expensive mess that erstwhile Chinese producers left behind.

But first and foremost, the required solar panel recycling capacity has to be built, as part of a comprehensive end-of-life infrastructure also encompassing uninstallation, transportation, and (in the meantime) adequate storage facilities for solar waste. If even the most optimistic of our early-replacement forecasts are accurate, there may not be enough time for companies to accomplish this alone. Government subsidies are probably the only way to quickly develop capacity commensurate to the magnitude of the looming waste problem. Corporate lobbyists can make a convincing case for government intervention, centered on the idea that waste is a negative externality of the rapid innovation necessary for widespread adoption of new energy technologies such as solar. The cost of creating end-of-life infrastructure for solar, therefore, is an inescapable part of the R&D package that goes along with supporting green energy.

It's Not Just Solar

The same problem is looming for other renewable-energy technologies. For example, barring a major increase in processing capability, experts expect that more than 720,000 tons worth of gargantuan wind-turbine blades will end up in U.S. landfills over the next 20 years. According to prevailing estimates, only five percent of electric-vehicle batteries are currently recycled — a lag that automakers are racing to rectify as sales figures for electric cars continue to rise as much as 40% year-on-year. The only essential difference between these green technologies and solar panels is that the latter doubles as a revenue-generating engine for the consumer. Two separate profit-seeking actors — panel producers and the end consumer — thus must be satisfied in order for adoption to occur at scale.

. . .

None of this should raise serious doubts about the future or necessity of renewables. The science is indisputable: Continuing to rely on fossil fuels to the extent we currently do will bequeath a damaged if not dying planet to future generations. Compared with all we stand to gain or lose, the four decades or so it will likely take for the economics of solar to stabilize to the point that consumers won't feel compelled to cut short the life cycle of their panels seems decidedly small. But that lofty purpose doesn't make the shift to renewable energy any easier in reality. Of all sectors, sustainable technology can least afford to be shortsighted about the waste it creates. A strategy for entering the circular economy is absolutely essential — and the sooner, the better.

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Advantages and Challenges of Wind Energy

Wind Energy Technologies Office, 2023

Wind energy offers many advantages, which explains why it's one of the fastest-growing energy sources in the world. To further expand wind energy's capabilities and community benefits, researchers are working to address technical and socio-economic challenges in support of a decarbonized electricity future.

Advantages of Wind Power

- Wind power creates good-paying jobs. There are over 120,000 people working in the U.S. wind industry across all 50 states, and that number continues to grow. According to the U.S. Bureau of Labor Statistics, wind turbine service technicians are the second fastest growing U.S. job of the decade. Offering career opportunities ranging from blade fabricator to asset manager, the wind industry has the potential to support hundreds of thousands of more jobs by 2050.
- Wind power is a domestic resource that enables U.S. economic growth. In 2022, wind turbines operating in all 50 states generated more than 10% of the net total of the country's energy. That same year, investments in new wind projects added $20 billion to the U.S. economy.
- Wind power is a clean and renewable energy source. Wind turbines harness energy from the wind using mechanical power to spin a generator and create electricity. Not only is wind an abundant and inexhaustible resource, but it also provides electricity without burning any fuel or polluting the air. Wind continues to be the largest source of renewable power in the United States, which helps reduce our reliance on fossil fuels. Wind energy helps avoid 329 million metric tons of carbon dioxide emissions annually – equivalent to 71 million cars worth of emissions that along with other atmospheric emissions cause acid rain, smog, and greenhouse gases.
- Wind power benefits local communities. Wind projects deliver an estimated $1.9 billion in state and local tax payments and land-lease payments each year. Communities that develop wind energy can use the extra revenue to put towards school budgets, reduce the tax burden on homeowners, and address local infrastructure projects.
- Wind power is cost-effective. Land-based, utility-scale wind turbines provide one of the lowest-priced energy sources available today. Furthermore, wind energy's cost competitiveness continues to improve with advances in the science and technology of wind energy.
- Wind turbines work in different settings. Wind energy generation fits well in agricultural and multi-use working landscapes. Wind energy is easily integrated in rural or remote areas, such as farms and ranches or coastal and island communities, where high-quality wind resources are often found.

Challenges of Wind Power

- Wind power must compete with other low-cost energy sources. When comparing the cost of energy associated with new power plants, wind and solar projects are now more economically competitive than gas, geothermal, coal, or nuclear facilities. However, wind projects may not be cost-competitive in some locations that are not windy enough. Next-generation technology, manufacturing improvements, and a better understanding of wind plant physics can help bring costs down even more.
- Ideal wind sites are often in remote locations. Installation challenges must be overcome to bring electricity from wind farms to urban areas, where it is needed to meet demand. Upgrading the nation’s transmission network to connect areas with abundant wind resources to population centers could significantly reduce the costs of expanding land-based wind energy. In addition, offshore wind energy transmission and grid interconnection capabilities are improving.
- Turbines produce noise and alter visual aesthetics. Wind farms have different impacts on the environment compared to conventional power plants, but similar concerns exist over both the noise produced by the turbine blades and the visual impacts on the landscape.
- Wind plants can impact local wildlife. Although wind projects rank lower than other energy developments in terms of wildlife impacts, research is still needed to minimize wind-wildlife interactions. Advancements in technologies, properly siting wind plants, and ongoing environmental research are working to reduce the impact of wind turbines on wildlife.

HYDROPOWER INDUSTRY SUPPLY CHAIN DEEP DIVE ASSESSMENT

1 Introduction

1.1 Role of hydropower in the energy industrial base sector

Hydropower is an important part of the U.S. Energy Sector Industrial Base, including the set of companies that research and develop, manufacture, and operate energy generation, storage, transmission, and distribution assets.

At the end of 2019, the U.S. conventional hydropower fleet (80.2 GW) was the fourth largest in the world by individual countries (after China, Brazil, and Canada) and the U.S. pumped storage hydropower (PSH) fleet (21.9 GW) was the third largest (after China and Japan). However, only 1.7 GW of conventional hydropower and 1.4 GW of PSH capacity were added in 2010–2019 (Uría-Martínez et al, 2021). Of this added capacity, the fraction that resulted from new builds was 33% for conventional hydropower and 3% for PSH; the rest resulted from upgrades to existing facilities. The average age of the U.S. fleet is 64 years for conventional hydropower and 45 years for PSH.[3] New capacity expansion is not anticipated to be the primary driver for the activity of domestic industrial companies supporting the U.S. hydropower fleets. Instead, the primary driver is expected to be the maintenance and modernization of the existing fleets. The exceptions could be PSH builds and some limited new small conventional hydropower plants.

In 2020, hydropower accounted for 36.7% of renewable electricity generation and 7.3% of total electricity generation in the United States (Johnson and Uría-Martínez, 2021). In some U.S. states (Washington, Idaho, Oregon, and Vermont), more than 50% of electricity generated in 2017–2019 was hydroelectric. Hydropower also provides flexibility and grid services that are essential to enable high penetrations of variable renewables and enhance grid reliability. U.S. PSH plants provide a higher percentage of many grid services than the percentage of capacity they represent in the electricity generation fleet. For instance, Gracia et al. (2019) report that hydropower provides approximately 40% of black start resources (vs. less than 10% generation capacity). The 2021 edition of the U.S. Hydropower Market Report (HMR) presents other examples of the U.S. hydropower fleet providing a larger share of ancillary services (such as frequency regulation and reserves) than the share of generation capacity it represents in several independent system operator (ISO) regions. The large shares of ancillary services provided by hydropower relative to its installed capacity are indicative of the flexibility offered by this generation technology. Additionally, PSH has been to date the preferred least-cost technology for long-duration energy storage and the demand for this type of storage asset is expected to grow substantially in the next few decades.

A robust supply chain is necessary to maintain and modernize the existing hydropower fleets and to support the grid in reliably integrating the additional variable renewable capacity needed to achieve the objective of a carbon pollution-free electricity grid in the United States by 2035. The National Hydropower Association (NHA) has compiled a list of more than 2,500 companies that report being part of the U.S. hydropower supply chain, including turbine manufacturers, machine shops, and engineering and consulting companies, among others.[4] In 2018, the number of jobs supported by the U.S. hydropower industry was estimated at 66,500 (Keyser and Tegen, 2020). The manufacturing and utilities sectors accounted for 27% and 26% of those jobs, respectively. The rest were distributed among professional and business services, trade and transportation, and construction sectors. Using a combination of data and input from stakeholder interviews, this report identifies vulnerabilities, challenges, and opportunities for the U.S. hydropower supply chain.

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[3] This age calculation is based on plant age rather than unit age. Individual units within a plant can be younger if they have undergone a major refurbishment or modernization.

[4] https://www.hydro.org/map/supply-chains/

1.2 Power and non-power benefits of hydropower dams

Hydropower provides multiple electricity-related value streams to the national power grid. In addition to clean, low-cost electricity services, hydropower dams can provide valuable non-power benefits to the nation. Based on data from the National Inventory of Dams (NID), approximately 60% of the dams connected to hydropower plants in the United States are also authorized for other purposes. Large hydropower plants are more likely to provide multiple non-power services among the 12 categories listed in the NID: hydropower, irrigation, flood control and storm water management, navigation, water supply, recreation, fire protection, fish and wildlife, debris control, tailing, grade stabilization, and “other”.[5] In many cases, the hydropower purpose is secondary to one or several non-power purposes.

Of all the purposes served by dams, hydropower is the one with the best-defined method for value quantification. The value of hydroelectricity is the electricity market energy price. In addition, several ISOs and regional transmission organizations (RTOs) have centralized capacity markets and conduct capacity auctions that can be an additional source of revenue for hydropower plants in those regions. In ISO/RTO regions, markets are also cleared for several of the ancillary services that hydropower provides such as frequency regulation and various types of reserves. For other services like black start, the plant owners receive payments from the ISO/RTO or balancing authority that are meant to cover the costs of providing the service.

The value of the non-hydropower uses of hydropower dams can be substantial and is estimated with valuation methods such as avoided damage costs of floods (flood control) and alternative transportation (navigation) or revenues from irrigated crops (irrigation) and water use (water supply). However, most of these economic benefits are not monetized. Applying these methodologies to federal multipurpose hydropower reservoirs (excluding PSH plants), Bonnet et al. (2015) produce estimates of the distribution of economic benefits per use for each federal agency. In the Tennessee Valley Authority (TVA) and U.S. Army Corps of Engineers (USACE) fleets, recreation is the purpose with the highest economic benefit (35%–40% of the total). Hydropower (energy revenue only) is the second most valuable purpose in the TVA fleet (~23%), and the third most valuable purpose in the USACE fleet (~17%). Irrigation is not an authorized purpose for reservoirs owned by TVA or USACE. In contrast, irrigation is an authorized purpose in most of Bureau of Reclamation’s reservoirs and it accounts for 60% of the economic benefit for their fleet. The energy revenue from the hydropower purpose accounts for 10% of total economic benefit in Reclamation’s fleet.

Although payments are made for some non-power services, the hydropower purpose is often the main source of revenue for financing the maintenance of the dam and enabling the provision of non-power services. Thus, indirectly, the hydropower supply chain also supports those other valuable services.

1.3 Growth potential of hydropower

This section discusses multiple estimates of growth potential for conventional hydropower and PSH, for the United States and globally. First, Section 1.3.1 presents estimates of the remaining resource potential which provide an upper bound to the additional conventional hydropower capacity that could theoretically be added given historical data on water flows and site topography. Second, Section 1.3.2 summarizes data on the capacity from projects that have been announced and are being actively pursued. Of those, only a fraction will make it to construction stage after completing all necessary feasibility evaluation studies, obtaining permits, and securing

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[5] Tailing dams do not store water but the by-products from mining operations.

financing. Finally, Section 1.3.3 provides estimates of the additional global hydropower capacity that could be needed to meet selected global decarbonization objectives.

1.3.1 Technical potential

In addition to the importance of modernizing the existing conventional hydropower and PSH fleets to maintain or enhance the power and non-power values listed above, several studies conducted within the last decade on resource assessment show that significant potential remains to build new capacity, both in the United States and globally, through retrofits of non-powered dams (NPDs) and conduits, new stream-reach developments (NSD), and PSH.

For the United States, Hadjerioua et al., (2012) found a potential capacity of 12.1 GW from the retrofit of NPDs with the top three basins being the Ohio, the Upper Mississippi, and the Arkansas-White-Red. For NSDs, Kao et al., (2014) identified a resource potential of 65.5 GW after excluding national parks, wild and scenic rivers, and wilderness areas. These studies are estimates of potential energy generation based on the river flows at the selected sites; further technical and economic feasibility studies would be required to determine which sites to develop. The Hydropower Vision study produced estimates of growth potential based on results from the ReEDS model that solves for the optimal (minimum cost subject to other constraints) set of resources to meet projected electricity demand out to 2050 (DOE, 2016). Given the set of policies enacted as of December 2015 and the resource assessment potentials identified in the aforementioned studies, the ReEDS model finds a potential of 13 GW of new conventional hydropower capacity and 36 GW of PSH capacity by 2050.[6] If those potentials were realized, they would represent a 16% increase in conventional hydropower capacity and more than double the existing PSH capacity. Most of the new conventional hydropower would come from upgrades to existing facilities (6.3 GW) and NPD retrofits (4.8 GW).

For global potential, the International Hydropower Association (IHA) presents regional estimates derived from a review of three recent studies. The estimated capacity potentials range from 350 GW in Europe to 1,100 GW in East Asia and Pacific (IHA, 2021). These are very large numbers when compared with the global installed hydropower capacity of 1,330 GW—1,171 GW of conventional hydropower and 159 GW of PSH—at the end of 2020 (IHA, 2021b). For PSH, several recent studies conducting global searches of potential sites worldwide point to an abundance of candidate locations (Stocks et al., 2021; Hunt et al., 2020).

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[6] The study assumed implementation of the Clean Power Plan which was being discussed at the time but was ultimately not enacted.

1.3.2 Development pipeline

1.3.2.1 United States

1.3.2.1.1 New projects

Studies that estimate remaining technical potential for additional hydropower capacity provide a useful upper bound, but a more informative outlook for the short to mid-term potential of new builds emerges from analyzing the project development pipeline.[7] Figure 1 and Figure 2 offer details about the composition and status of conventional hydropower and PSH projects in the U.S. development pipeline at the end of 2020.

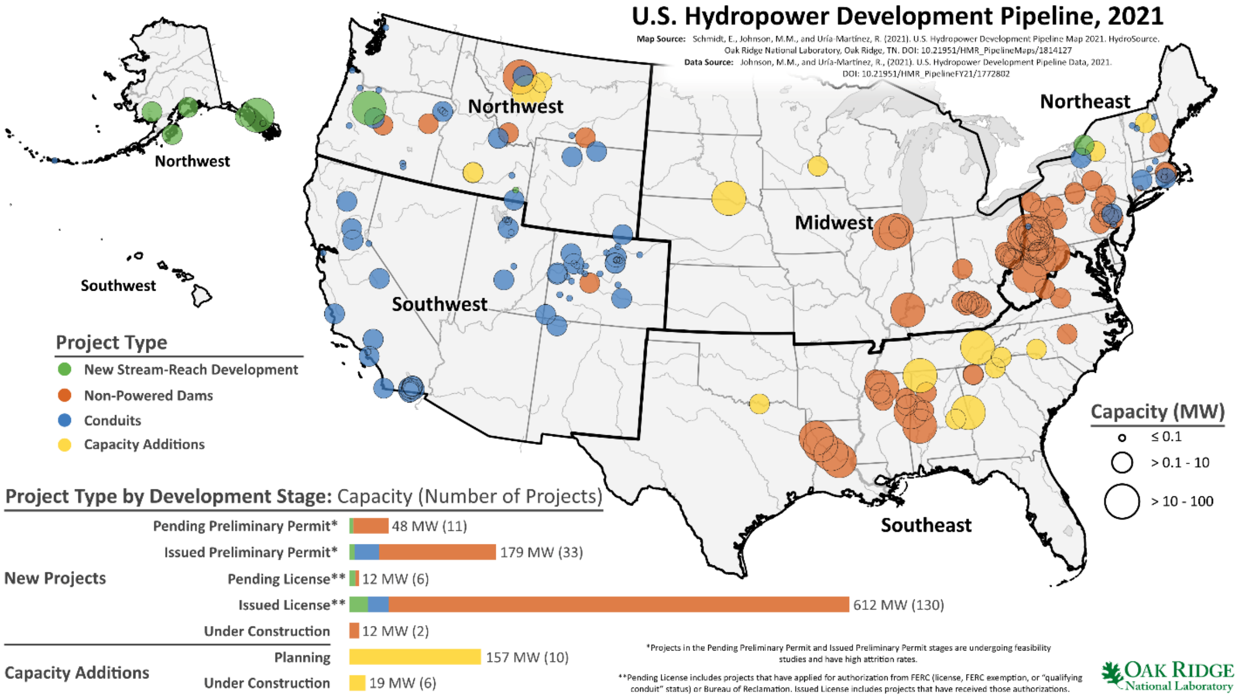

Figure 1. US. conventional hydropower project development pipeline by project type, region, size, and development stage (as of December 31, 2020).

Source: Schmidt et al. (2021)

Note: This map is available for download at https://hydrosource.ornl.gov/map/us-hydropower-development-pipeline-2021

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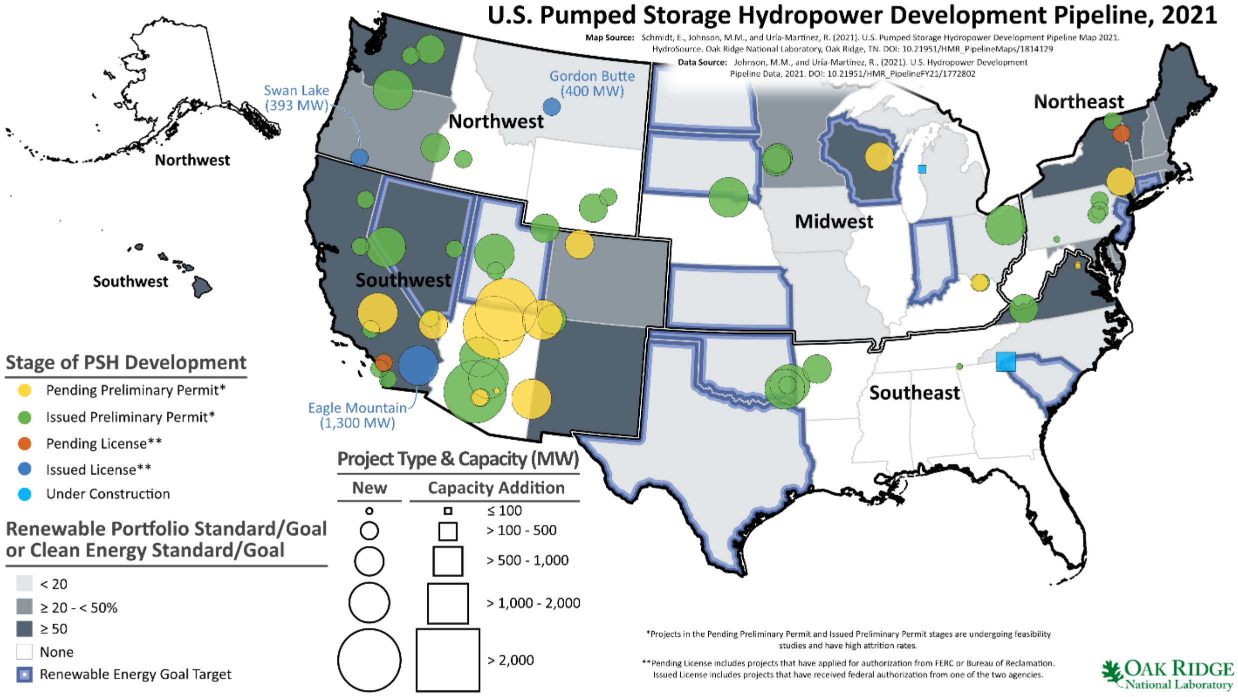
[7] The development pipeline numbers presented here include projects that have formally expressed interest in developing a conventional hydropower or PSH project that would require a FERC authorization (license, exemption, or approval as qualifying conduit) or a Bureau of Reclamation's lease of power privilege (LOPP). For the FERC pipeline, the following development stages are included: pending preliminary permit, issued preliminary permit, pending license (or exemption), issued license (or exemption), and projects under construction. For the LOPP pipeline, the following development stages are included: pending preliminary lease, issued preliminary lease, issued LOPP. To limit the number of categories shown in Figure 1, the stages of the LOPP process are presented under the most similar stage of the FERC development process. Pending preliminary lease is shown as Pending Permit, issued preliminary lease is shown as Issued Permit, and issued LOPP is shown as Issued License.



U.S. Pumped Storage Hydropower Development Pipeline, 2021

Map Source: Schmidt, E., Johnson, M.M., and Uría-Martínez, R. (2021). U.S. Pumped Storage Hydropower Development Pipeline Map 2021. HydroSource. Oak Ridge National Laboratory, Oak Ridge, TN. DOI: 10.21951/HMR_PipelineMaps/1814129

Data Source: Johnson, M.M., and Uría-Martínez, R., (2021). U.S. Hydropower Development Pipeline Data, 2021. DOI: 10.21951/HMR_PipelineFY21/1772802

*Projects in the Pending Preliminary Permit and Issued Preliminary Permit stages are undergoing feasibility studies and have high attrition rates.

**Pending License includes projects that have applied for authorization from FERC or Bureau of Reclamation. Issued License includes projects that have received federal authorization from one of the two agencies.

Figure 2. PSH project development pipeline by region and status in relation to state-level renewable energy targets (as of December 31, 2020)

Source: Schmidt et al. (2021b)

Note: This map is available for download at https://hydrosource.ornl.gov/map/us-pumped-storage-hydropower-development-pipeline-2021

At the end of 2020, there were 183 new projects (80 NPD retrofits, 94 conduit retrofits, and 9 NSD projects) in the U.S. conventional hydropower development pipeline, which is 15% lower than the average number of projects in the pipeline in 2016–2020. These 183 projects have a combined proposed capacity of 863 MW. The median capacity varies significantly across project types, from 89 kW for conduit retrofits to 4.5 MW for NPDs. The largest conventional hydropower project in the pipeline is the Uniontown Hydroelectric project in Indiana (66.6 MW). Most conduit retrofits are proposed in the Western half of the country and most NPDs are in the Eastern half. Eight of the nine NSD projects are either in Alaska or the Pacific Northwest. Over 70% of proposed capacity already has an issued Federal Energy Regulatory Commission (FERC) license; only two projects (two NPDs with combined capacity of 12 MW) were under construction at the end of 2020. Most other projects are at a much earlier stage of feasibility evaluation in which attrition rates have typically been very high.

The U.S. PSH development pipeline included 63 projects with combined proposed capacity of 46.7 GW at the end of 2020 (see Figure 2). This number is 17% higher than the average number of PSH projects in the pipeline in 2016–2020. Project sizes range from 10 MW to 3,600 MW and the median size is 500 MW. Twenty-two states had at least one PSH project in the pipeline at the end of 2020, with the greatest number of PSH projects in California, Nevada, and Arizona. Seventy percent of these PSH projects have preliminary permits to conduct feasibility evaluation studies. At the feasibility evaluation stage, just like with conventional hydropower, the attrition rate is very high. Three projects—Eagle Mountain (California, 1,300 MW), Swan Lake (Oregon, 393 MW), and Gordon Butte (Montana, 400 MW) already have a FERC license. No new PSH projects are currently under construction.

Aside from new projects in the development pipeline, 18 ongoing upgrades would add 176 MW to the existing conventional hydropower fleet and 250 MW to the existing PSH fleet.

1.3.2.1.2 Refurbishments and upgrades

The project development pipeline is only one dimension of U.S. demand for hydropower components, with substantial uncertainty as to the fraction of projects that will eventually be constructed. Since 1990, new construction has added 2.4 GW of conventional hydropower and 2.9 GW of PSH—3% and 13% of total installed capacity as of 2021, respectively. Most of the domestic activity for the U.S. hydropower supply chain in the past 30 years has been geared toward maintaining, refurbishing, modernizing, and upgrading the existing fleet.

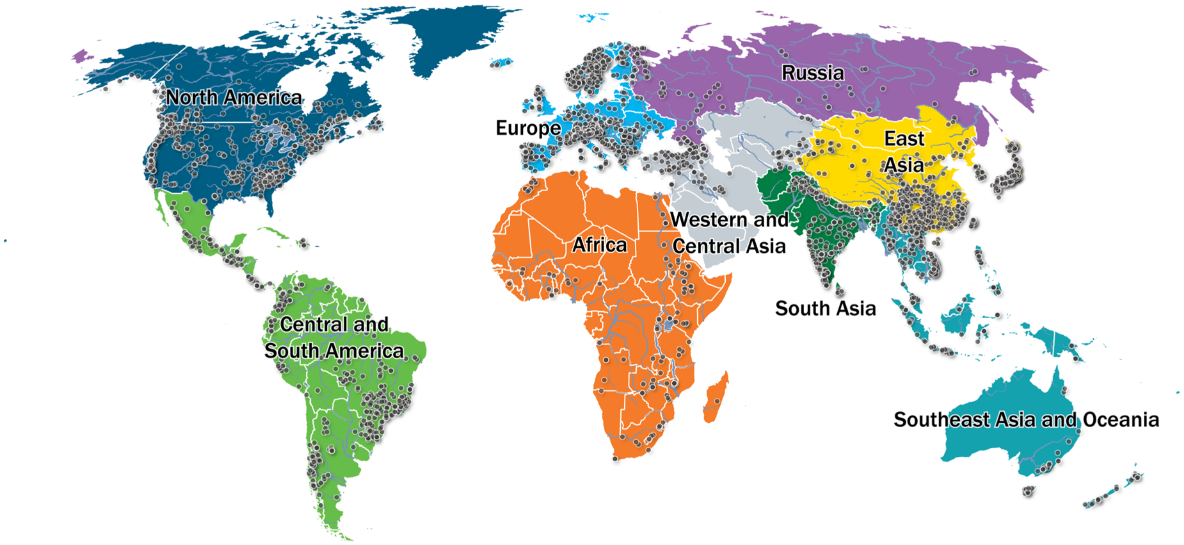
Uría-Martínez et al. (2021) report that at least $7.8 billion were invested in refurbishing and upgrading the U.S. conventional hydropower and PSH fleets during the 2010s. Turbine runner replacement or refurbishment, generator rewinds, installation of digital governors, and replacement or upgrades of floodgates or transformers were the most common items in the scope of the 339 tracked projects.

At the end of 2020, Industrial Information Resources reported planned new refurbishment and upgrade investments for 62 hydropower plants in the United States to start from 2021 to 2024. The estimated capital investment from these projects adds up to $4.4 billion. Sixty percent of this investment is in the early stages of developing a project justification, conducting preliminary design, and submission of authorization for expenditures. The most common scope items in these planned projects continue to be turbine modernization and generator rewinds. There are also several instances of governor and controls upgrades, and gate and crane refurbishments.

1.3.2.2 Global

Data on global hydropower development activity are of interest to U.S. supply chain participants for multiple reasons. First, U.S. manufacturers of hydropower components export part of their production to the global market and information on which world regions have most planned new projects can help them identify key target export markets. Second, given the interconnected nature of the global supply chain for hydropower components, the volume of hydropower development activity worldwide must be considered for an analysis of potential supply chain bottlenecks for the United States. This is especially the case for large turbines and generators where the number of suppliers is very limited.

The map in Figure 3 introduces the nine world regions considered through this report and shows where major conventional hydropower clusters are located.



Note: This map only includes projects ≥10 MW.

Figure 3. Map of operational conventional hydropower plants by world region

Source: Industrial Info Resources

Note: The dots represent the location of operational conventional hydropower plants

Based on data from GlobalData, a commercial provider of intelligence on key world industries, 151 GW of conventional hydropower and 30 GW of PSH were either under construction or had completed permitting and reached financial closure around the world at the end of 2020. An additional 188 GW of conventional hydropower and 49 GW of PSH were in the permitting phase. At an even earlier stage, plans have been announced for 268 GW of conventional hydropower and 53 GW of PSH without significant progress toward permitting or financing them. If 100% of projects in the Announced, Permitting, Financed, and Under Construction stages were built, they would result in a 57% increase in global conventional hydropower capacity and an 84% increase in global PSH capacity. Figure 4 and Figure 5 show the regional distribution of capacities at the various stages.

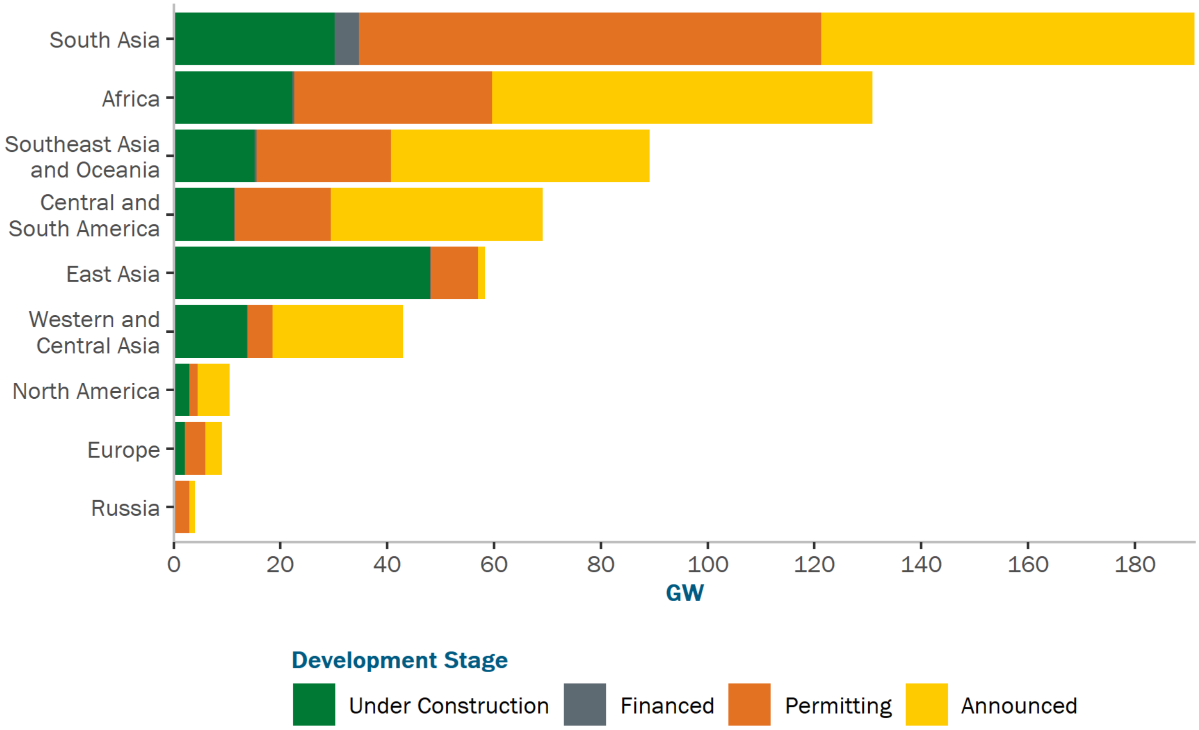


Figure 4. Global conventional hydropower development pipeline by region and development stage

Source: GlobalData

South Asia and Africa are the only two regions with more than 100 GW of conventional hydropower in the pipeline. East Asia leads the ranking in terms of conventional hydropower under construction (48 GW). North America, Europe, and Russia—the regions with the oldest conventional hydropower fleets—are the regions with the least amount of new capacity in the pipeline. For North America, 86% of the capacity shown in Figure 4 corresponds to projects located in Canada.

For conventional hydropower, given the size of the U.S. development pipeline relative to the global development pipeline, it should be expected that U.S. hydropower supply chain participants will pursue export opportunities in addition to supporting the domestic fleets.

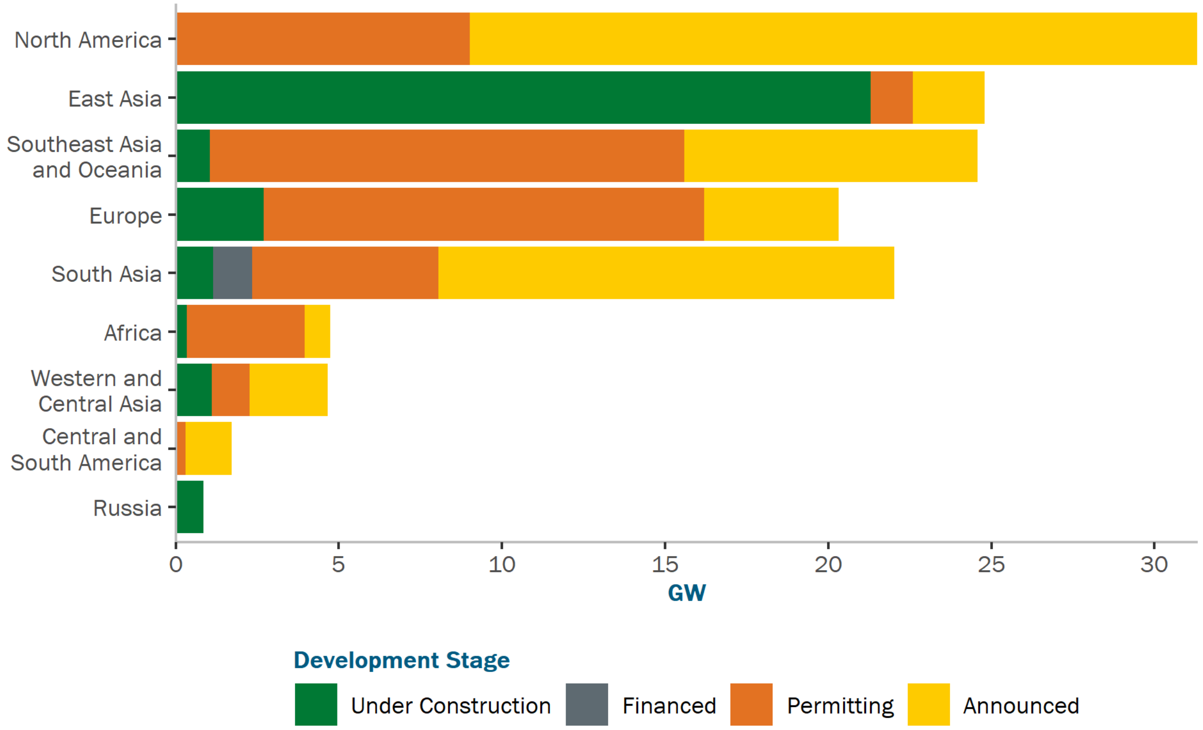


Figure 5. Global pumped storage hydropower development pipeline by region and development stage

Source: GlobalData

North America (defined here as the United States and Canada) leads the PSH pipeline and 45 of the 48 projects tracked by GlobalData in this region are in the United States.[8] However, none of the projects are under construction. North America and Central and South America are the only two regions with no PSH construction currently underway. In contrast, the region with the second largest PSH pipeline (East Asia), has 86% of the 25 GW in its pipeline under construction. Of the 23 PSH plants in the pipeline in that region, 18 are in China, 2 in Japan, and 3 in Mongolia. Europe and North America are the only two regions with more PSH capacity than conventional hydropower capacity in their development pipelines.

1.3.3 New hydropower required to meet decarbonization objectives

Figure 6 compares global hydropower installations in 2000–2018 with the estimated average annual global installations needed out to 2050 to meet different decarbonization objectives. IHA (2021) provides estimates of total hydropower capacity needed by 2050 for a scenario in which global warming is kept under 2 °C (850 GW) as well as the forecasted new hydropower needed based on the IEA's Net Zero Roadmap (1,300 GW).

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[8] GlobalData covers projects in all world regions, but its coverage of the U.S. development pipeline is not as complete or up-to-date as that in the U.S. dataset presented in Section 1.3.1.1. leading to some differences in the number of projects and capacity for the United States across the two datasets.

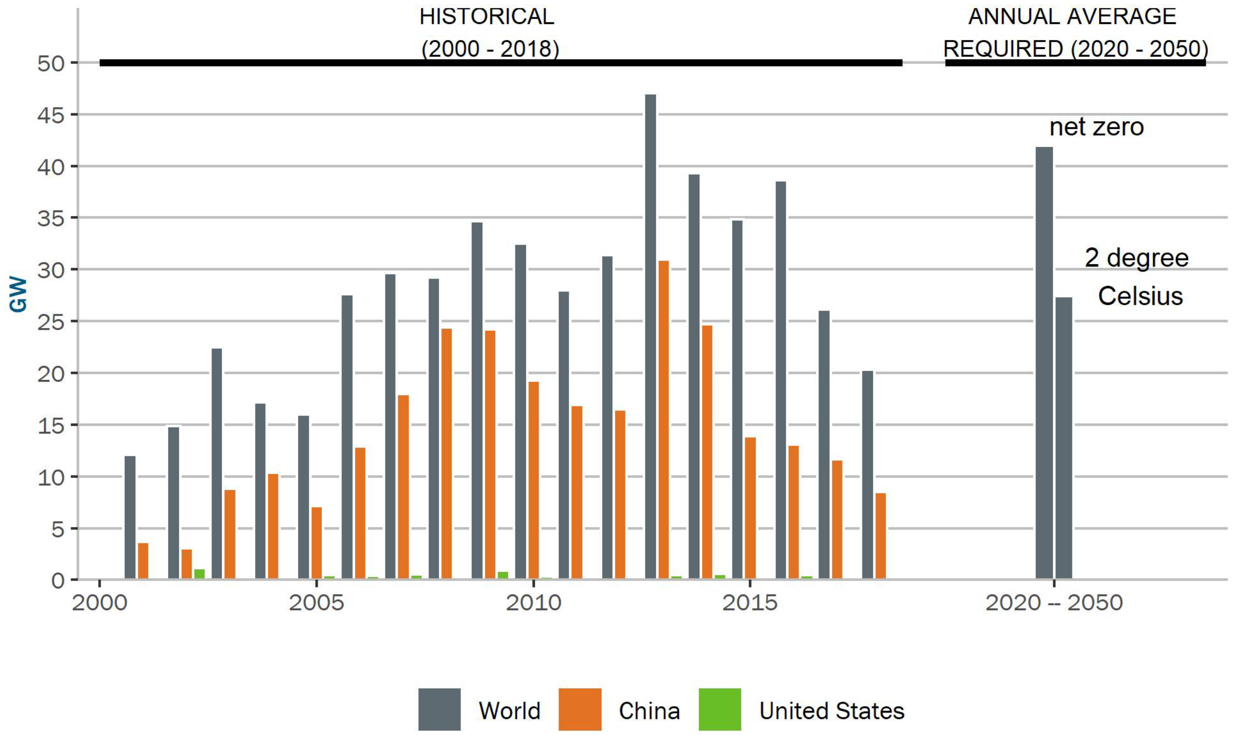


Figure 6. Recent hydropower (including PSH) installations versus average annual needs to 2050 to meet alternative decarbonization objectives.

Source: EIA, IHA (2021)

On average, from 2000 to 2018, 27 GW of hydropower (including PSH) were added globally per year. Maintaining that annual average from 2020 to 2050 would add 810 GW, very close to the estimated 850 GW needed by 2050 to keep global warming below 2°C. However, a substantial scale-up in construction would be required to construct the 1,300 GW estimated as necessary for a net zero energy sector by 2050. For comparison, the total capacity (conventional hydropower plus PSH) in the development pipeline at the end of 2020, presented in Figure 4 and Figure 5, would add 739 GW of which 321 GW are at a very early stage of development with substantial uncertainty about their progressing to construction.

Of the global capacity added from 2000 to 2018, 51% has been in China. If decarbonization-driven development substantially changes the regional fractions of new construction going forward, the supply chain might need to adjust accordingly in terms of manufacturing locations, workforce etc.

The manufacturing capacity required to service global demand for hydropower-specific components in the next three decades does not depend on greenfield projects alone. Figure 6 shows capacity added in new projects as well as through installation of additional turbine-generator units at existing plants and uprates (i.e., power rating increases) of existing units. However, Figure 6 does not include refurbished capacity. In some regions, most of the demand for hydropower components results from refurbishment or modernization of existing plants without adding significant new capacity. This is especially true for the United States where turbine manufacturers stated that refurbishments and upgrades have accounted for 90% or more of the domestic demand in recent years. On the other hand, globally, one major turbine manufacturer mentioned that their work has typically been in a ratio of one brownfield project to two greenfield projects. To reach a net zero energy sector, the hydropower supply chain would need to be scaled so that it can meet the demands for refurbishments, upgrades, and new construction.

2 Supply Chain Mapping

2.1 Technology Overview

The following is a brief description of hydropower energy generation to illustrate the key components. A hydropower plant converts potential energy, in the form of an elevated body of water, into kinetic energy through water flow, into mechanical energy by rotating the turbine, and then into electrical energy by rotating the generator. As the turbine spins so does the generator rotor whose outer surface is covered in electromagnets (field poles). As those electromagnets move past the copper windings covering the surface of the generator stator, alternating current is generated. A step-up transformer converts the alternating current to high voltage current that can be transported over the electric transmission grid. Water flow into the turbine is controlled through gates and valves, which allows for isolation of the turbine-generator units during maintenance or emergencies.

A hydropower plant often has multiple turbine-generator units which limits the number of single points of failure to plant operations. Figure 7 shows the major components of a Kaplan type turbine-generator unit. The configuration of hydropower plants is highly site-specific, with multiple custom components that require long lead times for their replacement. This section describes in more detail the characteristics and function of a list of hydropower plant components. All of them are critical to turbine-generator unit operations making their supply chains the focus of this study. Hydropower facilities contain highly customized components combined into systems that are designed to fit the specifics of their environment. This environment is dictated by water availability in terms of head and flow. Since components and overall facilities are unique, general arrangements will be similar, but interchangeability of components is limited.

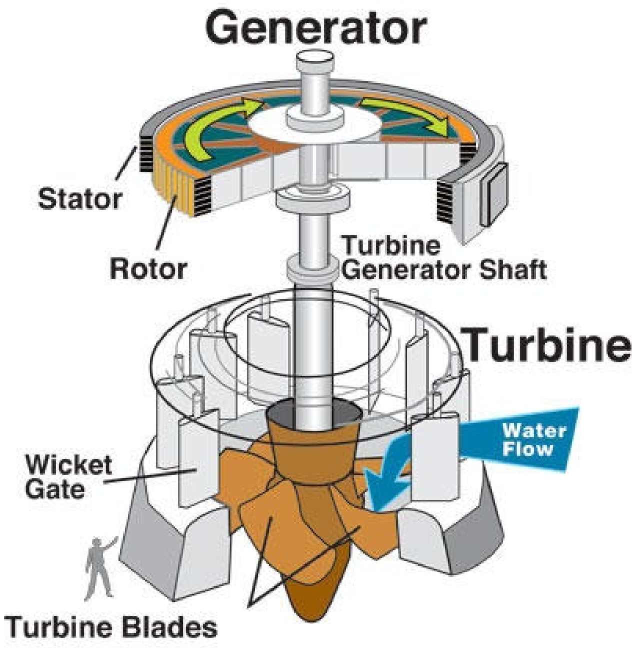


Figure 7. Diagram of a Kaplan-type hydroelectric turbine-generator unit

Source: Courtesy of U.S. Army Corps of Engineers. Wikimedia: Creative Commons License.

2.1.1 Turbine

There are multiple types of turbines and selection depends on the combination of water flow and head—the difference in elevation between the water intake point and the water discharge point—available at the site, among other factors. The two major families of turbines are impulse and reaction turbines. Reaction turbines, such as Francis and Kaplan, are fully immersed in water and are ideal for low-head, high-flow systems. Impulse turbines, such as Pelton, operate in air and driven by high-velocity jets of water and are the typical choice in high-head sites (Canyon Hydro, n.d.). Selecting the appropriate curvature for the turbine blades and high-quality casting materials are among the choices that help maximize the generation efficiency of the resulting unit.

The hydropower turbine has several components, mostly made of steel (carbon or stainless), that require custom design and fabrication:

- Scroll case: It is a custom-made, steel spiral casing that surrounds the turbine runner. It is the first component reached by the water flow as it exits the penstock. These are typically made of fabricated carbon steel plate.
- Runner: Blades (in reaction turbines) or buckets (in impulse turbines) designed to capture the maximum energy from the water passing through. Runners and blades are custom-made from steel (carbon or stainless) castings, forgings, and in some cases, plate.
- Wicket gates: Adjustable gates/vanes to control the flow of water through the turbine, made of steel (carbon or stainless) castings or forgings.
- Draft tube (only applies to reaction turbines): It connects the turbine outlet to the tailrace. They are custom-designed civil structures made of cemented concrete with a cast steel lining to avoid cavitation. The draft tube brings the pressure of the water flowing out of the turbine back to atmospheric pressure. Draft tubes are typically fabricated from carbon steel plate.
- Headcover: It provides separation of the wet turbine elements, including runner and wicket gates, from the dry powerhouse elements, including the generator and wicket gate operating servomotors. Headcovers are engineered to be pressurized on the water side and to support wicket gate elements. Components of the headcover may be constructed from steel plate, castings, and forgings.
- Bearings: Turbine guide bearings are typically bushings, made of babbitt, composite, or Polytetrafluoroethylene (PTFE), a Teflon-type material.

2.1.2 Generator

The description in this section draws primarily from a design manual for hydropower generators published by Bureau of Reclamation (Bureau of Reclamation, 1992). Generators, particularly for large units such as those with power rating greater than 100 MW, require custom design and fabrication. The major parts of a generator are:

- Shaft: It connects the generator with the turbine. It is typically made of forged steel.
- Rotor: It is the rotating part of the generator. It rotates at a fixed speed determined by the turbine. The rotor is connected to the shaft and its outer surface is covered with field poles.
    - The field poles are built from thin laminations of magnetic material.
    - The rotor spider transmits torque and rotation from the shaft to the rotor rim and poles and provides supporting structure for the poles. It is often made of forged and fabricated steel.
- Stator: It concentrates the magnetic field from the rotor to produce the induced voltage in the armature.

  - The stator frame provides the structure to support the stator core and windings. It is made of thick fabricated steel plates.
  - The stator core is made of stacked thin laminations of electrical grade steel and coated on each side with insulation. It is built inside a cage which is then attached to the stator frame (GE Energy, n.d.).
  - The stator windings are coils made of copper and insulating material and they are wedged into stator core slots. They are custom-made for each installation and spares must be acquired when the generator is first purchased to ensure availability when the need for repair arises.
    - Insulation materials for stator windings have changed over time and the standard base materials are now glass fibre, mica dust, or polyester fiber. There are also multiple options for the insulation binder materials. The standard used to be asphalt before the 1960s and since then polyester-vacuum pressure impregnation (VPI) hybrids and several kinds of epoxy have also been introduced (BBA, 2019).
- Bearings: Generator bearings may be roller type or journal type bushings. Thrust bearings are used to support the generator in vertical units, or to resist the hydraulic forces imparted by water on the turbine in horizontal reaction turbines. Typical bearing material is babbitt, composite, or PTFE material. Roller type bearings are used in some applications as well.

2.1.3 Governor

The governor regulates the rotational speed, power output, and system frequency of the turbine-generator units by controlling the flow of water through opening/closing of the wicket gates. It involves control and actuating components. Governors are hydraulic systems with common components across many industries. The below summary discusses how these hydraulic systems have changed over time.

- Speed sensing devices have changed over different generations of governors. Early mechanical-hydraulic governors had a fly-ball type pendulum. The second generation of electro-hydraulic governors had a frequency transducer as speed sensing device (Vu and Agee, 1998). In modern digital governors, the speed signals are provided by a digital control algorithm and electronic circuits.
- Hydraulic pressure units (HPUs) include a pressure oil tank, oil sump, air compressor, oil filtration system, oil pump or motor, and piping. Their function is to supply pressurized oil to a servomotor to adjust the position of the wicket gates. For emergency shutdowns (i.e., loss of station power or grid), systems will be equipped with an air-over-oil pressure tank or a bladder accumulator to stop water flow through the turbine.
- Controls can be mechanical, analog, or digital.
  - Digital governors help increase plant automation, include built-in diagnostic tools for better fault detection, and allow more precise turbine control. A digital governor is required by system operators for a plant to qualify for provision of certain ancillary services. A potential downside from digital governors is their frequent obsolescence that forces replacement of the programmable logic controllers (PLCs) every five to 15 years despite not having experienced any failures. Also, at least in some cases, a digital governor eliminates the option for manually controlling a unit.

2.1.4 Excitation system

The excitation system, consisting of electronic circuitry and components, supplies and regulates the amount of direct current (DC) needed by the generator rotor windings. Hydropower exciters are typically shaft-mounted rotating systems energized through contacting brushes. These are being replaced with modern equivalents, including:

- Static exciter: Static excitation systems can be of two types (inverting and semi-inverting) depending on the speed of generator field suppression required.
- Brushless or rotating rectifier exciter: It uses rotating rectifiers that are directly connected to the generator field poles, eliminating the need for brushes. It is used in smaller hydropower generators where large excitation current is not needed.

2.1.5 Switchgear

The generator switchgear is located between the generator and the step-up transformer and serves to synchronize the frequency, voltage, and phase of the electricity exiting the generator with those of the grid.

- Circuit breakers: There are four types depending on the medium they use for arc interruption: air, oil, sulfur hexafluoride (SF6), or vacuum.
- Surge arresters: They protect the generators from overvoltage.

2.1.6 Emergency closure systems

When closed, intake gate closure systems stop water from the dam reservoir from reaching the turbine. They are made of fabricated steel. For emergency deployment, they can be operated via accumulators on the hydraulic system, gravity deployment, or automated cranes. For normal operation, they can be operated with a hydraulic system, a wire rope hoist system, or a crane (Gore et al., 2001).

2.1.7 Penstock

The penstock is the conduit transporting water flow from the intake point to the turbine. A hydropower plant can have multiple penstocks to convey water to different units. Alternatively, a single penstock can be bifurcated or trifurcated to distribute the flow to multiple turbine-generator units.

Steel is the most common raw material for penstocks, but they can also be made from other materials, including wood stave (largely out of use for new installations but still present in some old projects), fiberglass, and high-density polyethylene plastic. Multiple materials and various wall thicknesses (as pressures increase) may be utilized in a single installation.

2.1.8 Bypass systems

In the event of inflow greater than turbine capacity, or turbine(s) being offline, alternative passages of water are required at hydroelectric generation plants.

- Spillways: Gated concrete structures having ideal shapes to pass flow. These are typically gated with large steel structures that operate using wire rope hoists or hydraulic hoists.
- Overflow spillway: These spillways are unregulated, meaning water is not controlled as it passes. Water will reach a specific elevation, then overflow this type of spillway. It is constructed of concrete.

- Turbine bypass: In facilities where the powerhouse is a significant distance away from the dam or spillway, a bypass system is required. These are typically valve-controlled systems within the penstock where a turbine inlet valve will be closed and a bypass valve opened on a parallel water passage route. A dissipation valve or structure will be placed at the bypass outlet to minimize energy in the water jet being discharged. The bypass and valve structures are largely made of steel, cast steel, and stainless steel.

2.1.9 Balance of plant

This category includes auxiliary systems such as compressed air systems, oil delivery and storage, plant temperature control, hoists, and components that are not hydropower-specific but still critical to plant operation such as batteries, transformers, and cranes.

2.2 Industry Structure

Along with a whole range of mechanical, electrical, and electronic components associated with moving water and operating the powertrain, consisting of the turbine and generator, a hydropower plant often includes extensive civil works and other supporting structures. Most of the materials and services for the construction of civil works and other structures in the United States are met by domestic companies.

Turbines and large generators are the key hydropower-specific components built by companies (or company divisions) exclusively dedicated to serve the hydropower sector. Thus, the industry structure discussed in this section focuses largely on the turbine-generator manufacturing supply chain.

Steel, stainless steel, and copper are the main raw materials needed to build many of the components listed in the previous section; they are the raw material industries most important for hydropower supply chains.

Even though turbines and generators operate as a unit, they are sometimes produced by separate companies. In the past, there was a greater separation between companies that supply turbines and generators as they require different types of expertise. The Bureau of Reclamation (1992) explains that, during the decades in which most of its fleet was constructed, there was only one U.S. manufacturer and a few international manufacturers that could provide both the turbine and the generator. To increase their procurement options, they typically announced requests for bids separately for turbines and generators. Nowadays, the major turbine manufacturers also provide generators either through self-production, where turbine manufacturers have acquired or merged with generator manufacturers to enhance their ability to supply the entire powertrain, or through joint ventures with generator manufacturers. For small units, several manufacturers offer “water-to-wire” packages where the turbine and generator are supplied as a set along with other components such as automated controls, turbine inlet valve, and switchgear.

The manufacturing process for a new turbine or turbine runner takes multiple years and involves many steps as designs are dictated by the water flow and head criteria of the specific site. The unit is first designed and tested computationally using Finite Element Analysis and Computational Fluid Dynamics methods. Then, for a new turbine runner design, a prototype might be produced and further tested, a step that can add one year to the process. The manufacturing process traditionally starts by ordering a steel casting from a foundry. The casting process involves heating up the material to its melting point and pouring it into a mold to obtain the desired shape. The resulting casting is then machined to introduce features that cannot be produced during the casting process. It has become standard to use computer numerical control (CNC) machining rather than conventional machining. CNC machining is a subtractive manufacturing process, where a tool chips away steel shavings from the initial single piece to achieve the desired shape, guided by computer-aided design (CAD) software (Formlabs, n.d.). Finally, turbine runners are manually polished to achieve a smooth finish.

The manufacturing process described in the previous paragraph follows subtractive manufacturing principles where the starting point is a solid block from which material is removed until the desired shape is achieved. In contrast, additive manufacturing (AM) is characterized by the absence of a mold, die, machine (e.g., mill, grinder), or other tool designed to produce the target geometry. Instead, AM processes involve depositing layers of materials and consolidating them to create a solid object. A wide range of metals or polymers are used in these processes and some final machining is often needed to achieve the exact dimensions required. This can be accomplished via post-build machining or with the use of a hybrid system in which there is a subtractive function available, along with the additive process, to provide more accurate geometry. AM processes are mostly still in the research and development (R&D) phase for applications in the hydropower industry, but some manufacturers have started applying them to the manufacturing of hydropower turbines either to produce components like blades in small turbines or to 3D-print casting molds.

Other turbine components such as the scroll case, head cover, wicket gates, or draft tube are also made of steel using manufacturing processes such as turning, forging, rolling, and bending. The various turbine components are finally welded together (Kafle et al., 2020).

For generators, many of the parts are made of steel using similar processes and tooling as discussed for turbine components. However, the stator winding coils require an entirely different manufacturing process. At a coil manufacturing facility, strands of copper to manufacture the copper windings are drawn from copper reels. The two main coil structures typically used in hydropower generators are single-turn bars or multi-turn coils. In multi-turn coils, strands are insulated. Multiple strands form a turn and additional insulation is applied at the turn level. Then, the turns are assembled into full loops and a spreading machine is used to create the basic coil shape. Next, ground wall insulation tapes are applied and the coils are cured. Single-turn bars do not make a full loop; they are “half-coils”. For small units, the coils are placed into the stator slots at the factory; for large units, placement into the stator slots takes place at the plant site.

Specialized machining shops are also key components of the hydropower supply chain to serve the needs of plant owners facing extinct supply chains for some of their plant components (e.g., some machine shops are able to reverse engineer old mechanical governor components) or needing refurbishment of custom components such as gates.

Once manufactured, transportation of the turbine and generator components within the United States can be by barge, rail, and/or truck depending on the size and weight of the components as well as the plant site location. Transportation logistics are considered by manufacturers in deciding whether the product can be shipped fully assembled or broken into multiple parts that can more easily be transported via truck for final assembly at the plant site. Barge transportation is used frequently for transporting large components to plants that are located on navigable main river stems. When manufacturing takes place overseas, ocean shipping is almost always the chosen transportation mode. However, there are also instances of air shipping when the dimensions of the component allow it and it is especially urgent for the plant owner to receive it.

The turbine-generator package is typically designed first, with the conveyance system and powerhouse designed around it. The turbine production and civil construction are typically parallel efforts. As the turbine and generator are being manufactured, there is significant back and forth between the turbine designers, facility design engineers, and construction companies. The foundation of the turbine-generator system is critical for alignment with the conveyance system, discharge system, and bypass system. The design and construction of the powerhouse will occur on a timeline to accept the turbine-generator package when it is shipped to the site. Climate-controlled shipping and storage may be considerations for the generator due to its sensitivity.

At the end of its operational life, hydropower plant materials for which there is an active market (steel, copper) are typically recycled. The value of these materials is often factored in as a credit in contractor bids. Some of the stakeholders interviewed acknowledged not giving much thought to other initiatives to avoid landfilling given the long operational life of most hydropower plant components and the recycling practices already in place. Some examples were mentioned where old turbine runners are used by the manufacturers for training schools or testing purposes.

Disposal of hazardous substances also receives special attention. The list of hazardous substances in a hydropower plant may include oil, asbestos (typically found on generator windings and insulations for units constructed from the 1930s to the 1980s), and lead (found sometimes in old turbine runners). Presence of hazardous substances associated with the copper or steel components can make their recycling more difficult.

2.3 U.S. Production Capabilities

NHA’s inventory of U.S. hydropower supply chain companies contains more than 2,500 entries but no easy way to categorize the goods or services provided by each company. Table 1 shows the top 10 states by number of companies in NHA’s inventory; together they account for more than 60% of the total number of companies.

Table 1. Top 10 States by Number of Companies in the U.S. Hydropower Supply Chain

State	Number of Companies
Pennsylvania	324
California	247
Washington	202
Wisconsin	147
Ohio	133
Illinois	129
Alabama	121
Oregon	109
Michigan	83
Massachusetts	80

Source: NHA

The ten states in Table 1 include the three with the largest installed hydropower capacities (Washington, California, and Oregon) but also others that have small hydropower fleets. For states like Pennsylvania (by far the one with the largest number of companies), Wisconsin, Ohio, and Michigan, it is their proximity to steel mills and related manufacturing that made them attractive. In fact, a large fraction of the companies that serve the hydropower supply chain are not exclusively dedicated to it. For instance, machine shops serve a variety of industries as do companies producing pipes or even those manufacturing small generators or industrial controls.

Why Aren't We Looking at More Hydropower?

By Lindsay Fendt – Ask MIT Climate – March 2, 2021

Hydropower is already a major source of power globally—it's the largest source of renewable electricity and one of the fastest growing—but there are limited places to build hydropower, and large dams carry a number of social and environmental concerns.

While wind and solar often dominate conversations about low-carbon electricity, hydropower provides much more electricity worldwide than any other low-carbon energy source—nearly eight times more than solar power and 1.5 times more than nuclear. And it's one of the fastest-growing sources of renewable energy: according to the International Energy Agency, hydro saw more growth between 2008 and 2018 than any other source of renewable electricity other than wind power.

"If you look at some of the most dramatic proposals for a pathway to zero carbon electricity system, they all need to incorporate a significant build out of hydropower," says John Parsons, an energy economist with MIT's Center for Energy and Environmental Policy Research.

However, large hydroelectric dams can't be built just anywhere. Hydro plants need a consistent supply of water and a large amount of land. Some countries have plenty of these resources; others do not.

Poorly planned hydropower can also cause more problems for the climate than it prevents. Hydro plants need large reservoirs to provide a steady stream of water. When these reservoirs are built, plants and other organic matter get flooded. This material decays over time, releasing greenhouse gases like carbon dioxide and methane. According to Parsons, there hasn't been much research measuring these emissions, but the studies that have been done have found huge differences from reservoir to reservoir.

"People are right to think of hydro as a low-carbon resource, but the variability is very high and there are some reservoirs that have lifecycle emissions of greenhouse gases that are higher per unit of electricity produced than a fossil plant," he says. "You don't want to just be advocating hydro everywhere."

Many wealthy countries, including the U.S., have already built out most of their suitable hydro resources. The countries adding large amounts of hydro are mainly growing economies in East Asia and South America. Places like China and Brazil have large planned hydro projects that will come online in the next few years, but rather than replace fossil fuel resources, these dams will be used to expand electricity access to areas that don't have it. These enormous projects generate large amounts of electricity and cost billions of dollars.

"Hydro resources often require a very long-term investment horizon," Parsons says. "When you invest in building out a hydro reservoir, it's usually as a part of a very big economic development strategy over a couple of decades."

Hydropower can also cause environmental and social problems. Reservoirs drastically change the landscape and rivers they are built on. Dams and reservoirs can reduce river flows, raise water temperature, degrade water quality and cause sediment to build up. This has negative impacts on fish, birds and other wildlife.

These environmental impacts often spill over to humans as well. The World Bank estimated in 2000 that between 40 and 80 million people had been directly displaced by dams and reservoirs.2 Another study from 2010 estimated that 472 million people downstream from large dams suffer from reduced food security, regular flooding or impacts on their livelihood.3

So while hydropower is a good source of low-carbon electricity, even countries with plenty of untapped water need to weigh the benefits of hydro against the environmental and social costs of dam projects. There's still room for hydro to grow, but most countries will not build out as much hydropower as they theoretically could—and that may be for the best.

Do We Have the Technology to Go Carbon-Neutral Today?

By Kathryn Tso – Ask MIT Climate – September 28, 2020

We still need new breakthroughs to decarbonize many parts of our modern economy, especially if we don't want to drive up the price of energy and goods. But we can make real progress with today's technology, and invest in good ideas for the next generation of low-carbon solutions.

What would our world look like if we became completely carbon neutral? Could we still enjoy today's electricity, transportation, heat and manufacturing if we put no more greenhouse gases into the atmosphere than we take back out? "Unfortunately, these are not solved problems," says Desiree Plata, MIT Professor of Civil and Environmental Engineering. "While we do have the technology to make a lot of systems nearly carbon neutral, none of these systems can run the same way they do today and the cost to implement [some of today's solutions] is prohibitively high."

First, the good news. We've gotten pretty good at making low-carbon electricity. Today, solar panels and wind turbines can make electricity at a similar price to coal or natural gas. And we can also use that clean electricity to drive (like with electric cars) and to heat our homes and water (like with electric furnaces and hot water heaters): things that today mostly run on oil or gas.

However, says Plata, it's not so simple to switch out the old, fossil fuel technologies for the new, low-carbon ones. Solar and wind power aren't always there when we need them, the way coal and gas are. "For example," Plata says, "solar energy is best captured and stored during the middle of the day, but is least accessible at night when the demand increases. One of the only technologies to meet that rapidly accelerating demand is fossil-derived carbon." In other words, we still need fossil fuels to fill the gap when we don't have enough sun or wind. To get more of our electricity from wind and solar, we first have to change the way we use and distribute electricity, or come up with better ways to store energy that can work on a large scale and at low cost.

Then there are areas where today's carbon neutral technologies can't match the performance of fossil fuels. "Transportation would have to change drastically, as carbon neutral energy cannot provide as much power for large vessels as fossil fuels," says Plata. "Think about air travel. Solar planes have to be very lightweight. So, passenger jets have to be shrunken down from the traditional form to much smaller units. Instead of an Air Bus, you need an Air Car." Heavy trucks and rail transport have similar limitations.

Finally, there are areas where our technology isn't ready to support a switch to cleaner energy sources at all. The steel and concrete manufacturing sectors in particular don't yet have options to stop using fossil fuels to generate the high amount of heat they need. So, the next best method is to capture and store the carbon dioxide these facilities emit when they burn fossil fuels. Some factories around the world, making everything from fertilizer to steel to gas, have been adding carbon capture technologies in recent years, effectively keeping their carbon emissions out of the atmosphere. And some coal- and gas-fired power plants have started to follow suit.

“This has grown appreciably in the last decade,” says Plata. However, “there is a significant cost to implement these technologies, measured in millions of dollars to stand up the needed infrastructure. This is not currently economical for most plants, and it only becomes economical if you put a price on the carbon to incentivize its trapping.” That’s one example of a political solution that could work alongside technological ones: if companies had to pay for the greenhouse gases they emit, they would have an incentive to become carbon neutral even with today’s technologies.

Just because we don’t have all the technology we need to overcome the climate crisis today doesn’t mean there’s nothing to be done. We are far from using today’s technologies to their full potential. Wind and solar power, carbon capture, and electrified heat and transportation all have lots of room to grow. And for those sectors where we still need new options, scientists and engineers are working on innovative approaches to energy storage, manufacturing, new transportation fuels, automated and low carbon air travel, and everything in between. “It’s a great time to be a technologist,” says Plata. “There are so many ways young scientists, engineers, and policy architects can contribute to solve these important problems.”

INTRODUCTION

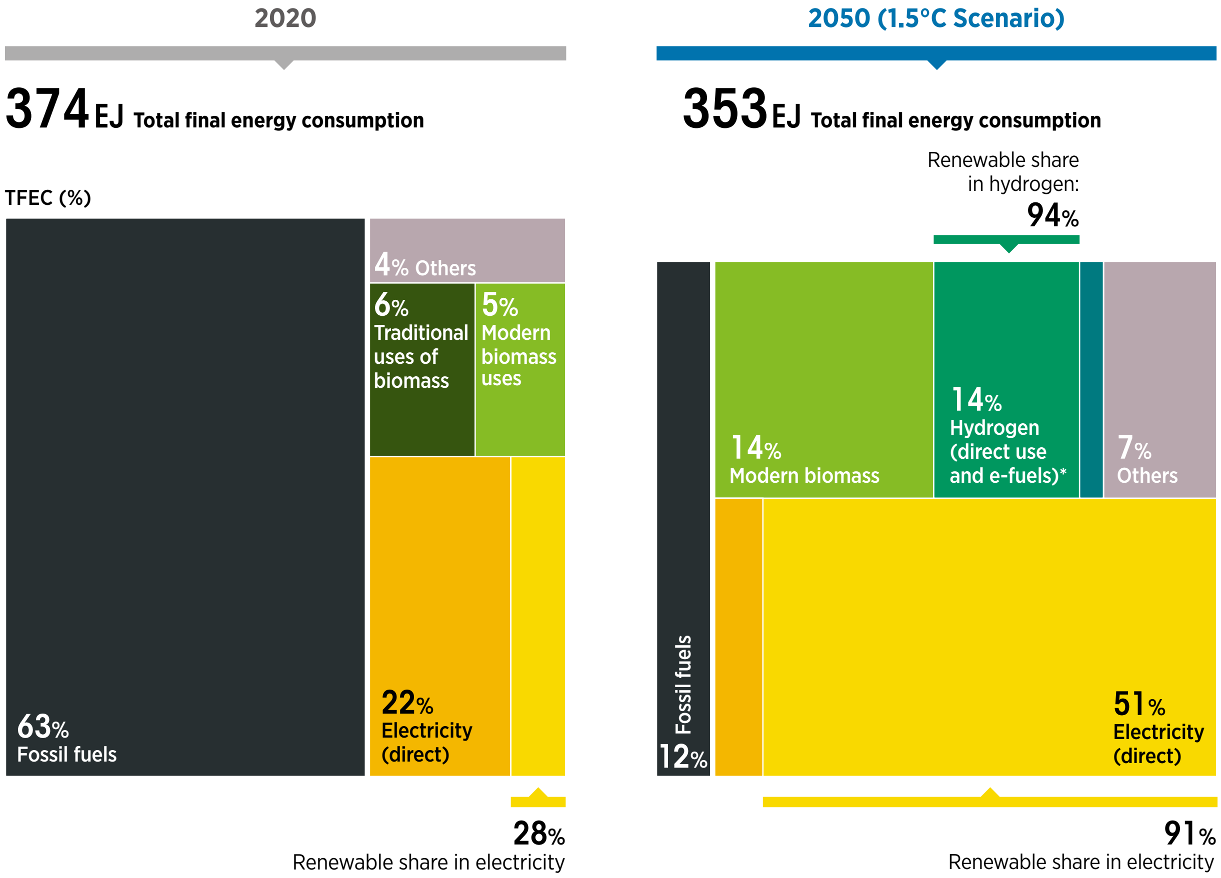
Systemic innovation is needed to achieve smart electrification of end-use sectors

The world has already begun a historic shift towards cleaner sources of energy. Rapid reductions in the cost of solar and wind technologies have led to widespread adoption of these technologies, which are now dominating the global market for new power generation capacity.

But the pace of change must accelerate if we are to meet sustainability and climate goals. We need an even faster expansion of renewables, along with a smarter, much more flexible electricity grid. Equally important is the need for significant increases in the range of products and processes that run on clean electricity in major end-use sectors, notably industry, buildings and transport.

Because the electrification of end uses enables the use of efficient technologies, widespread electrification – combined with efficiency measures – will decrease total global energy consumption. In IRENA's analysis, meeting the goals of the 2015 Paris Agreement on Climate Change will require the share of electricity in the energy mix to rise from 22% in 2020 to 51% in 2050, as shown in Figure I.1.

FIGURE I.1 | **Final energy mix in 2018 and 2050**



Source: (IRENA, 2023).

But the electrification of end uses alone is not enough. Electrification must be done in a "smart" way, both by interconnecting the power sector with other energy sectors, such as heat and mobility, and by enabling flexible sources across all energy sectors. Electric vehicles, for example, not only cut greenhouse gas emissions dramatically, they can also feed electricity to the grid, reducing the need to build additional generation capacity. Smart electrification, through sector coupling, flexibility and energy efficiency, thus prevents a higher electricity load for the power system and is a tremendously powerful tool for decarbonising the energy sector, including end uses.

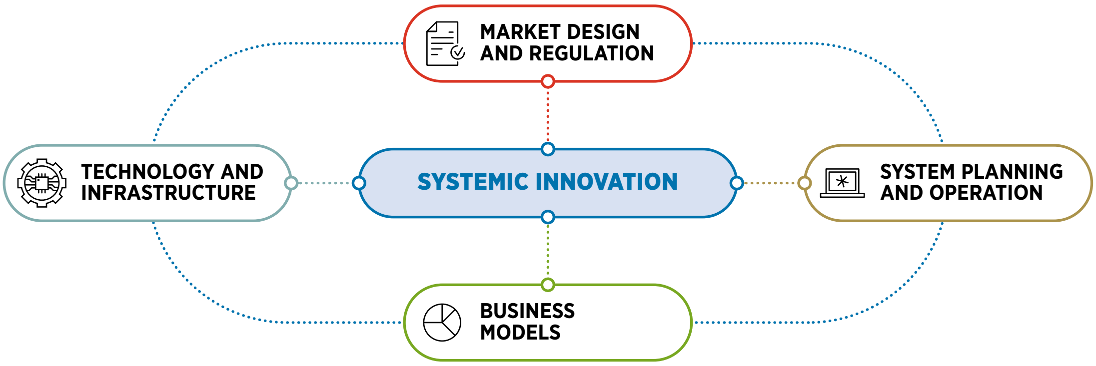
Smart electrification enables the power system to accommodate new loads in a cost-efficient manner. It also builds flexibility into the power system, thereby permitting the integration of a higher share of renewables and making the power system more robust and resilient. Smart electrification is the most cost-effective solution for decarbonising major end uses such as transport and heating.

Moreover, smart electrification with renewables creates a virtuous cycle. Electrification drives new uses and markets for renewables. That, in turn, accelerates the switch to electricity for end uses, creating even more flexibility and driving further growth in the use of renewables and continued technological innovation. Growth and innovation also cut costs and create additional opportunities for investment and business.

Innovation is the foundation for smart electrification and the global energy transformation. Most innovations cannot be implemented in isolation, nor are they limited to technology-based solutions. Along with innovation in technology and infrastructure, innovations are also needed in market design and regulation, system planning and operation, and business models. Innovative solutions will consequently emerge from the complementarities of advances across multiple components of energy systems and leveraging the synergies of these innovations in a process called *systemic innovation.*

The 100 key innovations identified in this report are spread across four dimensions: (1) technology and infrastructure, (2) market design and regulation, (3) system planning and operation, and (4) business models (Figure I.2). It is only by matching and leveraging synergies in innovations in all parts of the power system and end-use sectors and including all relevant actors and stakeholders that successful solutions can be implemented on the ground.

FIGURE I.2 | Dimensions of systemic innovation



Smart electrification cannot be pre-packaged. Optimal strategies for power system design and the application of innovation will vary among countries and their specific attributes, including both the technical and economic aspects of a given power system and its social and cultural context.

Electricity will be the main energy carrier in future energy systems

Achieving the Paris Agreement goal of limiting the increase in the global average temperature to 1.5°C relative to pre-industrial levels is the unifying principle behind IRENA's 1.5°C Scenario. To achieve that scenario, the share of electricity in total final energy consumption (TFEC) will have to grow from 21% in 2019 to 29% by 2030, and to 51% by 2050; this can be achieved through tremendous growth in technologies that operate on electricity, many of which are already available (IRENA, 2023). These include electric vehicles (EVs) and heat pumps, which provide heat for buildings and many industrial processes. In addition, end uses that are difficult to electrify directly, such as other industrial processes, can be electrified and decarbonised indirectly with "green" hydrogen produced using renewably generated electricity.

By 2050, global electricity demand is set to be 3 times what it was in 2020, posing challenges for power systems and raising the importance of energy efficiency. However, given the enormous benefits of electrification and decarbonisation, governments around the world should not see rapid, smart electrification as a threat or onerous task but rather as a golden opportunity to accelerate economic growth, improve energy security (Box I.1), reduce the growing impacts of climate change and achieve other important sustainability goals.

Table I.1 summarises the levels of electrification needed to reach the Paris Agreement targets.

TABLE I.1 | Electrification progress towards 2050 based on IRENA's 1.5°C Scenario

	Recent years	2030	2050
Share of direct electricity in total final energy consumption	22% (1)	29%	51%
Share of electricity in transport sector TFEC (%)	1% (2)	7%	52%
Share of electricity in the buildings sector (in TFEC terms)	34% (3)	53%	73%
Share of electricity in industry (TFEC)	20% (4)	25%	27%
Electric and plug-in hydrid light passenger vehicles stock (millions)	10 (5)	359	2 182
Passenger electric cars on the road (millions)	10.5 (6)	360	2 180
Electric vehicle chargers (millions)	1 (7)	372	2 300

	Recent years	2030	2050
Heat pumps in industry (in millions)	<1 (8)	35	80
Heat pumps in buildings (in millions)	58 (9)	447	793
Investment needed in heat pumps (USD billion/year)	64 (10)	237	230
Clean hydrogen production[b] (million tonnes per year)	0.7 (11)	125	523
Investment needs in clean hydrogen and derivitives infrastructure (including electrolysers, feedstock and infrastructure) (USD billion/year)	1.1 (12)	100	170
Industrial consumption of clean hydrogen (EJ)	0	14.4	40

Source: (IRENA, 2023b).

Notes: [1.] 2020; [2.] 2020; [3.] 2020; [4.] 2020; [5.] 2020; [6.] 2022; [7.] 2020; [8.] 2020; [9.] 2020; [10.] 2022; [11.] 2021 - clean hydrogen here refers to the combination of hydrogen produced by electrolysis powered by renewables (green hydrogen) and hydrogen produced from natural gas in combination with carbon capture and storage (blue hydrogen); [12.] 2022.

BOX I.1 | Electrification and energy security in Europe

The onset of the crisis in Ukraine in February 2022 triggered a severe energy crisis in Europe. Not only did the price of natural gas from Russia soar, but electricity prices also climbed steeply because of the still high use of gas to generate power. As a result, European industries, which are highly reliant on natural gas, are losing competitiveness, and energy bills for European citizens have soared dramatically.

This energy crisis is revealing the need for Europe to accelerate its energy transition. In addition to lessening the impacts of climate change, resilient and more secure energy systems will ensure stability, competitiveness, affordability and sustainability. Integrating high shares of renewables in the power system and using the resulting clean electricity to fuel end uses will decrease the dependence on gas that helped cause the current crisis. The current energy crisis in Europe may ultimately be an accelerator for the much-needed energy transition.

Snapshot freddy © Shutterstock.com

Innovation landscape for smart electrification of end-use sectors

This report presents a landscape of innovations to help policy makers formulate smart electrification strategies. As noted, it includes 100 key innovations for both direct and indirect electrification of end uses (Figure I.3 and Table I.2). The innovations were selected based on analysis of hundreds of real-world projects in consultation with more than 150 external experts from across the world. The report also provides a list of important topics often overlooked when developing smart electrification strategies.

The report is divided into three parts corresponding to three main power to X routes for smart electrification:

- **Power to mobility** maps 35 key innovations for smart electrification of the transport sector.
- **Power to heat or cooling** maps 35 key innovations for smart electrification of the heating and cooling sector across three segments: buildings, industry, and district heating and cooling.
- **Power to hydrogen** maps 30 key innovations for smart indirect electrification to produce green hydrogen with renewable electricity via electrolysis. This section is limited to green hydrogen production and infrastructure and does not cover further uses and processing of hydrogen.

Each of the avenues illustrated in Figure I.3 includes guidelines on how to implement key innovations.

FIGURE I.3 | Direct and indirect avenues for smart electrification

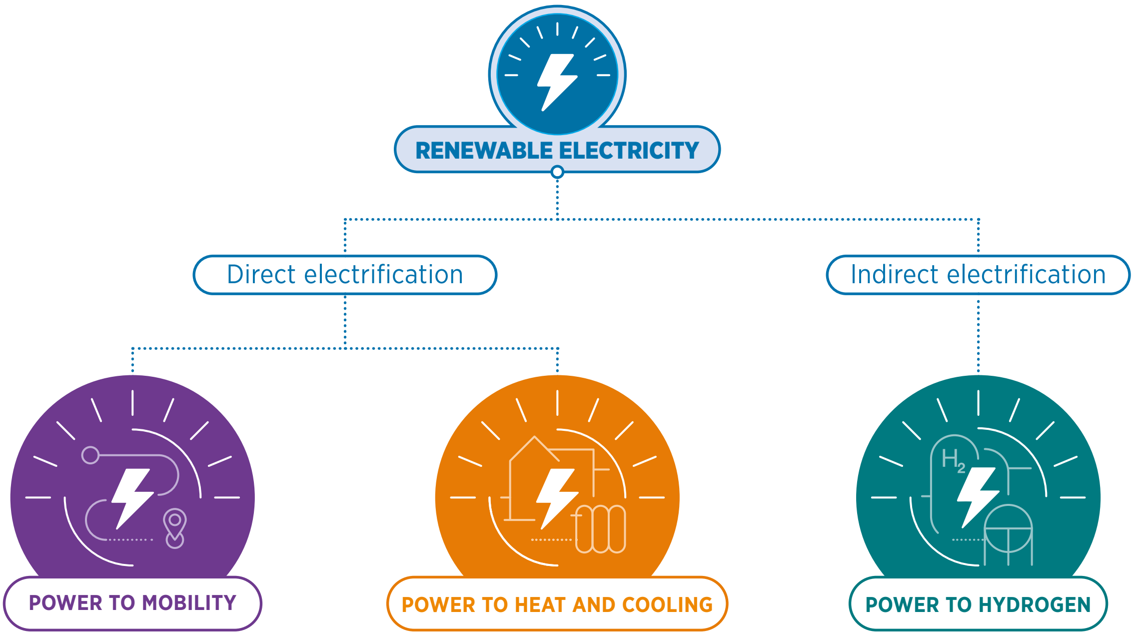


TABLE I.2 | **A hundred innovations for smart electrification of end uses spread across the four dimensions of systemic innovation**

POWER TO MOBILITY

35 INNOVATIONS

TECHNOLOGY AND INFRASTRUCTURE

- **1** EV model evolution
- **2** EV battery
- **3** Battery recycling technology
- **4** Diversity and ubiquity of charging points
- **5** Wireless charging
- **6** Overhead charging
- **7** Portable charging stations
- **8** V2G systems
- **9** Digitalisation for energy management and smart charging
- **10** Blockchain-enabled transactions
- **11** Smart distribution transformers
- **12** Smart meters and submeters

MARKET DESIGN AND REGULATION

- **13** Dynamic tariffs
- **14** Smart charging: local flexibility provision
- **15** Smart charging: system flexibility provision
- **16** “Right to plug” regulation
- **17** Streamlining permitting procedures for charging infrastructure
- **18** Standardisation and interoperability
- **19** V2G grid connection code

SYSTEM PLANNING AND OPERATION

- **20** Cross-sectoral co-operation and integrated planning
- **21** Including EV load in power system planning
- **22** Grid data transparency
- **23** Clean highway corridors
- **24** Operational flexibility in power systems to integrate EVs
- **25** Management of flexible EV load to integrate VRE
- **26** Management of flexible EV load to defer grid upgrades
- **27** EV as a resilience solution

BUSINESS MODELS

- **28** EV aggregators
- **29** EV load peak shaving using DERs
- **30** Battery second life
- **31** EV charging as a service
- **32** Electric mobility as a service
- **33** Ownership and operation of public charging stations
- **35** A single bill for EV charging at home and on the go
- **35** Battery swapping

Notes: AEM = anion exchange membrane; AI = artificial intelligence; ALK = alkaline; DER = distributed energy resources; DHC = district heating and cooling; EV = electric vehicle; IoT = Internet of Things; PEM = polymer electrolyte membrane; PPA = power purchase agreement; P2P = power-to-power; SOEC= solid oxide electrolyser cell; TES = thermal energy storage; TSO = transmission system operator; VRE = variable renewable energy; V2G = vehicle to grid.

POWER TO HEAT AND COOLING

35 INNOVATIONS

TECHNOLOGY AND INFRASTRUCTURE

- **1** Low-temperature heat pumps
- **2** Hybrid heat pumps
- **3** High-temperature heat pumps
- **4** Waste heat-to-power technologies
- **5** Medium- and high-temperature electricity-based applications for industry
- **6** Low-temperature TES
- **7** High-temperature TES
- **8** Fourth-generation DHC
- **9** Fifth-generation DHC
- **10** IoT for smart electrification
- **11** AI for forecasting heating and cooling demand
- **12** Blockchain-enabled transactions
- **13** Digitalisation as a flexibility enabler

MARKET DESIGN AND REGULATION

- **14** Dynamic tariffs
- **15** Thermal load flexibility
- **16** Flexible PPAs
- **17** Standards and certifications for improved predictability of heat pump operation
- **18** Energy efficiency programmes for buildings and industries
- **19** Building codes for power-to-heat solutions
- **20** Streamlining permitting procedures and regulations for thermal infrastructure

SYSTEM PLANNING AND OPERATION

- **21** Holistic planning for cities
- **22** Heat and cold mapping
- **23** Coupling cooling loads with solar generation
- **24** Smart operation with thermal inertia
- **25** Smart operation with seasonal thermal storage
- **26** Smart operation of industrial heating
- **27** Combining heating and cooling demand in district systems

BUSINESS MODELS

- **28** Aggregators
- **29** DERs for heating and cooling demands
- **30** Heating and cooling as a service
- **31** Waste heat recovery from data centres
- **32** Eco-industrial parks and waste heat recovery from industrial processes
- **33** Circular energy flows in cities – booster heat pumps
- **34** Community-owned district heating and cooling
- **35** Community-owned power-to-heat assets

Notes: AEM = anion exchange membrane; AI = artificial intelligence; ALK = alkaline; DER = distributed energy resources; DHC = district heating and cooling; EV = electric vehicle; IoT = Internet of Things; PEM = polymer electrolyte membrane; PPA = power purchase agreement; P2P = power-to-power; SOEC= solid oxide electrolyser cell; TES = thermal energy storage; TSO = transmission system operator; VRE = variable renewable energy; V2G = vehicle to grid.

POWER TO HYDROGEN

30 INNOVATIONS

TECHNOLOGY AND INFRASTRUCTURE

- **1** Pressurised ALK electrolyser
- **2** PEM electrolyser
- **3** SOEC electrolyser
- **4** AEM electrolyser
- **5** Compressed hydrogen storage
- **6** Liquefied hydrogen storage
- **7** Hydrogen-ready equipment
- **8** Digital backbone for green hydrogen production
- **9** Hydrogen leakage detection

MARKET DESIGN AND REGULATION

- **10** Additionality principle
- **11** Renewable PPAs for green hydrogen
- **12** Cost-effective electricity tariffs
- **13** Electrolysers as grid service providers
- **14** Certificates
- **15** Hydrogen purchase agreements
- **16** Carbon contracts for difference
- **17** Regulatory framework for hydrogen network
- **18** Streamlining permitting for electrolyser projects
- **19** Quality infrastructure for green hydrogen
- **20** Regulatory sandboxes

SYSTEM PLANNING AND OPERATION

- **21** Electricity TSOs including hydrogen facilities in their planning
- **22** Co-locating electrolysers with renewable generators (onshore and offshore)
- **23** Smart hydrogen storage operation and P2P routes
- **24** Long-term hydrogen storage
- **25** Co-operation between electricity and gas network operators

BUSINESS MODELS

- **26** Local hydrogen demand
- **27** Hydrogen trade
- **28** Hydrogen industrial hub
- **29** Revenues from flexibility provided to the power system
- **30** Sale of electrolysis by-products (oxygen and heat)

Notes: AEM = anion exchange membrane; AI = artificial intelligence; ALK = alkaline; DER = distributed energy resources; DHC = district heating and cooling; EV = electric vehicle; IoT = Internet of Things; PEM = polymer electrolyte membrane; PPA = power purchase agreement; P2P = power-to-power; SOEC= solid oxide electrolyser cell; TES = thermal energy storage; TSO = transmission system operator; VRE = variable renewable energy; V2G = vehicle to grid.

Resilient Energy
Platform

Renewable Energy to Support Energy Security

Background

Renewable energy plays an important role in supporting energy security[1] 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.

The Connection Across Energy Security and Resilience

Energy security and resilience are related and, in many cases, interlinked. Countries and jurisdictions think about the relationship between energy security and resilience in different ways. For example, the Government of Laos recently undertook a power sector vulnerability assessment that fed into a resilience action plan. This plan is seen as supporting a broader country objective to enable energy security. In most cases, energy security is seen as an overarching objective, and resilience is seen as an energy system characteristic that can contribute to energy security through enabling adaptation to changing conditions and recovery from disruptions. Figure 1 presents one perspective for considering the interlinkage across energy security and energy resilience.

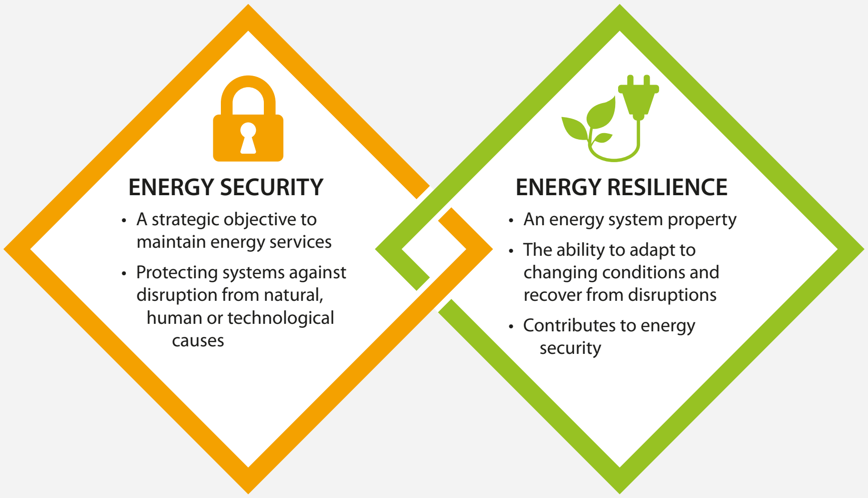

Figure 1. Interlinkage of Energy Security and Energy Resilience.

Illustration by Brittany Conrad, NREL

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, Bilello, 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, Bilello, Conzelmann, Mecray, et al. 2018).
- Changes in sea levels or storm surges can impact energy infrastructure close to shorelines, due to flooding (EPA).

How Can Renewable Energy Support Energy Security?

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 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).

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, longer term temperature changes, cyberattacks, and many others.

Learn more at: https://resilient-energy.org/guidebook

- Resource and fuel diversity—Having a majority reliance on one specific fuel type makes the power system vulnerable to fuel supply constraints or price fluctuations. Diversifying energy portfolios with renewable energy can help communities reduce dependence on fuel imports, especially in island nation settings. Further, renewable electricity prices are often stable, in contrast to regularly shifting fossil fuel prices due to geopolitical, market, or other factors (Olz, Sims, and Kirchner 2007).

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 recovery[2] 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 58004*

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

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