World Energy Overview

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World energy is produced from fossil fuels: oil, natural gas, and coal, and from nuclear energy, and renewable energy sources. There are three main groups of energy sources: conventional, that is, fossil fuels, nuclear, and renewable. The renewable energy sources are hydroelectric, wind, bioenergy, solar photovoltaics, solar thermal, geothermal, and ocean energy. The contribution from fossil fuels has been continuously declining, but in 2019, oil still contributed nearly one third of all energy produced, followed by coal and natural gas. The largest contribution from other sources is energy from biomass, then all other energy sources (Table 1). The replacement of fossil fuel energy by renewable energy takes place slowly but steadily and the dominance of fossil fuel energy sources is waning year after year.

History of Energy Consumption

Going back to the beginning of the nineteenth century, the nearly only energy type used was traditional biomass, with small contribution from coal (Fig. 1). Coal was known centuries before and used in limited ways, but the significance of coal was not established until the First Industrial Revolution in the mid-eighteenth century. The consumption of coal continued to increase throughout the nineteenth century. After almost a century of dominance by the traditional biomass and coal, new sources of energy such as oil, discovered in America in 1859, natural gas, and hydropower emerged in the early twentieth century as appreciable energy sources on a global level. It should be clear that individual countries or regions might have had historically different energy mix.

In the twentieth century, coal continued its dominance, energy generated from oil and natural gas showed steady increase. In the mid-century, nuclear energy technology advanced and it became a promising new form of energy. Steady gains in the overall proportion of the global energy came from hydropower and, somewhat surprisingly, from coal. Renewable energy sources, except hydro, wind, and solar primarily, first appeared in the global energy consumption composition and showed small but steady increase throughout the second part of the twentieth and into the twenty-first century.

Energy Consumption "Mix"

In the first part of the twentieth century, at the time of writing of this handbook, the energy generation ratios between different technologies, or energy mix, reveals overwhelming dominance of fossil fuels, with a combined contribution of 80% (Fig. 2). Individual fossil fuel sources for energy generation contribute to the following ratios: oil 31%, coal 26%, and natural gas 23%. Minority contributions to global energy generation are provided by hydropower (6%), traditional biomass (6%), nuclear (4%), and renewable energy generation technologies.

The rank is shown in Table 1.

The overall energy is used as heat or electricity and the ranking is different in terms of contribution to global electricity produced (Fig. 3).

Oil, which is the dominant energy source for transportation, powering internal combustion engines, has very little (3%) impact on the production of electricity. The pie chart reveals that the largest contributor to electricity generation in the world is coal, when burned in the thermal power stations. The next largest energy sources for electricity production are natural gas – also used in thermal power stations – hydroelectric power, and nuclear power. The relative ranking of electricity generation power sources is shown in Table 2.

Fossil Fuels

In 2021, roughly 80% of the total energy consumption and 61% of the global electricity came from fossil fuels. The

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entire transportation sector around the world is dependent on fossil fuels, primarily oil burned in internal combustion engines to power vehicles, buses, trains, airplanes, and ships. Coal burned in thermal power plants provides the largest portion of the world's electricity used to power homes, businesses, industrial operations, but also in transportation for trains or to charge batteries in electrical vehicles. Natural gas is used mostly to provide heat for homes, but also for electricity generation, transportation, and manufacturing.

Table 1 Rank and contribution to global energy produced among energy generation sources

Rank	1	2	3	4	5	6
Energy source	Oil 31%	Coal 26%	Natural gas 23%	Bioenergy 6%	Hydro 6%	Nuclear 4%
Rank, contd.	7	8	9	10	11	12
Energy source	Wind 2%	Solar PV 1%	Solar thermal 0.3%	Geothermal 0.2%	Ocean energy <<1%	Gas and steam turbines <<1%

Fossil fuels were formed over hundreds of thousands of years from decomposed plants and animals. The decomposition of organic matter under heat and pressure within the Earth's crust created solid (coal), liquid (oil), and gaseous (natural gas) material with high calorific value. The process of forming fossil fuels is extremely slow – to the order of thousands of years – and any fossil fuel taken from the ground and exploited cannot be replenished because the rate of current exploitation far surpasses the rate of formation. Effectively, we are now using fossil fuel reserves created thousands even millions of years ago and eventually these fossil fuels will be depleted. There are many predictions when each of the three fossil fuel types will be depleted at the current rate of use. A historical model based on empirical

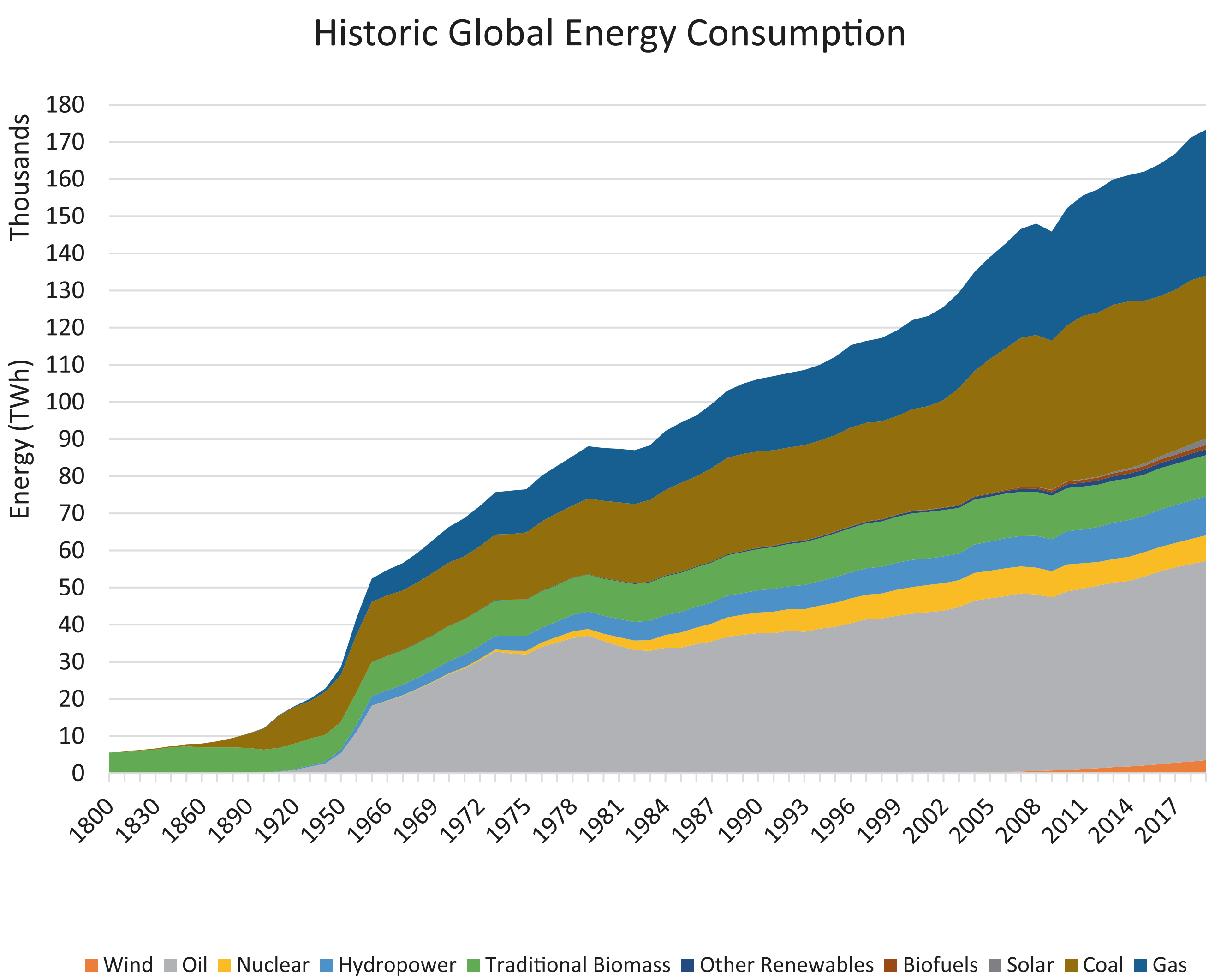

Fig. 1 Historic trend in global energy consumption distribution (1800–2021)

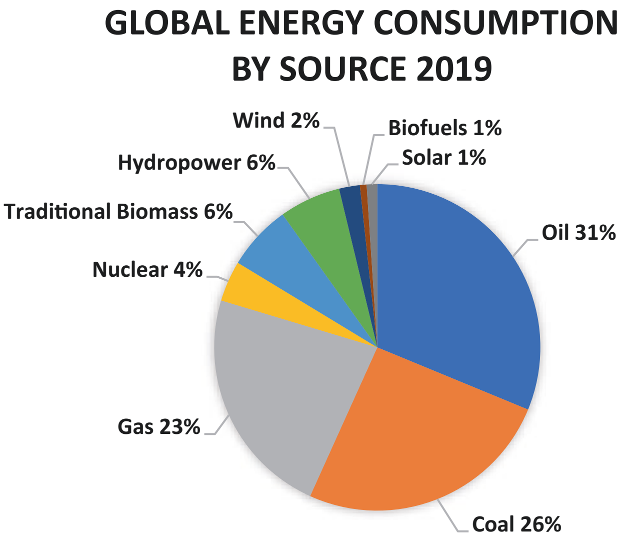

Fig. 2 Energy consumption in 2019

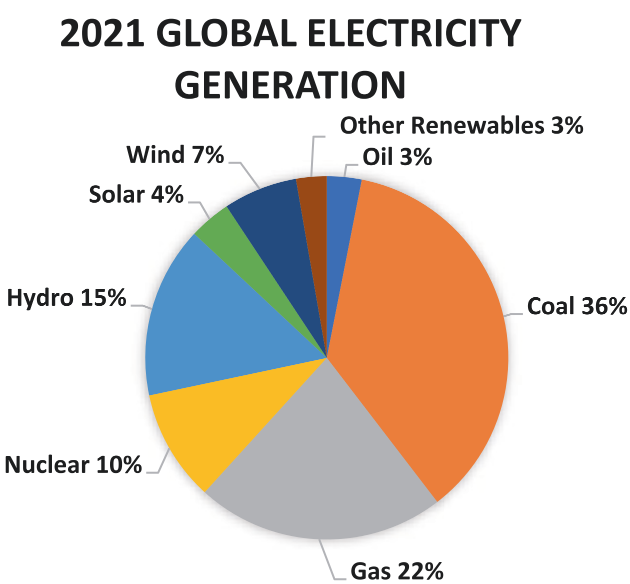

Fig. 3 Energy generation in 2021

data called Hubbert Curve claimed in 1956 that a decrease in exploitation of oil from a certain region, after a peak of used oil was reached, meant that all the reserves have already been discovered, followed by further decrease until the source is completely depleted. This suggested a far more Important conclusion that the reserves of oil, and other fossil fuels, on earth are limited, in other words, the rate of our use will lead to a rapid depletion. The actual shape of the Hubbert Curve and the timing of its peak is of course different for every region or a field from which oil is obtained, but the general principle does not change, and the amount of crude oil recovered follows a bell-shaped curve showing gradual decrease until the source is completely exhausted. As the crude oil is recovered from the waning reserves, the cost of its recovery increases until eventually, the cost of renewable energy resources such as wind, hydro, solar, and biomass becomes lower.

A convenient way to track availability of a fossil fuel is reserves-to-production ratio, R/P. This ratio effectively represents the number of years a source can continue to be exploited at a given rate of production, this, extraction. Looking at the R/P ratios reveals that oil is expected to be depleted in the next few decades, natural gas somewhat longer, while coal can remain a source of energy for at least a couple of centuries. Looking historically, crude oil reserves on earth would have been completely depleted in about two centuries, while it took several hundred thousand years for it to form.

Geopolitical Aspects of Fossil Fuels

Near-complete reliance of the world energy generation on fossil fuels and inevitable depletion in the near future (except coal) has created a long-term geopolitical instability that has led to local and global instability and numerous conflicts. It is obvious that a smart policy for any country is diversification of energy generation.

Oil

Crude oil, also defined as petroleum (meaning rock oil) fossil fuel, is a mixture of hydrocarbons that originates from the remains of marine animals and plants. During several millions of years, the organic material was buried under the layers of rock, silt, and sand and under conditions of heat and pressure. The very slow but complex processes transformed plant and animal material into petroleum used today. The oil is located in the reservoir rock and covered by an impermeable cap rock. The extraction is done by drilling through the cap rock (Fig. 4).

Crude oil contains various hydrocarbons and must be refined by separating different fractions based on boiling pints. A fractionation of one barrel, that is, 42 gallons of crude oil, typically gives 19.5 gallons of gasoline, 9.2 gallons of fuel oil, 4.1 gallons jet fuel, 2.3 gallons asphalt, 0.2 gallons kerosene, 0.5 gallons of lubricants, and 6.5 gallons of other petrochemical products.

The current global oil consumption is about 35 billion barrels per year and the reserves are estimated at roughly 1650 billion barrels, which means that at the current rate of consumption the oil will last approximately 47 years. Variations in oil production are expected in this period. First, a peak is predicted by 2035 at around 107 million barrels per day, followed by a decline to 96 million barrels per day and plateau by 2050. This trend is expected in response to a decreased demand for oil caused by an increased number of electrical vehicles (EVs).

Table 2 Rank and contribution to global electricity produced among energy generation sources

Rank	1	2	3	4	5	6
Energy source	Coal 36%	Natural gas 22%	Hydro 15%	Nuclear 10%	Wind 7%	Solar PV 4%
Rank, contd.	7	8	9	10	11	12
Energy source	Oil 3%	Bioenergy 2%	Solar thermal <<1%	Geothermal <<1%	Ocean energy <<1%	Gas and steam turbines <<1%

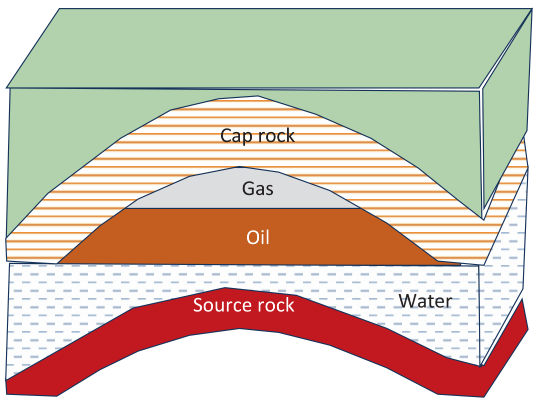

Fig. 4 Cross-section schematics of source rock and impermeable rock

Coal

The energy in coal comes from the energy stored in plants and trees that lived 200–300 million years ago, when the Earth was partly covered with swampy forests. The remains of plants decomposed and formed layer upon layer in the shallow swamp waters. Under heat and pressure from top layers and in the absence of oxygen and bacteria, this organic matter was transformed into coal. The cyclic process produced horizontal bands of peat and inorganic, sedimentary rock. Depending on the time passed, pressure, and heat, four different general categories, or "ranks." of coal were formed, lignite, sub-bituminous, bituminous, and anthracite. Anthracite is coal with the highest carbon content, between 86% and 98%, and a heat value of nearly 15,000 BTUs-per-pound. Bituminous coal has a carbon content ranging from 45% to 86% carbon and a heat value of 10,500 to 15,500 BTUs-per-pound. Sub-bituminous coal has 35–45%t carbon content and a heat value between 8300 and 13,000 BTUs-per-pound. Lignite is a geologically young coal which has the lowest carbon content, 25–35%, and a heat value ranging between 4000 and 8300 BTUs-per-pound.

The major use of coal is for the generation of electricity and about one third of world's electricity is produced from coal at 33% conversion efficiency. Coal is an impure fuel and its burning produced CO_2, SO_2, and NO_x, carcinogenic and mutagenic substances, including radioactive materials naturally occurring in coal. NO_x reacts with volatile organic compounds and ground level ozone to produce smog. Acid rain is formed when SO_2 and NO_x react with water and oxygen in the atmosphere to form acidic compounds that fall with rain. Coal ash is composed primarily of oxides of silicon, aluminum, iron, calcium, magnesium, titanium, sodium, potassium, mercury, and sulfur, plus small quantities of uranium and thorium. Typical emissions from a 500 MW coal-fired power plant in a year include 3,700,000 tonnes CO_2, 10,000 tonnes SO_2, 10,200 tonnes NO_x, 720 tonnes CO, 220 tonnes VOCs, 77 kg mercury, 102 kg arsenic, 52 kg lead.

Global production of coal is nearly 8 billion tons and the reserves-to-production ratio is estimated at over 200 years. The production is expected to hold steady at 8 billion short tons through 2040, after which a decline in coal use is predicted as it will be replaced in many applications by the renewables.

Natural Gas

Natural gas, like oil, is produced by the decomposition of marine microorganisms at the bottom of the seas. The decomposing organic matter gets covered with thicker and thicker layers of mud, silt, and sand, and an environment is created without oxygen, but with increasing pressure and heat. A slow process of decomposition takes hundreds of millions of years to produce the natural gas that we exploit today.

Natural gas production in the world is over 4 trillion cubic meters per year, while the global reserves are estimated at around 200 trillion. This suggests that the reserves-to-production ratio is roughly 50, which means that at the current level of production, global natural gas reserves will last approximately for another 50 years before being depleted.

Nuclear Energy

Electricity is produced in nuclear power plants based on the fission reaction of enriched uranium-235, in the form of UO_2 pellets enclosed in zirconium or stainless steel tubes. The reactor is started by slow-moving neutrons that cause fission of heavy nuclei into two mid-size nuclei with a release of energy. Uranium 235 can split in two different ways: one comprising tellurium and zirconium, and the other one barium and krypton. More neutrons are produced in both reactions. To control and stop the chain reaction, rods of cadmium or boron are inserted into the reactor to absorb neutrons. Enormous thermal energy created in the reaction is carried away by a cooling liquid that circulates through the reactor and creates steam to drive a turbine, which is connected to an electrical generator. A large source of cooling water is needed, such as a river or a lake. For protection from radiation, the reactor is surrounded by a reinforced concrete shell.

Nuclear power provides 10% of the global electricity generation and has the capacity of 400 GW worldwide. It is expected that the capacity would increase to over 500 GW by 2030, while some high estimates predict a rise to nearly 800 GW 2050. The conditions for such rise include implementation of novel technologies. Nuclear power plants are typically over 30 years old, while the service for some has been extended to 60 years, and to maintain the current role in the energy mix, a significant number of new power plants are necessary.

Renewable Energy Generation

Renewable energy, or sometimes called alternative energy, can be extracted for indefinite periods; it is freely available in nature and does not harm the environment. The types of renewable energy include solar, wind, hydro, biomass and biofuels, wave and tidal energy, and geothermal. The carbon emission from utilizing renewable energy is minimal compared with energy conversion from fossil fuels.

(For a more detailed description, consult *Renewable Energy Crash Course: A Concise Introduction* by Eklas Hossain and Slobodan Petrovic, Springer, 2022).

Renewable energy sources (RESs) are often called sustainable energy sources. The sustainability definition given in the Brundtland report from 1987 gives a broader meaning and calls sustainable energy as the energy that cannot be depletable on a human timescale, that does not lead to emission of greenhouse gases or other pollutants, and that does not contribute to social injustice or geopolitical imbalance.

Solar energy is the result of the nuclear fusion reactions inside the sun. The electromagnetic spectrum of solar radiation that reaches the Earth is based on the temperatures on the surface of the Sun of roughly 6000 °C. Solar energy is captured in photovoltaic (PV) devices, usually based on silicon, to produce electricity.

Solar PVs have reached a 1 TW of generation capacity in 2022. They contribute 1% to global energy and 4% to electricity production in the world. It is expected that the solar photovoltaic generation will experience an exponential growth to reach only recently unimaginable 8.5 TW by 2050.

Solar thermal technologies are converting solar energy into thermal energy and applying it for water heating, space heating, space cooling, district heating, and for industrial process heating. It is estimated that solar thermal can provide 60–90% of the hot water demand and 25–40% of the heating demand for the world. In 2019, solar thermal capacity for generating heat was close to 500 GW_{th} (thermal capacity), which generated nearly 400 TWh of energy.

Solar energy can also be used to generate electricity. In solar thermal power generation, solar radiation is first converted to heat, which then creates steam used in reactors to produce electricity. The global solar thermal power capacity was over 6 GW_{el} (electrical capacity) in 2020, which produced roughly 16 TWh of electricity. It is expected that the solar thermal power global capacity will surpass 14 GW_{el} by 2030.

Wind energy originates from the energy of the sun and differences in heating rates of the air masses. It is one of the most important renewable energy technologies. The wind turbines can be installed on the land and offshore. A special case of wind energy utilization is harnessing the power of ocean waves.

In 2022, estimated global wind capacity is over 800 GW and wind is providing 7% of the world's electricity. Wind capacity is expected to grow to 1 TW in 2022, 2 TW in 2029, and 5.9 TW in 2050. This 5.9 TW will include 1.7 TW of offshore wind.

Hydropower has the largest renewable energy technology capacity, providing around 15% of the world electricity. The origins of hydropower are in so-called water cycle, which is also getting its energy from the solar heating. On a small scale, hydropower satisfies the sustainability criteria with no adverse environmental impact. However, on a large-scale, massive dam installations result in major interruptions of Nature and the environment and can further lead to methane generation through anaerobic decay of vegetation.

In 2020, global installed hydropower capacity was 1.3 TW, which generated 4370 TWh of electricity. By 2030, hydro power is expected to surpass 1.5 TW capacity.

Bioenergy is energy derived from materials such as wool, found in the surface layer called the biosphere. The biosphere is essential for maintaining the Earth's atmosphere and is continuously replenished by the energy of the sun. Wood and other bioenergy feedstock, for example, crops, have potential to be sustainable without net increase in CO_2 emission if the rate of reforestation exceeds the rate of use. These biological materials or biomass can be burned directly to produce heat or power. They can also be converted through thermochemical (combustion, gasification, and pyrolysis) and biochemical (digestion and fermentation) routes to heat, electricity, and fuels used for transportation. Bioenergy is currently a significant energy source only in developing countries.

Bioenergy provides about 6% of the total energy produced on earth and about 25% of the world's electricity.

Ocean energy can be harnessed in three ways, as wave energy, as tidal energy, and as ocean thermal energy based on the water temperature differences. Wave energy is a concentrated form of solar energy because the winds that produce waves are caused by the atmospheric pressure differences as a result of solar heating. Ocean wave power depends on the height of a wave and the period between two successive waves. It is far more concentrated than solar or wind power as it can reach up to 70 kW per m of wave. Ocean energy depends, in addition, on the length of the coastal line where the waves occur. The global wave power resource is estimated at 2 TW, with electricity generation potential of about 2000 TWh annually.

The tidal energy is created by the gravitational pull of the moon on the world's oceans. The technology involves building a semipermeable dam or a tidal barrage across an estuary where the tide can be up to 15 m, compared with up to 3 m on a shore. Turbines used in the water passages are used to produce electricity from the rise and fall of water in the estuaries. The total power of tides across the world is 3 TW, from which up to 400 GW is exploited to produce electricity.

Ocean Thermal Energy Conversion (OTEC) produces energy from the temperature difference between surface water of the oceans in tropical and sub-tropical areas; and water at a depth of approximately 1000 m, which comes from the polar regions. A temperature difference of 20 °C is necessary for useful conversion. To convert this thermal gradient into electrical energy, the warm water can be used to heat and vaporize a liquid (known as a working fluid). This expanding vapor runs through a turbine generator and is then condensed back into a liquid by cold water brought up from the depths. The cycle is repeated.

The origin of geothermal energy is in the Earth's internal heat, which comes from conversion of kinetic and gravitational energy when the Earth was formed 5 billion years ago and from a decay of radioactive isotopes with long half-lives such as thorium 232, uranium 238, and potassium 40. These isotope materials are contained in the upper crystal rock. Heat is conducted through the main body of the Earth and exits through the surface mainly at the boundaries where the tectonic plates are in relative extension and compression. Geothermal resources include mainly hot water, but also rock several miles below the Earth's surface and can be accessed through drilling. Mile-or-more-deep wells can be drilled into underground reservoirs to tap steam and very hot water that can be brought to the surface for use in a variety of applications. The extracted hot water can be used for heating or steam can be used for electricity generation. Geothermal energy is renewable on a larger scale, but locally it can run out.

Geothermal global energy generation capacity is nearly 16 GW and it provides about 0.2% of the world's energy.

Energy Storage

One of the essential principles of energy generation and use is that the two should ideally match, which means that energy is available at the time of demand. The present energy systems do not completely meet this requirement and the effectiveness of the future energy systems depends critically on the transformation from random generation and unpredictable use to availability on demand. This can only be accomplished when energy storage becomes a central part of the overall system between energy generation and use.

Renewable energy sources (RESs) are intermittent and have a fluctuating nature. For example, the wind is not always blowing, and it changes speed, the solar photovoltaics generate electricity only during the day and when there are no clouds, and wave energy depends on the wind. Hydroelectric power is more predictable, but it still depends on the seasonal variations. Tidal power is available only at a certain time of the day. Geothermal power is reliable and predictable locally, but it is not available everywhere on earth. Biomass is similarly available only locally.

Energy production in large power plants is also not ideally matched with use. A nuclear of a coal-fired power plant requires long times to start and stop, while the demand fluctuates during those times. The only part of the overall energy system where there is a match involves energy storage. For example, in the transportation sector, fossil fuel oil is partially processed and stored in the form ready-for-use. The solution to provide a match between energy generation and consumption that the energy producers and distributors have been using is to store the energy in the electrical grid, where it is moved between the users depending on the energy demand. But, the energy grids' main purpose is to distribute energy, not to store it, and because of that, fluctuations and losses can occur and even large complete failures of the most sophisticated electrical grids. Electrical grids are not built for energy storage, and moving energy around until a user at some location needs it is certainly not the answer and does not provide energy security.

This leads to a concept of energy storage, the only sustainable and reliable way to utilize both renewable energy sources, but also conventional energy sources. The energy storage solutions include mechanical systems such as compressed air (CAES), flywheels, and pumped hydro; electrical systems such as supercapacitors and superconducting magnetic energy storage (SMES), electrochemical energy storage with electrolytic capacitors, batteries, and fuel cells; and thermal systems. Energy storage can be bulk, including pumped storage and compressed air; and distributed energy storage, including batteries, flywheels, and other.

Energy storage solutions should be matched with applications as some of them can provide large amounts of energy while the others store less energy, but can deliver it at a fast rate, which is described as high power. Pumped hydro and compressed air energy storage can store and subsequently deliver large energy, but cannot provide high power, while supercapacitors have high-power capabilities, but can store limited amounts of energy. Batteries and flywheels are available in types and sizes that cover both high energy and high-power ranges.

Global energy storage capacity is estimated to reach 12 TWh by 2026. In the energy storage mix, the dominant technology based on the overall contribution is pumped hydro. In 2012, pumped hydro contributed 98% of the overall energy storage capacity. However, the mix is changing largely due to rising popularity of different types of batteries and supercapacitors, and it is estimated that pumped hydro will contribute to about 42% of the global energy storage capacity in 2022. The pumped hydro is expected to grow in capacity from 127 GW_{el} in 2012 to 200 GW_{el} in 2026 and over 350 GW_{el} is expected by 2030. But the largest growth is the energy storage for the utility-scale batteries, where the new additions rose to 5 GWh in 2020 for a total of around 17 GW.

While the total number of installed energy storage systems is difficult to accurately track, the bulk systems have reached over 1000 systems worldwide. The mix of different technologies in terms of number of systems shows the dominance of battery technologies, primarily newer lithium–ion batteries as well as supercapacitors.

Energy Resiliency

Energy resiliency is a broad term that has many different definitions, but it can be summarized as a system's ability to anticipate, avoid, adapt, and respond to and recover from strong unexpected events. The International Energy Agency (IEA) defines energy system resilience as the capacity of the energy system to cope with hazardous events, to respond in ways that maintain essential functionality, and to learn and recover from said events. This definition alone conveys the complexity of this subject of resiliency.

A related and perhaps encompassed concept is that of energy security. This is mostly thought of as access to fuel or other energy sources. In the broad international economic landscape, fuel prices can be either stable or volatile. The depletion of fossil fuels is inevitable, but energy systems can adapt in the years leading up to this event by improving resiliency efforts. Energy security also refers to cybersecurity as more sensing and communication becomes remote and therefore more susceptible to cyber-attacks. A system's resiliency must include measures to prevent and recover from such cyber-attacks.

Energy security depends on the energy generation mix and although renewable energy generation has been added to the global power mix in recent years, the geographical regions that most need to increase their energy production have in fact low growth rates. This means that developing countries are exposed to pollution and climate change-related problems caused by the global situation with energy generation, without the opportunity to improve their economic growth. At the same time, developed countries that have created the problem in the first place are creating solutions that would benefit them. This is a trend that cannot continue. A prolonged, globally collaborative effort is necessary to properly address climate change and improve energy system resiliency across all parts of the world.

There are many types of events that can pose a threat to our energy systems. Some of them are natural disasters such as hurricanes, earthquakes, floods, volcanic eruptions, wildfires, and tornadoes. Many of these will occur more frequently as a direct result of the climate change so we need to prepare our infrastructure to withstand or quickly recover from such events. Other threats are more directly posed by human activities, including war, terrorist attacks, and labor strikes. A resilient system will be built with these threats in mind, it will be designed in anticipation of each threat, and with the capability to withstand or at least recover quickly from such occurrences. A different point of view sees the impracticality of building a system to withstand disaster events because the number and types of disrupting events is likely to evolve and change. It makes more sense instead to build systems with effective mitigation techniques to quickly restore functionality in case of any type of disturbance.

A common historical system response to disruptive events has been in so-called cascading failures, which happen when an event occurs that disrupts the flow of power in one location and the resulting displacement of power transmission can cause a number of failures in connected parts of the system. Events like these can take a long time to recover from since each failure needs to be rectified in order to restore complete functionality. However, cascading failures can be avoided by re-evaluating methods for generating, storing, and transporting energy. The most logical solution regarding resiliency is decentralizing power generation. At the moment, most individual country energy systems are centralized, meaning that the majority of energy is created in one place in fossil fuel, nuclear, or hydroelectric power plants and then transported using power lines to areas where the users are. With the penetration of more renewable energy into the energy generation mix, there is also an opportunity to utilize the nature of renewable energy sources and further localize (i.e., decentralize) energy production from solar, wind, hydro, ocean, geothermal, and bioenergy; and break up large energy infrastructure into smaller units, increasing the overall system resiliency. Each small unit or small energy system would include generation, storage, and transmission with the ability to operate independently or in tandem with neighboring systems. This decentralized power system is inherently more resilient than the current systems. In case of a disaster or local threat, a small system can quickly disconnect from other parts of the grid, preventing cascading failures, and after the disaster, it will be able recover faster by utilizing local resources. There are known examples of such systems that were successfully isolated during floods and storms and provided power to customers whose connection to the main grid was disrupted. More such systems have been constructed that are isolated from the grids and powered completely by renewables.

A critical aspect of an energy system resiliency is the need to have effective and resilient interaction among the system components, in addition to each component having its individual resiliency. This includes equipment for sensing, communication, and actuating responses. A proper answer to energy resiliency and system improvements starts with the complete understanding of the energy systems in individual countries and regions. This book is an attempt to build a database of energy systems, provide comparisons among countries and regions; and create the foundation for future growth and improvement.

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