Global Energy Perspectives

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Part 1: Basic elements for avoiding greenhouse gases and generating climate-neutral energy (technical toolbox)

Chapter 2-1

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2. Generation of climate-neutral energy and avoidance of greenhouse gases (technical toolbox)

2.1 Regenerative generation of electricity

Glossary to 2.1

Scenarios	**Description**
Net Zero Emissions until 2050 Scenario	A scenario that shows a narrow but achievable pathway for the global energy sector to reach net zero CO_2 emissions by 2050. It does not consider emission reductions outside the energy sector to achieve the planned targets.
Announced Policies Scenario	A scenario that assumes that climate pledges made by all governments worldwide, including Nationally Determined Contributions (NDCs) and longer-term net zero targets, are met in full and on time.
Stated Policies Scenario	A scenario reflecting the current policy framework, based on a sectoral assessment of existing policies and specific policies announced by governments worldwide.
Seasonality	Change of variables such as the energy yield of PV systems with the seasons. The calculation of a numerical value is carried out using time series analysis procedures.
Sustainable Development Scenario	An integrated scenario that aims to ensure access for all to affordable, reliable, sustainable and modern energy services by 2030 (SDG 7), significantly reduce air pollution (SDG 3.9) and take effective action to combat climate change (SDG 13).

2.1.1 Forms of renewable generation

Electricity availability plays an important role in global prosperity. Thanks to electricity availability, many necessary products can be manufactured, settlements, hospitals, households and schools are lit and mobility is made possible. At the global level, the proportion of people with access to electricity has risen steadily in recent decades. In 1990, around 71 % of the world's population had access to electricity; in 2016, the figure was 87 %.[1] Just over 35 % of global CO_2 emissions come from the power generation sector and therefore efforts are being made worldwide to gradually decarbonise the electricity grid through the use of renewable energy. [2]

In the last decade, the renewable energy industry has grown rapidly. To achieve the climate line, this industry will continue to grow rapidly - according to IRENA under its REMap scenario, the share of renewable energy in global electricity generation must increase to around 65 % by 2050.[3] Renewable energy sources fluctuate greatly over the season and diurnal cycle and therefore excess electricity needs to be stored to balance the fluctuations in electricity demand and generation. This report technically evaluates the operation of various types of green power generation and electricity storage. The installation costs, electricity generation costs for all types of power plants are considered along with their raw material requirements, water requirements and carbon footprint.

The first part of the chapter refers to the consideration of various forms of green electricity generation. It describes how these forms work. These methods include solar photovoltaics, CSP (see cjap. 2.1.1.2), onshore and offshore wind, hydropower, bioenergy and geothermal energy. Secondly, the development of the installation costs and electricity generation costs of these power plants over the last decade are presented, thirdly, the capacity factors are presented and chapter 2.1.4 deals with the carbon footprint and raw material requirements of all green electricity generation methods.

Nuclear energy is now the second largest source of low-carbon electricity: 440 operating reactors supplied about 2,600 TWh/a of electricity worldwide in 2020, equivalent to 10 % of the world's electricity supply.[4] Over the past 50 years, the use of nuclear energy has reduced CO_2 emissions by more than 60 Gt - almost two years of global energy-related emissions. However, in EU countries, nuclear power has begun to be phased out as it is seen as unsustainable and little new investment is being made in the sector - at a time when the world needs more low-carbon electricity. But according to the new EU taxonomy, new nuclear power plants will be

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[1] Cf. Our World in Data, (2019).
[2] Cf. Statista, (2020).
[3] Cf. IRENA, (2018).
[4] Cf. World Nuclear Association, (2022).

classified as sustainable until 2045, when a concrete plan for radioactive waste management will emerge from 2050 at the latest.

2.1.1.1 Generation through photovoltaics

The sunlight generates electric current on the panels through the so-called "photoelectric effect". Each panel generates a relatively small amount of energy, but it can be connected to other panels to multiply the amount of energy generated. Direct current is generated by a solar panel. In order for the solar electricity to be fed into the grid and used, it must be converted to alternating current using an inverter. The alternating current can then be used for the local power supply of electrical devices or forwarded to the grid and used elsewhere. The main components of a solar photovoltaic system are described below:

Solar module: A photovoltaic module converts light from the sun directly into electrical energy. The module consists of solar cells that are connected in series or parallel. Solar modules are available in flexible and rigid versions. Rigid solar modules usually consist of silicon-based solar cells that are hermetically encapsulated between two glass plates or a glass plate and a back sheet by means of embedding material. There are three types: Silicon polycrystalline, silicon monocrystalline and thin-film cells consisting of cadmium telluride or copper indium gallium di-selenide. Silicon cells have the highest efficiency (monocrystalline: 21 %, polycrystalline: 17 %). Thin-film cells have an efficiency of 11 to 12 %, but have the advantage in terms of production technology that they can be interconnected to form a complete module.[5]

Inverter: The direct current from the solar system on the module side is converted into alternating current. This conversion is required for most electrical devices or connection to the grid. Inverters are important for almost all solar energy systems and are usually the most expensive component after the solar modules themselves. Most inverters have a conversion efficiency of 90 % to 95 % or more and have important safety features, such as ground fault circuit interruption and islanding protection, where the inverter stops feeding power to the grid in the event of a grid failure.

Mounting: A mounting system is used to attach the modules to the ground or roof. This is usually made of steel or aluminium. The mounting system should be designed to withstand extreme weather events such as hurricane or tornado level wind speeds and/or high amounts of snow. For ground-mounted PV systems, the system can also be secured to the ground with either ballast or mechanical anchors. Some ground-mounted systems are also equipped with

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[5] Cf. Mertens, 2014.

tracking systems that use motors and sensors to track the sun, increasing the amount of energy generated but also increasing the cost of installation and maintenance.

The LCOE allows the comparison of the generation costs of solar PV with other energy generation technologies. In most countries, the electricity generation costs were already below 0.12 USD/kWh in 2018, and from a global perspective, the costs were between 0.06 USD/kWh and 0.26 USD/kWh.[6]

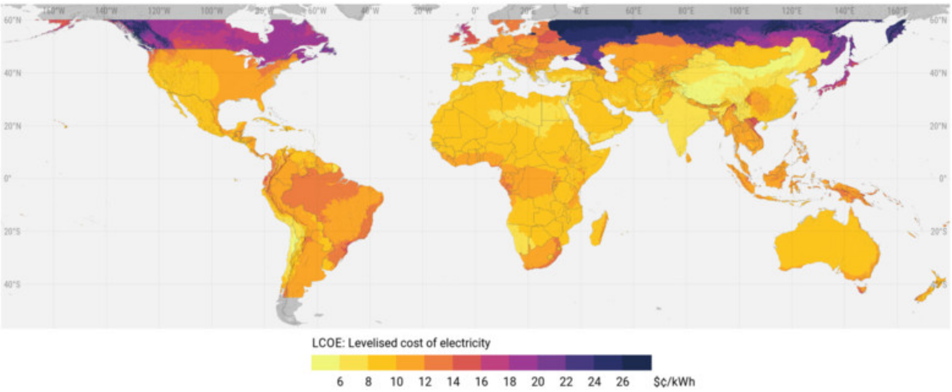

Figure 4: Production costs for solar photovoltaic electricity worldwide.

Source: Global Solar Atlas, (2018).

A long-term annual average of solar energy potential per installed capacity does not consider the variations in solar energy yield over the seasons. Therefore, Global Solar Atlas has presented a Seasonality Index,[7] which defines the ratio between the highest and lowest monthly total solar energy yields. High potential countries tend to have low seasonality, around below 2. Overall, 86 % of the world's population lives in 150 countries where the average Seasonality Index is below 2 and the solar energy yield per installed capacity is more than 3.5 kWh/kWp/day (see Figure 6).[8]

PV power generation can also be profitable in countries with low PV potential, such as Denmark,[9] UK[10] and Germany[11] . Importantly, there are several countries with high electricity tariffs (above 0.20 USD/kWh) that also have high PV potential (above 4 kWh/kWp/day). This group includes many island countries and countries with less developed electricity grids, where expensive and polluting small diesel generators are the main source of electricity generation

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[6] Cf. Global Solar Atlas, (2018).

[7] Cf. Global Solar Atlas, (2018).

[8] Cf. Global Solar Atlas, (2018).

[9] Electricity tariffs approx. 210 USD/MWh and the electricity production costs through photovoltaics between 110 USD/MWh and 130 USD/MWh.

[10] Electricity tariffs approx. 180 USD/MWh and electricity production costs through photovoltaics between 130 USD/MWh and 180 USD/MWh

[11] Electricity tariffs approx. 330 USD/MWh and the electricity production costs through photovoltaics between 100 USD/MWh and 120 USD/MWh.

today. In these countries, cheaper solar power can be generated in local island grids instead of buying expensive power from a grid that also requires expansion and maintenance. Of course, there is no solar power at night without storage, but photovoltaic power could at least be used to cover own consumption during the day. A complete picture can be seen by looking at electricity storage costs.

Figure 5: Solar PV potential per installed capacity vs. electricity tariffs.

Source: Global Solar Atlas, (2018).

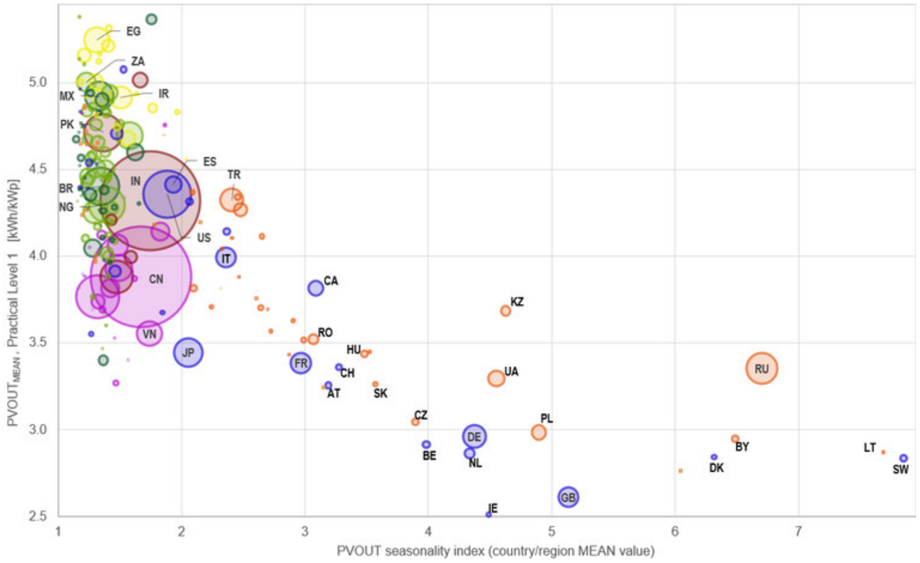

Figure 6: Solar energy potential per installed capacity vs. seasonality index.

Source: Global Solar Atlas, (2018).

In some African countries, solar electricity could be produced at costs between 0.06 and 0.08 USD/kWh, in some even below 0.06 USD/kWh.[12] In countries like Ghana[13] and Kenya[14] electricity tariffs are on average higher than the electricity production costs through solar photovoltaics (see appendix to 2.1, p. 66) and the Seasonality Index is also below 2 (see Figure 6). Furthermore, electricity tariffs in southern Spain are also higher than the LCOE of solar PV. Southern Spain has on average a solar PV potential just below 4.5 kWh/kWp/t. There, the Seasonality Index is on average 1.9 (see appendix to 2.3.4,). In summary, it can be said that regions with high electricity prices, without adequate electricity grid infrastructure, with low seasonality and high solar energy potential per kW of installed capacity can produce cost-effectively with decentralised photovoltaic systems.

In Figure 7 shows the installed solar photovoltaic capacity of all countries. The share of solar energy is shown in Figure 8[15] - a significant part of this is solar photovoltaics, as the installed capacity of photovoltaics worldwide is larger than that of CSP (see Figure 7 and Figure 12). In most countries the share of PV is still below 4 %. Luxembourg with 13 %, Italy with about 10 %, Malta with about 9.5 % and Chile and Japan with 9 % are the leading countries with large shares of solar energy in the electricity mix (see Figure 8).

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[12] Cf. Global Solar Atlas, (2018).

[13] Seasonality Index: 1.39, electricity tariffs: approx. 220 USD/MWh and the electricity production costs through photovoltaics: 110 USD/kWh and 120 USD/MWh

[14] Seasonality Index: 1.38, electricity tariffs: approx. 210 USD/MWh and the electricity production costs through photovoltaics: between 80 USD/kWh and 110 USD/MWh

[15] Photovoltaics and CSP included. Total global photovoltaic capacity: 1,134 GW. CSP total global capacity: 10 GW

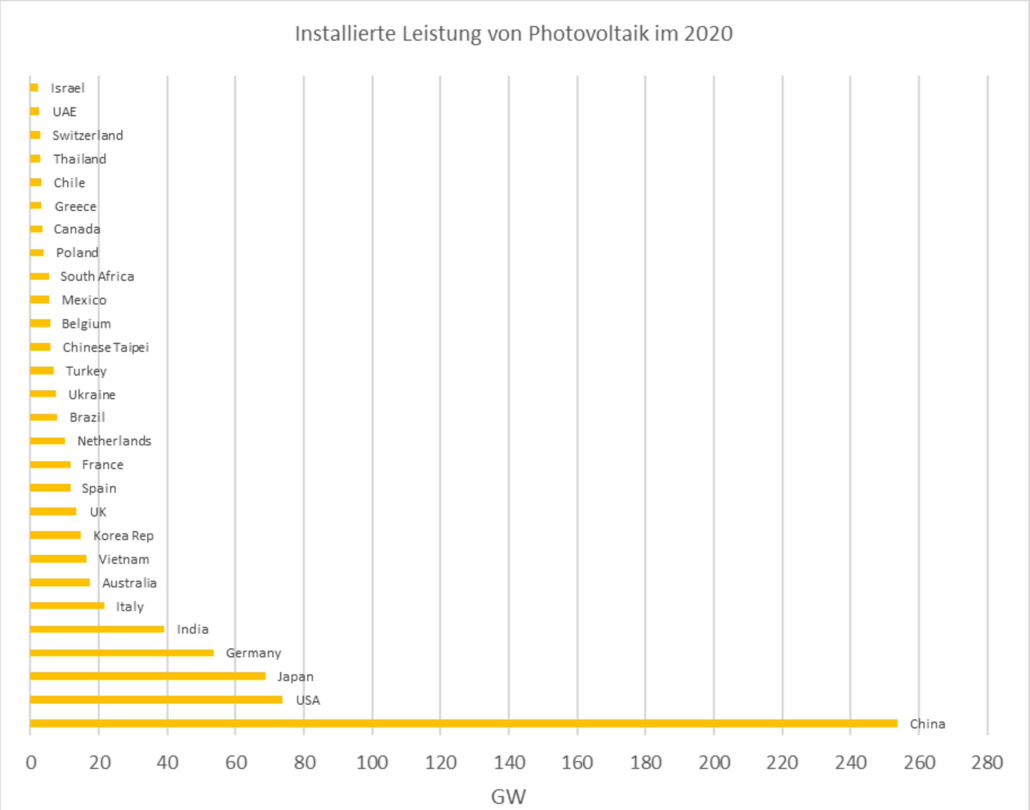

Figure 7: Installed capacity of solar photovoltaics in certain countries.

Source: IRENA, (2021).

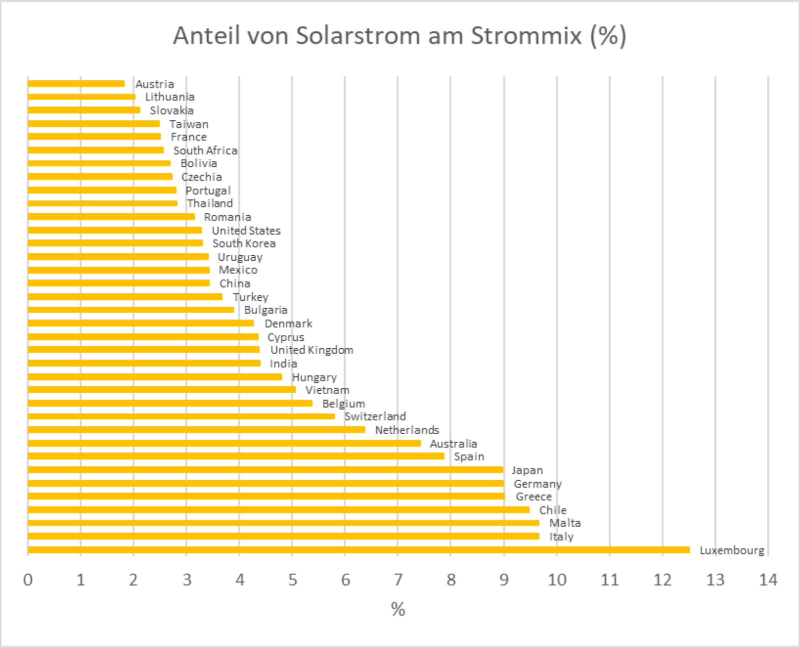

Figure 8: Share of solar power (solar photovoltaic and CSP) in the electricity mix of different countries.

Source: Our World in Data, (2022).

Despite the high installed capacities in China, the USA and Japan, the shares of solar energy in the electricity mix in these countries are respectively just over 3 %, 3.5 % and 9 % (see Figure 4 and Figure 5).

2.1.1.2 Generation through CSP

CSP technology uses mirrors to concentrate sunlight onto a receiver. The energy from the concentrated sunlight heats a high-temperature fluid in the receiver. The thermal energy is used to drive a turbine and consequently a generator to produce electricity. Solar thermal energy can also be used for a variety of other industrial applications such as water desalination, enhanced oil recovery, food processing, chemical production and mineral processing. Different types of CSP technology are explained below:

Solar tower system: Central receiver systems use sun-tracking mirrors called heliostats to concentrate sunlight onto a receiver at the top of a tower. A heat transfer fluid heated to about 600 ºC in the receiver is used to generate steam, which in turn is used in a turbine generator to produce electricity. Many research projects are looking at various other heat transfer or energy storage materials, as these have the potential to reach higher temperatures, leading to efficiency gains and lower costs. These potential energy storage materials range from air to sand particles to alternative mixtures of chemicals.[16]

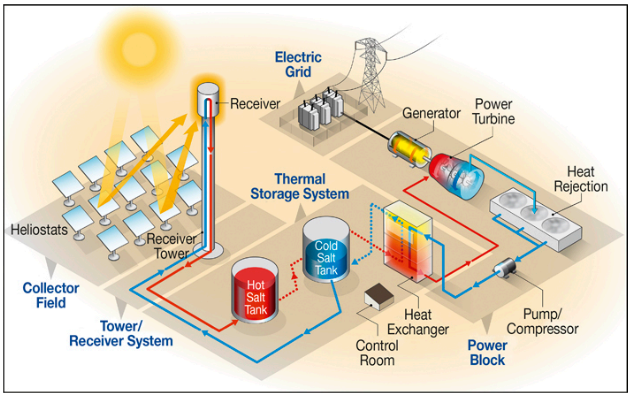

Figure 9: Central tower system of concentrated solar thermal.

Source: Karatairi & Ambrosini, (2018).

Parabolic trough system: In a parabolic trough system, solar energy is concentrated by parabolically curved, trough-shaped parabolic reflectors onto a receiver tube - the heat absorber tube - which runs about one metre above the curved surface of the mirrors. The temperature of the heat transfer fluid, usually thermal oil, flowing through the tube

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[16] Cf. Solar PACES, (2021).

is raised (from 293°C to 393°C) and the thermal energy is used in the thermal power plant to generate electricity in a steam generator. A trough solar collector array consists of several parabolic trough-shaped mirrors in parallel rows, oriented so that these uniaxial trough-shaped mirrors can track the sun from east to west during the day to ensure that the sun is continuously focused on the receiver tubes.

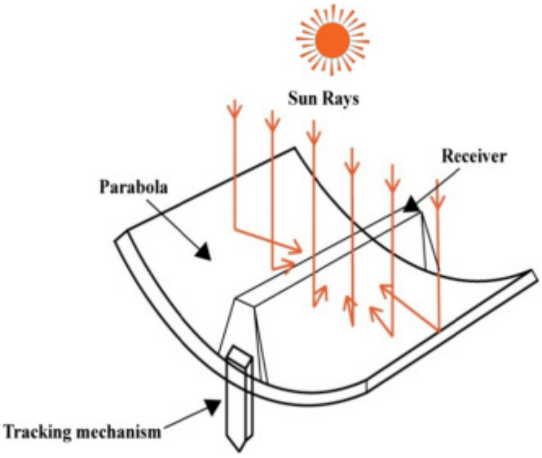

Figure 10: Parabolic Trough Collector.

Source: Joardder et al., (2017).

Parabolic mirror **system:** A parabolic mirror system consists of a parabolic point focus concentrator in the shape of a dish that reflects solar radiation onto a receiver mounted at the focal point. These concentrators are mounted on a structure with a two-axis tracking system to track the sun. The collected heat is used directly by a Stirling heat engine mounted on the receiver that moves with the dish structure. The dish can reach extremely high temperatures and is promising for use in solar reactors to produce fuels that require very high temperatures.

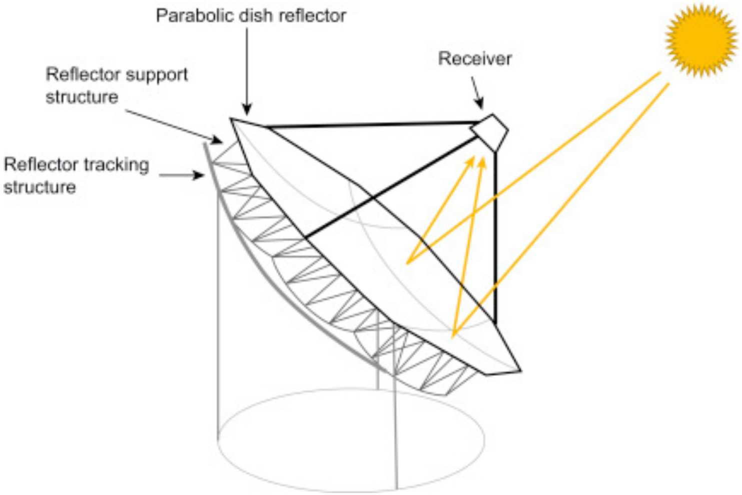

Figure 11: Parabolic mirror collector.

Source: Blanco & Miller, (2017).

In Figure 12 shows the worldwide installed capacities for CSP. Compared to solar photovoltaics, the installed capacities are much lower. Spain has the largest installed capacity of solar thermal power plants of about 2,300 MW (see Figure 12).

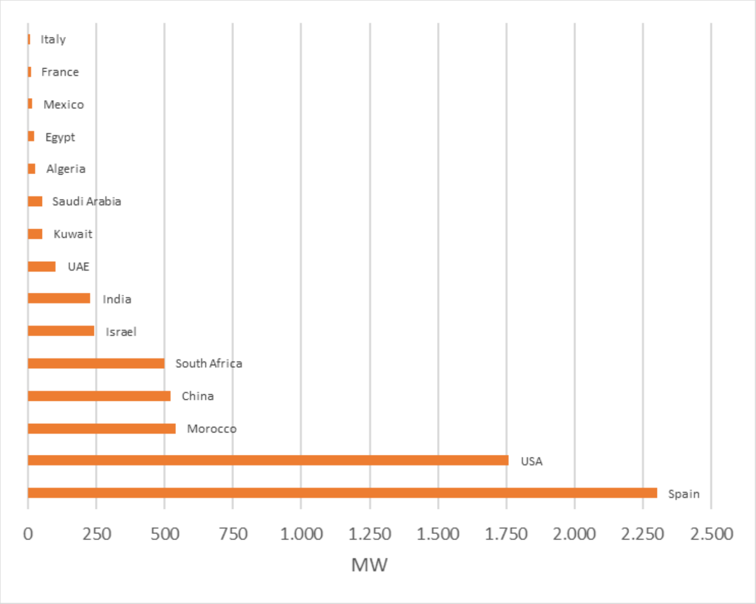

Figure 12: Installed CSP capacity in certain countries.

Source: IRENA, (2021).

2.1.1.3 Generation by onshore and offshore wind power plants

A wind turbine converts wind energy into electricity by using the aerodynamic force on the rotor blades. As the wind flows over the blade, the air pressure on one side of the blade decreases. The difference in air pressure on the two sides of the blade creates both lift and drag. The lift is stronger than the drag, which causes the rotor to turn. The rotor is connected to the generator, either directly or via a shaft and gearbox, which accelerate the rotation and allow for a physically smaller generator. This conversion of aerodynamic force into the rotation of a generator produces electricity. The main components of a wind turbine are shown in Figure 13 shown.

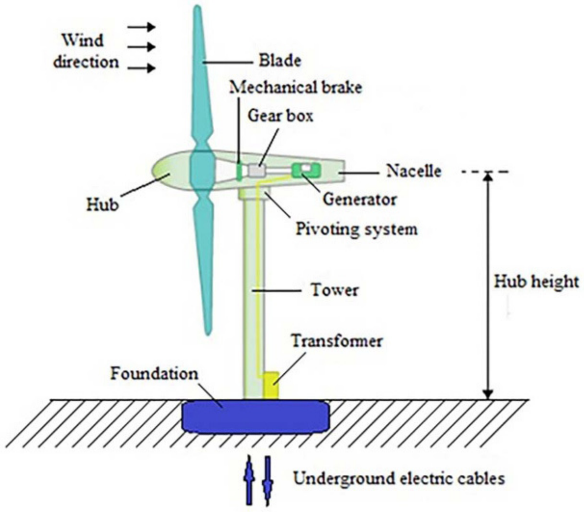

Figure 13: Onshore wind turbine components.

Source: Năstase, (2017).

Wind farms can be installed not only onshore but also offshore to take advantage of the stronger and less turbulent winds at sea. Currently, offshore wind farms are located in shallow waters and far from the coast,[17] from maritime transport routes, strategic naval facilities and areas requiring ecological protection. Figure 14 shows various support structures for offshore wind energy applications. In shallow waters and transitional waters, the monopile or jacket structures are used. Modern offshore wind farms may not require foundations buried in the seabed, but can be constructed with floating platforms and moorings, as shown in Figure 14 shown. Such constructions can facilitate the construction of wind farms in deeper waters and help to exploit the high wind capacities in deep offshore waters.

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[17] up to 60 metres deep

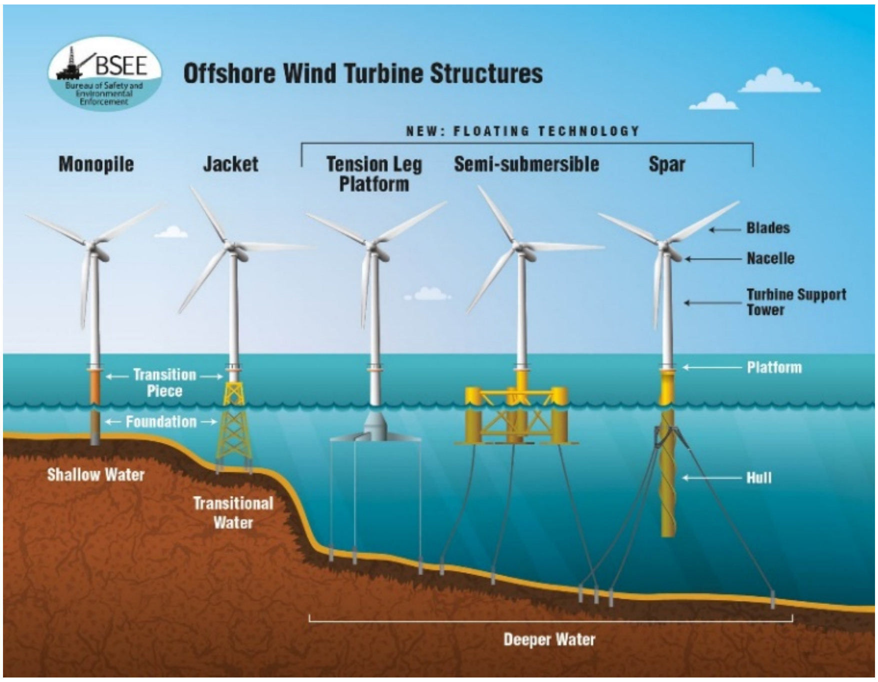

Figure 14: Offshore wind power.

Source: Windpower Engineering & Development, (2022).

Figure 16 and Figure 15 show the installed capacity of offshore and onshore wind power worldwide. The UK is the country with the highest installed offshore capacity, totaling 29 % of all global offshore wind.[18]

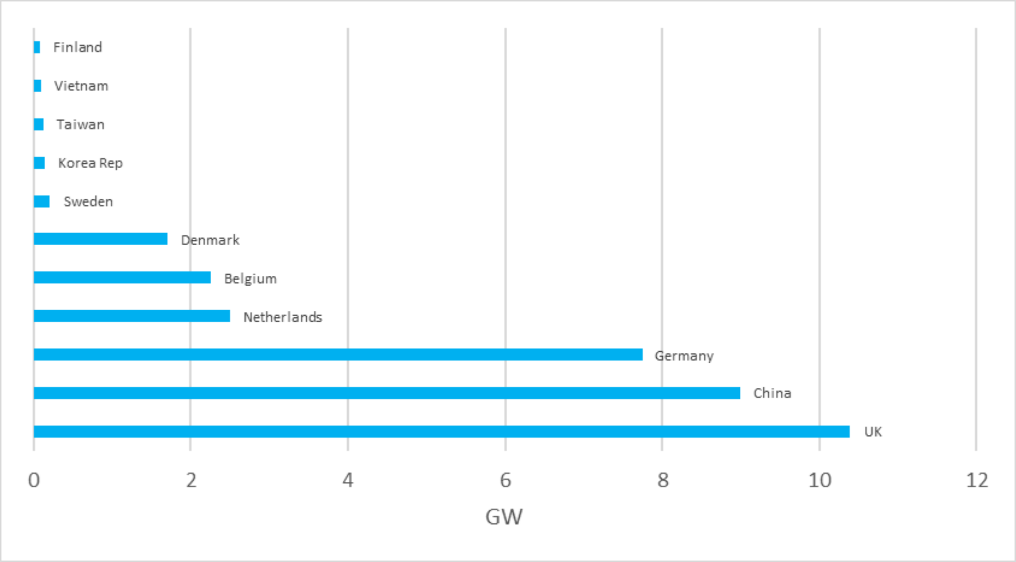

Figure 15: Installed capacity of offshore wind power worldwide.

Source: IRENA, (2021).

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[18] Cf. Wikipedia, 2022a.

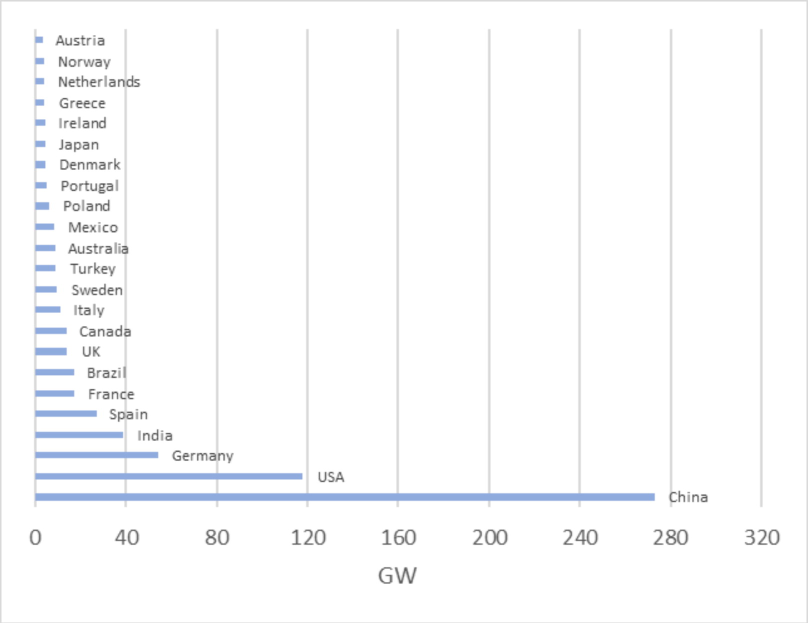

Figure 16: Installed capacity of onshore wind power worldwide.

Source: IRENA, (2021).

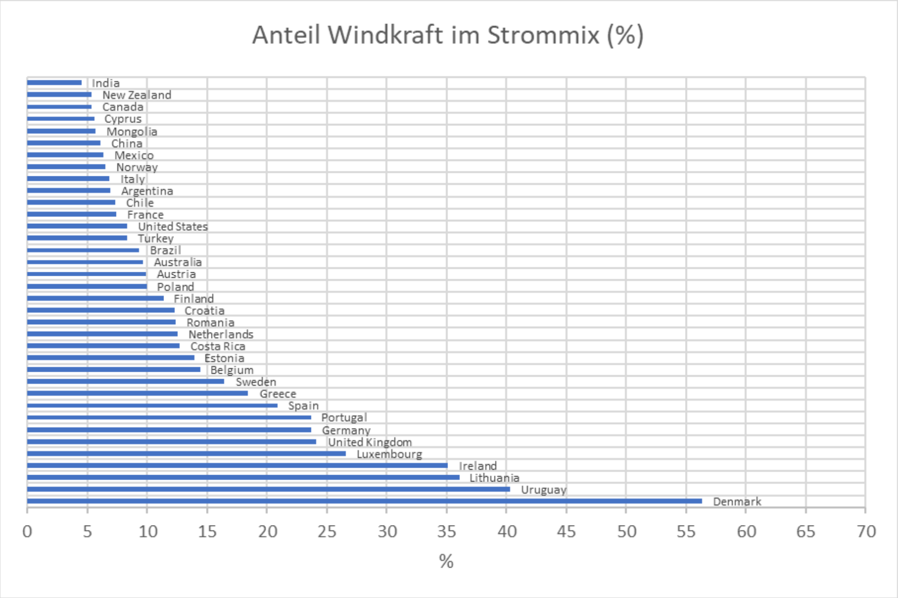

Figure 17: Share of onshore and offshore wind power in the electricity mix worldwide.

Source: Our World in Data, (2022).

Onshore and offshore wind contribute between 20 % and 40 % of electricity generation in countries such as Germany,[19] UK[20] and Uruguay[21] (see Figure 17). In China, Australia, Brazil and

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[19] 22 % of the electricity mix
[20] 24 % of the electricity mix
[21] 40 % of the electricity mix

the USA, the shares of wind power or electricity generation are between 5 % and 10 %.[22] In Kenya, the share of wind power in the electricity mix is around 11 %.

The largest share of wind power in the electricity mix was built up by Denmark with approx. 54 % (see Figure 17).

The low shares of wind power in the electricity mix in Russia, Australia and the USA are remarkable. Figure 18 shows the average annual net capacity factors for all land areas and the exclusive economic zones,[23] which extend up to 200 nautical miles off the coasts.[24] The spatial distribution of capacity factors correlates well with global wind speed maps, i.e. capacity factors are highest at high and low latitudes and lowest near the equator.

Some studies have investigated whether drag from large-scale wind farm development could reduce wind farm yields worldwide by slowing large-scale winds. It was found[25] that wind farm capacity factors depend on total wind capacity because large-scale expansion significantly lowers wind speeds beyond the local scale. Both point out that wind production at an installation density of 1.0 MW/km^2 is entering saturation of global wind resources and estimates in some studies assume much higher power densities. Some authors even give a maximum density in the order of 5.0 MW/km^2. Assuming that wind turbines with a maximum of 1.0 MW/km^2 should be distributed over a large area to have only negligible effects on wind speed, then the estimates of wind energy potential in the study of 5.0 MW/km^2 would have to be reduced by a factor of five. [26]

Figure 19 shows the largest oil and gas exporters such as Russia and Norway. They also have a very large onshore wind energy potential and this could be harnessed in the future, not only to meet the electricity demand in these countries, but also to be able to produce green hydrogen. This potential of each country would be one-fifth of the energy shown in the Figure 19 when related to an installation density of 1 MW/km^2 for wind farms. In addition, the distance of the potential wind farms from the existing electricity grid is also shown in Figure 19 is shown. In Russia and the United States, onshore wind farms are located quite close to the existing grid infrastructure with capacity factors between 26 % and 30 %. In Australia and Argentina, on the other hand, many wind resources are located far from the existing electricity grid infrastructure with capacity factors or between 30 % - 34 % and 34 % - 46 %.

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[22] Onshore and offshore

[23] without Antarctica

[24] for 90 m wind turbine hub height, IEC class I/II turbine (class I for offshore and class II for onshore), availability and array efficiency of the turbines.

[25] Cf. Amanda & David, (2013).

[26] Cf. Eurek et al., (2017).

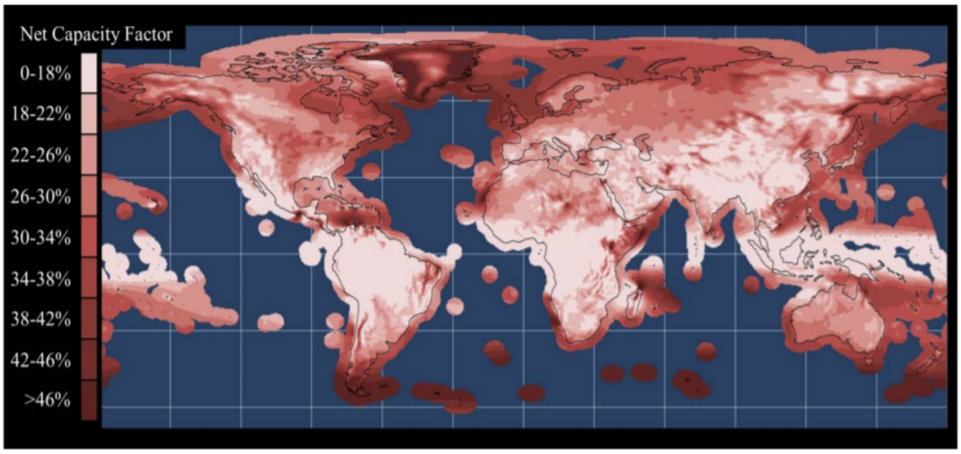

Figure 18: Global average annual net capacity factors (including availability and array efficiency of turbines) for land areas (excluding Antarctica) and offshore areas 200 nautical miles from the coastline.

Source: Eurek et al., (2017).

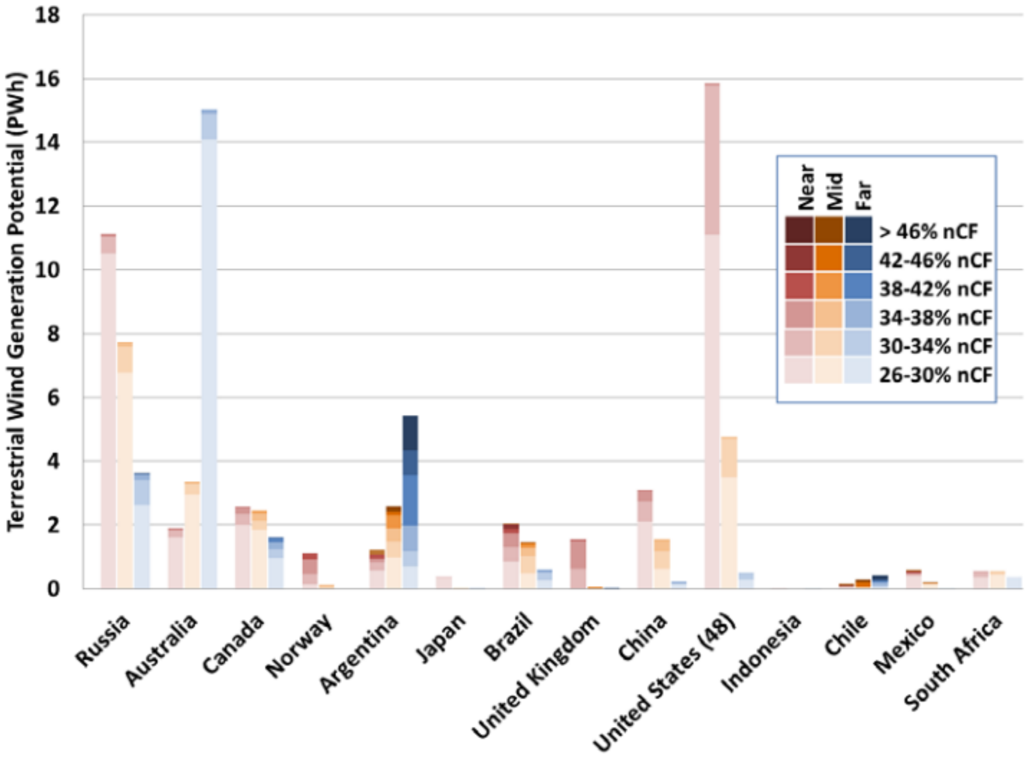

Figure 19: The onshore wind energy potential and capacity factors (nCF0) in exclusive economic zones (EEZ).

Source: Eurek et al., (2017).

Developing wind farms far from the coast in deep waters would be more expensive than onshore wind farms or wind farms close to the coast. But in the future, floating wind farms in deep water could make it possible to produce low-cost green hydrogen. The potential and higher capacity factors are attractive, e.g. in the USA the offshore wind potential is 4 PWh.[27]..In the

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[27] Cf. Terdiman, (2021).

deep waters of the Russian, Norwegian, American, Australian and Canadian ocean zones, high capacity factors between 30 % and 46 % are available (see Figure 20).

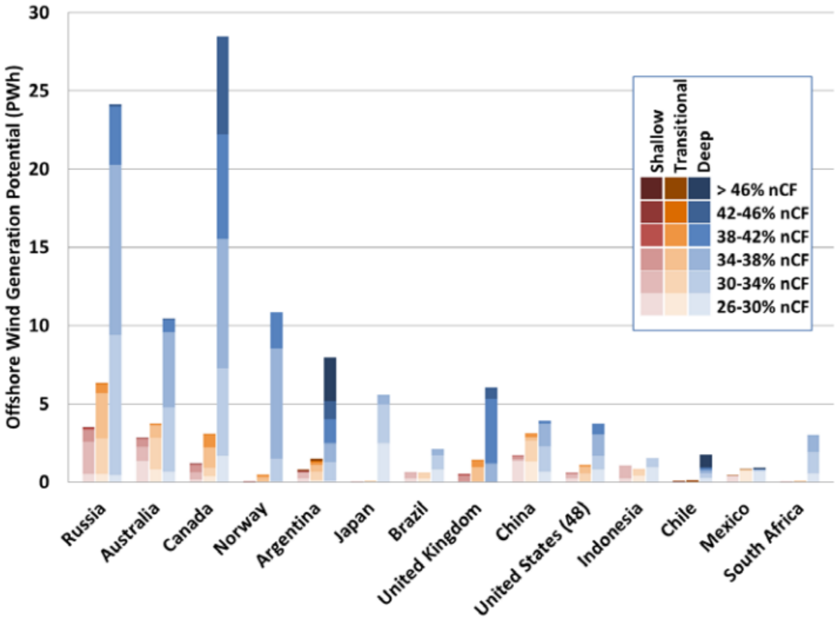

Figure 20: The offshore wind energy potential in exclusive economic zones (EEZ).

Source: Eurek et al., (2017).

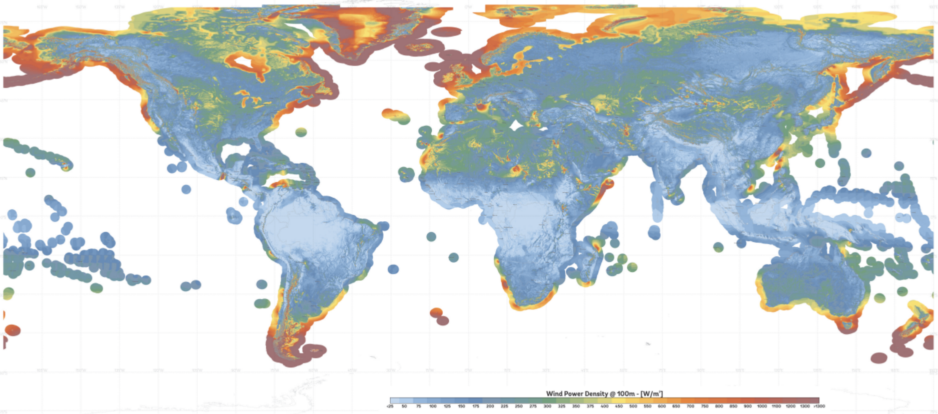

Figure 21: Power density of wind power (W/m^2) worldwide.

Source: Global Wind Atlas, (2022).

In African countries along the equator, Brazil, India and Southeast Asia, wind energy potentials are rather limited, see Figure 21.

2.1.1.4 Generation through hydropower plants

When generating electricity from hydropower, water is collected or stored at a higher location and directed through large pipes or tunnels to a lower location. At the end of its journey through the pipes, the falling water makes turbines turn. The turbines in turn drive generators that convert the mechanical energy of the turbines into electricity. Transformers then convert the AC voltage suitable for the generators into a higher voltage suitable for long-distance transmission. The building in which the turbines and generators are housed and into which the lines or pressure pipes are led is called the generator hall. The different types of hydroelectric power plants are described below, according to NREL:[28]

Dam facility: The most common type of hydropower plant is a dam facility. A dam facility, usually a large hydroelectric facility, uses a dam to store river water in a reservoir. The water can be used either to meet a changing demand for electricity or to maintain a constant level of the reservoir.

Diversion facility: A diversion facility diverts part of a river through a canal or pressure pipe.[29] A dam is not required for this purpose.

Run-of-river power plant: A run-of-river power plant uses the water within the natural discharge range of the river and requires little or no impoundment.

Pumped storage power plant: When demand for electricity is low, a pumped storage power plant stores energy by pumping water from a lower reservoir into an upper reservoir. During periods of high electricity demand, the water is returned to the lower reservoir to generate electricity.

Figure 22 shows the installed capacity of hydropower plants worldwide. Based on the total installed hydropower capacity, China is in first place, followed by Brazil, the USA and Canada. But the largest shares of hydropower in the country electricity mix are in Tajikistan and Norway (see Figure 23).

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[28] Cf. NREL, (2021).

[29] As in the classic water mills

Figure 22: Installed capacity of hydropower worldwide.

Source: IRENA, (2021).

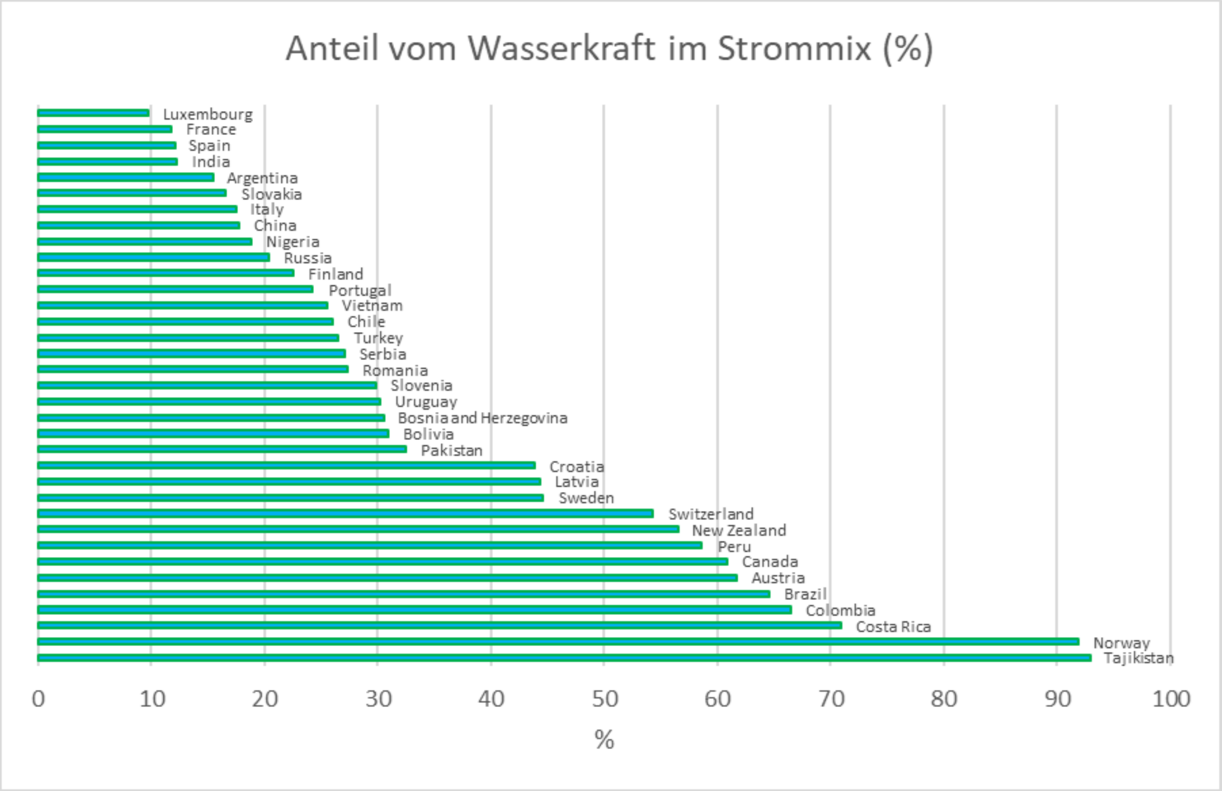

Figure 23: Share of hydropower in the electricity mix of certain countries worldwide.

Source: Our World in Data, (2022).

South America, Canada and Central Africa have the largest hydropower potentials per capita, although Asia has almost 50 % of the total global potential (see Figure 30). The total theoretical hydropower potential expresses the total amount of electricity that could potentially be generated if all available water resources were used for this purpose. A total of approx. 25 PWh/a (at a capacity factor of 50 %) could theoretically be generated globally from hydropower.[30]

However, according to one study, the global theoretical hydropower potential is about 52 PWh/year, which is divided among 11.8 million locations, based on the 7.5 arcsec GMTED2010 elevation data and runoff data from the Global Runoff Data Centre.31 However, this potential cannot be realised due to environmental and economic constraints. Figure 24 shows the global distribution of the theoretical hydropower potential and in Tabelle 1 these are quantified for the quotas.

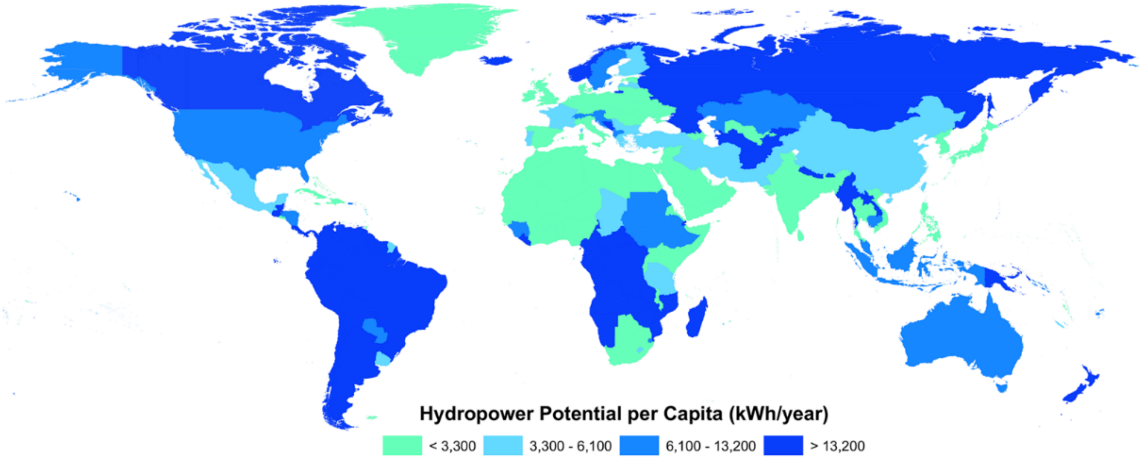

Figure 24: Theoretical hydropower potential worldwide - total potential and per capita potential.

Source: Hoes et al., (2017).

The installed capacities of large-hydro[32] power plants are typically over 100 MW, of small-hydro power plants between 1 MW and 10 MW, of mini-hydro power plants between 100 kW and 1 MW, and of micro-hydro between 5 kW and 100 kW.[33] Hydropower plants can impede fish migration, alter natural water temperatures, water chemistry, flow characteristics and silt levels, according to EIA.

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[30] Cf. EIA, (2021).

[31] Cf. Hoes et al., (2017). Under the boundary conditions mentioned in the study: Only river sites with a height difference greater than 1 m between two adjacent cells of 7.5 arcsec (≈225m at the equator) and a discharge $Q \geq 0.1$ m^3/s were selected as suitable hydropower sites.

[32] Hydroelectric power station

[33] Cf. Renewables First, (2016).

Table 1: The total theoretical hydropower potential of various continents.

Source: Hoes et al., (2017).

Plants:	Large (TWh/year)	Small (TWh/year)	Mini (TWh/year)	Micro (TWh/year)	Total (TWh/year)	
Asia	17,631	5,062	1,582	276	24,551	48%
North America	3,815	2,243	712	149	6,919	13%
Europe	971	854	328	86	2,240	4%
Africa	5,657	1,325	535	162	7,680	15%
South America	7,020	1,779	692	236	9,727	19%
Oceania	168	166	44	5	382	0.7%
Australia	34	84	46	14	177	0.3%
Global	35,296	11,513	3,939	929	51,677	100%
	68%	22%	8%	2%	100%	

Note that these numbers are the gross potential multiplied by a capacity factor of 0.5.

2.1.1.5 Production through bioenergy

Bioenergy plants convert renewable biomass fuels into heat and electricity using processes similar to those used for fossil fuels. There are three ways to use the energy stored in biomass, e.g. to generate electricity: direct combustion, bacterial fermentation to produce biogases and conversion to gaseous/liquid fuel. [34] Figure 25 shows the amount of electricity generated from bioenergy based on the type of fuel. Much of this electricity comes from solid fuels, with the remaining electricity coming from biogas, cane trash and municipal waste.[35] However, IRENA does not mention the type of process used for each fuel to generate electricity from it.[36] Typically, woody biomass such as wood chips, pellets and sawdust is burned or gasified to generate electricity.[37] Maize straw and wheat straw are baled for combustion or converted to gas in an anaerobic digester. Very moist waste, such as animal and human waste, is converted into a medium-energy gas in an anaerobic digester and then used to generate electricity and heat.

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[34] Cf. US Department of Energy Efficiency and Renewable Energy, (2021).
[35] Cf. IRENA, (2021).
[36] Cf. IRENA, (2021).
[37] Cf. FEMP, (2016).

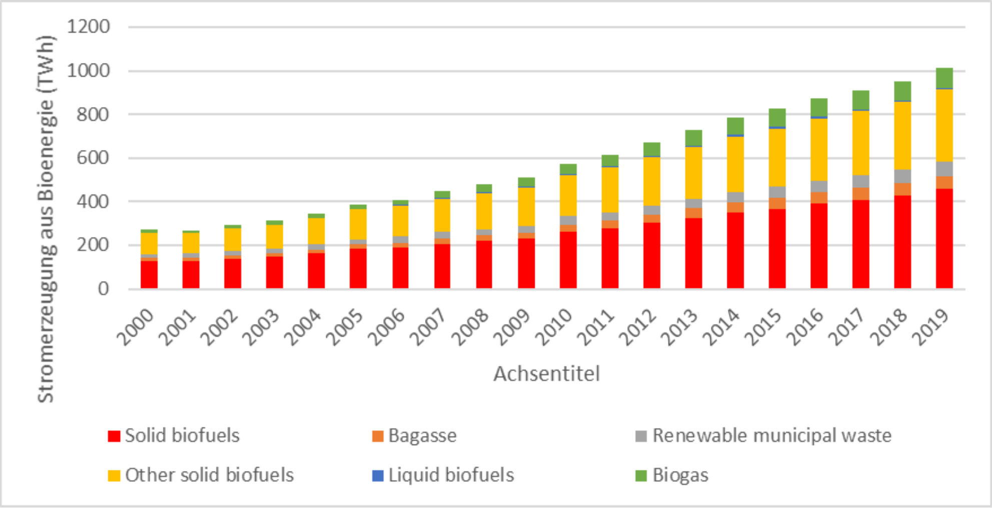

Figure 25: Electricity generation from various bioenergy sources.

Source: IRENA, (2021).

- **Combustion**: The largest share of electricity from biomass is generated by direct combustion. Biomass is burned in a boiler to produce high-pressure steam. This steam drives a turbine and a generator. Biomass can also be used to replace some of the coal in an existing coal-fired power plant, in a process called co-firing.[38] Instead of ending up in a landfill, the waste can be used as fuel.

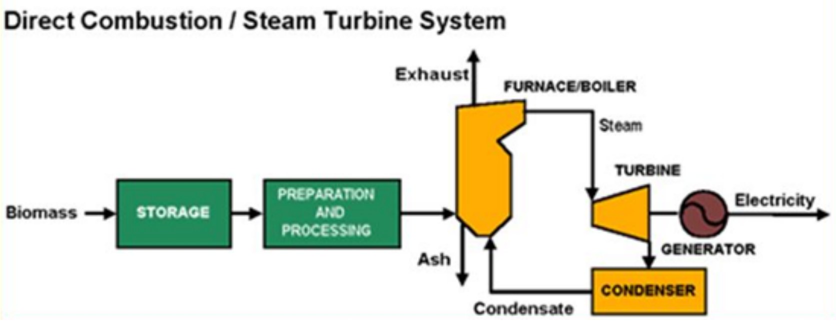

Figure 26: Direct combustion of biomass for electricity generation.

Source: FEMP, (2016).

In Sweden, for example, the waste is converted into energy as fuel and fed into the Swedish district heating system to meet the heating needs of 1,250,000 homes and the electricity needs of 680,000 homes. [39]

System costs tend to decrease as the size of the system increases. For a pure power generation system[40] in the range of 5 to 25 MW, costs are generally between 3,000 USD/kW and 5,000 USD/kW.[41] The cost of electricity for this system is 0.08 to 0.15

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[38] Cf. Victoria State Government, (2022).

[39] Cf. Vattenfall AB, (2021).

[40] Without combined heat and power

[41] Cf. FEMP, (2016).

USD/kWh, but can increase significantly with fuel costs.[42] Large systems require significant amounts of fuel,[43][44] resulting in longer transportation distances and increasing material costs. Small systems have higher operating and maintenance costs per unit of energy produced and lower efficiency than large systems.[45] Therefore, determining the optimal system size for a particular application is an iterative process.

- **Bacterial fermentation:** Organic waste with a high water content such as liquid manure, green waste and residual wood is fermented in the absence of air.[46] The main product (besides CO_2) is biomethane, which after further conditioning is either fed into the natural gas grid or used to generate electricity via a gas engine.

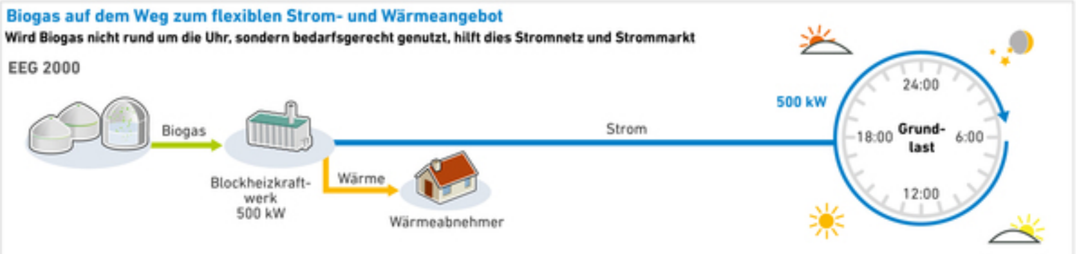

Figure 27: Electricity and heat generation from biogases.

Source: Renewable Energy Agency, (2022).

- **Gasification**: Biomass can be converted into a gaseous or liquid fuel through gasification and pyrolysis. In gasification, solid biomass material is exposed to high temperatures and very little oxygen to produce syngas[47] - a mixture consisting mainly of carbon monoxide and hydrogen. The gas can then be burned in a gas engine to produce electricity as well as heat, as shown in Figure 28.

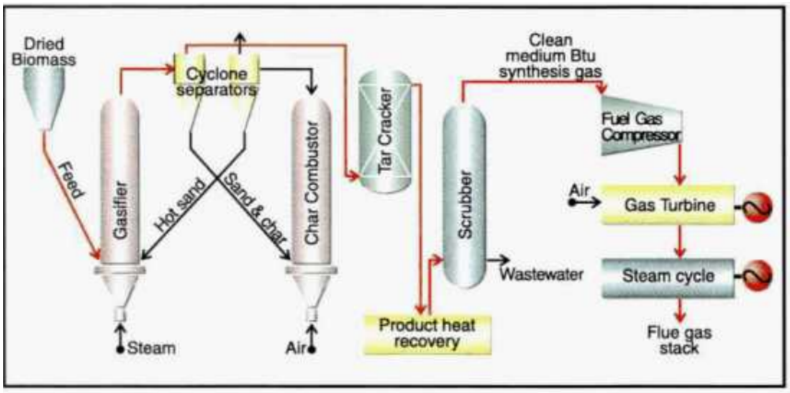

Figure 28. Gasification of biomass for electricity generation. Source: NREL, (2009).

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[42] Cf. FEMP, (2016).
[43] The calorific value of anthracite coal, for example, is twice as high as that of wood pellets.
[44] Cf. Forest Research, (2021).
[45] Cf. FEMP, (2016).
[46] anaerobic
[47] Syngas

Figure 29 shows the installed bioenergy capacity worldwide. Different categories of biomass resources were considered: Waste from forestry and agriculture, various organic sewage sludge streams and biomass production on land of different categories, e.g. grass production on pasture land, wood plantations and sugar cane on arable land.

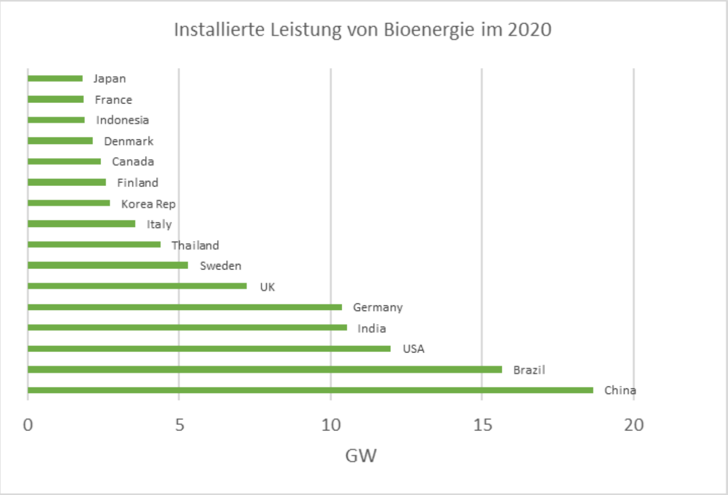

Figure 29: Installed capacity of bioenergy power plants worldwide.

Source: IRENA, (2021).

The potential for energy crops is largely dependent on the availability of land, given the growing global demand for food, coupled with environmental protection, sustainable land management and water resources. As much of the future availability of biomass resources for energy and materials depends on these complex and interrelated factors, it is not possible to evaluate the exact bioenergy potential, according to the IEA. The future biomass potential is projected to be between 40 EJ/a and 1,100 EJ/a. [48]

2.1.1.6 Generation through geothermal energy

Geothermal plants essentially work in the same way as a coal-fired or nuclear power plant, the main difference being the heat source. In geothermal energy, the heat from the earth replaces the boiler of a coal-fired power plant or the reactor of a nuclear power plant. The turbines are driven by the hot steam from the earth and are connected to the generator that produces the electricity.

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[48] Cf. IEA Bioenergy, 2007.

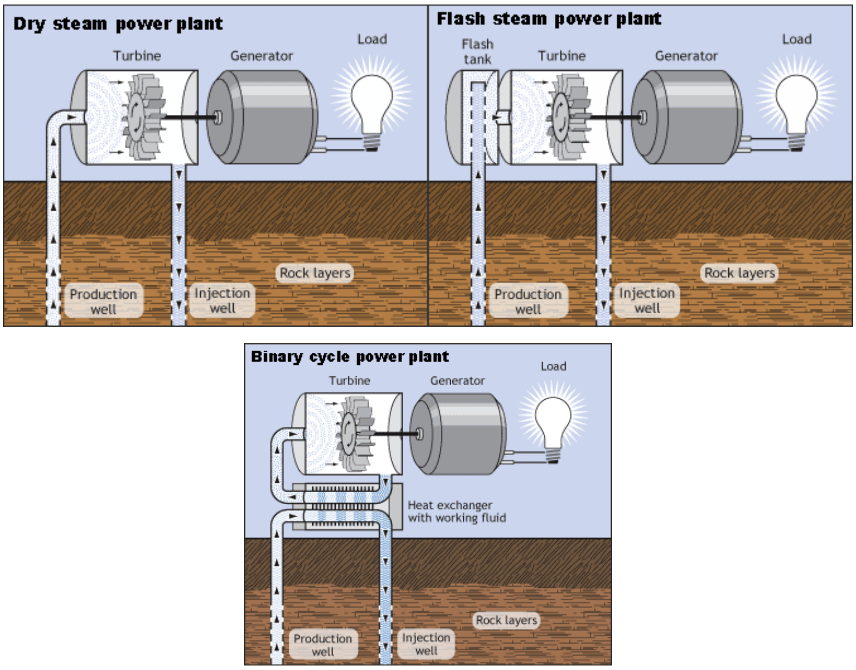

Figure 30: Various types of geothermal power plants.

Source: EIA, (2022).

There are three types of geothermal power plants according to the EIA: [49]

- *Dry steam power plants*: These use steam directly from a geothermal reservoir to drive generator turbines. The first geothermal power plant was built in 1904 in Tuscany, Italy, where steam rose from natural springs.
- *Flash steam system power plants*: In this type of power plant, hot water is extracted from the earth's interior under high pressure and converted into steam by expansion (flash), which then drives generator turbines. When the steam cools, it condenses into water and is reintroduced into the ground for reuse.
- *Binary cycle*: In binary cycle power plants, the geothermal energy is transferred in a heat exchanger to a working fluid, which is thereby vaporised. The steam generated in this way is used to drive a turbine.

Figure 31 shows the installed capacity of geothermal power plants worldwide - the USA has the largest installed geothermal capacity of about 2.6 GW. The global potential for geothermal power generation is between 70 and 80 GW. However, only 15 % of the world's known geothermal reserves are used for electricity generation, resulting in only 13 GW being converted. [50] Geothermal energy is the second largest renewable energy source in Indonesia after hydropower and a clean alternative to coal-fired power generation.

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[49] Cf. EIA, (2022).

[50] Cf. World Bank, (2017).

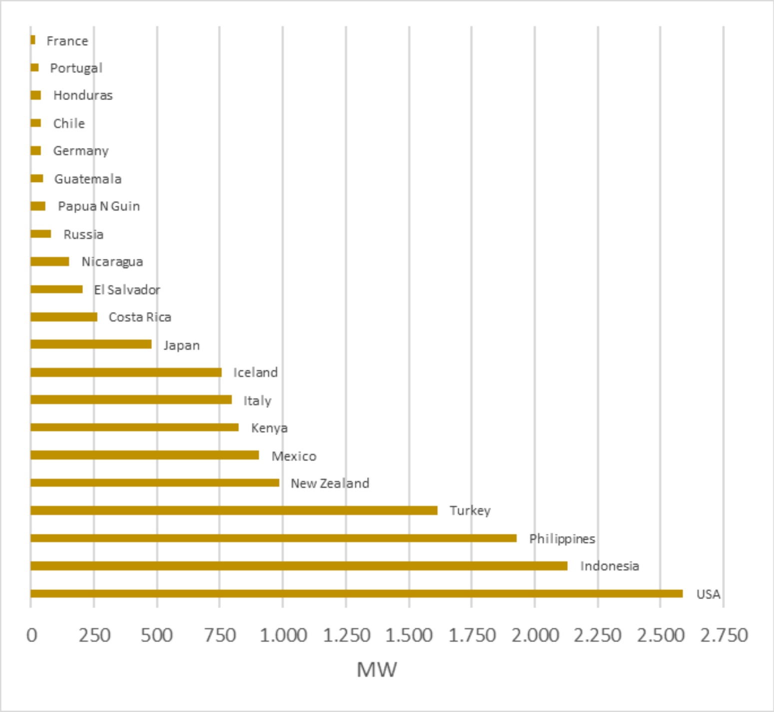

Figure 31: Installed capacity of geothermal power plants in certain countries.

Source: IRENA, (2021).

Geothermal plants are located in geological "hot spots" that tend to have a higher earthquake risk. There is evidence that geothermal systems can lead to even greater earthquake frequency. However, geothermal systems can increase the risk of small earthquakes.[51] The process involves pumping water into the ground at high pressure to break up underground hot rock deposits, similar to the technology used to hydraulically extract natural gas.[52] The seismic risk associated with enhanced geothermal systems can be reduced by locating the plants at a reasonable distance from major fault lines. In closed-loop systems, the gases extracted from the well do not enter the atmosphere but are re-injected into the ground after the heat is released, so air emissions are low. In contrast, open loop systems release hydrogen sulphide, carbon dioxide, ammonia and methane into the air.

2.1.2 LCOE and learning curves

Due to the high cost degression through series and mass production of solar modules, inverters, MPPT (see glossary), the electricity production costs of utility-scale photovoltaic systems in 2020 have fallen by 85 % compared to those in 2010. Therefore, electricity from large-scale solar photovoltaic systems has become one of the cheapest ways to generate electricity.

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[51] hot, dry rock

[52] Cf. Scientific American, 2010.

Wind turbines are becoming increasingly taller and can be built more cheaply with longer blades.[53] Thus, more energy can be generated from wind at a lower cost. Electricity from onshore wind farms is the cheapest type of green electricity followed by green hydropower and solar power (see Figure 32). The LCOE of offshore wind has also halved over the last decades, but it is still almost twice as high as onshore wind due to the higher installation costs of offshore. The LCOE of CSP plants has fallen to one-third in recent decades. There have been no notable reductions in LCOE for other types of electricity generation (see Figure 32).

At the beginning of the last decade, the installation cost of large solar plants was around 4,500 USD/kW$_p$ and in 2010 a total of only 40 GW of photovoltaics were installed worldwide. After the recession in 2009, the demand for alternative and low-CO_2 energy generators such as photovoltaics increased. Rapid growth of the photovoltaic module manufacturing industry in Germany, China and the USA, growing demand for solar PV equipment worldwide, and automation of production caused installation costs to decrease. By 2020, the installation cost of a large PV system from a global perspective has dropped to 850 USD/kW$_p$ on average, according to IRENA (see Figure 33). In contrast, the installation costs for onshore wind power plants have not decreased as rapidly as the installation costs of PV, although the total installed capacity has grown by 350 %.

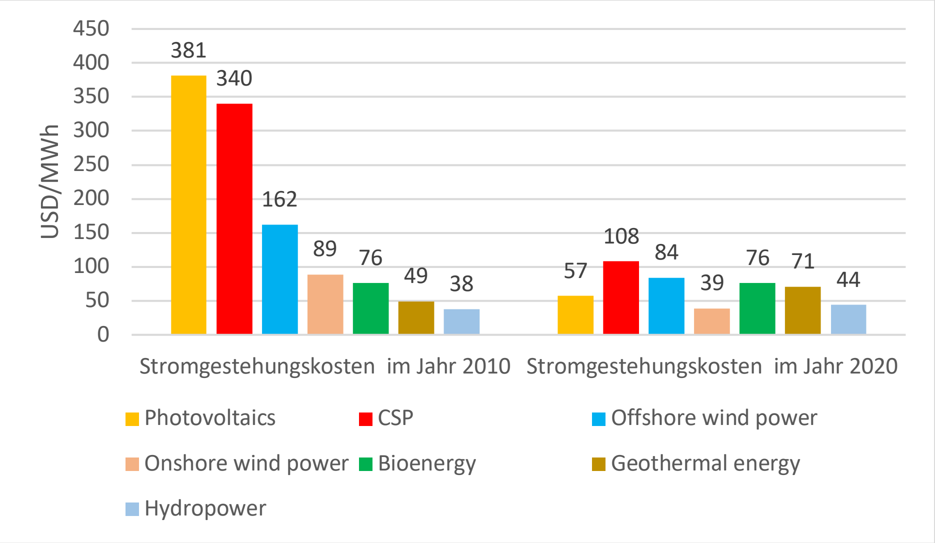

Figure 32: Comparison of the LCOE of different types of electricity generation in 2010 and 2020.

Source: IRENA, (2021).

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[53] Cf. Wind Energy: The Facts, (2022).

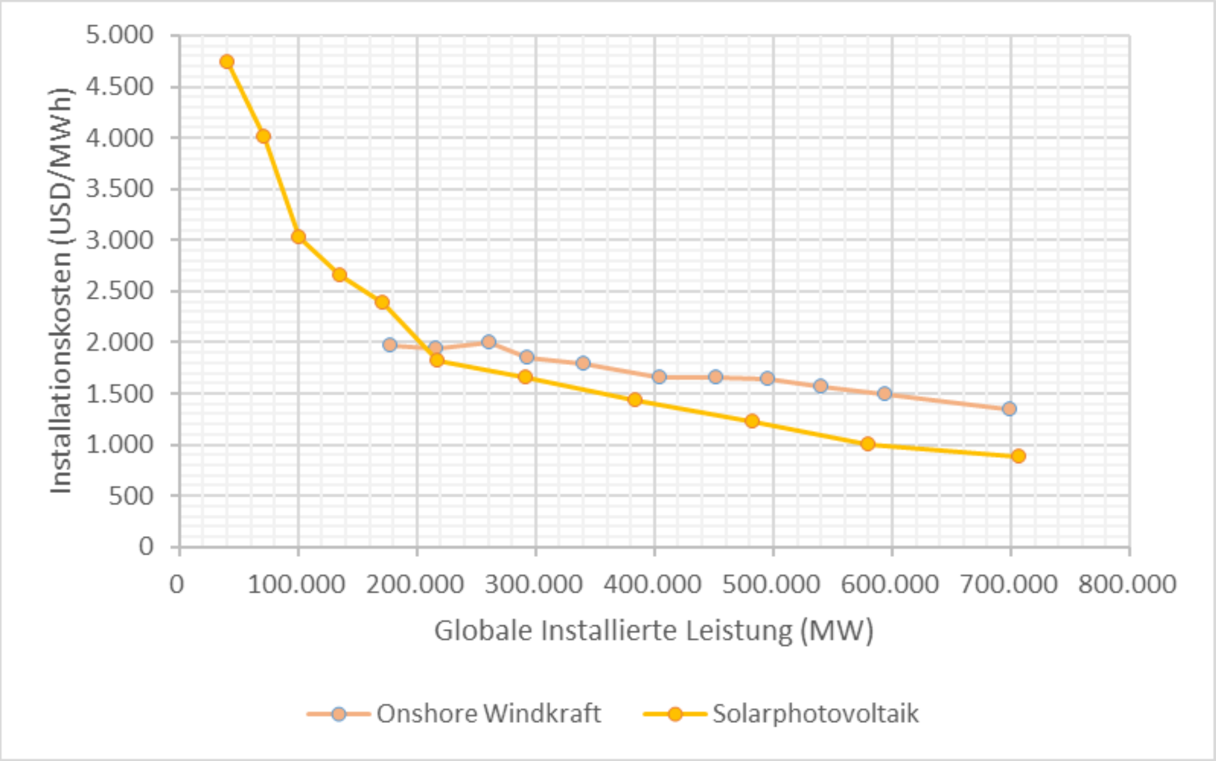

Figure 33: Learning curves of solar photovoltaics and onshore wind power, from 2010 to 2020.

Source: IRENA, (2021).

The installation costs of CSP plants have halved in recent decades. The total installed capacity as well as the installation costs in 2020 were significantly lower than those for large solar photovoltaic plants. Photovoltaic plants are not location-dependent and could also be installed on roofs. In contrast, CSP plants need to be installed in solar deserts and require a mirror/reflector to concentrate the solar radiation on the tower or on oil in pipelines and additionally melt salt to store the heat, as well as other equipment such as solar tracking, condensers and steam turbines.

The installation costs for offshore wind are of course higher than for onshore wind and they have not fallen as significantly as the installation costs of large-scale solar photovoltaics.

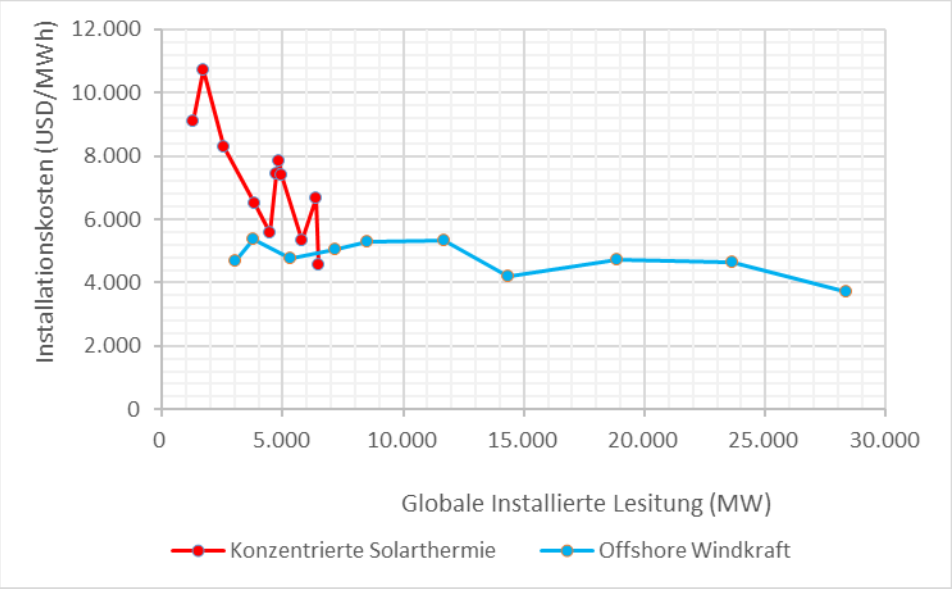

Figure 34: Learning curves of CSP and offshore wind from 2010 to 2020.

Source: IRENA, (2021).

2.1.3 Capacity factors

Full load hours are a measure of the optimum utilisation level of a technical system. Full load hours refers to the time for which a plant would have to be operated at nominal power in order to generate the same amount of electrical energy as the plant actually converted within a specified period of time, during which breaks in operation or partial load operation can also occur. The figure usually refers to a period of one calendar year and is mainly applied to power plants. The annual utilisation factor or capacity factor derived from the number of full-load hours is the relative full-load utilisation in a year,[54] i.e. the number of full-load hours divided by 8,760 hours, the number of hours in a year with 365 days.[55]

Thanks to the independence from weather and daily changes in solar irradiation and wind speeds, geothermal and bioenergy power plants have higher capacity factors. Hydropower plants are typically dependent on reliable water sources or rain, these plants have a capacity factor of about 45 % from a global perspective (see Figure 35). Compared to onshore, offshore wind plants get stable and turbulence-free wind and therefore have higher full load hours (see Figure 35).

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[54] Capacity factor

[55] Cf. Wikipedia, 2022b.

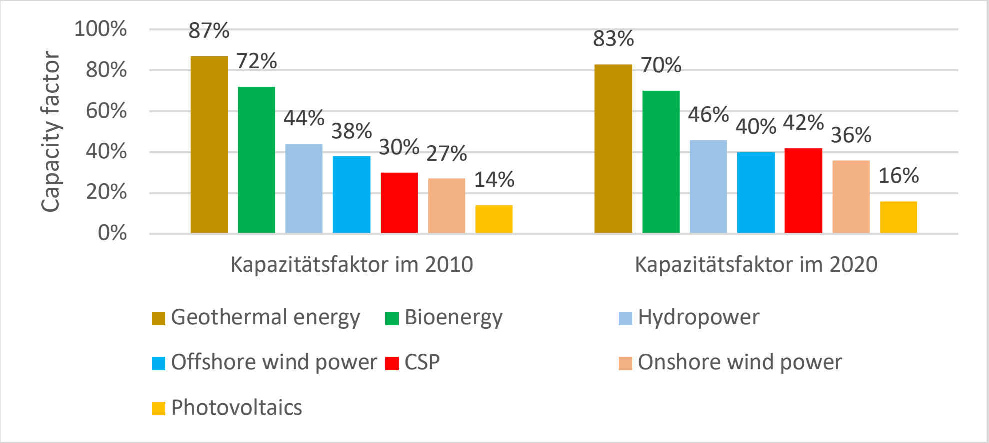

Figure 35: Capacity factors of various types of electricity generation.

Source: IRENA, (2021).

The capacity factor of solar photovoltaics is lower and more variable than that of a coal-fired or nuclear power plant because PV locations, solar radiation, clouds and air temperatures strongly influence the yield of a solar plant and constantly change throughout the day and the seasons, thus also changing the solar energy yield. It is precisely for this reason, and the lack of a low-cost electricity storage system, that the electricity grid cannot be easily defossilised with the implementation of large-scale solar PV systems, although the installation cost per kW is thus reduced (see Figure 35). On average, the capacity factor worldwide for large solar plants is 16 % and has increased slightly compared to 2010 (see Figure 35).

The capacity factor for solar plants is highly dependent on location. According to one study, capacity factors in central Europe can be around 15 %, in southern Spain almost 20 %.[56] In northern China, California, Arizona, northern and central Africa, southwestern China and large parts of Australia, on the other hand, capacity factors can be around 25 %.

2.1.4 Raw material requirements, emissions and environmental impact of renewable electricity generation

NREL has evaluated about 3,000 published life cycle studies of electricity generation from wind, photovoltaic, CSP, bioenergy, geothermal, hydropower, nuclear, natural gas and coal technologies, as well as lithium-ion batteries, pumped storage and hydrogen storage. Some experts have defined strict criteria to systematically evaluate these studies and to find out the emissions over the life cycle of the power generation technology.

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[56] Cf. Wu et al., (2022).

On average, emissions from crystalline silicon and thin-film cell PV systems are around 50 g CO_2 eq/kWh. CdTe (see glossary).

Thin-film cell modules have a better emissions balance than silicon-based modules. The maximum emission is about 200 g CO_2 eq/kWh. The emissions of harmful pollutants (e.g. SO_2, NOx, particulates) during the life cycle of a PV system are largely proportional to the amount of fossil fuels burned in the different stages of manufacturing various components of a PV system, especially during material processing and manufacturing; therefore, the emission profiles are similar to those of greenhouse gas emissions. Life cycle SO_2 emissions are 120, 100 and 60 mg/kWh for polycrystalline, monocrystalline and CdTe modules, respectively, and NOx emissions are 65, 58 and 30 mg/kWh.[57] The CSP plants also have a better emission balance over the life cycle compared to coal-fired or gas-fired power plants (see Figure 37).

According to the IEA and IRENA collaboration, recycling or reusing solar modules at the end of their approximately 30-year lifespan is likely to make an estimated 78 Mt of raw materials and other valuable components available globally by 2050 (see Figure 36). If fully recycled back into the economy, the value of the recovered material could exceed USD 15 billion by 2050.

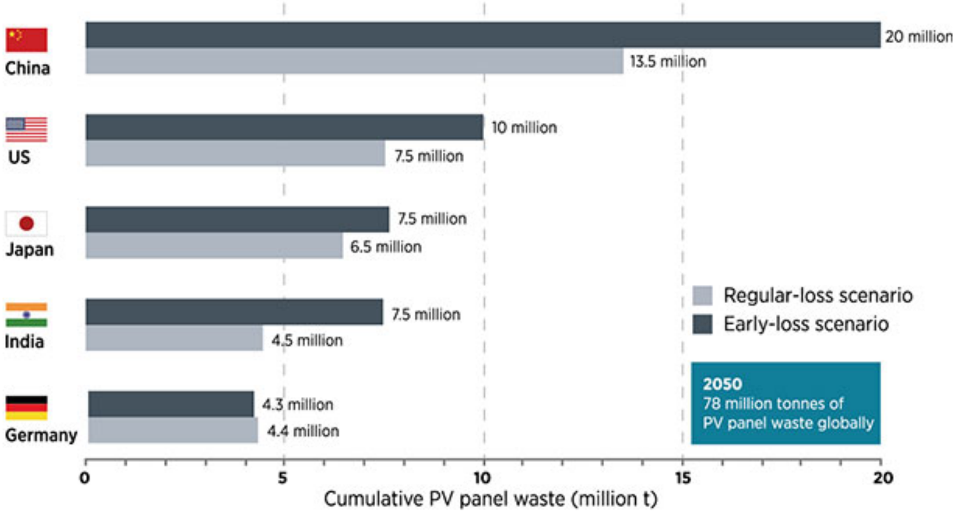

Figure 36: Projections of waste production from the solar PV industry in 2050.

Source: IRENA, (2016).

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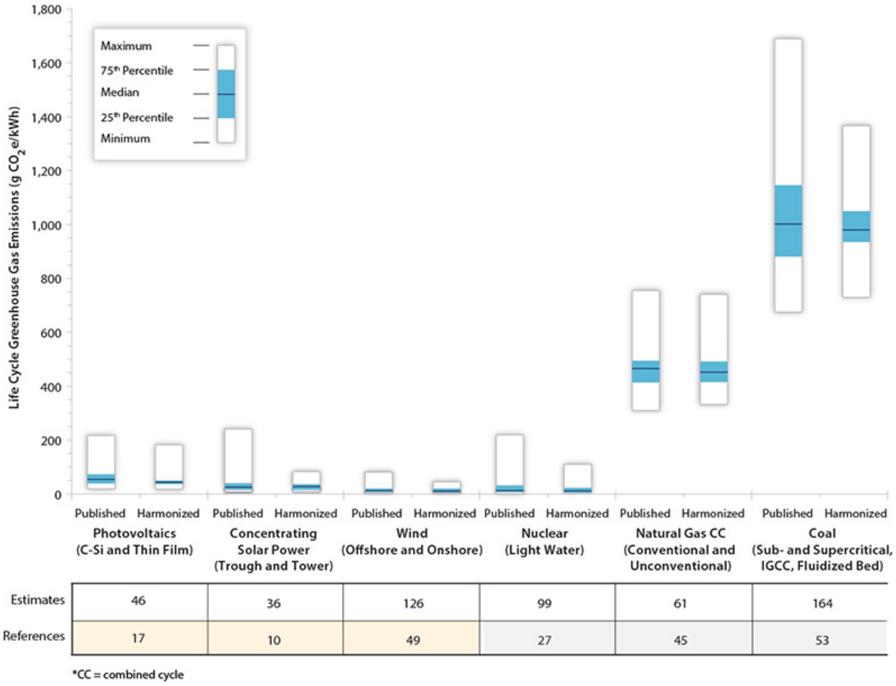
[57] Cf. Fthenakis et al., 2011



	Photovoltaics	Concentrating Solar Power	Wind	Nuclear	Natural Gas CC	Coal
Estimates	46	36	126	99	61	164
References	17	10	49	27	45	53

*CC = combined cycle

Figure 37: Emissions in the life cycle of various types of electricity generation.

Source: NREL, (2020).

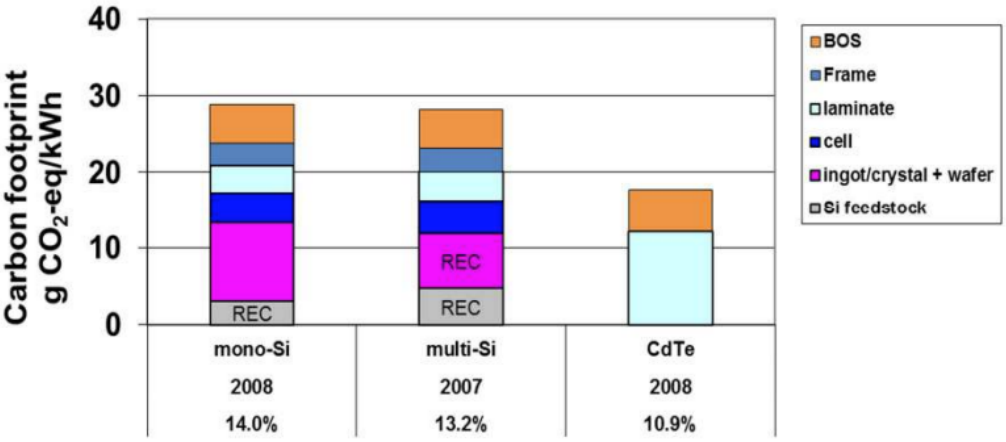


Figure 38: Life cycle GHG emissions of roof-mounted PV systems for European production and installation at a Southern European solar irradiance of 1700 kWh/m2/a, a performance ratio of 0.75 and a lifetime of 25 years.

Source: Fthenakis et al., 2011.

The situation concerning scarce raw materials is described in detail in chapter 2.13.

Appendix to 2.1

Examples of electricity generation in some countries (Ghana, Kenya, Spain) are given in chapter 0 on page 119 shown.