CHAPTER 9

Solar Power Generation

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1 Introduction

In less than two hours, enough sunlight strikes the earth to satisfy the world economies' annual energy demand. Despite this abundance of solar energy, the conversion of sunlight into usable energy forms only represents a tiny fraction of today's global energy supply. Yet, the share of solar energy in global energy supply, especially in the electricity sector, is rising rapidly. Unprecedented deployment has taken place in the last decade, stimulated by efforts to improve energy access, security of supply and mitigate climate change. Between 2010 and 2017, the global installed capacity of solar generation increased more than

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M. Hafner, G. Luciani (eds.), *The Palgrave Handbook of International Energy Economics*, https://doi.org/10.1007/978-3-030-86884-0_9

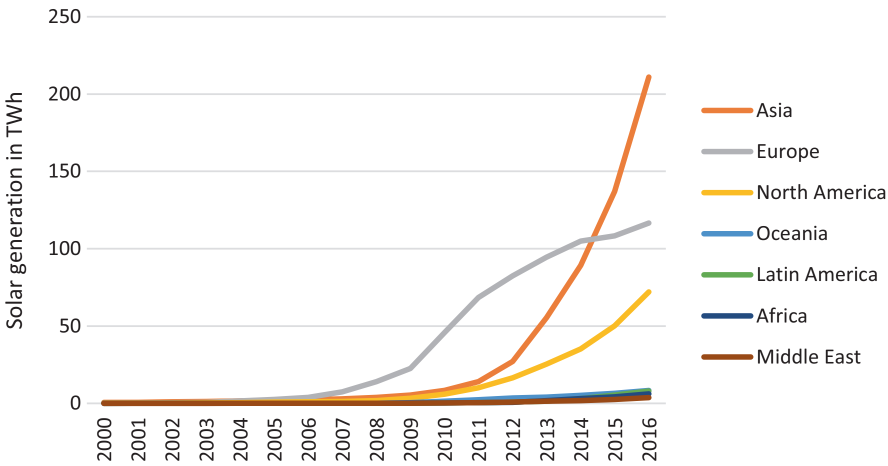

Fig. 9.1 Power generation from solar energy by region (in TWh). (Authors' own elaboration, data from IRENA 2020)

tenfold from 34 GW to 437 GW (IRENA 2020). Steep learning curves and the economies of scale enabled technological improvements and, in consequence, have led to massive cost reductions.

Solar photovoltaics (PV), the conversion of light into electricity using semiconducting materials, were one of the most expensive electricity-generating technologies when first employed in astronautics in the late 1950s. By 2020, it has become an economically viable energy source for many applications. An alternative technical process to generate electricity from solar radiation is concentrated solar power (CSP). Yet, the latter, accounted for less than 3% of all solar power in global electricity generation in 2017 (IRENA 2020).

PV is the third most important renewable energy source in terms of global capacity after hydro and wind power. Globally, solar energy is mostly used in Asia, Europe and North America with the strongest rise in Asia, mostly driven by China and India (Fig. 9.1). According the World Energy Outlook of the International Energy Agency, solar PV may become the largest technology in terms of global installed capacity in the Stated Policies Scenario by 2035 (IEA 2019).

2 Technical Characteristics of Solar Energy

A brief introduction to the technical characteristics of solar energy provides the necessary background information to better understand its economics.

2.1 Solar PV

The main components of photovoltaic cells are semiconducting materials such as silicon and germanium. In these materials, sunlight releases charge carriers (electrons), which create an electrical field. As source of electricity generation, this field induces a direct electrical current. This process is known as the photovoltaic effect. Electricity generation exploiting this effect is not only possible from direct sunlight, but also from its diffuse components, implying that PV cells also generate electricity with cloudy skies.

Photovoltaic cells are integrated in solar arrays. Inverters (to invert DC current from solar panels into AC), transformers, electrical protection devices, wiring and monitoring equipment are summarized as balance of system (BOS). In some cases, BOS also includes sun-tracking systems, which increase the yield by positioning the panels towards the sun.

The three major types of solar PV technology are monocrystalline cells, polycrystalline cells and thin firm cells, of which the first two make up more than 95% of global module production (Fraunhofer ISE 2019).

Monocrystalline solar cells have the highest efficiency rates, typically 15–20% but the highest quality panels can reach up to 23% efficiency. As for all solar panels, the efficiency of monocrystalline panels depends on ambient temperature. On average, efficiency declines by about 10% when the ambient temperature rises by 25 °C (Quaschning 2019). Featuring high efficiencies, monocrystalline solar panels are space efficient, i.e. they require smaller ground areas to generate the same amount of electricity compared to other technologies. They also live the longest with most manufacturers putting a 25-year warranty on monocrystalline solar panels. Their main disadvantage is the high cost, because manufacturing requires the highest-grade silicon.

Polycrystalline silicon cells are cheaper because of a simpler production process and the amount of waste silicon is less compared to monocrystalline cells. The efficiency of these panels is typically lower (13–16%). They also have a slightly lower heat tolerance, which means that polycrystalline perform slightly worse in high temperatures than monocrystalline panels.

Thin film solar cells deposit one or several thin layers of photovoltaic material onto a substrate. Most thin-film modules have efficiencies of around 9–11%. Their mass production makes them cheaper than crystalline based solar cells. Thin film solar panels are mostly used in applications where panel sizes are not an issue. Another advantage is that they can be more easily integrated into facades and roofs.

When comparing efficiencies, it is important to differentiate between efficiencies of single cells, of panels and of the entire installation including converter and transformer. In the last 10 years, the efficiency of average commercial silicon modules increased from about 12% to 17% (Fraunhofer ISE 2019). Lab cell efficiencies of close to 50% when concentrating light rays and applying new materials demonstrate the potential for further efficiency increases at the production level (Geisz et al. 2020).

2.2 Concentrated Solar Power

Concentrated solar power (CSP) does not exploit the photovoltaic effect. Instead, mirrors are used to focus solar rays to heat a fluid. Similar to

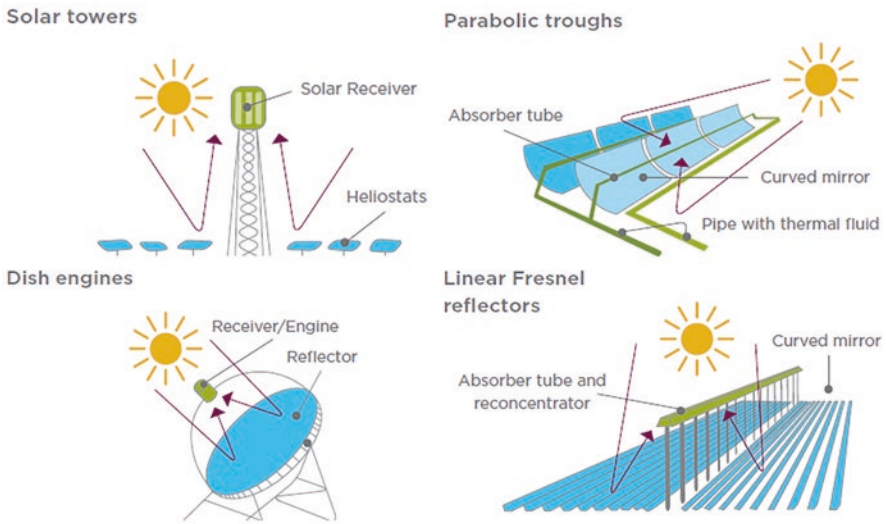

Fig. 9.2 Concentrated solar power technologies. (Source: Qader and Stückrad 2016)

conventional power plants, the thermal energy then drives a turbine to generate electricity. A downside of the CSP technology is that direct radiation is required for the process, because diffuse radiation cannot be focused. CSP plans are therefore mostly sited in countries with high direct radiation and a dry climate (see section on solar potential), for example, in northern Africa and the Middle East.

One major advantage of the CSP technology compared to solar PV is that heat can be stored at comparatively low cost. Equipped with molten salt vessels as thermal energy storage, most CSP plants have a steadier generation profile during the day and extend electricity generation long beyond sunset.

The four main construction types of CSP plants are solar towers, parabolic troughs, linear Fresnel reflectors and small-scale dish engines (Fig. 9.2). Parabolic trough and solar tower CSP plants are the most mature CSP technologies and lead new installations by far (REN21 2019).

CSP technologies can be grouped into point concentration systems (solar towers and dish engines), and linear concentration systems (parabolic troughs and linear Fresnel reflectors). Technologies based on point concentration systems achieve higher temperatures (up to 1200 °C) than linear concentration technologies (300–550 °C), and thus yield higher thermal efficiencies. However, focusing a large number of mirrors on a single point is highly complex and leads to high construction and maintenance costs. By contrast, linear concentration technologies require less land than point concentration systems.

Parabolic troughs and tower systems have first been built commercially in the 1980s. Whereas learning potentials in well-developed, mature steam processes, such as steam turbines, condensers and generators have been exhausted, further technological improvements are expected in other components. For example, higher storage potentials could be reached by using new fluids or particles that enable transfer and storage of sun energy at higher temperatures; enhanced mirror materials could reduce costs and increase reflectivity; and information technology can be used to detect system failures, reducing operation and maintenance costs, in particular of complex point concentration systems; such technological innovations could further improve the technology's efficiency and further reduce costs (Desai and Bandyopadhyay 2017; Islam et al. 2018).

3 Applications of Solar Energy

Photovoltaic systems have long been used in specialized applications as standalone installations (island systems). Grid-connected PV systems were first constructed in the 1990s. Nowadays, solar energy for electricity generation is applied on the wide range between small roof-top PV systems and large utility scale solar parks. In contrast to the modular solar PV, CSP is mostly deployed in large-scale power plants.

PV and CSP in large-scale solar parks, directly connected to the high voltage grid, are used to generate electricity on a commercial-scale. The largest solar power plants around the world are PV parks with installed peak capacities of up to 2 GW per site, the order of magnitude of a large nuclear power plant. The largest solar PV parks are located in India, China and the Middle East.

The modularity of solar PV (and dish engine CSP plants) also allows small-scale deployment. Roof-top PV systems have increased significantly, fostered by falling costs and governmental support policies. On a small-scale, roof-top PV serves self-consumption or supplies local mini-grids. In most countries, distributed residential systems already have generation costs below (the energy portion of) retail electricity prices, making the deployment of solar PV for self-consumption economically attractive (IEA 2020b). Behind-the-metre business models, increasingly comprising battery storage, allow to self-consume electricity generated by roof-top PV. In remote off-grid rural areas, particularly in developing countries with good solar resources, decentralized solar power feeding into local mini-grids may provide electricity access in places where a connection to the national grid is too expensive. In urban areas, roof-top PV could provide a back-up for an unreliable grid supply. In these applications, roof-top PV does not compete against large-scale power plants but against other small-scale generation units such as diesel generators. Often, solar is not only the most sustainable alternative but also economically viable. This increasing economic attractiveness of small-scale PV systems could lead to rapid expansion of decentralized PV capacity.

Aside from power generation, CSP can also generate steam, which can be used in other sectors, for example, in enhanced oil recovery or steam-using industry processes. Thus, CSP technologies could be elements of sector coupling to enable further decarbonization of economies.

4 Costs of Solar Energy

Investment costs are by far the highest cost component of solar energy. Variable operation costs of solar energy are close to zero because it uses no fuel other than solar radiation, which is free of charge. This cost structure is structurally different compared to conventional generation technologies. In this section, we discuss the development of investment and maintenance costs.

4.1 Declining Investment Costs of Solar Energy

Between 2010 and 2018, the average total installation costs of solar PV declined by 74% (Fig. 9.3). These exceptional cost reductions were made possible by extraordinarily high growth rates of PV capacity. The compound annual growth rate of PV installations was 36.8% between 2010 and 2018 (Fraunhofer ISE 2019). The learning curve (or experience curve) is another indicator of cost reduction. It describes how prices decline when the number of manufactured goods increases. Learning curves of solar PV modules were particularly steep: they have followed a 20–22% cost reduction for each doubling of capacity during the last four decades (Fraunhofer ISE 2019). Within the module, PV cells

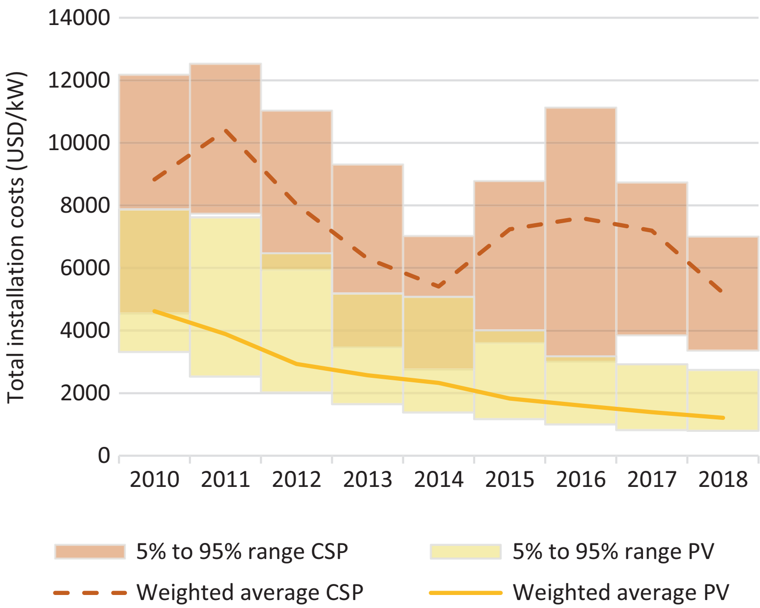

Fig. 9.3 Development of installation costs for solar PV and CSP. (Authors' own elaboration, data from IRENA 2020)

account for the highest cost shares. The three main factors driving the cost reductions of PV cells were (i) increasing sizes of manufacturing plants (economies of scale), (ii) improved module efficiency (technological advances), and (iii) a decline in costs of purified silicon. A high share of the recent cost reductions can be traced back to the rapid expansion of cell manufacturing in China, where about 70% of all PV modules are produced (Fraunhofer ISE 2019). Due to the modularity of PV panels, long distance transportation of the panels is easier than for most other generation technologies, such as, for example, blades and towers of wind turbines, which are usually manufactured locally. The market for solar panels is therefore a global market, characterized by large-scale manufacturing sites and high competition with cost-cutting effects.

The decline in balancing of system costs was led by inverter cost reductions. While PV modules historically had the largest share in total cost, in 2020 the overall BOS costs account for up to 40–60% of total PV investment costs (IEA 2020b).

Similar to solar PV, high upfront capital investment costs are also a major barrier for CSP technologies. They account for almost four fifth of the total costs. Throughout the past decade, average installation costs of CSP plants have been falling from 8800 USD/kWh in 2010 to 5,200 USD/kWh in 2018 (Fig. 9.3), albeit less constantly than they have been for solar PV. The uneven trajectory can be explained by a much lower number of new installations and an uneven buildout among countries. Until 2013, most capacity additions occurred in Spain and the United States, incentivized by generous past incentive schemes. But no new capacity has entered commercial operation in Spain since 2013 and in the United States since 2015. Current capacity extensions are led by China and Morocco (REN21 2019).

4.2 Operation and Maintenance Costs of Solar Energy

A second relevant cost driver of solar energy is the operation and maintenance (O&M) costs. To ensure high levels of technical performance of the solar system, it is necessary to identify and replace broken modules of a PV plant, or receivers and mirrors of a CSP plant. Particularly dusty areas (e.g. deserts) require regular cleaning of mirrors and modules. Both tasks make up for significant costs (IRENA 2020). Large-scale solar plants benefit from significant economies of scale in these O&M costs.

The development of large-scale power plants has increased the demand for tools for inspection and monitoring. Drones are often used in the solar industry due to their wide range of surveillance and monitoring capabilities. The formerly manual process of monitoring is increasingly replaced by data driven monitoring solutions. With sensing elements, drones capture the necessary data in less time and a more accurate form, which is then digitally processed. This enables long range inspection and easy control of plants and thereby reduces operation and maintenance costs significantly.

4.3 LCOE of Solar Energy

The levelized cost of electricity (LCOE) combines investment and operation costs. It is defined as the average cost of electricity per unit of electricity output. The LCOE is a good metric to measure cost reductions and technological improvements of a technology. However, this indicator should not be used to compare different technologies. It is highly sensitive to the number of full load hours of a technology and it neglects the value of electricity, i.e. how much electricity is valued at the time when generated (see Chap. 15 on system integration).

In 2018, the LCOEs of Solar PV ranged from 60 to 210 USD/MWh with a global average of 85 USD/MWh (IRENA 2019c). Further cost declines are expected to reach 20–80 USD/MWh in 2030 and 14–50 USD/MWh in 2050 (IRENA 2019a). The LCOEs of CSP technologies have also been falling throughout the last decade. In the US, the LCOE of CSP halved from 340 USD/MWh in 2010 to 190 USD/MWh in 2018 (IRENA 2019c), and is even expected to fall to 50 USD by 2030 (US Department of Energy 2020).

LCOEs decline when costs are reduced but also when the electricity output increases. Such increase is reflected in rising capacity factors (also utilization rates or load factors), describing the ratio of generated electricity to installed capacity. A capacity factor of 20% implies that the electricity generation is equivalent to this generator operating 20% all hours in the year at full capacity. As we will discuss in the following sections, capacity factors strongly depend on the location of solar energy installations and the natural resources.

5 Generation Pattern of Solar Energy

Solar generation is highly variable. Power generation with solar energy is limited to daytime given that the sun does not shine at night. Consequently, capacity factors of solar power plants (without storage) are lower compared to other technologies and typically range between 10% and 20% in most regions, reaching up to 25% at the best spots in desert locations. Since 2010, the global weighted average capacity factor of utility scale PV systems has been constantly increasing (Fig. 9.4). Three major drivers explain rising capacity factors (IRENA 2019c). First, solar PV is increasingly deployed in regions with higher irradiation levels. Second, tracking systems that follow the movement of the sun are increasingly employed, which increases the yield. And third, system losses have been reduced, for example through improvements in the efficiency of inverters.

Figure 9.4 shows that the capacity factors of CSP experienced a significantly stronger increase compared to PV. The main reason for this development is the increasing combination of CSP plants with thermal storage. This helps shifting generation into hours without sunlight, thereby allowing capacity factors exceeding 30–40%. Storage and turbine dimensioning allow to theoretically achieve capacity factors of over 90%, which is however not economical. The

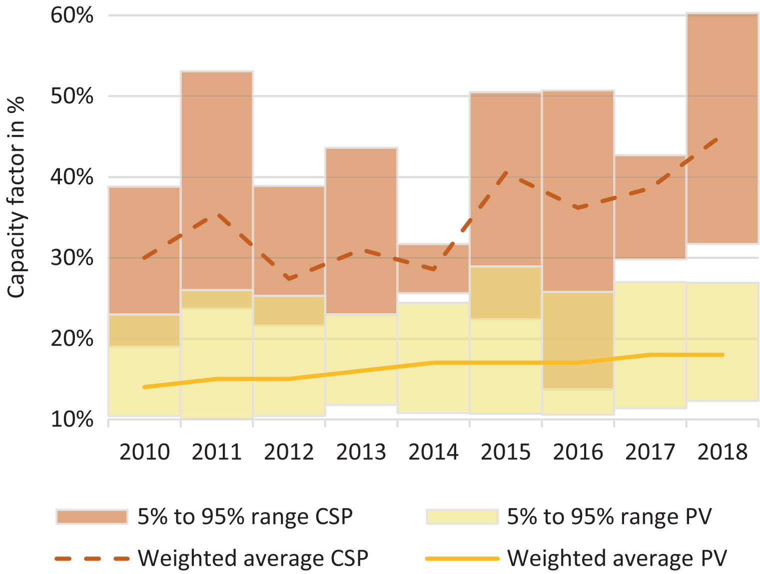

Fig. 9.4 Capacity factors of solar PV and CSP. (Authors' own elaboration, data from IRENA 2020)

high fluid temperatures of solar power CSP plants are best suited for storage. This technology has therefore the highest realized capacity factors of up to 70% (IRENA 2020). Due to the extension with thermal storage, generation patterns of CSP plants differ from solar PV. This flexibility provides an additional value compared to the non-dispatchable solar PV (Pfenninger et al. 2014).

Because of its comparatively low capacity factors, the share of solar energy in the generation mix of a country is usually lower than its share in terms of total installed capacity. A second relevant effect resulting from its generation pattern is the high concentration of solar energy generation in few hours of the day. In these hours, most PV plants of an area generate electricity. The high simultaneous electricity supply of solar generation has a depressing effect on electricity wholesale prices. In countries with high shares of solar energy, solar market values are significantly lower than for other technologies, implying that revenues from selling electricity from solar generation are, on average, lower than average wholesale electricity prices (Hirth 2013). This effect is known as merit order effect and it applies in particular to solar PV because its generation is most concentrated in time.

6 Potential of Solar Energy

The potential of solar energy varies strongly across the globe (Fig. 9.5). Depending on solar irradiance levels, solar capacity factors are highest close to the equator and decline towards the poles. The highest potential for solar

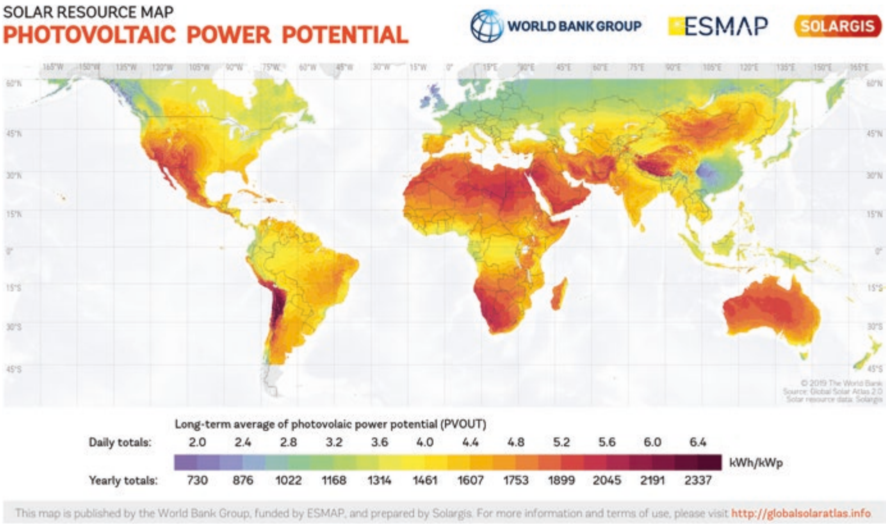

Fig. 9.5 The geographical potential of solar energy. (Source: Global Solar Energy Atlas 2019)

energy lies in the Atacama Desert in South America, the Sahara region, in the Middle East, the Gobi desert in western China, Australia and the western part of the United States. Solar irradiation in these areas is more than twice as strong as in eastern China and most northern European countries where large parts of global solar energy installations are located. Consequently, the electricity output, and with it the electricity generation costs, varies by a factor of up to two depending on the location.

CSP technologies are even more dependent on direct solar radiation than Solar PV plants and need direct normal irradiance values of at least 1800 kilowatt-hours per square meter per year. Their applicability is thus much more limited. However, well suited conditions can be found on all continents, including regions in south-western United States, the Middle East and North Africa, South Africa, Australia, Mexico, Chile and Southern Europe.

In addition to daily patterns, solar generation features seasonal patterns, especially at higher degrees of latitude, i.e. towards the poles. Close to the equator, solar irradiance increases but also cloud cover tends to be higher. In these areas, solar energy output remains relatively stable throughout the year; the position of the sun varies less and the time of sunrise and sundown remain similar.

7 Policy Instruments and Support Schemes

The strong increase in solar buildout would not have been possible without enabling government policies. These include research and development funding and development policies, which led to the development of a solar industry. This development was in particular driven by guaranteed feed-in tariffs which were first implemented in Germany in 2000.

The design of effective support schemes for solar energy needs to take into account the cost and finance structure of solar generation: as discussed in previous sections, solar plants are very capital intensive. Most expenses of solar power generation occur during construction, early in the project's lifetime. Higher cost of capital, for example due to high interest rates, strongly affects the project's profitability because expenditures in these years are recovered a decade later. The economic viability of solar therefore strongly declines with increasing cost of capital. Gas-fired power plants, in comparison, have comparatively low construction costs and a significant share of the expenses, fuel costs and emission costs, are settled when revenues from power generation accrue.

One main target of support schemes is thus to reduce the cost of capital, for example by lowering risks for project developers. Initially, feed-in tariffs were the primary support scheme for solar energy, which was mostly built on a small-scale by private households. By guaranteeing fixed feed-in tariffs, uncertainty about future revenues declined. Also, the risk of electricity price variations is mitigated for investors. With these support schemes, solar projects became profitable. Starting in 2010, many countries began to determine the level of feed-in tariffs for large-scale projects in auctions. In these auctions, projects compete for a predefined amount of supported capacity and only the most cost-efficient ones get financial support. Since the late 2010s, a shift from subsidy driven development to a competitive pricing model becomes visible in many markets. This also includes bilateral Power Purchase Agreements (PPA) between producers and off-takers, such as utilities and industry, absent of governmental support.

The less mature CSP technologies are still dependent on policy support in order to be economically viable. Due to their higher LCOE compared to solar PV, support schemes would need to reflect better the system benefits provided by CSP's dispatchability to foster a further development of CSP technologies. System stabilizing effects such as the ability to generate electricity during demand peaks will become increasingly important as energy systems decarbonize and move towards high shares of renewable energy sources.

8 Outlook

Unleashing the huge potential of solar energy will be key to achieve global climate targets and to limit global warming (IRENA 2019a). Continuous policy support is thus granted in many countries around the globe. In addition to support schemes, further cost declines and innovations drive the rapid expansion of solar energy. As in many other markets, digitalization drives cost reductions in the solar sector. Predictive algorithms based on big data and artificial intelligence enable an optimized adjustment of solar PV modules and CSP mirrors to the sun's position in order to maximize the power output. New monitoring and control systems reduce maintenance costs. Further improvements in terms of sustainability and cost reductions could be achieved by recycling materials, for example, silicon.

Driven by increasing cost competitiveness and policy support, solar energy is highly dynamic. Between 2019 and 2024, the IEA predicts solar to be the fastest growing energy source worldwide with an increase in total installed capacity of around 700 GW (IEA 2020a), more than doubling the 2018 level of 490 GW (IRENA 2019b). China, the European Union, the United States, India and Japan are expected to drive this development (IEA 2020b). By 2050, IRENA expects the total installed capacity of Solar PV to exceed 8000 GW—equalling 16 times the 2018 level (IRENA 2019b). The solar industry needs to prepare for this rising global demand—scaling up investments is therefore key in the next decade.

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