FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES

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SUMMARY

The present study (2021) compares the levelized cost of electricity (LCOE) of renewable energy technologies for electricity generation with conventional power plants. The future cost ratio between the different power generation technologies is also compared for the years 2030 and 2040. For the cost development of renewables, cost development based on technology-specific learning rates (LR) and market scenarios are used.

The focus is on the LCOE of photovoltaic (PV), wind power plants (WPP) and bioenergy plants in Germany. For the first time, PV battery systems are included in the study, as they represent a growing segment of the German power system market. As a reference, the development of the LCOE for newly built conventional power plants (lignite, hard coal, combined cycle gas turbines (CCGT), gas turbine) is also examined. Figure 1 shows the LCOE for renewable and fossil power plants potentially built in 2021.

Depending on the type of systems and solar irradiation, PV systems have a LCOE between 3.12 and 11.01 €cent/kWh, excluding value-added tax (VAT). The study distinguishes between smaller rooftop PV systems (< 30kWp), large rooftop PV systems (> 30kWp), and ground-mounted utility-scale PV systems (> 1MWp). Currently, specific system costs lie within the range

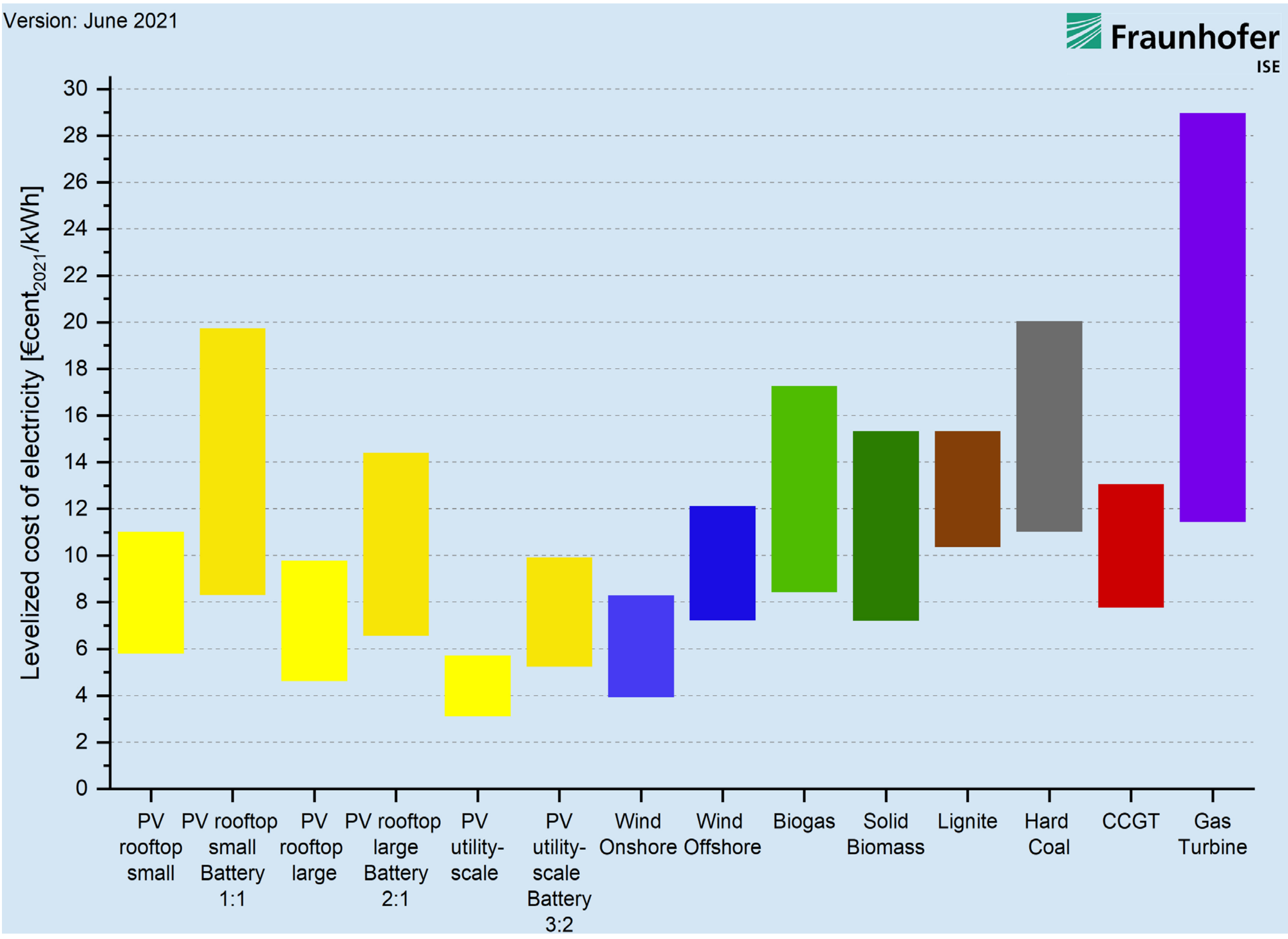

Figure 1: LCOE of renewable energy technologies and conventional power plants at locations in Germany in 2021. Specific investments are considered using a minimum and maximum value for each technology. The ratio for PV battery systems expresses PV power output (kWp) over usable battery usable capacity (kWh).

of 530 to 1600 EUR/kWp. Thus, they have continued to follow a decreasing trend, especially for large systems. For smaller rooftop systems, however, a trend towards slightly more expensive systems can be detected. The LCOE for PV battery systems currently range between 5.24 and 19.72 €cent/kWh. This wide range is the result of cost differences for battery systems (500 to 1200 EUR/kWh) in combination with cost differences for PV systems and varying levels of solar irradiation. In addition, battery storage systems can contribute to system security in the electricity system and the stabilization of feed-in curves or battery discharges high demand periods.

The LCOE of onshore wind power plants in 2021, with specific plant costs ranging from 1400 to 2000 EUR/kW, are between 3.94 and 8.29 €cent/kWh. As a result, PV systems and onshore wind power plants are, on average, the least expensive technologies in Germany, both among renewable energy technologies as well as all other power plants. Offshore wind power plants also continue to record decreasing LCOE. With up to 4500 full load hours, offshore wind power plants achieve electricity production costs between 7.23 €cent/kWh and 12.13 €cent/kWh. The specific plant costs are between 3000 and 4000 EUR/kW, including the connection to the mainland.

For the first time, a distinction was made between biogas and solid biomass in the LCOE of bioenergy. In addition, heat utilization was also assumed, which lowers the LCOE. The LCOE of biogas range from 8.45 to 17.26 €cent/kWh at substrate costs of 3.84 €cent/kWhth. For solid biomass plants, LCOE are slightly lower between 7.22 and 15.33 €cent/kWh, mainly due to lower substrate costs considered here.

The LCOE of potentially newly built coal-fired power plants (hard coal and lignite) have risen considerably due to increased CO_2 certificate prices; the LCOE are above 10 €cent/kWh. If a lignite-fired power plant were built today, LCOE of 10.38 to 15.34 €cent/kWh could be expected. The LCOE of large coal-fired power plants are somewhat higher, at between 11.03 and 20.04 €cent/kWh. The LCOE of combined cycle power plants is somewhat lower at between 7.79 and 13.06 €cent/kWh. Gas turbine power plants for short-term flexible use land at 11.46 and 28.96 €cent/kWh. As described above, the decisive factor here is the CO_2 price, as the energy source prices were assumed to be constant due to declining demand.

Forecast of LCOE in Germany through 2040

Figure 2 shows the results for the future development of the LCOEs in Germany until 2040. The illustrated range reflects the possible cost variations in the input parameters (e.g. power plant prices, solar irradiation, wind conditions, fuel costs, number of full load hours, costs of CO_2 emission certificates, etc.), which are listed in Tables 1 to 6. This methodology is exemplarily explained for the cost range of PV: The upper limit of the LCOE results from the combination of a PV power plant with a high procurement price at a location with low solar irradiation (e.g. northern Germany). Conversely, the lower limit is defined by the most inexpensive solar system at locations with high solar irradiation in southern Germany. This same process is carried out for wind and biomass power plants as well as conventional power plants. The usual financing costs on the market and the surcharges for risks are included in detail and are specific to each technology. This provides a realistic comparison of the power plant locations, technology risks and cost developments. The level of financing costs has considerable influence on the LCOE and the competitiveness of a technology. Furthermore, all of the costs and discount rates in this study are calculated with real values (reference year 2021). Due to the high costs of coal-fired power plants in 2021, the LCOE of these power plant types are not extrapolated for the future, but are at least at the 2021 levels and significantly higher if CO_2 certificate prices rise.

For PV systems, a learning rate (LR) of 15% is assumed. In 2040, the LCOE ranges from 3.58 to 6.77 €cent/kWh for small rooftop PV systems and from 1.92 to 3.51 €cent/kWh for ground-mounted systems. From 2024, the LCOE of all PV systems without battery storage is below 10 €cent/kWh. PV system prices drop to below 350 EUR/kW by 2040 for ground-mounted systems and to as low as 615 to 985 EUR/kW for small-scale systems. In 2030, electricity generation from a PV battery system is projected to be cheaper than from a CCGT power plant. In 2040, even small PV battery systems can be expected to reach LCOEs between 5 and 12 €cent/kWh, provided battery storage prices drop to the assumed 200 to 720 EUR/kWh.

The LCOE of onshore wind power plants are among the lowest of all technologies, together with PV utility-scale. From current LCOE between 3.94 and 8.29 €cent/kWh, costs will decrease in the long term to between 3.40 and 6.97 €cent/kWh. For the future trend, a LR of 5% is expected. Improvements are mainly expected in higher full load hours and the development of new sites with specialized low wind power plants. Offshore wind power plants still have a strong cost reduction potential compared to onshore wind power plants. By 2040, the LCOE will drop to values between 5.87 and 9.66 €cent/kWh, depending on location and wind supply.

Since cost reductions are expected to be low for biogas and solid biomass power plants, no learning rates are used for the technologies. This leads to constant LCOE until 2040 of 8.45 to

17.26 €cent/kWh for biogas and of 7.22 to 15.33 €cent/kWh for solid biomass, each taking into account revenues from heat generation. For bioenergy, the availability, heat utilization and fuel costs of the substrate are decisive for the future development of the LCOE.

Due to rising CO_2 prices, the LCOE of CCGT power plants will increase from current values between 7.79 and 13.05 €cent/ kWh to values between 9.19 and 25.05 €cent/kWh in 2040. Gas turbines account for an even higher LCOE between 15.29 and 28.69 €cent/kWh in 2040.

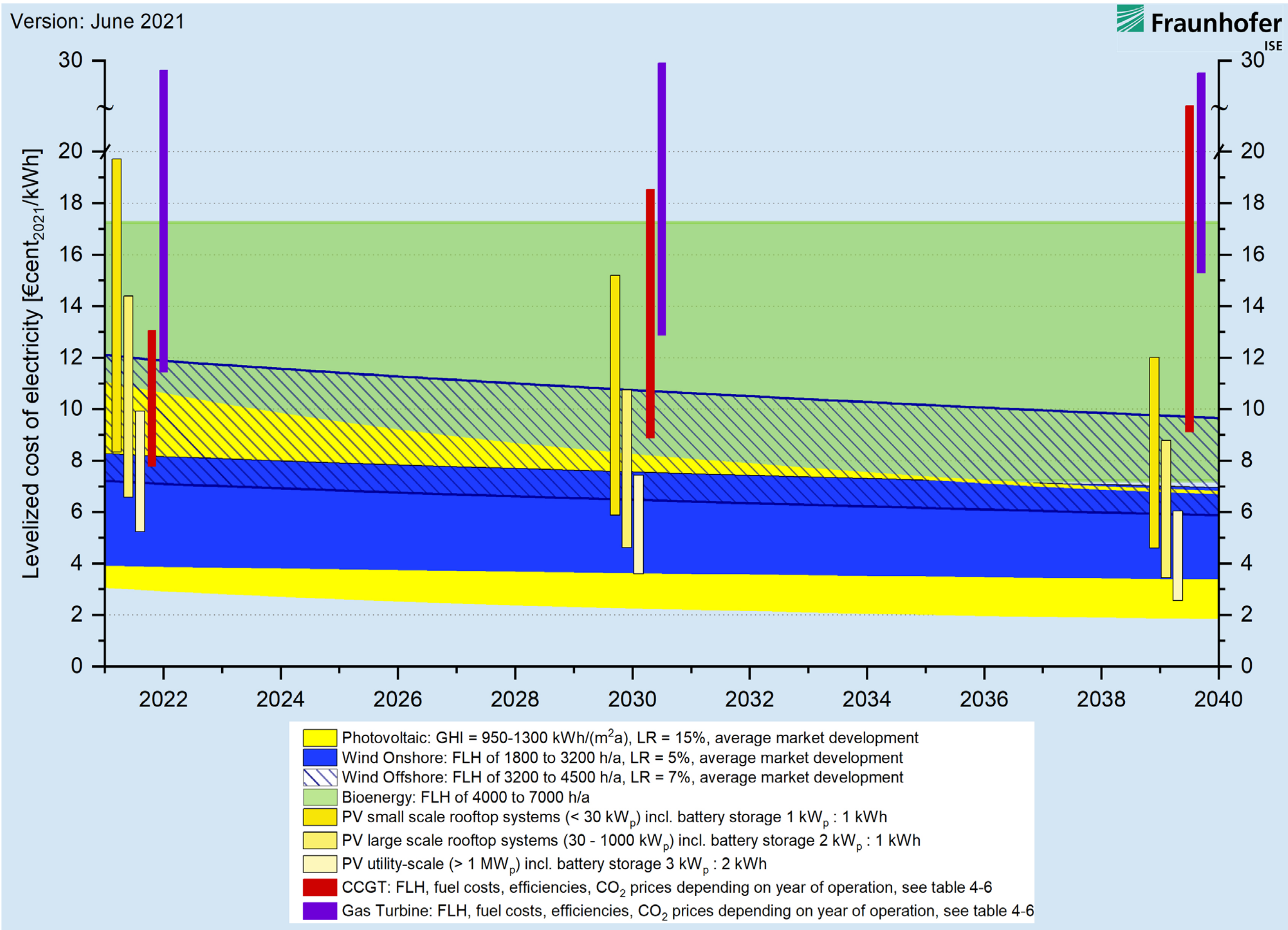

Figure 2: Learning-curve based forecast of the LCOE of renewable energy technologies and gas-fired power plants in Germany until 2040. Calculation parameters are listed in Tables 1 to 6. The LCOE value per reference year refers in each case to a new plant in the reference year.

Finally, a comparison of LCOE (i.e., the cost of generating electricity, taking into account the construction or purchase of the plant) of renewables with the operating costs of conventional power plants was carried out (see Figure 3). For this purpose, the operating costs of existing lignite-fired power plants and CCGT power plants (with and without heat extraction) are compared with the LCOE of new onshore wind plants, small rooftop PV systems and large ground-mounted PV systems. It is shown that in 2021 the LCOE of renewables are at least on a par with the operating costs of conventional power plants. In some cases, wind onshore plants and ground-mounted PV systems are already below the operating costs of conventional power plants, as these can reach values below 4 €cent/kWh only in some instances. With further decreasing LCOE for new renewable energy plants and the expectation that CO_2 prices will continue to rise in order to achieve the climate goals, the operating costs of CCGT and lignite-fired power plants will be at the level of small rooftop PV systems in 2030. In the case of lignite, even far exceeding this level. Only if the use of heat in district heating grids is possible via heat extraction, then CCGT power plants can still achieve operating costs of 4 to 5 €cent/kWh. In 2040, even the operating costs of CCGT power plants with heat utilization will exceed 5 €cent/kWh. Normal CCGT power plants have operating costs of over 9 €cent/kWh, lignite power plants of over 13 €cent/kWh.

The analysis shows how even existing conventional fossil power plants will reach very high operating costs by 2030 at the latest, while the LCOE of new renewable energy plants will be significantly lower.

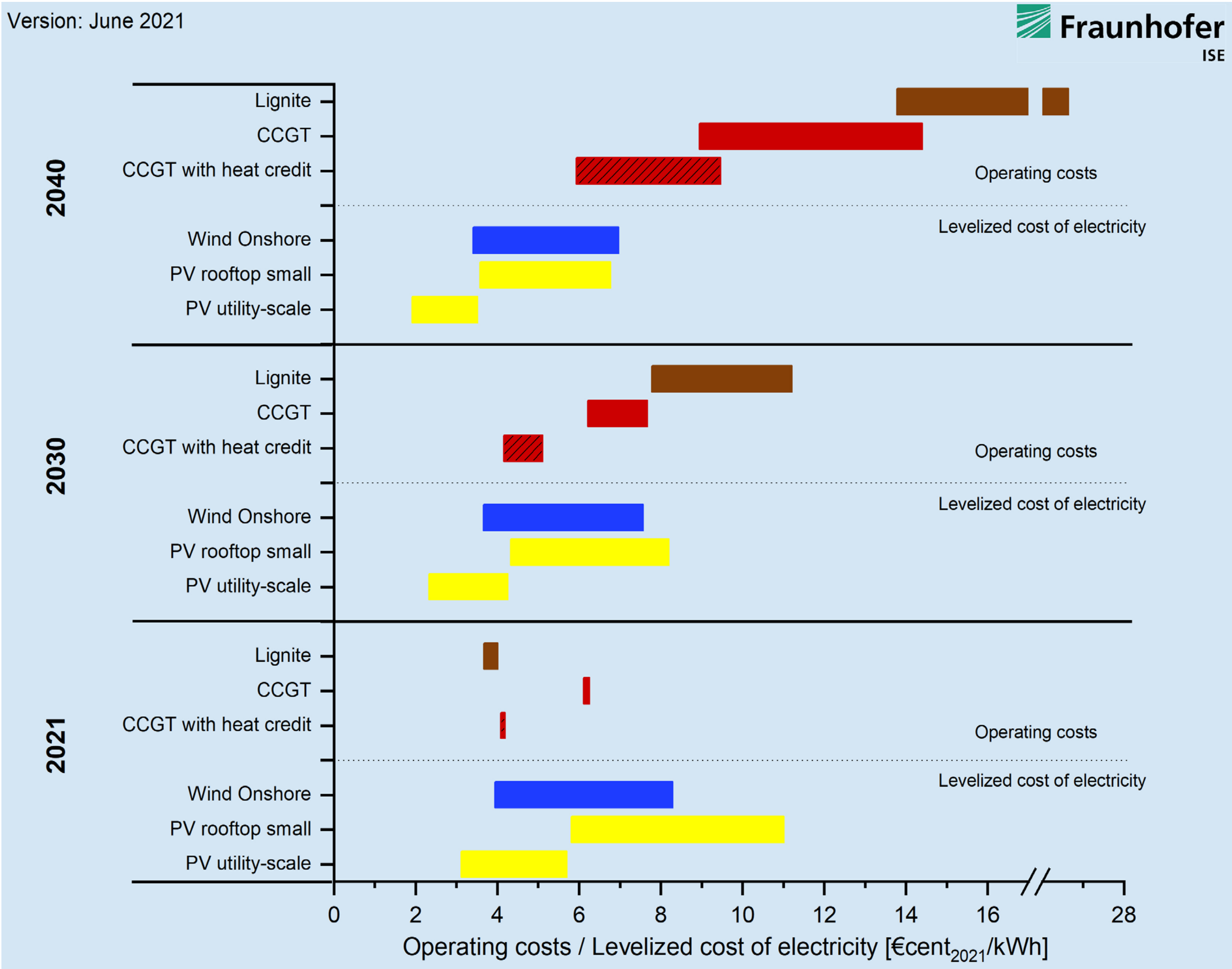

Figure 3: Comparison of LCOE of renewables with operating costs of existing conventional fossil-fuel power plants in 2021, 2030, and 2040

1. OBJECTIVE OF THIS ANALYSIS

Decarbonization and transformation of the energy system are associated with both technical and economic efforts. The cost of current and future power generation is heavily dependent on the cost of expanding and operating power plants. The costs of renewable energy technologies in particular have changed dramatically in recent years. This development is driven by technological innovations such as the use of less-expensive and better-performing materials, reduced material consumption, more efficient production processes, increasing efficiencies as well as automated mass production of components. For these reasons, the aim of this study is to analyze the current and future cost situation as transparently as possible in the form of LCOE.

Central contents of this study

- Analysis of the current situation and the future market development of photovoltaic (PV), wind power plants (WPP) and bioenergy plants in Germany
- Economic modeling of technology-specific LCOE (as of June 2021) for different types of installations and site conditions (e.g. solar irradiation and wind conditions) on the basis of common market financing costs
- Economic analysis of photovoltaic and battery storage systems
- Assessment of the different technology and financial parameters based on sensitivity analyzes of the individual technologies
- Forecast of the future LCOE of renewable energy technologies until 2040 using learning curve models and market growth scenarios
- Forecast of LCOE of existing conventional power plants in 2021, 2030 and 2040 under estimation of future operating costs
- Analysis of the current situation and future market development of photovoltaic and solar thermal power plants (CSP) for locations with favorable solar irradiation
- Insights into the statistical evaluation of PV systems in the core energy market data register (Marktstammdatenregister - MaStR)

In order to be able to realistically model the variations in market prices and fluctuations in full load hours (FLH) within respective technologies, upper and lower price limits are indicated. These limits are chosen based on a technology cost analysis of individual components, market and literature research as well as latest reports from current power plants. It should be noted that market prices are often based on applicable feed-in tariffs and are therefore not always in free competition. Characteristics of individual technologies that cannot be mapped into LCOE, such as the advantages of easily integrable energy storage, the number of FLH, decentralized power generation, capacity for follow-up operation and time of day availability, have not been taken into account. The technologies are evaluated and compared based on standard market financing costs and historically proven learning curves. As a reference, the current and future LCOE of new conventional power plants (brown coal, hard coal, combined cycle power plants and gas turbines) are calculated. In addition, the future operating costs of conventional power plants are compared with the LCOE of renewables.

The LCOE of renewable technologies depends largely on the following parameters:

Specific investment cost (CAPEX)
for the construction and installation of power plants with upper and lower limits; determined based on current power plant and market data

Local conditions
with typical solar irradiation and wind conditions for different locations and full load hours (FLH) in the energy system

Operating cost (OPEX)
during the power plant's operational lifetime

Lifetime of the plant

Financing condition
earnings calculated on the financial market and maturity periods based on technology-specific risk surcharges and country specific financing conditions taking into account the respective shares of external and equity-based financing.

The following power generation technologies are studied and assessed in various design sizes with respect to the current level of LCOE at local conditions in Germany:

Photovoltaic power plants (PV)
Modules based on crystalline silicon solar cells

- Small rooftop systems (≤ 30 kWp) – »PV rooftop small«
- Large rooftop systems (> 30 kWp) – »PV rooftop large«
- Ground-mounted utility-scale power plants (> 1 MWp) – »PV utility-scale«

For the PV power plants, locations in Germany with global horizontal irradiation (GHI) of 950 to 1300 kWh/(m²a) are studied. Standard modules with multi-crystalline silicon solar cells are taken into consideration.

Photovoltaic systems with battery storage

- Small rooftop systems (≤ 30 kWp) plus battery – ratio of the power output of the PV system in kWp to the usable capacity of the battery storage in kWh 1:1 - »PV rooftop small incl. battery 1:1«
- Large rooftop systems (> 30 kWp) plus battery with PV battery ratio 2:1 – »PV rooftop large incl. battery 2:1«
- Ground-mounted utility-scale power plants (> 1 MWp) plus battery with PV battery ratio 3:2 – »PV utility scale incl. battery 3:2«

The combination of PV system and battery storage is estimated using market-typical dimensions (evaluation of market master data register and results of innovation tenders) of battery capacity to PV power output.

Wind power plants (WPP)

- Onshore (turbine size 2 – 4 MW)
- Offshore (turbine size 3 – 6 MW)

The operation of onshore WPP in Germany is studied at 1800 to 3200 FLH per year as well as offshore WPP at 3200 to 4500 FLH per year. In addition, high wind speed sites for both onshore and offshore WPP are investigated. Sites with FLH between 3000 and 4000 h for onshore WPP and between 4000 and 5000 h offshore are selected, corresponding to conditions in the northeast of the UK.

Bioenergy power plants

- Biogas plants (> 500 kW) with substrate (renewable raw materials and excrements)
- Plants that use solid biomass fuels

Heat utilization is also specified. It lowers the LCOE because part of the costs is allocated to the heat quantity.

Conventional power plants

- Lignite-fired power plants (1000 MW)
- Hard coal power plants (800 MW)
- Combined Cycle Gas Turbine power plants (CCGT power plants, 500 MW)
- Gas turbine power plants (200 MW)

For comparison, the LCOE of new conventional power plants with different development paths for FLH as well as for prices of CO_2 emission certificates and fuels (lignite, hard coal or natural gas) are analyzed. Heat utilization from CCGT power plants is specified as a special case in the detailed analysis. It lowers the LCOE, since part of the costs is allocated to the heat volume.

Concentrated solar power plants (CSP)

- Parabolic trough power plants (100 MW) with thermal storage – "CSP"

For locations with high solar irradiation, not only photovoltaic technology, but solar thermal power plants (concentrated solar power) are also investigated. As CSP power plants can only be used to generate electricity under high direct irradiation, the analysis focuses on locations with direct normal irradiation (DNI) of 2000 kWh/(m²a) (e.g. in Spain) and locations with 2500 kWh/(m²a) (e.g. in the MENA countries).

Nuclear power plants, hydropower plants and geothermal power plants are not considered. As new constructions, they either no longer have any relevance in the German electricity system, have relatively low technical potential or have very site-specific cost parameters that present a high degree of complexity when recording costs as part of an LCOE analysis.

» Levelized Cost of Electricity: Renewable Energy Technologies « version 2021 - Comparison to the previous studies

The present study is a methodological and content update of the March 2018 (Kost et al. 2018), December 2013 (Kost et al. 2013), May 2012 (Kost et al. 2012) and December 2010 (Kost und Schlegl 2010) versions and addresses current trends in cost development over the last three years. In addition to previous changes described below, the following changes have been made in the 2021 version.

In this study (version 2021), the LCOE of PV systems are expanded. The analysis now also includes the concept of PV storage systems. In 2020, home storage systems with a total capacity of 850 MWh were installed. In the April 2021 innovation tender, all 18 bids awarded were PV battery systems (258 MW PV capacity). The main evaluation, therefore, also includes all size categories with battery storage systems.

The size categories of PV systems are adjusted according to the current market situation in Germany (small rooftop PV systems up to 30 kW, larger rooftop systems on businesses or commercial buildings larger than 30 KW, and large ground-mounted systems larger than 1 MW).

In addition to biogas plants, biomass plants combusting solid biomass are also considered.

Combined heat and power is considered for bioenergy plants and CCGT power plants.

The development of fuel prices, CO_2 prices and full load hours is adjusted according to the current targets for Germany towards a climate neutral energy system in 2050. Specifically compared to the last study, higher bandwidths and target values in 2050 are chosen for CO_2 certificate prices. Fuel prices and full load hours are lowered, as worldwide consumption is assumed to decline. In addition, the emitted CO_2 emissions and thus also the energy quantities must be significantly lowered with regard to 2050.Due to a continued very low interest rate level, more favorable financing conditions for power plants result. While the interest rate for 20-year federal bonds was still 1.07% in 2017, it has dropped to an average of 0.25% in 2021 (as of April 2021), in particular due to the effects of Covid-19. However, interest rates are expected to increase in coming years. Therefore, the average interest rate level is expected to be somewhat higher than today.

The following key changes implemented in the 2018 version have been retained:

For WPP, there is no distinction between high wind-speed and low wind-speed turbines. Increasing FLHs are assumed for both onshore and offshore turbines, which correlates with the current market trend of increasing ratio between the rotor diameter and the nominal power of the generator, as well as the increasing hub height.

Apart from that, both fixed and variable operational costs are considered for WPP. Fixed operating costs consist of non-revenue related maintenance and repair costs, management and lease costs, and the costs of insurance. Both fixed and variable operating costs are also taken into account for conventional power plants, which form a significant proportion of the LCOE, as these include fuel costs and the costs of CO_2 certificates in addition to the costs of auxiliary materials and raw materials.

2. HISTORICAL DEVELOPMENT OF RENEWALE ENERGY TECHNOLOGIES

Over the past 15 years, the global renewable energy market has seen strong growth (see Figure 4). The further increased competitiveness compared to conventional power plants and the international efforts against climate change (Paris Agreement) have opened up additional markets and fields of application for renewables. Worldwide, renewables are among the most economical types of electricity generation in almost all countries. Investment conditions for renewables are excellent in many countries, as meeting climate targets has become a much higher priority. Investments in technologies that burn fossil fuels are increasingly restricted or no longer pay off.

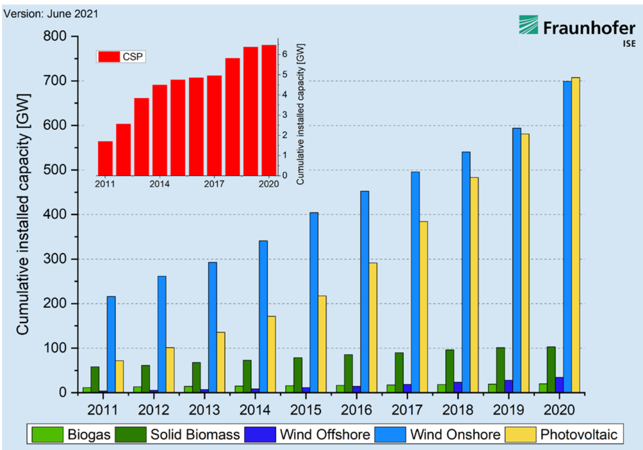

Figure 4: Global cumulative installed capacity 2011-2020 of PV, onshore and offshore wind, biomass plants and CSP (IRENA 2021a).

The strong market growth of renewables and the substantial investments in new power plants were accompanied by intensive research efforts, resulting in improved system solutions with higher efficiencies, lower production and operating costs. In combination with mass production, the specific investments and thus the LCOE of all technologies analyzed here were significantly reduced. Further decreases in the LCOE will allow the competitiveness and sales potential of the technologies to continue to grow significantly and contribute to a further dynamic market development of renewables.

The amount of renewable energy power plant capacity installed worldwide was just under 2800 GW at the end of 2020, a good 260 GW more than in 2019 (IRENA 2021a). The amount of power plant capacity installed worldwide to generate electricity from all renewable sources was just under 2800 GW at the end of 2020, a good 260 GW more than in 2019 (IEA 2020) 35 and 37 GW more than the year before. The installed capacity of nuclear power plants was 392 GW (WNA 2021), 4 GW less than the year before.

Due to different cost and market structures as well as support schemes, the markets for individual technologies have developed very differently. The market for wind power plants reached competitive market prices at an early stage and has therefore found markets in many countries even without incentive programs. The installed capacity currently totals 733 GW, including 699 GW onshore and 34 GW offshore, each with new installations in 2020 of about 105 and 6 GW, respectively (IRENA 2021a). By the end of 2020, the installed capacity of photovoltaics totaled 707 GW with new capacity additions of 126 GW and has caught up with wind power. Since 2016, the annual addition of PV capacity has been higher than that of wind (IRENA 2021a). In Germany, the total installed capacity of wind power plants amounted to 62 GW and of PV systems to 54 GW at the end of 2020.

The global outlook for market development of wind power plants remains positive. Growth forecasts for offshore wind power plants assume an increasing share of annual installations from the current 10% to around 20% (GWEC 2020b).

The photovoltaic market has developed into the most important segment of renewables in terms of capacity due to the strong expansion of production capacities, particularly in Asia, using highly automated production lines. A further very strong expansion of production capacities and growth of the PV market is expected, but no longer as severe price declines as in the past.

The expansion of bioenergy plants has a significantly lower volume compared to photovoltaics and wind power. The market for biogas plants has grown most strongly in Germany in the last 10 years, followed by China and Turkey. This is mainly due to the remuneration schemes in these respective countries. The capacity addition of solid biomass plants has been led by China in the past 10 years, followed by India and Brazil (IRENA 2021a). In Germany, the total installed capacity of bioenergy plants at the end of 2020 was 10.4 GW (AGEE-Stat 2021).

In addition to the technologies described above, which are used in Germany, solar thermal power plants can play an important role for power generation in countries with higher solar irradiation. CSP power plants have been gaining market shares in some countries since 2007, following the first installations in the USA in the 1980s, so that almost 6.5 GW have now been installed (IRENA 2021). Especially in the sunny MENA (Middle East and North Africa) countries, but also in China, the concept of CSP power plants is currently being pursued by policy makers due to the advantages of thermal energy storage.

For the forecast of the LCOE until 2040, this study uses learning curve models to estimate future developments. The learning curve models are based on market scenarios for each technology with a forecast of the future market developments taken from reference scenarios of various studies (Table 13 in the appendix). The technology-specific market scenarios give each technology a development horizon, which is influenced by numerous technological, energy-political and economic decision-making variables over the next twenty years. For all technologies, there is considerable uncertainty about the actual realizable market development until the year 2040. Market development in the coming years will depend in particular on the implementation of the Paris climate targets. However, the actual market development of each technology is crucial for the temporal progress of the cost degression in the learning curve model. The presented developments of LCOE are therefore potential development paths based on current market developments from different scenarios and technology-specific assumptions such as learning rate, but also depending on location factors such as realized full load hours.

3. INPUT DATA FOR THE CALCULATION OF LEVELIZED COST OF ELECTRICITY

Technology and financing parameters

A detailed explanation of the methodology of LCOE and learning rate is found in the Appendix on page 36.

Upper and lower price limits that do not take outliers into account is calculated for all technologies based on the data research; the regular market costs for installation of power plants varies between them. Uniform amounts of investments are assumed for all locations. In practice, one must take into account that the investments in power plants in markets that have not yet been developed can be considerably higher in some cases. Table 1 shows the investment costs in EUR/kW (nominal capacity) for all technologies considered that were determined based on market research on currently installed power plants in Germany as well as taking external market studies into account. Within the technologies, the system costs were distinguished based on power plant size and power plant configuration.

For PV, the upper and lower limits for the installation cost are differentiated according to the system sizes of small rooftop systems up to 30 kWp, large rooftop systems greater than 30 kWp and ground-mounted PV systems (> 1 MWp). By using these costs, the LCOE for each point of time for investment and construction are calculated. The technical and financial lifetime was set at 30 years for PV systems. The experience of Fraunhofer ISE in the field of plant monitoring reflects the longer lifetime – previously lifetime was set at 25 years. Battery storage was investigated in a typical constellation with a PV system. While in practice a wide range of ratios of PV power output to battery storage can be found, three currently typical ratios were examined for the analysis. It is assumed that in the area of PV home battery storage system, the power output of the PV system in kWp corresponds to 1:1 capacity of the battery storage in kWh. In the area of large-scale rooftop systems, a ratio of 2:1 is assumed. In the area of ground-mounted systems, a ratio of 3:2 is assumed. The costs for battery storage systems refer to the usable capacity, including installation costs. The service life for battery storage was assumed to be 15 years. Thus, after this time, a replacement of the battery is incurred at reduced costs.

The data for offshore wind were obtained from current and completed projects in the German North Sea and Baltic Sea. The input parameters for onshore wind power are also taken from current, planned and recently completed projects.

CAPEX [EUR/kW]	Wind onshore	Wind offshore	Biogas	Solid biomass	Lignite	Hard coal	CCGT	Gas turbine
2021 low	1400	3000	2500	3000	1600	1500	800	400
2021 high	2000	4000	5000	5000	2200	2000	1100	600

CAPEX	PV rooftop small (≤ 30 kWp)	PV rooftop large (> 30 kWp)	PV utility-scale (> 1 MWp)	PV rooftop small incl. battery storage (≤ 30 kWp, PV output to battery capacity 1:1)	PV rooftop large incl. battery storage (> 30 kWp, PV output to battery capacity 2:1)	PV utility-scale incl. battery storage (> 1 MWp, PV output to battery capacity 3:2)
Unit	[EUR/kWp]	[EUR/kWp]	[EUR/kWp]	[EUR/kWh]	[EUR/kWh]	[EUR/kWh]
2021 low	1000	750	530	500	600	500
2021 high	1600	1400	800	1200	1000	700

Table 1: Specific CAPEX in EUR/kW or EUR/kWh for current plants in 2021 (excluding value-added tax).

Currently, a large number of bioenergy plants with a wide variety of feedstocks, technologies and applications are in operation. In this study, a distinction is made only between electricity generation from solid biomass and from biogas. Electricity generation from biogas plants is calculated based on different substrates typical for agricultural biogas plants. The substrates used are cattle slurry and silage maize, whereby silage maize is considered with a mass-related share of 47% (FNR 2020; Fraunhofer IEE 2019). Heat generation through biogas plants presents an important operating parameter and is also included in the calculation of the LCOE, taking into account a self-supply of heat of the biogas plants of 25%. In this study, biogas plants with a size of 500 kW_{el} are depicted, as due to previous EEG structures, the average plant size is currently around 500 kW_{el} (Matschoss et al. 2019). Electricity generation from solid biomass covers a wide range of biogenic fuels and in Germany is mainly generated from the combustion of wood (waste wood, landscape wood residues, forest wood residues, wood pellets and other industrial wood) (FNR 2020; Fraunhofer IEE 2019). In this study, wood chips from forest wood residues, landscape wood residues and bark are used as fuel for biomass plants ≥ 500 kW_{el} (Fraunhofer IEE 2019). Heat generation of bioenergy plants with combustion of solid biomass in form of heating energy is also specified in the calculation of the electricity generation costs. Since CHP plants generate heat as well as electricity, the total generation cost cannot be allocated to electricity generation alone. The heat credit is calculated from the fuel costs that would be incurred for heat generation, but is available at no cost from the heat generated in the combined production of the electricity-fueled CHP plant.

The following parameters are used in the calculation of LCOE for mid-2021 and future installations (Table 2). The financing parameters have been continuously analyzed since the previous studies in 2010, 2012, 2013 and 2018. The risk and investor structure of each type has been adapted. It has to be noticed that the financing conditions (in the form of interest rate for debt and equity) might increase again, especially for future projects.

In many studies, the aspect of technology specific financing conditions is not sufficiently analyzed. Often, similar discount rates are assumed for all analyzed technologies and locations. This can lead to divergent LCOE compared to real LCOE. In this study, the discount rates are determined specifically for each technology by applying the market capital cost (and the parameter weighted average costs of capital – WACC) for each investment. The WACC consists of a share for the interest rate on debt and the return on equity. Large power plants constructed and operated by large investors and institutions have a higher WACC due to the expected return of the investor compared to small and medium size projects that are constructed by private persons or business partnerships. The return on equity expected by investors for technologies with lower maturity (e.g. offshore wind) are additionally higher compared with established technologies. It can be expected that the financial conditions will be equalized after increase of installed capacity as the risk premium for new technology sinks with increasing experience.

Since the WACC is derived from the usual interest rates and expected returns on the market, which are given in nominal values, the nominal value of the WACC is calculated first. This

	Wind onshore	**Wind offshore**	**Biogas**	**Solid biomass**	**Lignite**	**Hard coal**	**CCGT**
Lifetime in years	25	25	25	25	40	30	30
Share of debt	80%	70%	80%	80%	60%	60%	60%
Share of equity	20%	30%	20%	20%	40%	40%	40%
Interest rate on debt	3.5%	5.0%	3.5%	3.5%	5.0%	5.0%	5.0%
Return on equity	7.0%	10.0%	8.0%	8.0%	11.0%	11.0%	10.0%
WACC nominal	4.20%	6.50%	4.40%	4.40%	7.40%	7.40%	7.00%
WACC real	2.96%	5.24%	3.20%	3.20%	6.20%	6.20%	5.80%
OPEX fix [EUR/kW]	20	70	4% of CAPEX	4% of CAPEX	32	22	20
OPEX var [EUR/kWh]	0.008	0.008	0.004	0.004	0.0045	0.004	0.003
Annual degradation	0	0	0	0	0	0	0

	PV rooftop small (≤ 30 kWp)	PV rooftop large (> 30 kWp)	PV utility-scale (> 1 MWp)	PV rooftop small incl. battery (≤ 30 kWp, 1:1)	PV rooftop large incl. battery (> 30 kWp, 2:1)	PV utility-scale incl. battery (> 1 MWp, 3:2)
Lifetime in years	30	30	30	15	15	15
Share of debt	80%	80%	80%	80%	80%	80%
Share of equity	20%	20%	20%	20%	20%	20%
Interest rate on debt	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
Return on equity	5.0%	6.5%	6.5%	5.0%	6.5%	6.5%
WACC nominal	3.40%	3.70%	3.70%	3.40%	3.70%	3.70%
WACC real	2.20%	2.50%	2.50%	2.20%	2.50%	2.50%
OPEX fix [EUR/kW]	26	21.5	13.3	0	6.0-10.0*	6.7-9.3*
OPEX var [EUR/kWh]	0	0	0	0	0	0
Annual degradation	0.5%	0.25%	0.25%	0	0	0
Battery replacement costs	-	-	-	40-50% of initial investment	35% of initial investment	30% of initial investment
Efficiency	-	-	-	90%	90%	90%
Annual charge cycles	-	-	-	200	100-300**	100-300**

Table 2: Input parameter for LCOE calculation. The real WACC is calculated with an inflation rate of 1.2%.
** related to the PV system power output (corresponds to 2% of the battery investment costs)*
** Since the battery lifetime is assumed to be fixed, the annual charge cycles only have an influence on the value of the battery storage loss. A high number of cycles (high losses) is used for the upper limit of the LCOE, a low number of cycles (low losses) is used to calculate the lower limit of the LCOE.*

nominal value is then converted into a real value by taking an assumed 1.2% p.a. inflation rate into account. This value has been lowered from 2.0% compared to previous studies.

The decisive factor for the calculation of the LCOE is that all payment streams are assumed at either nominal or real levels. A mixture of real and nominal values is incorrect and not permitted. To carry out the analysis on nominal values, the annual inflation rate has to be projected by 2040. Since the forecast for the inflation rate over the long term is very imprecise and difficult, cost predictions are generally completed using real values. All costs stated in this study therefore refer to real values from 2021. The LCOE provided for future years in the figures always refer to new installations in the respective years. The LCOE of a single project remains constant over its operational lifetime and is therefore identical to the value of the year of installation.

A second factor influencing return on equity is the project-specific risk: The higher the risk of default, the higher the return on equity required by the investor. In order to keep the capital costs low, a high share of debt with low interest rate is desirable. It is, however, also limited by the project-specific risk: The higher the risk of default, the lower the amount of debt that banks provide to the project. Since offshore wind parks continue to evince a high project-specific risk, the average capital costs are correspondingly higher than for comparable onshore projects. If loans with low interest rates are available in sufficient amount, for example from the KfW banking group, interest rates on debt of approximately 1 to 3% can be achieved depending on the technology. This is currently the case for small PV power plants, for which the effective interest rate of a KfW loan is currently only 1.75% for the highest rating class – with a 20-year maturity and 20-year fixed interest (KfW 2021). In general, interest rates are intentionally set somewhat higher as actual rates are currently very low due to the COVID-19 pandemic and are expected to increase in the future.

In international comparisons of locations, one must keep in mind that the financing conditions differ, similar to the environmental conditions such as solar irradiation and wind conditions. Especially in the case of renewable energy projects, whose economic efficiency is significantly dependent on feed-in compensation, the country-specific risk of default of these payments, such as caused by national bankruptcy, must be taken into account. Another factor is the availability of subsidized loans at favorable interest rates. Germany offers here very favorable framing conditions for investments in renewable energy.

Local Conditions

Solar irradiation and Full Load Hours (FLH)

The amount of electricity yield at each power plant location is an important parameter with a considerable influence on the LCOE of renewable energy technologies. In the case of solar technologies, the amount of diffuse or direct solar irradiation (depending on the technology) plays an important role. The FLH of a wind farm can be calculated from the wind conditions at the power plant location as a function of the wind speed. In the case of biogas, however, the number of FLH is not supply dependent but is determined by the demand, availability of substrate and power plant design.

For that reason, exemplary locations with specific FLH for wind farms should be studied as well as locations with specific energy sources from solar irradiation (see Table 3). At typical locations in Germany, the global horizontal irradiation (GHI – consisting of diffuse and direct irradiation) is in the range of 950 and 1300 kWh per square meter per year (see Figure 29). This corresponds to a solar irradiation of 1100 and 1510 kWh/(m²a) onto an optimally oriented PV system (both in terms of southward orientation and optimum tilt angle). After subtracting losses of electricity generation in the PV system, an average annual electricity yield between 935 and 1280 kWh per installed kWp is obtained. The full load hours of the plants decrease accordingly if the plants are aligned to the east or west, for example, because the roof pitch is the same, or if the plants are mounted flatter. Under certain circumstances, both aspects can be optimal from an economic efficiency calculation and from the owner's point of view, taking into account the use of self-generated electricity.

The wind conditions are also location-dependent. Onshore WPP can reach FLH of only 1800 hours per year at unfavorable locations. The level of FLH, however, can reach values of up to 3200 hours at selected locations near the coast in Germany. The average FLH for onshore WPP constructed in 2016 is at 2721 hours per year (Fraunhofer IWES 2018). Much higher FLH can be reached by offshore power plants with values between 3200 hours at coastal areas and 4500 hours at locations with large distance to the coast (in the North Sea). Due to the trend of increasing size and distance from the coast, offshore power plants are expected to reach 5500 FLH in the best case (Reuter und Elsner 2016). This refers to an annual growth of 0.6%. Therefore, an annual growth of FLH for new installations is assumed to be 0.5%.

Biogas plants and plants using biogenic solid fuels can easily achieve a capacity utilization of 80-90% in Germany, which corresponds to over 7000 FLH per year. Driven by the flexibility premium introduced by the EEG, a flexible operation of the plants is increasingly sought, which leads to decreasing full load hours. The aim of the flexibility premium is to increase the flexible share of the biogas plant's electricity production. This serves to compensate for the supply dependency of electricity generation from solar and wind. For this reason, a range between 4000 and 7000 full load hours is applied (DBFZ 2015).

Compared to most renewable energy technologies, the annual electricity generation and thus the number of FLH of a conventional power plant depends on the respective demand, the costs for fossil fuels and thus also on the competitiveness of the technology in the energy system. Currently, the full load hours of lignite average 4625 hours across all plants. Hard coal averaged 1640 hours and economic CCGT power

PV system (standard modules)	GHI [kWh/(m²a)]	Solar irradiation on PV modules [kWh/(m²a)]	Electricity generation per 1 kWp with optimal angle of inclination and south orientation [kWh/a]
Northern Germany	950	1100	935
Central Germany	1120	1300	1105
Southern Germany	1300	1510	1280
Wind power plants (2 - 5 MW)	**Wind speed at 120 m hub height [m/s]**	**Wind full load hours [h]**	**Electricity generation per 1 kW [kWh/a]**
Onshore: Inland Germany	5.5	1800	1800
Onshore: Northern Germany	6.4	2500	2500
Onshore: Coastal and high wind locations Germany	7.8	3200	3200
Offshore: Short distance from coast	7.8	3200	3200
Offshore: Medium distance from coast	8.7	3600	3600
Offshore: Very good locations	10.3	4500	4500

Table 3: Annual returns at typical locations of PV and wind (Source: Fraunhofer ISE).

Full load hours of conventional power plants [h/a]		Lignite	Hard coal	CCGT	Gas turbine	Biogas	Solid biomass
Year 2020	High	7300	6200	8000	3000	7000	7000
	Low	5300	2600	3000	500	4000	4000
Year 2030	High	5300	3300	7000	3000	7000	7000
	Low	2300	2300	2000	500	4000	4000
Year 2040	High	2000	2000	5000	2000	7000	7000
	Low	0	0	0 / 1000	0 / 1000	4000	4000
Year 2050	High	2000	2000	4000	2000	7000	7000
	Low	0	0	0 / 1000	0 / 1000	4000	4000

Table 4: Development of full load hours (FLH) for conventional power plants and bioenergy plants.

plants 6500 hours in 2020 (Fraunhofer ISE 2021b). In the course of increasing electricity generation from renewables, rising CO_2 certificate prices and the planned coal phase-out, however, the FLH of conventional power plants are continuously decreasing. In this study, the FLH for all new plants will fall continuously until 2040. For lignite, the average value of FLH in 2040 thus falls to below 2000 hours per year and for CCGT to 5000. Higher FLH can reduce the LCOE of fossil power plants and vice versa, as the market situation or demand development allows it.

Fuel Cost

Substrate costs vary considerably for biogas power plants. The costs differ owing to the options for purchasing substrates or using substrates generated by biogas operators inhouse. Additionally, the shares of the various substrates differ between power plants. For example, a biogas plant commissioned in 2010 in Bavaria uses an average substrate mix of 35% silage maize, 35% cattle slurry/cattle manure, 15% grass silage and 15% whole plant silage (DBFZ 2019). Thereby, the methane yield of the individual substrates varies between 106 Nm³/t FM (ton wet mass) for silage maize (DBFZ 2015) and 12 Nm³/t FM for pig slurry (FNR 2020). Furthermore, different costs are incurred for the substrates. For example, the substrate costs for the purchase of maize silage are 39 EUR/t FM (Fraunhofer IEE 2019) and for cattle and pig slurry 3 EUR/t FM (Guss et al. 2016). Substrate costs for self-produced substrate can be assumed to be near zero. The energy-related costs of the respective substrates are calculated from the methane yield, the substrate costs and the energy yield of methane (9.97 kWh/Nm³). The average substrate costs applied in this study therefore amount to 3.84 €cent/kWh$_{th}$. Fuel costs for solid biomass combustion also vary depending on the raw material used. In Germany, biomass cogeneration plants are predominantly operated with wood chips from forest residues, waste wood, landscape conservation wood, and wood pellets (FNR 2020). Due to the varying costs, this study considers blended wood of forest wood residues, landscape wood residues and bark, for which fuel costs in the amount of 1.53 €cent/kWh$_{th}$ are incurred. (Fraunhofer IEE 2019).

To compare the LCOE of renewable energy technologies and conventional power plants, assumptions about the efficiencies and CO_2 emissions of these power plants are needed. The assumptions for the typical power plant sizes are for lignite between 800 and 1000 MW, for hard coal between 600 and 800 MW, for CCGT power plants between 400 and 600 MW and for gas turbines 200 MW. Through further technological improvements, the efficiency of new power plants will increase for lignite from 45% to 48%, for hard coal from 46% to 49% and for CCGT from 60% to 62%. The price trends for fuels are assumed with very moderate increases. Due to a possible shortage of CO_2 allowances, a long-term increase of the allowance price is assumed (see Tables 4-6). CO_2 certificate prices as well as fuel prices reflect a world that pursues greenhouse gas neutrality. This means that energy-related CO_2 emissions in Germany will trend quasi towards 0 by 2050. Accordingly, the IEA's "Sustainable Development" scenario for fuel prices was used, which assumes a strong decrease in the consumption of conventional energy sources. The CO_2 certificate price rises

Fuel prices [EUR/MWh]	2021	2025	2030	2035	2040
Lignite	2.0	2.0	2.0	2.0	2.0
Hard coal	10.0	10.0	10.0	10.0	10.0
Natural gas	25.0	25.0	16.0	16.0	17.0
Substrate biogas	38.4	38.4	38.4	38.4	38.4
Substrate solid biomass	15.0	15.0	15.0	15.0	15.0

Table 5: Assumptions about fuel prices are based on values (Hecking et al. 2017; Fraunhofer IEE 2019; IEA 2020)

Efficiency conventional power plants [%]	2021	2030	2040
Lignite - electrical	45.0	-	-
Hard coal - electrical	46.0	-	-
CCGT - electrical	60.0	61.0	62.0
CCGT - thermal	33.0	33.5	34.0
Biogas - electrical	40.0	40.0	40.0
Biogas - thermal	44.0	44.0	44.0
Solid biomass - electrical	25.0	25.0	25.0
sold biomass - thermal	35.0	35.0	35.0

Table 6: Efficiency development for large power plants (Wietschel et al. 2010; Fraunhofer IEE 2019)

CO_2 certificate prices [EUR/t CO_2]	2021	2025	2030	2035	2040
Lower Value	32	40	80	120	150
Upper Value	36	65	120	180	300

Table 7: CO_2 certificate price (own assumption)

4. LEVELIZED COST OF ELECTRICITY OF ENERGY TECHNOLOGIES IN 2021

In this chapter, the LCOE of the renewable energy technologies PV, wind, biogas and solid biomass at locations in Germany are determined using market data on specific investments, operating costs and other technical and financial parameters. Reference calculations for conventional power plants (lignite, hard coal, CCGT and gas turbines) with different configurations, construction and operation strategies provide LCOE values for comparison.

In southern Germany, the LCOE for small PV rooftop systems (< 30 kWp) at locations with a global horizontal irradiation (GHI) of 1300 kWh/(m²a) lies between 5.81 and 8.04 €cent/kWh. LCOE values between 7.96 and 11.01 €cent/kWh are reached at locations in northern Germany with a GHI of 950 kWh/(m²a). The results depend on the amount of the specific investments, which is assumed to range from 1200 EUR/kWp to 1600 EUR/kWp. Larger rooftop PV systems (> 30 kWp) can produce electricity at a LCOE between 4.63 and 7.14 €cent/kWh in southern Germany and between 6.34 and 9.78 €cent/kWh in northern Germany, each with specific investments between 750 and 1400 EUR/kWp. Ground-mounted PV systems (> 1 MWp) currently reach LCOE values between 3.12 and 4.16 €cent/kWh in southern Germany and between 4.27 and 5.70 €cent/kWh in northern Germany, with specific installation costs of 53 EUR/kW to 800 EUR/kW.

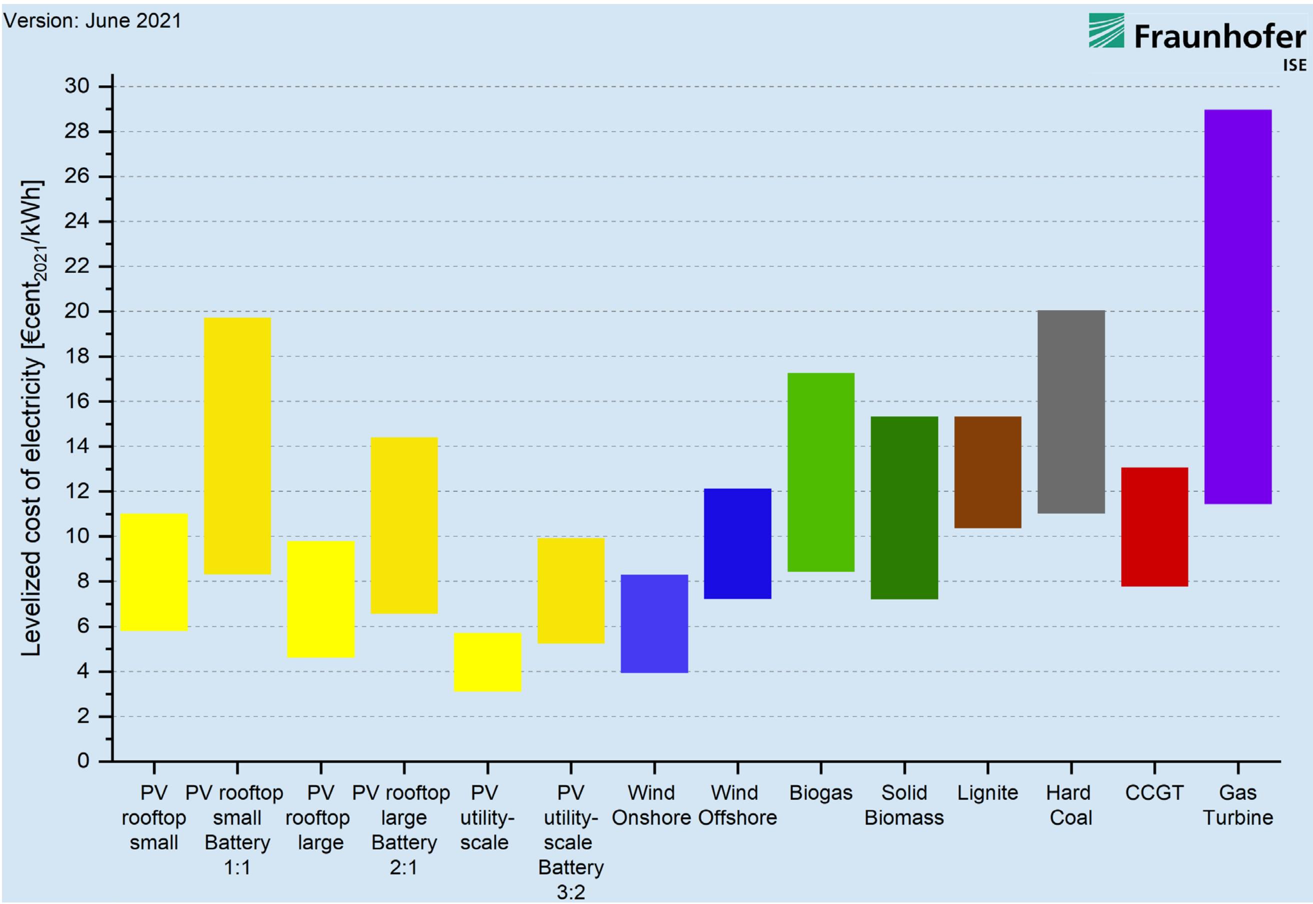

Figure 5: LCOE of renewable energy technologies and conventional power plants at different locations in Germany in 2021. Specific system costs are considered with a minimum and a maximum value per technology. The ratio for PV battery systems expresses PV power output (kWp) over battery storage capacity (kWh). Further assumptions in Tables 3 to 6.

The LCOE for PV battery systems refers to the total amount of energy produced by the PV system minus storage losses. The storage losses are calculated based on the capacity of the battery storage, the assumed number of cycles and the efficiency of the battery. Accordingly, the LCOE for small-scale PV battery systems ranges from 8.33 to 19.72 €cent/kWh. The results include differences in PV costs, battery costs (500 to 1200 EUR/kWh), and varying solar irradiation. For larger rooftop PV systems with battery storage, the LCOE ranges from 6.58 to 14.40 €cent/kWh, for battery costs between 600 and 1000 EUR/kWh. For ground-mounted PV with battery storage systems, LCOE are calculated to be between 5.24 and 9.92 €cent/kWh; for this, investment costs for battery storage of 500 to 700 EUR/kWh were assumed. The prices for smaller systems are in part lower, as these are standardized products, whereas larger battery systems tend to be individualized projects that additionally incur costs for project development, project management, and infrastructure. The range of investment costs is smaller for the larger sizes, as there is more competitive pressure.

The LCOE of onshore WPP with an average installation cost of 1400 EUR/kW and a very high annual FLH of 3200 hours is 3.94 €cent/kWh. However, such locations in Germany are very limited. LCOE in less suitable locations in Germany range up to a value of 8.29 €cent/kWh, depending on the specific investment and the annual FLH (see Table 3). In comparison, the cost of offshore WPP is significantly higher, displaying values between 7.23 €cent/kWh and 12.13 €cent/kWh, despite higher FLH of 3200 to 4500 per year.

The LCOE of biogas is between 8.45 and 17.26 €cent/kWh with substrate costs of 3.84 €cent/kWh. For solid biomass plants, the LCOE is slightly lower between 7.22 €cent/kWh and 15.33 €cent/kWh, mainly due to substrate costs. For both biomass and biogas, heat credits, also referred to as revenue from heat generation, have been subtracted from the LCOE. This means that the values given here refer only to bioenergy with cogeneration. Plants without heat utilization have significantly higher LCOE.

Based on the current conditions on the electricity market with respect to FLH and fuel prices for each technology, the following LCOE for conventional power plants are determined: Lignite power plants built today achieve an LCOE between 10.38 and 15.34 €cent/kWh for the selected operation parameters (with a low CO_2 price today and a sharply rising CO_2 price in the future). The LCOE for large hard coal power plants shows slightly higher values between 11.03 and 20.04 €cent/kWh. CCGT power plants achieve values between 7.79 and 13.06 €cent/kWh, while the LCOE of gas turbines is considerably higher, ranging between 11.46 and 28.96 €cent/kWh.

One must keep in mind that the LCOE calculation does not include the possible flexibility of a power generation technology or the worth of the generated electricity. For example, the specific seasonal and daily generation of each technology is different. Differences due to the flexible use of power plants or the provision of ancillary services in relation to the market sales price of electricity obtained are not reflected in the LCOE (see also Chapter 8).

Photovoltaics

Market development and forecast

At the end of 2020, the global installed PV capacity exceeded 707 GWp with global additions in 2020 amounting to around 127 GWp. This represents a market growth of 30% compared to the 98 GWp installed globally in 2019 (IRENA 2021a). Currently China dominates the global PV market in both production and installation. At the same time, more countries are installing PV on a significant scale, as PV systems increasingly prevail in free competition and can thus be implemented independent of subsidy programs. The PV market growth is now driven by purely economic reasons.

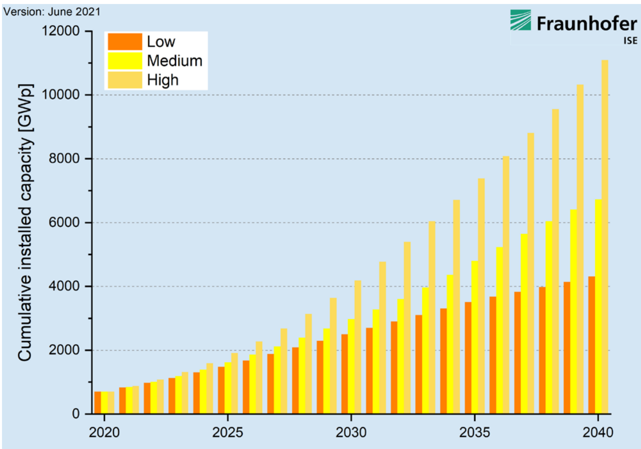

Figure 6: Market development scenarios of cumulative installed power plant capacity [GW] for PV until 2040, own scenarios.

This leads to the assumption that the global PV market will continue to grow strongly. The three market development scenarios "High", "Medium" and "Low" on which the study is based assume a continuous reduction in annual market growth. The assumed market growth in 2021 of 24%, 20% and 18% for the "High", "Medium" and "Low" scenarios, respectively, flattens out to 5% (High, Medium) and 4% (Low) by 2040. For 2040, the scenarios result in total capacity of 11,100 GW, 6700 GW, and 4300 GW, respectively. The scenarios of cumulative installed power plant capacity are shown in Table 11.

Performance Ratio of PV systems

The Performance Ratio is used frequently to compare the efficiency of grid-connected PV systems at different locations and with different module types. It describes the ratio of the actual energy yield (final electrical energy) of a PV system and its rated power output. The nominal power of a PV system is usually expressed in kilowatt peak (kWp) and is based on the power of the PV modules in the PV system measured under Standard Testing Conditions (STC). The actual usable energy yield of the PV system is influenced by the real operating conditions at the system location. Deviations of the actual module yield in comparison with STC conditions may arise for various reasons, such as different solar radiation values, shading and soiling of the PV modules, reflection on the module surface at oblique incident angles, spectral deviation from STC conditions, and increasing module temperature. Other losses in the PV system are caused by electric mismatch of modules, resistive losses in the AC and DC wiring, inverter losses and eventual losses in the transformer. New, optimally oriented PV systems achieve performance ratios between 80 and 90% in Germany (Reich et al. 2012).

Price and cost development

Since 2018, wholesale prices for crystalline modules in Germany have fallen significantly from 430 EUR/kWp to 310 EUR/kWp in 2020. The lowest net price for crystalline modules was 190 EUR/kWp in the third quarter of 2020. There continues to be a difference between the price levels of Chinese and German manufacturers: In 2018, Chinese manufacturers were able to offer their modules at an on average 80 EUR/kWp lower price than German manufacturers. In 2020, the gap was only 50 EUR/kWp (EuPD Research 2021).

The costs for inverters and balance of system (BOS) components like mounting system and cables, as well as their installation costs, dropped, though not as strongly as PV module prices. While in 2005, solar modules constituted almost 75% of the system costs, this share is around 30% today, even for rooftop PV systems.

Table 1 shows price bands for PV systems of different size classes. The costs for a small PV system (up to 30 kWp) are currently between 1000 and 1600 EUR/kWp. For larger PV systems above 30 kWp, the costs are currently 750 to 1400 EUR/kWp. PV ground-mounted systems with power outputs starting at 1 MWp reach investment costs of 530 to 800 EUR/kWp. These values include all component and installation costs associated with the PV power plant. In some cases, investments below the specified price ranges can be realized under certain conditions of purchase. Compared to the 2018 study, significantly larger ranges are given for the specific investment. The reasons for this are due to broader power definition in this study and a market development in which the location, design of the plant or the roof and building conditions have a strong influence on the prices of the systems. This leads to a higher variation in specific costs.

The current LCOEs of PV systems are shown in Figure 7 for various power plant sizes and costs at different solar irradiation (based on Table 3). The number following power plant size stands for the global horizontal irradiation (GHI) at the power plant location in kWh/(m²a). PV systems in northern Germany produce approximately 935 kWh/a, while PV systems in southern Germany yield up to 1280 kWh/a.

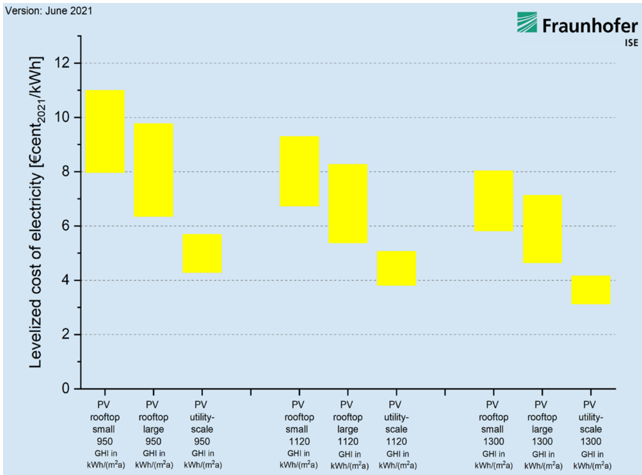

Figure 7: LCOE of PV systems in Germany based on system type and solar irradiation (GHI in kWh/(m²a)) in 2021.

The strong price decline in investment for PV power plants has continued to lead to significantly lower LCOE. Ground-mounted utility-scale power plants in northern Germany already achieve a LCOE below 6 €cent/kWh and in the south below 4.5 €cent/kWh respectively. The LCOE of large PV rooftop systems are between 9.78 €cent/kWh in northern Germany and 4.63 €cent/kWh in southern Germany. Small PV rooftop systems in Germany generate electricity at LCOE between 5.81 and 11.01 €cent/kWh, and thus are well below the average electricity costs for households.

Since PV still has significant cost reduction potential along the entire value chain and for all components, it can be expected that investment costs and thus LCOE will continue to fall in the medium and long term - apart from possible price fluctuations due to special market events. Based on the current market development as well as the warranty offered by most module manufacturers, the lifetime of PV modules was increased from 25 to 30 years in this study. Considered separately, the increase in lifetime by 5 years leads to an average reduction in LCOE of 8%.

A sensitivity analysis performed for a small PV system in Germany demonstrates the LCOE's strong dependency on the solar irradiation and specific investments (see Figure 8). The influence of the capital costs of the investment (WACC) on the LCOE should not be underestimated, as the differences can be relatively large and slightly outside the parameter variation of 80 to 120% shown. Slightly different operating costs have a smaller impact on the LCOE of PV systems, as they represent only a minor part of the total costs. System lifetime has a strong impact on costs in that with longer lifetimes, even systems that have already depreciated continue to produce electricity at very low operating costs.

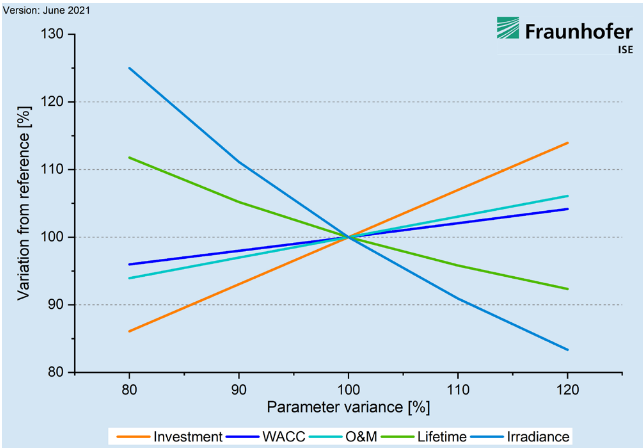

Figure 8: Sensitivity analysis of a small PV system with a GHI of 1120 kWh/(m²a) and investment of 1300 EUR/kW.

Photovoltaics with battery storage systems

In order to increase self-consumption of photovoltaic electricity or to stabilize the grid feed-in, electricity storage systems are being used more frequently. These are commonly battery storage systems, which is why they are included in the analyses of this version of the LCOE study. Compared to PV, wind power and bioenergy, lithium-ion battery storage is a comparatively young technology. Accordingly, the market is characterized by strong growth and sharply declining prices. Since PV battery systems are used in different applications, the LCOE calculation distinguishes between three different application areas:

PV home battery storage (small rooftop PV): Here, the focus is on increasing self-consumption, although stand-alone solutions are also frequently in demand. Since electricity for self-consumption from PV systems under 30 kWp is exempt from taxes and levies, battery storage systems can achieve savings by increasing the self-consumption rate. The electricity generated by the PV battery system thus competes with the cost of grid electricity purchased by residential and commercial customers. The ratio of battery storage capacity to PV power output has steadily increased in recent years as battery prices have declined. Therefore, a 1:1 ratio is assumed for the study. Between 2013 and 2018, PV home storage systems were subsidized through a KfW program, which caused strong market growth. Subsequently, individual German states continued their own subsidy programs. Installation figures continue to rise even after the end of the KfW programs.

Medium-sized battery storage (with large rooftop PV): These are often PV battery systems used by commercial and industrial customers. Battery storage systems can often provide multiple benefits: In addition to increasing self-consumption rates, battery storage systems can also be used for peak shaving, uninterruptible power supply, or electric vehicle charging, for example. The ratio of PV power output to battery capacity can vary widely in this segment. A ratio of 2:1 was assumed. Due to often lower electricity prices in the commercial-trade-services and industrial sectors, few PV storage systems have been deployed to date. However, as battery prices continue to fall, further growth is expected here as well.

Large battery storage systems in combination with ground-mounted utility-scale PV systems (PV ground-mounted): So far, such projects have been promoted within the framework of innovation tenders and this offer has been well received. The benefit of the battery storage is primarily the stabilization of electricity generation of the power plant park and the hopedfor marketing at higher rates. The ratio of PV power output to battery capacity can also vary a lot here; a ratio of 3:2 is realistic for current systems.

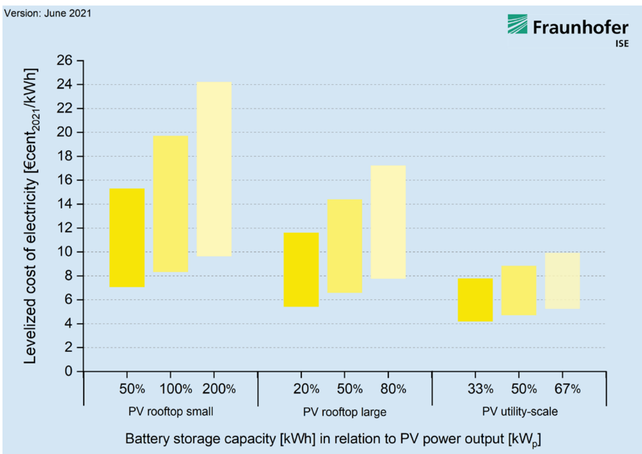

Figure 9: LCOE for PV battery systems as a function of the ratio of PV power output to battery capacity.

Figure 9 shows the LCOE for PV battery systems depending on the type and size of the PV system and the ratio between PV system power output and storage capacity. The range for the resulting LCOE is significantly larger than for the other renewable energy technologies as three parameters are varied: the investment cost for the PV system, the investment cost for the battery storage system, and solar irradiation. Thus, the lowest LCOE occurs at low investment costs and high solar irradiation. The highest LCOE apply to systems with high investment costs and low solar irradiation. The charge cycles of the battery storage were assumed to be the same in all cases (based on Table 2), since this value is only an estimate and the influence on the LCOE is very small. The cost assumptions are given in Table 1, and other input parameters are listed in Table 2.

The LCOE increases with increasing battery capacities, since a larger battery means higher investment costs at constant or even slightly decreasing electricity generation due to battery losses. The bandwidth increases with increasing battery capacity, since this means that an increasing share for battery investment costs is included in the calculation. Battery storage capacity has a smaller impact on the low LCOE value and a larger impact on the upper limit. This is due to the multiplication of the specific battery storage cost by the battery size. At the assumed PV-to-battery ratio of 1:1 (100% in the graph), the LCOE for small PV battery systems ranges from 8.33 to 19.72 €cent/kWh. With a half the battery storage size (50%), the LCOE drops to between 7.06 and 15.32 €cent/kWh. For a larger battery storage capacity, the LCOE increases to 9.63 to 24.23 €cent/kWh. For large rooftop PV systems with battery storage - with a wide range of system configurations implemented in practice - the LCOE decreases to 5.41 to 11.61 €cent/kWh for a small battery storage size (capacity is 20% of the PV system power output) and increases to 7.76 to 17.24 €cent/kWh for a larger battery storage size (80%). For large-scale storage, a PV-to-battery ratio of 3:2 was assumed (67%); at this point, two smaller battery storage sizes are examined. In this case, the LCOE can decrease from 4.71 to 8.85 €cent/kWh (50%) and 4.20 to 7.79 €cent/kWh (33%), respectively.

The sensitivity analysis for the LCOE of PV battery systems shows, as in the analysis for PV systems, a strong dependence on solar irradiation. Investment costs also have a strong influence, with the investment for PV having a larger impact than the investment for the battery, due to the larger absolute values (1300 EUR/kWp compared to 850 EUR/kWh). The influence of the WACC on the LCOE is, as for PV, possibly also higher than shown here, due to the sometimes large differences of the absolute value. The efficiency and the number of charge cycles of the battery storage have less influence.

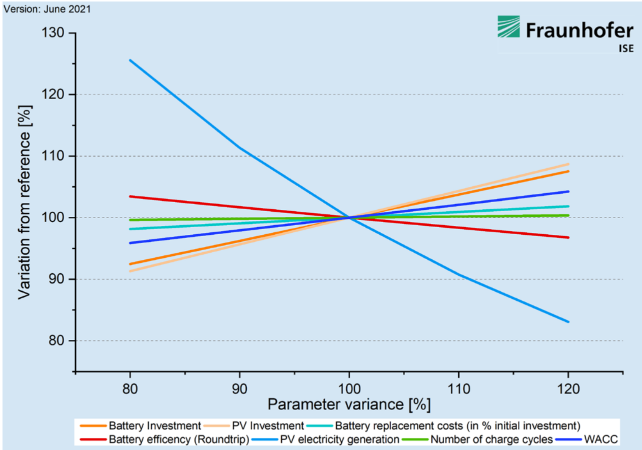

Figure 10: Sensitivity analysis for rooftop small-scale PV system with battery system assuming a GHI of 1120 kWh/(m²a), PV investment of 1300 EUR/kW, battery investment of 850 EUR/kWh, and battery replacement cost of 45% of initial investment.

A large share of the stationary battery storage systems installed today is based on lithium-ion technology. The global cumulative capacity of lithium-ion batteries is estimated at 195 GWh for 2019. However, electric vehicles accounted for the largest share of this total, as well as the largest annual growth. Therefore, stationary battery storage prices are also strongly influenced by the automotive market. Consumer electronics also have a large market share, but slower growth. Stationary energy storage had a market share of less than 5% of the total market, but upward trending. For all three applications - PV home storage, commercial and industrial storage, and large-scale storage in Germany - continued growth is also assumed. Thus, the price reduction is simultaneously driven by a growing global market as well as increasing installation numbers in Germany.

Wind power plants (WPP)

Of the renewables, wind power is the one that has been demonstrating high competitiveness against conventional power generation for the longest time, and its global market penetration is correspondingly strong. The top five markets for new installations in 2019 were China, the U.S., the U.K., India, and Spain; these five markets together accounted for 70% of global installations. However, in most regions, there are markets for WPP with consistent if unspectacular growth (GWEC 2020b).

By the end of 2020, the total capacity of all installed WPP increased to a volume of more than 730 GW. The market has shown continuous growth in the past. It is expected that the total capacity of onshore wind power will reach a good 1500 GW in 2030 and about 3500 GW in 2040 (GWEC 2016; IRENA 2021b). Offshore wind power is assumed to have a total global capacity of 200 GW in 2030 and just under 1000 GW in 2050

(GWEC 2020a; IRENA 2021b). The share of wind energy in total electricity generation in Germany was 27% in 2020, of which 21.7% was generated by onshore WPP. Wind power remained the largest source of renewable electricity generation in 2020, accounting for 53% of the total (Fraunhofer ISE 2021a).

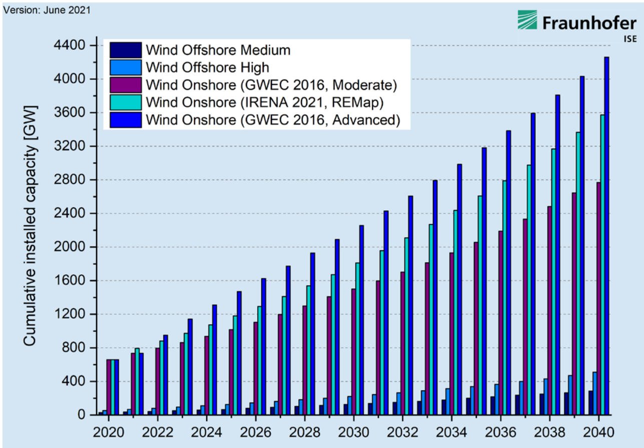

Figure 11: Market forecasts of cumulative wind power according to (GWEC 2016; IRENA 2021b).

The LCOE of WPP is highly dependent on local conditions with respect to both onshore and offshore power plants, as well as on the achievable FLH. In general, locations with favorable conditions are distinguished from those with unfavorable wind conditions. Favorable locations have average wind speeds of more than 7.8 m/s. Locations with unfavorable locations are often located inland; the average annual wind speed is lower and the ground is rougher because of agriculture and forest cover. A current trend indicates that manufacturers are striving to construct taller towers and to increase the rotor surface area in proportion to the generator power output. This corresponds with an effort to increase yield, enabling profitable operation also at locations with less favorable wind conditions. Taller towers and longer rotor blades, however, lead to greater material and installation costs that can only be justified by a significant increase in FLH. Thanks to ongoing technical refinement, an increase in FLH can be expected for future power plants and thus an annual increase in the FLH which would lead to improvements in the LCOE for WPP.

The LCOE of onshore WPP are calculated for sites with an average annual wind speed of 5.5 m/s and 6.4 m/s, respectively. 1800 (at the first location) and 2500 FLH per year (at the second location) are achieved. Very good wind locations on the coasts are represented by a location with 7.8 m/s and 3200 FLH.

As shown in Figure 12 As shown in Figure 9, the LCOE of onshore WPP at coastal locations with favorable wind conditions with 3200 FLH ranges between 3.94 and 5.01 €cent/kWh. Locations with less-favorable wind conditions achieve LCOE values from 6.38 to 8.29 €cent/kWh, depending on the specific investments. If it is possible to achieve 2500 FLH at the respective location, the LCOE reaches values between 4.82 and 6.19 €cent/kWh, which is lower than the LCOE of new hard coal power plants. Compared to the costs of the previous study, no significant change in LCOE can be observed in Germany for 2021, especially due to slightly stagnating installation costs.

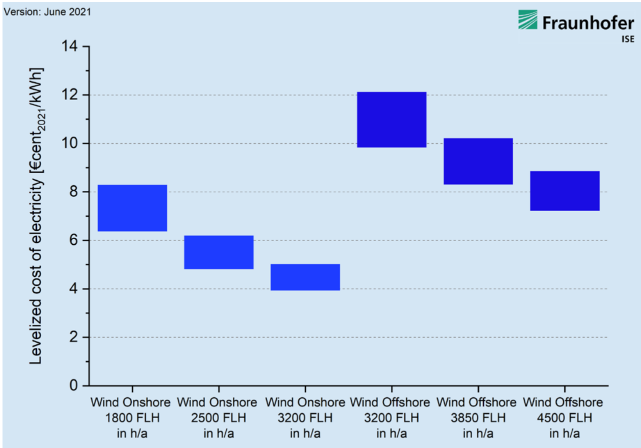

Figure 12: LCOE of wind power plants by location and full load hours in 2021.

In contrast, the analysis of current offshore WPP (including locations with higher FLH up to 4500) shows higher LCOE than onshore WPP. This is due to the necessary use of more resistant and expensive materials, the elaborate anchoring in the seabed, cost-intensive installation and logistics of the plant components and higher maintenance expenditure. However, a decrease in system costs and lower maintenance costs can be expected due to more reliable systems in the future. Currently, the LCOE of offshore wind power plants at very good locations ranges from 7.23 to 8.85 €cent/kWh (Figure 12). However, these sites, which are often located far from the coast, are subject to the disadvantage of a complex and expensive grid connection, as well as the need to bridge the greater ocean depth; sites with a lower number of full load hours (3200 h) achieve LCOE of 9.84 to 12.13 €cent/kWh. This puts offshore wind power plants above the LCOE for onshore wind power plants considering all conditions (and locations), with the exception of very high wind speed offshore locations, where offshore wind power plants have comparable LCOE to onshore wind power plants. The advantage of offshore installations is the higher number of FLH, as well as lower noise pollution and increased public acceptance, if minimum levels for the distance to the coast and environmental protection requirements are met. However, network connectivity problems still delay current offshore projects. These technology-specific risks lead to higher capital costs as well as well as demand for financial security from creditors, which results in higher WACC for offshore projects compared to onshore wind parks.

While there is significant scope for cost reductions in offshore wind power plants, achieving a level comparable to onshore wind power plants currently appears difficult due to higher cost of installation and maintenance. Yet, recent years show that with the realization of numerous projects, project costs are decreasing faster than expected in previous studies. For example, the latest offshore wind farms that have recently been commissioned or are still under construction, such as Arcona Basin, Albatros, Borkum II and Hohe See all have specific installation costs of less than 4000 EUR/kW, which is significantly lower than the most expensive projects reported in the previous studies. At the same time, offshore plants also benefit from the fact that they can often feed in electricity when other renewable energy plants are unable to provide generation volumes. This will become an economic advantage in the coming years.

The sensitivity analysis for onshore WPP identifies savings in power plant investments as the primary goal for realizing future cost reduction potential. Similar to PV, the sensitivity analysis reacts strongest to this parameter. Furthermore, reducing maintenance costs can also make an important contribution.

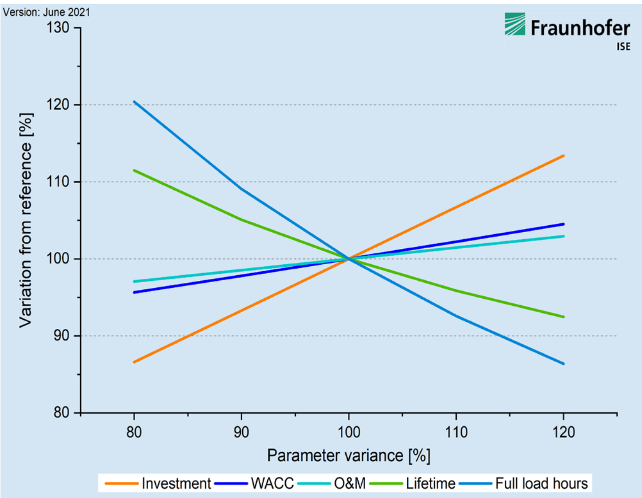

Figure 13: Sensitivity analysis of onshore wind power plants with 2500 FLH, specific investment of 1600 EUR/kW.

Bioenergy plants

The market for biogas plants has been characterized by numerous ups and downs. While between 2009 and 2011 about 600 MW were added annually, the average addition in the following years until 2019 was only about 260 MW. In 2019, the total installed capacity of biogas plants was around 5000 MW in Germany (Fachverband Biogas 2020). Despite the addition of biogas plants and their capacity increase in Germany, no significant reduction in specific investment costs can be observed over the last few years. Therefore, no learning rate is applied for biogas plants.

There was dynamic growth in the use of solid biomass for electricity generation, particularly after the introduction of the EEG. However, the number of newly commissioned bioenergy plants using solid biomass has increased only slightly since 2014 (Fraunhofer IEE 2019). The installed capacity of biogenic solid fuels for electricity generation accounted for approximately 1.5 GW at the end of 2020 (AGEE-Stat 2021). Similar to biogas plants, no learning rate for the technology is applied to plants using solid biomass.

In this study, unlike the previous study (Kost et al. 2018), heat extraction is included in the specification for bioenergy plants. A heat credit is therefore included in the LCOE.

Figure 14 shows the LCOE of large biomass plants with solid biomass and biogas plants (> 500 kW_{el}) for different FLH with and without consideration of a heat credit. In addition, specific investments with values between 2500 and 5000 EUR/kW for biogas plants and 3000 and 5000 EUR/kW for solid biomass are included in the calculation. By taking into account heat utilization and thus a heat credit, a significant reduction in LCOE can be observed. For biogas plants with heat utilization, a high number of FLH and low specific investment, the LCOE is 8.45 €cent/kWh - whereby an own heat demand of 25% is considered. The LCOE of biogas plants without heat credit is significantly higher at 13.43 €cent/kWh. The LCOE for biogas plants with low full load hours and high specific investments are 17.26 €cent/kWh and 22.24 €cent/kWh with and without heat credit, respectively. For plants using solid biomass, the LCOE for a high number of full load hours and low specific investments with and without heat credit are 7.22 €cent/kWh and 11.15 €cent/kWh, respectively. At low full load hours and high specific investment costs, however, the LCOE with and without heat credit are significantly higher at 15.32 €cent/kWh and 19.26 €cent/kWh, respectively.

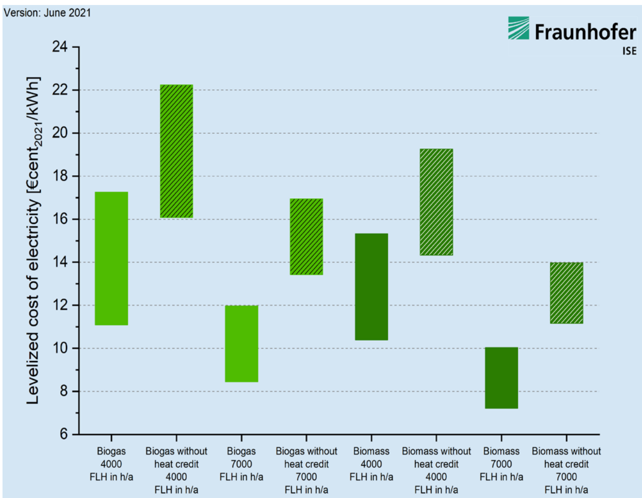

Figure 14: LCOE of biomass and biogas power plants with and without heat utilization at different full load hours in 2021.

The sensitivity analysis of the biogas plants in Figure 15 shows that substrate costs are the largest determinant of the LCOE. FLH and investment costs also have a big influence on the LCOE. For example, LCOE decreases by 0.49 €cent/kWh compared to the reference case when FLH are increased by 20%. In comparison, the LCOE decreases by 0.90 €cent/kWh if the substrate costs are reduced by 20%. It can be concluded that the use of predominantly manure and agricultural residues as substrate can further reduce the LCOE of biogas plants. A change in lifetime, WACC and O&M costs have a lesser impact on the LCOE.

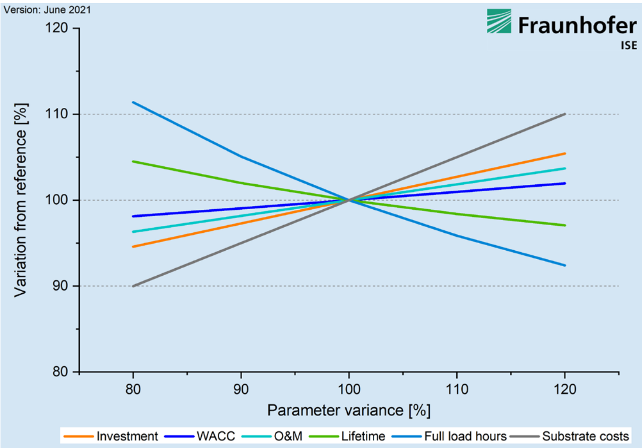

Figure 15: Sensitivity analysis for biogas power plants with specific investment of 2500 EUR/kW and 6000 full load hours.

Figure 16 shows, that for bioenergy plants combusting solid biomass, in addition to the substrate and investment costs, FLH have a significant effect on the LCOE. A reduction of full load hours by 20% results in an increase of the LCOE by 0.82 €cent/kWh. Varying the substrate and investment costs also has a significant effect. Reducing the investment costs by 20% decreases the LCOE by 0.59 €cent/kWh, while reducing substrate costs by 20% increases the LCOE by 0.52 €cent/kWh. The LCOE changes the least when varying the parameter WACC and O&M costs.

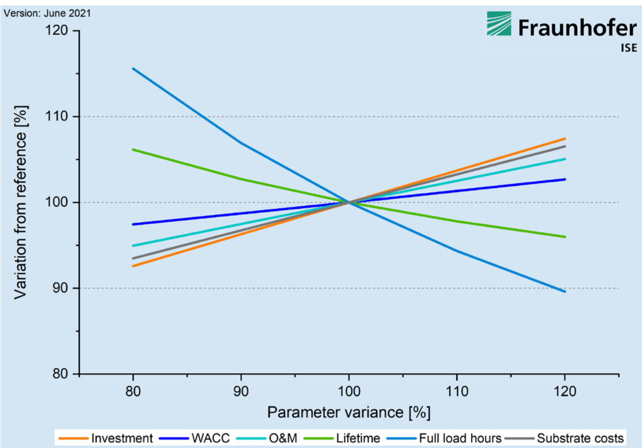

Figure 16: Sensitivity analysis for biomass power plants with specific investment of 3000 EUR/kW and 6000 full load hours

Conventional power plants

Market development and forecast

Coal-fired power plants accounted for around 28% of the world's installed power plant capacity in 2019, at around 2124 GW. Globally, the largest amount of electricity is produced by coal-fired power plants (37%) (IEA 2020). China produces the largest amount of coal-fired electricity. At the same time, China was the largest consumer of coal in 2019, accounting for 52% of total coal consumption. The second largest market is in India, followed by the US. By comparison, Europe's total coal consumption was similar to that of the U.S. at about 7% (bp 2020).

While net electricity generation from lignite in Germany amounted to 30% and hard coal to 22% in 2012 (BNetzA 2018), in 2020 the share of lignite in net electricity generation was only 16.8% and that of hard coal about 7.3% (Fraunhofer ISE 2021a). The installed capacity of lignite-fired power plants has remained almost constant since 2002 at 20.3 GW, while the installed capacity of hard coal-fired power plants has fallen slightly from over 28 GW in 2002 to 23.7 GW in 2020 (Fraunhofer ISE 2017). According to the Coal-fired Power Generation Phase-out Act (KVBG), Germany will phase out coal-fired power generation by 2038. However, it will be reviewed in 2026, 2029, and 2032, respectively, whether the closures can be moved up to achieve a complete phase-out by 2035 (BMU 2021).

In 2017, a total gas power plant capacity of around 1788 GW was installed worldwide with an electricity production of 6317 TWh (IEA 2020) making natural gas (at 23%) the second largest source in electricity production worldwide. Over half of all gas-fired power plants are installed in OECD countries. The OECD countries in the Americas account for 27% of the worldwide installed capacity, followed by European OECD countries (15%) and Asian OECD countries (9%). In the non-OECD countries, Russia has the largest installed capacity of gas-fired power plants with 7%, due to its large gas reserves. The Middle East as a whole has a share of 14%. There is 4% of the world's capacity installed in China and 2% in India.

In 2020, gas-fired power plants contributed a share of around 11.7% of net electricity generation (Fraunhofer ISE 2021a). Since 2002, the installed capacity of gas-fired power plants in Germany has increased from 20.3 GW to 30.5 GW. According to the grid development plan, installed gas capacity is expected to increase to 37.8 GW by 2030 (50Hertz Transmission GmbH et al. 2017).

Price and cost development

The LCOE of gas and coal-fired power plants are strongly dependent on the achievable FLH. In Germany, lignite-fired power plants currently (year 2020) reach full load hours of between 5300 and 7300, hard coal-fired power plants between 2600 and 6200, and CCGT power plants between 3000 and 8000 (Fraunhofer ISE 2021b). The FLH that a power plant can achieve depend on the variable marginal costs of the individual power plant, as the deployment of power plants on the market is determined by the merit order. As a result, the development of FLH is essentially dependent on a forecast of fuel and CO_2 certificate prices, the development of renewable electricity feed-in and the composition of the power plant fleet. Due to their dependence on developments on the national and international markets, the above-mentioned variables are subject to considerable uncertainty, which is why a wide range of FLH was specified for the technologies. Figure 17 shows the LCOE for the year 2021 of conventional power plants using lignite, hard coal, combined-cycle gas turbines (CCGT) and gas turbines, each for a specific range of FLH (see assumptions), the CO_2 allowance price from Table 7, the fuel prices from Table 5 and for the minimum and maximum specific investments from Table 1.

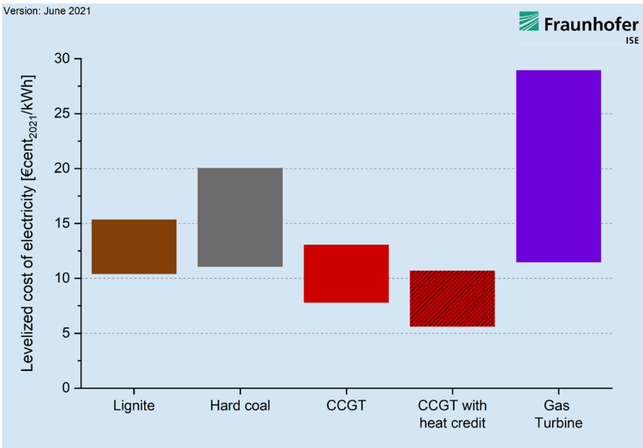

Figure 17: LCOE of conventional power plants in 2021 with varying CO_2 certificate and fuel prices as well as specific investments.

In contrast to the previous study, among the fossil-fueled power plants, newly built CCGT power plants currently have the lowest LCOE, ranging from 7.79 to 13.06 €cent/kWh (compared to potentially newly built coal-fired power plants). The advantages of CCGT power plants are their greater flexibility and their lower CO_2 emissions compared to coal-fired power plants. If the heat credit is also considered, the LCOE of CCGT power plants is between 5.59 and 10.70 €cent/kWh. The heat credit is calculated from the fuel costs that would be incurred for heat generation but is available at no additional charge as a result of the heat generated during the cogeneration of the electrically powered CCGT power plant. The electricity cost of potentially new lignite-fired power plants ranges from 10.38 to 15.34 €cent/kWh, making them slightly more expensive than CCGT power plants. As classic base-load power plants, lignite-fired power plants have very low generation flexibility and are therefore only suitable to a certain extent for flanking fluctuating renewables. The LCOE of potentially new hard-coal-fired power plants are significantly higher, at 11.03 to 20.04 €cent/kWh, despite lower specific investment than lignite. Highly flexible gas turbines have even higher LCOE at 11.46 and 28.96 €cent/kWh, but are highly flexible and, due to lower acquisition costs, more favorable at lower utilization below 500 FLH per year.

To compare: PV ground-mounted systems at locations with a GHI of 1300 kWh/(m²a) achieve a LCOE of 3.12 €cent/kWh, while onshore WPP at locations with 3200 FLH have an LCOE of 3.94 €cent/kWh. As a result, The LCOE of ground-mounted PV systems and onshore WPP are well below the LCOE of all conventional power plants. In fact, the LCOE of small rooftop PV systems at good locations in the south and in central Germany are also significantly lower than the LCOE of all other (newly built) conventional power plants. Figure 17 clearly shows that the LCOE of conventional power plants depend to a large extent on achievable full load hours. For CCGT power plants, the +/- 20% variation in FLH results in a difference to average LCOE of approximately +/- 0.8 €cent/kWh. The specific investments also have a significant influence on the LCOE. For CCGT power plants, these lead to a difference in LCOE of 0.55 €cent/kWh at low full load hours.

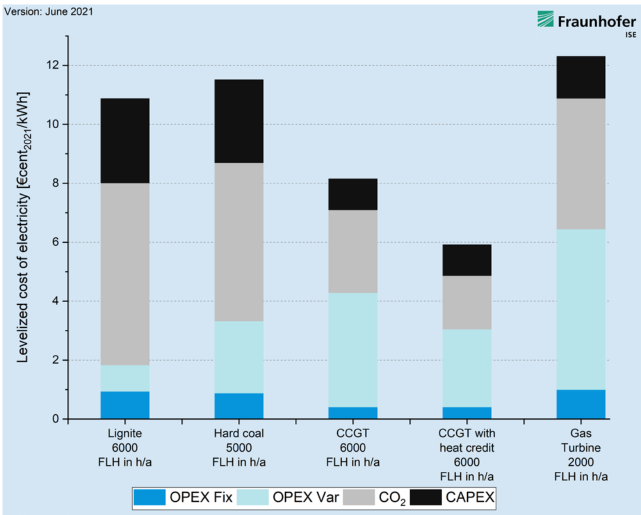

Figure 18: Components of LCOE of conventional power plants in 2021 with lower end CO_2 certificate prices as well as specific investments.

Figure 18 shows the components of the LCOE for conventional power plants, broken down into fixed and variable operating costs, CO_2 certificate costs and plant construction costs. CO_2 certificate costs account for the highest share of costs for coal-fired power plants, while for gas-fired power plants it is the gas price, followed by CO_2 certificate costs. Without considering CAPEX, the operating costs of conventional power plants are already more expensive than large-scale and ground-mounted PV systems and onshore WPP at good locations in Germany. The operating costs of hard coal and lignite power plants are significantly higher than the LCOE of newly constructed small-scale PV systems and offshore wind power plants.

In the future, due to a higher share of renewable electricity, the expected phase-out of coal and the anticipated phase-out of fossil natural gas, the FLH of conventional power plants will decrease dramatically. Conventional power plants are thus showing a trend in the opposite direction compared to renewable technologies: Costs will rise in the future. On the one hand, this trend is due to rising CO_2 certificate prices, and on the other hand, it is due to the expected significantly lower FLH. It can be presumed that it will not necessarily be the low-cost conventional form of generation that will survive on the market, but rather the one that can demonstrate a high degree of flexibility in terms of startup and shutdown variability, i.e. preferably power plants based on natural gas.

5. FORECAST OF LCOE UP TO 2040 IN GERMANY

For renewable energy technologies, cost projections can be described using historically observed learning curves whose progress over time builds on the different market projections for the period up until 2040. For photovoltaic and wind technology, an average learning rate (LR) and progress ratio (PR = 1 - learning rate) could be described for the past 20 years. The per watt investments in PV modules decreased in the past following a LR of 25%. A LR of 15% is assumed for the forecast of the future development of the LCOE of PV systems, as suggested by (Wirth 2021). In comparison, a learning rate of 5% is assumed for onshore wind power plants and 7% for offshore wind power plants (Tsiropoulos et al. 2018), corresponding to a progress ratio of 95% and 93%, respectively (however, wind energy is assumed to simultaneously increase electricity output (full load hours) over time). For battery storage, no reliable data on LR is available so far given the small market scale and different uses for battery systems. Therefore, assumptions were made for the price reduction up to 2030 and 2040 (see Table 8).

The modeling of the LCOE shows differing development dynamics for the individual technologies, depending on the aforementioned parameters, financing conditions (WACC), market maturity and development of the technologies, current specific investments (EUR/kW) and site conditions (Figure 19).

Almost all newly installed PV systems in Germany today can generate electricity for under 11.5 €cent/kWh. At a GHI of 950 kWh/(m²a), the costs - even for smaller rooftop systems - drop below 10 €cent/kWh by 2024 and below 8 €cent/kWh by 2027. Larger ground-mounted systems already generate their electricity for 3.5 €cent/kWh at a GHI of 1300 kWh/(m²a). In 2040, the LCOE ranges from 3.58 to 6.77 €cent/kWh for small rooftop PV systems and from 1.92 to 3.51 €cent/kWh for ground-mounted systems. Large rooftop PV systems in Germany generate electricity in 2040 at LCOE between 2.85 and 6.02 €cent/kWh. PV system prices drop to below 350 EUR/kW for ground-mounted systems and to between 615 and 985 EUR/kW for small systems by 2040.

The LCOE for PV battery systems can decrease by about 40% by the year 2040. The values were calculated for a constant ratio of PV system power output to battery storage capacity. However, with decreasing battery storage prices, the ratio could shift toward greater battery capacities. If the ratio remains constant, the LCOE for PV battery systems could decrease to between 4.60 and 12.01 €cent/kWh for small systems, 3.44 to 8.79 €cent/kWh for large rooftop systems, and 2.56 to 6.04 €cent/kWh for ground-mounted systems by 2040.

Depending on the location, onshore wind power plants can achieve LCOE comparable to those for PV power plants in good locations. From current LCOE of between 3.94 and 8.29 €cent/kWh, costs will decrease in the long term to between 3.40 and 6.97 €cent/kWh. Due to rising CO_2 certificate prices, the LCOE for CCGT power plants in 2040 is forecast to be between 9.19 and 25.05 €cent/kWh. Gas turbines have higher

CAPEX [EUR/kWh]	2021 low	2021 high	2030 low	2030 high	2040 low	2040 high
Battery storage for PV rooftop small (≤ 30 kWp, 1:1)	500	1200	300	960	200	720
Battery storage for PV rooftop large (30 kWp – 1 MWp, 2:1)	600	1000	360	750	180	600
Battery storage for PV utility-scale (> 1 MWp, 3:2)	500	700	300	530	150	420

Table 8: Assumptions for the calculation of LCOE of PV battery systems in 2030 and 2040. Shown is the battery storage price in EUR/kWh usable capacity, including installation, excluding VAT.

LCOE between 15.29 and 28.69 €cent/kWh in 2040. For offshore wind, on the other hand, slightly greater cost reduction potentials are available due to a higher LR. This can noticeably reduce LCOE by 2040. The LCOE is expected to decrease from 7.23 and 12.13 €cent/kWh to between 5.87 to 9.66 €cent/kWh by 2040. System prices of offshore turbines will then be between 2540 and 3400 EUR/kW. For bioenergy plants, constant LCOE are assumed in the range of 7.22 to 17.26 €cent/kWh. The availability, the heat utilization and the fuel costs of the substrate are decisive for the future development of the LCOE.

In the long term, PV systems in regions with high solar irradiation and wind power plants located inland with profitable wind conditions have the lowest LCOE. Both technologies can significantly underprice the LCOE of fossil fuel plants by 2040. The developments in technology and costs in recent years have significantly improved the competitiveness of wind power and PV. Particularly in the case of PV, strong cost reductions could be implemented, so that PV and onshore wind power are the cheapest technologies for power generation (in terms of new power plants) in Germany. For WPP, the increase in FLH due to larger plant dimensions and the reduction in plant costs, significantly contribute to the low LCOE. The analysis of the LCOE in this study shows that forecasts for PV presented in the previous versions of this study (2010, 2012, 2013, 2018) are even undercut due to strong market growth and significant price reductions for PV systems. Another reason for this is that both technology and financing costs have become significantly cheaper.

Since future construction of new coal-fired power plants in Germany is quite unlikely, the LCOE of PV and onshore wind are compared with the operating costs of existing lignite-fired and CCGT power plants for the years 2030 and 2040, respectively, in Figure 20. The operating costs of conventional power plants consist of variable operating costs, fuel costs, and CO_2 certificate price costs. At CO_2 certificate prices of around 35 EUR/t, the operating costs for lignite-fired power plants are lower than for onshore wind power plants at very good locations and as low as newly constructed PV ground-mounted systems in southern Germany. However, even at the low-est projected CO_2 certificate price in 2030, the operating costs of a coal-fired power plant will be more expensive than ground-mounted PV systems and onshore wind power plants. For gas-fired power plants, operating costs in 2030 are between 6 and 8 cents,

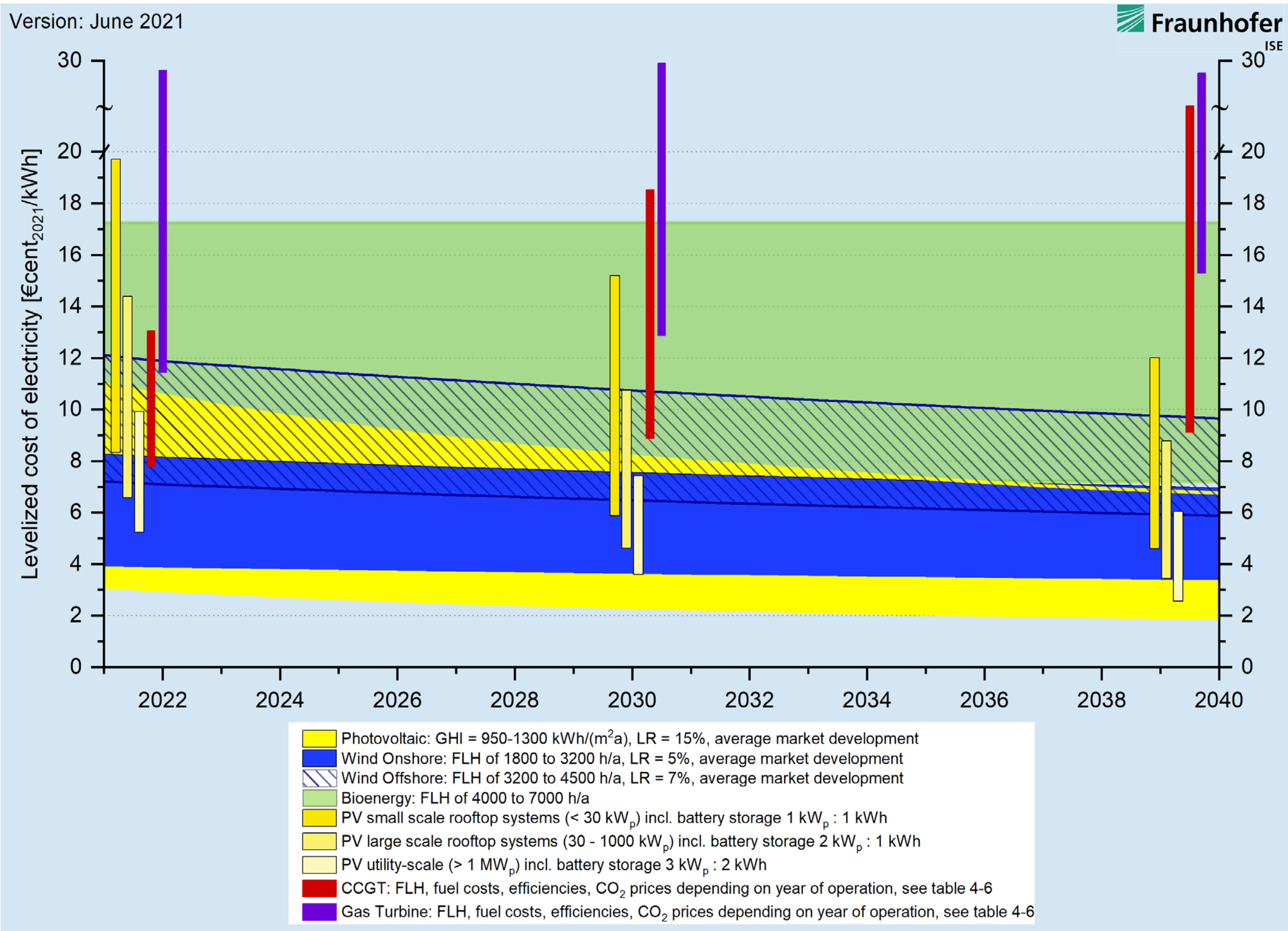

Figure 19: Learning-curve based forecast of the LCOE of renewable energy technologies and gas-fired power plants in Germany until 2040. Calculation parameters are listed in Tables 1 to 6. The LCOE value per reference year refers in each case to a new plant in the reference year.

which is roughly comparable to small PV systems and onshore wind power plants at suboptimal locations in Germany. A comparison in 2040 shows that conventional power plants will be significantly more expensive than PV and onshore wind power plants as an electricity generating source.

With the costs estimated in this study, the LCOE for PV ground-mounted systems correspond to values between 2 and 4 €cent/kWh in Germany in the long term, WPP slightly above. These values are not significantly higher than the values for which electricity can be generated from PV and WPP in regions with even better solar and wind conditions. Currently, there are several studies on the production of hydrogen using low-cost renewable electricity, especially in the regions of North Africa. It is often assumed that these regions are capable of generating electricity from ground-mounted PV systems with LCOE of 2.5 €cent/kWh (Hank 2020). Based on the analysis in this study, ground-mounted PV systems in southern Germany will already be able to achieve these costs by 2028. With costs of less than 2 €cent/kWh from 2038 on, the question arises how competitive a production of synthetic energy carriers and hydrogen will be in many parts of the world (including Germany). With sufficient availability of land for the power plants, hydrogen could then be produced close to consumption. The advantage of this constellation, in addition to the reduced independence from energy imports, is the elimination of transport costs, which are a significant factor in the total cost of hydrogen liquefaction. With costs of less than 2 €cent/kWh from 2038, the possibility of domestic hydrogen production in Germany becomes very attractive, as this could lead to more favorable costs of green hydrogen due to the avoided transport costs.

Sensitivity analyses of learning curves for PV and wind

In a sensitivity analysis, the specific investment costs, lifespan, weighted average cost of capital (WACC), FLH and operating costs are examined regarding their impact on the LCOE.

Figure 21 and Figure 22 show the range of LCOE for small PV installations and onshore WPP in Germany with respect to different combinations of LRs and market scenarios (see Table 12 and Table 13). Based on the assumed low costs, the LCOE valu-

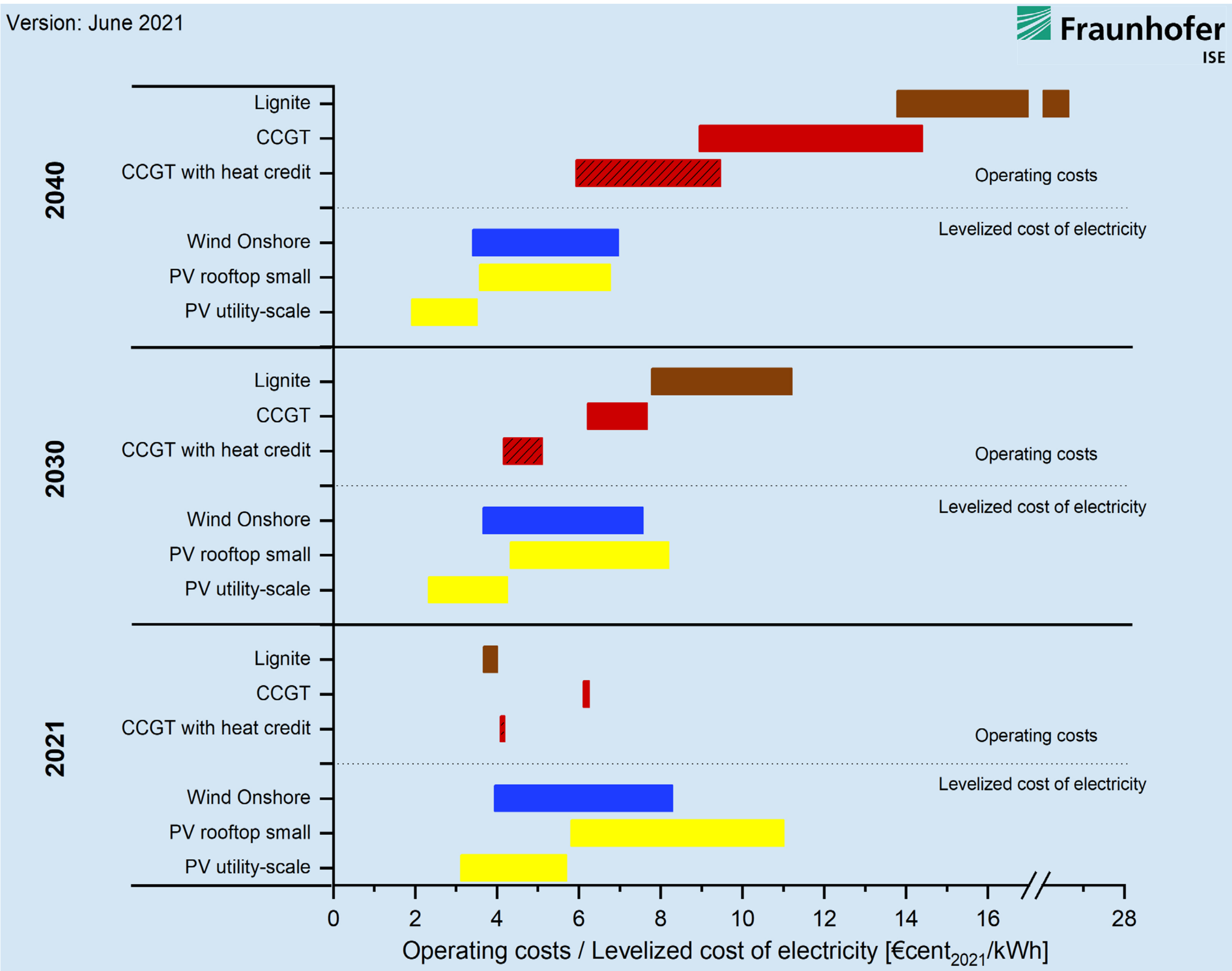

Figure 20: Comparison of the LCOE of newly installed PV and onshore wind power plants as well as the operating costs of existing lignite-fired and CCGT power plants.

es show variations of up to 12% depending on the parameters used. This demonstrates the uncertainty of the learning curve model when varying input parameters are used, yet at the same time, it reflects a potential range for the cost development of each technology.

For small PV systems at sites with a GHI of 950 kWh/m²a, LCOE between 3.20 €cent/kWh and 4.00 €cent/kWh can be identified in 2040, depending on the scenario assumption. For onshore wind, only minor future cost reductions can be expected due to the current low LCOE (3.32 - 3.51 €cent/kWh).

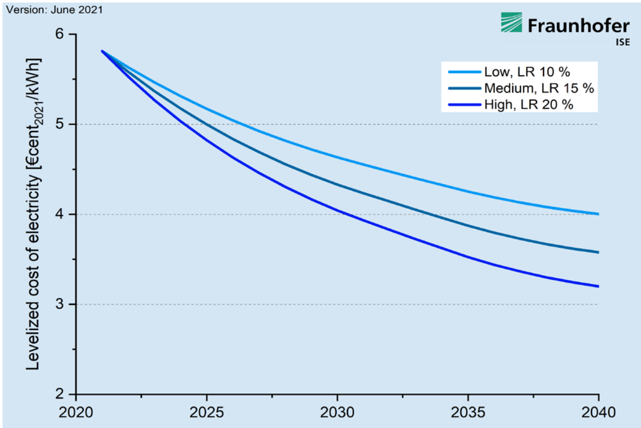

Figure 21: Sensitivity analysis for the forecast of LCOE of small-scale PV systems, investment cost in 2021 = 1000 EUR/kW, GHI=950 kWh/(m²a).

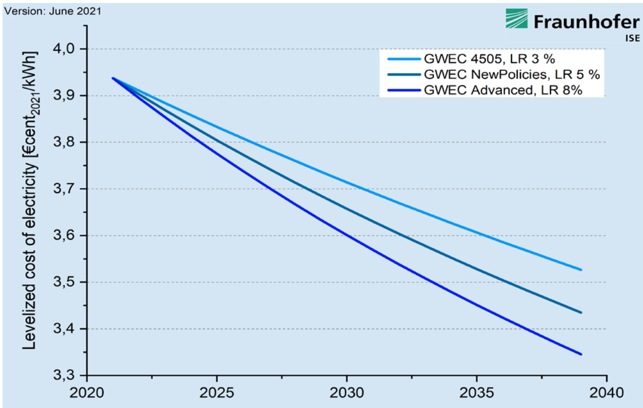

Figure 22: Sensitivity analysis for the forecast of LCOE of onshore WPP, investment cost in 2021 1400 EUR/kWh, FLH increase from 3200 h/a in 2021 to 3520 h/a in 2040.

6. LCOE FOR RENEWABLES IN REGIONS WITH HIGH SOLAR IRRADIATION AND FAVORABLE WIND CONDITIONS

This chapter analyzes photovoltaic (PV) and Concentrated Solar Power (CSP) plants for regions with higher solar irradiation as well as WPP at locations with higher FLH than in Germany. Since CSP power plants can only be used for electricity generation under high direct solar irradiation, the analysis of CSP focuses on sites with direct normal irradiation (DNI) of 2000 kWh/(m²a) (e.g. in Spain) and sites with 2500 kWh/(m²a) (e.g. in the MENA countries). By integrating thermal salt storage, the generated thermal energy can be stored, which enables the plant to feed electricity into the grid regardless of current weather conditions or the time of day. This integrated storage option distinguishes CSP from WPP and PV systems. Particularly the countries with very strong DNI have developed extensive expansion plans for CSP power plant projects, often in sunny desert areas (New Energy Update 2017).

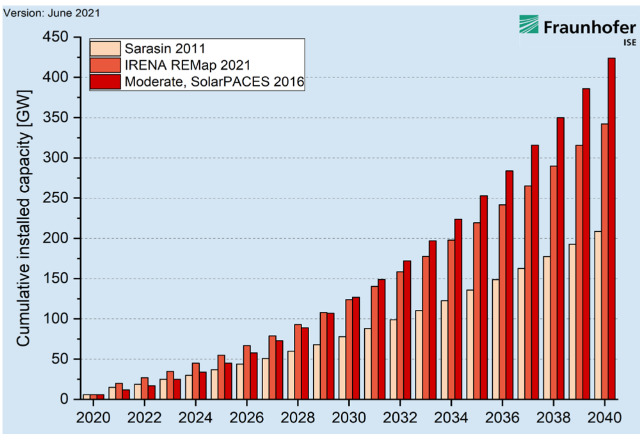

Figure 23: Market forecast solar thermal power plants 2020-2040 (Sarasin Bank 2011; SolarPACES 2016; IRENA 2021b).

At the beginning of 2021, CSP power plants with a total capacity of 6.5 GW were in operation worldwide. Additional plants with a total capacity of 5 GW are currently under construction or in the planning or development phase; the Chinese market in particular has been focusing on new CSP power plants in recent years.

The analysis of LCOE for CSP power plants is based on data from realized parabolic trough and tower technology power plant projects in Spain, the USA and the Middle East, as well as China. The CAPEX of CSP plants with integrated storage for 8 hours were between 3000 and 4000 EUR/kWh (early 2021).

Of the solar thermal power plant technologies, the parabolic trough power plants and tower power plants with a size of 100-200 MW designed with thermal storage (8 hours) are considered. They are simplified as a single technology: CSP. Solar thermal power plants concentrate DNI into a focal point where the heat is then used either directly or indirectly to generate electricity. Three locations were considered to calculate the LCOE of PV and CSP. The site with the lowest GHI of 1450 kWh/(m²a) was only analyzed for a PV system, as direct solar irradiation at this site is too low. Therefore, the CSP technology is only analyzed at sites with DNI of 2000 kWh/(m²a)) and 2500 kWh/(m²a). PV systems are analyzed at corresponding sites with GHI of 1800 kWh/(m²a) and 2000 kWh/(m²a).

Locations with very good wind conditions were considered for wind power plants. These sites can be found either for onshore wind energy near the coast of the Atlantic or the North Sea in Europe where 3000 to 4000 full load hours can be reached. Offshore wind power plants can reach FLH of 4000 to 5000 at some locations in Europe in marine areas with very high wind speeds, for example in the North Sea and the Atlantic around Great Britain.

In a pure cost comparison for the year 2021, PV systems without battery storage at locations with high solar irradiation (DNI of 2000 kWh/(m²a)) have lower LCOE compared to CSP with integrated thermal storage. Due to a comparatively smaller market growth, the costs for CSP power plants with integrated thermal storage (full load hours up to 3600 h) are currently below 6 €cent/kWh, while PV utility-scale systems achieve a LCOE below 2.5 €cent/kWh at equal solar irradiation.

The LCOE of the analyzed CSP power plants equipped with storage range from 7.66 to 9.67 €cent/kWh at a DNI of 2000 kWh/(m²a). In regions with solar irradiation of up to

2500 kWh/(m²a), such as in MENA countries or the deserts in California, LCOE of 5.85 to 9.67 €cent/kWh can be achieved.

LCOE of 4 to 6 €cent/kWh can be achieved for onshore wind power plants at favorable wind sites such as in the northeast of the UK. This is almost completely below the cost of CSP, but higher than PV in MENA countries with high solar irradiation.

Offshore wind power plant costs are slightly higher between 5 and 7 €cent/kWh in the North Sea on the Scottish coast.

The sensitivity analysis shows that compared to the reference case (7.57 €cent/kWh) a 20% reduction in investment would result in LCOE of 6.36 €cent/kWh (see Figure 25). A higher DNI has a similarly strong, positive impact on the LCOE.

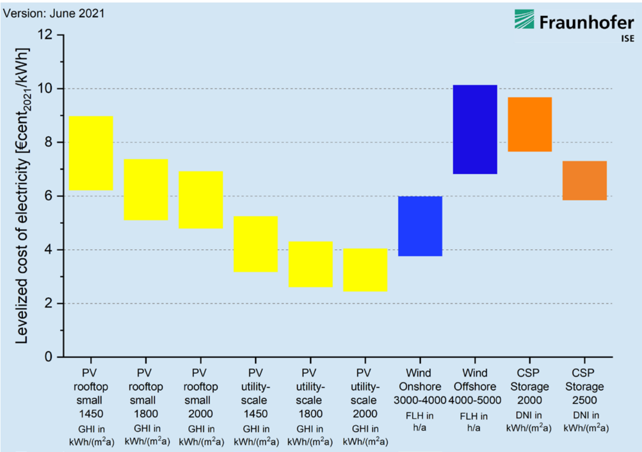

Figure 24: LCOE for renewables at locations with high solar irradiation and favorable wind conditions in 2021.

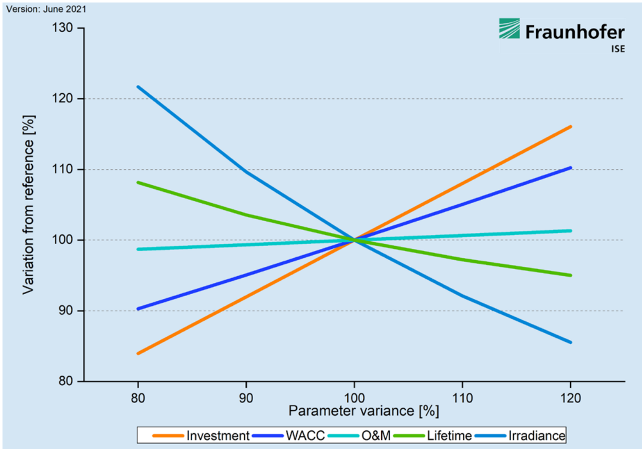

Figure 25: Sensitivity analysis of CSP (100 MW with storage) with an annual DNI of 2500 kWh/(m²a) and specific investment of 3600 EUR/kW.

PV systems	GHI [kWh/(m²a)]	Solar irradiation on PV moduls [kWh/(m²a)]	Electricity generation per 1 kWp [kWh/a]
Southern France	1450	1670	1380
Southern Spain	1800	2070	1680
MENA	2000	2300	1790
CSP power plants	**GHI [kWh/(m²a)]**	**Direct normal irradiation (DNI) [kWh/(m²a)]**	**Electricity generation per 1 kW [kWh/a]**
Southern Spain	1800	2000	3300
MENA	2000	2500	4050
Wind power plants	**Wind speed [m/s]**	**Full load hours [h]**	**Electricity generation per 1 kW [kWh/a]**
Wind onshore	7.5 - 9.5	3000 - 4000	3000 - 4000
Wind offshore	9.5 - 11	4000 - 5000	4000 - 5000

Table 9: Annual yields at typical locations of PV and CSP (Source: Fraunhofer ISE).

For calculation purposes, the following assumptions were made with respect to the technologies.

	PV rooftop (< 30 kWp)	PV utility-scale (> 1 MWp)	CSP	Wind onshore	Wind offshore
Lifetime in years	30	30	35	25	25
Share of debt	80%	80%	70%	80%	70%
Share of equity	20%	20%	30%	20%	30%
Interest rate on debt	5.0%	5.0%	6.5%	5.5%	6.5%
Return on equity	7.0%	8.5%	11%	9.0%	10.0%
WACC nominal	5.4%	5.7%	7.9%	6.2%	7.6%
WACC real	3.3%	3.6%	5.7%	4.1%	5.4%
OPEX fix [EUR/kW]	26	13.3	20	20	70
OPEX var [EUR/kWh]	0	0	0.01	0.008	0.008
Annual degradation	0.25%	0.25%	0	0	0

Table 10: Input parameters for LCOE calculation for energy technologies in regions with high solar irradiation.

Forecast of LCOE until 2040 for renewables with high solar irradiation and favorable wind conditions

The forecast of LCOE up to 2040 is also carried out for PV, wind and CSP technologies at locations with high solar irradiation or wind speed. Samadi (2018) compiled different learning rates of CSP power plants from literature and reported that the learning rate for each component (solar field, thermal storage, power block) varies between 3% and 12%. Based on this, an averaged LR of 7.5% can be calculated, which relates to the entire power plant. Similar learning rates as in Chapter 5 are used for PV and WPP.

By 2040, the LCOE of CSP may drop to values between 4.28 €cent/kWh and 6.80 €cent/kWh (see Figure 22). For CSP, the decisive factor will be the extent to which CSP installations in markets with high solar irradiation are promoted in the coming years. As for onshore WPP, in 2040 they will produce electricity at LCOE of between 3.10 and 4.90 €cent/kWh at very good locations in Europe. For offshore wind, the LCOE in 2040 will be between 5.40 and 7.95 €cent/kWh. For PV, at locations with good solar irradiation in the MENA regions, LCOE can be less than 3 €cent/kWh for small rooftop systems and about 1.5 €cent/kWh for utility-scale PV.

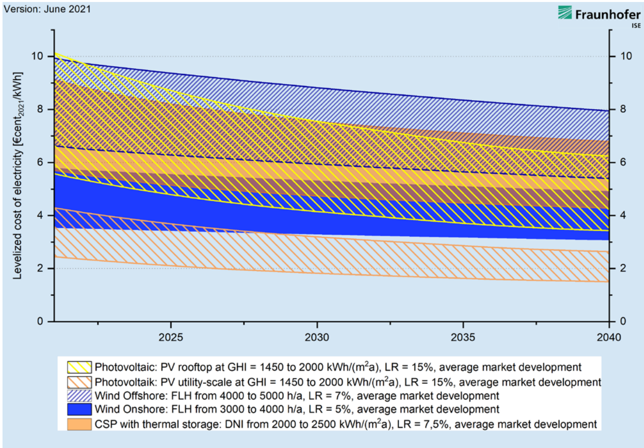

Figure 26: Development of LCOE for wind power plants, PV systems and CSP plants with integrated thermal storage at sites with high wind speed (m/s) and solar irradiation kWh/(m²a).

7. EXCURSUS: STRUCTURAL EVALUATION OF PV CAPACITY ADDITIONS

As of January 2021, all power generation units in Germany connected to the general supply grid must be entered in the core energy market data register (Marktstammdatenregister - MaStR). This also applies to the steadily growing number of photovoltaic systems. In addition to the master data already recorded under the EEG, such as power output and location, the core energy market data register now also records additional information about the PV systems, such as orientation, inclination, use of electricity storage and power output limitation. Fraunhofer ISE evaluates the available information on a regular basis and releases relevant results to the public.[1] More extensive evaluations are possible and can be commissioned from Fraunhofer ISE. In the following, two exemplary evaluations are presented, which were created on the basis of the available data in MaStR.

The following figure shows that most PV systems are built facing south, which is the most favorable direction for system yield. In 2019, the share of south-facing systems was 42%, followed by south-west systems with 19% and south-east

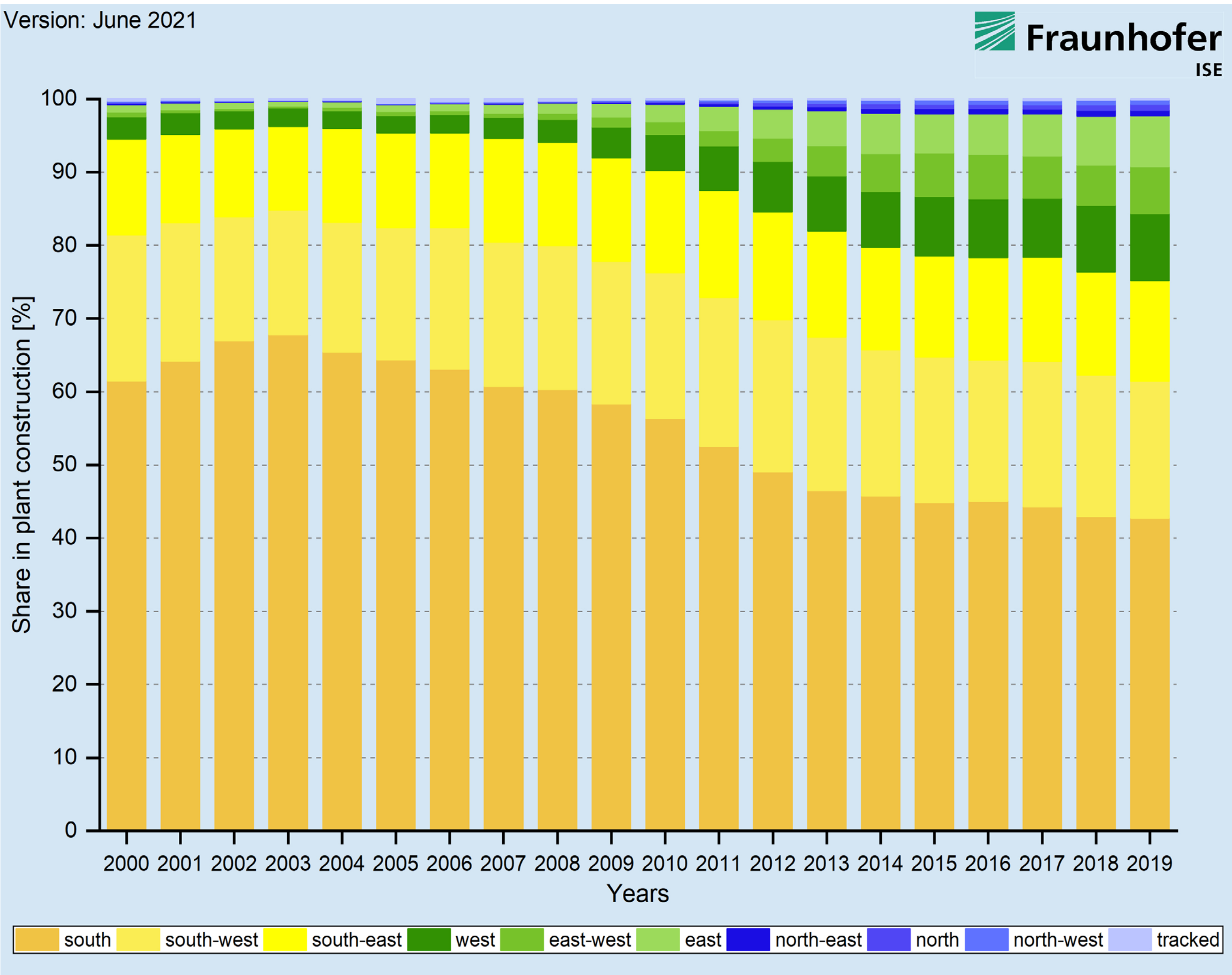

Figure 27: Relative shares of different orientation of PV systems in historical system expansion. Source: Own calculation based on MaStR data registered starting from 31.01.2019 (data as of 03.03.2020) (BNetzA 2020).

systems with 14%. West-facing systems (9%) are slightly more common than east-facing systems (7%). The final relevant group is east-west systems with 6%.

In general, the share of systems installed in directions other than south has increased. While the share was 39% in 2000, it increased to 58% by 2019. Yield losses can occur as a result, but the amount of these losses depends strongly on the inclination angle of the system. With an optimal angle of inclination (which varies with direction, latitude and season), yield losses can be minimized and typically lie between 5-10%. Only systems facing north (2% of systems in 2019) can have lower yields of up to 50%. Increasing variation in orientation leads to a better distribution of electricity generation throughout the day.

In 2019, the majority (54%) of installed systems had an inclination angle between 20 and 40 degrees. 20% of the installations had an even steeper inclination between 40 and 60 degrees. However, the percentage of installations with a small inclination angle < 20 degrees has increased significantly over the past 20 years: From 5% in 2000 to 24% in 2019. The following developments and installation strategies can be cited as reasons for the increased use of small angles in PV systems: Increasing installations of east/west-facing systems, possibility of tighter packing densities and reduction of bearing loads in windy conditions. For installations whose orientation is east or west, small angles are advantageous for PV system yield. Tighter packing densities allow more PV modules to be installed in a limited space.

[1]Link: https://www.ise.fraunhofer.de/de/presse-und-medien/presseinformationen/2021/vermehrter-zubau-von-grossen-pv-aufdachanlagen-mit-kleinen-neigungswinkeln-in-ost-west-richtung.html

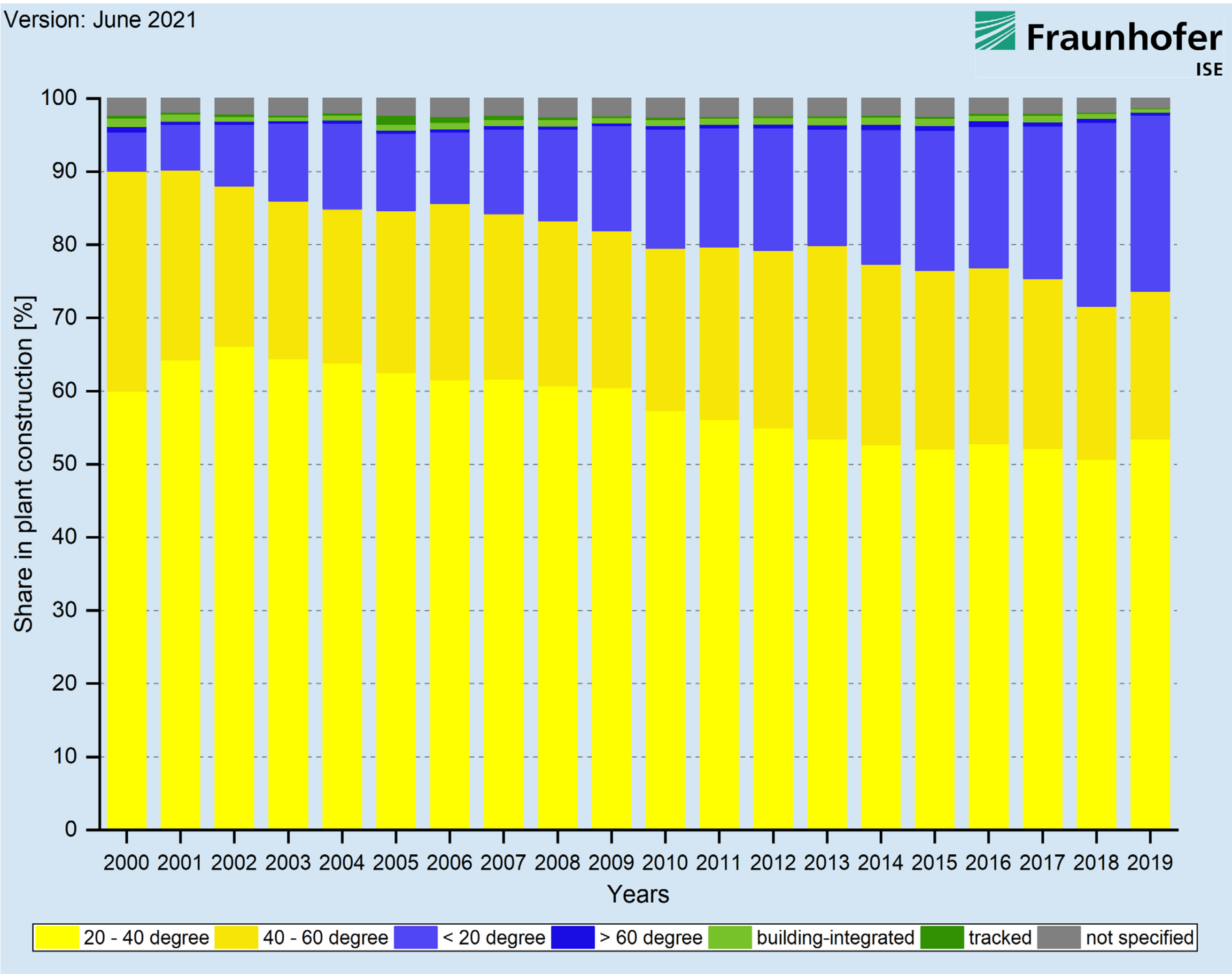

Figure 28: Relative shares of different inclination angles of PV systems in system expansion historically. Source: Own calculation based on MaStR data registered starting from 31.01.2019 (data as of 03.03.2020). (BNetzA 2020).

8. APPENDIX

Calculation of LCOE

The Levelized Cost of Electricity (LCOE) method allows power plants with different generation and cost structures to be compared with each other. The LCOE is calculated by comparing all costs incurred over the lifetime of the power plant for the construction and operation and the total amount of energy generated.

The calculation can be conducted either based on the net present value method (NPV) or the so-called annuity method. When applying the net present value method, the expenses for the investment, as well as the payment flows of revenues and expenditures during the power plant's lifetime, are calculated by discounting related to a shared reference date. For this purpose, the present values of all expenses are divided by the present value of electricity generation. A discounting of power generation initially seems incomprehensible from a physical point of view but is a consequence of financial mathematical transformations. The underlying idea is that the generated electricity implicitly corresponds to the revenue from the sale of this energy. Thus, the further this income is in the future, the lower the associated present value. The total annual expenditure throughout the entire operating period consists of the investment expenditure and the operating costs, which arise during the lifetime. For the calculation of the LCOE for new power plants, the following applies (Konstantin 2013):

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

LCOE Levelized Cost of Electricity in EUR/kWh

I_0	Investment expenditure in EUR
A_t	Annual total cost in EUR per year t
$M_{t,el}$	Produced amount of electricity in kWh per year
i	Real interest rate in %
n	Economic lifetime in years
t	Year of lifetime (1, 2, ...n)

The total annual costs are composed of fixed and variable costs for the operation of the power plant, maintenance, servicing, repairs and insurance payments. The share of debt and equity can be explicitly included in the analysis by the weighted average cost of capital (WACC) over the discount factor (interest rate). The discount factor depends on the amount of the equity, the return on equity over the lifetime, the borrowing costs and the share of the contributed debt.

Furthermore, the following applies for the formula of the total annual costs in the calculation of LCOE:

Total annual costs A_t =
fixed operating costs
+ variable operating costs
(+ residual value/ disposal of the power plant)

Through discounting all expenditures and the quantity of electricity generated over the lifetime to the same reference date, the comparability of LCOE is assured.

Through discounting all expenditures and the quantity of electricity generated over the lifetime to the same reference date, the comparability of LCOE is assured. LCOE represents a comparative calculation on a cost basis and not a calculation of feed-in tariffs. These can only be calculated by adding further influencing parameters. Selfconsumption regulations, tax legislation, and realized operator revenues make it difficult to calculate a feed-in tariff from the results for the LCOE. A further restriction arises from the fact that a calculation of LCOE does not take into account the value of the electricity produced within an energy system in a given hour of the year. At this point, it is to be emphasized that this method is an abstraction of reality aiming at making different power plants comparable. The method is not suitable for determining the profitability of a specific power plant. For this purpose, a financial calculations, which takes into account all income and expenditure with a cash flow model must be carried out.

The calculation of LCOE using the annuity method can be understood as a simplification of the NPV method and exists in two different versions. On the one hand, LCOE can be defined as the quotient of the annualized investment and operating costs and the average electricity yield. The calculation is based on the following formula (Allan et al. 2011; Gross et al. 2007; Lai und McCulloch 2016):

$$LCOE = \frac{(I_0 + \sum_{t=0}^{n} \frac{A_t}{(1+r)^t}) * ANF}{\frac{\sum_{t=1}^{n} M_t}{n}}$$

The annuity factor (ANF) is calculated as follows:

$$ANF_{t,i} = \frac{i * (1+i)^t}{(1+i)^t - 1}$$

In an even simpler version, LCOE is calculated with the assumption that the amount of electricity produced annually and the annual operating costs are constant over the entire period of observation (Brown et al. 2015; Tegen et al. 2012):

$$LCOE = \frac{(I_0 * ANF) + A}{M}$$

Although the calculation of LCOE based on the annuity methods offers the advantage of a lower calculation effort, but depending on the selected input parameters, significant deviations from the calculation using the NPV can occur. Since the application of the NPV method for the calculation of LCOE best reflects reality, the LCOE in the present study were calculated on the basis of the NPV method.

To account for heat generation in a combined heat and power (CHP) plant, such as bioenergy plants and CCGT power plants, the heat credit methodology is used. Since CHP plants generate not only electricity but also heat, the total generation cost cannot be allocated to electricity generation alone. Heat credit, also referred to as revenue from heat generation, is defined as the value of heat delivered by the CHP plant, calculated per unit of electricity generated by the plant over its lifetime. The heat credit is calculated from the fuel costs that would be incurred to generate the heat, but is available at no cost from the heat generated in the combined production of the electricity-fueled CHP plant. Heat credits vary widely from study to study (Bratanova et al. 2015). In this study, the heat credit is calculated from the difference between the overall efficiency of a CHP plant and the electrical efficiency. This results in the difference between the real fuel and operating costs and those incurred when the power plant is used exclusively for heat generation (Koch et al. 2020; Schröder et al. 2013).

Learning curve models

Based on the results of the LCOE for 2021, learning curve models can be created, with the help of market projections until 2030 and 2040. The models allow statements about a future development of power plant prices and thus also LCOE. The learning curve concept represents a relationship between the cumulative quantity produced (market size) and the decreasing unit costs (production costs) of a good. If unit quantities double and costs fall by 20%, the learning rate is said to be 20% (Progress Ratio PR = 1 - learning rate). The relationship between the quantity xt produced at time t, the costs $C(x_t)$ compared to the output quantity at reference point x_0 and the corresponding costs $C(x_0)$ and the learning parameter b is as follows for the learning rate:

$$C(x_t) = C(x_0)(\frac{x_t}{x_0})^{-b}$$

$$LR = 1 - 2^{-b}$$

see Ferioli et al. (2009), Wright (1936).

By forecasting power plant prices $C(x_t)$ for the period under consideration using the learning curve models (assuming literature values for the learning rate or PR), the LCOE can thus be calculated up to the year 2040.
In combination with market scenarios for future years, annual figures can be assigned to the cumulative market variables in each case, so that the development of LCOE can be forecast in a time-dependent manner.

Evaluation of the methodology and use of LCOE

The LCOE method has become a very practical and valuable comparative method to analyze different energy technologies in terms of cost. The LCOE calculation method is internationally recognized as a benchmark for assessing the economic viability of different generation technologies as well as of individual projects and enables the comparison of different energy technologies with respect to their cost (Allan et al. 2011, p. 23; Joskow 2011, p. 10; Lai und McCulloch 2016, p. 2; Liu et al. 2015, p. 1531; Orioli und Di Gangi 2015, p. 1992). The high level of transparency and clarity is one of the reasons why the cost metric has prevailed. At the same time the method is able to reflect the key factors of the production cost throughout the lifetime of the power plant in just one number (Allan et al. 2011, p. 24; Díaz et al. 2015, p. 721; Tidball et al. 2010, p. 59). From an economic point of view, LCOE contains the most important factors contributing to the economic evaluation of a project (Myhr et al. 2014, p. 715). As LCOE is just one number, it causes a great reduction in complexity and allows a quick and easy comparison of different alternatives. In addition, the approach has a broad range for its application (Branker et al. 2011, p. 4471; Ouyang und Lin 2014, p. 65).

However, there are limits for this approach by representing the project cost in a single number. For example, an analysis with a sole focus on LCOE increases the risk of a misinterpretation and a resulting wrong decision due to the narrow viewpoint. The LCOE is also a method associated with uncertainties. These can be explained primarily by the fact that the calculation requires all values relating to the entire lifetime of the power plant, some of which must be predicted. Branker et al. (2011, p. 471) point out a further weak spot that the calculation often focuses too strongly on the static value of the electricity production costs, while the calculation basis is not transparent. For this reason, it is important that the assumptions for each calculation are sufficiently substantiated and comprehensible. It has to be clear which cost drivers are included. Joskow (2011, p. 1) emphasizes that electricity is a temporally heterogeneous good, which means that the value of the electricity depends on the time at which it is generated. The value of the electricity depends not only on the technology used but is also influenced by the interaction between the power plants in a considered system. However, it is reasonable to assume that the value which is calculated by using data of the energy-only market today will be different in a system with even higher shares of renewables. The value of CO_2-free power generation will increase significantly.

LCOE can be used to support the decision-making process. However, conclusive statements about the economic viability of a technology cannot be made on the sole basis of the LCOE method. At this point, it should not be forgotten that LCOE is a cost-based indicator and does not include revenues.

Data appendix

	Low	Medium	High
2020	707.5	707.5	707.5
2021	835	849	877
2022	977	1,010	1,079
2023	1,133	1,192	1,317
2024	1,303	1,395	1,593
2025	1,485	1,618	1,912
2026	1,679	1,861	2,275
2027	1,880	2,121	2,684
2028	2,087	2,397	3,141
2029	2,295	2,685	3,643
2030	2,502	2,980	4,189
2031	2,702	3,278	4,776
2032	2,905	3,606	5,397
2033	3,108	3,966	6,044
2034	3,310	4,363	6,709
2035	3,509	4,799	7,380
2036	3,684	5,231	8,081
2037	3,832	5,650	8,809
2038	3,985	6,045	9,557
2039	4,144	6,408	10,322
2040	4,310	6,728	11,096

Table 11: Development of the global cumulative installed capacity of PV [GW], own scenarios (Fraunhofer ISE)

Technology	Learning rate (LR)	Market scenario	Variation of the LRs	Variation of scenarios
PV rooftop small	15%	Medium scenario	20%, 10%	ISE low, ISE high
PV rooftop large	15%	Medium scenario	20%, 10%	ISE low, ISE high
PV utility-scale	15%	Medium scenario	20%, 10%	ISE low, ISE high
Wind onshore	5%	Onshore wind moderat	8%, 3%	GWEC 450S, GWEC Advanced
Wind offshore	7%	Offshore wind	-	-
CSP	7.5%	IRENA REMap	10%, 4%	SolarPACES 2016, Sarasin 2011
Biogas	-	-	-	-
Solid biomass	-	-	-	-
Lignite	-	-	-	-
Hard coal	-	-	-	-
CCGT	-	-	-	-
Gas turbines	-	-	-	-

Table 12: Overview of LR and market scenarios

Technology	Scenario	Source	2025 [GW]	2040 [GW]	Applied in the calculations
Wind offshore	Offshore Wind	ISE	125	510	X
Wind onshore	Onshore Wind moderat	GWEC 2016, moderate (adjusted by ISE)	1,016	2,767	X
Wind onshore	Onshore Wind advanced	GWEC 2016, advanced (angepasst von ISE)	1,470	4,259	
Wind onshore	IRENA REMap 2021	IRENA REMap, 2021	1,179	3,572	
PV	Low-scenario	ISE	1,485	4,310	
PV	Medium-scenario	ISE	1,618	6,728	X
PV	High-scenario	ISE	1,912	11,096	
CSP	Sarasin 2011	Sarasin Bank, 2011	37	209	
CSP	IRENA REMap 2021	IRENA REMap, 2021	55	342	X
CSP	Moderate policy	SolarPACES, 2016	45	424	

Table 13: Overview of scenarios and development targets for PV, CSP and WPP

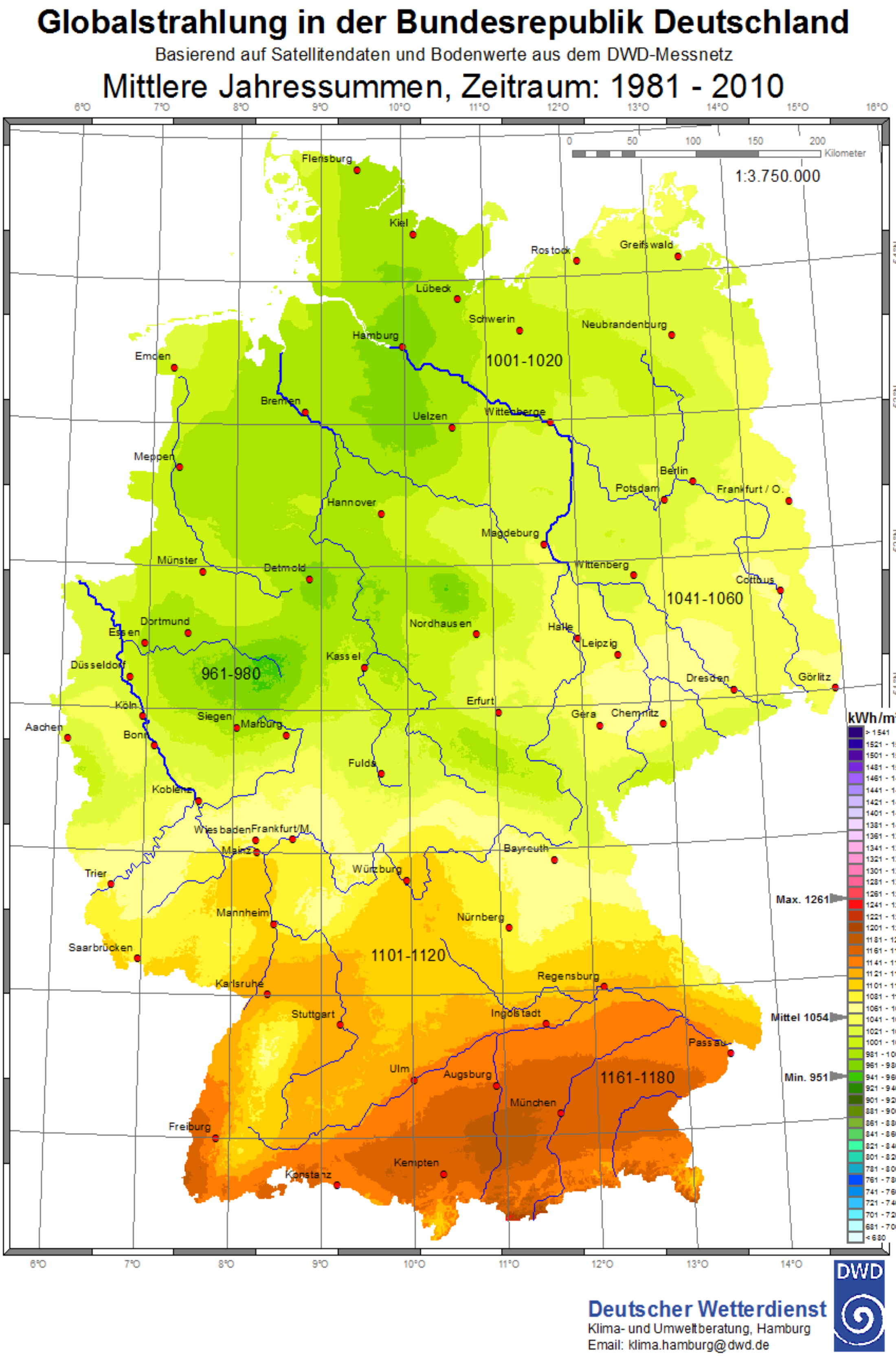

Figure 29: Average annual sum of global irradiation [kWh/m²] in Germany from 1981-2010 (DWD 2013)

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ENERGY SYSTEM ANALYSIS AT THE FRAUNHOFER ISE

In recent years, renewable energy technologies have undergone a vertiginous development: The prices have dropped significantly, while at the same time the installed capacity of renewable energy technologies has increased strongly. Worldwide, renewable energy technologies, especially photovoltaics and wind power have not merely become an important sector of the energy industry but are, through their growth, contributing to major changes in the energy system.

New, interesting questions arise from this change, questions primarily focused on the integration and the interaction of the renewable energy technologies in the system: How can the cost-effective use of renewable energy technologies be achieved in various regions? How can different technologies be combined in order to optimally cover the need for energy? How will the energy system as a whole develop? At what points must this development be supported by the state?
Fraunhofer ISE addresses these questions with a variety of answers in the following focus areas of the division:

- Energy Economics of Energy Systems
- Techno-Economic Assessment of Energy Technologies
- Decarbonization Strategies and Business Models
- Asset Planning and Business Strategies in the Energy Market
- Smart Cities and Sustainable Energy Systems for Cities and Districts
- Assessment of Resources for the Energy Transition

At Fraunhofer ISE, various energy technologies are analyzed from technical and economic viewpoints, for example on the basis of the LCOE. Furthermore, it is possible to optimally design the use of renewable energy technologies for a power plant park, a state or a region by studying the interaction of the components with respect to specific target criteria.

The business area Energy System Analysis studies the transformation of the energy system by very different methodological approaches: On the one hand, a multi-sector target system for a specific CO_2 reduction goal can be identified according to minimum costs to the national economy. On the other hand, investment decision models can be used to show how the system will develop under certain framing conditions and how the interaction of the components in the energy system works. This way, our models can offer a solid foundation for decisions concerning the framing conditions of any future energy supply.

An additional pillar of the business field of Energy System Analysis is the development of business models under consideration of altered framing conditions in different markets. We develop options for a more frequent usage of renewable energy technologies in the future, even in countries where they have not been widely disseminated to date. This way, Fraunhofer ISE offers a comprehensive method of analysis as well as research and studies on technological and economic issues in order to master the challenges presented by a changing energy system.

Further information and persons of contact are available:

www.ise.fraunhofer.de/en/business-areas/power-electronics-grids-and-smart-systems/energy-system-analysis.html

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