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Study

Levelized Cost of Electricity Renewable Energy Technologies

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LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES

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CHRISTOPH KOST
PAUL MÜLLER
JAEL SEPÚLVEDA SCHWEIGER
VERENA FLURI
JESSICA THOMSEN

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

CONTENTS

Contact Person:
Dr. Christoph Kost
christoph.kost@ise.fraunhofer.de

Fraunhofer Institute
for Solar Energy Systems ISE
Heidenhofstraße 2
79110 Freiburg
www.ise.fraunhofer.de

Directors of Institute:
Prof. Dr. Hans-Martin Henning
Prof. Dr. Andreas Bett

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SUMMARY

The present study provides an overview of the current and future levelized cost of electricity (LCOE) for various power generation technologies. It analyzes the LCOE from today, in the year 2024, up to the year 2045. The analysis focuses on renewable energy sources such as photovoltaic (PV), wind energy (WPP), and bioenergy plants in Germany. Additionally, PV battery systems and photovoltaic installations on agricultural land (Agri-PV) are considered, as they represent a growing market in the German power system.

For comparison, the LCOE of these renewable energy technologies are also calculated for newly constructed conventional power plants such as lignite, hard coal, gas and steam turbine power plants (CCGT), gas turbines, and nuclear power plants. Furthermore, for the first time, the costs of gas turbines, gas and steam turbine power plants, and fuel cells operated with green hydrogen are examined. Another part of the study deals with an LCOE analysis of gas turbines that will be converted from natural gas to hydrogen in 2035.

Figure 1 shows the calculated LCOE for renewable and conventional power plants that are potentially built in 2024. The displayed cost ranges reflect the existing range of calculation parameters (e.g., plant prices, solar radiation, wind availability,

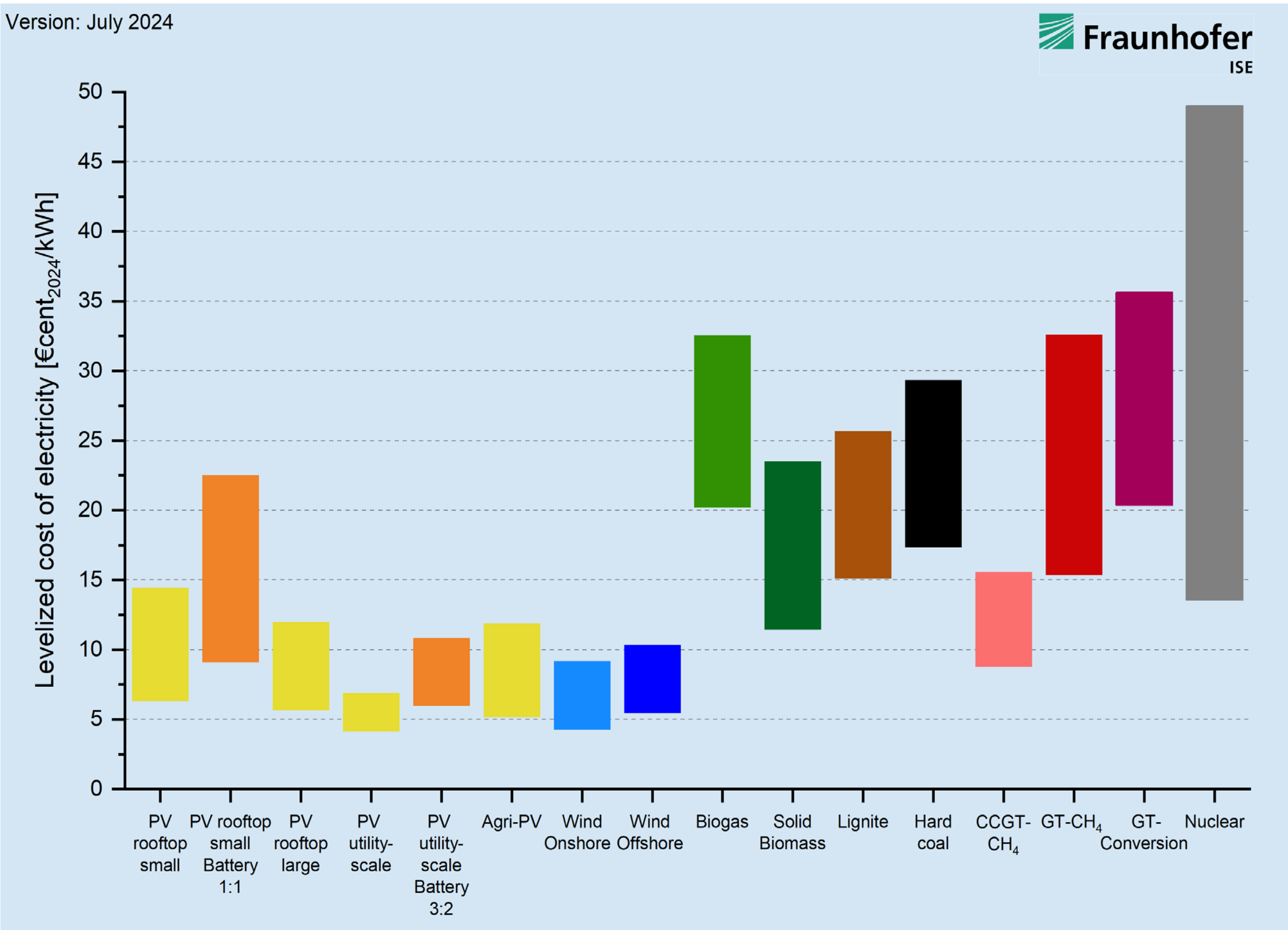

Figure 1: LCOE of renewable energy technologies and conventional power plants at locations in Germany in 2024. Specific investments are considered using a minimum and maximum value for each technology.

number of full load hours, cost of CO_2 emission certificates, etc.), which are described in detail in Tables 1 to 7. This methodology is illustrated using the photovoltaic cost range as an example: The upper limit of the levelized cost of electricity (LCOE) results from the combination of a PV system with a high purchase price at a location with low solar irradiation (e.g., northern Germany). Conversely, the lower limit is defined by the most affordable available systems at locations with high irradiation in southern Germany. This approach is similarly applied to all other technologies using the corresponding reference parameters.

The market-standard financing costs and risk premiums are taken into account in detail and on a technology-specific basis in the LCOE calculations, and they are also listed in tables. The study aims to enable a comparison of power plant locations, technology risks, and cost developments. In this study, all costs and discount rates are calculated using real values (base year 2024). As a result, a direct comparison of the numerical values between this study and previous publications is not permissible. The specific investments for the year 2024 were determined through market research and cost studies. Compared to the previous study, the absolute values have mostly increased due to the high inflation of recent years. Consequently, the LCOE in this version of the study systematically appears higher due to inflation.

The results of the study show that the levelized cost of electricity (LCOE) for PV systems vary between 4.1 and 14.4 €cents/kWh, depending on the type of system and solar irradiation. The study distinguishes between small rooftop PV systems (<30 kW), large rooftop PV systems (>30 kW), ground-mounted PV systems (>1 MW), and Agri-PV (500 kW – 2 MW). The specific system costs currently range between 700 and 2000 EUR/kW$_p$ and have mostly increased, particularly for small systems.

The LCOE for PV battery systems varies between 6.0 and 22.5 €cents/kWh. The wide range is due to the significant cost differences for battery systems (400 to 1000 EUR/kWh) in combination with the cost differences for PV systems and varying levels of solar irradiation. The use of battery storage provides added value by making the generated electricity available at different times of the day.

The LCOE for onshore wind turbines in 2024 is between 4.3 and 9.2 €cents/kWh, based on specific system costs of 1300 to 1900 EUR/kW. As a result, ground-mounted PV systems and onshore wind turbines are the most cost-effective technologies in Germany, not only among renewable energies but also among all types of power plants. Offshore wind turbines, with up to 4500 full load hours, achieve LCOE between 5.5 and 10.3 €cents/kWh. The specific system costs range between 2200 and 3400 EUR/kW, including the connection to the mainland.

For bioenergy, the LCOE is differentiated between biogas and solid biomass, with heat utilization considered, leading to a reduction in LCOE. The LCOE for biogas, with substrate costs of 8.8 €cents/kWh$_{th}$, ranges between 20.2 and 32.5 €cents/kWh. In the case of solid biomass plants, the LCOE is lower, ranging between 11.5 and 23.5 €cents/kWh.

The LCOE for potentially newly constructed coal-fired power plants (hard coal and lignite) exceeds 15 €cents/kWh due to rising CO_2 certificate prices. For a new lignite power plant, the LCOE would currently be between 15.1 and 25.7 €cents/kWh. The LCOE for large hard coal power plants is slightly higher, between 17.3 and 29.3 €cents/kWh. Combined cycle gas turbine (CCGT) power plants have lower LCOE, ranging between 10.9 and 18.1 €cents/kWh. Gas turbine power plants for short-term flexible operation have LCOE between 15.4 and 32.6 € cents/kWh. The CO_2 price plays a crucial role here. While the fuel prices for natural gas, hard coal, and lignite are projected to remain approximately constant due to the anticipated supply and demand situation, the CO_2 price is expected to rise, and the price for green hydrogen is forecasted to fall (see assumption tables). The LCOE for gas turbines built in 2024 and converted from natural gas to hydrogen in 2035 ranges between 20.4 and 35.6 €cents/kWh. The LCOE for newly constructed nuclear power plants ranges between 13.6 and 49.0 €cents/kWh. The wide range of costs is primarily due to the intervals of full load hours and investment costs considered, which are explained in the assumptions. In an energy system with a high share of renewable energies, the LCOE of nuclear power plants would likely be significantly higher than that of natural gas or hydrogen power plants. However, to achieve a complementary operation between renewable power plants and nuclear power plants, the technical flexibility of nuclear power would also be of great importance. This is only partially feasible from a technical and economic perspective. In this study, the follow-up costs of nuclear power and the costs of waste disposal are not included in the LCOE.

Forecast of LCOE in Germany until 2045

Figure 2 shows the results of the calculations for the development of levelized costs of electricity (LCOE) in Germany until 2045. The cost trends for the construction and operation of all technologies are considered. By 2045, the LCOE for small rooftop PV systems will range between 4.9 and 10.4 €cents/kWh, and between 3.1 and 5.0 €cents/kWh for ground-mounted PV systems.

Starting from 2024, the LCOE of all PV systems without battery storage will be below 15 €cents/kWh. The prices for PV systems are expected to decrease by 2045, potentially falling to below 460 EUR/kW for ground-mounted systems and to between 660 and 1306 EUR/kW for small systems. By 2035, electricity generation from a PV-battery system is predicted to be significantly cheaper on average than from a combined cycle gas turbine power plant. By 2045, even small PV-battery systems could achieve LCOE between 7 and 19 €cents/kWh, assuming battery storage prices decrease to the projected range of 180 to 700 EUR/kWh.

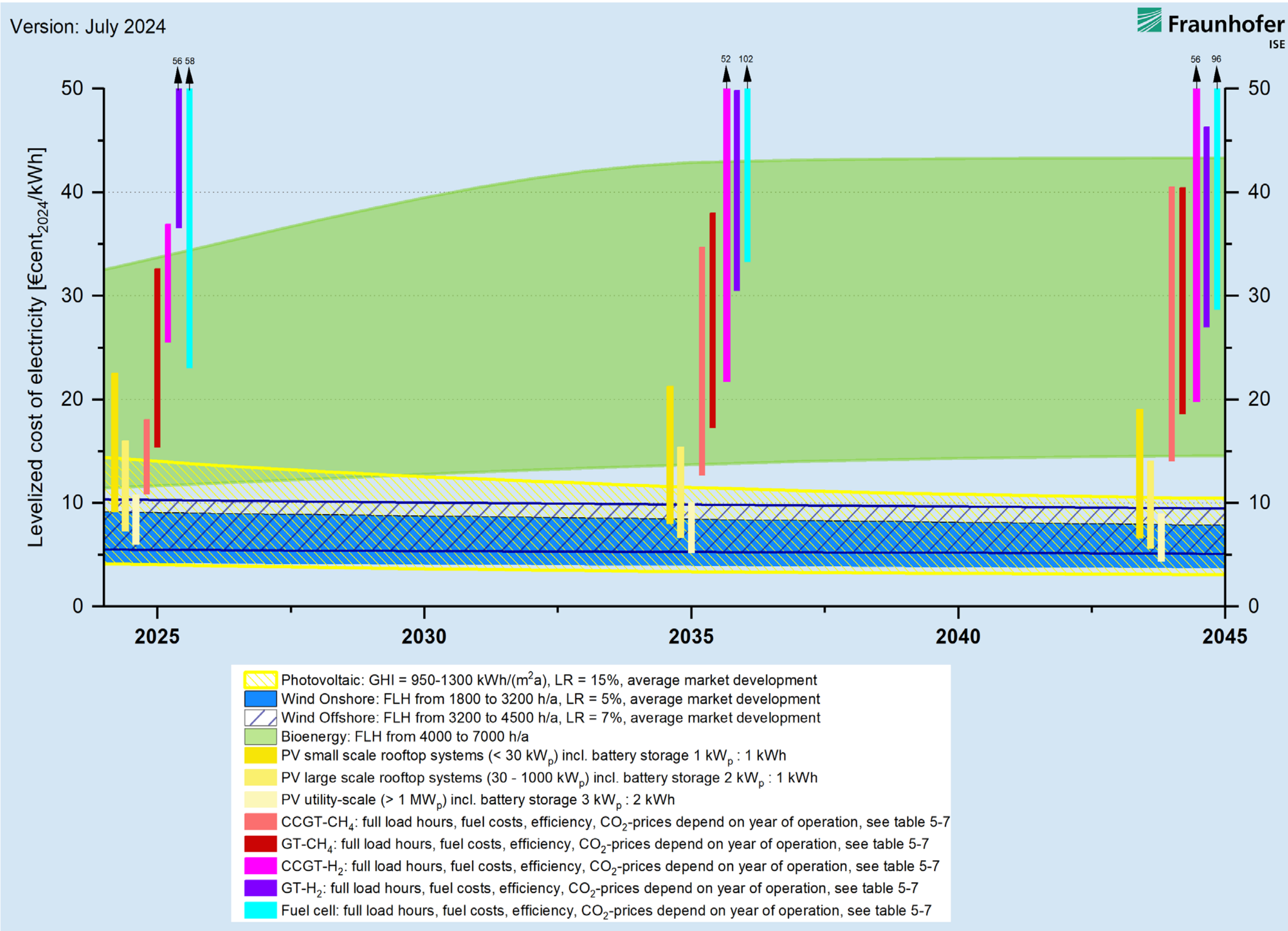

Figure 2: Learning-curve based forecast of the LCOE of renewable energy technologies and gas-fired or hydrogen power plants without heat extraction in Germany until 2045. Calculation parameters are listed in Tables 1 to 6. The LCOE value refers in each case to a new plant in the reference year.

The LCOE for onshore wind turbines is among the lowest of all technologies, along with ground-mounted PV systems. From the current LCOE of 4.3 to 9.2 €cents/kWh, the costs are expected to decrease long-term to 3.9 to 8.3 €cents/kWh. Improvements are mainly anticipated from an increase in full load hours and the development of new sites with specialized low-wind turbines. Offshore wind turbines have a similarly strong potential for cost reduction compared to onshore turbines. By 2045, LCOE is expected to decrease to between 5.5 and 10.2 €cents/kWh, depending on the location and wind availability. For biogas plants and solid biomass plants, only slight cost reductions are expected. This leads, under the assumption of rising substrate prices, to LCOE by 2045 of 25.4 to 43.3 €cents/kWh for biogas and 14.6 to 31.9 €cents/kWh for solid biomass, each considering the revenues from heat generation. For bioenergy, the future development of LCOE is particularly influenced by the availability, heat extraction, and fuel costs of the substrate.The levelized costs of electricity (LCOE) for combined cycle gas turbine plants are projected to increase from 10.9 to 18.0 € cents/kWh in 2024 to between 14.1 and 40.5 € cents/kWh by 2045, driven by rising CO_2 prices and decreasing full load hours over the period from 2024 to 2045. For gas turbines, a similar cost increase is expected, from 15.4 to 32.67 € cents/kWh in 2024 to 18.6 to 40.5 € cents/kWh in 2045. The LCOE for repurposed gas turbines, which will be hydrogen-powered starting in 2035, are comparable to those of conventional gas-fired power plants still running on natural gas. However, there is a notable difference between newly installed hydrogen (H_2) power plants and conventional gas turbines in 2024, with the cost discrepancy narrowing by 2035. In that year, the LCOE for hydrogen power plants are expected to average between 30.5 and 49.8 €cents/kWh. By 2045, these costs are projected to decrease to between 27.0 and 46.3 €cents/kWh.

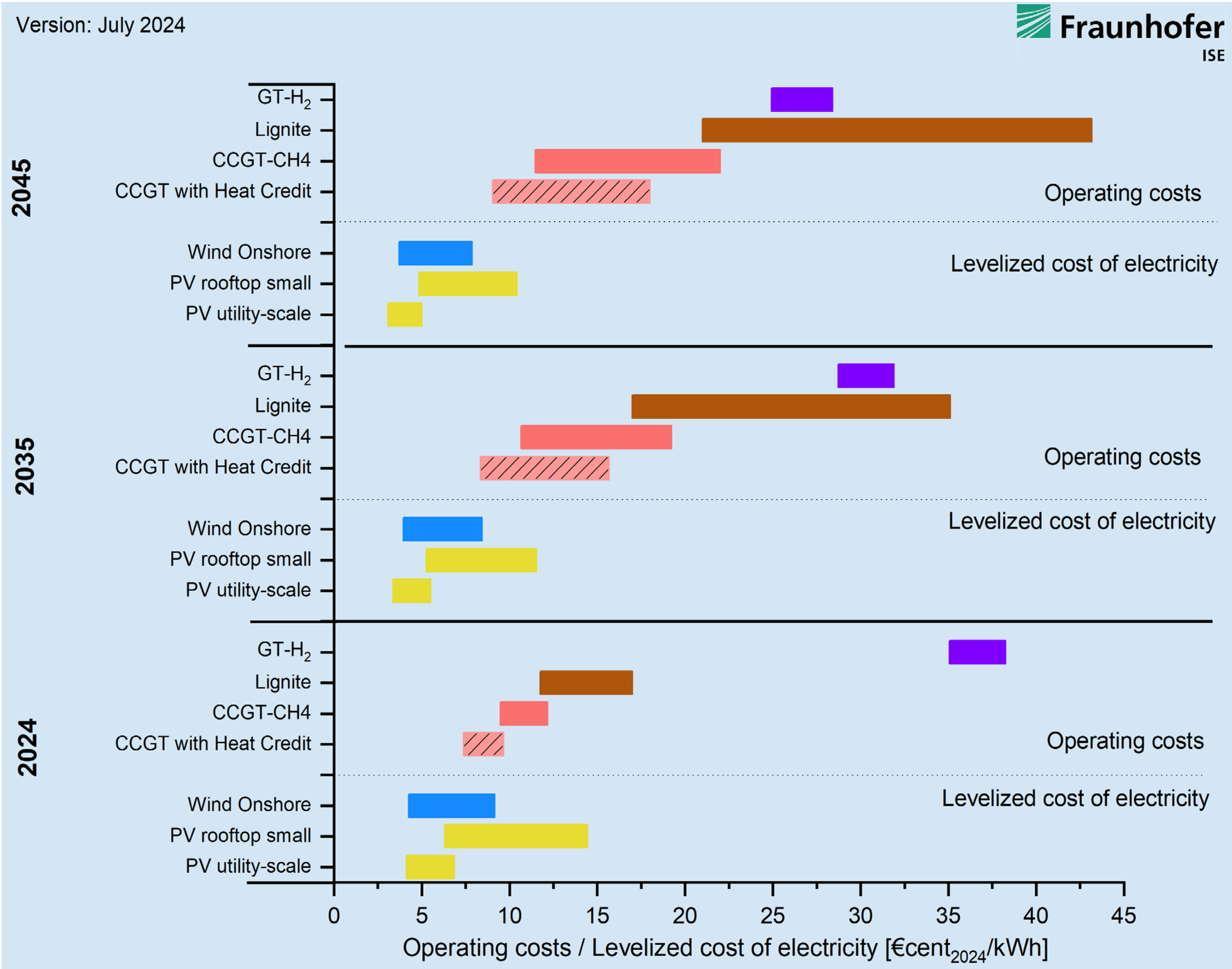

Figure 3: Comparison of LCOE of renewables with operating costs of existing conventional fossil-fuel power plants in 2024, 2035, and 2045

When comparing the LCOE of hydrogen and natural gas CCGT capacities over time and considering the energy sources used, a significant cost divergence is also evident. This is primarily due to the higher fuel prices of hydrogen compared to natural gas. The costs of CO_2 certificates do not influence the pricing in the case of hydrogen. The projected LCOE for 2045 shows that the assumed cost range for hydrogen-powered CCGT plants is between 19.8 and 56.4 €cents/kWh, while for natural gas-powered CCGT plants, the costs range between 14.1 and 40.5 €cents/kWh. The wide range of LCOE for both technologies is partly due to the broad range of CO_2 price assumptions and the increase in full load hours within the forecast period.

For fuel cells, the costs are expected to rise until 2035 due to the transition to green hydrogen, followed by a decrease by 2045, with values ranging between 28.7 and 96.1 €cents/kWh. It is important to note that the LCOE for fuel cells is highly dependent on full load hours. Since a degrading utilization rate was assumed for the lower bound of full load hours, the upper bound for the LCOE is high when directly comparing the technology with others.

In conclusion, a comparison was conducted between the levelized cost of electricity (LCOE) from renewable energy sources and the operating costs of conventional power plants (as shown in Figure 3). This comparison included the operating costs of existing lignite coal-fired power plants and combined cycle gas turbine plants (with and without heat extraction) against the LCOE of new onshore wind farms, small rooftop PV systems, and large ground-mounted PV systems. The results indicate that by 2024, the LCOE of large-scale renewable energy installations will be significantly lower than the operating costs of conventional power plants, especially for onshore wind and ground-mounted PV systems. Only in cases where heat extraction allows the use of heat in district heating networks CCGT can plants still achieve operating costs of 7.4 to 9.7 €cents/kWh. By 2035 and 2045, even the operating costs of CCGT plants with heat extraction will exceed 8 € cents/kWh. CCGT plants without heat extraction are projected to have operating costs above 10 € cents/kWh, and lignite coal-fired power plants are expected to exceed 15 € cents/kWh. Due to the rising CO_2 price dynamics, the LCOE for lignite is expected to more than double by 2045.

1. OBJECTIVE OF THIS ANALYSIS

Decarbonization and the transformation of the energy supply system involve both technical and economic efforts. The costs of electricity generation are a significant cost factor, varying by technology and depending on the construction and operational expenses of each power generation facility. Over the past 15 years, the costs for renewable energy technologies have notably decreased, driven by technological innovations such as the use of cheaper and more efficient materials, reduced material usage, more efficient production processes, improvements in efficiency, and the automated mass production of components.

On the other hand, integrating hydrogen-based power generation technologies to balance the fluctuating supply from renewable sources is becoming increasingly important in the future energy mix. The current edition of this study aims to provide a transparent, forward-looking, and technology-neutral depiction of the levelized costs of electricity (LCOE) for all power generation technologies relevant to the German energy system. In light of the ongoing debate about the economic and system-relevant role of nuclear power, this technology has also been considered. The study also analyzes how the LCOE depends on full load hours, given that a renewable energy-based system requires complementary flexible power plants with low full load hours.

Central contents of this study

- Analysis of the current situation and the future market development of photovoltaic, wind power plants and bioenergy plants in Germany
- Economic modeling of technology-specific LCOE (as of July 2024) for different types of installations and site conditions (e.g. solar irradiation and wind conditions) on the basis of common market financing costs
- Forecast of the future LCOE of renewable energy technologies until 2045 using learning curve models and market growth scenarios
- Forecast of LCOE of existing conventional power plants in 2024, 2035 and 2045, including estimation of future operating costs
- Economic analysis of photovoltaic with battery storage systems
- Assessment of the different technology and financial parameters based on sensitivity analysis of the individual technologies
- 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 (lignite, hard coal, nuclear, combined cycle power plants and gas turbines), as well as flexible power plants and fuel cells operated with hydrogen are considered, 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 Conditions
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 reference year for prices is 2024.

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
Modules based on Crystalline Silicon Solar Cells

- Small rooftop systems (≤ 30 kW_p) – "PV rooftop small"
- Large rooftop systems (> 30 kW_p) – "PV rooftop large"
- Ground-mounted utility-scale power plants (> 1 MW_p) – "PV utility-scale"
- Agri-Photovoltaics (0.5-2 MW_p) –"Agri-PV"

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 kW_p) plus battery – ratio of the power output of the PV system in kW_p to the usable capacity of the battery storage in kWh 1:1 - "PV rooftop small incl. battery 1:1"
- Large rooftop systems (> 30 kW_p) plus battery with PV battery ratio 2:1 – "PV rooftop large incl. battery 2:1"
- Ground-mounted utility-scale power plants (> 1 MW_p) 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

- Onshore (turbine size 2 – 5 MW)
- Offshore (turbine size 6 – 15 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 4000h for onshore WPP and between 4000 and 5000h 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 (Mixedwood)

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

Conventional Power Plants using Fossil Fuels

- 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 (GT, 200 MW)

For comparison, the LCOE of new conventional power plants with price ranges for 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.

Flexible Power Plants using Hydrogen

- Combined Cycle Gas Turbine power plants (CCGT power plants, 500 MW, newly built and converted)

- Gas turbine power plants (GT, 50 - 200 MW, newly built and converted)
- Fuel cells (50 MW)

Gas power plants are also analysed for the use of green hydrogen as a fuel. In the case of retrofitting gas turbines and combined cycle plants, it is assumed that by 2035, a fuel switch from natural gas to hydrogen will occur. This involves an additional investment of 15% of the initial capital expenditure (CAPEX), which is factored into the levelized cost of electricity (LCOE). The fuel-specific cost parameters are adjusted in the year of the conversion to accurately reflect the plant's utilization over its lifetime. For fuel cells, it is also assumed that a switch from natural gas to hydrogen will take place in 2035.

Nuclear Power Plants

- Nuclear power plant (1200 MW)

The analysis is conducted considering representative cost parameters for new power plant constructions within the European economic context and in alignment with the energy policy planning of the German energy system.Costs for the waste disposal are not included.

(Small) hydropower plants and power plants utilizing heat from deep geothermal energy are not considered, as new constructions of these types offer relatively low technical potential or have highly location-specific cost parameters, making the cost assessment within a levelized cost of electricity (LCOE) analysis highly complex.

» Levelized Cost of Electricity: Renewable Energy Technologies « version 2024 - Comparison to the previous studies

The present study is a methodological and content update of the June 2021 (Kost et al. 2021), 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 2024 version.

- Agri-photovoltaic systems, i.e., installations integrated with ongoing agricultural activities beneath them, are included.
- Hydrogen power plants, fuel cells, and nuclear power plants are now also analyzed.
- For dispatchable power plant types, an analysis is conducted based on full-load hours to capture the system effects of flexible power plants with low full-load hours in a renewable energy-based system.
- The development of fuel prices (natural gas, biomass), CO_2 prices, and full-load hours has been adjusted in line with Germany's current targets for a climate-neutral energy system by 2045. Fuel prices and full-load hours have been updated accordingly.
- Due to increased inflation over the past two years, financing costs are higher than in the previous study. CAPEX values have also been adjusted for inflation.

2. HISTORICAL DEVELOPMENT OF RENEWALE ENERGY TECHNOLOGIES

Over the past 20 years, the global market for renewable energy has experienced strong growth (see Figure 4). The increased competitiveness compared to conventional power plants and the international efforts to combat climate change (Paris Agreement) have opened up additional markets and applications for renewable energy. In almost all countries worldwide, renewable energy is among the most cost-effective forms of electricity generation. The investment conditions for renewable energy are very favorable in many countries, as the priority of meeting climate goals has significantly increased. Investments in technologies involving the combustion of fossil fuels are increasingly limited or no longer economically viable.

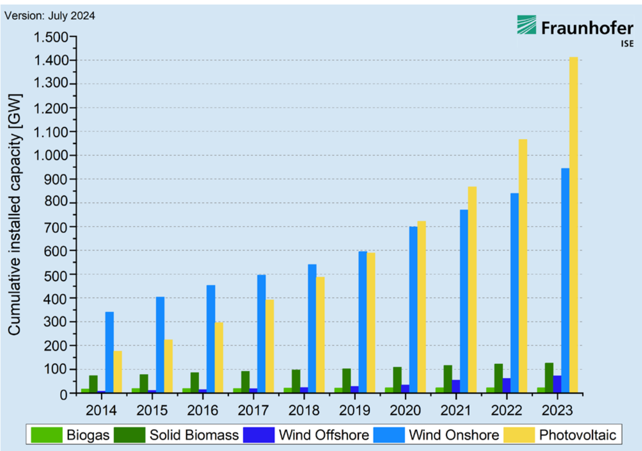

Figure 4: Global cumulative installed capacity 2014-2023 of PV, onshore and offshore wind, biomass plants (IRENA 2024).

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.

By the end of 2023, the globally installed power generation capacity for all renewable energies amounted to nearly 3870 GW, which is about 470 GW more than in 2022 (International Renewable Energy Agency (IRENA) 2024). For comparison, the globally installed capacity of coal and gas power plants in 2022 was 2079 GW and 1800 GW, respectively (Global Energy Monitor 2024), while the installed nuclear power capacity in 2022 was 393.4 GW (Nuclear Energy Institute 2024).

Due to differing cost and market structures, as well as support measures, the markets for individual technologies have developed very differently across countries. The currently installed capacity of wind energy amounts to 1017 GW, with 944.5 GW onshore and 73.6 GW offshore, with new installations in 2023 of about 105 GW and 11 GW, respectively (International Renewable Energy Agency (IRENA) 2024). The globally installed capacity of photovoltaics grew to 1412 GW by the end of 2023, with an addition of 346 GW, surpassing wind power. Since 2016, the annual addition of PV capacity has exceeded that of wind energy. In Germany, the total installed capacity at the end of 2023 was 69 GW for wind energy and 82 GW for PV systems (International Renewable Energy Agency (IRENA) 2024). The global outlook for the wind energy market remains positive. The year 2023 was a record year for electricity generation from wind energy, with approximately 10% of the world's electricity being produced by wind energy systems. In China alone, 75 GW was newly installed. Growth forecasts for wind energy anticipate an annual growth of about 15% in installations over the next five years. This equates to more than 136 GW of new installations annually by 2027 (Global Wind Energy Council 2023; World Wind Energy Association 2024).

The photovoltaic market has become the most significant segment of renewable energy in terms of capacity, driven by the strong expansion of production capacities, particularly in Asia, using highly automated production lines. It is expected that the production capacities and growth of the PV market will continue to expand rapidly. However, the absolute price reductions will be significantly smaller than in the past, as PV modules have already become very affordable, with further cost reductions expected to come primarily from efficiency improvements.

Compared to photovoltaics and wind energy, the expansion of bioenergy plants has been much smaller in scale. The market for biogas plants has grown the most in Germany over the past 10 years, followed by China and Turkey, primarily due to the remuneration policies in these countries. The increase in capacity for solid biomass plants over the last 10 years has been led by China, followed by India, Brazil, and Japan. In Germany, the total installed capacity of bioenergy plants at the end of 2023 was 10.0 GW (International Renewable Energy Agency (IRENA) 2024).

For the forecast of levelized cost of electricity (LCOE) until 2045, this study uses learning curve models to estimate future developments. These learning curve models are based on market scenarios for each technology, with forecasts of future market developments drawn from reference scenarios in various studies (Table 13 in the appendix). The technology-specific market scenarios provide a development horizon for each technology, which will be influenced by numerous technological, energy policy, and economic decision variables over the next twenty years. There is uncertainty regarding the actual market development that can be realized by 2045 for all technologies. Market development in the coming years will largely depend on the implementation of the Paris climate goals. However, the actual market development of each technology is crucial for the timing of cost degression in the learning curve model. Therefore, the LCOE developments presented here are potential development pathways based on current market trends from various scenarios and technology-specific assumptions such as learning rates, as well as location factors like 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 for calculating the Levelized Cost of Electricity (LCOE) and learning rates for estimating future cost developments can be found in the appendix starting on page 40.

For all technologies, an upper and lower price range is determined based on data research, excluding outliers, within which the market-standard costs for the installation of the systems vary. Uniform investment levels are assumed for all locations. In practice, it should be noted that investment costs can be significantly higher in less developed markets or at less developed sites.

Table 1 shows the investment costs in EUR/kW of rated capacity for all the considered technologies, derived from market research on current power plant installations in Germany, as well as from external market studies. The values do not include value-added tax.

In the field of photovoltaics, upper and lower limit values for the installation costs can be determined based on system size for small systems up to 30 kW_p, large rooftop systems above 30 kW_p, and ground-mounted systems above 1000 kW_p. These values are used to calculate the levelized cost of electricity for the investment point or construction of the system. The technical and financial lifespan for PV systems is assumed to be 30 years. Battery storage systems were analyzed in a typical configuration alongside PV systems. While in practice there is a wide range of ratios between PV capacity and battery storage, three currently typical ratios were examined for this analysis. It is assumed that for residential PV storage systems, the PV capacity in kW_p corresponds to a 1:1 ratio with the battery storage capacity in kWh. For rooftop-mounted large systems, a 2:1 ratio is assumed. For ground-mounted systems, a 3:2 ratio is assumed. The costs for battery storage refer to the usable capacity, including installation costs. The lifespan of battery storage systems is assumed to be 15 years. Therefore, after this time, the battery would need to be replaced at reduced costs.

The data for offshore wind energy systems were obtained from ongoing and completed projects in the German North Sea and Baltic Sea. The input parameters for onshore wind energy systems were 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	H2 Gasturbine	H2 CCGT	Fuel cell	Nuclear
Investment 2024 low	1300	2200	2894	3473	1850	1700	900	450	550	1100	5000	6000
Investment 2024 high	1900	3400	5788	5788	2550	2300	1300	700	1200	2400	8000	16000

CAPEX [EUR/kW]	PV rooftop small (<= 30 kW_p)	PV rooftop large (>30 kW_p)	PV utility-scale(> 1 MW_p)	Agri-PV (0.5-2 MW_p)	PV rooftop small incl. battery storage (<= 30 kW_p, PV output to battery capacity 1:1)	PV rooftop large incl. battery storage (> 30 kWp – 1 MW_p, PV-output to battery capacity 2:1)	PV utility-scale incl.battery storage (> 1 MW_p, PV output to battery capacity 3:2)
Unit	[EUR/kW_p]	[EUR/kW_p]	[EUR/kW_p]	[EUR/kW_p]	[EUR/kWh]	[EUR/kWh]	[EUR/kWh]
Investment 2024 low	1000	900	700	900	500	450	400
Investment 2024 high	2000	1600	900	1700	1000	800	600

Table 1: Specific CAPEX in EUR/kW or EUR/kWh for current plants in 2024 (Source: Fraunhofer ISE intern, Lazard 2024)

Currently, there are a wide variety of bioenergy plants operating with different raw materials, technologies, and application areas. In this study, only the generation of electricity from solid biomass and biogas is considered. Electricity generation from biogas plants is calculated based on different substrates typical for agricultural biogas plants. The main substrates used are cattle slurry and silage maize, with silage maize accounted for at a mass-based proportion of 54% (dena - Deutsche Energie-Agentur 2021). The heat generation from biogas plants is an important operational parameter and is included in the calculation of the levelized cost of electricity, considering an internal heat supply of 25% for the biogas plants. In this study, biogas plants with a size of 500 kW_{el} are represented, as the average plant size currently stands at 500 kW_{el} due to earlier EEG regulations (IZES, DBFZ, UFZ 2019). Electricity generation from solid biomass covers a wide range of biogenic fuels and in Germany primarily involves the combustion of wood (waste wood, landscape management wood, forest residue wood, bark, and other industrial wood) (Fachagentur Nachwachsende Rohstoffe e.V. (FNR)). In this study, wood chips with a moisture content of 35% from forest residue wood are assumed as the fuel for biomass plants of 500 kW_{el} or larger. The heat generation from bioenergy plants using solid biomass in the form of heating energy is also specified in the calculation of the levelized cost of electricity. Since combined heat and power (CHP) plants generate both electricity and heat, the total production costs cannot be solely attributed to electricity generation. The heat credit is calculated based on the fuel costs that would have been incurred for heat generation but is instead freely available from the heat produced in the coupled production of the electricity-driven CHP plant.

Since a market ramp-up and thus a cost reduction for fuel cells is expected, declining CAPEX has been applied in the techno-economic parameters of the technology. The lower limit of full-load hours is projected to be 2600 hours per year by 2045, while the upper limit is 6000 hours.

The parameters motivated and discussed below are included in the calculation of the average levelized cost of electricity for the period mid-2024 and future installations (Table 2).

In many studies, identical discount rates are often applied for all technologies and locations under investigation, leading to deviations from the actual levelized cost of electricity. In this study, the discount rates are determined for each technology based on the market-standard capital costs (weighted average cost of capital - WACC) for the respective investment and are composed proportionally of the interest on debt and return on equity. Large power plants, which are constructed and operated by major institutional investors, have a higher weighted average cost of capital (WACC) due to the return on equity demanded by the investor, compared to smaller or medium-sized plants that are built by private individuals or cooperatives. The return on equity required by investors is also higher for technologies with a shorter market history—such as fuel cells—than for more established technologies. It is expected that financing parameters will converge as installed capacity increases, as risk premiums for new technologies decrease with growing experience. The financing parameters have been further analyzed since the last study in 2021 and have been adjusted to reflect the risk and investor structure of each technology. When considering future levelized costs of electricity, it is important to note that

	Wind onshore	Wind offs-hore	Biogas	Solid Biomas-se	Lignite	Hard coal	CCGT	GT	CCGT H2	GT H2	Fuel cell	Nu-clear
Lifetime in years	25	25	25	25	40	30	30	30	30	30	12	45
Share of debt [%]	80	70	80	80	60	60	60	60	60	60	60	60
Share of equity [%]	20	30	20	20	40	40	40	40	40	40	40	40
Interest rate on debt [%]	5.5	7.0	5.5	5.5	7.0	7.0	7.0	7.0	7.0	7.0	8.0	8.0
Return on equity [%]	7.0	10.0	8.0	8.0	11.0	11.0	10.0	10.0	11.3	11.3	12.0	12.0
WACC nominal [%]	5.8	7.9	6.0	6.0	8.6	8.6	8.2	8.2	8.7	8.7	9.6	9.6
WACC real [%]	3.9	6.0	4.2	4.2	6.8	6.8	6.4	6.4	6.9	6.9	7.8	7.8
OPEX fix [EUR/kW]	32	39	4% von CAPEX	4% von CAPEX	42	37	20	23	25	23	30	100
OPEX var [EUR/kWh]	0.007	0.008	0.004	0.004	0.005	0.005	0.005	0.004	0.005	0.005	0.016	0.007
Annual degra-dation	0	0	0	0	0	0	0	0	0	0	0	0

	PV rooftop small (≤ 30 kWp)	PV rooftop large (> 30 kWp)	PV utility-scale (> 1 MWp)	Agri-PV (0,5-2 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	30	15	15	15
Share of debt	80%	80%	80%	80%	80%	80%	80%
Share of equity	20%	20%	20%	20%	20%	20%	20%
Interest rate on debt	5.0%	5.0%	5.0%	5.0%	3.0%	3.0%	3.0%
Return on equity	5.0%	6.5%	6.5%	6.5%	5.0%	6.5%	6.5%
WACC nominal	5.0%	5.3%	5.3%	5.3%	3.4%	3.7%	3.7%
WACC real	3.2%	3.5%	3.5%	3.5%	2.2%	2.5%	2.5%
OPEX fix [EUR/kW]	26	21.5	13.3	13.3	0	4.5-8.0*	5.3-8.0*
OPEX var [EUR/kWh]	0	0	0	0	0	0	0
Annual degradation	0.25%	0.25%	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 1.8% (Source: Fraunhofer ISE intern)
** 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.*

financing conditions (in terms of debt or equity returns) can both increase and decrease. Since the WACC is derived from market-standard interest rates and return expectations, which are given in nominal values, the nominal WACC values are first calculated. This nominal value is then converted into a real value by applying an assumed inflation rate of 1.8% per year. This value has been increased again compared to previous studies because the average inflation rate has risen significantly.

For calculating the levelized cost of electricity, it is crucial that all cash flows are considered either nominally or in real terms. Mixing real and nominal values is incorrect and impermissible. To perform the calculation based on nominal values, the annual inflation rate up to 2045 would first need to be forecasted. Since predicting the inflation rate over long periods is very imprecise and challenging, cost forecasts for long periods are usually done using real values. Therefore, all costs indicated in this study also refer to real values as of 2024. The indication of levelized costs of electricity for future years always refers to new installations in the respective years. For an installed plant, the average levelized costs of electricity remain constant over its lifetime and are therefore identical to the figure given in the year of installation.

A second factor influencing the return on equity is project-specific risk: the higher the default risk, the higher the return on equity demanded by the investor. To keep capital costs low, a high share of low-cost debt capital is desirable. However, this is also limited by project-specific risk: the higher the default risk, the less debt capital banks are willing to provide. Since offshore wind farms still have a higher project-specific risk compared to, for example, onshore wind farms, the average capital costs are correspondingly higher. If sufficient subsidized loans are available—for example, from the KfW banking group—debt capital interest rates of around 5% to 7% can be achieved depending on the technology.

When comparing sites across countries, it is important to note that not only do environmental factors such as solar radiation and wind availability vary, but so do financing conditions. Another factor is the availability of low-interest subsidized loans. Specifically, the location of Germany offers favorable conditions for investments in renewable energy.

Local Conditions

Solar Irradiation and Full-Load Hours (FLH)

The level of electricity yield at the power plant's location is a key parameter with significant influence on the levelized cost of electricity (LCOE) for renewables. In solar technologies, depending on the technology, the amount of diffuse or direct solar radiation plays a role. For wind energy systems, full-load hours can be calculated from the wind availability at the plant's location based on wind speed. In contrast, for biogas and biomass, the number of full-load hours is not dependent on resource availability but is instead determined by factors such as demand, substrate availability, and plant design.

Therefore, exemplary locations with specific energy yields from solar radiation and locations with specific full-load hours for wind energy systems are examined (see Table 3). At typical locations in Germany, global horizontal irradiance (GHI—comprising both diffuse and direct radiation) ranges between 950 and 1300 kWh per square meter per year (horizontal) (Figure 29). This corresponds to solar radiation of 1100 to 1510 kWh/(m²a) on an optimally oriented PV system (both in terms of southward direction and optimal tilt angle). After accounting for losses within the PV plant, this results in an average annual electricity yield between 935 and 1280 kWh per installed kW_p. The full-load hours of the systems decrease accordingly if, for example, the systems are oriented east or west due to roof inclination or if they are mounted at a flatter angle. Both aspects could potentially be optimal from an economic perspective when considering self-consumption of electricity.

Wind availability is also site-dependent. Onshore systems can have full-load hours as low as 1800 hours per year at poor locations. However, at select coastal locations in Germany, full-load hours can reach up to 3200 hours. The average value for onshore wind energy systems built in 2016 is 2721 full-load hours per year (Fraunhofer IWES 2018). A yearly increase of 0.5% in full-load hours is assumed for onshore wind energy systems. Offshore systems achieve significantly higher full-load hours, with values ranging from 3200 hours per year near the coast to up to 4500 hours per year at more distant locations in the North Sea. Due to the higher environmental turbulence in offshore systems during inflow, it is assumed that full-load hours will remain constant despite the trend toward increasingly larger system dimensions (Dr. Martin Dörenkämper 2022).

Biogas plants and facilities using biogenic solid fuels in Germany can easily achieve a utilization rate of 80-90%, which corresponds to over 7000 full-load hours per year. Driven by the flexibility premium introduced by the Renewable Energy Act (EEG), a more flexible operation of plants is increasingly sought, leading to a reduction in full-load hours. The goal of the flexibility premium is to increase the share of flexible electricity production from biogas plants. This helps to balance the supply-dependence of electricity generation from solar and wind. Therefore, a range of 4000 to 6300 full-load hours is considered (DBFZ 2015).

Unlike most renewable energy technologies, the annual electricity generation and thus the number of full-load hours of a fossil power plant depends on factors such as demand, CO_2 costs, and fossil fuel prices, as well as the hourly competitiveness of the technology within the energy system. In 2023, the average full-load hours for lignite plants across all installations were 4366 hours (Burger, Bruno 2024). For hard coal, an average of 2050 hours was achieved in 2023, and for gas-fired com-

PV system (standard modules)	GHI [kWh/(m²a)]	Solar irradiation on PV modules [kWh/(m²a)]	Electricity generation per 1 kW_p with optimal angle of inclination and south orientation [kWh/a]
Northern Germany	950	1100	935
Central and Eastern 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 intern).

Full load hours of conventional power plants [KWh/a]		Lignite	Hard coal	CCGT-CH_4	CCGT-H_2	GT-CH_4	GT-H_2	Fuel Cell	Nuclear	Solid Biomass	Biogas
Year 2024	High	6300	5200	6300	6300	3000	3000	6300	6300	6300	6300
	Low	4300	3000	3000	3000	500	500	3000	4300	4300	4300
Year 2035	High	3650	2650	4500	4500	3000	3000	4500	5000	5000	5000
	Low	1150	1150	1000	1000	500	500	1000	2000	2000	2000
Year 2045	High	1000	1000	2500	2500	2000	2000	4000	4000	4000	4000
	Low	500	500	500	500	500	500	1000	2000	2000	2000

Table 4: Development of full-load hours (FLH) for conventional power plants and bioenergy plants in the system path to climate neutrality (Source: own assumption based on current values in 2024)

bined cycle and turbine systems, the average was 2241 hours (Burger, Bruno 2024). With the increasing share of electricity generation from renewables and rising CO_2 certificate prices, the full-load hours of conventional power plants are expected to steadily decrease. For lignite, hard coal, and gas-fired combined cycle plants, the average full-load hours are expected to fall significantly below 2000 hours per year by 2045. Higher full-load hours can reduce the LCOE of conventional power plants if allowed by market conditions or demand. Conversely, lower full-load hours lead to higher LCOE. The assumptions are based on the political objectives and climate protection targets for the German energy system. The calculation of comprehensive system-level LCOE for a technology requires more detailed analysis than is covered in this study. This would involve examining the use of generation technologies within the context of the specific energy system, including generation, consumption, and transmission structures. The full-load hours, in particular, impact the economic viability of generation technologies and must be considered within the system-specific context.

To conduct a technology-neutral and system-independent assessment within this study, a detailed investigation of the full-load hour dependence of controllable technologies was carried out (see Figure 18). To ensure the general validity of the results, system- and location-specific cost factors were excluded. Therefore, no additional costs for backup power plants, curtailment, or grid expansion associated with the expansion of renewable capacities are included. Likewise, decommissioning costs or the potential disposal of radioactive material are not internalized within the scope of the study.

Fuel Cost

The substrate costs for biogas plants vary significantly. The costs differ due to the options of purchasing substrates or using self-produced substrates by biogas operators. Additionally, the proportions of different substrates vary from plant to plant. For example, a biogas plant with a capacity of 500 kW_{el} uses an average substrate mix of 60% silage maize, 20% cattle slurry/manure, 10% grass silage, and 10% whole crop silage (WCS). The methane yield of the individual substrates varies, ranging from 99 Nm³/t fresh mass (FM) for silage maize to 17 Nm³ for dairy cattle slurry (Fachagentur Nachwachsende Rohstoffe e.V. (FNR)). The costs for these substrates also differ. For instance, the purchase cost of high-quality silage maize is around 34 Euros/t FM (Harms 2023), while cattle and pig slurry cost 11.20 and 13.66 €/m³, respectively (BockholtKarl 2022). For self-produced substrates, the costs can be nearly diminishing. Biogas can achieve a methane yield of 50-75%, corresponding to 9.97 kWh/Nm³ (Fachagentur Nachwachsende Rohstoffe e.V. (FNR)). In this study, average substrate costs of 8.75 €Cent/kWh_{th} for biogas plants are assumed (dena- Deutsche Energie-Agentur 2021). The fuel costs for the combustion of solid biomass also vary depending on the raw material used. In Germany, biomass cogeneration plants are primarily fueled with wood chips from recycled wood, landscape management wood, forest residues, and bark (Fachagentur Nachwachsende Rohstoffe e.V. (FNR)). In this study, wood chips with 35% moisture content are assumed as fuel, costing 2.4 €Cent/kWh_{th} (carmen-ev).

For a comparison of the levelized cost of electricity (LCOE) between renewables and conventional power plants, assumptions regarding efficiency and CO_2 emissions of the power plants are necessary. The assumptions for typical plant sizes are 800 to 1000 MW for lignite, 600 to 800 MW for hard coal, and 400 to 600 MW per site for combined-cycle gas turbine plants, and 200 MW for gas turbine (GT) plants. Through further technical improvements, the net efficiency of new plants increases from 38% to 40% for lignite, from 39% to 41% for hard coal, and from 60% to 62% for CCGT. The price paths for lignite, hard coal, and natural gas are assumed to develop relatively steadily. The price for hydrogen gradually decreases from 150 to 100 €/

MWh by 2045 (Heizkostenvergleich 2024, Fraunhofer ISE a). Due to a potential scarcity of CO_2 certificates, a long-term increase in certificate prices is also assumed (see Table 7). The CO_2 certificate prices and fuel prices are aligned with the goal of greenhouse gas neutrality by 2045. This means that energy-related CO_2 emissions in Germany will approach zero by 2045. The CO_2 certificate price increases to values between 175 and 375 €/t by 2045 due to Germany's climate targets.

Fuel Prices [EUR/MWh]	2024	2030	2035	2040	2045
Lignite	2.3	2.3	2.3	2.3	2.3
Hard Coal	11.6	11.6	11.6	11.6	11.6
Natural Gas	38.0	27.0	27.0	27.0	27.0
Green Hydrogen	150	150	129	111	100
Uranium	8.0	8.0	8.0	8.0	8.0
Substrate Biogas	87.5	99.6	103.3	106.7	110.2
Substrate Solid Biomass	23.8	25.5	26.4	27.3	28.2

Table 5: Assumptions about fuel prices (Hecking et al. 2017; Fraunhofer IEE 2019; IEA 2020; carmen-ev; dena- Deutsche Energie-Agentur 2021; Burger, Bruno 2024)

Efficiency Conventional Power Plants [%]	2024	2035	2045
Lignite - Electrical	38.0	39.0	40.0
Hard Coal - Electrical	39.0	40.0	41.0
CCGT - Electrical	60.0	61.0	62.0
CCGT - Thermal	20.0	20.0	20.0
Nuclear	35.0	35.0	35.0
Fuel cell - Electrical	53.0	53.0	53.0
Fuel cell - Thermal	27.0	27.0	27.0
Biogas - Electrical	40.0	40.0	40.0
Biogas - Thermal	44.0	44.0	44.0
Solid Biomass - Electrical	32.7	32.7	32.7
Solid Biomass - Thermal	52.3	52.3	52.3

Table 6: Efficiency development for large power plants (Wietschel et al. 2010; Fraunhofer IEE 2019; Fachagentur Nachwachsende Rohstoffe e.V. 2014; AG Energiebilanzen e. V. 2023; Lazard 2024, Fraunhofer ISE own assumptions)

CO_2 Certificate Prices [EUR/t CO_2]	2024	2030	2035	2040	2045
Lower value	75	100	125	150	175
Higher Value	90	150	225	300	375

Table 7: CO_2 certificate price (Heizkostenvergleich 2024)

4. LEVELIZED COST OF ELECTRICITY OF ENERGY TECHNOLOGIES IN 2024

In this chapter, the levelized cost of electricity (LCOE) for renewable energy technologies such as PV (photovoltaic), wind, biogas, and solid biomass at locations in Germany is determined based on market data concerning specific investments, operating costs, and other technical and financial parameters. Conventional power plants (lignite, hard coal, nuclear, combined cycle gas turbines, and gas turbines), as well as flexible hydrogen power plants and fuel cells, are also analyzed under various plant configurations and assumptions for construction and operation.

In southern Germany, the LCOE for small PV systems (<30 kW_p) at locations with horizontal global radiation of 1300 kWh/(m²a) ranges between 6.3 and 10.6 €Cent/kWh, while in northern Germany, with radiation of 950 kWh/(m²a), it ranges between 8.7 and 14.4 €Cent/kWh. The results depend on the level of specific investments, which were estimated to range between 1000 and 2000 EUR/kW_p. Larger PV rooftop systems (>30 kW_p) can now produce electricity at LCOE ranging from 5.7 to 8.8 €Cent/kWh in southern Germany and from 7.8 to 12.0 €Cent/kWh in northern Germany, with specific investments between 900 and 1600 EUR/kW_p. Large ground-mounted PV systems (>1 MW_p) currently achieve LCOE values between 4.1 and 5.0 €Cent/kWh in southern Germany and 5.7 to 6.9 €Cent/kWh in northern Germany, as the most cost-effective systems have specific investment costs of 700 EUR/kW

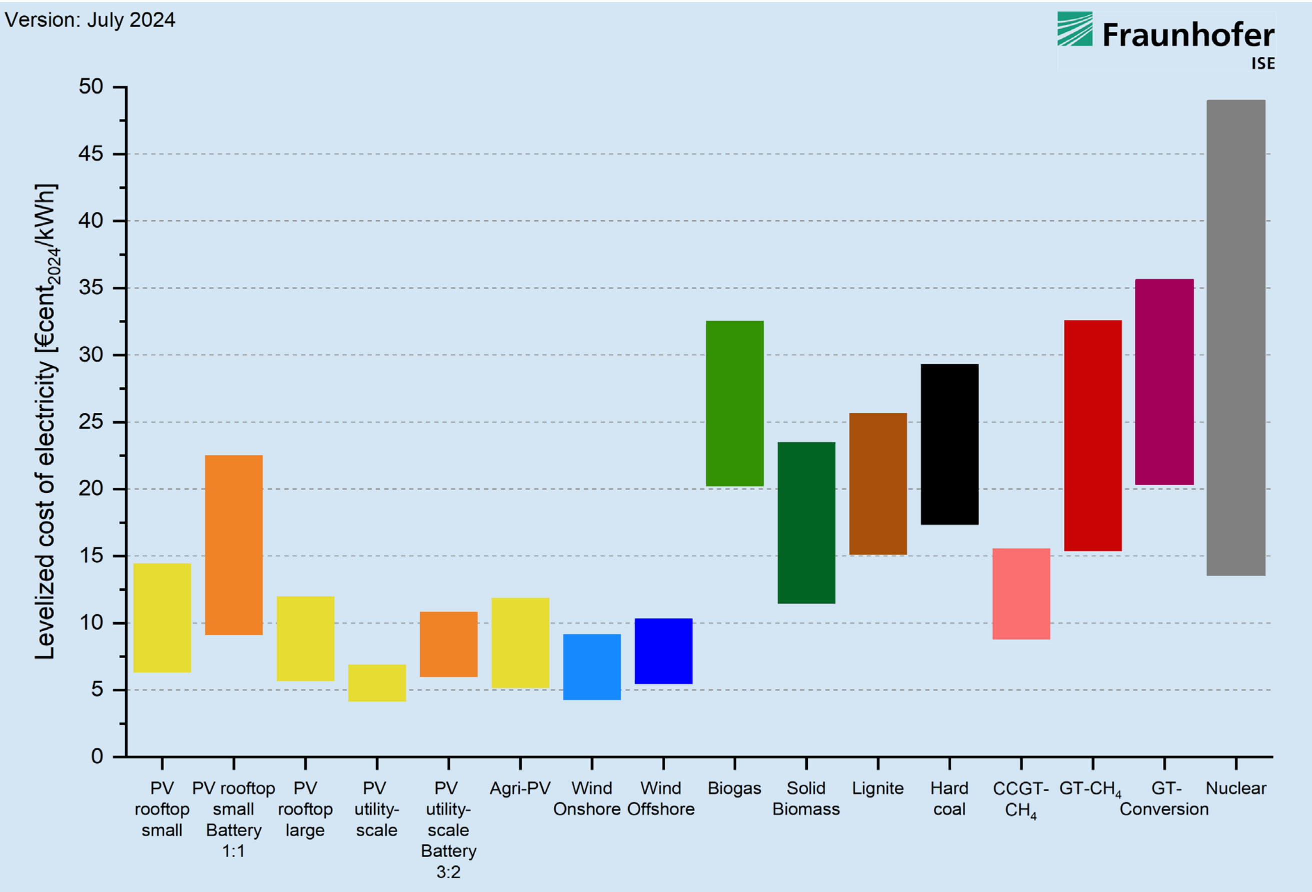

Figure 5: LCOE of renewable energy technologies and conventional power plants at different locations in Germany in 2024. Specific system costs are considered with a minimum and a maximum value per technology. The ratio for PV battery systems expresses PV power output (kW_p) over battery storage capacity (kWh). Further assumptions in Tables 1 to 7.

or 900 EUR/kW, making ground-mounted PV systems the most economical.

Against the backdrop of increasing land-use conflicts between food production and climate policy, agrivoltaics (Agri-PV) offers a promising solution through dual-use and is therefore increasingly in focus. The technical potential in Germany is 2900 GW. A distinction is made between closed PV greenhouses and open Agri-PV systems. This study focuses on open Agri-PV systems, which are further divided into ground-mounted modules used for grassland and arable farming, as well as elevated modules. Medium-high structures up to 2.1 m are also used for arable farming, while high structures (up to 4 m) are suitable for tall-growing fruits and vegetables. The LCOE for Agri-PV systems ranges from 5.2 to 8.7 €Cent/kWh in southern Germany and from 7.1 to 11.9 €Cent/kWh in northern Germany. The specific investments for Agri-PV systems are similar to those for larger PV systems, ranging between 900 and 1700 EUR/kW_p.

The LCOE for PV-battery systems is calculated based on the total energy produced by the PV system, minus storage losses. These losses are derived from the battery storage capacity, the assumed number of cycles, and the battery efficiency. The LCOE for small PV-battery systems ranges from 9.1 to 22.5 €Cent/kWh, depending on differences in PV costs, battery costs (500 to 1200 EUR/kWh), and varying levels of irradiation. For larger PV rooftop systems with battery storage, the LCOE ranges from 7.3 to 16.0 €Cent/kWh, with battery costs of 450 to 800 EUR/kWh. For large ground-mounted PV systems with battery storage, the LCOE is between 6.0 and 10.8 €Cent/kWh, assuming investment costs for the battery storage of 400 to 600 EUR/kWh. The range of investment costs is smaller for larger systems due to increased competition. Onshore wind turbines with average installation costs of about 1600 EUR/kW have LCOE of 4.3 €Cent/kWh at sites with very high annual full-load hours of 3200, but such sites are limited in Germany. Therefore, the costs of systems at less favorable locations vary up to 9.2 €Cent/kWh, again depending on specific investment and annual full-load hours achieved (Table 3). In comparison, the average investment costs for offshore wind turbines are 2800 EUR/kW. Despite higher full-load hours of 3200 to 4500 per year, the LCOE is significantly higher, ranging from 5.5 €Cent/kWh to 10.3 €Cent/kWh.

The LCOE for biogas, assuming substrate costs of 8.8 €Cent/kWh_{th}, ranges between 20.1 and 32.5 €Cent/kWh. For solid biomass plants, the LCOE is slightly lower, between 11.5 and 23.5 €Cent/kWh, mainly due to lower substrate costs of 2.4 €Cent/kWh_{th}. For both biomass and biogas, the LCOE accounts for heat credits, also referred to as revenues from heat generation, meaning that the values provided here only apply to bioenergy with combined heat and power (CHP). Plants without heat extraction have significantly higher LCOE.

For conventional power plants, the current market conditions, including full-load hours and fuel prices per technology, result in the following LCOE: lignite power plants built today can have LCOE ranging from 15.1 to 25.7 €Cent/kWh under the selected operating parameters (with a relatively low current CO_2 price). The LCOE for large hard coal power plants is slightly higher, ranging between 17.3 and 29.3 €Cent/kWh. CCGT plants today achieve LCOE values between 10.9 and 18.1 €Cent/kWh. The LCOE for flexible gas power plants is significantly higher, ranging from 15.4 to 32.6 €Cent/kWh.

The LCOE for nuclear power, by comparison, ranges from 13.6 to 49.0 €Cent/kWh. It is important to note that externalized costs, such as the disposal of spent fuel rods, are not included. If a switch from natural gas to hydrogen is considered for the gas turbine in 2035, the LCOE for the installation year 2024 ranges from 20.4 to 35.6 €Cent/kWh. As of 2024, fuel cells have LCOE ranging from 23.1 to 59.0 €Cent/kWh.

It is important to consider that the LCOE calculation does not account for the potential flexibility of a generation technology or the value of the generated electricity. For example, seasonal and day-specific generation differs greatly between technologies. Differences due to the flexible use of power plants or the provision of system services regarding the achieved market sale price of electricity are not considered in the LCOE (see Chapter 7).

Photovoltaics

Market development and forecast

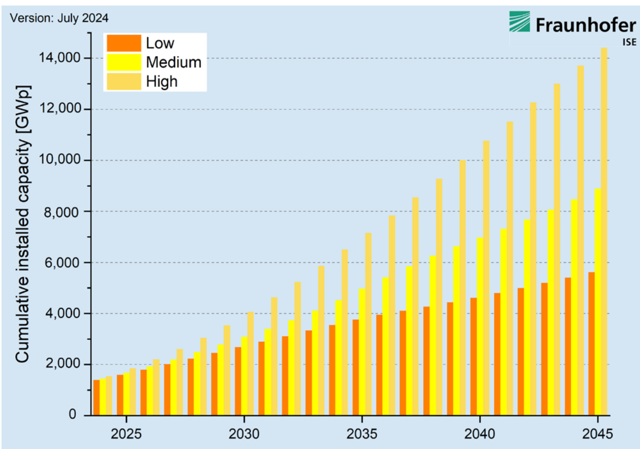

Figure 6: Scenarios for the market development of the cumulative installed power plant capacity [GW] for PV until 2045, own scenarios.

At the end of 2023, the globally installed PV capacity exceeded 1400 GW_p, with global additions in 2023 reaching approximately 413 GW_p. This represents a market growth of 58% compared to 2022, when around 252 GW_p were installed (John Fitzgerald Weaver 2023; International Renewable Energy Agency (IRENA)). The global PV market is currently dominated by China, both in production and installation. However, more and more countries are installing PV on a significant scale, as PV systems increasingly succeed in free market competition, allowing them to be implemented independently of subsidy programs. As a result, PV market growth is increasingly driven by purely economic factors.

Therefore, it is expected that the global PV demand market will continue to grow strongly. The three scenarios underlying the study — "High," "Medium," and "Low" — all assume a gradual reduction in annual market growth. The assumed market growth for 2024 of 24%, 20%, and 18% for the "High," "Medium," and "Low" scenarios, respectively, tapers off to 5% (High, Medium) or 4% (Low) by 2045. For the year 2045, the scenarios result in total capacities of 14400 GW, 8900 GW, and 5600 GW. The scenarios for cumulative installed power capacity are listed 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 (kW_p) 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 2021, wholesale prices for crystalline modules in Germany have fallen significantly from 310 EUR/kW_p to 270 EUR/kW_p in 2023. The lowest net price for crystalline modules in the fourth quarter of 2023 was 270 EUR/kW_p. There remains a price difference between Chinese and German manufacturers: In 2022, Chinese manufacturers were able to offer their modules on average 40 EUR/kW_p cheaper than German manufacturers. This gap remained at 40 EUR/kW_p in 2023 (EuPD Research - Christoph Suwandy).

The costs for inverters and Balance-of-System (BOS) components, such as mounting systems and cables, as well as their installation, also decreased, though not to the same extent as PV modules. While in 2005 the cost share of solar modules accounted for almost 75% of system costs, today, even for rooftop systems, this share is below 30%.

Figure 7 illustrates cost bands for PV systems of different sizes. The costs for a small PV system (up to 30 kW_p) currently range between 1000 and 2000 EUR/kW_p. For larger PV systems over 30 kW_p, the costs currently range between 900 and 1600 EUR/kW_p. Large ground-mounted PV systems with capacities starting from 1 MW_p have investment costs between 700 and 900 EUR/kW_p, while Agri-PV systems with capacities ranging from 500 kW_p to 2 MW_p, the costs are between 900 and 1700 EUR/kW_p. It should be noted that Agri-PV systems can have a nominal capacity of several hundred megawatts. Consequently, the investment costs for larger installations are lower.

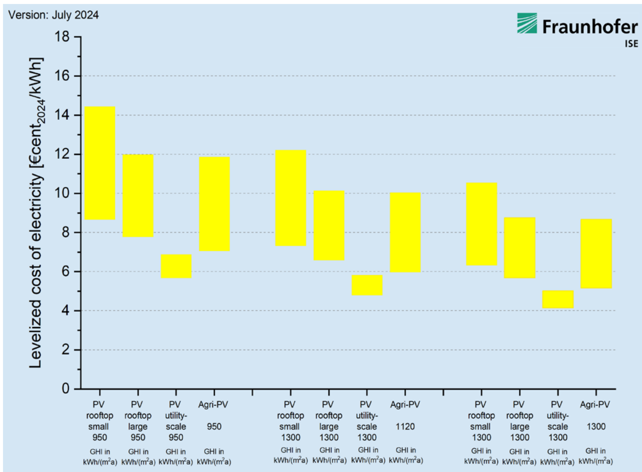

Figure 7: LCOE of PV systems in Germany based on system type and solar irradiation (GHI in kWh/(m²a)) in 2024.

These values include all costs associated with the components and installation of the PV system. In some cases, under specific purchasing conditions, systems can even be realized below the mentioned price ranges. Compared to the last study in 2021, significantly broader ranges for specific investments are given for rooftop PV systems. This is due to market developments where factors such as location, system design, and roof and building conditions strongly influence system prices, leading to greater variability in specific costs.

The current values of PV electricity generation costs for various system sizes and costs under different irradiation levels are shown in Figure 7 (referencing Table 3). The number following the system size indicates the annual irradiation at the system's location. Optimally oriented systems in the north produce about 935 kWh/a, while systems in southern Germany can yield up to 1280 kWh/a.

The price reduction in system investments has led to continued very low PV electricity generation costs. Ground-mounted PV systems in northern Germany can already achieve electricity generation costs below 7.0 €Cent/kWh, while in southern Germany, these costs are below 4.2 €Cent/kWh. The electricity generation costs for Agri-PV systems range between 5.2 and 11.9 €Cent/kWh, making them higher. Large rooftop PV systems can have electricity generation costs ranging from 12.0 €Cent/kWh in northern Germany to 5.7 €Cent/kWh in southern Germany. Small rooftop PV systems in Germany generate electricity at costs between 6.3 and 14.4 €Cent/kWh, significantly below the average household electricity costs. Since photovoltaic technology still has substantial cost reduction potential across the entire value chain and in all components, it is expected that system costs will continue to decline in the medium to long term—barring any price fluctuations due to specific market events. Based on current market developments and the warranties offered by most module manufacturers, the lifespan of PV modules in this study is set at 30 years.

A sensitivity analysis for a small PV system in Germany shows a strong dependence of electricity generation costs on irradiation and specific investments (see Figure 8). The lifespan of the systems has a significant impact on electricity generation costs, as systems that have already been depreciated can continue to produce electricity at very low operating costs over a longer lifespan. In contrast, slightly varying operating costs and the capital costs of the investment (WACC) have a minor impact on the electricity generation costs of PV systems.

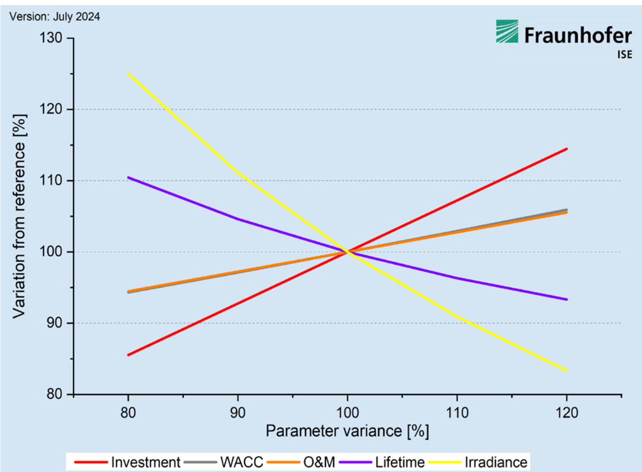

Figure 8: Sensitivity analysis for small PV system under the conditions of horizontal global radiation of 1120 kWh/(m²a) and an average investment cost of 1500 EUR/kW

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 kW_p 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. The number of PV systems installed with battery storage has significantly risen, with nearly 80% of PV systems under 30 kW_p now equipped with battery storage.

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 hoped for 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.

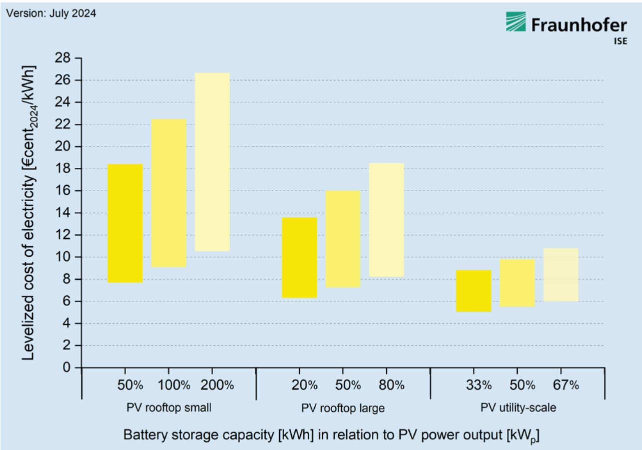

Figure 9: LCOE for PV battery systems as a function of the ratio of PV power output to battery capacity.

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 rising battery capacities, since a larger battery means higher investment costs at constant or even slightly decreasing electricity generation due to battery losses. The bandwidth broadens with increasing battery capacity, since this means that a rising 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.

For a PV-battery ratio of 1:1 (100% in the graph), the LCOE for small PV-battery systems ranges between 9.1 and 22.5 €cents/kWh. With a halved battery storage size (50%), the LCOE decreases to 7.7 to 18.4 €cents/kWh. With larger battery storage capacity, the LCOE increases to 10.5 to 26.7 €cents/kWh. For large rooftop PV systems with battery storage, where a wide range of system configurations are practically implemented, the LCOE ranges from 7.3 to 16.0 €cents/kWh with a PV-battery ratio of 2:1 (50% in the graph). The LCOE drops to 6.3 to 13.6 €cents/kWh for a small battery storage size (capacity is 20% of the PV system's power output) and rises to 8.2 to 18.5 €cents/kWh for a larger battery storage size (80%). For large-scale storage, a PV-battery ratio of 3:2 was assumed (67%), where two smaller battery storage sizes were analyzed. The LCOE can decrease from 6.0 to 10.8 €cents/kWh to 5.5 to 9.8 €cents/kWh (50%) or 5.1 to 8.8 €cents/kWh (33%).

The sensitivity analysis for the LCOE of PV battery systems, similar to the analysis for PV systems, shows a strong dependence on irradiation and thus on PV electricity generation. Investment costs also have a significant impact, with PV investments having a greater influence than battery investments due to their larger absolute values (1500 EUR/kW$_p$ compared to 750 EUR/kWh). The influence of the weighted average cost of capital (WACC) on LCOE may also be higher than presented here due to large differences in absolute values, similar to PV systems. The efficiency and the number of full-load cycles of the battery storage have a lesser impact.

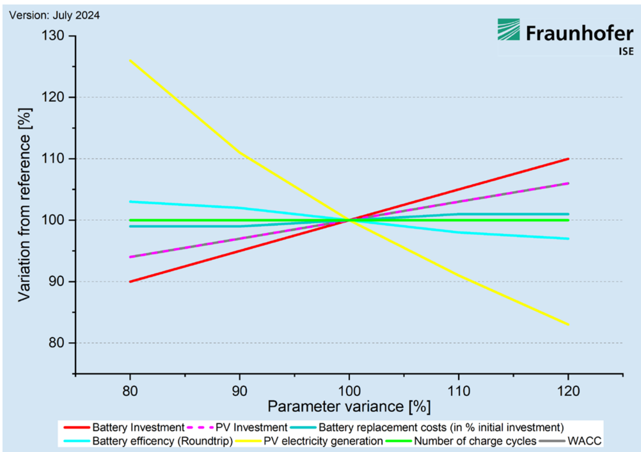

Figure 10: Sensitivity analysis for rooftop small-scale PV system with battery system assuming a GHI of 1120 kWh/(m²a), PV investment of 1500 EUR/kW, battery investment of 750 EUR/kWh, and battery replacement cost of 45% of initial investment.

A large proportion of today's installed stationary battery storage is based on lithium-ion technology. The worldwide cumulative capacity of lithium-ion batteries is estimated to be around 700 GWh in 2022 (Fleischmann et al. 2023). However, electric vehicles had the largest share of this and also the highest annual growth. As a result, the prices for stationary battery storage are strongly influenced by the vehicle market. Consumer electronics also have a significant market share but are experiencing slower growth. Stationary energy storage accounted for about 5% of the total market. Strong further growth is also expected for all three application areas – residential PV storage, commercial and industrial storage, and large-scale storage in Germany. Therefore, price reductions are driven by both a growing global market and increasing installation numbers in Germany.

Wind Power Plants (WPP)

Among renewable energy sources, wind power has long demonstrated high competitiveness compared to conventional power generation, leading to significant global market penetration. The four most important markets for new installations in 2022 were China, the USA, Brazil, and Germany, which together accounted for 69 percent of global installations. However, most regions have markets for wind energy installations with steady growth (Global Wind Energy Council 2023; World Wind Energy Association 2023). By the end of 2023, the global total capacity of all installed wind turbines reached 1017 GW. The market has shown continuous growth up to 2023. From 2023 to 2027, it is expected that 680 GW of wind energy will be newly installed, including 130 GW of offshore wind turbines. By 2030, two terawatts of installed capacity are anticipated (Global Wind Energy Council 2023; International Renewable Energy Agency (IRENA) 2024). The total capacity of onshore wind energy is expected to reach approximately 1500 GW by 2030 (Global Wind Energy Council 2023). For offshore wind energy, a global capacity of 500 GW is projected by 2030, and nearly 2000 GW by 2050 (World Forum Offshore Wind e.V. 2023; Global Wind Energy Council 2023). In Germany, wind power accounted for 26% of total electricity generation in 2022, of which 19.9% was from onshore wind turbines.

Within renewable electricity generation, wind power remained dominant in 2022 with a 50.5% share (Fraunhofer ISE 2024). 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 full-load hours. 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 full-load hours. Thanks to ongoing technical refinement, an increase in full-load hours can be expected for future power plants and thus an annual increase in the full-load hours 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 full-load hours. As shown in Figure 12, the LCOE for onshore wind turbines at coastal high-wind locations with 3200 full-load hours ranges between 4.3 and 5.5 €cents/kWh. Locations with weaker wind resources achieve LCOE between 7.1 and 9.2 €cents/kWh, depending on specific investments. If 2500 full-load hours can be achieved at the site, LCOE ranges from 5.3 to 6.8 €cents/kWh, which is lower than the LCOE of new coal-fired power plants. Compared to the costs in previous studies, a systematic increase in LCOE in Germany is observed in 2024, mainly due to rising inflation.

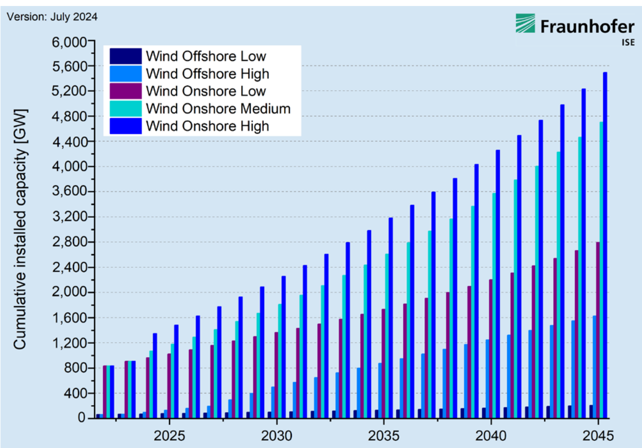

Figure 11: Market forecasts of cumulative wind power according to (GWEC 2016; RENA 2021; Global Wind Energy Council 2023; GWEC 2016a).

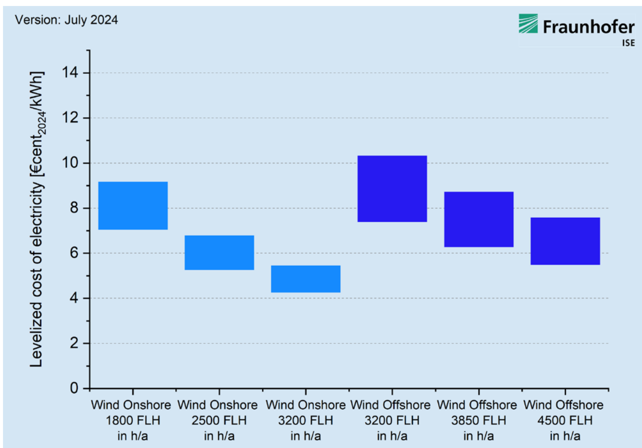

Figure 12: LCOE for wind turbines by location and full-load hours in 2024.

In contrast, the analysis of current offshore wind turbines shows that even at locations with higher full-load hours (up to 4500 full-load hours), LCOE remains higher than for onshore turbines. This is due to the need for more durable, expensive materials, complex seabed anchoring, costly installation and logistics of components, and higher maintenance requirements. However, in the future, cost reductions are expected due to learning effects, more reliable turbines, and lower maintenance costs. Currently, offshore wind turbines at very good sites achieve LCOE between 5.5 and 7.6 €cents/kWh. These often distant offshore locations face the challenge of expensive grid connections and the need to bridge greater water depths; sites with fewer full-load hours (3200 h) achieve LCOE between 7.4 and 10.3 €cents/kWh. As a result, offshore wind turbines generally have higher LCOE than onshore turbines, except for offshore sites with very high wind speeds where LCOE can be comparable to onshore wind turbines. The advantage of offshore installations lies in the higher number of full-load hours, lower noise pollution, and higher public acceptance, provided minimum distances from the coast and environmental protection regulations are met. Technology-specific risks lead to higher capital costs and security requirements from lenders, resulting in higher WACC for offshore projects compared to onshore wind farms. Although there is significant potential for cost reductions in offshore wind turbines, achieving a level comparable to onshore wind turbines remains challenging due to the higher installation and maintenance efforts. However, recent years have shown that the costs of projects are decreasing faster than expected in previous studies, as seen in new offshore wind farms such as OWP Arcadis Ost 1, Baltic Eagle, Gode Wind 3, and Borkum Riffgrund 3, which all have specific installation costs of less than 4,000 €/kW, significantly lower than earlier projects reported in previous studies. Additionally, offshore installations benefit from being able to feed electricity into the grid when other renewable energy sources are not generating. This will offer an economic advantage in the coming years.

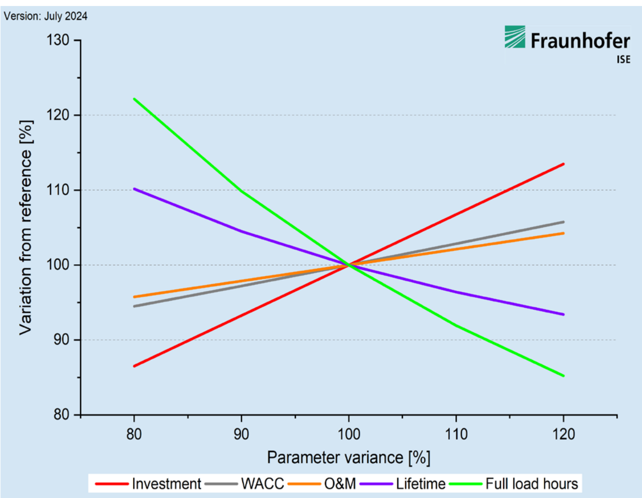

Figure 13: Sensitivity analysis of onshore wind power plants with 2500 FLH, specific investment of 1600 EUR/kW.

The sensitivity analysis for onshore wind turbines identifies investment cost reductions as the primary target for future cost reduction potential. Like in PV systems, the sensitivity analysis shows strong responsiveness not only to investment costs but also to site selection. Moreover, extending the lifespan of wind turbines can also play a crucial role.

Bioenergy Plants

The market for biogas plants has been characterized by numerous ups and downs. While approximately 300 MW were added annually in Germany between 2016 and 2020, the installed capacity has stagnated at a total of 5.9 GW since 2021 (Fachverband Biogas 2023). Despite the increase in biogas plant capacity in Germany, there has been no significant reduction in specific investment costs in recent years. Therefore, no learning rate is applied to biogas plants. The use of solid biomass for electricity generation experienced dynamic growth, particularly after the introduction of the EEG (Renewable Energy Act). However, the number of newly commissioned bioenergy plants using solid biomass has only slightly increased since 2020 (Fraunhofer IEE 2019). The installed capacity of biogenic solid fuels for electricity generation amounted to around 1.5 GW by the end of 2023 (AGEE-Stat 2021). Similar to biogas plants, no learning rate is applied to solid biomass plants. The heat extraction from bioenergy plants is accounted for and factored into the levelized cost of electricity (LCOE) with an appropriate heat credit.

Figure 14 shows the LCOE of large solid biomass plants and biogas plants (>500 kW_{el}) for different full-load hours with and without considering heat extraction. To represent the growing need for flexibility in a renewable energy-based system, the annual full-load hours decrease as the plant ages. Specific investments ranging between 2900 and 5800 €/kW for both biogas and solid biomass plants are included in the calculation. Accounting for heat extraction and thus applying a heat credit results in a significant reduction in LCOE. For biogas plants with high full-load hours and low specific investments, the LCOE considering heat extraction, with an internal heat demand of 25%, is 16.5 €cents/kWh. Without heat extraction, the LCOE for biogas plants is considerably higher at 27.9 €cents/kWh. The LCOE for biogas plants with low full-load hours and high specific investments is 23.3 €cents/kWh with heat extraction and 34.8 €cents/kWh without. For solid biomass plants with high full-load hours and low specific investments, the LCOE is 12.6 €cents/kWh with heat extraction and 17.1 €cents/kWh without. For plants with low full-load hours and high specific investments, the LCOE is significantly higher at 16.0 €cents/kWh with heat extraction and 20.4 €cents/kWh without.

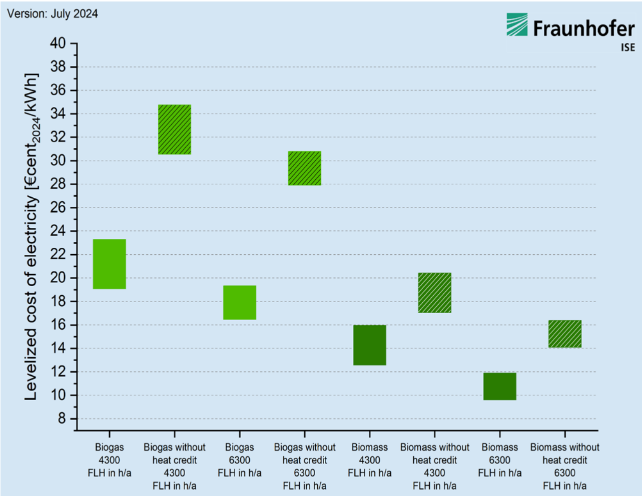

Figure 14: LCOE of biomass and biogas power plants with and without heat utilization at different full-load hours in 2024.

The sensitivity analysis of biogas plants in Figure 15 indicates that substrate costs and full-load hours have a major impact on LCOE. The LCOE decreases by 8.2 €cents/kWh compared to the reference case when full-load hours are increased by 20%. In comparison, the LCOE decreases by 9.6 €cents/kWh when substrate costs are reduced by 20%. This suggests that using only manure and agricultural residues as substrates can further lower the LCOE of biogas plants. Changes in investment costs and plant lifespan have a similarly significant effect on LCOE. Changes in operating costs and WACC have a lesser impact.

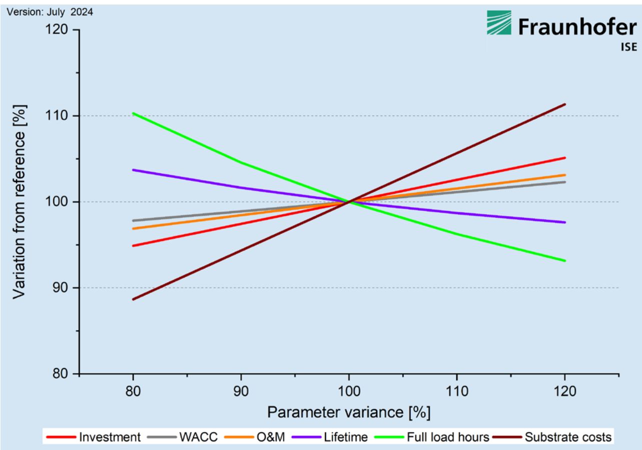

Figure 15: Sensitivity analysis for biogas power plants with specific investment of 4300 EUR/kW and 6000 full-load hours.

Figure 16 shows that for bioenergy plants using solid biomass, full-load hours and substrate costs notably influence LCOE. A 20% reduction in full-load hours leads to an LCOE increase of 1.8 €cents/kWh. Similarly, a 20% reduction in substrate costs results in a 1.4 €cents/kWh increase in LCOE. Investment costs and lifespan also have an impact. Reducing investment costs by 20% decreases LCOE by 1.0 €cents/kWh. Variations in WACC and operating costs have the least effect on LCOE.

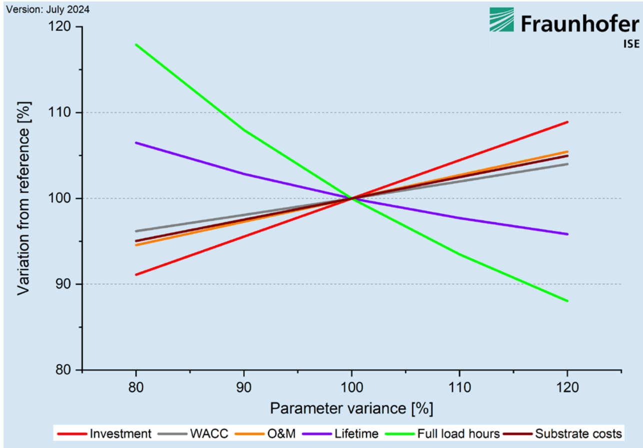

Figure 16: Sensitivity analysis for biomass power plants with specific investment of 4600 EUR/kW and 6000 full-load hours

Conventional Power Plants

Market Development and Forecast

In 2022, coal power plants accounted for about 24.5% of the global installed capacity at approximately 2079 GW (Global Energy Monitor 2024; Statista 2024). Consequently, coal plants produce the largest share of electricity worldwide at 35.6% (Ember 2024). China alone is responsible for about 50% of global coal consumption for electricity. The second-largest market is India, followed by the USA (IEA - International Energy Agency). In 2012, lignite accounted for 30% of Germany's net electricity generation, and hard coal 22% (BNetzA 2018). By 2023, lignite's share had dropped to 18.0% and hard coal's to about 7.8%. The installed capacity of lignite and hard coal plants has slightly decreased in recent years to 18.5 and 18.9 GW (Burger, Bruno 2024). According to the Coal Phase-Out Act (KVBG), Germany will exit coal-fired power generation by 2038.

In 2022, approximately 1800 GW of gas power capacity was installed worldwide (Boom and Bust Gas 2022). Gas plants are the second-largest source of global electricity generation after coal, with 22.5% of production. Gas-fired power plants generated 6444 TWh of electricity (Ember 2024). Over half of all gas plants are installed in OECD countries, with the USA accounting for 33% of the global capacity, followed by Europe (12%) and OECD Asia (4%). In non-OECD countries, Russia has the largest installed capacity at 5.8%, followed closely by China at 5.7% (Ember 2024). In 2023, gas power plants contributed about 10.3% to Germany's net electricity generation. Since 2002, Germany's installed gas capacity has grown from 20.3 GW to 35.99 GW (Burger, Bruno 2024). The grid development plan predicts an increase in installed gas capacity to 37.8 GW by 2030 (50Hertz Transmission GmbH et al. 2017).

Currently, there is no energy-economic provision of electricity through hydrogen-powered gas turbines and combined-cycle gas turbines in Germany. However, this is set to change as part of the federal government's power plant strategy by the late 2030s. According to the strategy, up to four 2.5 GW "H2-ready" capacities will initially be auctioned, which will gradually transition to full hydrogen use instead of natural gas between 2035 and 2040 (BMWK 2024). To integrate hydrogen plants competitively into the existing power system, they are planned to be embedded in a capacity market. Additionally, the goal is to install so-called hydrogen sprint plants and hybrid plant capacities. The latter concept involves developing and testing the entire hydrogen chain, from variable renewable electricity generation to electrolysis, storage, and re-electrification (BMWK 2024). The final version of the power plant strategy is expected to be approved by the federal cabinet shortly.

The global installed capacity of nuclear power was about 393.4 GW in 2022 (Nuclear Energy Institute 2024). The largest capacity is in the USA with 92 nuclear plants (24.1%), followed by France (15.6%), China (13.3%), Japan (8.1%), and Russia (7.1%). Nuclear plants currently account for the fourth-largest share of global electricity production at 9.2% (Ember, 2024). Nuclear capacity has stagnated since 2010. In 2022, Germany had an installed nuclear capacity of 4.1 GW, contributing 6.7% to net electricity generation (Burger, Bruno 2024). On April 15, 2023, Germany shut down its remaining three nuclear plants, completing its planned nuclear phase-out.

Price and Cost Development

The LCOE of fossil fuel plants is highly dependent on achievable full-load hours. In 2023, the average full-load hours for lignite were 4366 hours, 2050 hours for hard coal, and 2241 hours for gas-powered CCGTs and gas turbines (Burger, Bruno 2024). The full-load hours a plant can achieve are determined not only by technical restrictions but also by variable marginal costs, as plant dispatch is determined by the merit order. Therefore, the development of full-load hours primarily depends on forecasts for fuel and CO_2 certificate prices, the growth of renewable power generation, and the composition of the power plant fleet.

Figure 17 shows the LCOE for 2024 for lignite, hard coal, gas CCGTs, nuclear plants, and fuel cells, each based on the assumptions set out. For technologies that can technically and economically utilize heat extraction, the LCOE is also displayed with consideration of heat revenue. In addition to conventional gas power plants running on natural gas, the exclusive use of hydrogen is considered, as well as a mid-lifecycle conversion from natural gas to hydrogen. Figure 18 analyzes these technologies across different full-load hours to demonstrate the full range of applications. Figure 19 examines the impact of CAPEX and OPEX on the LCOE and the relative cost components.

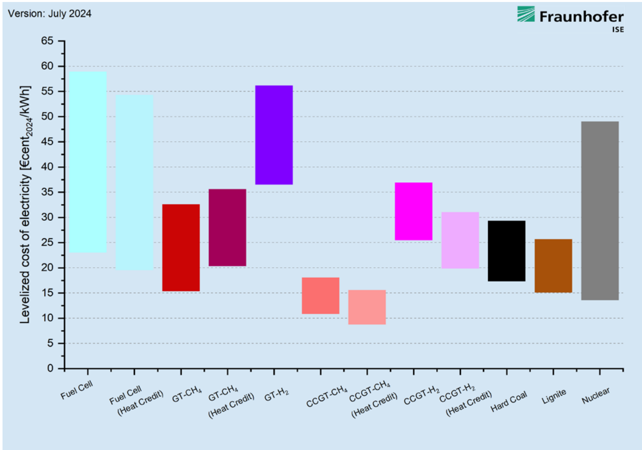

Figure 17: LCOE of conventional power plants in 2024 with varying CO_2 certificate and fuel prices as well as specific investments.

Among fossil-fueled power plants, newly installed combined cycle gas turbine plants currently have the lowest levelized cost of electricity (LCOE), ranging between 10.9 and 18.1 €cents/kWh. This does not yet account for potential heat revenues. Advantages of CCGT plants include their higher flexibility and lower CO_2 emissions compared to coal-fired power plants. When considering additional heat credits, the LCOE for CCGT plants falls between 8.8 and 15.6 €cents/kWh. The heat credit is calculated based on the fuel costs that would be incurred for heat production but is instead provided for free from the waste heat generated during the combined production of electricity in CCGT plants.

The theoretical LCOE for new lignite power plants ranges between 15.1 and 25.7 €cents/kWh, making them more expensive than CCGT plants. As traditional baseload power plants, lignite power plants have very low operational flexibility and are therefore only partially suitable for supporting fluctuating renewable energies. The LCOE for potentially new hard coal power plants is even higher, ranging between 17.3 and 29.3 €cents/kWh, despite having lower specific investment costs than lignite plants. Highly flexible gas turbines have similar LCOEs, ranging from 15.4 to 32.6 €cents/kWh, but due to their lower upfront costs, they are more cost-effective than hard coal plants when running below 500 full-load hours per year. The wide range in LCOEs is due to the broad range of potential full-load hours considered, between 500 and 3000 hours.

It also shows that the LCOE of a gas turbine retrofitted for hydrogen in 2035 would be slightly higher, in the range of 20.4 to 35.6 €cents/kWh. The deviation compared to conventional gas-fired plants is due to the retrofit to green hydrogen in 2035, which involves an additional investment of 15% of the original CAPEX. Furthermore, the assumed fuel costs for hydrogen are high compared to natural gas, even when considering CO_2 costs for natural gas. The LCOE for fuel cells in 2024 ranges between 23.1 and 59.0 €cents/kWh. The wide range is due to both the high investment costs and the assumed range of full-load hours. In high-utilization contexts, fuel cell costs decrease significantly. When accounting for heat revenues, the costs are reduced to between 19.6 and 54.3 €cents/kWh. The LCOE for a new nuclear power plant built in 2024 is estimated to range between 13.6 and 49.0 €cents/kWh. This result must be viewed in the context that significant societal costs, such as waste disposal, are externalized and not included in the cost calculation. Moreover, most nuclear plants are only limitedly capable of providing grid flexibility, which will be crucial in the future energy system. In Figure 18, the full-load-hour-dependent LCOEs of nuclear power are compared with those of other technologies.

In comparison, ground-mounted PV systems at locations with a solar radiation level of 1300 kWh/(m²a) achieve LCOE of 3.12 €cents/kWh, while onshore wind turbines at locations with 3200 full-load hours achieve 3.94 €cents/kWh. Therefore, the LCOEs for ground-mounted PV systems and onshore wind are significantly lower than for electricity from all conventional power plants. Even the LCOEs for small rooftop PV systems in favorable locations in southern and central Germany are considerably cheaper than those of any other (newly built) conventional power plants.

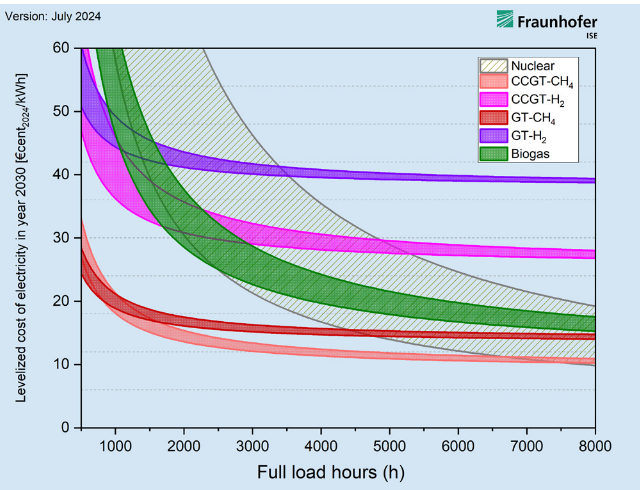

Figure 18: Electricity generation costs for conventional thermal power plants depending on the full-load hours in the installation year 2030

Since the LCOE depend on the utilization rate of the power generation technologies, Figure 18 illustrates the full-load-hour dependence for installations in 2030. All cost values are discounted to 2024 as usual. All set cost parameters are held constant while the full-load hours are varied within the range of 500 to 8000 hours. The graphical analysis is conducted for a selection of technologies. It shows a clear distinction between highly flexible power generation technologies, like CCGT and gas turbines, and inflexible technologies, such as nuclear power. The LCOEs display different sensitivities to variations in full-load hours, especially in the low-utilization range, where high sensitivity is observed for nuclear power and biogas generation. In the high-utilization range, natural gas CCGT remains the least costly thermal power generation option in 2030.

Figure 19 illustrates the components of the levelized cost of electricity (LCOE) for a selection of dispatchable power plants, broken down into fixed and variable operating costs, CO2 certificate costs, and initial investment costs. Additionally, the division of these cost components according to the lower and upper parameter boundaries is shown for each technology. All cost shares are normalized such that their sum equals 100%. The figure shows a significant difference in the relative share of variable operating costs in total costs between the lower and upper parameter values. In this context, the variable operating costs are calculated as the sum of fuel costs and other variable costs, as outlined in Table 2.

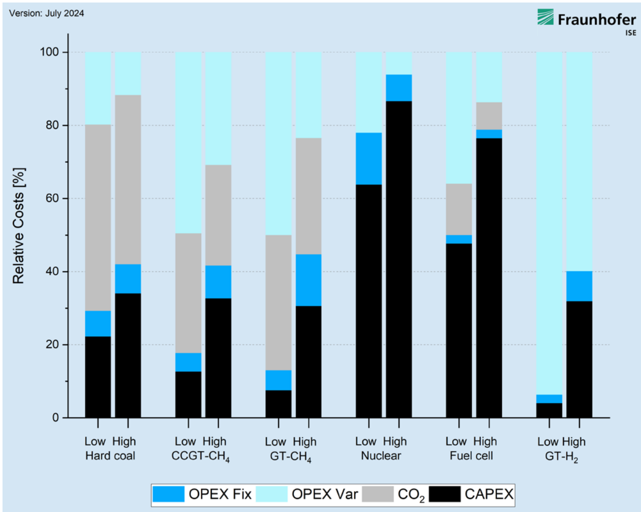

Figure 19: Components of LCOE of conventional power plants in 2024 with lower and upper limits

In the case of combined cycle gas turbine and gas turbine power plants, it is evident that for the lower parameter ranges (lower LCOE), the largest cost component consists of variable operating costs. Hydrogen gas turbines, due to the currently high cost of hydrogen, have by far the highest variable operating expenses (OPEX). On the other hand, the costs for CO_2 certificates in 2024 still represent a smaller share of total costs. For hard coal plants, CO_2 certificate costs account for roughly half of the total costs, making them more significant. Notably, in nuclear power and fuel cell plants, initial investment costs represent the largest cost component. Overall, the comparison reveals a clear contrast between capital-intensive technologies that require high full-load hours and flexible technologies characterized by low CAPEX but high variable operating costs.

While nuclear power is expected to become less economically viable in Europe due to decreasing full-load hours, the competitiveness of fuel cells and hydrogen gas turbines is expected to increase. Both technologies show significant potential for cost reductions through economies of scale, driven by technological advancements, infrastructure development, and a decreasing cost of hydrogen.

Excluding CAPEX, it becomes clear that the operating costs of conventional power plants in Germany are already more expensive than those of large-scale PV and ground-mounted PV systems, as well as onshore wind turbines at favorable locations. The operating costs of hard coal and lignite plants are even significantly higher than the LCOE of newly built ground-mounted PV systems and also higher than that of offshore wind turbines.

In the future, due to the increasing share of renewable energy, the expected phase-out of coal, and the likely phase-out of fossil natural gas, the full-load hours of conventional power plants will decline sharply. This will lead to an opposing trend compared to renewable technologies: conventional power generation costs will rise. This trend is driven both by increasing CO_2 certificate prices and by the expected significantly lower utilization rates. It is likely that the market will not favor the cheapest form of conventional generation but rather the one offering high flexibility in start-up and shut-down variability, favoring gas and hydrogen-

5. FORECAST OF LCOE UP TO 2045 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 2035 and 2045 (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 less than 14 €cents/kWh. At an annual irradiation (GHI) of 950 kWh/(m²a), even smaller rooftop systems are expected to fall below 14.5 €cents/kWh by 2024 and below 13.4 €cents/kWh by 2027. Larger ground-mounted systems at sites with 1300 kWh/(m²a) annual irradiation already produce electricity for as low as 5.0 €cents/kWh today. By 2045, LCOE for small rooftop PV systems will range between 4.9 and 10.4 €cents/kWh, while for ground-mounted systems, it will range between 3.0 and 5.0 €cents/kWh. Large rooftop systems in Germany will generate electricity in 2045 at LCOE between 4.3 and 8.7 €cents/kWh. PV system prices are expected to decrease by 2045 to between 457 and 588 EUR/kW for ground-mounted systems and to as low as 653 to 1306 EUR/kW for small systems.

The LCOE for PV-battery systems could reduce by up to 30% by 2045. These figures are based on a constant ratio between PV system capacity and battery storage capacity. However, with decreasing battery storage prices, this ratio could shift toward larger storage capacities. With a constant ratio, the LCOE for PV-battery systems could decrease by 2045 to between 6.6 and 19.1 € cents/kWh for small systems, 5.6 to 14.0 € cents/kWh for large rooftop systems, and 4.3 to 9.0 €cents/kWh for ground-mounted systems.

Depending on the wind location, onshore wind turbines can achieve similar costs as PV systems at favorable sites. From the current LCOE ranges of between 4.3 to 9.2 €cents/kWh to 3.7 to 7.9 €cents/kWh in the long term.

CAPEX [EUR/kWh]	**2024 low**	**2024 high**	**2035 low**	**2035 high**	**2045 low**	**2045 high**
Battery storage for PV rooftop small (≤ 30 kW_p, 1:1)	500	1000	288	840	180	700
Battery storage for PV rooftop large (30 kW_p – 1 MW_p, 2:1)	450	800	270	675	150	580
Battery storage for PV utility-scale (> 1 MW_p, 3:2)	400	600	225	473	130	400

Table 8: Assumptions for the calculation of LCOE of PV battery systems in 2035 and 2045. Shown is the battery storage price in EUR/kWh usable capacity, including installation, excluding VAT.

Figure 20 illustrates the projected LCOE for generation technologies expected to be integrated into the European electricity market and fulfill physical electricity demand in the future. The cost ranges shown refer to installations in 2030.

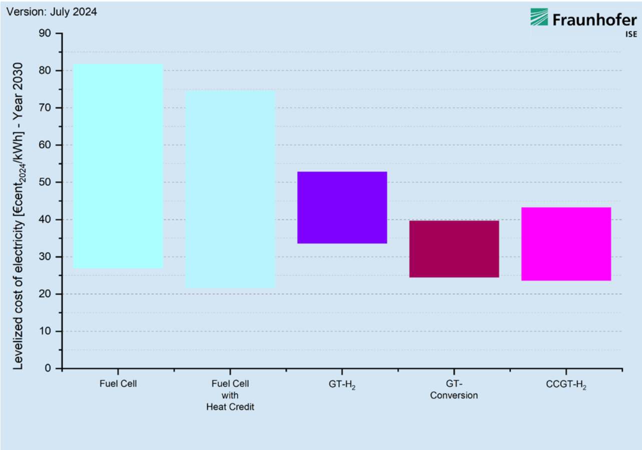

Figure 20: LCOE for new thermal power plant technologies in Germany in the installation year 2030. Specific generation costs are taken into account with a minimum and a maximum value per technology.

The figure highlights that hydrogen-powered combined-cycle gas turbine (CCGT-H_2) plants (23.6 – 43.3 €cents/kWh) and gas turbines converted to H_2 in 2035 (24.5 – 39.7 €cents/kWh) have the lowest LCOE in direct comparison. The hydrogen-powered gas turbine has lower efficiency than the hydrogen CCGT, resulting in higher LCOE of 33.6 – 52.9 €cents/kWh within the considered range of full-load hours. However, in highly flexible operating scenarios with low full-load hours, the costs converge. The LCOE of gas turbines converted to green hydrogen illustrate that a turbine built in 2030 and converted in 2035 has only slightly higher LCOE compared to a conventional gas turbine. According to the analysis, converting to hydrogen in 2035 has a limited impact on the long-term economic viability of gas turbines. This conclusion holds under the assumption that all costs are spread over a 30-year technical lifespan and that additional investments for the conversion do not exceed 15% of the initial capital expenditure (approximately 90 €/kW).

The LCOE of fuel cells (26.9 – 81.8 €cents/kWh) show the widest range due to large variations in investment costs and full-load hours. Given the high share of CAPEX in total costs, operating with high full-load hours is most economical for fuel cells. By also monetizing heat generation, the LCOE can be reduced to a range of 21.6 to 74.6 €cents/kWh.

Figure 21 illustrates the cost dynamics for specific technologies over the timeline until 2045. While continuous cost ranges are shown for biogas/biomass, PV, and wind, other generation technologies are evaluated for 2024, 2035, and 2045. In this analysis, biogas and biomass are grouped together as bioenergy. Since the upper bound of LCOE for biogas is systematically higher than for biomass, and biomass consistently has a lower bound, biogas determines the upper limit, and biomass the lower limit, of the LCOE range. Due to rising CO_2 certificate prices, the LCOE for natural gas-fired CCGT plants in 2045 is projected to be between 14.1 and 40.5 €cents/kWh. The LCOE of CCGT plants is expected to increase significantly due to rising CO2 prices, with strong cost variability depending on the certificate price assumptions and the assumed full-load hours. Similarly, natural gas turbines are projected to have higher LCOE between 18.6 and 40.5 €cents/kWh in 2045.

The LCOE for hydrogen-based gas plants decreases steadily over the timeline, reaching 27.0 to 46.3 €cents/kWh in 2045. For fuel cells, LCOE increases until 2035, when the conversion to hydrogen occurs. This is because natural gas, which incurs rising variable costs due to CO_2 pricing, is used as fuel until 2035. The economic feasibility of converting fuel cells to hydrogen will depend on fuel prices, certificate costs, and other subsidy regimes and may deviate from the year assumed in this study.

The average LCOE of hydrogen CCGT increases over the period considered, with the range of costs widening as the years progress. The cost-reducing effect of lower fuel prices is offset by a decreasing number of full-load hours. A higher number of full-load hours results in a significant reduction in LCOE for hydrogen CCGT, making it realistic to achieve LCOE of 14.5 to 51.1 €cents/kWh by 2045 in heat-led systems or those benefiting from heat credits.

Offshore wind energy shows somewhat larger potential for cost reduction due to a higher learning rate, leading to a significant decrease in LCOE from current values of 5.5 to 10.3 €cents/kWh to around 5.1 to 9.4 €cents/kWh by 2045. By then, installation costs are expected to range between 1968 and 3042 EUR/kW. For bioenergy plants, LCOE in 2045 will range from 14.6 to 43.3 €cents/kWh, heavily dependent on factors such as feedstock availability, heat extraction, and substrate fuel costs. In the long term, PV systems at high-irradiation locations and WEA at wind-rich onshore sites will have the lowest LCOE, far outperforming fossil fuel plants by 2045. Recent technology and cost trends have significantly improved the competitiveness of both wind and PV. Notably, PV costs have decreased so much that PV is now, alongside onshore wind, one of the cheapest generation technologies for new power plants in Germany. For wind energy, alongside reduced equipment costs, the increase in full-load hours due to larger turbines is a key factor driving lower LCOE. The 2024 LCOE analysis highlights that previous cost-reduction trends for PV, shown in earlier versions of this study (2010, 2012, 2013, 2018, 2021), have now shifted due to high inflation despite strong market growth and substantial price drops for PV systems. However, both technology and financing costs remain much lower than before.

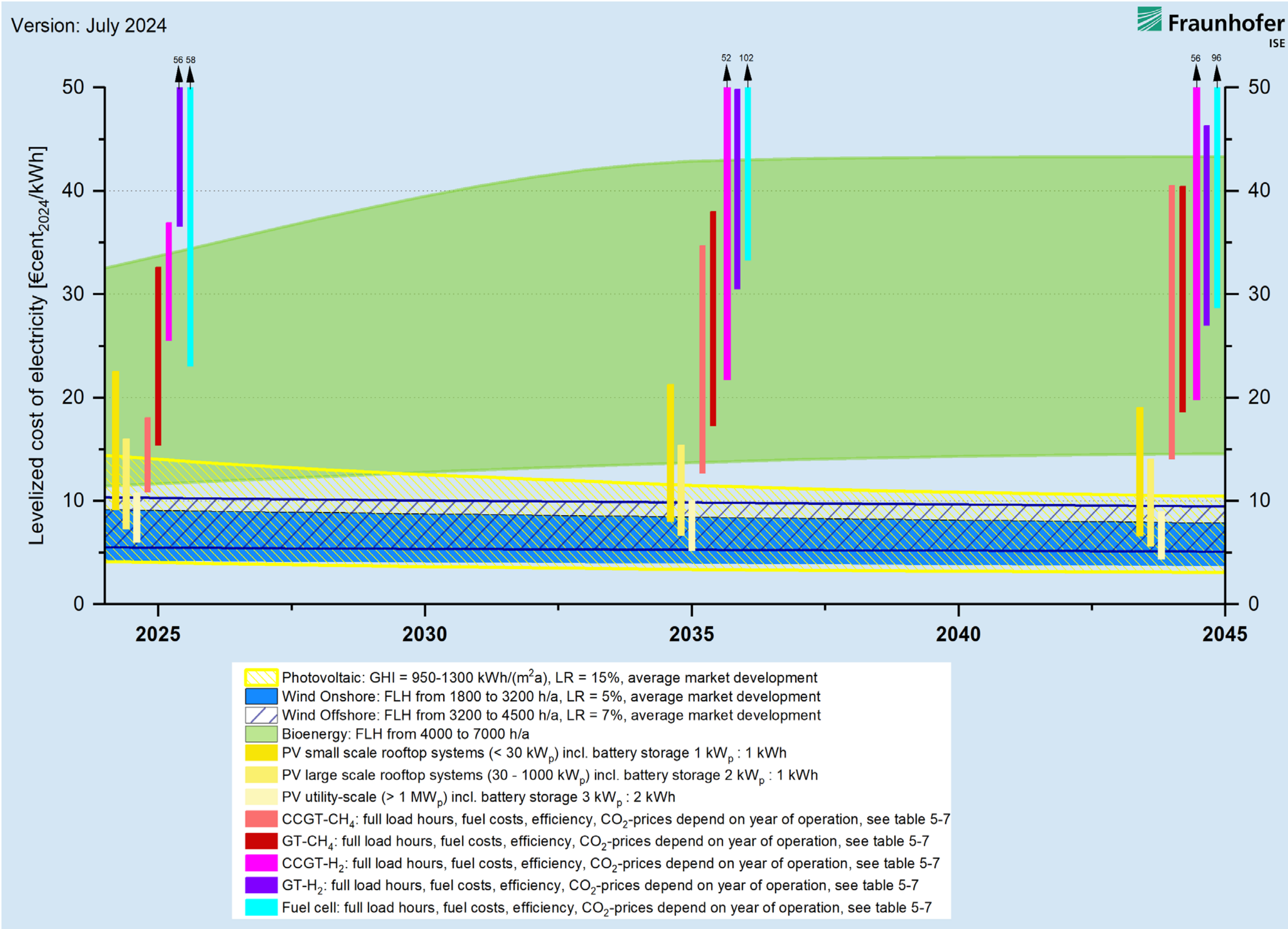

Figure 21: Learning-curve based forecast of the LCOE of renewable energy technologies and gas-fired power plants in Germany until 2045.

A comparison of the LCOE for renewable energy with the operational costs of conventional power plants reveals significant, with and without heat extraction, are compared to the LCOE of new onshore wind farms, small PV rooftop systems, and large-scale PV ground-mounted systems. The operational costs of conventional plants consist of variable OPEX, fuel costs, and CO_2 certificate costs. This comparison clearly indicates that renewable energy technologies, particularly wind and solar, offer significantly lower generation costs than fossil-fuel-based plants, marking a continued shift toward renewables as the most economically viable option for electricity generation in the future.

In 2024, the levelized cost of electricity (LCOE) for large-scale renewable energy plants, particularly onshore wind farms and ground-mounted PV systems, is significantly lower than the operating costs of conventional power plants without heat extraction. Onshore wind farms and large ground-mounted PV systems have the lowest costs, while small rooftop PV systems have slightly higher but still comparatively low costs. Lignite power plants have operating costs exceeding 11 €cents/kWh, combined cycle gas turbine plants over 10 €cents/kWh, and even CCGT plants with heat extraction reach operating costs between 6.5 and 8.6 €cents/kWh. The operating costs of hydrogen gas turbines are by far the highest, ranging from 35.1 to 38.3 €cents/kWh. This is directly attributable to the high fuel costs.

In 2035, the LCOE for renewable energies remains low, while the operating costs of conventional power plants rise. Lignite power plants cost over 17 € cents/kWh, CCGT plants still over 11 € cents/kWh, and CCGT plants with heat extraction average over 9 €cents/kWh. Additionally, there is a noticeable widening of cost ranges for all three fossil generation technologies. This is primarily due to the spread in the costs of CO_2 certificates and the full-load hour intervals, which are parameters in the calculation of operating costs. Hydrogen gas turbines continue to have by far the highest operating costs, exceeding 26 €cents/kWh. In contrast, the LCOE for rooftop PV systems falls below 10 €cents/kWh.

By 2045, the operating costs of conventional power plants continue to rise, while the LCOE for renewable energies remains low. The costs for lignite power plants exceed 22 € cents/kWh due to increasing CO2 pricing. The operating costs of CCGT plants exceed 12 €cents/kWh, and CCGT plants with heat extraction are above 9 €cents/kWh. In contrast, the LCOE for onshore wind farms and PV systems stabilizes in the range of 5 to 10 €cents/kWh.

In summary, the data show that renewable energies, particularly large ground-mounted PV systems and onshore wind farms, are already more cost-effective than conventional power plants as of 2024. These cost advantages continue through 2045 and are further amplified by the rising operating costs of conventional power plants, particularly due to higher CO_2 prices. By 2045, it is expected that, within the assumed full-load hours range, the operating costs of hydrogen-powered gas turbines will be, on average, lower than those of lignite. According to the cost estimates in this study, the long-term electricity generation costs for ground-mounted PV systems in Germany will range between 5 and 10 €cents/kWh, while wind farms will remain under 10 €cents/kWh. These values are not significantly higher than the costs of generating electricity from PV and wind energy in regions with even better solar and wind conditions.

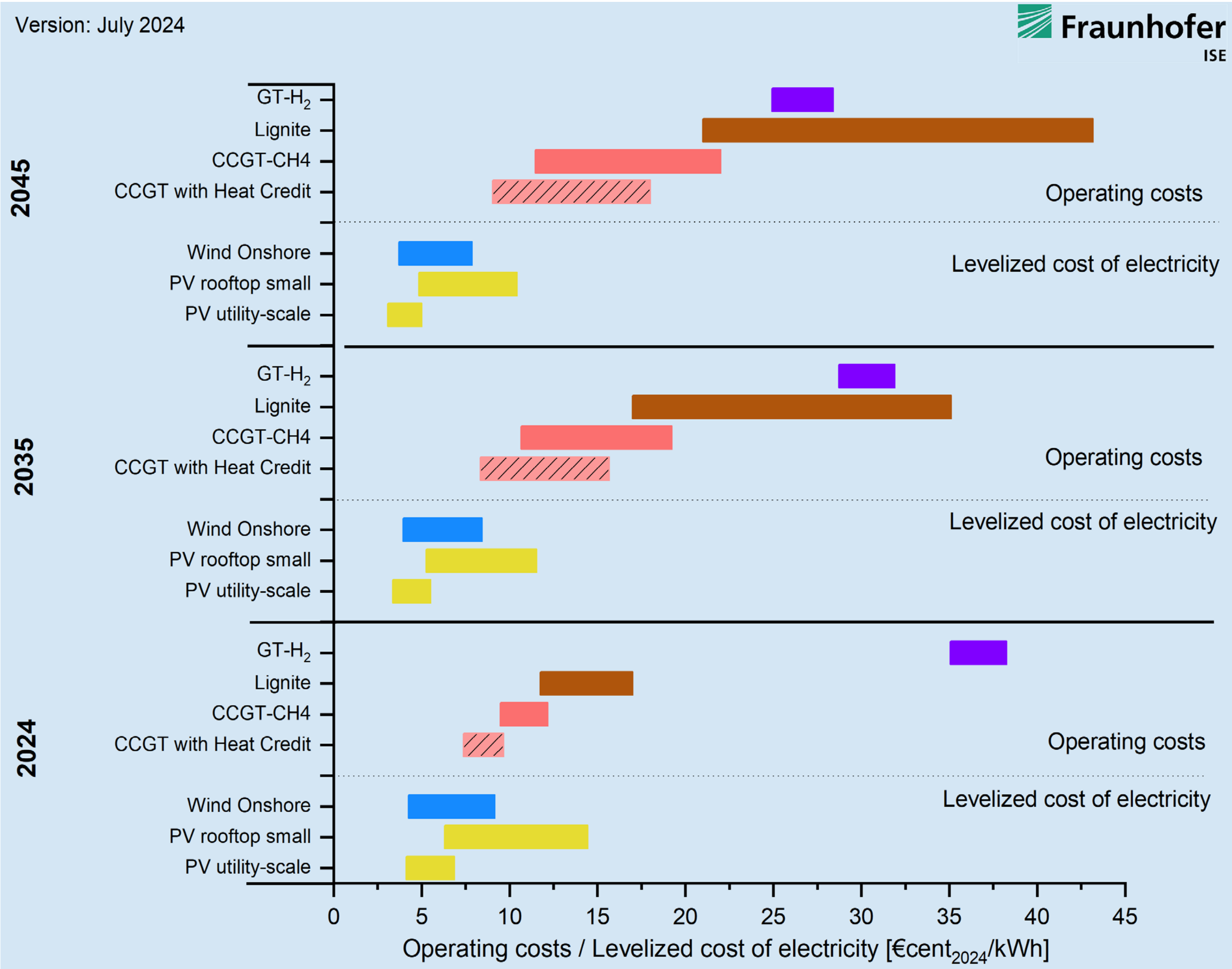

Figure 22: Comparison of the LCOE of newly installed PV and onshore wind power plants as well as the operating costs of existing lignite-fired and CCGT power plants.

Sensitivity Analyses of the Learning Curves for PV and Wind

In a sensitivity analysis, parameters such as specific investment, operational lifespan, weighted average cost of capital (WACC), full-load hours, and operating costs can be examined regarding their impact on the LCOE.

Figures 23 and 24 illustrate the range of LCOE for small PV systems and onshore wind farms in Germany, for different combinations of learning rates and market scenarios (see Tables 12 and 13). Starting from today's low costs, the values show fluctuations of up to 12%, depending on the parameters used. This reflects the uncertainty of the learning curve model for different input parameters, while also indicating a potential range for the cost development of each technology.

For small PV systems at locations with a Global Horizontal Irradiance (GHI) of 1300 kWh/m² per year, LCOE between 4.5 and 5.3 €cents/kWh can be identified by 2045. For onshore wind energy, only slight future cost reductions are expected due to the already low current LCOE, ranging between 3.7 and 3.8 € cents/kWh.

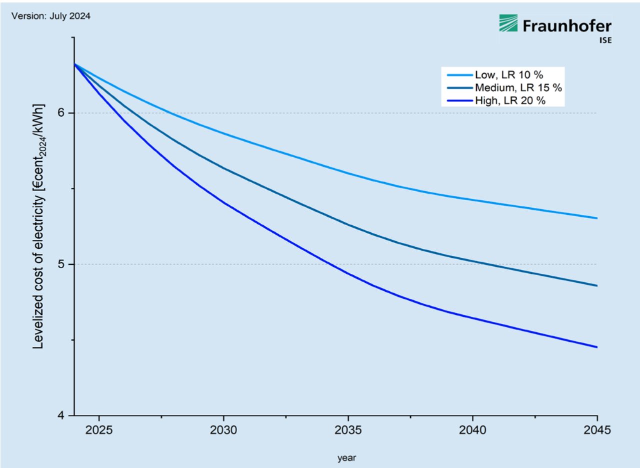

Figure 23: Sensitivity analysis for the forecast of LCOE of small-scale PV systems, investment cost in 2024 = 1000 EUR/kW, GHI=1300 kWh/(m²a).

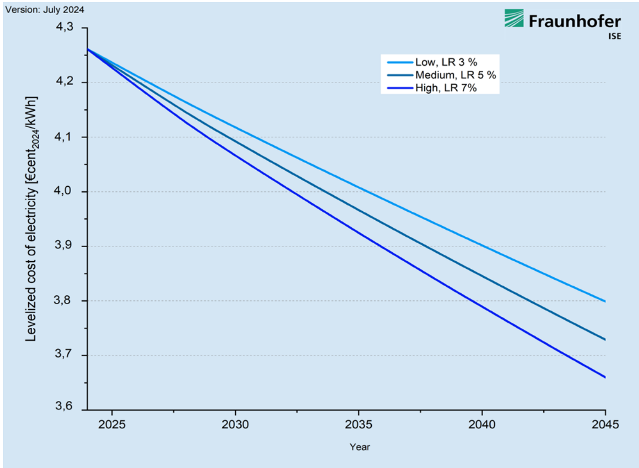

Figure 24: Sensitivity analysis for the forecast of LCOE of onshore WPP, investment cost in 2024 1300 EUR/kWh, FLH increase from 3200 h/a in 2024 to 3553 h/a in 2045.

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

This chapter analyzes photovoltaic technologies for regions with higher solar irradiation and wind turbines at locations with higher full-load hours than those in Germany.

To calculate the levelized cost of electricity for PV, three locations were considered, each with a Global Horizontal Irradiance (GHI) of 1450 kWh/(m² per year), 1800 kWh/(m² per year), and 2000 kWh/(m² per year). For wind turbines, locations with excellent wind conditions were used. These locations are typically found near the coastlines of the Atlantic Ocean or the North Sea in Europe, where onshore wind farms can achieve 3000 to 4000 full-load hours. For offshore wind farms, in some sea areas with very strong winds in the North Sea and the Atlantic Ocean around the UK, full-load hours can reach between 4000 and 5000.

PV systems	GHI [kWh/(m²a)]	Solar irradiation on PV moduls [kWh/(m²a)]	Electricity generation per 1 kW_p [kWh/a]
Southern France	1450	1670	1380
Southern Spain	1800	2070	1680
MENA	2000	2300	1790
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 (Source: Fraunhofer ISE).

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

	PV rooftop (< 30 kW_p)	PV utility-scale (> 1 MW_p)	Wind onshore	Wind offshore
Lifetime in years	30	30	25	25
Share of debt	80%	80%	70%	70%
Share of equity	20%	20%	30%	30%
Interest rate on debt	7.0%	7.0%	8.5%	6.5%
Return on equity	7.0%	8.5%	10.0%	10.0%
WACC nominal	7.0%	7.3%	9.0%	7.6%
WACC real	5.1%	5.4%	7.0%	5.4%
OPEX fix [EUR/kW]	26	13.3	39	70
OPEX var [EUR/kWh]	0	0	0.008	0.008
Annual degradation	0.25%	0.25%	0	0

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

Small rooftop PV systems at locations with high solar irradiation (GHI of 2000 kWh/m² per year) have lower LCOE, ranging from 5.3 to 11.8 €cents/kWh. Ground-mounted PV systems at such locations have LCOE between 3.5 and 5.4 €cents/kWh.

For onshore wind farms at good wind locations, such as the northeast of the UK, LCOE can range from 4.3 to 7.7 €cents/kWh, which is higher than PV in the MENA regions with high solar irradiation. The costs for offshore wind are slightly higher, ranging between 5.4 and 9.1 €cents/kWh in the North Sea off the Scottish coast.

Prognosis of LCOE for Renewable Energy by 2045 in Regions with High Solar Irradiance and Strong Wind Speeds

The projection of LCOE by 2045 is also conducted for PV and wind turbine technologies at locations with high solar irradiance and strong wind speeds. Similar learning rates to those used in Chapter 5 are applied for PV and wind turbines. By 2045, the LCOE for onshore wind farms could decrease to between 3.5 and 5.7 €cents/kWh (see Figure 25). For offshore wind farms, the LCOE in 2045 is projected to be between 5.0 and 8.3 €cents/kWh.

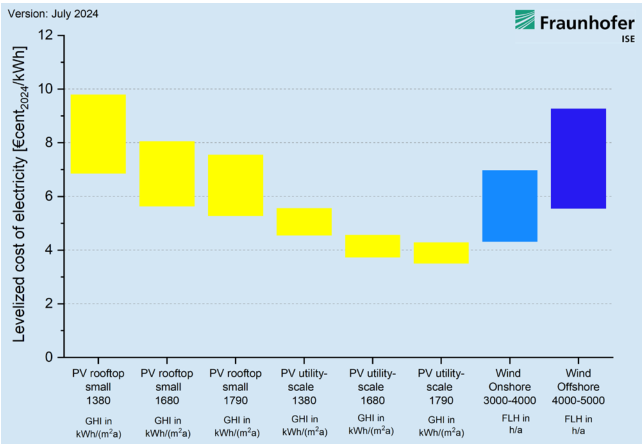

Figure 25: Levelized cost of electricity for renewable energies at locations with high solar radiation and good wind speeds in 2024.

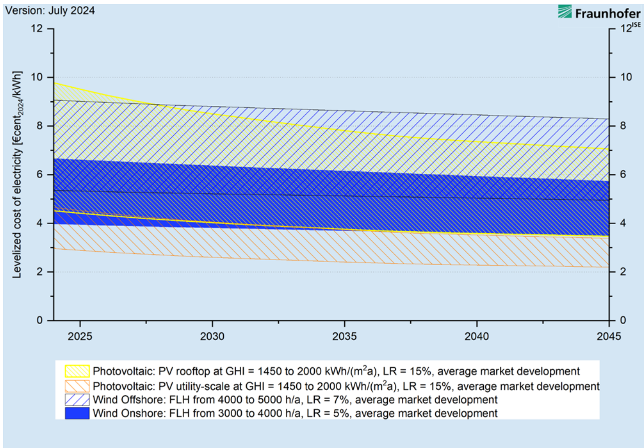

Figure 26: Development of LCOE for wind turbines and PV systems at locations with high wind speed (m/s) and solar radiation kWh/(m²a).

For PV systems, at locations with good solar irradiance in the MENA region, the LCOE could range from 4.0 to 8.4 €cents/kWh for small rooftop installations and less than 3.9 €cents/kWh for ground-mounted PV systems.

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. 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.

In the category of building systems with a capacity of 10 to 20 kW, a sharp increase was observed in 2021, with a rise from 3% in 2020 to 12% in 2021 of the share in capacity additions. This trend could be linked to an amendment of the Renewable

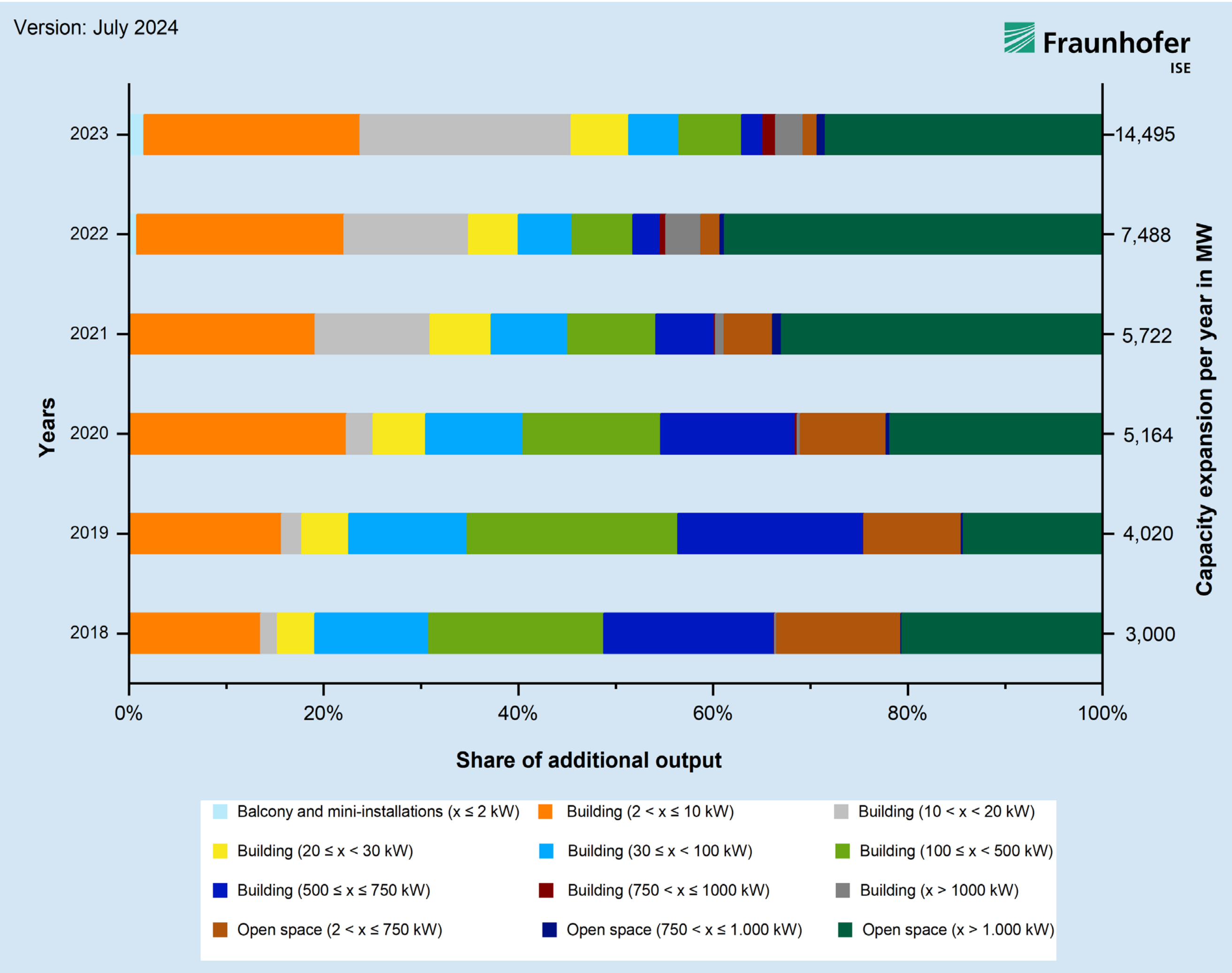

Figure 27: Relative shares of different orientation of PV systems in historical system expansion. Source: Own calculation based on MaStR data registered starting from 31.01.2019 (data as of 06.02.2024) (BNetzA 2024A).

Energy Sources Act (EEG) in 2021, which raised the capacity limit for tax simplifications, such as the elimination of income tax through an application for "hobby" status, as well as the EEG surcharge on self-consumption, from 10 kW to 30 kW. Significant growth was also observed in 2023, with a 22% share compared to 13% in 2022. Balcony and mini systems (up to 2 kW) accounted for 1.5% of capacity additions in 2023, while they represented 29% of system installations (in terms of the number of systems installed) for the year. In general, the share of building systems up to 30 kW has increased significantly since 2020, reaching up to 51% in 2023. This trend, likely driven by changes in the EEG, is expected to continue in the future.

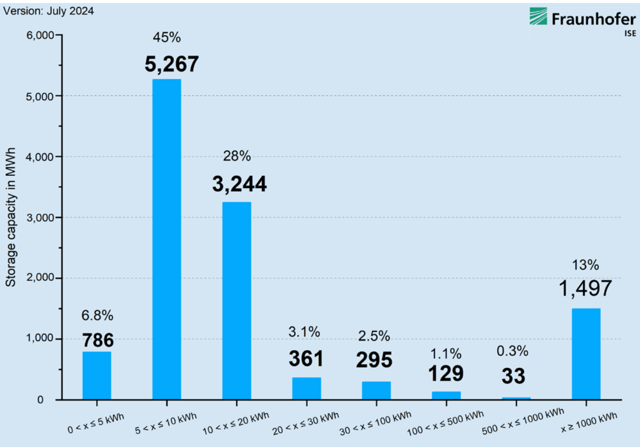

Figure 28: Distribution of the inventory (storage capacity) of battery storage systems by capacity class by the end of 2023 in percent and absolute values in MWh. Source: Own calculation based on MaStR data (as of February 6, 2024) (BNetzA 2024a).

Although large-scale systems have had a minimal impact on the number of installations in recent years, they account for a significant portion of the installed capacity. The importance of larger PV systems and ground-mounted installations in capacity additions has steadily increased over time, reducing the significance of smaller systems. The share of building systems with capacities between 30 and 750 kW has grown over the observed period, reaching a peak of 53% in 2019. These systems mainly include PV installations on commercial building rooftops. The growth in this segment cannot be attributed to specific causes but is instead due to a combination of factors, including falling PV system prices, rising electricity prices, and increased corporate environmental commitments. However, in 2022, the significance of this segment declined significantly due to the increased share of 10-30 kW systems, dropping to just 15%. Despite their low number, ground-mounted systems continue to account for a substantial share of capacity additions, increasing from 25% in 2019 to 31% in 2023.

By August 2023, the German government's expansion target of 9 GW had already been exceeded, with an increase of 14.5 GW. The Federal Network Agency (BNetzA) reported a capacity addition of 14.1 GW for 2023 (as of January 5, 2024). The discrepancy is mainly due to the earlier evaluation date, and a large number of retroactive registrations are expected in the first month after commissioning.

Figure 28 shows the distribution of battery storage capacity by storage class by the end of 2023. It reveals that 45% of the total storage capacity is provided by storage systems with a capacity between 5 and 10 kWh. Storage systems with capacities of 10 to 20 kWh account for 28%. Storage systems with a capacity of more than 1 MWh represent 13%, while storage systems smaller than 5 kWh account for 7%. This shows that the total capacity is mainly made up of home storage (up to 30 kWh) and large-scale storage (from 1,000 kWh). Storage systems in the commercial and industrial sectors (30 to 1,000 kWh) are relatively insignificant.

For more information on statistics related to photovoltaics and batteries, visit the Fraunhofer ISE website (https://www.ise.fraunhofer.de) and energy-charts.info. Fraunhofer ISE also publishes the PV Status Report, which includes extensive information on the PV market and PV systems (https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html).

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
2024	1396	1445	1545
2025	1592	1676	1854
2026	1799	1928	2206
2027	2014	2197	2603
2028	2236	2483	3046
2029	2460	2781	3533
2030	2681	3087	4063
2031	2895	3396	4632
2032	3113	3735	5234
2033	3330	4109	5863
2034	3547	4520	6507
2035	3760	4972	7158
2036	3948	5419	7838
2037	4106	5853	8544
2038	4270	6262	9270
2039	4441	6638	10011
2040	4618	6970	10762
2041	4803	7318	11516
2042	4995	7684	12264
2043	5195	8069	13000
2044	5403	8472	13715
2045	5619	8896	14401

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%	PV low, PV high
PV rooftop large	15%	Medium scenario	20%, 10%	PV low, PV high
PV utility-scale	15%	Medium scenario	20%, 10%	PV low, PV high
Wind onshore	5%	Onshore wind moderate	7%, 3%	Wind onshore high
Wind offshore	7%	Offshore wind	-	-
Biogas	-	-	-	-
Solid biomass	-	-	-	-
Lignite	-	-	-	-
Hard coal	-	-	-	-
CCGT	-	-	-	-
Gas turbines	-	-	-	-

Table 12: Overview of LR and market scenarios

Technology	Scenario	Source	2030 [GW]	2045 [GW]	Applied in the calculations until 2045
Wind offshore	Offshore Wind moderate	ISE	102	209	X
Wind offshore	Offshore Wind high	GWEC 2023	500	1625	
Wind onshore	Onshore Wind moderate	GWEC 2016, low (adapted by ISE)	1364	2796	X
Wind onshore	Onshore Wind high	GWEC 2016, advanced (adapted by ISE)	2255	5489	
Wind onshore	Onshore Wind moderate	IRENA REMap, 2021	1811	4703	
PV	PV Low-scenario	ISE	2681	5619	
PV	PV Medium-scenario	ISE	3087	8896	X
PV	PV High-scenario	ISE	4063	14401	

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

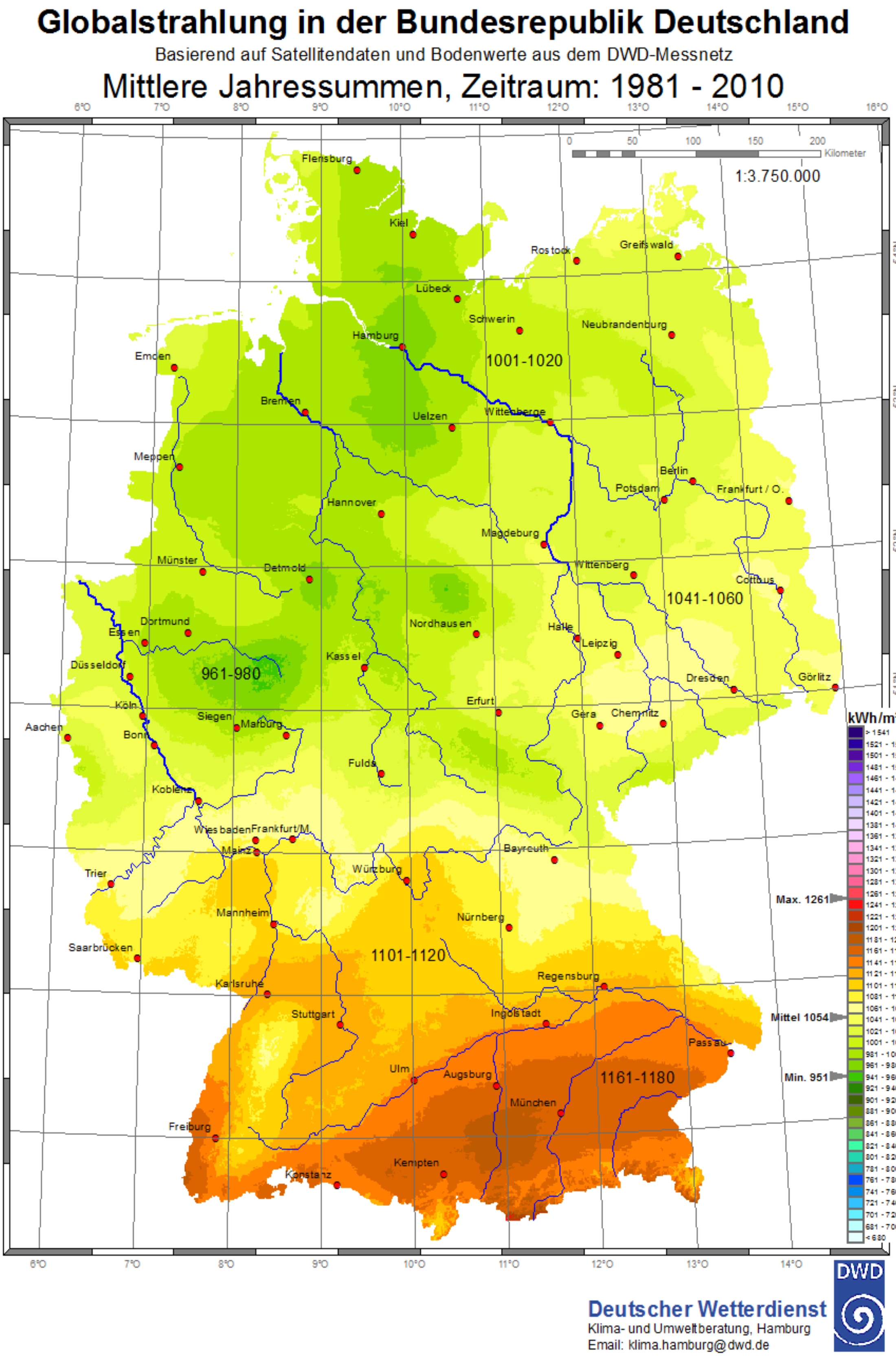

Figure 29: Average annual sum of global irradiation [kWh/m²] in Germany from 1981-2010 (DWD 2013)

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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
- Potential assessment of energy technologies
- Resource assessment for the energy transition
- Social science analyses related to energy technologies and the energy system
- Business models, flexibility, and marketing

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:

https://www.ise.fraunhofer.de/en/business-areas/system-integration/energy-system-analysis.html

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Contact

Dr. Christoph Kost
Energy System Analysis
christoph.kost@ise.fraunhofer.de

Fraunhofer Institute for Solar
Energy Systems ISE
Heidenhofstraße 2
79110 Freiburg, Germany
www.ise.fraunhofer.de/en

Directors
Prof. Dr. Hans-Martin Henning
Prof. Dr. Andreas Bett