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LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES

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CHRISTOPH KOST
SHIVENES SHAMMUGAM
VERENA JÜLCH
HUYEN-TRAN NGUYEN
THOMAS SCHLEGL

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

CONTENTS

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

Heaf of Business Area
Energy Systems Analysis:
Dr. Thomas Schlegl

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

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

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SUMMARY

The present study analyzes the levelized cost of electricity (LCOE) of renewable energy technologies in the first quarter of 2018 and predicts their future cost development until 2035 based on technology-specific learning rates (LR) and market scenarios.

The main focus of the study is on the LCOE of photovoltaic (PV), wind turbines and biogas plants in Germany. As a reference, the development of the LCOE for newly constructed conventional power plants (brown coal, hard coal, combined cycle gas turbines (CCGT), gas turbines) is also analyzed. Figure 1 shows the LCOE for both renewable and fossil power plants built in 2018.

Depending on the type of systems and solar irradiance (950 to 1300 kWh/m²a of global horizontal irradiance (GHI) in Germany), PV systems have a LCOE between 3.71 and 11.54 $€_{Cents}$/kWh, excluding value-added tax (VAT). As of today, the specific system costs lie within the range of 600 to 1400 EUR/kWp and are primarily dependent on the type of plants. This study distinguishes between small PV rooftop systems, large PV rooftop systems and PV ground-mounted utility-scale systems. The LCOE for all types of PV systems continues to show a decreasing trend, thus increasing the margin between them and the average end-customers electricity price of 29.23$€_{Cents}$/kWh, including VAT (BDEW 2017).

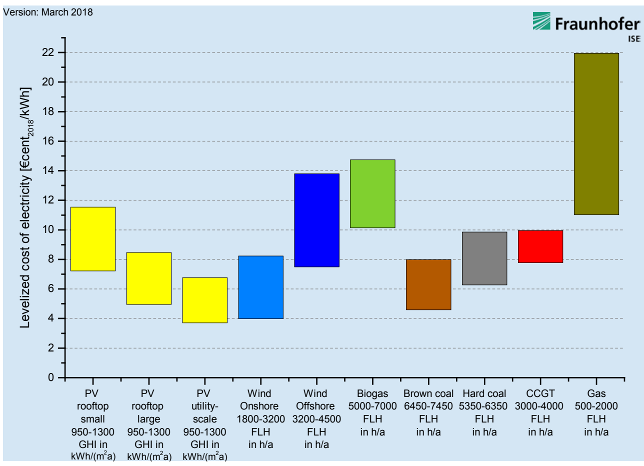

Figure 1: LCOE of renewable energy technologies and conventional power plants at locations in Germany in 2018. The value under the technology refers in the case of PV to the global horizontal irradiance (GHI) in kWh/(m²a), for the other technologies to the annual full load hours (FLH). Specific investments are taken into account with a minimum and maximum value for each technology.

The LCOE of onshore wind turbines in 2018, with specific plant costs of 1500 to 2000 EUR/kW, ranges between 3.99 and 8.23 $€_{Cents}$/kWh. As a result, PV systems and onshore wind turbines are, on average, the least expensive technologies in Germany, both among renewable energy technologies as well as fossil power plants. Onshore wind farms at very good locations already produce electricity at lower costs than newly erected coal or CCGT power plants. Despite higher average full load hours of up to 4,500 hours per year, the LCOE of offshore wind turbines from 7.49 to 13.79 $€_{Cents}$/kWh is significantly higher than onshore wind turbines. This is owed to higher investment and installation costs as well as higher operating and financing costs for offshore installations (specific system costs of 3100 to 4700 EUR/kW).

The LCOE of biogas power plants (specific plant costs between 2000 and 4000 EUR/kW) ranges between 10.14 $€_{Cents}$/kWh (7000 full load hours) and 14.74 $€_{Cents}$/kWh (5000 full load hours). A heat utilization is not considered in the calculations.

In terms of the conventional power plants, the LCOE of brown coal lies between 4.59 and 7.98 $€_{Cents}$/kWh, of hard coal 6.27 to 9.86 $€_{Cents}$/kWh and of combined cycle power plants 7.78 to 9.96 $€_{Cents}$/kWh, depending on the assumed full load hours and CO_2 certificate prices. The range of costs is mainly attributed to the large variation in full load hours. Since the full load hours result from the variable marginal costs of the individual power plant, they are dependent on the forecast of fuel prices, CO_2 certificate prices, development of renewable electricity feed-in and composition of the power plant complex.

The study also calculates the LCOE of PV home storage systems. It lies between 16.34 and 47.34 €$_{Cents}$/kWh in 2018. Both the costs of electricity generation by PV systems and the storage costs are taken into account in the calculation. The large variation in the LCOE is a result of the wide range in the investment costs of PV battery storage as well as the consideration of different storage sizes and their potential to increase the self-consumption rate.

Prognosis of LCOE in Germany through 2035

Figure 2 shows the results for the future development of the LCOEs in Germany until 2035. The illustrated range reflects the possible cost variations in the input parameters (e.g. power plant prices, irradiance, wind conditions, fuel costs, number of full load hours, costs of CO_2 emission certificates, etc.), which are listed in Tables 1 to 6. This methodology is exemplarily explained for the cost range of PV: The upper limit of the LCOE results from the combination of a PV power plant with a high procurement price at a location with low solar irradiance (e.g. northern Germany). Conversely, the lower limit is defined by the most inexpensive solar system at locations with high solar irradiance in southern Germany. This same process is carried out for wind and biomass power plants as well as conventional power plants. The usual financing costs on the market and the surcharges for risks are included in detail and are specific to each technology. This provides a realistic comparison of the power plant locations, technology risks and cost developments. The level of financing costs has considerable influence on the LCOE and the competitiveness of a technology. Furthermore, all of the costs and discount rates in this study are calculated with real values (reference year 2018). The specific investments in 2018 are calculated based on market research and cost studies.

For PV systems, a LR of 15% is assumed. By 2030, the LCOE of PV systems will sink below the value of 4.70 (rooftop systems) and 2.41 €$_{Cents}$/kWh (ground-mounted utility-scale power plant). From 2025 onwards, even small PV rooftop systems in southern Germany will generate electricity at a lower cost than newly installed hard coal or CCGT power plants in 2025. The specific PV system costs in 2035 will be between 350 and 815 EUR/kWp. By 2035, utility-scale PV power plants in southern Germany will generate electricity at a considerably low cost, way below the average LCOE for all fossil fuel power plants.

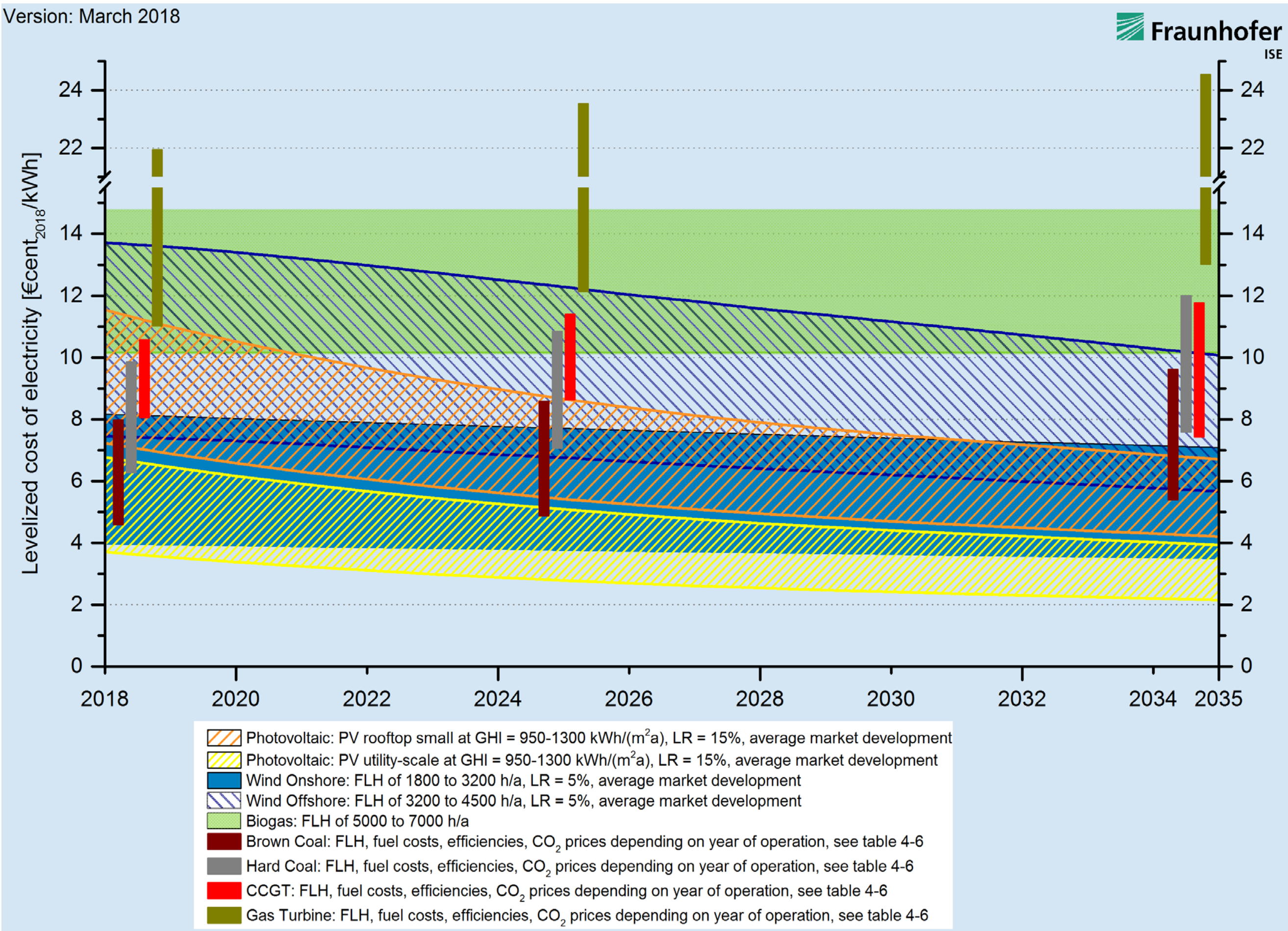

Figure 2 Learning-curve based predictions of the LCOE of renewable energy technologies and conventional power plants in Germany by 2035. Calculation parameters are listed in Tables 1 to 6. The LCOE value per reference year refers respectively to a new plant in that particular year.

The current LCOE of onshore wind power is already at the level of brown coal power plants and in some cases below the LCOE of hard coal and CCGT power plants. For the future trend, a LR of 5% is anticipated. Improvements are mainly expected through higher full load hours and also new installations with special low-speed turbines. The expected increase in costs for fossil fuel power plants will nevertheless further improve the competitiveness of onshore wind power plants, i.e. the cost of electricity generation at high wind speed onshore locations in 2035 will be well below the levels for all fossil power plants, at LCOEs between 3.49 to 7.09 $€_{Cents}$/kWh. Offshore wind turbines still have a strong cost reduction potential compared to onshore wind turbines. Depending on location and wind supply, electricity generation costs will fall to between 5.67 and 10.07 $€_{Cents}$/kWh by 2035. The increase in LCOE of conventional power plants is owed to the expected reduction of full load hours as well as the higher price of CO_2 emission certificates in the future.

Since only slight decreases in cost are expected for biogas power plants, no LRs for biogas are assumed. This leads to constant electricity production costs until 2035 (10.14 to 14.74 $€_{Cents}$/kWh excluding heat generation).

1. OBJECTIVE OF THIS ANALYSIS

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

Central contents of this study

- Analysis of the current situation and the future market development of photovoltaic (PV), wind turbines (WT) and biogas plants in Germany
- Economic modeling of technology-specific LCOE (status 1. quarter of 2018) for different types of installations and site conditions (e.g. solar irradiance and wind conditions) on the basis of common market financing costs
- Assessment of the different technology and financial parameters based on sensitivity analyzes of the individual technologies
- Forecast the future LCOE of renewable energy technologies until 2035 using learning curve models and market growth scenarios
- Analysis of the current situation and future market development of photovoltaic and solar thermal power plants (CSP) for locations with favorable solar irradiance
- Analysis of electricity generation costs of PV storage systems

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 storage, the number of FLH, decentralized power generation, capacity for follow-up operation and time of day availability, have not been taken into account. The technologies are evaluated and compared based on standard market financing costs and historically proven learning curves. As a reference, the current and future LCOE of new conventional power plants (brown coal, hard coal, combined cycle power plants and gas turbines) are calculated.

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

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

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

Operating cost
during the power plant's operational life time

Lifetime of the plant

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

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

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

- Small rooftop systems (5 - 15 kWp) – »PV rooftop small«
- Large rooftop systems (100 - 1000 kWp) – »PV rooftop large«
- Ground-mounted utility-scale power plants (larger than 2 MWp) – »PV utility scale«

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

Wind energy power plants

- Onshore (2 - 4 MW)
- Offshore (3 - 6 MW)

The operation of onshore wind turbines in Germany is studied at 1800 to 3200 FLH per year as well as offshore wind power at 3200 to 4500 FLH per year.

Biogas power plants

- Biogas power plants (> 500 kW) with substrate (silo maize, swine manure, etc.)

For the entire time period applied in the analysis, a constant substrate price of 3.03 $€_{Cents}$/kWh is assumed since no cost increases are expected in the future (Scheftelowitz et al. 2016). The possible operation of a biogas plant as an electricity-heat cogeneration power plant with additional heat output and the corresponding profits are not accounted for in this study.

Conventional power plants

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

For comparison, the LCOE of new conventional power plants with different development paths for FLH as well as for prices of CO_2 emission certificates and fuels (brown coal, hard coal or natural gas) are analyzed.

Concentrated solar power plants (CSP)

- Parabolic trough power plants (100 MW) with thermal storage - parabolic

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

Of solar thermal power plant technologies, only parabolic trough technology is analyzed. Fresnel systems and tower power plants, which are currently being developed and built, are not considered in this study.

»Levelized Cost of Electricity: Renewable Energy Technologies« version March 2018 - Comparison to the previous studies

This study is an update of the versions from November 2013 (Kost et al, 2013), May 2012 (Kost et al, 2012) and December 2010 (Kost and Schlegl, 2010). The methodology and content have been improved and the current trends in cost development in the last four years have been taken into account.

Besides that, the LCOE of PV systems were expanded to include the combination of PV systems and batteries, which are installed by private persons and investors to profit from the self-consumption of electricity from their PV modules. The sizes of the PV systems are updated according to the current market situation (small rooftop PV between 5 and 15 kWp, large rooftop PV on commercial buildings between 100 and 1000 kWp and ground mounted utility scale PV plants from 2 MWp onwards).

In terms of wind energy, the low wind-speed turbines and high wind-speed turbines are not distinguished. Increasing FLHs are assumed for both onshore and offshore turbines, which correlates with the current market trend of increasing ratio between the rotor diameter and the nominal power of the generator, as well as the increasing hub height. This trend justifies the slight increase of the investment costs compared to 2013. However, the costs are expected to decrease again in the future.

Apart from that, both fixed and variable operational costs are considered for wind turbines. The fixed operational costs consist of the yield-independent repair and maintenance works, management, lease and insurance costs. Even the conventional power plants are designated with fixed and variable operational costs, which contributes to a significant amount in the LCOE as it consists of among others fuel and CO_2-certificate costs. Since there is a large uncertainty in the conventional power plants, a wide range of input parameters for fuel and CO_2 price as well as FLH are chosen. This is especially true for the CO_2-certificate prices, where a considerably wider range relative to the previous study is chosen here in order to portray the uncertainty.

Furthermore, the financial conditions for the power plants are more favorable in this study since the interest rate is currently much lower than in 2013. The average interest rate for 20 years in 2013 was around 2.6%. In contrast, the interest rate fell to 1.07% in 2017 (Status: November 2017). However, the possibility of an increase in the interest rate in the future cannot be neglected. Therefore, a smaller interest rate is used in this study relative to that in the previous version, which implies that an increase could be expected in the future.

2. HISTORICAL DEVELOPMENT OF RENEWABLE ENERGY TECHNOLOGIES

Throughout the past 15 years, the global market for renewable energies has experienced a strong growth (see Figure 3). In recent years, the market for renewable energies has been pushed forward by its growing competitiveness compared to conventional power plants. Furthermore, the commitment to long-term energy targets has created an even more stable climate for investments in renewable energies. Positive response can be seen from lawmakers in several countries towards the prospect of the scarcity and price increase of fossil energy sources as well as climate problems. At the same time, the emergence of more technology applications further profits the renewable energy technologies by making them more competitive even without investment supports.

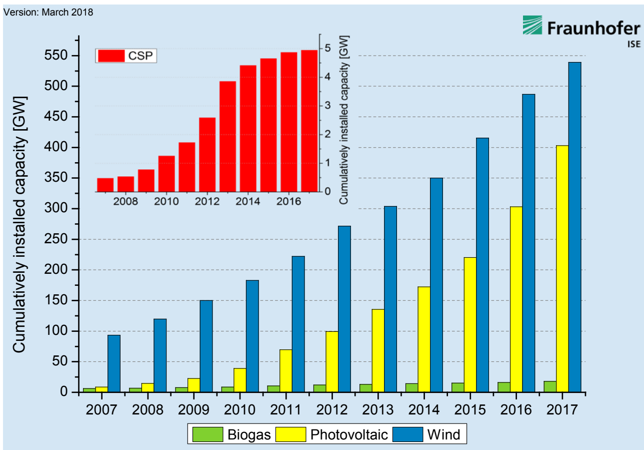

Figure 3: Global cumulatively installed capacity 2007-2017 of wind power, PV, biogas and CSP according to GWEC 2018, REN21 2017, and IRENA 2018 respectively. Values of 2017 are stated under reserve due to lack of sources to cross-check the data.

The strong market growth of renewable energies and the high investments in new power plants were accompanied by intensive research efforts, which led to improved system solutions with higher degrees of efficiency, lower production costs and lower operation costs. In combination with an increase in mass production, the specific investment costs and thus the LCOE of all technologies analyzed in this study, other than biogas power plants, could be significantly lowered. A further decrease of the LCOE will, in turn, lead to an increase of the market potentials of the technologies within the next years and will contribute to a continuing dynamic market development of renewable energies (AEE 2015).

The extent of the global expansion of renewable energy power plant capacities including large-scale hydropower plants increased significantly by the end of 2016 with a total installed capacity of more than 2000 GW (REN21 2017). In comparison, the current globally installed capacity of nuclear power plants amounts to just about 400 GW (IAEA 2018). While the installed capacity of nuclear power plants increased only by 9 GW between 2000 and 2012, the increase amounted to 266 GW for wind power and to about 100 GW for PV installations (Schneider M. and Forggatt 2013).

Due to different cost and market structures as well as support schemes, the markets for individual technologies have developed very differently. The market for wind power plants reached competitive market prices at an early stage and has therefore found markets in many countries even without incentive programs. The installed capacity of wind turbines currently sums up to 539 GW, with new installations reaching about 52 GW in 2017 (GWEC 2018). The installed capacity of PV adds up to approximately 403 GW at the end of 2017 and is thus lower than that of wind power. Nevertheless, with around 100 GW in 2017, significantly more capacity was added to PV power than to wind power (PV magazine 2018). In comparison, the new installation of wind power in 2012 was still above of PV. In Germany, the total installed wind power in 2017 amounts to just under 56 GW and thus has exceeded the total capacity of PV capacity of about 43 GW (Fraunhofer ISE 2017A).

The LCOE of wind power plants in locations with strong winds, which is competitive compared to conventional power generating technologies, has enabled the establishment of wind power plants in various markets, including in emerging and developing countries. Despite good growth forecasts for offshore wind power, problems in the implementation phase of new wind turbines have led to their current share of just over

3% of the total installed wind power capacity. A partially high prioritization of offshore wind energy is contrasted by high additional efforts for the technical implementation, which often leads to delays in project realizations.

The photovoltaic market has also become an important segment within renewable energies through the expansion of production capacity, particularly in Asia, where highly automated production lines are used. Considerable production overcapacities have led to high competition within the PV industry since 2009. Since 2011, this has led to significant price declines and sometimes unexpected market dynamics.

The market for biogas plants has grown the most in Germany in the last 10 years, followed by Austria and England. A market for biogas plants is increasingly developing in the USA as well as in China. The reason lies above all in the remuneration regulations of the respective countries.

In addition to the technologies described above, which are used in Germany, solar thermal power plants can play an important role for power generation in countries with higher irradiance. CSP power plants have been gaining market shares in some countries since 2007, following the first installations in the USA in the 1980s. A capacity of 5100 MW has now been installed (mainly in Spain and the USA) (data from our own market research). Especially in the sunny MENA countries (Middle East and North Africa), the concept of CSP plants is currently being pursued by political decision-makers due to the advantages of thermal energy storage and the possibility of high added local value.

For the forecast of the LCOE until 2035, this study uses learning curve models to estimate future developments. In particular, high LRs of up to 20% have been observed for wind technology and crystaline PV throughout the last 20 years (Fraunhofer ISE 2017B). The learning curve models are based on market scenarios for each technology with a forecast of the future market developments, which are taken from reference scenarios of various studies (Table 11 in the appendix). The technology-specific market scenarios give each technology a development horizon, which is influenced by numerous technological, energy-political and economic decision-making variables over the next twenty years. For all technologies, there is considerable uncertainty about the actual realizable market development until the year 2035, as this is very dependent on the amount of specific investments and usable full-load hours, the need to integrate storage options, the regulatory environment of the different markets and last but not least the price development of conventional energy sources. However, the actual market development of each technology is crucial for the temporal progress of decreasing trends in costs. The presented developments in LCOE are therefore potential development paths based on current market developments from various reference scenarios and technology specific assumptions such as LR and FLH.

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

Technology and financing parameters

A detailed explanation of the methodology of LCOE is found in the Appendix on page 37.

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

For PV, the upper and lower limits for the installation cost are differentiated according to the system sizes of small rooftop systems up to 15 kWp, large rooftop systemy up to 1000 kWp and ground-mounted PV systems. By using these costs, the LCOE for each point of time for investment and construction are calculated. The financial lifetime of PV is set to 25 years. Longer lifetimes and operation of PV are also reported by the plant monitoring of Fraunhofer ISE.

Data for offshore wind power plants is obtained by currently constructed and commissioned projects in the German North Sea and Baltic Sea. The input parameters for onshore power plants are also taken from currently planned or commissioned projects.

Electricity generation from biomass is solely calculated for power plants which burn biogas based on different substrates. The substrates used are swine manure und silo corn (with a share of 40% of silo corn). Heat generation in CHP biogas power plants is an important operational parameter and increases the economic value of the power plants. However due to the focus of this study on electricity generation, it is not included in the calculation of the LCOE. At this time there are many bioenergy power plants in operation. Power plant size is generally between 70 and 1000 kW_{el}, whereby power is generated using solid, liquid or gaseous bio-fuels. New power plants or expansions of power plants are being advanced primarily in the biogas sector (DBFZ 2012). Additionally, flexible power plants will be needed in future for the integration of fluctuating power generation from wind power and photovoltaic power plants (VDE 2012). Flexible operation of biogas power plants in load-following operation mode is possible. In this study, only LCOE of biogas power plants with a size of around 500 kW_{el} are calculated because power plants of this capacity currently hold the largest market share (Stehnull et al, 2011).

The following parameters are used in the calculation of LCOE for installation constructed at beginning of 2018 and in the future (Table 2). The financing parameters have been continuously analysed since the first studies in 2010, 2012 and 2013. The risk and investor structure of each type has been adapted. Currently, the available financing conditions are very attractive.

CAPEX [EUR/kW]	PV rooftop small (5-15 kWp)	PV rooftop large (100-1000 kWp)	PV utility-scale (> 2 MWp)	Wind onshore	Wind offshore	Biogas	Brown coal	Hard coal	CCGT	GT
Investment 2018 low	1200	800	600	1500	3100	2000	1600	1300	800	400
Investment 2018 high	1400	1000	800	2000	4700	4000	2200	2000	1100	600

Table 1: Specific CAPEX in EUR/kW of current power plant installations

Therefore, capital costs are assumed to be lower than in the study of 2013. It has to be noticed that the financing conditions (in the form of interest rate for debt and equity) might increase again, especially for future projects.

In many studies, the aspect of technology specific financing conditions is not sufficiently analyzed. Often, similar discount rates are assumed for all analyzed technologies and locations. This can lead to divergent LCOE compared to real LCOE. In this study, the discount rates are determined specifically for each technology by applying the market capital cost (and the parameter weighted average costs of capital – WACC) for each investment. The WACC consists of a share for the interest rate on debt and the return on equity. Large power plants constructed and operated by large investors and institutions have a higher WACC due to the expected return of the investor compared to small and medium size projects that are constructed by private persons or business partnerships. The return on equity expected by investors for technologies with lower maturity (e.g. offshore wind) are additionally higher compared to established technologies. It can be expected that the financial conditions will be equalized after increase of installed capacity as the risk premium for new technology sinks with increasing experience.
Since the WACC is derived from the usual interest rates and expected returns on the market, which are given in nominal values, the nominal value of the WACC is calculated first. This nominal value is then converted into a real value by taking an assumed 2% p.a. inflation rate into account.

The decisive factor for the calculation of the LCOE is that all payment streams are assumed at either nominal or real levels. A mixture of real and nominal values is incorrect and not permitted. To carry out the analysis on nominal values, the annual inflation rate has to be projected by 2035. Since the forecast for the inflation rate over the long term is very imprecise and difficult, cost predictions are generally completed using real values. All costs stated in this study therefore refer to real values from 2018. The LCOE provided for future years in the figures always refer to new installations in the respective years. The LCOE of a single project remains constant over its operational lifetime and is therefore identical to the value of the year of installation.

A second factor influencing return on equity is the project-specific risk: The higher the risk of default, the higher the return on equity required by the investor. In order to keep the capital costs low, a high share of debt with low interest rate is desirable. It is, however, also limited by the project-specific risk: The higher the risk of default, the lower the amount of debt that banks provide to the project. Since offshore wind parks continue to evince a high project-specific risk, the average capital costs are correspondingly higher than for comparable onshore projects.
If loans with low interest rates are available in sufficient amount, for example from the KfW-Bankengruppe, interest rates on debt of approximately 2 to 4% can be achieved depending on the technology. This is currently the case for small PV power plants, for which the effective interest rate of a KfW loan is currently only 2.63% for the highest rating class – with a 20-year maturity and 20-year fixed interest (KfW 2018). Since there is currently a very low rate of interest and this value is expected to increase, the interest rate on debt is set slightly higher to 3.5% for PV installations.

	PV rooftop small (5-15 kWp)	PV rooftop large (100-1000 kWp)	PV utility-scale (> 2 MWp)	Wind onshore	Wind offshore	Biogas	Brown coal	Hard coal	CCGT	GT
Lifetime [in years]	25	25	25	25	25	30	40	40	30	30
Share of debt	80%	80%	80%	80%	70%	80%	60%	60%	60%	60%
Share of equity	20%	20%	20%	20%	30%	20%	40%	40%	40%	40%
Interest rate on debt	3.5%	3.5%	3.5%	4.0%	5.5%	4.0%	5.5%	5.5%	5.5%	5.5%
Return on equity	5.0%	6.5%	6.5%	7.0%	10.0%	8.0%	11.0%	11.0%	10.0%	10.0%
WACC nominal	3.8%	4.1%	4.1%	4.6%	6.9%	4.8%	7.7%	7.7%	7.3%	7.3%
WACC real	1.8%	2.1%	2.1%	2.5%	4.8%	2.7%	5.6%	5.6%	5.2%	5.2%
OPEX fix [EUR/kW]	2.5% of CAPEX	2.5% of CAPEX	2.5% of CAPEX	30	100	4.0% of CAPEX	36	32	22	20
OPEX var [EUR/kWh]	0	0	0	0.005	0.005	0	0.005	0.005	0.004	0.003
Degradation	0.0025	0.0025	0.0025	0	0	0	0	0	0	0

Table 2: Input parameter for LCOE calculation. The real WACC is calculated with an inflation rate of 2%.

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

Local Conditions

Irradiance and Full Load Hours (FLH)

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

For that reason, exemplary locations with specific FLH for wind farms should be studied as well as locations with specific energy sources from solar irradiance (see Table 3). At typical locations in Germany, there is a global horizontal irradiance (GHI – consisting of diffuse and direct irradiance) in the range between 950 and 1300 kWh per square meter and year onto the horizontal surface (Figure 25). This corresponds to a solar irradiance between 1100 and 1510 kWh/(m²a) onto an optimally oriented PV power plant. After subtracting losses of electricity generation in the PV system, an average annual electricity yield between 935 and 1280 kWh per installed kWp is obtained.

The wind conditions are also location-dependent. Onshore wind turbines can reach FLH of only 1800 hours per year at unfavourable locations. The level of FLH, however, can reach values of up to 3200 hours at selected locations near the coast in Germany.

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

Biogas power plants are operated in Germany with a utilization rate of 80 – 90% (which refers to over 7000 FLH). Due to the flexibility premium in the EEG law, the power plants are increasingly operated by a flexible operation mode. This leads, however, to decreasing FLH. The objective of the flexibility premium is an increase of the flexibly electricity generation by biogas power plants. By this change, the fluctuating feed-in of solar and wind should be better balanced. Consequently, the range of FLH of biogas plants is assumed between 5000 and 7000.

PV plant (location)	Global horizontal irradiance [kWh/(m²a)]	Irradiance on PV modules with optimal angle of inclination [kWh/(m²a)]	Electricity generation per 1 kWp with optimal angle of inclination [kWh/a]
Northern Germany	950	1100	935
Central and Eastern Germany	1120	1300	1105
Southern Germany	1300	1510	1280
Wind power plant (2 - 5 MW)	**Wind speed at 120m 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 area Germany	7.8	3200	3200
Offshore: Short distance from coast	7.8	3200	3200
Offshore: Middle 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 power (Source: Fraunhofer ISE).

In comparison to most of the renewable energy technologies, conventional power plants generate their electricity output based on the hourly demand, cost of fossil fuels and the hourly merit order in the energy system. The current FLH of brown coal power plants is at 6950 hours on average. Coal-fired power plants are at 5850 hours and CCGT plants at 3500 hours on average in Germany (BMWI 2017a).

In the German energy transformation process, the increasing electricity generation from renewables reduces the FLH of conventional power plants. This study estimates continuously reducing FLH for all new conventional power plants (brown coal and coal -1% per year, CCGT -0.5%, gas turbines constant FLH). The average value of FLH for brown coal reduces to 5350 hours in 2035 and for CCGT to 3100 hours. Higher FLH can reduce the LCOE of fossil power plants and vice versa, as the market situation or demand development allows it.

Fuel Cost

Substrate costs vary considerably for biogas power plants. The costs differ owing to the options for purchasing substrates or using substrates generated by biogas operators in-house. Additionally, the shares of the various substrates differ between power plants. For example, in 2009, a biogas plant in Baden-Württemberg, utilized an average substrate mix which consisted of 30% liquefied manure, 5% solid manure, 43% silo maize, 12% grass silage, 5% whole plant silage (GPS) and 5% other substrate (Stehnull et al, 2011). In this , the methane yield for the individual substrates was between 106 Nm³/tFM (ton wet mass) for silo maize (Scholwin et al, 2011) and 12 Nm³/tFM for liquefied pig manure (Taumann 2012). Different costs accumulate for the substrates. Thus the substrate costs for the purchase of maize silage are around 31 EUR/tFM (Scholwin et al, 2011) and for liquefied pig manure around 3 EUR/tFM (DBFZ 2010). Substrate costs for substrate produced in-house can be assumed to be near zero. Average substrate costs of 0.03 EUR/kWh_{th} are assumed by considering the conversion of the methane yield and the methane energy production of 9.97 kWh/Nm³.

To compare the LCOE of renewable energy technologies and conventional power plants, assumptions about the efficiencies and CO_2 emissions of these power plants are needed. The assumptions for the typical power plant sizes are for brown coal between 800 and 1000 MW, for hard coal between 600 and 800 MW, for CCGT power plants between 400 and 600 MW and for gas turbines 200 MW. Through further technological improvements, the efficiency of new power plants will increase for brown coal from 45% to 48%, for hard coal from 46% to 51% and for CCGT from 60% to 62%. The price trends for fuels are assumed with very moderate increases. Due to a possible shortage of CO_2 allowances, a long-term increase of the allowance price is assumed (see Tables 4-6).

Fuel prices [EUR/MWh]	2018	2020	2025	2030	ab 2035
Brown Coal	1.8	1.8	1.8	1.8	1.8
Hard Coal	9.6	11.1	11.5	13.4	15.2
Natural Gas	21.0	25.1	27.1	32.2	33.8
Substrate Biomass	30.3	30.3	30.3	30.3	30.3

Table 4: Assumptions about fuel prices are based on values of (Prognos AG 2013; Hecking et al. 2017; Schlesinger et al. 2014; World Bank 2017; DLR Rheinland-Pfalz 2017; Scheftelowitz et al. 2016)

Efficiency conventional power plants [%]	2018	2020	2030
Brown Coal	45.0	46.5	48.5
Hard Coal	46.0	50.0	51.0
CCGT	60.0	61.0	62.0
Biomass	40.0	40.0	40.0

Table 5: Efficiency development in large power plants (Wietschel et al. 2010)

CO_2 certificate prices [EUR/t CO_2]	2018	2020	2025	2030	ab 2035
Lower value	5.3	5.0	12.5	20.0	30.0
Upper value	5.3	15.0	32.5	50.0	70.0

Table 6: CO_2 certificate price (own assumptions)

4. LEVELIZED COST OF ELECTRICITY OF ENERGY TECHNOLOGIES

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

In southern Germany, the LCOE for small PV rooftop systems at locations with GHI of 1300 kWh/(m²a) lies between 7.23 and 8.43 €$_{Cents}$/kWh while LCOE values between 9.89 and 11.54 €$_{Cents}$/kWh are reached at locations in northern Germany with an irradiance of 950 kWh/(m²a). The results depend on the amount of the specific investments, which is assumed to range from 1200 EUR/kWp to 1400 EUR/kWp. Rooftop PV power plants up to 1000 kWp can produce electricity at a LCOE between 4.95 and 6.18 €$_{Cents}$/kWh in southern Germany and between 6.77 and 8.46 €$_{Cents}$/kWh in northern Germany, each with specific investments between 800 and 1000 EUR/kWp. Ground-mounted PV power plants currently reach LCOE values between 3.71 and 4.95 €$_{Cents}$/kWh in

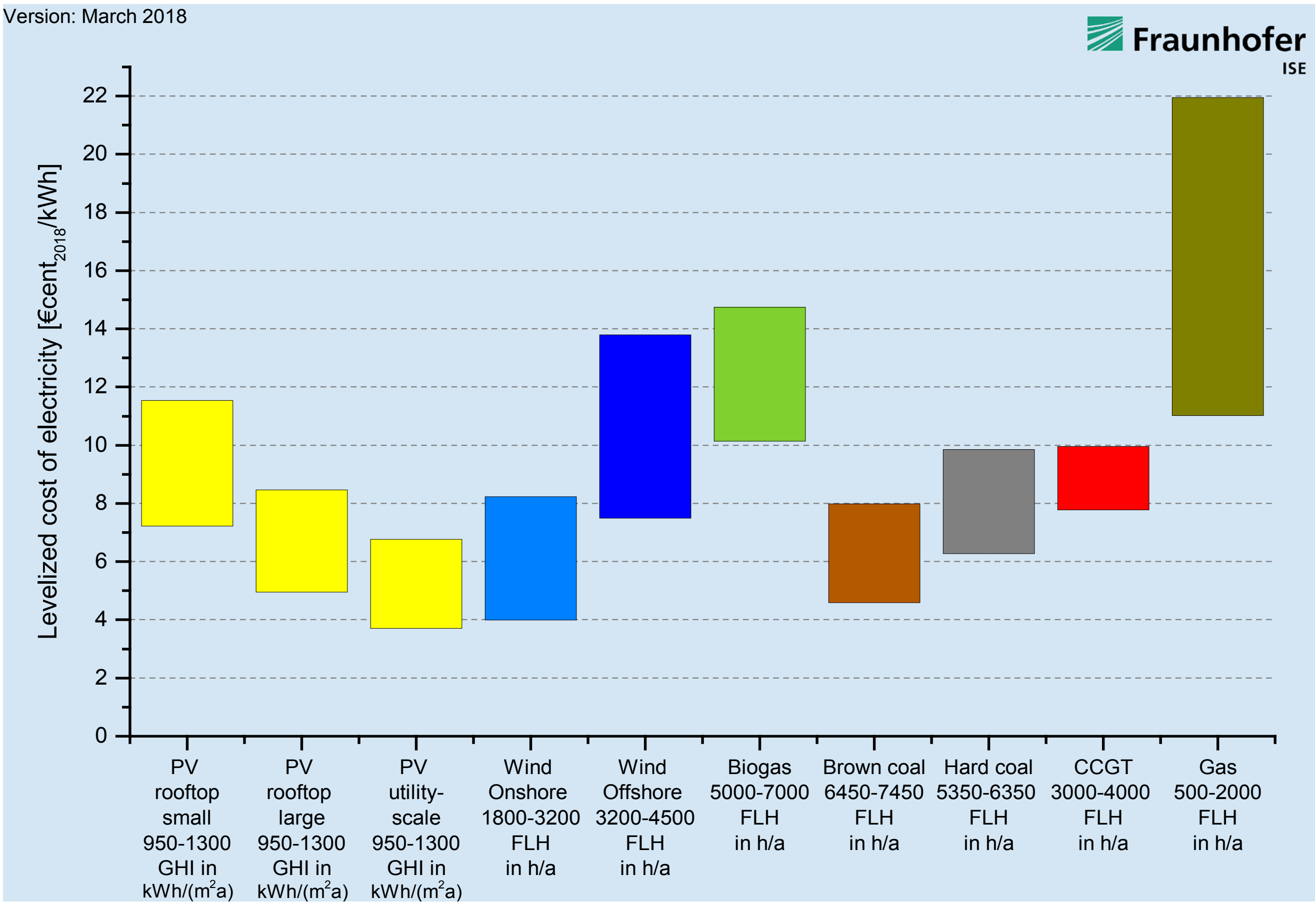

Figure 4: LCOE of renewable energy technologies and conventional power plants at different locations in Germany in 2018. The value under the technology refers in the case of PV to solar irradiance (GHI) in kWh/(m²a); in the case of other technologies it reflects the number of full load hours of the power plant per year. Specific investments are taken into account with a minimum and maximum value for each technology. Additional assumptions are presented in Table 4-Table 6.

southern Germany and between 5.08 and 6.77 €$_{Cents}$/kWh in northern Germany, with specific installation costs of 600 EUR/kW to 800 EUR/kW. Therewith, the LCOE of all kinds of PV systems in Germany is significantly lower than the average net electricity price for households of about 20 €$_{Cents}$/kWh excluding VAT (which corresponds to the net energy price of average electricity price for private households at 29 €$_{Cents}$/kWh as published by BDEW 2017).

The LCOE of onshore wind power with an average installation cost of 1500 EUR/kW and a very high annual FLH of 3200 hours is 3.99 €$_{Cents}$/kWh. However, such locations in Germany are very limited. LCOEs in less suitable locations in Germany range up to a value of 8.23 €$_{Cents}$/kWh, depending on the specific investment and the annual FLH (see Table 3). In comparison, the cost of offshore wind turbines is significantly higher, displaying values between 7.49 €$_{Cents}$/kWh and 13.79 €$_{Cents}$/kWh, despite higher FLH of 3200 to 4500 per year. The considerably more complex grid connection of offshore sites for the grid operator is not included in the electricity generation costs. The LCOE of biogas plants ranges between 10.14 and 14.74 €$_{Cents}$/kWh for substrate prices of 3.03 €$_{Cents}$/kWh$_{th}$.

Based on the current conditions on the electricity market with respect to FLH and fuel prices for each technology, the following LCOEs for conventional power plants are determined: Brown coal power plants built today achieve an LCOE between 4.59 and 7.98 €$_{Cents}$/kWh for the selected operation parameters (e.g. a very low CO_2 price today and a sharply rising CO_2 price in the future). The LCOE for hard coal shows slightly higher values between 6.27 and 9.86 €$_{Cents}$/kWh. CCGT power plants achieve values between 7.78 and 9.96 €$_{Cents}$/kWh, while the LCOE of gas-fired turbines is considerably higher, ranging between 11.03 and 21.94 €$_{Cents}$/kWh.

One must keep in mind that the LCOE calculation does not include the possible flexibility of a power generation technology or the worth of the generated electricity. For example, the specific seasonal and daily generation of each technology is different. Differences due to the flexible use of power plants or the provision of ancillary services in relation to the market sales price of electricity obtained are not reflected in the LCOE (see also Chapter 7).

Photovoltaics
Market development and forecast

At the end of 2017, the global installed PV capacity exceeded 400 GWp and the global expansion in 2017 amounted to around 100 GWp. This represents a market growth of over 30%, compared to the 76.6 GWp installed globally in 2016 (Hill 2017). Currently China dominates the global PV market in both production and installation. At the same time, more countries are installing PV on a significant scale, as PV plants increasingly prevail in free competition and can thus be implemented independent of subsidy programs. The PV market growth is now driven by purely economic reasons.

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

This leads to the assumption that the global PV market will continue to grow strongly. All three scenarios "High", "Medium" and "Low", upon which the study is based, assume a continuous reduction in annual market growth. The expected market growth of 30%, 25% or 20% for the respective scenarios ("High", "Medium" and "Low") will decline to 10% (for "High" and "Medium") and 5% (for "Low") respectively by 2035. For the year 2035, the three scenarios result in a total capacity of 9000 GWp, 5200 GWp and 3000 GWp respectively. The scenarios of the cumulatively installed power plant performance are shown in Table 10.

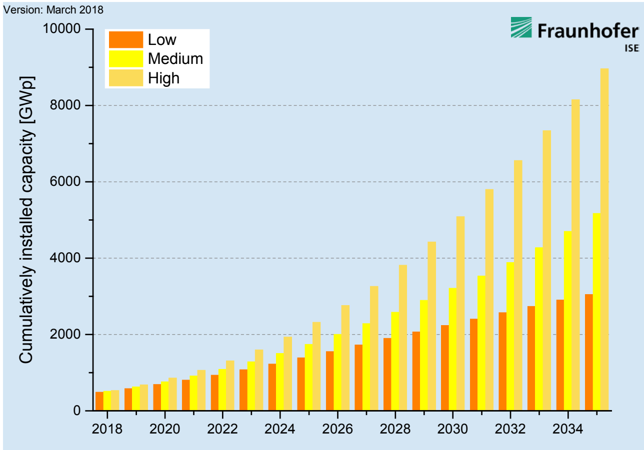

Figure 5: Market development scenarios of cumulatively installed power plant capacity [GW] for PV 2018-2035, own scenarios.

Development of prices and costs

Since 2016, wholesale prices for crystalline modules in Germany have dropped significantly from an average of just under 540 EUR/kWp (pvXchange 2018) to 440 EUR/kWp (BSW 2018) in 2018. The lowest net price for crystalline modules in the first quarter of 2018 was 340 EUR/kWp (BSW 2018). An approximation towards the price level of China could be observed: While the average wholesale price in 2016 still amounted to just under 530 EUR/kWp, it fell to almost 400 EUR/kWp in 2018 (as of the first quarter of 2018). In 2013, the price difference between the modules in Germany and China was significantly larger: While prices in Germany were around 770 EUR/kWp, in China they were significantly lower at 550 EUR/kWp.

The costs for inverters and balance of system (BOS) components like mounting system and cables, as well as their installation costs, dropped, though not as strongly as PV module prices. While in 2005, solar modules constituted almost 75% of the system costs, this share is around 50% today, even for rooftop PV systems. Table 1 shows the price bands for PV systems of different size classes. The costs for small PV systems (5 to 15 kWp) currently range from 1200 to 1400 EUR/kWp. For larger PV systems up to 1000 kWp, the costs currently amount to 800 to 1000 EUR/kWp. Ground-mounted utility-scale power plants with capacities above 2000 kWp show investment costs between 600 and 800 EUR/kWp. These values include all component and installation costs associated with the PV power plant. In some cases, investments below the specified price ranges can be realized under certain conditions of purchase.

The current LCOEs of PV systems are shown in Figure 6 for various power plant sizes and costs at different irradiance values (according to Table 3). The number following power plant size stands for the annual global horizontal irradiance at the power plant location in kWh/(m²a). Power plants in northern Germany produce approximately 935 kWh/(m²a), while power plants in southern Germany yield up to 1280 kWh/(m²a).

The strong decline in investment prices for PV power plants has led to significantly lower LCOEs compared to 2013. Ground-mounted utility-scale power plants in northern Germany can already achieve a LCOE below 5 $€_{Cents}$/kWh and in the south below 4 $€_{Cents}$/kWh respectively. The LCOE of large PV rooftop systems lies between 8.46 $€_{Cents}$/kWh in northern Germany and 4.95 $€_{Cents}$/kWh in southern Germany. Small PV rooftop systems in Germany generate electricity at LCOE between 11.54 and 7.23 $€_{Cents}$/kWh, and thus are well below the average electricity costs for households. As all PV technologies still have a clear potential for cost reduction, a continued decrease in the investment costs and consequently the LCOE in the medium to long term is to be expected – apart from possible price fluctuations due to special market events. Additionally, the lifetime of PV systems is also expected to increase. Today, many module producers already guarantee their module performance for over 25 years. In case of an increase of the lifespan of power plants from 25 to 30 years, the LCOE will sink by another 8.5%.

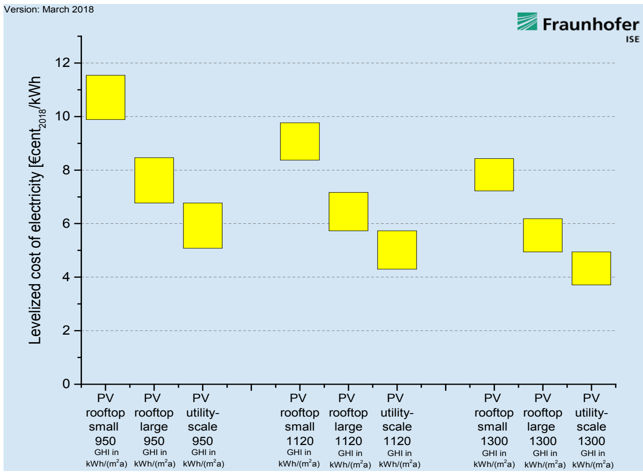

Figure 6: LCOE of PV plants in Germany based on system type and solar irradiance (GHI in kWh/(m²a)) in 2018.

A sensitivity analysis performed for a small PV plant in Germany demonstrates the LCOE's strong dependency on the solar irradiance and specific investments (see Figure 7). The sharp decline in the LCOE in the last years can be explained by the lower module prices. The influence of the capital costs for investment (WACC) on the LCOE is not to be underestimated, since the differences here can be relatively large and slightly outside of the parameter variance of 80 to 120% shown here. Operating costs change more slightly and have a smaller influence on the LCOE of PV plants, since they only constitute a minor share of the total costs. The system lifespan has a strong effect on the costs. With longer lifespans, plants that have already amortized continue to produce electricity at very low operating costs.

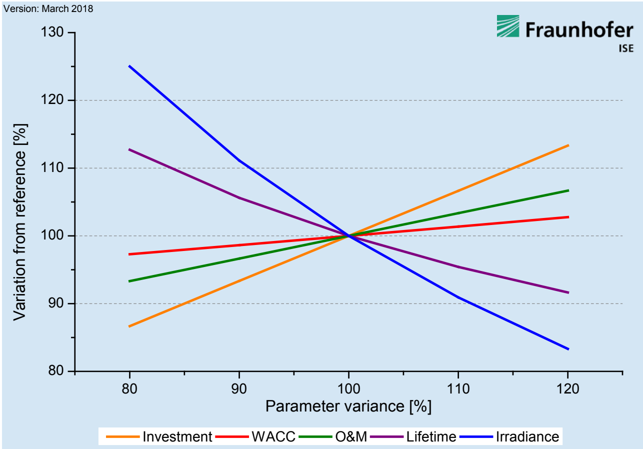

Figure 7: Sensitivity analysis of a small PV system with a GHI of 1120 kWh/(m²a) and investment of 1300 EUR/kW

Wind power plants

Of all renewable energy technologies, wind power currently has the strongest market penetration due to its competitiveness compared to conventional power generation. Initially strongest in the markets of Denmark and Germany, the world market in recent years has changed showing the strongest growth in China, India and the USA (GWEC 2013).

By the end of 2017, the total capacity of installed wind power has increased to over 500 GW. The market has shown continuous growth in the past. The total capacity of onshore wind is expected to reach more than 1100 GW in 2025 and about 1500 GW in 2030 (GWEC 2017a; GWEC 2017b). For offshore wind energy, a global total capacity of 65 GW in 2025 and of 126 GW in 2030 is expected (DW 2017, IRENA 2016).

The share of wind power in total electricity generation in Germany amounted to 17.6% in 2017, of which 14.5% came from onshore wind energy (Burger 2017). Wind energy continues to account for 46.6% of renewable electricity generation in 2017 (Burger 2017).

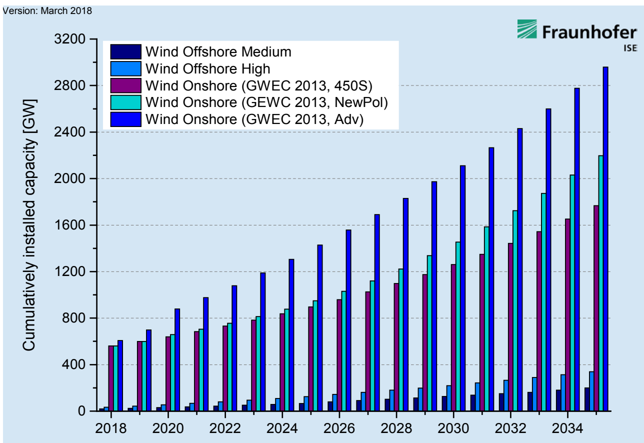

Figure 8: Market forecasts of cumulative wind power according to (GWEC 2013).

The LCOE of wind power is highly dependent on local conditions with respect to both onshore and offshore power plants, as well as on the achievable FLH. In general, locations with favorable conditions are distinguished from those with unfavorable wind conditions. Favorable locations have average wind speeds of more than 7.8 m/s. Locations with unfavorable locations are often located inland; the average annual wind speed is lower and the ground is rougher because of agriculture and forest cover.

A current trend indicates that manufacturers are striving to construct higher towers and increase the rotor area in proportion to the generator capacity. This corresponds with an effort to increase yields, enabling profitable operation also at locations with less favorable wind conditions. Higher towers and longer rotor blades, however, lead to greater material and installation costs that can only be justified by a significant increase in FLH. Thanks to ongoing technical refinement, an increase in FLH can be expected for future power plants and thus an annual increase in the FLH which would lead to improvements in the LCOE for wind power.

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

As shown in Figure 9, the LCOE of onshore wind turbines at coastal locations with favorable wind conditions with 3200 FLH ranges between 3.99 and 4.85 $€_{Cents}$/kWh. Locations with less-favorable wind conditions achieve LCOE values from 6.72 to 8.23 $€_{Cents}$/kWh, depending on the specific investments. If it is possible to achieve 2500 FLH at the respective location, the LCOE reaches values between 4.97 and 6.07 $€_{Cents}$/kWh, which is lower than the LCOE of new hard coal power plants.

In contrast, the analysis of current offshore wind power (including locations with higher FLH up to 4500) shows higher LCOE than onshore wind power. This is due to the necessary use of more resistant and expensive materials, the elaborate anchoring in the seabed, cost-intensive installation and logistics of the plant components and higher maintenance expenditure. However, a decrease in system costs and lower maintenance costs can be expected due to more reliable systems in the future. Currently, the LCOE of offshore wind turbines at very good locations ranges from 7.79 to 9.95 $€_{Cents}$/kWh. However, these locations are often distant from the coast and are disadvantaged by a complex and expensive network connection, as

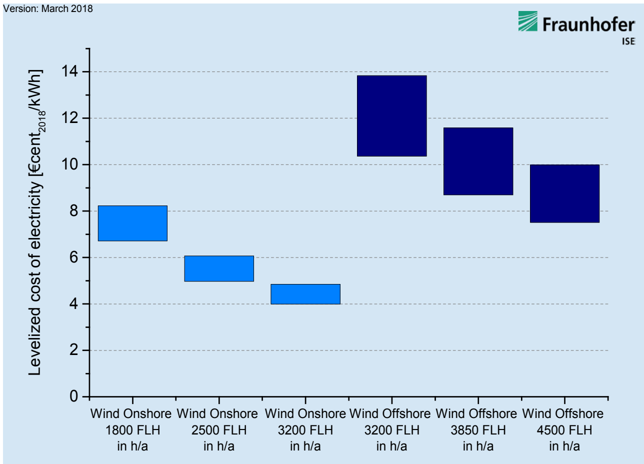

Figure 9: LCOE of wind power by location and full load hours in 2018.

well as the need to bridge the greater depth of the sea. Locations with less FLH (3200 h) show a LCOE between 10.33 and 13.79 $€_{Cents}$/kWh. This puts offshore wind turbines above the cost of electricity for onshore wind turbines under almost all conditions (and locations). The advantage of offshore installations is the higher number of FLH, as well as lower noise pollution and increased public acceptance, if minimum levels for the distance to the coast and environmental protection requirements are met. However, network connectivity problems still delay current offshore projects. These technology-specific risks lead to higher capital costs as well as well as demand for financial security from creditors, which results in higher WACC for offshore projects compared to onshore wind parks.

The margin for cost reductions in offshore wind power is limited by the large expenditures for installation and maintenance. Therefore, achieving parity with onshore wind power seems quite difficult at the moment. However, the past years have shown that project costs tend to decrease faster than expected with the realization of numerous projects. The sensitivity analysis for onshore wind power identifies savings in power plant investments as the primary goal for realizing future cost reduction potential. Similar to PV, the sensitivity analysis reacts strongest to this parameter. Furthermore, reducing maintenance costs can also make an important contribution.

Biogas power plants

The market for biogas power plants is characterized by numerous ups and downs. While around 600 MW were added annually from 2009 to 2011, the annual additional capacity was only about 240 MW in the following two years. In 2016, the total installed capacity of biogas power plants in Germany was more than 4200 MW (Fachverband Biogas 2017). Despite the expansion of biogas plants in Germany, observations show no reduction in specific investment costs in recent years. Indeed, the specific investment costs of installations even increased between 2005 and 2009 (Stenull et al., 2011). Therefore, no LR for biogas plants is assumed. In this study, heat offtake is not taken into account, in order to preserve the basis for comparison with the LCOE of other technologies. A heat credit is therefore not taken into account in the LCOE.

Figure 11 shows the LCOE of large biogas power plants (>500 kW_{el}) for different FLH. Furthermore, the specific investments between 2000 and 4000 EUR/kW are included in the calculations. Biogas power plants with high FLH and lower specific investment costs evidence a LCOE of at least 10.14 $€_{Cents}$/kWh. The LCOE of biogas plants with low FLH and high specific investments will be significantly higher and can reach up to 14.74 $€_{Cents}$/kWh. The largest determinant of the electricity production costs of biogas plants are the substrate costs, but FLH also have a major impact on the LCOE. The LCOE will drop by more than 0.75 $€_{Cents}$/kWh, if FLH are increased by 20%. In comparison, the LCOE drops by

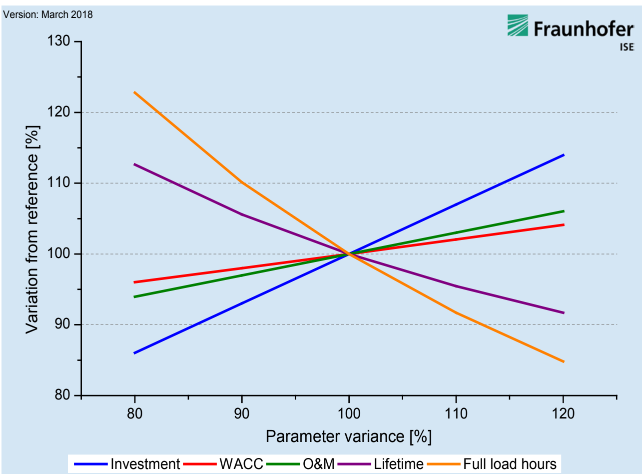

Figure 10: Sensitivity analysis of onshore wind power 2500 FLH, specific investment of 1800 EUR/kW.

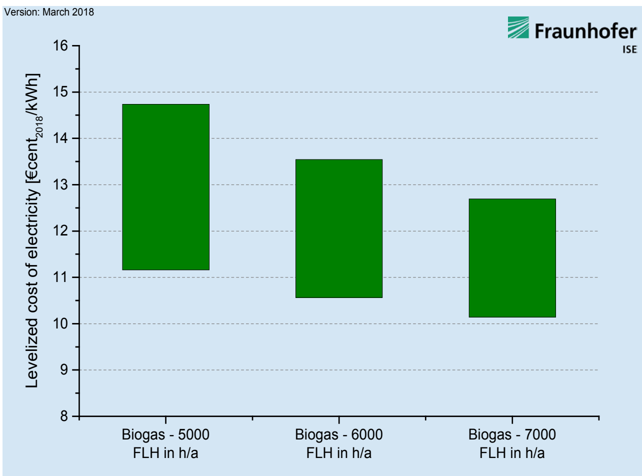

Figure 11: LCOE of biogas power plants at different FLH in 2018.

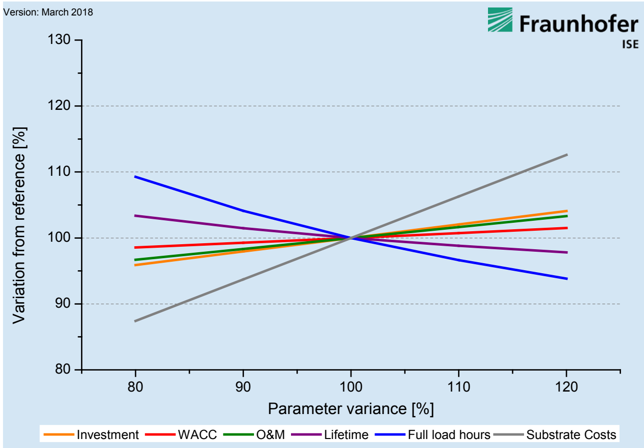

Figure 12: Sensitivity analysis for biomass power plants with specific investment of 3000 EUR/kW and 6000 FLH.

1.5 $€_{Cents}$/kWh if substrate costs are reduced by 20%. A change in the lifespan and the O&M costs has a smaller impact on the LCOE. If the lifespan were to be increased by 20%, the LCOE would merely decrease by 0.25 $€_{Cents}$/kWh; and if O&M costs were to be reduced by 20%, the LCOE would drop by 0.4 $€_{Cents}$/kWh. Of the observed parameters, a change in WACC has the least impact on the cost of electricity.

Conventional power plants

Market development and forecast

Coal-fired power plants

Worldwide, the installed capacity of coal-fired power plants is about 2000 GW, or 32% of the total global installed power plant capacity. In fact, the largest share of electricity worldwide is produced by coal-fired power plants (40%), followed by gas-fired power plants with 22% (IEA, 2017). China produces the largest amount of coal-generated electricity. At the same time, China is the largest consumer of coal worldwide with a share of 50%. The OECD countries of the Americas constitute the second largest market, followed by the Asian-Oceanic OECD countries. The fourth largest market is Eastern Europe and Eurasia, where the OECD countries of Europe currently have the lowest coal-fired electricity production. India, the Association of Southeast Asian Nations and South Africa are all future markets.

While net electricity generation from brown coal in Germany amounted to 30% and hard coal to 22% in 2012 (BNetzA 2018, Kost et al., 2013), the share of brown coal in net electricity production in 2017 was only 24% and that of hard coal about 15% (Fraunhofer ISE 2018). The installed capacity of brown coal and hard coal power plants has been virtually constant at 20.9 GW and 28.32 GW since 2002 (Fraunhofer ISE 2017). In the long term, brown coal capacities are expected to decline to 11.8 GW (50Hertz Transmission GmbH et al., 2013), and hard coal capacities to 20.2 GW by 2033.

Gas power plants

In 2017, a total gas power plant capacity of around 1700 GW was installed worldwide with an electricity production of 4299 TWh (EIA 2017), making natural gas the second largest source in electricity production worldwide. Over half of all gas-fired power plants are installed in OECD countries. The OECD countries in the Americas account for 27% of the worldwide installed capacity, followed by European OECD countries (15%) and Asian OECD countries (9%). In the non-OECD countries, Russia has the largest installed capacity of gas-fired power plants with 7%, due to its large gas reserves. The Middle East as a whole has a share of 14%. In China, 4% and in India 2% of the global capacity is installed respectively. The markets in Africa, Central and South America are currently very small. Big growth markets are Brazil - with a growth rate of 6% between 2008 and 2035 - and India. Furthermore, the markets in Africa, Mexico and Chile will grow strongly until 2035. Capacities are also slightly in decline in Russia and Japan (EIA 2017).

In 2017, gas-fired power stations accounted for around 8% of net electricity generation in Germany (Fraunhofer ISE 2018). Since 2002, the installed capacity of gas-fired power plants in Germany has increased from 20.3 GW to 29.9 GW. According to the grid development plan, an increase of the installed gas capacity to 30.5 GW – 37.8 GW in 2030 is assumed (50Hertz Transmission GmbH et al., 2017).

Price and cost development

The LCOE of gas and coal power plants is heavily dependent on the achievable FLH. In Germany, brown coal power plants currently reach FLH between 5000 and 7600, hard-coal power plants achieve FLH between 3500 and 6500 and CCGT achieve FLH between 2000 and 5000. The FLH, which can be achieved by a power plant, depend on the variable marginal costs of the individual power plant, since the usage of power plants on the market is determined by the merit order. As a result, the development of FLH is essentially dependent on a forecast of prices for fuel and CO_2 certificates, the development of feed-in of renewable electricity and the composition of the power plant park. Because these variables are dependent on developments on national and international markets, they are subject to considerable uncertainty. Therefore, a large range of values for FLH has been specified for these technologies.

Figure 13 shows the LCOE of conventional power plants using brown coal, hard coal, combined cycle gas turbines (CCGTs) and gas turbines for 2018, for a range of FLH, the CO_2 allowance price from Table 6, the fuel prices from Table 4 and for the minimum and maximum specific investments from Table 1.

Brown coal currently has the lowest LCOE, ranging from 4.59 to 7.98 $€_{Cents}$/kWh. As a classic base load power plant, however, brown coal-fired plants have a very low generation flexibility and are therefore only of limited use for flanking fluctuating renewable energy technologies. The LCOE of hard coal-fired power plants, despite their lower specific investment compared to brown coal, is significantly higher at 6.27 to 9.86 $€_{Cents}$/kWh. The LCOE of combined cycle power plants ranges between 7.78 and 9.96 $€_{Cents}$/kWh and are therefore slightly more expensive than coal-fired power plants. Advantages of the combined cycle power plants are their higher flexibility and lower specific CO_2 emissions compared to coal-fired power plants. Highly flexible gas turbines have even higher electricity generation costs at 11.03 and 21.94 $€_{Cents}$/kWh. They are, however, highly flexible and with fewer than 1000 FLH per year, are less expensive than other technologies due to their low acquisition costs.

To compare: PV ground-mounted systems at locations with global irradiance of 1300 kWh/(m²a) achieve a LCOE of 3.71 $€_{Cents}$/kWh, while onshore wind energy plants at locations with 3200 FLH have an LCOE of 3.99 $€_{Cents}$/kWh. As a result, the LCOE of ground-mounted PV systems and onshore wind turbines are well below the LCOEs of all conventional power plants. Figure 13 emphasizes the heavy dependence of the LCOE of conventional power plants on the achievable FLH. For CCGT plants, the variation in FLH of +/- 20% results in a LCOE difference of approximately +/- 0.4 $€_{Cents}$/kWh. The specific investments also have a significant impact on the LCOE, which in CCGT leads to a difference of 0.7 $€_{Cents}$/kWh at low FLH.

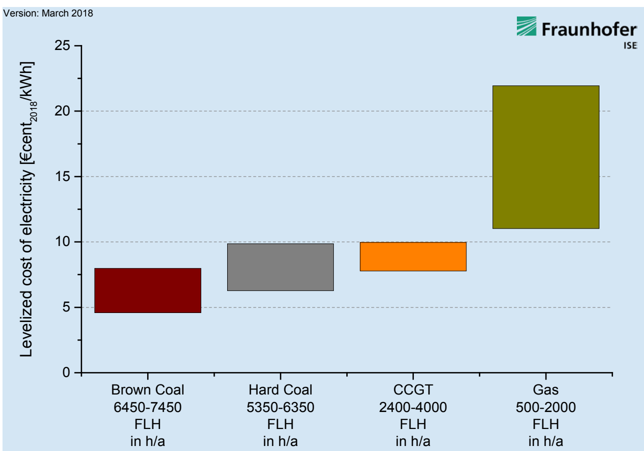

Figure 13: LCOE of conventional power plants in 2018 with varying CO_2 certificate and fuel prices as well as specific investments.

In the future, the FLH of conventional power plants will decline, with an increasing share of renewable electricity. Contrary to the trend in renewable technologies, the costs of conventional power plants will increase in the future. On the one hand, this trend results from rising prices for fossil fuel and CO_2 certificates, and on the other hand from the significantly lower amount of FLH expected for conventional power plants in the future. It can be assumed that it will not necessarily be the least expensive of the conventional power plants that remains successful on the market, but rather those power plants that show the highest flexibility for ramping up and down will prevail, i.e. natural gas power plants.

Photovoltaics with storage

Privately used PV systems are increasingly being installed in combination with battery storage systems. This chapter examines the the costs of electricity generation and storage for PV rooftop systems combined with battery storage. Battery storage helps increase the self-consumption, enabling the plant owner to increase savings especially during times of rising electricity prices and falling technology costs. Figure 14 schematically shows the energy flows of the electricity from the PV storage system. The electricity from the PV system is consumed directly in the household, when possible. At times of low consumption and high PV production, the battery storage can be charged. Furthermore, surpluses can be delivered to the power grid. For the calculation of the LCOE of PV battery storage, only the amount of energy, which is provided by the energy storage within the household, is considered (self-consumption through battery). Here, the costs for the stored PV electricity are included in the costs. The remaining electricity (direct consumption and feed-in to electricity grid) is represented with the LCOE calculated in the previous chapters.

Table 7 gives the input data used in calculating the LCOE for PV battery systems, which are to be installed in 2018 or 2030. The CAPEX of the battery storage are defined here as the net prices per useful capacity. The price data for lithium-ion batteries from the first half of 2017 together with an estimated price reduction for the beginning of 2018 are used. Since the battery

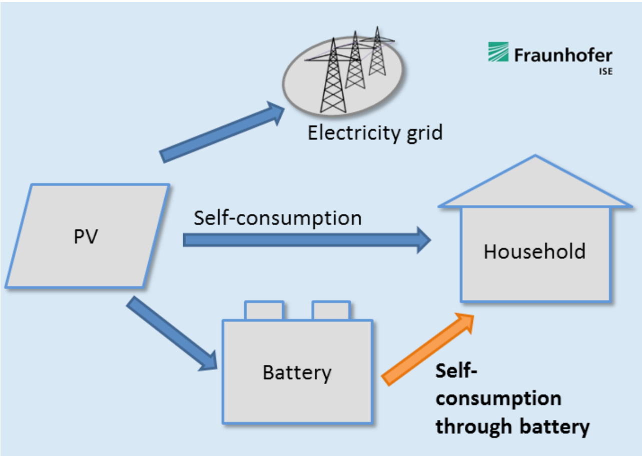

Figure 14: Schematic diagram of the energy flows of electricity from private PV rooftop systems

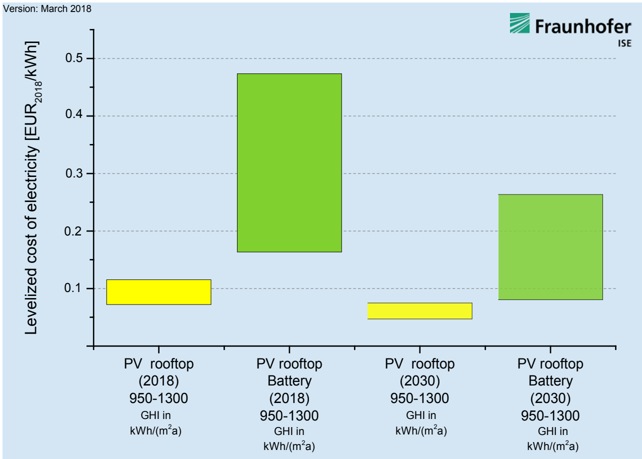

Figure 15: LCOE of PV battery storage in comparison to LCOE of PV rooftop systems

storage is usually installed simultaneously with a PV system, no additional installation costs are taken into account. The ratio of battery capacity to PV power determines the increase in self-consumption, which is to be achieved. This factor is used to adjust the battery costs to correspond to a PV power of 1 kWp. The analysis period is 25 years, concurring with the calculation of the LCOE of small PV systems. Within this period, one replacement of the battery, which is estimated at 60% of the original price, is assumed. The annual expenditures take into account the costs for the battery replacement and the costs for electricity from the PV system. The electricity production costs of small PV systems serve as the purchasing costs for the electricity consumed. The losses associated to charging and discharging as well as the self-discharge is taken into account when purchasing electricity. Since consumer prices for battery storage have dropped significantly over the past years and a further strong reduction is expected for the future, reduced costs for the year 2030 are assumed.

Figure 15 shows the LCOE for electricity from PV battery storage compared to electricity from small PV systems. The LCOE for PV battery storage currently ranges from 16.34 to 47.34 $€_{Cents}$/kWh. With battery prices from 200 to 650 EUR/kWh and reduced costs of PV, the LCOE falls to values between 8.05 and 26.35 $€_{Cents}$/kWh in 2030.

The fact that PV battery storage systems serve a different market than the other power generation technologies has to be taken into account: by increasing the self-consumption quota and exempting this electricity from taxes and levies (at a PV system capacity of less than 10 kWp), the electricity generated from the PV battery system can compete with the costs for electricity from the grid, which amount to around 20 $€_{Cents}$/kWh excluding VAT (which corresponds to the net energy price of average electricity price for private households at 29 $€_{Cents}$/kWh as published by BDEW 2017). Additionally, the fact that investors will always consider a mixed

Year of installation		2018		2030		
	Unit	Low	High	Low	High	Sources 2018
CAPEX Battery (net, per usable capacity)	EUR/kWh	560	1220	200	650	(Figgener et al. 2017, S.47) (assumed by using further annual price reduction, similar to the years 2013 to 2016)
Ratio of battery capacity to PV capacity	kWh/kWp	0.5	1	0.5	1	Own assumptions
Replacement cost of battery	% of CAPEX	60	60	60	60	Average purchase price (Lorenz, Schröder 2014)
WACC real	%	1.765	1.765	1.765	1.765	Own assumptions
Lifetime of first battery	year	10	10	15	15	Own assumptions
Efficiency of battery (roundtrip)	%	95	90	95	95	Own assumptions
Self discharge rate	%/month	1	1	1	1	Own assumptions
LCOE PV	$€_{cent}$ /kWh	7.23	11.54	4.70	7.50	See section 4
Increase of self-consumption rate through battery	%	20	30	20	30	As result of the ratio PV to battery (Weniger et al. 2015, S.29)
Financial lifetime	year	25	25	25	25	Own assumptions
Electricity generation of PV system	kWh/kWp	1280	935	1280	935	Own assumptions

Table 7: Input parameters for the calculation of LCOE from PV battery storage systems

calculation should be noted. When installing a PV storage system, a household can directly use part of the electricity at the favorable LCOE of the PV system. Another part of the electricity is temporarily stored and consumed via the battery. In addition, revenues are generated through the sale of PV electricity. Therefore, PV storage system can be an economical investment even at comparatively high electricity generation costs.

Prognosis for the LCOE up to 2035 in Germany

Cost forecasts can be generated for renewable energy technologies by using historically observed learning curves, whose progress over time builds on the different market forecasts for the timespan up to 2035. For PV and wind turbines, an average LR, or Progress Ratio (PR = 1 - LR), could be determined for the past 20 years: In the past, the investments per Watt of PV modules sank following a LR of 25% (Fraunhofer ISE 2017B). A LR of 15% is applied, as suggested by Bhandari and Stadler (2009) and Wirth (2017), for the LCOE of PV systems in the future. By comparison, a LR of 5% (moderate scenario, see Table 11) is used for onshore and offshore wind turbines (however, an increase in the FLH over time is assumed for wind energy).

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 16). Today, almost all newly installed PV systems in Germany can generate electricity for less than 14 $€_{Cents}$/kWh. With a global horizontal irradiance (GHI) of 950 kWh/(m^2a), even the costs for small rooftop plants will drop below 10 $€_{Cents}$/kWh in 2022. Larger ground-mounted plants already produce electricity for less than 4 $€_{Cents}$/kWh with an annual irradiance of 1300 kWh/(m^2a). In 2035, the LCOE will range from 4.20 and 6.71 $€_{Cents}$/kWh for small PV roof systems and between 2.16 and 3.94 $€_{Cents}$/kWh for ground-mounted installations. Large rooftop PV systems in Germany will be able generate electricity at LCOE between 2.88 and 4.92 $€_{Cents}$/kWh in 2035. Beyond 2025, even small rooftop PV systems in Southern Germany will generate electricity at a lower cost than newly installed hard coal or CCGT power plants, which will then generate electricity at a cost of 7.05 to 11.40 $€_{Cents}$/kWh. Plant prices for PV will decrease to less than 400 EUR/kW for ground-mounted systems up to 2035 and to 700 to 815 EUR/kW for small systems.

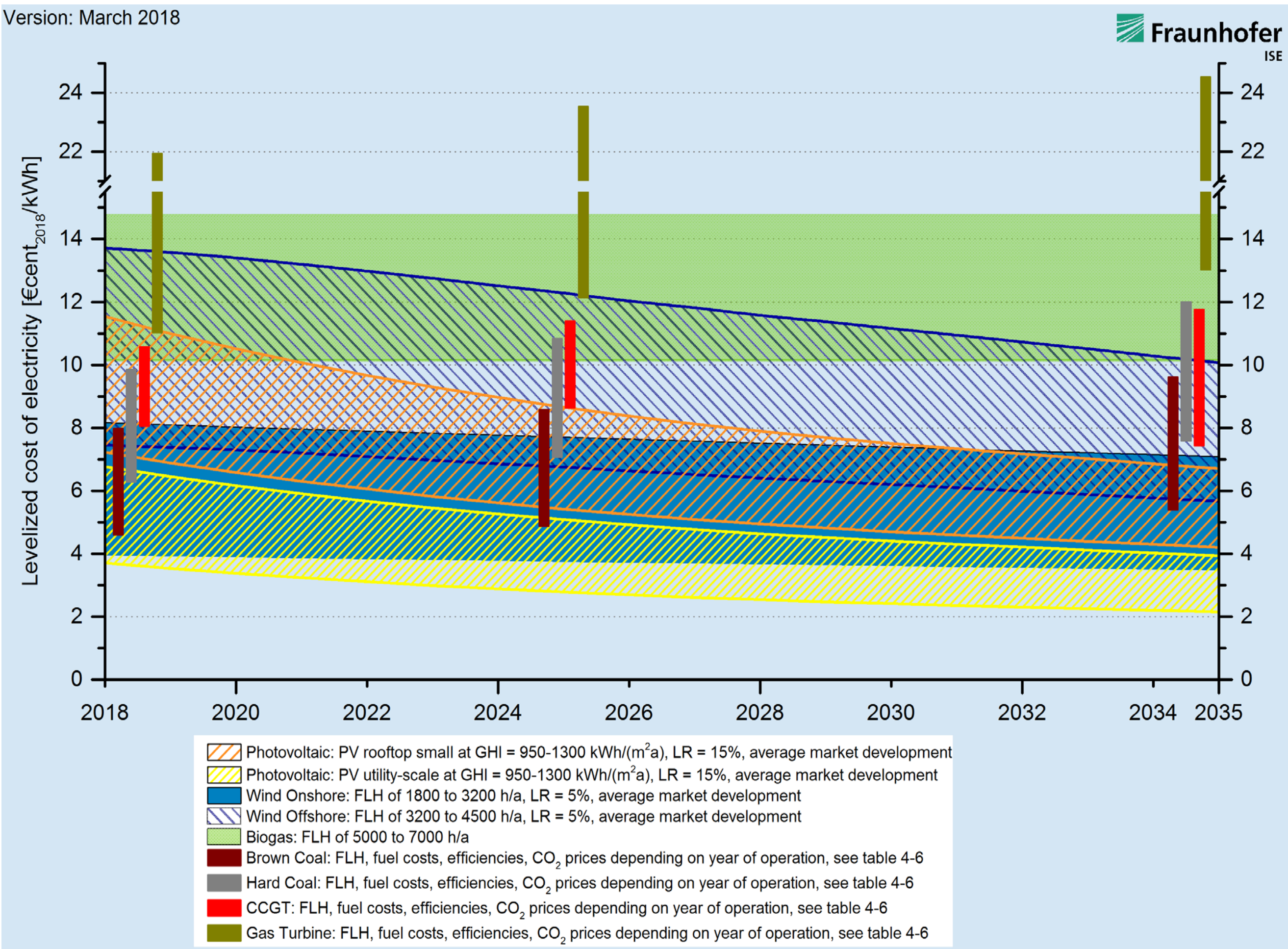

Figure 16: Forecast for the development of LCOE of renewable energy technologies as well as conventional power plants in Germany by 2035.

Depending on the location, onshore wind turbines can achieve comparable LCOE with PV power plants in good locations. From current LCOE between 3.99 and 8.23 $€_{Cents}$/kWh, the costs decrease in the long term to 3.49 and 7.09 $€_{Cents}$/kWh. Onshore wind turbines are already comparable to brown coal-fired power plants regarding their LCOE. Rising CO_2 certificate prices and decreasing FLH are the reasons for increasing LCOE for brown coal-fired power plants to between 5.35 and 9.62 $€_{Cents}$/kWh by 2035. In offshore wind turbines a slightly greater cost reduction potential would be available due to a stronger market growth. This can noticeably reduce the LCOE from the much higher levels until 2035. The LCOE is expected to decrease from 7.49 and 13.79 $€_{Cents}$/kWh to a range of 5.67 to 10.07 $€_{Cents}$/kWh in 2035. The system prices of offshore turbines lie between 2610 and 3950 EUR/kW. For biogas power plants, the LCOE is expected to range from 10.14 to 14.74 $€_{Cents}$/kWh. The availability and the fuel costs of the substrate are particularly crucial for the future LCOE development.

In the long term, both PV systems in regions with high solar irradiance and wind turbines located inland with profitable wind conditions have the lowest LCOE. Both technologies can significantly underprice the LCOE of fossil fuel plants by 2035. The developments in technology and costs in recent years have significantly improved the competitiveness of wind power and PV. Particularly in the case of PV, strong cost reductions could be implemented, so that PV and onshore wind power are the cheapest technologies for power generation (in terms of new power plants) in Germany. For wind turbines, the increase in FLH due to larger plant dimensions and the reduction in plant costs, significantly contribute to the low LCOE. The analysis of the LCOE in this study shows that forecasts for PV presented in the previous versions of this study (2010, 2012, 2013) are even undercut due to strong market growth and significant price reductions for PV systems. Another reason for this is that both technology and financing costs have become significantly cheaper.

Sensitivity analyses of the used learning curves for PV and wind

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

Figure 17 and Figure 18 show the range of LCOE for small PV installations and onshore wind power in Germany with respect to different combinations of LRs and market scenarios (see Table 10: Overview of LR and market scenarios for PV, CSP and wind power and Table 11: Overview of Scenarios and Development Targets for PV, CSP and wind power). Based on the assumed low costs, the LCOE values show variations of up to 15% depending on the parameters used. This demonstrates the uncertainty of the learning curve model when varying input parameters are used, yet at the same time, it reflects a potential range for the cost development of each technology.

For small photovoltaic systems at locations with a GHI of 950 kWh/(m²a), a LCOE between 4.70 and 6.96 $€_{Cents}$/kWh can be identified in 2035 depending on the scenario assumptions. For onshore wind energy, only minor future cost reductions are expected due to the currently low LCOE (between 3.38 and 3.57 $€_{Cents}$/kWh).

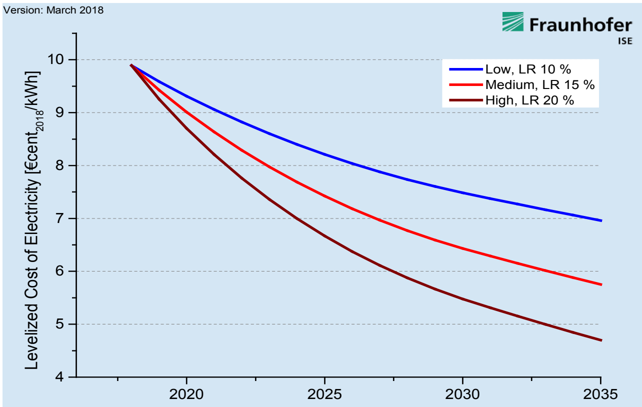

Figure 17: Sensitivity analysis for the LCOE forecast of small PV plants, investment costs in 2018 = 1200 EUR/kW, GHI=950 kWh/(m2a).

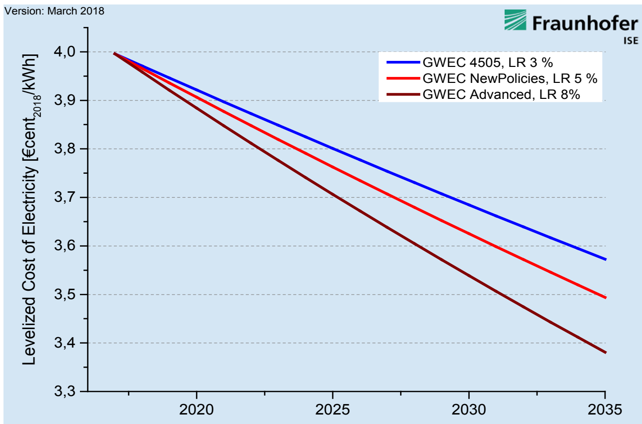

Figure 18: Sensitivity analysis for the LCOE forecast of Onshore-wind power, investment costs in 2018 = 1500 EUR/kWh, FLH are increasing from 3200 h/a in 2018 to 3500 h/a in the year 2035.

5. LCOE FOR RENEWABLE ENERGY TECHNOLOGIES IN REGIONS WITH HIGH SOLAR IRRADIANCE

This chapter analyzes photovoltaic (PV) and Concentrated Solar Power (CSP) plants for regions with very high solar irradiance and calculates the respective LCOE. Since CSP power plants can only be used to generate electricity under high direct irradiance, the analysis of CSP focuses on locations with a Direct Normal Irradiance (DNI) of 2000 kWh/(m²a) (for example in Spain) and locations with 2500 kWh/(m²a) (for example in the MENA countries). By integrating thermal salt storage, the generated thermal energy can be stored, which enables the plant to feed electricity into the grid independent from the current weather conditions or the time of day. This integrated storage option differentiates CSP from wind power and PV systems. Particularly the countries with a very strong direct normal radiation (DNI) have developed extensive expansion plans for CSP power plant projects, often in sunny desert areas (New Energy Update 2017).

As of the beginning of 2018, 4.5 GW of CSP power plants are installed globally. Further plants with a total capacity of 5 GW are currently either under construction or in the planning and development phase. Particularly, the Chinese market has been targeting new CSP power plants in recent years.

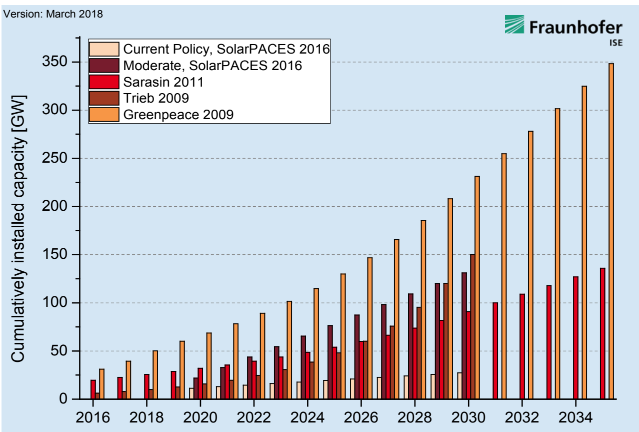

Figure 19: Market forecast for cumulative power plant capacity for CSP from 2016-2035, (Sarasin Bank 2011), (Trieb et al. 2009), (Greenpeace 2009), (Greenpeace International et al. 2016).The values of the Sarasin and Greenpeace scenarios beyond 2030 have been extrapolated in order to calculate the system price until 2035 using the learning curve model (see chapter 7)

The analysis of LCOE for CSP power plants is based in particular on the data of realized power plant projects of parabolic trough and tower technology in Spain, the USA and the Middle East. The installation costs of CSP systems with integrated storage for 8 hours was between 3600 and 4000 EUR/kW at the beginning of 2018.

Among solar thermal power plant technologies, only those, which are currently being developed and constructed (parabolic trough and tower plants), will be examined. To simplify, they are represented as one technology called "CSP". The study examines 100-200 MW parabolic trough power plants, which are equipped with thermal storage (8 hours). Information from the reference power plants, site-specific irradiation, proportion of natural gas used for hybrid operation (<5% of total electricity production) and plant-specific output serve as a basis for calculating the LCOE of solar thermal power plants.

Solar thermal power plants only concentrate DNI into a focal point where it is converted into electricity or heat. Therefore, for both technologies, only locations with an annual DNI of 2000 and 2500 kWh/(m²a) are considered, as described e.g. in southern Spain and in the MENA countries. On the other hand, three different sites are assumed to calculate the LCOE of PV. The first location with the lowest global radiation of 1450 kWh/(m²a) is only studied for a PV system, as the DNI at this location is too low for CSP. PV systems is also examined at respective locations with a global irradiance (GHI) of 1800 kWh/(m²a) and 2000 kWh / (m²a).

In comparing the LCOE of PV systems and CSP power plants at locations with high irradiance (DNI of 2000 kWh/(m²a)) for 2018, the PV plants show lower LCOEs compared to CSP. The LCOE of CSP power plants with integrated heat storage (FLH up to 3600 h) is currently below 10.12 $€_{Cents}$/kWh, while ground-mounted PV systems with the same amount of irradiance reach a LCOE below 3.1 $€_{Cents}$/kWh. To compare, the LCOE of onshore wind turbines at a site with 2500 FLH ranges between 5.34 and 6.55 $€_{Cents}$/kWh.

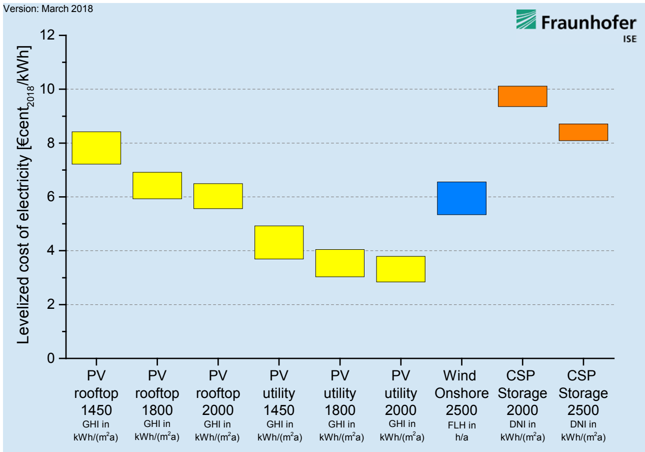

Figure 20: LCOE for renewable energies at locations with high annual solar irradiance in 2018.The values under the technology refers to solar irradiance in kWh/(m²a) (GHI for PV),kWh/(m²a) (DNI for CSP) and h (full load hours for wind power plants).

The LCOE of the analyzed CSP power plants with storage ranges from 9.36 $€_{Cents}$/kWh to 10.12 $€_{Cents}$/kWh at a DNI of 2000 kWh/(m²a). In regions with higher solar irradiance of up to 2500 kWh/(m²a), such as in MENA states or deserts in California, LCOEs between 8.09 and 8.71 $€_{Cents}$/kWh can be achieved for CSP power plants.

Cost reductions in CSP technology can be expected for the upcoming years due to market growth and increased mass production, higher levels of automation, project experience, the use of improved materials and components as well as due to further major projects. The reported feed-in tariff of US$ 7.3/kWh for a power plant in Dubai with 700 MW (consisting of the parabolic trough and tower technology), which is expected to be operational by 2022, can be seen as a positive signal for the cost development of CSP. Moreover, CSP is the only technology up to now that has the possibility of a large scale inclusion of storage. With the expanding use of renewable energies, this brings an increasingly bigger advantage that has not yet been acknowledged enough on the market.

The sensitivity analysis shows that a 20% reduction of investment compared to the reference case (8.09 $€_{Cents}$/kWh) would result in an LCOE of 6.97 $€_{Cents}$/kWh (see Figure 21). A higher DNI has a similarly strong, positive impact on the LCOE.

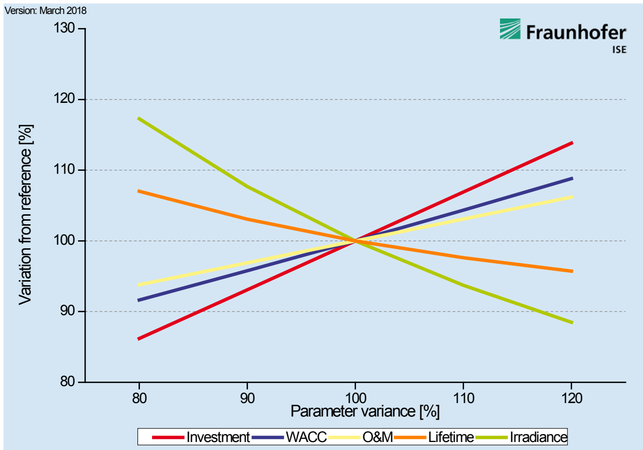

Figure 21: Sensitivity analysis of CSP (100 MW with storage) with an annual irradiance DNI of 2500 kWh/(m²a) and specific investment of 3600 EUR/kW.

PV plant	Global horizontal irradiance [kWh/(m²a)]	Irradiance on PV modules with optimal angle of inclination [kWh/(m²a)]	Electricity generation per 1 kWp [kWh/a]
Southern France	1450	1670	1380
Southern Spain	1800	2070	1680
MENA	2000	2300	1790

CSP plant	Global horizontal irradiance [kWh/(m²a)]	Direct normal irradiance (DNI) [kWh/(m²a)]	Electricity generation per 1 kW [kWh/a]
Southern Spain	1800	2000	3300
MENA	2000	2500	4050

Table 8: Annual yields at typical locations of PV and CSP (Source: Fraunhofer ISE)

For the technologies, the following assumptions have been made for the calculation:

	CSP	PV rooftop small (5-15 kWp)	PV utility-scale (> 2 MWp)	Wind-Onshore
Lifetime [years]	30	25	25	25
Share of debt [%]	70	80	80	80
Share of equity [%]	30	20	20	20
Interest rate on debt (nom) [%]	6.5	5.5	5.5	6.0
Return on equity (nom) [%]	11.0	7.0	8.5	9.0
WACC nominal [%]	7.9	5.8	6.1	6.6
WACC real [%]	4.7	2.7	3.0	3.5
OPEX fix [EUR/kW]	0	2.5% of CAPEX	2.5% of CAPEX	30
OPEX var [EUR/kW]	0.028	0	0	0.005
Degradation	0	0.0025	0.0025	0

Tabelle 9: Input parameters for LCOE calculation for energy technologies in regions with high solar irradiance

Forecast of LCOE until 2035 for solar technologies with high solar irradiance

The forecast of electricity generation costs up to the year 2035 is also carried out for PV and CSP at locations with high solar irradiance. Investigations by the German Aerospace Center DLR provide different LRs for the individual components (solar field, thermal storage, power block) with values ranging between 2% and 12% for CSP power plants (Viebahn et al., 2008, Trieb et al. at. 2009). From this, an average LR of 7.5% can be calculated, which refers to the total power plant. Other studies assume LR with values of 10% (Greenpeace 2009) or 4% - 8% (Sarasin Bank 2011).

By 2035, the LCOE for CSP can be reduced to values between 5.75 and 6.93 $€_{Cents}$/kWh, as shown in Fig. 22. The extent, to which the installation of CSP will be driven in markets with high irradiance in the next years, will be crucial for CSP.

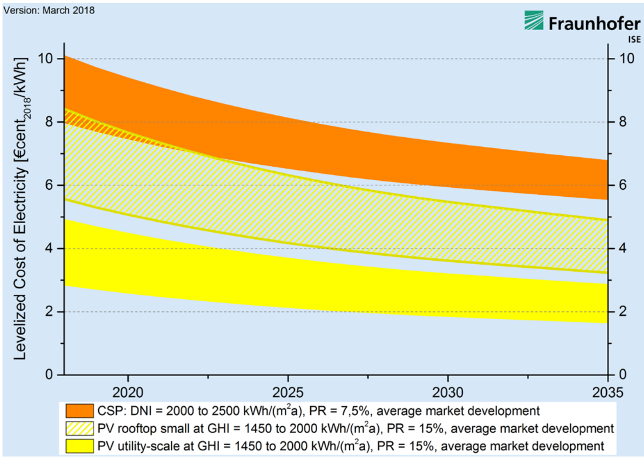

Figure 22: Development of LCOE for PV and CSP at locations with high solar irradiance kWh/(m²a).

6. OUTLOOK: LCOE AND SYSTEM INTEGRATION OF RENEWABLE ENERGY TECHNOLOGIES

The steady decline in the LCOE of renewable energy technologies, as well as the increasing costs for fossil power plants, leads to an ever better competitive position of renewable energy technologies, which leads to rapidly growing applications and markets, in which an economic operation of renewables is feasible without subsidies. This is also underlined by the results of the auctions for photovoltaics and onshore and offshore wind with very low bid values in Germany in 2017 (BNetzA 2017). In Germany, this development is politically supported by the federal government's energy concept with the target of reducing greenhouse gas emissions by 80-95% by 2050 compared with 1990 levels while phasing out of nuclear energy by 2022. Many studies have demonstrated that renewable energies will play the central role in a future energy system (Leopoldina, acatech, Akademienunion 2017).

The increasing installation of fluctuating power generating sources and the associated higher shares in the power supply will lead to a fundamental change in the power supply system. This means that the interaction of the individual components and actors will change. In addition to the LCOE, other factors play a decisive role in the analysis and evaluation of a technology in the energy system. For example, the "value" of the electricity will become more important, which means its availa-

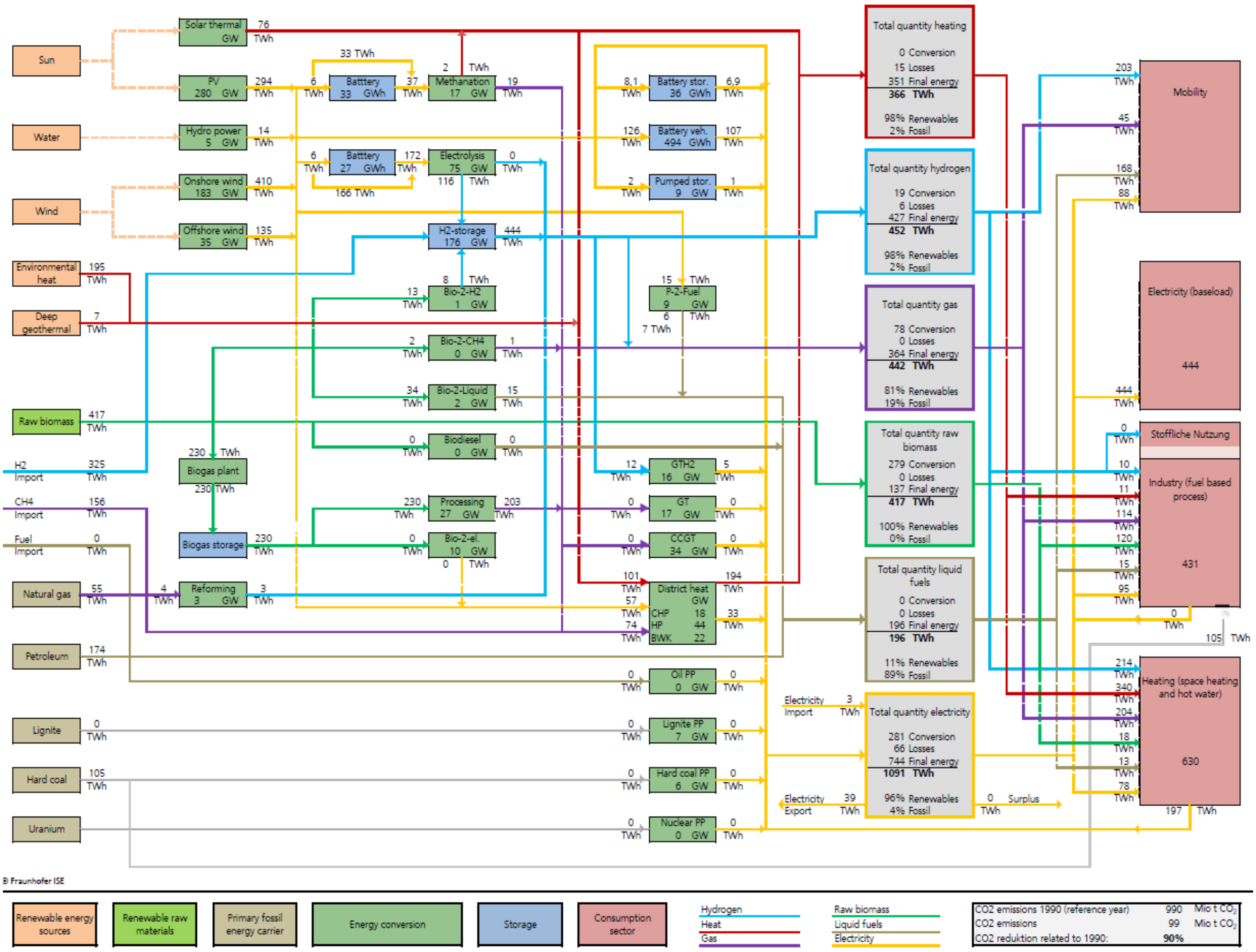

Figure 23: Scheme of the energy system depicted in the simulation model REMod with exemplary values of a scenario in 2050. The diagram shows all conversion paths from fossil primary energy or renewable energies to the respective consumption sectors

bility in times of high demand, the controllability of plants and the ability to take over system services such as the provision of reactive power or the stabilization of frequency and voltage. There are various possible combinations of how such an energy system can be designed at the national, regional and local level.

Given the assumption that demand can be met at all times, energy system models can either provide a cross-sectoral energy system for a set goal, such as CO_2 reduction (see results of the REMod model (Henning and Palzer 2015, described in Henning and Palzer (2013)), or for the electricity sector with a high share of renewable energy technologies (e.g. ENTIGRIS (www.entigris.org)).

The energy system model REMod, which has been developed at Fraunhofer ISE, looks at the entire energy system, considering the many different interfaces and points of contact between the different sectors (electricity, heat, transport, industry etc.) (see Figure 23). The basic functionality of the model REMod is based on the cost-based structural optimization of an energy supply system whose energy-related CO_2 emissions do not exceed a given target value or target path. REMod calculates an optimized transformation path, so that all relevant generators, converters and consumers are dimensioned to minimum costs and that the energy balance of the entire system is met at every hour. Thus, a techno-economic evaluation of transformation paths of the German energy system from today until the year 2050 can be carried out and the role of individual technologies can be analyzed.

For an appropriate mapping of the development of renewable energy technologies, the spatial distribution of resources should always be considered as an important factor, since different possibilities for investment in technologies arise for each location. The energy system model ENTIGRIS is an optimization model for the expansion of German and European electricity sector, which can be used to analyze optimal distribution of renewable and conventional power plants as well as grid expansion in high regional resolution (see figure 24).

To answer the question of how such a target system can be achieved, it is important to identify the transformation pathway of the energy system in achiving the target system. Various factors are important for the transformation: politically driven incentives, framework conditions or technical restrictions as well as the economic viability of technologies. It is therefore important to analyze the conditions which are favorable for an investor to invest in the different components of the energy system. The LCOE and its development into the future can facilitate this analysis and the investment decision making.

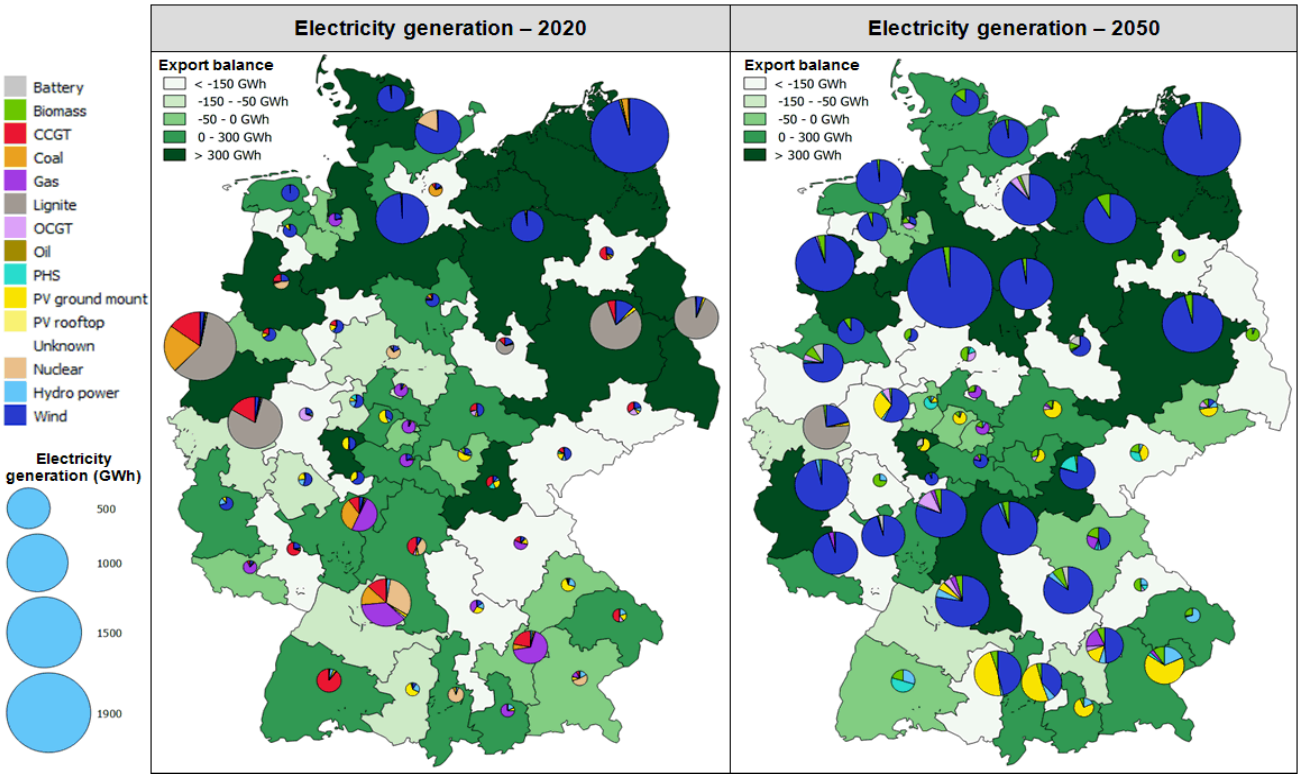

Figure 24: Development of installed capacity in Germany until 2050 as example results from the model ENTIGRIS (Heendeniya, C.B., 2017)

7. APPENDIX

Calculation of LCOE

The method of Levelized Cost of Electricity (LCOE) allows a comparison of power plants with different generating and cost structures. The LCOE results from the comparison of all costs, which arise throughout the lifetime of the power plant for the construction and operating of the plant, with the sum of the generated amount of energy throughout the life cycle. The calculation can be conducted either on the basis of 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 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 LCOE for new 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 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 the LCOE:

Total Annual Costs A_t =
Fixed operating costs
+ Variable operating costs
(+ residual value/disposal of the plant)

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

The 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. Self-consumption regulations, tax legislation and realized revenues of the operators complicate the calculation of a feed-in tariff from the results of 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 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 the 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, the 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 and 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, the 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 the LCOE based on the annuity methods offers the advantage of a lower calculation effort, 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 the LCOE best represents the reality, the LCOE in the present study are calculated on the basis of the NPV method.

Learning curve models

In addition to the analysis of the LCOE for 2018, it is possible to calculate the future development of plant prices and the corresponding LCOE with the help of learning curves generated using the market projections through 2020 and 2035. The learning curve concept represents a relationship between the cumulative produced quantity (market size) and the decreasing unit costs (production costs) of a good. If the number of units doubles and the costs decrease by 20%, this is called a Learning Rate (LR) of 20% (Progress Ratio PR = 1 - learning rate). The relationship between the quantity x_t produced at the time t, the cost $C(x_t)$ compared to the output quantity at the reference point x_0 and the corresponding cost $C(x_0)$ 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 the system prices $C(x_t)$ for the considered period using the learning curve models (assuming literature values for LR or PR), the LCOE can thus be calculated by the year 2035. In conjunction with market scenarios for the future years, respective annual figures can be assigned to the cumulated market sizes, so that the development of LCOE can be predicted temporally independent.

Evaluation of the methodology and use of LCOE

The LCOE 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. Lai and McCulloch 2016, p.2, Liu et al 2015, p.1531, Orioli and 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, the 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 and 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 the only 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.

The LCOE can be used to support decision-making. However, conclusive statements about the economic viability of a technology cannot be made on the basis of a single analysis with the LCOE method. Still, it should be noted that the LCOE is a cost-based figure and does not include revenues.

Data Appendix

	Low	Medium	High
2016	306	306	306
2017	410	410	410
2018	492	512	533
2019	585	630	682
2020	690	762	859
2021	808	915	1065
2022	937	1089	1311
2023	1078	1285	1599
2024	1229	1503	1935
2025	1389	1744	2322
2026	1555	2006	2763
2027	1726	2286	3261
2028	1899	2584	3815
2029	2070	2894	4426
2030	2236	3212	5090
2031	2403	3533	5802
2032	2572	3887	6557
2033	2739	4276	7344
2034	2903	4703	8151
2035	3048	5174	8967

Table 10: Development of the global cumulative installed capacity of PV [GW]

Technology	Learning rate (LR)	Market scenario	Variation of the LRs	Variation of scenarios
PV rooftop small	15 %	Medium scenario	20%, 10%	ISE low, ISE high
PV rooftop big	15 %	Medium scenario	20%, 10%	ISE low, ISE high
PV Utility scale	15 %	Medium scenario	20%, 10%	ISE low, ISE high
Wind Onshore	5 %	Onshore Wind moderate	8%, 3%	GWEC 450S, GWEC Advanced
Wind Offshore	5 %	Offshore Wind	-	-
CSP	7.5 %	Average scenario	10%, 4%	Sarasin 2010, Greenpeace 2009
Biogas	-	-	-	-
Brown coal	-	-	-	-
Hard coal	-	-	-	-
GuD	-	-	-	-
Gas turbines	-	-	-	-

Table 11: Overview of the LR and the market scenarios of analyzed technologies

Technology	Scenario	Source	2020	2035 (if not stated otherwise) [GW]	Applied in the calculations
Wind offshore	Offshore Wind	ISE, EWEAwind power	54	339 (2030)	X
Wind onshore	Onshore Wind moderat	GWEC 2013, moderate (adjusted by ISE)	658	2196	X
Wind onshore	Onshore Wind advanced	GWEC 2013, advanced (adjusted by ISE)	879	2959	
PV	IEA Roadmap Vision	IEA, 2010	390	1446	
PV	Medium-Scenario	ISE	763	5174	X
PV	EPIA Policy Driven	EPIA, 2013	759	2695 (2030)	
PV	EPIA Business as Usual	EPIA, 2013	464	1591 (2030)	
PV	Sarasin extrapolated	Sarasin Bank, 2011	710	1853 (2030)	
CSP	Sarasin 2011	Sarasin Bank, 2011	32	91 (2030)	
CSP	Greenpeace 2009	Greenpeace 2009	69	231 (2030)	
CSP	Trieb 2009	Trieb et. al., 2009	16	150 (2030)	X
CSP	Current Policy	SolarPACES, 2016	11	27 (2030)	
CSP	Moderate Policy	SolarPACES, 2016	22	131 (2030)	

Table 12: Overview of the scenarios and expansion goals for PV, CSP and wind energy

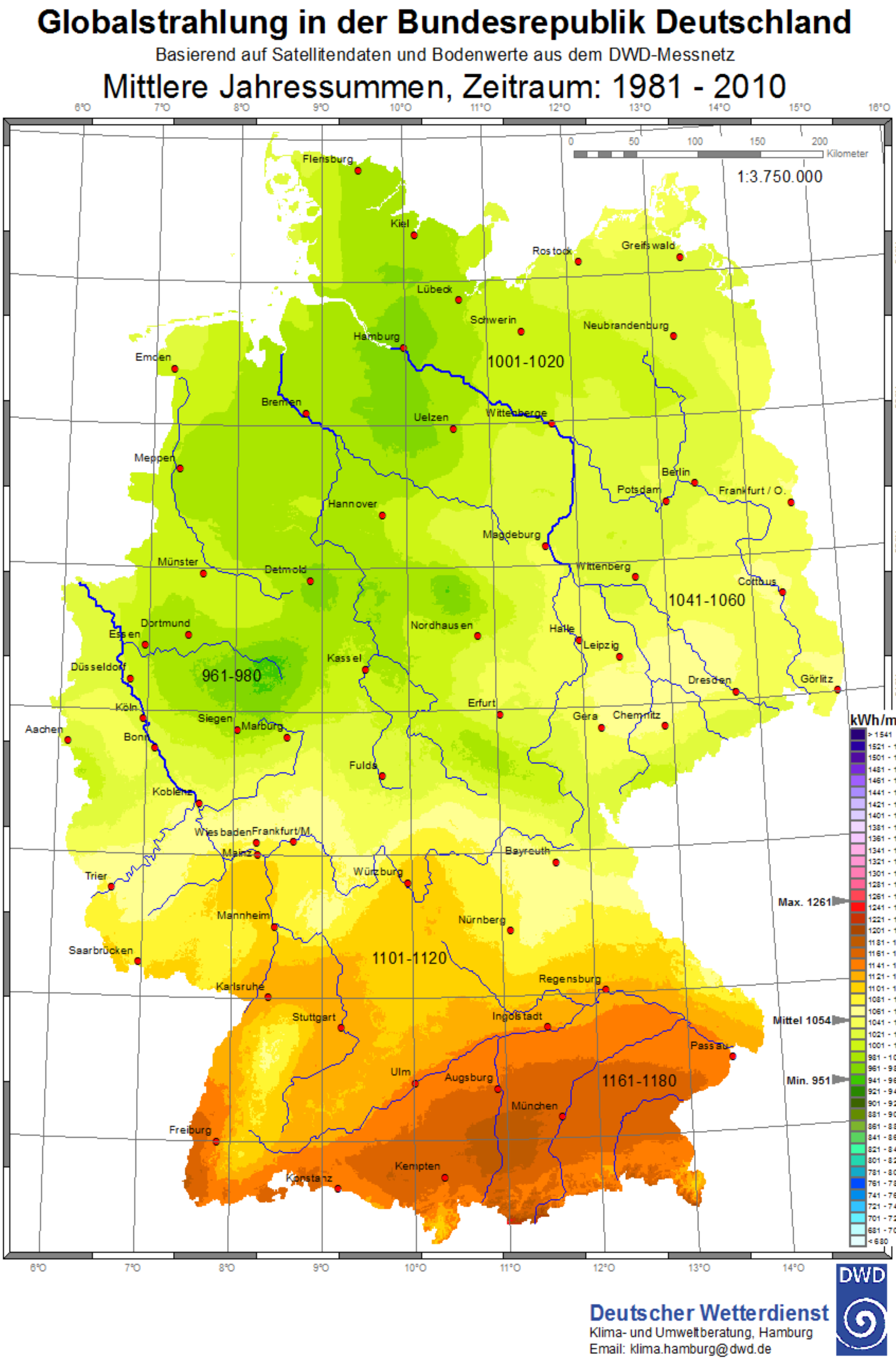

Figure 25: Average annual sum of global irradiance [kWh/m²] in Germany from 1981-2010 (DWD 2013)

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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:

- Techno-Economic Assessment of Energy Technologies
- Market Analysis and Business Models
- Planning and Operating Strategies of Power Plants
- National and Regional Energy Supply Concepts
- Modeling of Energy Supply Scenarios

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

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

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

Further information and persons of contact are available:

www.ise.fraunhofer.de/en/business-areas/energy-system-analysis

FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEM

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

Head of Business Area Energy System Analysis:
Dr. Thomas Schlegl

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

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