FRAUNHOFER INSTITUT FOR SOLAR ENERGY SYSTEMS ISE

LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES

STUDY

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Levelized Cost of Electricity Renewable Energy Technologies

Study

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SUMMARY

The present study analyzes the levelized cost of electricity (LCOE) of renewable energy technologies in the third quarter of 2013. It predicts their future cost development through 2030 based on technology-specific learning curves and market scenarios.

The main focus is on the LCOE for photovoltaics (PV), wind power and biomass power plants in Germany. As a reference value, the development of the LCOE for new conventional power plants was assessed (brown coal, hard coal, combined cycle gas turbines (CCGT)). Figure 1 shows the calculated LCOE of renewable energy technologies and fossil fuel power plants that were constructed in 2013.

PV power plants reached LCOE between 0.078 and 0.142 Euro/kWh in the third quarter of 2013, depending on the type of power plant (ground-mounted utility-scale or small rooftop power plant) and insolation (1000 to 1200 kWh/m²a GHI in Germany). The specific power plant costs ranged from 1000 to 1800 Euro/kWp. The LCOE for all PV power plant types reached parity with other power generation technologies and are even below the average end-customer price for electricity in Germany of 0.289 Euro/kWh (BMWi 2013).

Wind power at very good onshore wind locations already has lower costs than new hard coal or CCGT power plants. Currently the LCOE for onshore wind power (spec. invest between 1000 and 1800 Euro/kW) are between 0.045 and 0.107 Euro/kWh. Despite the higher annual average full load hours (up to 4000 hours), offshore wind power with just 0.119 to 0.194 Euro/kWh shows considerably higher LCOE than onshore wind power. The reasons for this are the expensive installation as well as higher operating and financing costs for offshore power plants (spec. invest between 3400 and 4500 Euro/kW).

The LCOE from biogas power plants (spec. invest between 3000 and 5000 Euro/kW) is between 0.135 Euro/kWh (substrate costs 0.025 Euro/kWh$_{th}$, 8000 full load hours) and 0.215 Euro/kWh (substrate costs 0.040 Euro/kWh$_{th}$, 6000 full load hours). A heat usage is not considered in the calculations.

In the case of conventional power plants, brown coal profits the most from the low prices of CO_2 allowances. Depending on the assumed full load hours, the fuel costs and the price of CO_2 allowances, the LCOE for brown coal is at 0.038 to 0.053 Euro/kWh, from hard coal at 0.063 to 0.080 Euro/kWh and from CCGT power plants at 0.075 to 0.098 Euro/kWh. The full load hours of conventional power plants are integrated into the LCOE with a decreasing tendency, corresponding to the forecasted increasing renewable energy share. Values in Figure 1 therefore only reflect the amount of full load hours for 2013; assumptions for the future are given in Table 4.

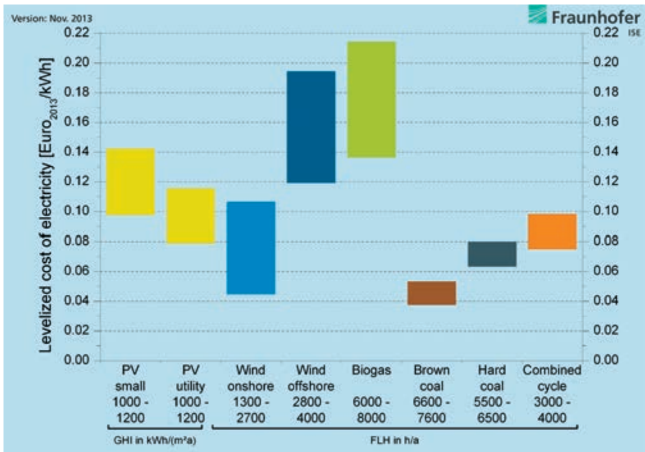

Figure 1: LCOE of renewable energy technologies and conventional power plants at locations in Germany in 2013. The value under the technology refers in the case of PV to the insolation global horizontal irradiation (GHI) in kWh/(m²a), for the other technologies it refers to the number of full load hours (FLH) for the power plant per year. Specific investments are taken into account with a minimum and maximum value for each technology.

Forecast of the LCOE in Germany through 2030

Figure 2 shows the results for the future development of the LCOE in Germany through 2030. The range reflects the possible cost variations in the **input parameters** (e.g. power plant prices, insolation, wind conditions, fuel costs, number of full load hours, costs of CO_2 emission allowances, etc., see **tables 1 to 7**). This methodology will be explained for the cost range of PV: The upper limit of the LCOE results from the combination of a PV power plant with a high procurement price at a location with low solar irradiation (e.g. Northern Germany). Conversely, the lower limit is defined by the most inexpensive solar system at locations with high solar irradiation in Southern Germany. This same process is carried out for wind and biomass power plants as well as conventional power plants. The usual financing costs on the market and the surcharges for risks are included in detail and are specific to the 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 were calculated with real values (reference year 2013). The specific investments in the third quarter of 2013 were calculated based on market research and cost studies.

Due to the consolidation of the PV market, no significant price reductions are expected on the market through 2014. After this a progress ratio (PR) of 85% (corresponding to a learning rate of 15%) is assumed which will lead to further cost reductions. **By the end of the next decade, the LCOE of PV power plants will sink to the range of 0.055 to 0.094 Euro/kWh** so that even small rooftop PV systems will be able to compete with onshore wind power and the increased LCOE from brown coal (0.06 to 0.08 Euro/kWh), hard coal (0.08 to 0.11 Euro/kWh) and CCGT power plants (0.09 to 0.12 Euro/kWh). The specific power plant investments will then be 570 to 1020 Euro/kWp. **PV utility-scale power plants in Southern Germany will drop considerably below the average LCOE for all fossil fuel power plants by 2030.**

Today the LCOE from onshore wind power is already at a very low level and will only decrease by a small amount in the future. Improvements are expected primarily by a higher number of full load hours and the development of new locations with specialized low wind turbines. Thanks to the expected increase in prices for fossil fuel power plants, the competitiveness of **onshore wind power** will however continue to improve and the **LCOE at locations with favorable wind conditions will reach parity with that of brown coal power plants by 2020 at the latest.** In 2030, the local conditions will be especially decisive if onshore wind power can produce less expensive electricity than PV power plants. **Offshore wind power still has (compared with onshore wind power) great potential for reducing costs. Through 2030, the generation costs depending on location and wind conditions will drop to values between 0.096 and 0.151 Euro/kWh.**

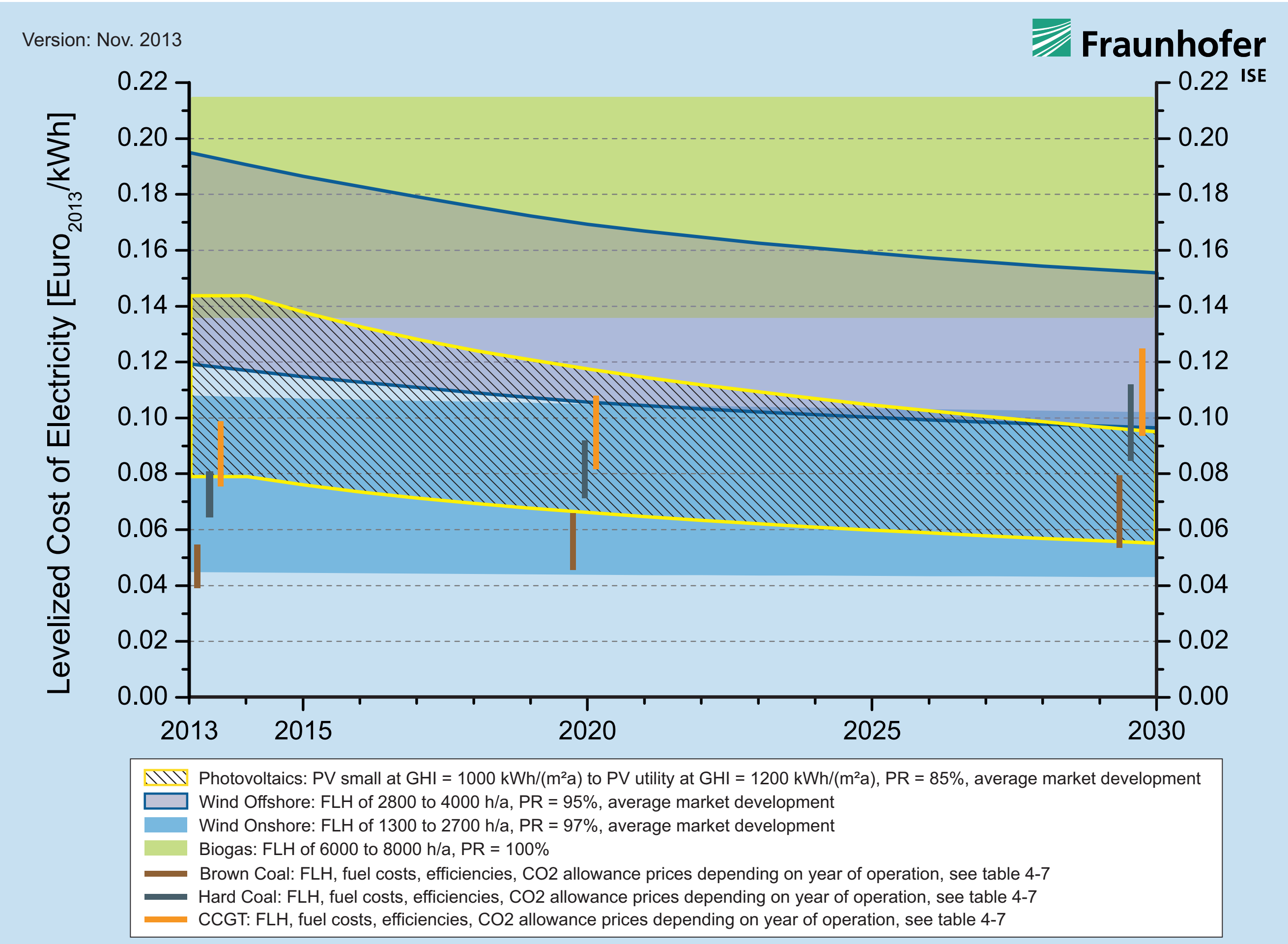

Figure 2: Learning-curve based predictions of the LCOE of renewable energy technologies and conventional power plants in Germany by 2030. Calculation parameters in Tables 1 to 7.

Since only **slight decreases in cost** are expected **for biogas power plants**, no learning rates are recorded for biogas. This leads, in turn, to constant LCOEs by 2030 (0.135 and 0.215 Euro/kWh without earnings from heat cogeneration).

Solar Technologies in Regions with High Irradiation

In the second part of the study we examine solar technologies for regions with favorable sunlight conditions. Since these markets are often less developed and the political environment is unstable in comparison to Central Europe, for example the MENA region (Middle East, North Africa), a risk surcharge of around 2% is considered in the capital costs. Based on these assumptions, the LCOE of PV is, compared to Germany, not significantly lower as one might expect.

The technologies concentrating solar power (CSP) and concentrating photovoltaics (CPV) are analyzed at locations with a high direct normal irradiation of 2000 kWh/(m²a), corresponding to Southern Spain, and 2500 kWh/(m²a), corresponding to the MENA region. PV power plants are investigated at the respective locations with a global horizontal irradiation of 1800 kWh/(m²a) and 2000 kWh/(m²a) as well as an additional location with a low solar irradiation of 1450 kWh/(m²a), corresponding to Southern France.

At the considered irradiation range of 1450 to 2000 kWh/(m²a), the LCOE from PV in 2013 lies under 0.120 Euro/kWh for all PV power plant types. At 2000 kWh/(m²a), PV utility-scale power plants are already able to produce power for 0.059 Euro/kWh and therefore have a LCOE that is comparable to power generated from oil, gas and coal. In countries without high subsidies in the electricity sector, the LCOE for PV therefore lies below the price for the end-customer. Here investments in PV can be profitable without national support programs. By 2030, the costs for PV electricity at locations with high solar irradiation will fall to 0.043 to 0.064 Euro/kWh.

Parabolic trough power plants with thermal storage capacity of eight full load hours at locations with an annual direct normal irradiation (DNI) between 2000 and 2500 kWh/(m²a) today have a LCOE from 0.139 to 0.196 Euro/kWh. Due to the considerable cost reductions for PV in recent years, PV has a cost advantage over CSP. The advantage of the ability to store energy and the dispatchability of CSP, however, was not taken into

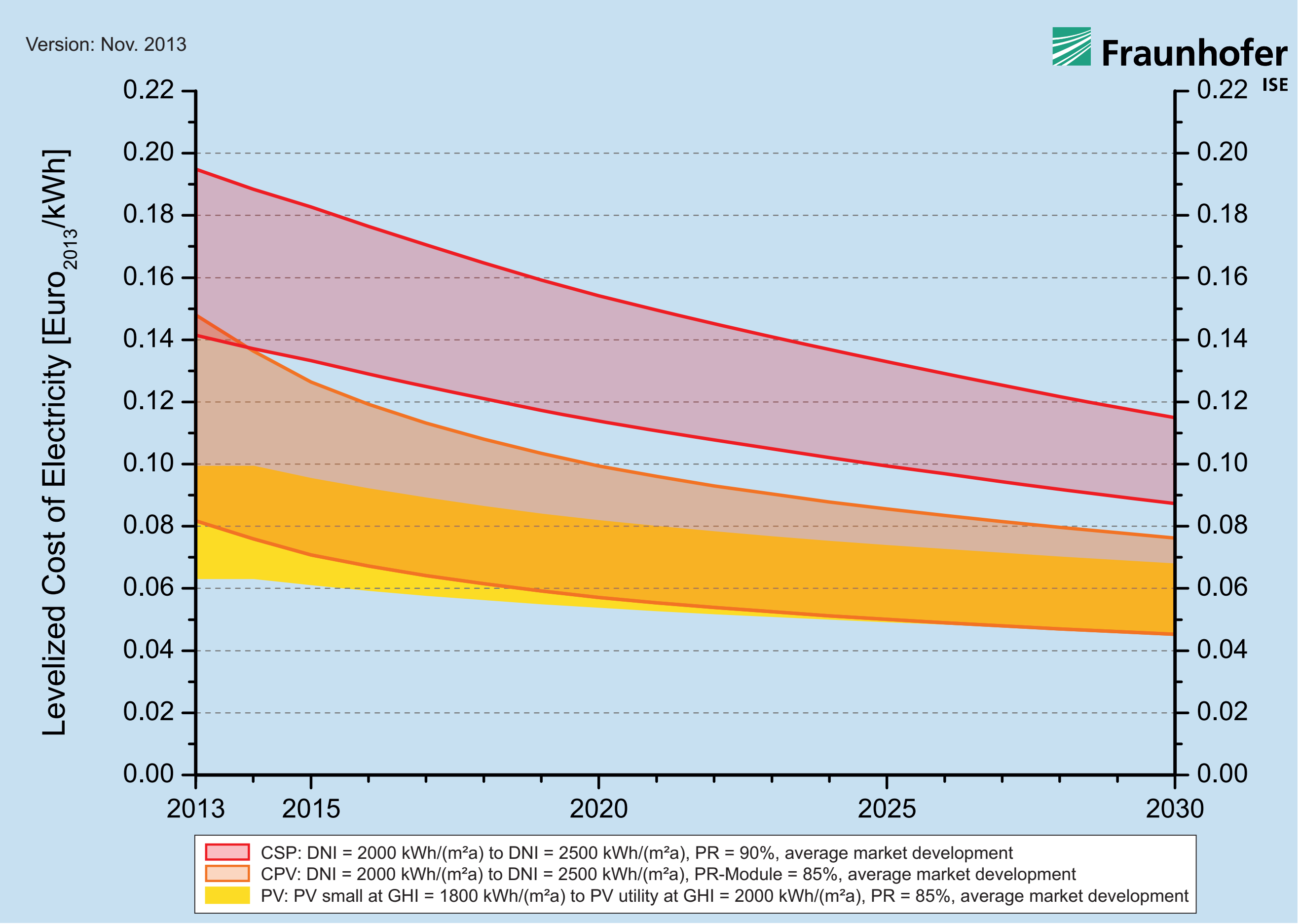

Figure 3: Learning curve based prediction of LCOE of various solar technologies at locations with high solar irradiation by 2030.

account here. With positive world market developments, cosiderable cost reduction will be possible for CSP by 2030, enabling the LCOE to reach values around 0.097 to 0.135 Euro/kWh. This would then correspond to a specific investment for a solar thermal parabolic trough power plant with storage system of 2900 to 3700 Euro/kW.

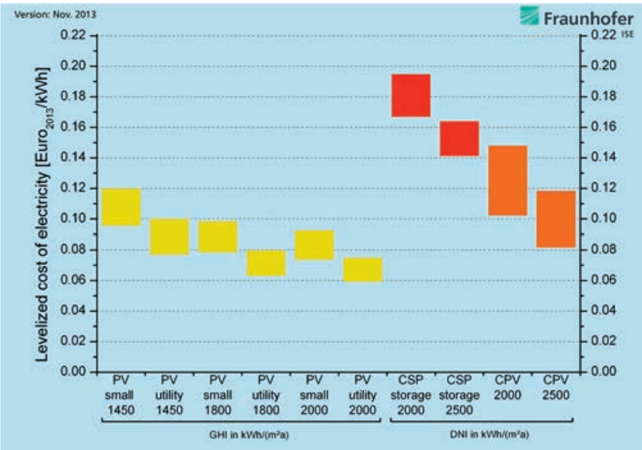

Figure 4: LCOE of renewable energy technologies at locations with high solar irradiation in 2013.
The value under the technology refers to the solar irradiation in kWh/(m²a): GHI for PV, DNI for CPV and CSP.

After the significant decrease in costs in recent years, concentrating photovoltaic power plants at locations with a DNI of 2000 or 2500 kWh/(m²a) can reach LCOE from 0.082 to 0.148 Euro/kWh in 2013. The young technology CPV could, if positive market development continues through 2030, reach a cost reduction ranging between 0.045 and 0.075 Euro/kWh. The power plant prices for CPV would then be between 700 and 1100 Euro/kWp.

For CSP and CPV, there are still great uncertainties today concerning the future market development and thus also the possibility of achieving additional cost reductions through technological development. The analysis, however, shows that these technologies have potential for reducing the LCOE and encourages a continued development of these technologies.

LCOE of Renewable Energy Technologies Study, Version November 2013

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

LCOE presents a basis of comparison for weighted average costs of different power generation technologies. This concept allows the accurate comparison of different technologies. It is not to be equated with the feed-in compensation. The actual spot value of electricity is determined by the daily and hourly variations and weather-related fluctuations in supply and demand and therefore cannot be represented by LCOE. An additional information about the methodology for LCOE can be found in the Appendix on page 36.

1. OBJECTIVE OF THIS ANALYSIS

In contrast to the tendency of increasing energy prices for fossil and nuclear power sources, levelized cost of electricity (LCOE) of all renewable energy technologies have been falling continuously for decades. 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 that reason, the objective of this study is to analyze the current and possible future cost situation.

Central contents of this study

- Analysis of the current situation and future market development of photovoltaics (PV), wind power and biogas power plants in Germany.

- Economic modelling of the technology-specific LCOE (status 3rd quarter of 2013) for different types of power plants and local conditions (e.g. solar irradiation and wind conditions) on the basis of common market conditions.

- Assessment of the different technology and financial parameters based on sensitivity analyzes of the individual technologies.

- Forecast for the future LCOE of renewable energy technologies through 2030 based on learning curve models and market scenarios.

- Analysis of the current situation and future market development of PV, concentrating solar power (CSP) and concentrating photovoltaics (CPV) for a location with favorable solar irradiation.

The technologies are assessed and compared on the basis of historically documented learning curves and conventional market financing costs. The current and future LCOE for new conventional power plants (brown coal, hard coal, combined cycle power plants) are calculated as a reference.

In order to be able to realistically represent the usual variations in market prices and fluctuations in full load hours within the respective technologies, upper and lower price limits are stated. Note that the market prices are often oriented on the feed-in tariffs in force and therefore are not always moving in free competition with each other. Not taken into account are characteristics of individual technologies that cannot be represented in the LCOE such as advantages of easily integrated storage, number of full load hours, decentralized power generation, load-following operation capability and availability depending on clock time.

The level of LCOE of renewable technologies depends significantly on the following parameters:

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

Local conditions
with typical irradiation and wind conditions for different locations and full load hours in the energy system.

Operating costs
during the power plant's operational life time.

Operational life of the power plant

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

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

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

- Small rooftop systems (up to 10 kWp) – PV small
- Large rooftop systems (10 - 1000 kWp) – PV large
- Ground-mounted utility-scale power plants (larger than 1000 kWp) – PV utility-scale

For the PV power plants, we studied locations in Germany with a GHI of 1000 to 1200 kWh/(m²a). Additionally the LCOE was analyzed at locations with a GHI of 1450 kWh/(m²a) to 2000 kWh/(m²a) (corresponds to the region from Southern France to North Africa and/or the MENA countries). Standard modules with multi-crystalline silicon solar cells were taken into consideration.

Wind energy power plants

- Onshore (2 - 3 MW): High- and low-wind power plants
- Offshore (3 - 5 MW)

The operation of onshore wind power in Germany is studied at 1300 to 2700 full load hours per year as well as offshore wind power at 2800 to 4000 full load hours per year.

Biogas power plants

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

The costs of power generation from biogas were studied taking into account different substrate prices between 0.025 Euro/kWh_{th} and 0.04 Euro/kWh_{th}. Operation as an electricity-heat cogeneration power plant with additional heat output and thus achievable 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)

The LCOE of new conventional power plants based on brown coal, hard coal and natural gas with different development paths for the full load hours as well as different prices for CO_2 emission allowances and fuels were analyzed as a reference.
For locations with high solar irradiation, CPV and large CSP power plants were studied along with photovoltaic technology. Since CPV and CSP can only be used for power generation under higher direct irradiation, the analysis concentrates on locations with a DNI of 2000 kWh/(m²a) (for example in Spain) and locations with 2500 kWh/(m²a) (for example in MENA countries).

Concentrating Photovoltaics (CPV)

- Concentrating photovoltaics (>1 MWp) with dual-axis tracking

Tracked CPV power plants are analyzed on the large power plant scale which convert the energy from direct irradiation into electricity with concentrator techniques in highly efficient modules.

Concentrating Solar Power Plants (CSP)

- Parabolic trough power plants (100 MW) with and without thermal storage - parabolic
- Power plants with Fresnel technology (100 MW) – Fresnel
- Solar power tower plants (100 MW) with thermal storage – tower

Of the various CSP plant technologies, three different technologies (parabolic trough power plants, Fresnel systems and solar power tower plants) that are currently being developed and built were studied.

2. HISTORICAL DEVELOPMENT OF RENEWABLE ENERGY TECHNOLOGIES

In the past ten years, the worldwide market for renewable energy technologies has shown considerable growth (see Figure 5). Especially in recent years, there has been increasing competitiveness with conventional power plants which has given additional impetus to the global market for renewable energy technologies which until then had been carried primarily by state subsidy programs.

The introduction of subsidy programs for renewable energy technologies and setting of long-term goals in energy policy created a stable investment climate in many states. The lawmakers in many states reacted to the foreseeable scarcity of fossil energy sources and the climate issue. Thanks to an early entry into the market for renewable energy technologies, they attempted to initiate a transformation process to an energy system based on renewable energy technologies and building of production capacities and installations of renewable energy technologies, and profit from their development on a macroeconomic level. At the same time, more and more technological developments were and are being created, in which renewable energy technologies are also competitive without support for investments.

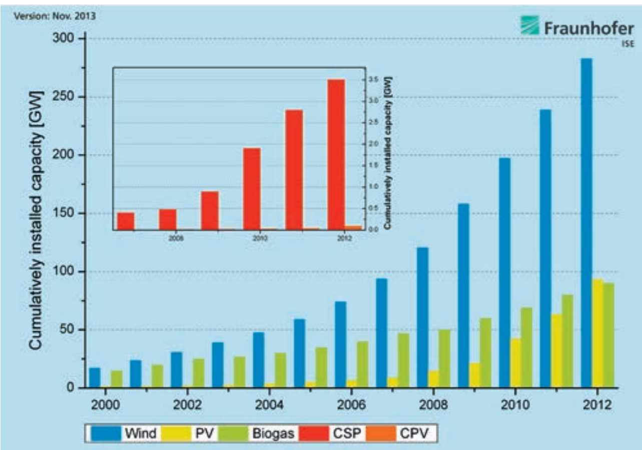

Figure 5: Global cumulatively installed capacity 2000-2012 of PV, CSP, wind power and CPV according to Fraunhofer ISE, GWEC 2013, Sarasin 2011, EPIA 2013.

The strong market growth of renewable energy technologies and the high investments in new power plants were accompanied with intensive efforts in research, which resulted in improved systems solutions with higher efficiencies, lower production costs as well as lower operating costs. In combination with increasing mass production, it was possible to considerably decrease the costs of specific investments and with them the LCOE for all technologies analyzed here. Further decreases in the LCOE will once again allow the profit potentials for the technologies to grow considerably in the coming years and contribute to a continued dynamic market development for renewable energy technologies.

The scope of the worldwide expansion of power plant capacities for renewable energy technologies has become clear through the installed total capacity of nearly 500 GW by the end of 2012 and the annual investment in new power plants of up to 244 billion US$ in 2012 (numbers from REN21 (2012)); additionally, a power plant capacity of around 1000 GW is installed in large-scale hydro-electric power plants. To provide a comparison: the currently installed capacity of nuclear power plants worldwide is 366 GW. During the period 2000 to 2012, the installed capacity from nuclear power plants only increased by 9 GW, while the increase for wind power was 266 GW and around 100 GW for solar power plants (World Nuclear Industry Status Report 2013).

Based on the different cost and market structures, but also on the subsidy measures, the markets for the individual technologies developed quite differently. For this reason, the market for wind power developed competitive market prices early and therefore found sales markets in numerous countries even without market stimulus programs. The installed capacity currently adds up to nearly 284 GW, whereby the new installations reached 44 GW in 2012 (GWEC 2013). Among the renewable energy technologies, wind power, referenced to the installed capacity, continued to have higher sales than photovoltaics at 31 GWp in 2012. According to a study by Bloomberg New Energy Finance, the new installation for PV in 2013 at 36.7 GWp was, however, for the first time over that of wind power, which is estimated at 35.5 GW. The LCOE of wind power at onshore locations with favorable wind conditions is competitive compared to conventional power generation technologies, which makes it possible to establish wind power in a number of markets including developing and newly industrialized countries. In spite of good forecasts for growth for offshore wind power, problems in the realization phase of new power plants has resulted in the current reality constituting less than 1.5% of the total capacity of all installed wind power. A somewhat higher prioritization of offshore wind power is currently facing off against higher costs in the technical implementation during project realization, with the frequent result of this situation being project delays.

The photovoltaic market has also developed into an important segment within the renewable energy market thanks to the expansion of production capacities, especially in Asia, using highly automated assembly lines. Thanks to considerable excess production capacities, there has been terrific competition in the PV industry since 2009. This has led, since 2011, to considerable reductions in prices and, to some extent, to unexpected market dynamics.

In recent years, the market for biogas power plants has grown considerably in Germany, followed by Austria and the United Kingdom. The reason for this is primarily found in the rules for financial compensation in the respective countries. Markets for biogas power plants are developing in the USA as well as in China.

Along with the technologies described above that are being used in Germany, the two technologies CPV and CSP can play an important role in power generation in countries with favorable solar irradiation conditions. Concentrating photovoltaics is in an early phase of market development compared to PV technologies based on wafer silicon and CdTe that have been established on the market longer. After isolated prototypes and smaller power plants with capacities of a few 100 kW were installed in the period from 2001 to 2007, power plants in the MW range have been increasingly installed since 2008. The market has grown continuously in recent years with a market volume of 50 MW in 2012 but remains small compared to other renewable energy technologies.

In regions with favorable solar irradiation conditions, CSP plants, after the first installations of power plants in the USA in the 1980s, have been re-discovered in some countries since 2007, so that in the meantime 3500 MW have been installed (primarily in the USA and Spain, data from own market research). The concept of the CSP plant is currently being intensively pursued by local political decision makers, most of all in the MENA countries with favorable solar irradiation conditions due to the advantages of thermal energy storage and the possibility of local value creation.

For the forecast of LCOE through 2030, this study uses the learning curve model to estimate future developments. This made it possible, especially for wind technology and silicon PV, to observe learning rates of up to 20% in the last 20 years (Albrecht 2007, Neij 2008). Since it has not been possible to form long-term stable learning curves for CPV and CSP, observation of the learning curves for these technologies is laden with greater insecurities. 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 different studies (Table 8 in the Appendix). A development horizon for each technology derives from the technology-specific market scenarios; however, it will also be influenced by numerous technology, energy policy and economic variables affecting decision making in the next 20 years. There is considerable uncertainty for all technologies with respect to what market development is actually feasible through 2030, since this is quite highly dependent on the amount of specific investments and useable full load hours, the necessity of integrating storage options, the regulatory environment of the various markets and not least of all on the price development of conventional energy sources. The actual market development for each technology is, however, decided for the chronological development of decreasing trend in costs. The developments in LCOE depicted here are therefore potential paths of development based on current market developments from various reference scenarios and technology-specific assumptions such as learning curves and full load hours.

3. APPROACH AND ASSUMPTIONS

Technology and Financing Parameters

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

Upper and lower price limits that do not take outliers into account are 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 amounts of investment in Euro/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. Inside the technologies, the system costs were distinguished based on power plant size and power plant configuration.

In the area of PV power, it was possible to indicate upper and lower limits for the installation costs by power plant size for small power plants up to 10 kWp, large rooftop power plants up to 1000 kWp and utility-scale power plants, on the basis of which it was possible to calculate the LCOE of the investment in 2013. The operational lifetime of PV power plants was set at 25 years, which reflects the experiences of the Fraunhofer ISE in the area of power plant monitoring.

Onshore wind power is classified in power plants for locations with favorable and unfavorable wind conditions. This distinction is expressed in different assumptions with respect to the relationship between rotor and generator size and the therewith associated full load hours at the respective location as well as in the cost assumptions for the turbine. The data for offshore wind power were gleaned from running and completed projects in the German North Sea and Baltic, such as Baltic1 and Borkum West2.

Power generation from biomass was calculated solely for power plants burning biogas based on different substrates. Hereby medium to large biogas power plants are analyzed. Heat generation in CHP biogas power plants is an important operational parameter and increases the economic efficiency of the power plants. However, due to the focus of this study on power 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 biofuels. 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 biogas power plants with a size of

[Euro/kW]	PV small	PV large	PV utility scale	Wind onshore	Wind offshore	Bio-gas	CPV	CSP-Parabol without storage	CSP-Parabol with 8h-storage	CSP-Fresnel without storage	CSP-Tower with 8h-storage	Brown coal	Hard coal	Combined cycle
Investment 2013 low	1300	1000	1000	1000	3400	3000	1400	2800	5200	2500	6000	1250	1100	550
Investment 2013 high	1800	1700	1400	1800	4500	5000	2200	4900	6600	3300	7000	1800	1600	1100

Table 1: Investments in Euro/kW for current power plant installations

500 kW_{el} are shown because biogas power plants of this capacity class, greater than 500 kW, currently hold the highest share of the market (Stehnull et al, 2011).

For CSP, this study investigates parabolic trough power plants of a size up to 100 MW that are designed with or without thermal storage (8 hours). Additionally, solar tower plants (with storage) and Fresnel power plants were modelled. Information about the reference power plants, location-specific solar irradiation, percentage of natural gas used for hybrid operation (<10% of total electricity production) and power plant-specific capacity provide the basis for calculating the LCOE of CSP.

Concentrating photovoltaic power plants are being constructed on a larger scale in the USA, China, Italy and South Africa. The information refers to two-axis tracking power plants that are built with a capacity greater than 10 MW.

The following discussed parameters are included in the calculation of the average LCOE for the third quarter of 2013 (Table 2). The financing parameters have been analyzed in detail since the first study from 2010 and adapted to the risk and investor structure of the individual technologies, since the selected discount rate has considerable influence on the calculated LCOE. In many studies, this aspect was not adequately investigated, identical discount rates were often assumed for all technologies and locations investigated, which resulted in deviations from the actual LCOE.

The discount rates in this study are therefore determined for each technology through the usual capital costs on the market (weighted average costs of capital - WACC) for the respective investment and are comprised in part of external capital interest and equity capital earnings. Large power plants that are built and operated by large institutional investors have, due to the

	Germany									Regions with high solar irradiation			
	PV small	PV large	PV utility scale	Wind On-shore	Wind Off-shore	Brown coal	Hard coal	Com-bined cycle	Bio-mass	PV small	PV large/ utility	CSP	CPV
Lifetime [in years]	**25**	**25**	**25**	**20**	**20**	**40**	**40**	**30**	**20**	**25**	**25**	**25**	**25**
Share of equity	20%	20%	20%	30%	40%	40%	40%	40%	30%	20%	20%	30%	30%
Share of debt	80%	80%	80%	70%	60%	60%	60%	60%	70%	80%	80%	70%	70%
Return on equity	6.0%	8.0%	8.0%	9.0%	14.0%	13.5%	13.5%	13.5%	9.0%	8.0%	10.0%	13.5%	13.5%
Interest rate on debt	4.0%	4.0%	4.0%	4.5%	7.0%	6.0%	6.0%	6.0%	4.5%	6.0%	6.0%	7.0%	7.0%
$WACC_{nom}$ (Weighted Average Cost of Capital)	4.4%	4.8%	4.8%	5.9%	9.8% (8.8%)*	9.0%	9.0%	9.0%	6.2%	6.4%	6.8%	9.7% (8.8%)*	9.7% (8.2%)*
$WACC_{real}$	**2.4%**	**2.8%**	**2.8%**	**3.8%**	**7.7% (6.7%)***	**6.9%**	**6.9%**	**6.9%**	**4.1%**	**4.7%**	**4.7%**	**7.5% (6.7%)***	**7.5% (6.1%)***
Annual operation costs [in Euro/kWh]				**0.018**	**0.035**							**0.028**	
Annual fixed operation costs [in Euro/kW]	**35**	**35**	**35**			**36**	**32**	**22**	**175**	**35**	**35**		**35**
Annual reduction of electricity output	0.2%	0.2%	0.2%	0.0%	0.0%					0.2%	0.2%	0.2%	0.2%
CO_2 emissions [in kg/kWh]						0.36	0.34	0.20					
Fuel costs considered						x	x	x	x				

**falling financing costs untill 2030 for technologies with low market penetration in 2013*

Table 2: Input parameters for calculation of economic efficiency

amount of investment return required by the investor, a higher WACC than small power plants or medium-sized power plants that are constructed by private persons or business partnerships. The return on investment that investors require for technologies with a short market history – like offshore wind power, CSP and CPV – are also higher than for established technologies. One can expect that the financing parameters will approach parity after a corresponding increase in the installed capacity, since the risk surcharges for new technologies will decrease with increasing experience. For this reason, a continuous decreasing trend in the WACC is taken into account for the technologies offshore wind power, CSP and CPV, down to one percentage point by 2030.

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 not permitted and is an error. To complete the calculation on the basis of nominal values, the annual inflation rate through 2030 must first be predicted. Since the forecast for the inflation rate over the long term is very imprecise and difficult, cost predictions for the long term are generally completed using real values. All costs stated in this study therefore refer to real values from 2013. The information about LCOE for future years shown in the figures for the various scenarios always refer to new installations in the respective years. In a power plant that has been constructed, the average LCOE remains constant over its operational lifetime and is therefore identical to the information for the year of installation.

A second factor which influences the amount of return on investment is the project-specific risk: The higher the risk of default, the higher the return on investment required by the investor. In order to keep the capital costs low, the highest possible amount of favorable external capital is desirable. It is, however, also limited by the project-specific risk: The higher the risk of default, the lower the amount of external capital that banks will provide. Since offshore wind parks continue to evince a high project-specific risk as they have in the past, the average capital costs are correspondingly higher than for comparable onshore projects.

If subsidy credits are available in sufficient amount, for example from the KfW Group, external capital interest rates of around 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 subsidy credit is currently only 4.39% for the highest credit rating class – with a 20-year maturity and 20-year fixed interest (KfW 2013). Since there is currently a very low rate of interest, the external capital returns on investment for PV power plants is estimated conservatively at 4%.

In international comparisons of locations, one must keep in mind that the financing conditions differ, as do the environmental conditions such as solar irradiation and wind conditions. Especially in the case of regenerative projects, whose economic efficiency is significantly dependent on state-controlled 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 power plants. Locations in Spain and especially in the MENA countries, admittedly, have considerably higher values for solar irradiation, but for a realistic comparison of the LCOE, the actually observed and less-advantageous financing conditions must be taken into account.

Local Conditions Studied

Irradiation – Full Load Hours

The amount of electricity yield at the 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 radiation plays a role depending on the technology (PV, CPV or CSP). The full load hours 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 full load hours is not supply-dependent but is determined by the demand, availability of substrate and power plant design.

For that reason, exemplary locations with specific full load hours for wind farms should be studied as well as locations with specific energy sources from solar irradiation (see Table 3). At typical locations in Germany, there is a global horizontal irradiance (GHI – consisting of diffuse and direct irradiation) in the range between 1000 and 1200 kWh per square meter and year onto the horizontal surface (Figure 34). This corresponds to a solar irradiation between 1210 and 1320 kWh/(m^2a) onto an optimally configured PV power plant. After subtracting losses inside the PV power plant, this produces an average annual electricity yield between 1050 and 1140 kWh per installed kWp. Considerably higher annual electricity yields are recorded in locations in Southern Europe with 1380 - 1680 kWh/kWp or in the MENA countries with up to 1790 kWh/kWp.

Solar thermal and concentrating photovoltaic power plants concentrate only direct irradiation into a focal point where it is converted into electricity or heat. For this reason only locations with an annual direct normal irradiance (DNI) from 2000 and 2500 kWh/(m²a), such as found in south Spain and in the MENA countries, are taken into account for both technologies

The wind conditions are also location-dependent. Onshore wind power can evince full load hours of only 1300 hours at poor locations. The level of full load hours, however, can reach values of up to 2700 hours at selected locations near the coast in Germany. In order to complete a power plant specification, power plants were calculated up to a number full load hours of 2000 hours per year with a power plant design for locations with unfavorable wind conditions. Locations with higher average wind speeds and the resulting higher full load hours are calculated using the data for power plants with favorable wind conditions (high wind speed power plants). The average value for all onshore wind power operated in Germany in the years 2006 – 2011 was between 1500 and 1800 full load hours per year (high average fluctuations are possible). Offshore power plants achieve much higher totals for full load hours with values between 2800 hours per year in areas near the coast and up to 4000 hours per year at locations far from the cost in the North Sea (EWEA 2009, IWES 2009).

PV system (standard module)	Irradiation on PV module at optimal angle		Electricity output per 1 kWp	
Germany North (GHI 1000 kWh/(m²a))	1150	kWh/(m²a)	1000	kWh/a
Germany Center and East (GHI 1050 kWh/(m²a))	1210	kWh/(m²a)	1040	kWh/a
Germany South (GHI 1200 kWh/(m²a))	1380	kWh/(m²a)	1190	kWh/a
Southern France (GHI 1450 kWh/(m²a))	1670	kWh/(m²a)	1380	kWh/a
Southern Spain (GHI 1800 kWh/(m²a))	2070	kWh/(m²a)	1680	kWh/a
MENA (GHI 2000 kWh/(m²a))	2300	kWh/(m²a)	1790	kWh/a
Wind power plant (2 - 5 MW)	**Full load hours of wind**		**Electricity output per 1 kW**	
Onshore: Germany center and south (wind speed 5.3 m/s; 130m hub height)	1300	h/a	1300	kWh/a
Onshore: Germany near the coast and strong wind locations (wind speed 6.3 m/s; 80m hub height)	2000	h/a	2000	kWh/a
Onshore: Atlantic coastline UK (wind speed 7.7 m/s; 80m hub height)	2700	h/a	2700	kWh/a
Offshore: Areas near the coast (wind speed 7.9 m/s; 80m hub height)	2800	h/a	2800	kWh/a
Offshore: Medium distance to coastline (wind speed 8.7 m/s)	3200	h/a	3200	kWh/a
Offshore: Locations far from the coast (wind speed 9.5 m/s)	3600	h/a	3600	kWh/a
Offshore: Very good locations (wind speed 10.3 m/s)	4000	h/a	4000	kWh/a
CSP power plant (100 MW)	**Direct normal irradiation (DNI)**		**Electricity output per 1 kW** (additionally dependent on storage size, 8h)	
Parabolic with storage (Southern Spain)	2000	kWh/(m²a)	3300	kWh/a
Parabolic with storage (MENA)	2500	kWh/(m²a)	4050	kWh/a
Fresnel (Southern Spain)	2000	kWh/(m²a)	1850	kWh/a
Fresnel (MENA)	2500	kWh/(m²a)	2270	kWh/a
Solar tower with storage (Southern Spain)	2000	kWh/(m²a)	3240	kWh/a
Solar tower with storage (MENA)	2500	kWh/(m²a)	3980	kWh/a
CPV power plant	**Direct normal irradiation (DNI)**		**Electricity output per 1 kWp**	
CPV (Southern Spain)	2000	kWh/(m²a)	1560	kWh/a
CPV (MENA)	2500	kWh/(m²a)	2000	kWh/a

Table 3: Annual yields at typical locations of PV, CPV, CSP and wind power (source: Fraunhofer ISE)

Development of full load hours (FLH) of conventional power plants	Brown coal	Hard coal	Combined cycle
FLH 2013 medium	7100	6000	3500
FLH 2013 low	6600	5500	3000
FLH 2013 high	7600	6500	4000
FLH 2020 medium	6800	5700	3500
FLH 2020 low	6300	5200	3000
FLH 2020 high	7300	6200	4000
FLH 2030 medium	5800	4800	3100
FLH 2030 low	5300	4300	2600
FLH 2030 high	6300	5300	3600
FLH 2040 medium	4900	4100	2900
FLH 2040 low	4400	3600	2400
FLH 2040 high	5400	4600	3400
FLH 2050 medium	4300	3600	2600
FLH 2050 low	3800	3100	2100
FLH 2050 high	4800	4100	3100

Table 4: Development of full load hours of conventional power plants (Prognos (2013), own representation)

Biogas power plants are currently being operated in Germany with a very high number of full load hours. For process-based reasons but also driven by the currently applicable rules for feed-in tariffs, the power plants run quite constantly and therefore achieve full load hours between 6000 and 8000 per year (Stehnull et al. 2011). Based on the assumption that newly constructed biogas power plants will achieve higher full load hours (at 8000 h c.f. (FNR 2010), (Stehnull et al, 2011)), a value of 7000 average full load hours is assumed for biogas power plants. The values for full load hours are varied between 6000 h and 8000 h in the framework of the sensitivity analysis. In the future, biogas power plants will compensate for the fluctuating output from solar and wind, which could result in sinking full load hours.

Compared with most renewable energy technologies, the annual power production and with it the number of full load hours for a conventional power plant is depending on the particular demand, the costs for fossil fuels and with it also the competitiveness of the technology in the energy system. At this time, the full load hours for brown coal power plants lie at an average of 6200 hours for all power plants (calculation for the year 2012 from EEX-data). For hard coal, an average of 6000 hours is achieved and for economical CCGT power plants 3500 hours. In the course of the transition to renewable energy technologies in Germany and the increase of power generation from renewable energy technologies, however, the full load hours for conventional power plants are sinking.

This study includes in its calculation through 2050 the continued decrease in full load hours for all new power plants so that the energy yield in the calculation decreases from year to year (see Table 4). In the case of brown coal, for example, the average value of the full load hours in 2050 sinks to 4300. Higher full load hours can reduce the LCOE of fossil fuel power plants, if the competitive environment and demand situation permits this, and correspondingly lower full load hours will lead to an increase in the LCOE.

Fuel costs

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 from power plant to power plant. For example, in operating year 2009 of a biogas plant in Baden-Württemberg, an average substrate mix was used 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 Euro/tFM (Scholwin et al, 2011) and for liquefied pig manure around 3 Euro/tFM (DBFZ 2010). Substrate costs for substrate produced in-house can be assumed to be near 0 Euro/tFM. Average substrate costs of 0.03 Euro/kWh_{th} are assumed in the conversion of the methane yield and the methane energy production of 9.97 kWh/Nm³. In order to illustrate a changed composition of the substrate, the substrate costs are varied in the sensitivity analysis in a range between 0.025 Euro/kWh_{th} and 0.04 Euro/kWh_{th}.

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 and for CCGT power plants between 400 and 600 MW per location. 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 to evince very moderate increases. Due to a possible scarcity of CO_2 allowances, a long-term increase of the allowance price is assumed (see Tables 5-7).

Fuel price [$Euro_{2013}$/kWh]	2013	2020		2030		2040	2050
		lower	upper	lower	upper		
Brown coal	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
Hard coal	0.0114	0.0103	0.0114	0.0112	0.0175	0.0188	0.0200
Natural gas	0.0287	0.0276	0.0320	0.0287	0.0363	0.0398	0.0470
Substrate for Biomass	0.0300	0.0250	0.0400	0.0250	0.0400	0.0400	0.0400

Table 5: Assumptions about fuel prices (BMWi (2013), NEP (2013), BMU (2012), Prognos (2013))

Development of energy conversion efficieny of conventional power plants	2013	2020	2030
Brown coal	45.0%	46.5%	48.5%
Hard coal	46.0%	50.0%	51.0%
Combined cycle	60.0%	61.0%	62.0%
Biomass	40.0%	40.0%	40.0%

Table 6: Development of efficiency in large power plants (ISI (2010))

CO_2 allowance price [$Euro_{2013}/tCO_2$]	2013	2020	2030	2040	2050
lower value (own calculation)	5,3	17	28	35	40
upper value (Prognos)	5.3	21.7	42	50.7	55
medium value	5.3	19.3	35	42.9	47.5

Table 7: CO_2 allowance price (NEP (2013), Prognos (2013))

4. TECHNOLOGIES IN GERMANY

In the comparison of technologies carried out here, the LCOE of renewable energy technologies is determined for PV, biogas and wind power at locations in Germany 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 and CCGT) provide comparative LCOE values which were also investigated for various power plant configurations as well as different assumptions for the construction and operation of these power plants. Compared to the results of the study from 2012, the LCOE decreased not only due to lower power plant prices but also due to including real discount rates that are lower than the nominal values after taking the inflation rate into consideration.

Onshore wind power with average installation costs of around 1400 Euro/kW at locations with high annual foll load hours of 2700 shows the lowerst LCOE among the renewable technologies with 0.045 Euro/kWh. However, these locations are limited in Germany (see Figure 6). For that reason, the costs for power plants at poorer locations vary up to 0.107 Euro/kWh, again

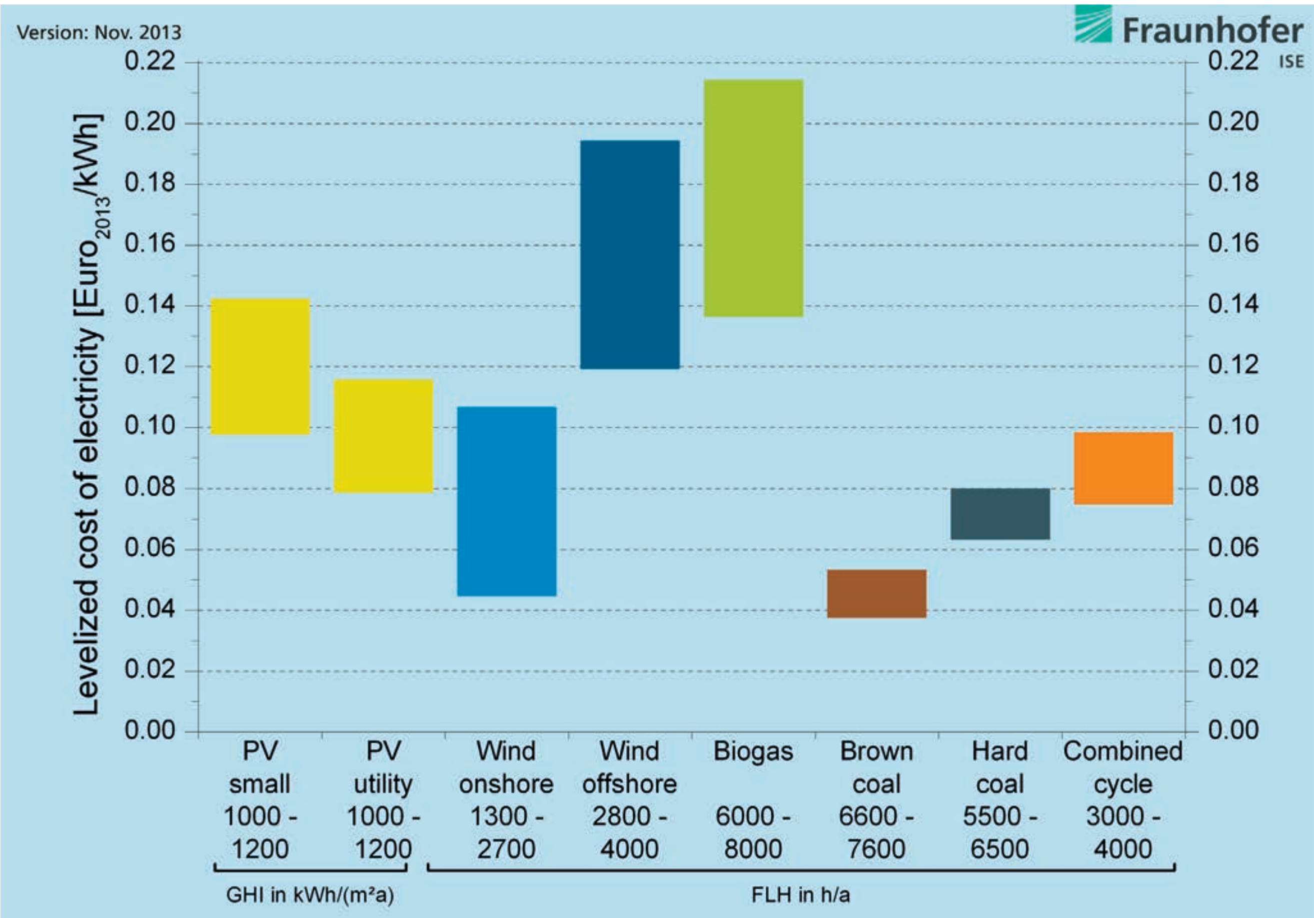

Figure 6: LCOE of renewable energy technologies and conventional power plants at locations in Germany in 2013. The value under the technology refers in the case of PV to solar irradiation (GHI) in kWh/(m²a); in the case of other technologies it reflects the number of FLH of the power plant per year. Specific investments are taken into account with a minimum and maximum value for each technology. Additional assumptions are presented in Table 3-7.

depending on the specific investment as well as the annual full load hours achieved there (see Table 1 and 4). In comparison to the study from 2012, there are considerably different costs for locations with either favorable or unfavorable wind conditions, since a location specific power plant design was taken into account for the first time. Accordingly, the costs for offshore wind power were considerably higher with values ranging between 0.119 Euro/kWh and 0.194 Euro/kWh, in spite of a high numbers of full load hours at offshore locations. The higher costs of the offshore wind power projects are associated to the upward corrections of the amounts of investment of projects currently under construction. It is to note, that the costs of grid connections for the power grid operators at offshore locations are not taken into account in the LCOE.

The LCOE of small PV systems at locations with GHI of 1200 kWh/ (m²a) in Southern Germany lies between 0.098 and 0.121 Euro/kWh and at locations in Northern Germany with an irradiation of 1000 kWh/(m²a) LCOE between 0.115 and 0.142 Euro/kWh are reached. The results depend on the amount of the specific investments, which is assumed to range from 1300 Euro/kWp to 1800 Euro/kWp.

Today, ground-mounted utility-scale PV power plants are already reaching LCOE values between 0.079 and 0.098 Euro/kWh in Southern Germany and 0.093 to 0.116 Euro/kWh in Northern Germany, since the more favorable power plants have already achieved specific investments of 1000 Euro/kWp or 1 Euro/Wp. This means that the LCOE of all types of PV power plants in Germany lies considerably below the average electricity costs for households in Germany of 0.289 Euro/kWh (Status: April 2013, BMWi 2013). The LCOE of biomass at current substrate costs of 0.025 to 0.04 Euro/kWh_{th} falls between 0.136 and 0.215 Euro/kWh.

In contrast to the last studies, the LCOE of conventional power plants were explicitly calculated for this study and not externally referenced. Under the current conditions on the electricity market with the respective full load hours and fuel prices, this yields to the following LCOE of each technology: Brown coal profits the most from the very low CO_2 prices in 2013 and reach LCOE from 0.038 to 0.053 Euro/kWh for the selected operational parameters. The LCOE of large hard coal power plants is somewhat higher, between 0.063 and 0.080 Euro/kWh. Today, CCGT power plants are achieving LCOE values between 0.075 and 0.098 Euro/kWh, which explicitly reflects the current trend toward idling gas power plants which therefore are difficult to refinance.

One must keep in mind that the calculation of the LCOE does not include the possible flexibility of a power generating technology or the value of the electricity generated. For example, seasonal and daily generation differs terrifically for the individual technologies. Neither are differences arising from the flexible employment of power plants or the supply of system services taken into account with reference to the actual market sale price in the figure for the LCOE. The authors recommend here a further refinement of the methodology of LCOE or adding other energy system models.

Photovoltaics

Market Development and Forecast

At the end of 2012, the PV market had surpassed the limit of 100 GWp installed capacity worldwide. However, the annual new installations, which were at around 31 GWp, aere only slightly above the level of 30 GWp from the previous year. This is specifically attributable to a reduction in the feed-in tariffs in key markets (i.e. in Germany). With 17 GWp of new installations, Europe was, as before, the most important market for photovoltaics in 2012. In the coming years, however, higher growth rates are expected especially in China, Japan, India and North America (EPIA 2013). In 2013, the German PV market is expected to fall below the 4 GWp mark, which will be more than compensated for by the growth in the aforementioned regions so that one can count on a moderate growth in the worldwide PV market for 2013 as well. At the start of July, the State Council in China raised its solar target for 2015 to 35 GW of installed power by 2015. With the current 10 GW of installed capacity, this corresponds to an annual new construction of around 12 GWp through 2015 (IWR 2013). China is therefore expected to be the most important PV market in the coming years. In Japan as well, high feed-in compensation is providing for rapid market growth. In the first quarter of 2013, the Japanese market grew 270% compared to the previous year with respect to newly installed capacity. With respect to sales, Japan will be the largest PV market in 2013, while China will top the list for newly installed capacity (IHS 2013). Keep in mind that the worldwide PV market now has an increasingly broad base and is no longer being exclusively carried by Europe. The global PV sales market no longer depends on just a few countries and is therefore more resistant to changes of the subsidy conditions in individual countries. Additionally, in some regions photovoltaic projects are increasingly realized independent from subsidy programs and are beginning to gain ground in open competition in larger numbers.

The worldwide PV market of 31 GWp in 2012 faced world-production capacities of over 50 GWp. This led to ruinous competition between the module manufacturers in which several well-known manufacturers were forced to file for bankruptcy.
An added factor is that many factories can no longer cover their costs in production at the current prices, especially if they do not have the newest generation of manufacturing equipment. A reduction in the subsidy rates on important key markets has further increased price pressure and now encompasses the entire supply chain from the construction transaction to raw materials suppliers. Thus, considerable potentials for cost reductions were identified. Nevertheless, it is still expected that significant further price reductions will only emerge after the consolidation phase ends. The current market consolidation will lead to the condition for manufacturers once again being able to cover their production costs at the current low prices.

Even the market for production equipment of manufacturing silicon, wafers, PV cells and modules, which is dominated by German machine builders, will need to withstand the period of excess capacity in production equipment. At the same time, Asian manufacturers will attempt to eliminate the technological advantage of European and North American machine builders in order to be competitive once demand is growing again.

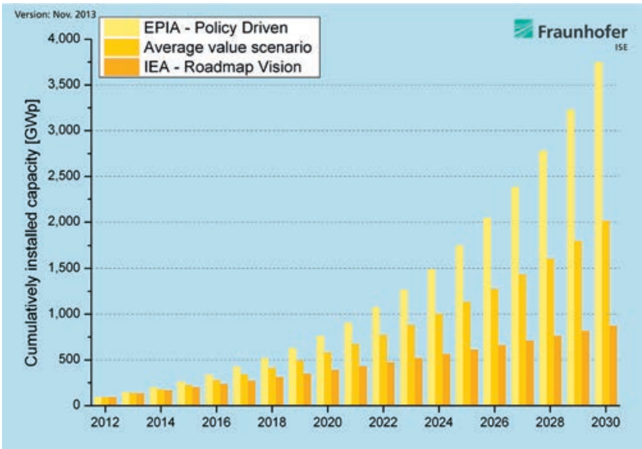

Figure 7: Market forecast for cumulative power plant capacity for PV 2012-2030 according to IEA (2010), EPIA (2013) and own calculations

According to the studies investigated here, the global demand market for PV will continue to see strong growth in the coming years. The basis for the market forecast came from "Global Market Outlook for Photovoltaics" of the European Photovoltaic Industry Association (EPIA 2013) and a Technology Roadmap from the IEA from the year 2010. In the EPIA study, two scenarios were presented: "Business as Usual" and "Policy Driven". They predict the market development through 2017. These scenarios were extrapolated for the years 2018 to 2030 with an annual growth rate of 10% (Business as Usual) or 15% (Policy Driven). Figure 7 shows the extrapolated market forecasts through 2030 for EPIA - Policy Driven (2013) and IEA - Roadmap Vision (2010), as well as an average value scenario for available market forecasts (compare Table 9).

Performance Ratio of PV Systems

The performance ratio is often used to compare efficiency of PV systems at different locations and with different module types. The performance ratio describes the ratio between the actual energy yield (alternating current output) in a PV system and its nominal capacity. The nominal capacity of a PV system is generally expressed in kilowatt peak (kWp). It describes the measured generator capacity under normed STC conditions (standard testing conditions) for the PV modules of the PV system. The actual useable energy yield from the PV system is influenced by the real operating conditions at the system location. Aside from variable solar irradiation values, deviations in the module yield compared to STC conditions can result from shading and accumulation of dirt on the PV module, reflections on the module surface when the light strikes it diagonally, spectral deviation from the normal spectrum as well as from module temperature. Along with the deviations in operating conditions for the PV module, additional losses in the PV system also occur, through electrical maladjustment of the modules, ohmic losses in the DC wiring, inverter losses, ohmic losses in the AC wiring as well as losses in the transformer if any. New, optimally designed PV power plants in Germany achieve performance ratios between 80 and 90% (Reich 2012).

Development of Prices and Costs

Since the beginning of 2012, the wholesale prices for crystalline PV modules from Europa sank by 32% from 1.07 Euro/Wp (January 2012) to 0.73 Euro/Wp (October 2013). The prices for crystalline modules from China dropped during this same period from 0.79 Euro/Wp to the current 0.58 Euro/Wp and thus by 27% (pvXchange 2013). Lately, the prices for crystalline Si-PV modules, especially for multi-crystalline Si-PV from China, increased slightly again. This situation is the topic of an intensive debate within the international PV industry, since the Chinese manufacturers, who are supported by the Chinese government, are being accused of price dumping in order to achieve a dominant position on the market after a period of market consolidation. In light of the enormous price and margin pressure, one must assume that currently only a few cell and module manufacturers can sell their products with positive margins. Nearly all large PV manufacturers were in the red in 2012 and Q1/2013. Market analysts from IHS assume that 2013 marks a change in the trend and that manufacturers leading in cost will once again return to the profitable zone.

The strong decline in the price of solar modules also led to a reduction in the prices for PV systems. Admittedly, the costs for inverters and BOS plant components (Balance-of-System components) such as assembly systems and wiring as well as for their installation did not drop to the same degree. While in 2005, solar modules constituted a nearly 75% share of the system costs, today it is only 40 to 50%. At the same time, this means that the proportional value added on the target market is increasing.

Table 1 shows price ranges for PV power plants of various size classes in Germany. The prices for a small PV systems (up to 10 kWp) are currently between 1300 and 1800 Euro/kWp. For larger PV systems up to 1000 kWp, the prices currently range between 1000 and 1700 Euro/kWp. PV utility-scale power plants with capacities above 1000 kWp are achieving investment costs ranging from 1000 to 1400 Euro/kWp. These values include all costs of components and of installing the PV power plant. According to this information, the average costs for PV plants sank by up to 25% since the previous study from May 2012.

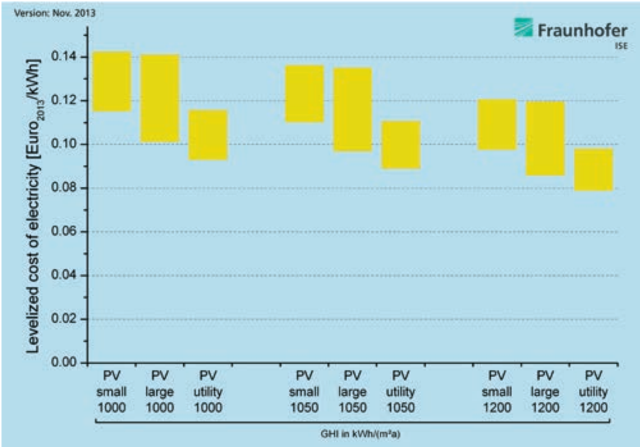

Figure 8: LCOE of PV plants in Germany based on system type and irradiation (GHI in kWh/(m²a)) in 2013.

The values of current PV LCOE are shown in Figure 8 for various power plant sizes and costs at different irradiation 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 the north produce approximately 1000 kWh/(m²a), while power plants in Southern Germany supply up to 1190 kWh/(m²a). In Southern Spain and the MENA countries, values that are in some cases considerably higher, up to 1790 kWh/(m²a) are achieved.

The stark decline in prices for these power plant investments has a substantial influence on the development of the PV LCOE. Even in Northern Germany it is already possible to achieve a LCOE of under 0.15 Euro/kWh. Consequently, the costs for photovoltaically generated electricity from all types of PV power plants in Germany are beneath the average household price of electricity. At locations in Southern Germany, in the meantime, even small PV systems are achieving a LCOE between 0.11 and 0.13 Euro/kWh. Based on the preceding massive decline in prices and the current market situation, no continued significant reduction in the PV LCOE is to be expected in the favorable classes of power plants until 2014, and in expensive power plants the extra margins will melt away in this period. Since all PV technologies, however, still have a clear potential for cost reduction, one must count on a continued decrease in the LCOE in the medium to long term. Today, many module manufacturers are already offering guarantees on the performance of their modules that exceed 25 years. In the event that the operational lifespans of power plants increase from 25 to 30 years, the LCOE of these power plants will sink by another 7%.

A sensitivity analysis for a small PV plant in Germany demonstrates the strong dependency of the LCOE on irradiation and specific investments (see Figure 9). This explains the stark decrease in the LCOE in the last year owing to the decline in module prices. The capital costs for investment (WACC) have an influence on the LCOE which 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 that vary slightly have a smaller influence on the LCOE of PV plants, since they constitute only a minor portion of the total costs. The operational lifetime of the system has, to that extent, a strong effect on the costs, since with longer lifespans plants that have already amortized will continue to produce electricity at very low operating costs.

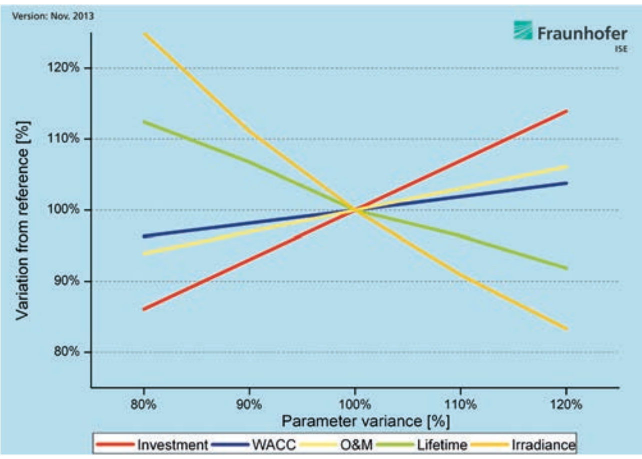

Figure 9: Sensitivity analysis of a small PV system with a GHI of 1050 kWh/(m²a) and investment of 1500 Euro/kW

Wind Power Plants

Of all renewable energy technologies, wind power currently has the strongest market penetration due to its competitiveness to conventional power generation. Starting from markets such as Denmark and Germany, there has been a change in the world market in recent years with the strongest growth in China, India and the USA (GWEC 2013). By the end of 2012, the total capacity of all installed wind farms increased to a volume of 280 GW (GWEC 2013) of which offshore wind power held a share of 5 GW (EWEA 2013).

The market showed continuous growth in the past. Various studies predict a future market volume with a total capacity of between 1600 and 2500 GW in 2030 (see Figure 10). Thereof, the share of offshore wind power is expected to be 40 GW by 2020 and 150 GW by 2030 (EWEA 2011). Given that the forecast from EWEA (2011) refers only to Europa, Fraunhofer ISE developed a corresponding estimate for the global market.

In 2013 onshore wind farms at favorable locations achieved a competitive LCOE compared to conventional power generation technologies such as coal, natural gas and nuclear power. In Germany, wind power achieves a 7.7% share of the total power generated, which shall also be significantly increased in the future through the expansion of wind offshore capacities (BMU 2013). Wind power continued in 2012 to constitute the largest share in regenerative energy production with 33.8% (BMU 2013).

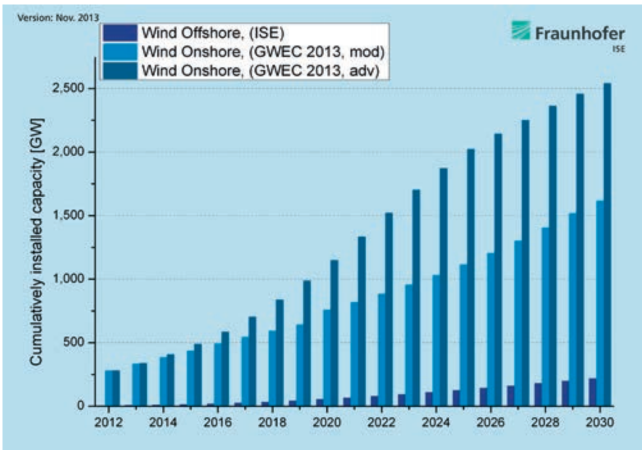

Figure 10: Market forecasts cumulative wind power 2012-2030 according to GWEC (2013) and Fraunhofer ISE

The LCOE of wind power is highly dependent on local conditions both with respect to on and offshore powe plants as well as the achievable full load hours. In general, we distinguish between locations with favorable and unfavorable wind conditions. We generally refer to locations with average wind speeds of over 7 m/s as locations with favorable wind conditions, while the average annual wind speeds at locations with unfavorable wind conditions is lower than this. In Germany, the latter are often located inland, where, firstly, the average annual wind speed is often lower and, secondly, the ground is rougher because of agriculture and forest cover. The increased roughness of the terrain reduces wind speed. Currently, we observe that manufacturers of wind power plants increasingly advance the refinement of their power plant designs to the end of increasing yield at locations with unfavorable wind conditions. This is done in part through tower height or through increasing the contacted rotor surface in proportion to the generator capacity and makes it possible to achieve around 2000 full load hours at locations with an average annual wind speed of around 6.3 m/s. Greater tower heights and longer rotor blades, however, lead to higher material and installation costs that can only be justified by a significant increase in full load hours compared to a conventional power plant for locations with favorable wind conditions. Thanks to ongoing technical refinement, one can expect of future power plants that full load hours at locations with unfavorable wind conditions will increase. However, this is not yet reflected in the LCOE of 2013.

The LCOE of wind power s for two locations with unfavorable wind conditions were calculated as having an average annual wind speed of 5.3 m/s and 6.3 m/s respectively. At the first location 1300 full load hours and at the second 2000 per year were achieved in this way. Very good locations for favorable wind conditions on the coasts are covered by a location with 7.7 m/s and 2700 full load hours.

As shown in Figure 11, the LCOE of onshore wind power at coastal locations with favorable wind conditions with 2700 full load hours was between 0.044 Euro/kWh and 0.054 Euro/kWh. Locations with less-favorable wind conditions achieved a LCOE from 0.061 to 0.107 Euro/kWh, depending on the specific investments. If it is possible to achieve 2000 full load hours at the location in question, the LCOE reaches values between 0.061 and 0.076 Euro/kWh, putting it in the same range as the LCOE of new hard coal power plants.

By way of contrast, the analysis of current offshore wind farms even for locations with higher full load hours (up to 4000 full load hours) have a higher LCOE than onshore wind power. This is attributable to the need to use more-resistant, more-expensive materials, the expensive process of anchoring power plants in the seafloor, cost-intensive installation and logistics for the power plant components as well as high maintenance costs. However, one can expect sinking power plant costs in the future owing to learning curve effects. Currently, offshore wind farms at very good locations achieve a LCOE of 0.114 to 0.140 Euro/kWh (Figure 11). These locations are often far from the coast and are subject to the disadvantage of a time- and labor-intensive and, therefore, expensive process of integration into the grid as well as the need to bridge greater sea depths; locations with lower numbers of full load hours achieve a LCOE from 0.123 to 0.185 Euro/kWh. This means that the LCOE of offshore wind farms at all locations is higher than the LCOE for onshore wind power. The advantage of offshore power plants is seen in the higher figure for full load hours as well as the lower noise pollution and higher acceptance from the local population if the lower limits for distance to coast and environmental protection regulations are observed. Admittedly, there are regulatory weaknesses that considerably delay the integration of current offshore projects into the grid. These technology-specific risks lead to higher capital costs as well as demands from securitization from external creditors, resulting in higher WACC for offshore projects compared to onshore wind parks. This problem shall be simplified through the "Network Development Plan Offshore" presented in early 2013. It provides for, among other things, the joint connection of several wind parks as well as liability for operators of transmission networks for the on-time connection of these wind parks (Hegge-Goldschmidt 2013).

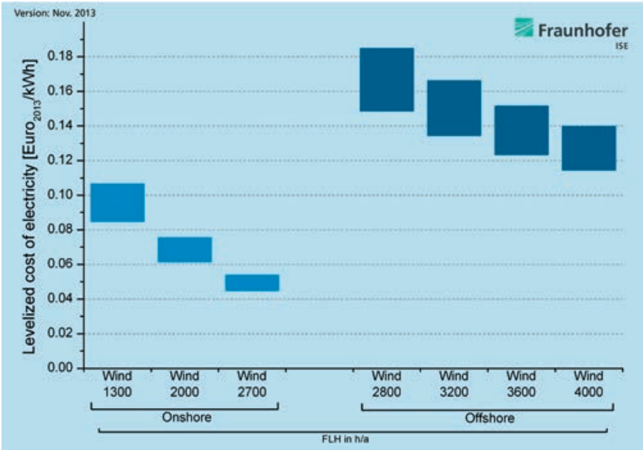

Figure 11: LCOE of wind power by location and full load hours in 2013

The leeway for cost reductions in offshore wind power is limited due to the high expenses for installation and maintenance, which at this time makes achieving parity with onshore wind power quite difficult. However, future cost reducing effects from increased market growth are to be expected since extensive installation of offshore wind farms will just be starting in numerous countries such as our neighboring countries on the North Sea in coming years.

The sensitivity analysis for onshore wind power identifies savings in power plant investments as the primary goal of future cost reduction potentials. As with PV, the sensitivity analysis reacts most strongly to this parameter. Furthermore, the reduction of maintenance costs can make an important contribution.

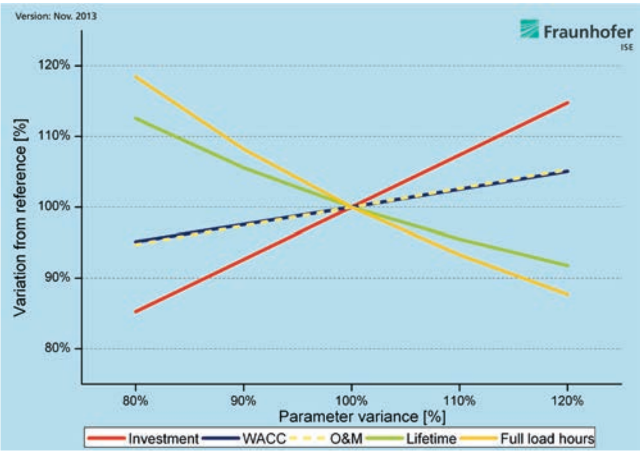

Figure 12: Sensitivity analysis of onshore wind power with 2000 full load hours, specific investment of 1400 Euro/kW

Biogas Power Plants

Through 2012, around 7500 biogas power plants were build in Germany with an installed capacity of 3350 MW (Biogas 2013). There was considerable new construction of 1000 power plants per year primarily in the years 2009 to 2011. In 2012, however, only 340 power plants were constructed in Germany and a forecast for 2013 assumes the construction of another 250 new power plants. In spite of the new construction of biogas power plants in Germany, no reduction in the specific investment costs in recent years can be identified. The specific investment costs for power plants between 2005 and 2009 remain essentially unchanged (Stehnull et at, 2011). For that reason a PR of 100% is assumed for biogas power plants.

As already mentioned, there is a requirement that biogas power plants make use of the heat they generate. It specifies that at least 60% of the power generated in the power plant must be generated in cogeneration of electricity and heat. The heat must be used according to the requirements set forth in EEG 2012 (BMELV 2012). In this study, however, 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 13 shows the LCOE from large biogas power plants (>500kW$_{el}$) for differing full load hours as well as variable substrate costs between 0.025 Euro/kWh$_{th}$ and 0.04 Euro/kWh$_{th}$. Also included in the calculation are the specific investments with values between 3000 Euro/kW and 5000 Euro/kW. For biogas power plants with high substrate costs of 0.04 Euro/kWh$_{th}$ and low full load hours, the resulting LCOE lies between 0.190 Euro/kWh and 0.215 Euro/kWh. If substrate costs remain the same and full load hours reach 7000 h, a lower LCOE of around 0.01 Euro/kWh results. A change in the substrate prices has a larger influence on the LCOE. If they are reduced from 0.04 Euro/kWh$_{th}$ to 0.03 Euro/kWh$_{th}$, the LCOE sinks to 0.02 Euro/kWh, if the same full load hours of 6000 h are assumed. If lower substrate costs of 0.025 Euro/kWh$_{th}$ and high full load hours of 8000 h are assumed, the LCOE can even drop to a level between 0.135 Euro/kWh and 0.155 Euro/kWh. Along with the substrate costs, the full load hours also have a major influence on the LCOE from biogas power plants (see Figure 15). Thus, the LCOE sinks by a 0.01 Euro/kWh, if the full load hours are increased by 20%. Slighter effects on the LCOE are seen in a change of the operational lifespan and the O&M costs. If the operational lifespan can be increased by 20%, the LCOE only sinks by 0.005 Euro/kWh; if the O&M costs are reduced by 20%, the LCOE likewise drops by 0.005 Euro/kWh. Additionally a change in the WACC has the least effect on the LCOE.

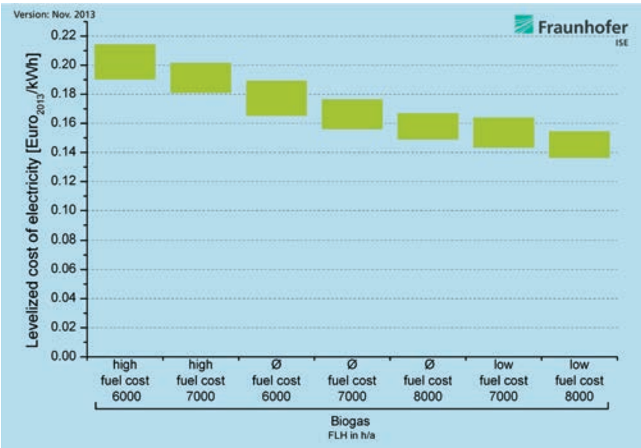

Figure 13: LCOE of biogas power plants at different substrate costs and full load hours in 2013

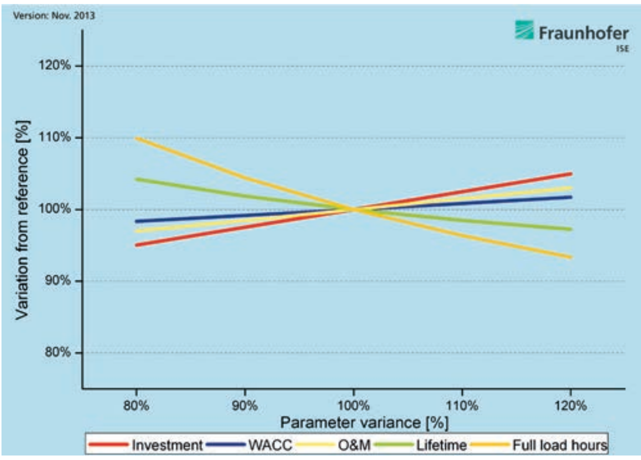

Figure 14: Sensitivity analysis for biomass power plants with specific investment of 4000 Euro/kW and 7000 full load hours

Excursus: Conventional Power Plants

Market Development and Forecast

Coal-fired Power Plants

Coal-fired power plants currently have a 32% share of the worldwide installed power plant capacity with 1581 GW. This means that the largest quantity of electricity produced worldwide is produced by coal-fired power plants (41%), followed by gas-fired power plants with 21% (IEA, 2011). China produces the largest amount of electricity generated by coal. The second largest market is the OECD countries of America, followed by the Asian-Oceanic OECD countries. The fourth largest market is Eastern Europe and Eurasia, whereby 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. The IEA assumes that there will be a continued increase in worldwide coal-fired power plant capacity through 2015. In China, alone it is assumed that power plant capacities will double, whereby the markets in the Asian-Oceanic OECD countries and Eastern Europe/Eurasia are more likely to decrease over the long run. Starting in 2020, according to the IEA, the worldwide coal-fired power plant capacity will fall again, driven by the decommissioning of old power plants, until it falls slightly below today's level by 2030. (IEA, 2012)

In Germany, in 2012, around 30% of the net power generation came from brown coal – and 22% from hard coal-fired power plants (BNA, 2013). This means that coal-fired plants also produce the largest share of electricity in Germany. In 2013, in Germany, there was a net capacity of 24.5 GW_{net} hard coal – and 20.9 GW_{net} brown coal installed (ISE, 2013). It is expected that, in the long term, brown coal capacities will decrease down to 17.6 – 18.0 GW_{net} by 2023 and by 2033 to 11.8 GW_{net} (NEP, 2013). The hard coal capacities will also decrease to values of 25.0 – 31.9 GW_{net} in 2023 and 20.2 GW_{net} in 2033.

Gas Power Plants

In 2009, there were worldwide 1298 GW gas power plants capacity installed. Gas power plants have, after coal power plants, the second largest share of electricity production worldwide. A quantity of 4299 TWh (IEA, 2011) was generated. More than half of all gas power plants are installed in the OECD countries. The OECD countries of America have a 33% share of the total capacity installed worldwide followed by OECD Europa (15%) and OECD Asia (10%). Among non-OECD countries, Russia, because of its massive gas reserves, has the largest installed capacity of gas power plants with 8%, the entire Middle East has a total share of 9%. Of the capacity installed worldwide, 3% is in China, 2% in India. The markets in Africa, Central and South America are currently very small. According to the IEA, the large growth markets are Brazil – with a growth rate of 6% between 2008 and 2035 – and India. The markets in Africa, Mexico and Chile will also grow considerably by 2035. In Russia and Japan, the capacities are declining slightly (IEA, 2011).

In Germany, around 49 TWh of electricity were generated by gas power plants in 2012. This corresponds to a share of 10% (ISE, 2013). According to the grid development plan, an increase in installed gas capacity is assumed, from today's 26.5 GW_{net} to 30 GW_{net} in 2023 and 41 GW_{net} in 2033 (ÜNB, 2013).

Price and Cost Development

The LCOE from coal power plants is highly dependent on the achievable full load hours. In Germany, brown coal power plants currently achieve an average of 7100, hard coal power plants around 6000, and economical gas power plants with 3500 full load hours (calculation according to installed capacity and produced quantity of electricity (BNA, 2013) and (ISE, 2013)). The full load hours that a power plant can achieve are dependent on the variable marginal costs of the individual power plant, since the unit commitment on the market is determined by the Merit-Order. This means that the development of full load hours is essentially dependent on the predictions regarding prices for fuel and CO_2 allowances, the development of electricity feed-in from renewable energy technologies and the construction of the power plant park. The sizes mentioned are laden with considerable uncertainties due to their dependency on the developments on the national and international markets.

Figure 15 shows the LCOE of 2013 from brown coal, hard coal and CCGT power plants, in each case for the spectrum of full load hours from Table 4, the CO_2 allowance prices from Table 7, the fuel prices from Table 5 as well as the minimum and maximum specific investments from Table 1.

Brown coal currently has the lowest LCOE, which lies between 0.038 and 0.053 Euro/kWh. As classical base load power plants, brown coal power plants, however, have little flexibility in generating and are only partly suitable for flanking fluctuation output from renewable energy technologies. The LCOE from hard coal power plants lies with 0.063 to 0.080 Euro/kWh considerably higher than this, in spite of lower specific investment costs than brown coal. The LCOE from CCGT power plants have a range between 0.075 and 0.098 Euro/kWh and are therefore more expensive than hard coal power plants. Advantages of CCGT power plants are their greater flexibility and lower CO_2 emissions compared to hard coal power plants. By way of comparison, admittedly, the LCOE from onshore wind plants at locations with 2700 full load hours lies at 0.044 Euro/kWh above the cost for brown coal electricity, the costs of hard coal and CCGT power, however, lie above this.

Figure 15 makes clear that the LCOE from conventional power plants depends in a large degree on the achievable full load hours. For CCGT power plants, the variation in full load hours yields a difference in the average LCOE of +/- 0.005 Euro/kWh. The specific investments have a considerable influence on the LCOE, which are considerably more pronounced with CCGT power plants than with hard coal and brown coal power plants. In the case of CCGT power plants, there is, with lower full load hours, a difference in the LCOE of 0.017 Euro/kWh.

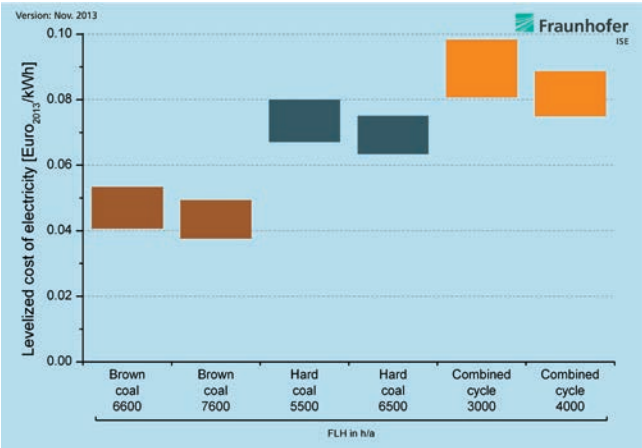

Figure 15: LCOE conventional power plants in 2013 with variable prices for CO_2 allowances and fuels as well as specific investments in 2013

In the future, conditioned on a higher share of renewably generated electricity, the full load hours for conventional power plants will decrease. For conventional power plants, the trend runs counter to that seen with renewable energy technologies: The costs will rise in the future. On the one hand, this trend is attributable to increasing costs of fuel and CO_2 allowances, on the other to the expected, considerably lower full load hours.

Figure 16 shows the LCOE from hard coal power plants for the year 2020 for power plants with full load hours between 5200 and 6200 h, specific investments between 1100 and 1600 Euro/kW, CO_2 allowance prices between 17 and 29 Euro/tCO_2 as well as fuel prices between 0.0103 and 0.0114 Euro/kWh in all combinations.

The LCOE lies between 0.061 and 0.091 Euro/kWh. Full load hours have the greatest influence on the LCOE in cases with either low or high fuel costs. The investments have a very major influence on the LCOE at constant low installations and fuel costs. The variation of LCOE owing to allowance prices has a clearly lower influence than full load hours and costs for the construction of power plants. The influence of fuel costs is the smallest.

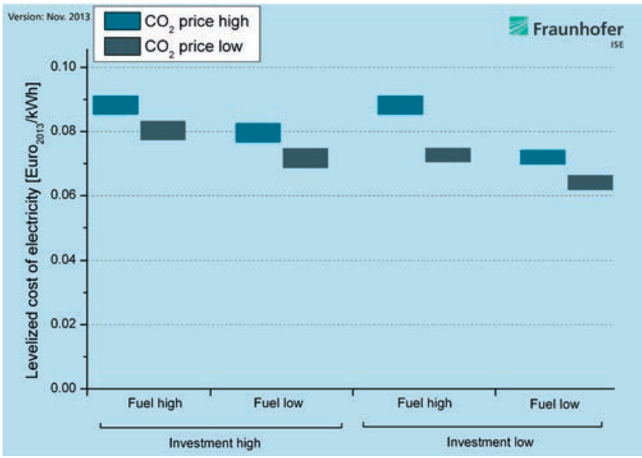

Figure 16: LCOE from hard coal depending on investment, full load hours, CO_2 allowance prices and fuel prices in 2020

Forecast for the LCOE through 2020 and 2030 in Germany

For renewable energy technologies, cost forecasts can be generated based on historically observed learning curves whose progress over time builds on the different market forecasts for the period 2020 to 2030. For photovoltaics and wind technology, it has been possible to describe an average learning rate and/or progress ratio (PR= 1 - learning rate) in the last 20 years. The investments per Watt of PV modules sank in the past following a PR of 80%. For the forecast of future development in the LCOE from PV, we count on a PR of 85%, as suggested by Bhandari and Stadler (2009). Since the PV industry is currently in a consolidation phase, in which companies are attempting to gradually return to the profitable zone, and since PV system prices have also fallen disproportionally in the last three years, predominantly lateral movement is expected for the time being and through the end of 2014 before the system prices will fall further as of 2015 following a learning rate of 85%.

By way of comparison, the costs of wind power in recent years followed a PR of 97%, where it has earlier been 87 – 92% (ISET, 2009). For offshore wind power, no authoritative PR could be determined based on the low market volume. Since the current offshore projects on the one hand makes recourse to already developed onshore-technology and on the other still expect offshore-specific developments, a PR of 95% is assumed for offshore wind power in this study.

Modeling the LCOE shows a variable development dynamic for the individual technologies, depending on the parameters discussed here, the financing conditions (WACC), market maturity and development of the technologies (PR), current specific investments (Euro/kW) and local conditions (Figure 17).

Today, nearly all newly installed PV power plants in Germany can generate power for under 0.15 Euro/kWh. At an annual irradiation of 1000 kWh/(m²a), the costs even for smaller rooftop systems will fall by 2018 under the 0.12 Euro/kWh mark. Larger utility-scale power plants with an annual irradiation of 1200 kWh/(m²a) will already be generating their power for less than 0.08 Euro/kWh. Starting in 2025 the LCOE of both of these types of plants will fall below the value of 0.11 or 0.06 Euro/kWh respectively. Starting in 2020, utility-scale PV plants in Southern Germany will generate power less expensively than likewise newly installed hard coal or CCGT power plants, which then achieve a LCOE of 0.08 to 0.11 Euro/kWh. The plant prices for PV will sink for utility-scale plants to 570 Euro/kW and for small plants from 800 to 1000 Euro/kW.

Depending on the wind conditions at the location, comparable prices can be achieved for onshore wind power plants as for PV power plants at good locations. Only locations with annual full load hours exceeding 2000 hours can achieve a lower LCOE compared to the best PV power plants over the long term. From the current LCOE between 0.044 Euro/kWh and 0.107 Euro/kWh, the costs will sink long-term to 0.043 and 0.101 Euro/kWh. Today, there is already onshore wind power with comparable or more favorable LCOE than those for hard coal and CCGT power plants. Increasing CO_2 allowance prices and decreasing full load hours are the reasons why an increasing LCOE is predicted for brown coal power plants as well through 2030, with a rise from 0.052 to 0.079 Euro/kWh predicted. With offshore wind power, however, there is somewhat greater potential for cost reduction thanks to higher learning rates. This can significantly decrease the LCOE from the considerably higher values in 2013 through 2030. The reduction in the LCOE is expected from today's values between 0.12 and 0.19 Euro/kWh to a good 0.10 to 0.15 Euro/kWh in 2030. The power plant prices then lie between 2600 and 3500 Euro/kW. For biogas power plants, we assume a constant LCOE that moves in the range from 0.136 to 0.214 Euro/kWh. Here the availability and the fuel costs of the substrate are decisive for the future development of the LCOE.

Over the long-term, PV power plants at high-irradiation locations and wind power at onshore locations with favorable wind conditions have the lowest LCOE. Both technologies can considerably lower the LCOE from fossil power plants by 2030. The technology and cost developments of recent years have considerably improved the competitiveness of wind power and

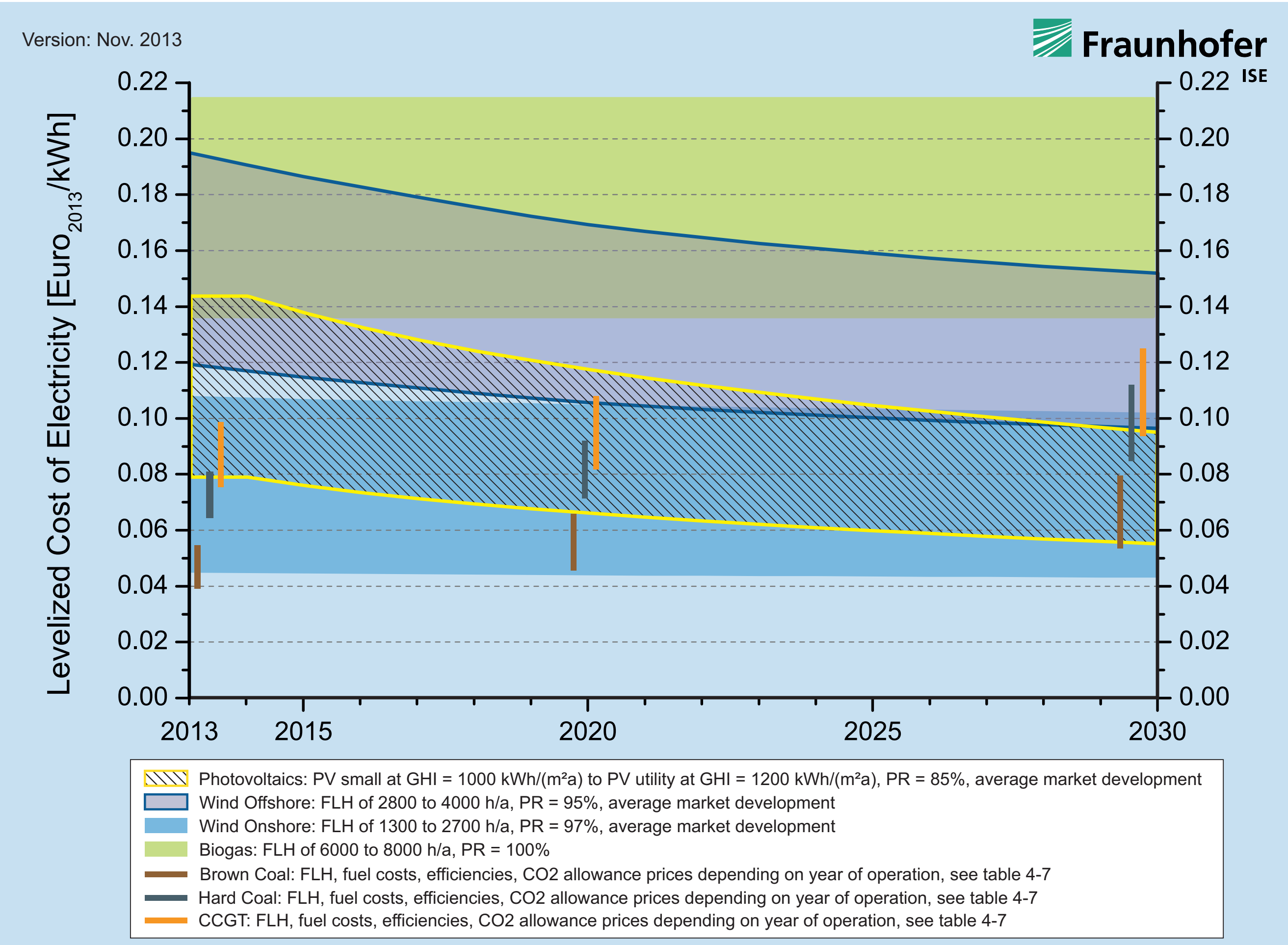

Figure 17: Forecast for the development of LCOE of renewable energy technologies as well as conventional power plants in Germany by 2030

PV. Especially in the case of PV, it was possible to realize such significant cost reductions that it has long since ceased to be the most expensive renewable energy technology in Germany. The analysis of the LCOE in 2013 shows that the price forecasts for PV presented in the last versions of this study (2010 and 2012) could clearly see their prices revised downward by the strong market growth and the considerable price reductions for PV. The reason for this is that these forecasts for the LCOE are subject to great uncertainties due to the learning curves (Ferioli, 2009). This engenders a series of questions: To what extent will the learning curve be continued in the future through innovative developments and new production technologies or even see downward revisions in price? How will the markets develop in the future or how will the financing costs develop in a national or international economic environment? For this reason, sensitivity analyses of the learning curves with different PRs are presented for the individual technologies.

Sensitivity Analyses of the Learning Curves used for PV and Wind

Figures 18 and 19 show a different combination of PRs and market scenarios (see Tables 8 and 9) in the spectrum of LCOE of small PV systems and onshore wind power in Germany. Starting from an average value for the current costs, the values evince fluctuations from 10 to 20% depending on the parameters used. This expresses the uncertainty of the learning curve model if different input parameters are used. At the same time, it reflects a potential bandwidth for cost development of individual technologies.

For small photovoltaic power plants at locations with energy yields of 1050 kWh/kWp, LCOE between 0.06 Euro/kWh and 0.10 Euro/kWh can be identified for each scenario. For onshore wind power, only slight future cost reductions (0.060 – 0.068 Euro/kWh) are to be expected due to the low current LCOE.

Cost Development of PV

The PV industry is currently in a phase of market consolidation, characterized by worldwide excess capacities in production facilities, enormous price pressure from sinking compensation tariffs on many markets and market prices for solar modules that do not cover the costs. As a consequence, there are bankruptcies and mergers among module and cell manufacturers. At the same time, the cost pressure on suppliers, builders and manufacturers of system components has increased tremendously. In order to adequately reflect this situation, a consolidation phase lasting through the end of 2014 is taken into account in the forecast for further development in the LCOE, one in which an industry-wide recovery from the results of the unexpectedly severe decline in prices is expected. This assumes that module and cell manufacturers will be able to produce again at levels covering their costs, for which there are already positive indications. Thus IHS analysts expect increasing demand and sales in the PV industry for 2013. Additionally, long-term supply contracts for silicon are expiring for many cell manufacturers so that they can profit from the greatly decreased costs in new contracts. An increase in the global PV market also provides for an increased load on existing production facilities which will cause the specific overhead costs on the cells/modules produced to sink (IHS, 2013).

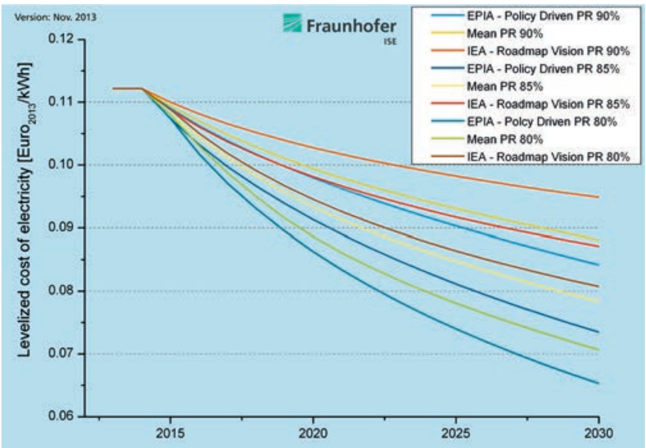

Figure 18: Sensitivity analysis for the forecasts for LCOE of small PV power plants, investment 1500 Euro/kW, GHI=1050 kWh/(m²a)

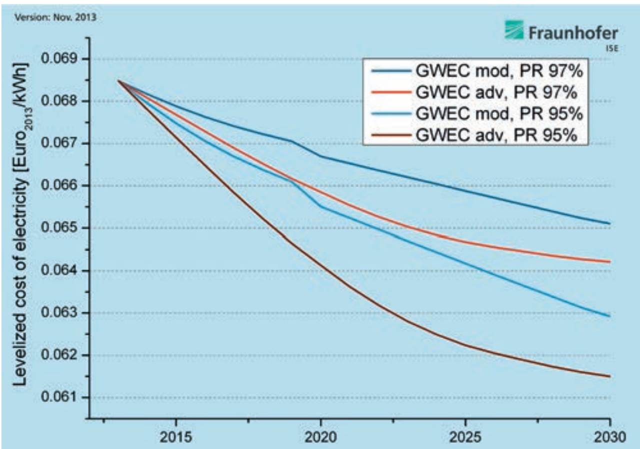

Figure 19: Sensitivity analysis for the forecasts for LCOE of onshore wind power, investment 1400 Euro/kWh, FLH=2000 h/a

5. TECHNOLOGIES FOR HIGH SOLAR IRRADIATION

In this chapter, the three technologies photovoltaics (PV), concentrating solar thermal power (CSP) and concentrating photovoltaics (CPV) are analyzed for regions with high solar irradiation and the LCOE is calculated for each.

To calculate the LCOE of PV, CPV and CSP, three locations were considered. The first location was the one with the lowest GHI, only 1450 kWh/(m²a), and was only studied for a PV power plant since the direct irradiation is too low for concentrating technologies at this location. For this reason, CSP and CPV were only analyzed at locations with a high direct normal irradiation (DNI) of 2000 kWh/(m²a) and 2500 kWh/(m²a). PV power plants were studied at corresponding locations with global horizontal irradiance (GHI) of 1800 kWh/(m²a) and 2000 kWh/(m²a).

In the pure cost comparison for 2013 between PV with CPV and CSP plants at locations with high irradiation (2000 kWh/(m²a)), PV shows lower LCOE than CSP. Due to the weaker market growth compared to PV, the LCOE of CSP plants with integrated thermal storage (up to 3600 full load hours) is currently below 0.19 Euro/kWh, while utility-scale PV power plants achieve a LCOE of less than 0.10 Euro/kWh with the same irradiation. Depending on the irradiation, CPV plants lie between 0.08 and 0.14 Euro/kWh (Figure 20).

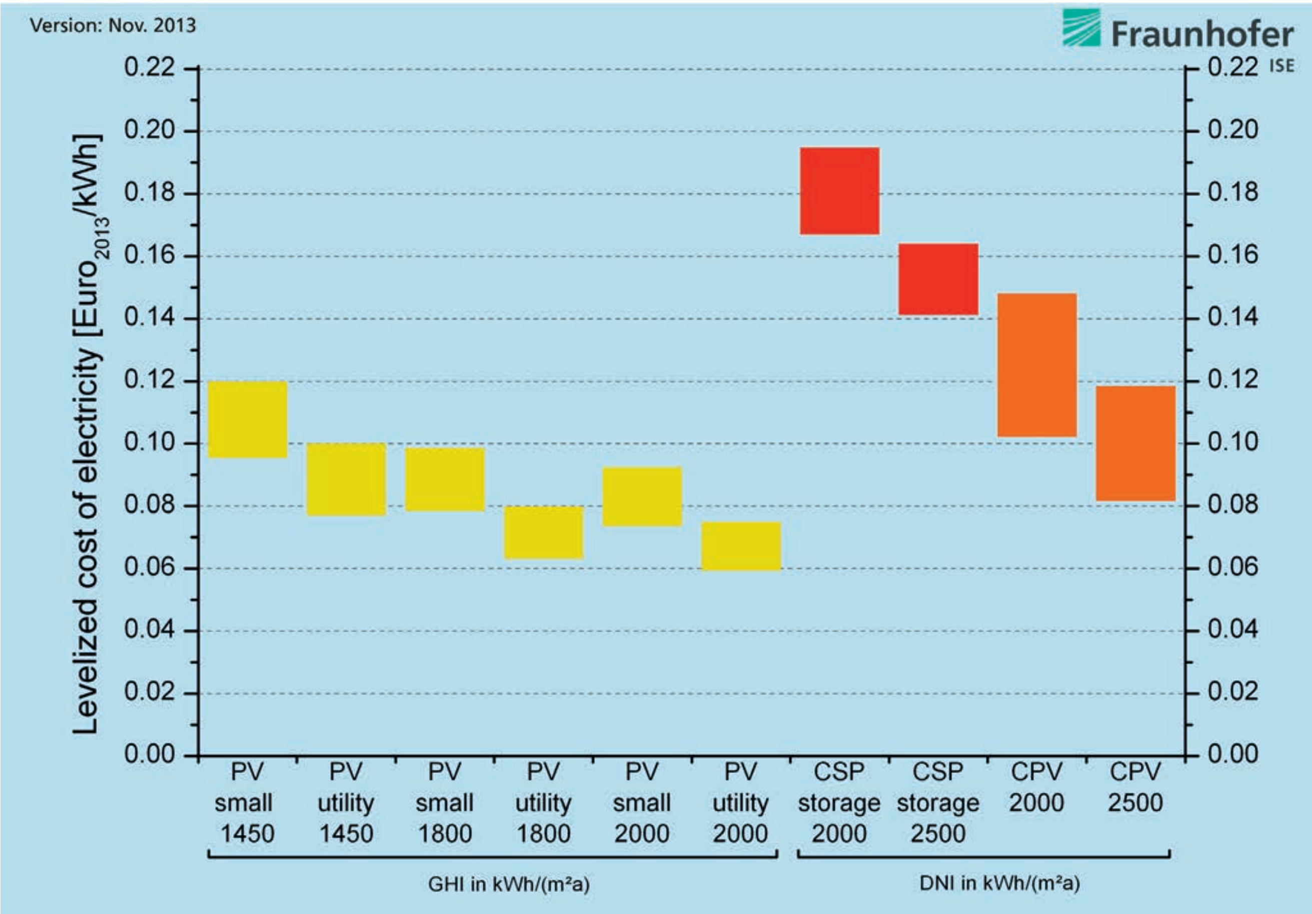

Figure 20: LCOE of renewable energy technologies at locations with high solar irradiation in 2013
The value given under the name of the technology refers to the solar irradiation in kWh/(m²a) (GHI for PV, DNI for CPV and CSP)

Photovoltaic Power Plants

At locations with high global horizontal irradiation (GHI) of 1800 kWh/(m²a) in Southern Spain and/or 2000 kWh/(m²a) such as in the MENA countries, the LCOE fell from 0.10 to 0.06 Euro/kWh (Figure 21). In regions with an irradiation of 1450 kWh/(m²a) such as in France, the LCOE lies at approximately 0.08 to 0.12 Euro/kWh. The higher financing costs at locations such as Spain or the MENA countries, however, increase the LCOE, so that the advantage of considerably higher irradiation is lost in part (see Table 2 for financing assumptions).

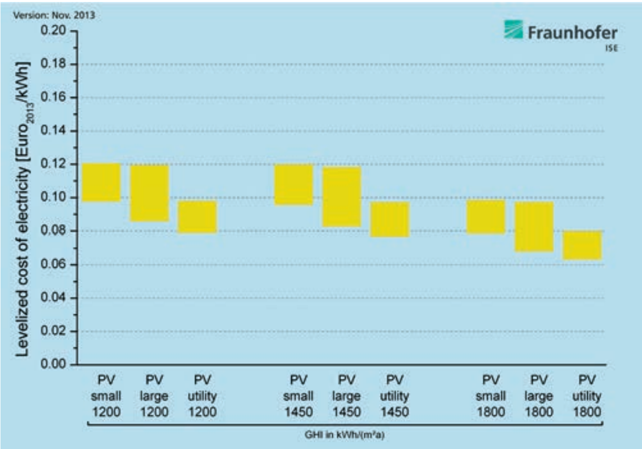

Figure 21: LCOE of various PV plant types at three locations with high solar irradiation kWh/(m²a) in 2013

Concentrating Solar Power Plants

Owing to their technological properties, CSP can be operated efficiently primarily in areas with good solar resource with an annual DNI of over 2000 kWh/(m²a). Thanks to the integration of molten salt thermal storage systems, they can temporarily store thermal energy and thereby feed electricity into the grid independently of the current weather conditions or time of day. This integrated storage option is what essentially distinguishes CSP from wind power and PV. Triggered by attractive governmental subsidies in the USA and Spain, CSP plant technology experienced a new boom between 2005 and 2011, after the construction of nine power plants in California with a total capacity of 354 MW between 1980 and 1990 had been unable to generate any growth effects. Especially countries with very high direct normal irradiation (DNI) developed extensive expansion plans for CSP projects (CSP Today, 2011), often in desert areas. Thanks to the steep decline in prices for photovoltaics, CSP technologies have, however, come under considerable pressure especially in Spain and the USA, so that several planned power plant projects had to be delayed or cancelled. At the same time, the "Arab Spring" and the therewith associated somewhat uncertain political circumstances in some countries of the MENA region put the brakes on expansion plans for CSP. By way of contrast, other countries such as Morocco or Kuwait are continuing to follow ambitious plans. In the USA, ambitious CSP projects such as the two solar power tower plants Ivanpah (377 MW) and Crescent Dunes (110 MW) are being implemented, and are to be put into operation in 2013. In the past, Greenpeace (2009), Trieb (2009) and Sarasin (2011) have predicted considerable market growth for CSP plants. These forecasts also serve as a basis in this study since there are no updated market forecasts that take into account the somewhat difficult developments of the last two years (see Figure 22).

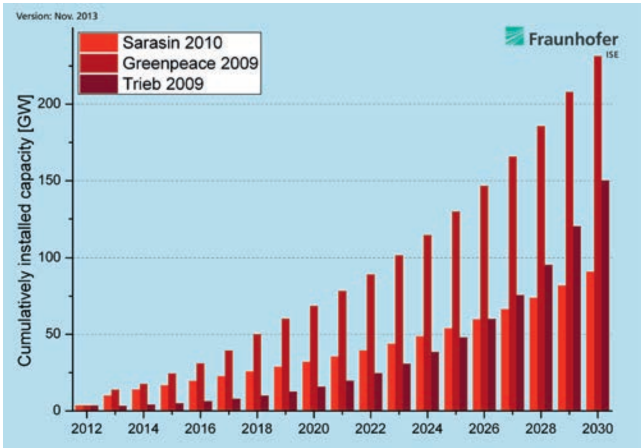

Figure 22: Market forecast for cumulative power plant capacity for CSP 2012-2030, Sarasin (2010), Trieb (2009), Greenpeace (2009)

Mid-2013, there are CSP plants with a total capacity of 3.5 GW in operation worldwide. Additional power plants with a total capacity of 2.5 GW are currently under construction and about 7 GW are in the planning or development phase. (CSP Today Project Tracker, Status 7.8.2013)

The analysis of the LCOE of CSP plants is based especially on the data for realized power plant projects with parabolic trough and tower technology in Spain and the USA on whose basis it was possible to develop the power plant parameters and investment information for parabolic trough power plant projects with power plant capacities of 50 MW such as Andasol1-3 (CSP plant with storage of 8h) or Shams1 with 100 MW in Abu Dhabi. These power plant projects are compared with the LCOE of the Gemasolar solar tower in Spain which has a power plant capacity of 20 MW and a storage capacity of 15 full load hours. Additionally, the cost information on the solar power tower plants in the USA was taken into account. The size of the thermal energy storage is indicated by the number of full load hours for which the turbine can be supplied with energy from a fully charged storage without solar irradiation present.

Due to the low overall installed capacity of linear Fresnel technology to date, only individual projects could be taken into account as reference for this study. One example is a new 30 MW Fresnel power plant in Spain. A broad market analysis of many projects is not possible at this time since many power plant projects are in the development phase and the actual costs are often not published. What is true of all three technologies is that the power plant-specific configuration and the design of the power plant are still subject to considerable technological refinement. This is apparent in the many differing power plant concepts which are specified according to the manufacturer but also according to the location and demand for power (dimensioning of the storage).

The LCOE of the analyzed CSP plants with thermal storage and with a DNI of 2000 kWh/(m²a) are between 0.160 Euro/kWh and 0.196 Euro/kWh (Figure 23). This means that they frequently perform better than parabolic trough power plants without thermal storage, whose values are between 0.251 Euro/kWh and 0.156 Euro/kWh. The reason for this is that a larger solar mirror field combined with molten salt thermal storage provides for better utilization of the power plant turbine and therefore higher numbers of full load hours.

Solar power tower plants with thermal storage (0.184 – 0.210 Euro/kWh) tend to perform slightly worse compared to parabolic trough power plants with thermal storage (0.161 – 0.197 Euro/kWh). Linear Fresnel power plants without thermal storage (0.142 – 0.179 Euro/kWh) by contrast are in part a considerably less expensive solution compared to parabolic trough power plants without thermal storage (0.156 – 0.251 Euro/kWh). In regions with higher solar irradiation of up to 2500 kWh/(m²a), such as in the MENA countries or the deserts in California, a LCOE of 0.121 Euro/kWh can be achieve for CSP technologies without thermal storage and 0.136 Euro/kWh for technologies with thermal storage.

Cost reductions are foreseeable in the coming years for CSP technology, compared to the first reference power plants; they will come from higher automation, project experience, use of improved materials and components as well as additional large projects (Fraunhofer and Ernst&Young, 2011). One positive signal for CSP's cost development is the reported feed-in tariffs of 0.135 US$/kWh for the solar power tower plant crescent dunes (NREL 2013) in the USA, which is set to go online in 2013. However, these values can only be achieved with the aid of very favorable credits or tax advantages. To date, CSP is the only technology in which large-scale thermal storages can be integrated. This brings an ever greater advantage with the increasing expansion of renewable energy technologies that has not yet been adequately honored by the market.

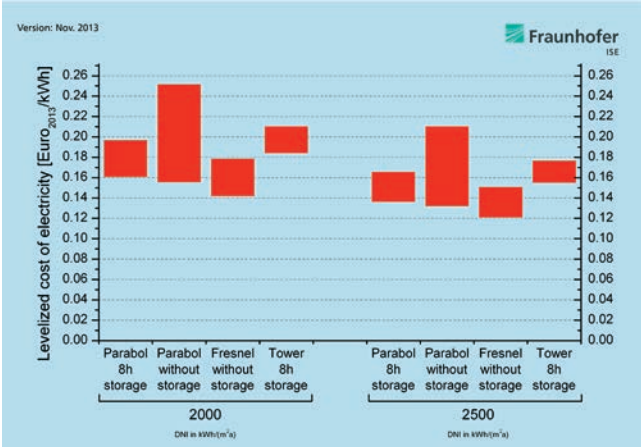

Figure 23: LCOE of CSP plants with a nominal capacity of 100 MW, by plant type and irradiation (DNI in kWh/(m²a)) in 2013

The sensitivity analysis shows that investments reduced by 20% would, compared to the reference case, lead to a LCOE of 0.128 Euro/kWh (see Figure 24). A higher DNI has a similarly strong, positive influence on the LCOE..

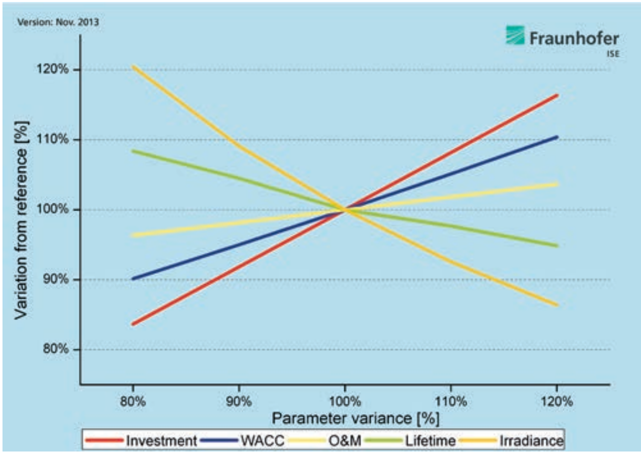

Figure 24: Sensitivity analysis for CSP (100 MW with thermal storage) with annual DNI of 2000 kWh/(m²a) and specific investment of 6000 Euro/kW

Concentrating Photovoltaic Power Plants

Concentrating photovoltaics is especially interesting for inexpensive power generation in sun-rich regions with DNI values of more than 2000 kWh/(m²a). The systems are differentiated especially according to the concentration factor. The largest share, more than 85% of the capacity installed to date, is in the form of high concentrating photovoltaics with two-axis tracking. With this technology, sunlight is focused on a solar cell through inexpensive optic lenses or mirrors. Through concentrating the sunlight onto a small cell area at a concentrating factor of 300 to 1000, highly efficient but comparatively expensive multiple solar cells based on III-V semiconductors (e.g. multi-junction solar cells made of GaInP/GaInAs/Ge) can be used. There are also low-concentrating systems with a maximum 100 times concentration which track on one or two axes. Silicon-based solar cells are primarily used in these plants.

Concentrating photovoltaics has only been established on the market in recent years. The first power plant exceeding the 1 MW-level was realized in Spain in 2006. Since then, an increasing number of commercial power plants have been installed in the MW range annually, whereby some power plants already evince capacity of more than 10 MW. Along with the trend toward larger power plant units, there is a noticeable regional diversification of the market. While the first power plants were installed solely in Spain, CPV power plants have also been realized in several other countries since 2010. Regional key areas include the USA, China, Italy, Australia and South Africa. Compared to conventional photovoltaics, the CPV market is still small, with a market volume of just 50 MW in 2012. Several large power plants with capacities in the range of 50 MW each are currently under construction and others are in advanced phases of project development (Figure 25).

Reasons for the construction of the first large-scale power plants using high concentrating photovoltaics are found for one in the continuous increase in the efficiency of individual modules, now over 32%, and 27% AC for entire systems that has been seen in recent years (Wiesenfarth, 2012), combined with additional predicted increases in efficiency for CPV systems to over 30% in the coming years (EU PV Technology Platform 2011; Pérez-Higueras 2011). Another factor is that CPV, with its tracking systems, is profiting from a balanced electricity production and higher energy yield over the course of the day. At the same time, the size of the power plants can be scaled over a wide performance range, whereby the project implementation of larger CPV power plants at 20 to 100 MW is nearly as rapid and flexible as in photovoltaics. CPV power plants also evince a low demand for area, since the foundations of the tracking units are relatively small. This makes it possible to continue to use the land for agriculture. High concentrating photovoltaics evinces advantages in hot climates in particular, since the output of the solar cells used does not decline as precipitously at high temperatures as that of conventional silicon solar cells. Additionally, most CPV technologies do not need any kind of cooling water in operation. Current system prices, including installation for CPV power plants with a capacity of 10 MW, lie between 1400 and 2200 Euro/kW (Sources: GTM 2013, industry survey). The large range of prices results from the different technological concepts as well as the still-young and regionally variable markets. Today, the calculated LCOE from 0.102 to 0.148 kWh/Euro for a location with a DNI of 2000 kWh/(m²a) can already provide a basis for comparison with the analyzed values for PV utility-scale power plants and CSP in spite of the small market volume (see Figure 26 and 21).

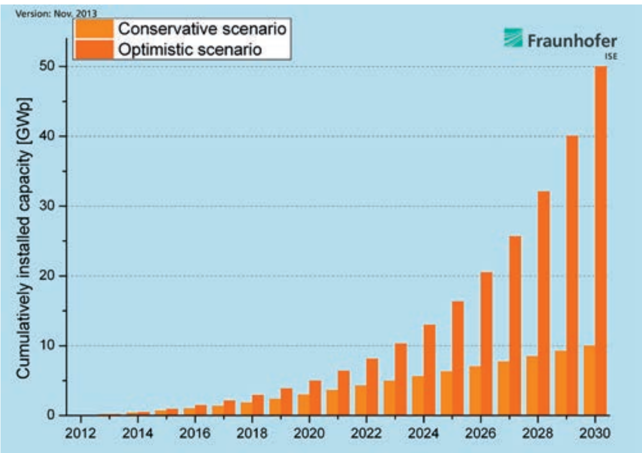

Figure 25: Market forecast of cumulative power plant capacity for CPV for 2012-2030 (Fraunhofer ISE, 2013)

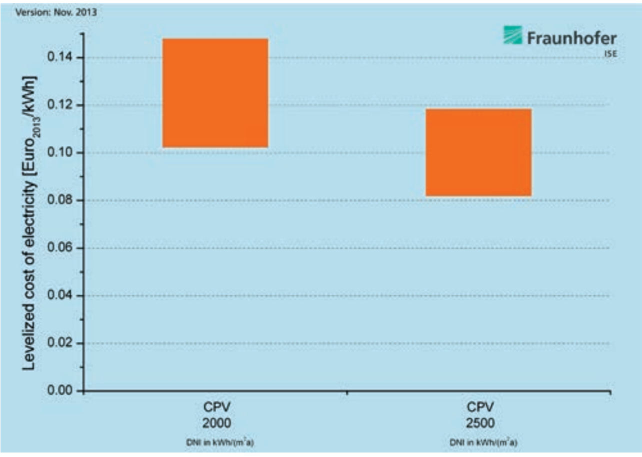

Figure 26: LCOE of CPV by irradiation (DNI in kWh/(m²a)) in 2013

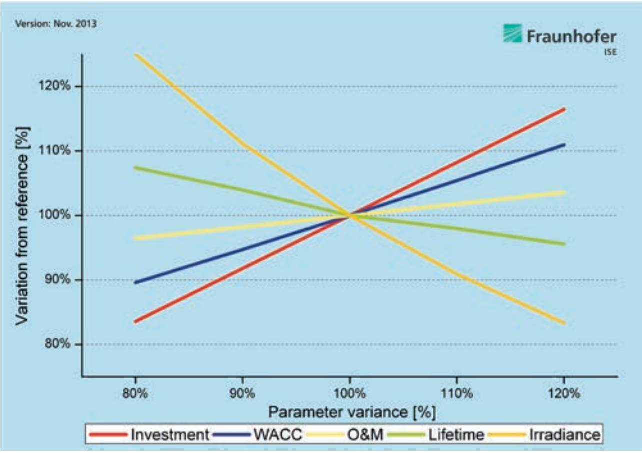

Figure 27: Sensitivity analysis of CPV (irradiation DNI = 2000 kWh/(m²a), investment = 1800 Euro/kW)

Forecast for the LCOE through 2030 for Solar Technologies under High Solar irradiation

The forecast for the LCOE through 2030 was likewise completed for the technologies PV, CPV and CSP at locations with high solar irradiation. Studies by the German Aerospace Center (German: Deutsches Zentrum für Luft- and Raumfahrt, abbreviated DLR) yield different PRs for the individual components in CSP plants (solar field, thermal storage, power block) with values between 88% and 98% (Viebahn 2008, Trieb 2009). This yields an average PR of 92.5%, which refers to the entire power plant. Other studies assume PRs with values of 90% (Greenpeace, 2009) or 92% – 96% (Sarasin, 2009). Experience-based values for prices and learning curves have not yet been recorded for CPV and described in the literature. However, a high potential for cost decreases is seen. GTM Research predicts CPV system costs of 1.2 $/W in 2020, which corresponds to a decrease in cost of 51% compared to 2012 (GTM 2013). Technological improvements play an important role in this, such as reduction in system losses and higher efficiencies. Furthermore, cost reductions are expected through economies of scale, for example owing to a higher degree of automation in production and increasing market power in the purchase of materials. A PR of 85% is assumed for the CPV module and used in the conservative scenario shown in Figure 25. The remaining system components (inverters, wiring, etc.) come from the PV field and have already been refined. In order to account for this, the PR and market development of the PV is assumed there, which is a more mature market status. The division of investments into modules and components is done in a 1-to-1 ratio.

By 2030, the LCOE from CSP can sink to values between 0.096 Euro/kWh and 0.134 Euro/kWh. In the case of CPV, a cost decrease between 0.040 Euro/kWh and 0.076 Euro/kWh would be possible (Figure 26). For both technologies, the decisive factor will be the extent to which the installations of CSP and CPV will be continued in the markets with high solar irradiation in the coming years.

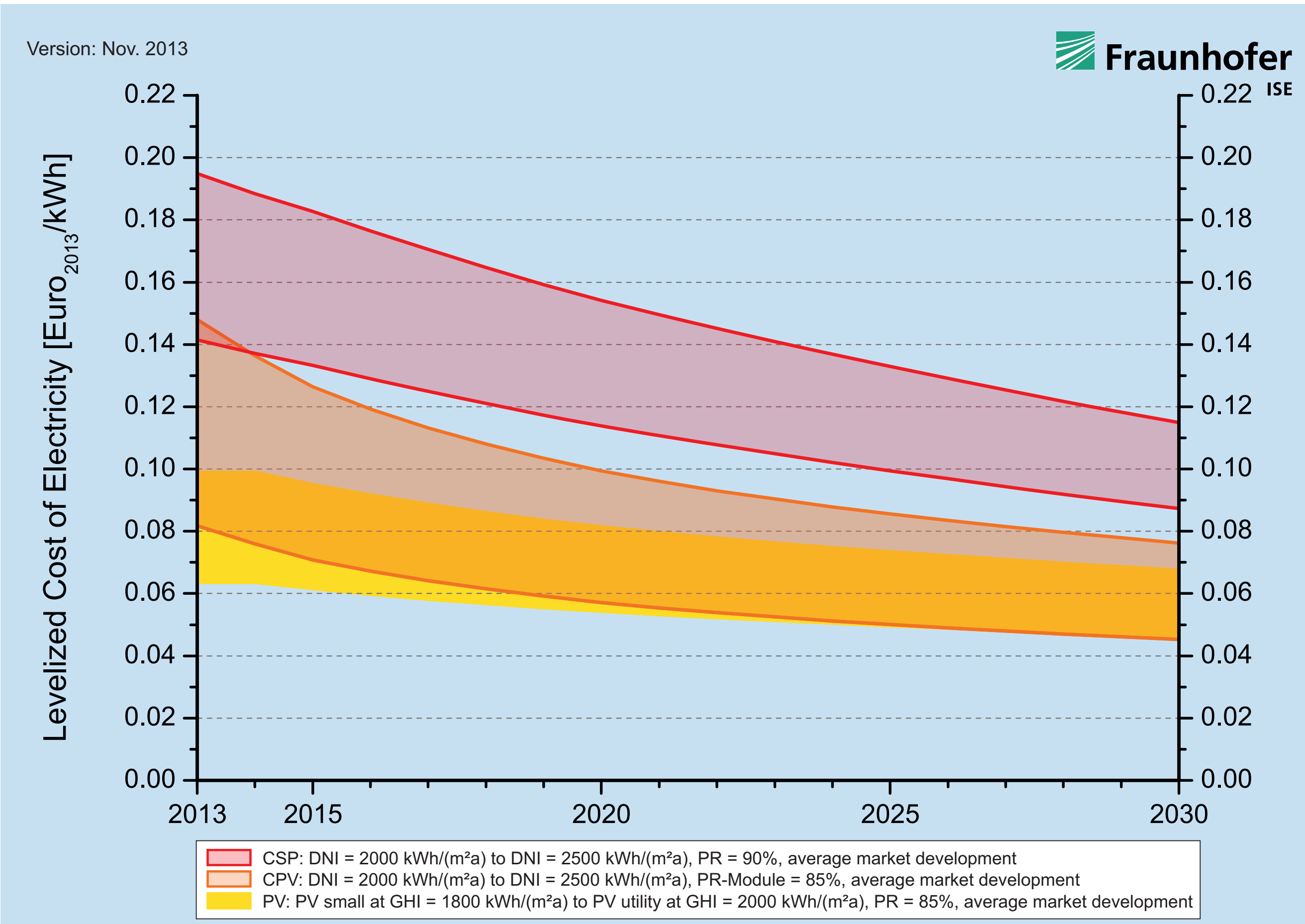

Figure 28: Development of the LCOE of PV, CSP and CPV plants at locations with high solar irradiation kWh/(m²a)

Sensitivities of the Learning Curves used for CPV and CSP

The following two figures show the spectrum of LCOE for CPV and CSP for different combinations of PRs and market scenarios. Starting from an average value for today's costs, the values show fluctuations of 10 to 20%, depending on the parameters used.

Concentrating solar power plants could be able to produce, according to calculations with different learning curves, electricity for 0.10 Euro/kWh by 0.12 Euro/kWh by 2030. In the case of CPV power plants, the LCOE could lie between 0.06 and 0.07 Euro/kWh.

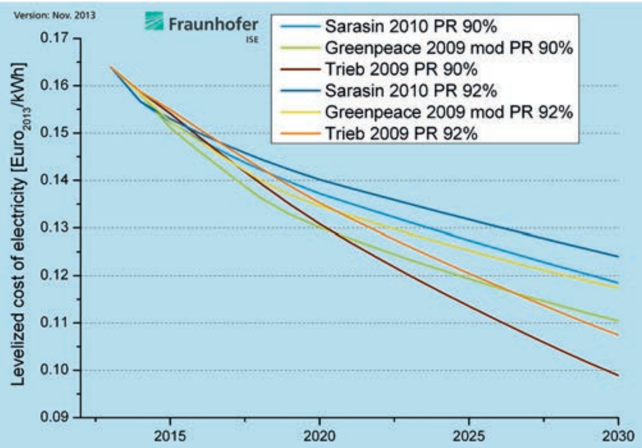

Figure 29: Sensitivity analysis for the forecast of LCOE CSP, investment 6000 Euro/kW, DNI=2500 kWh/(m2a).

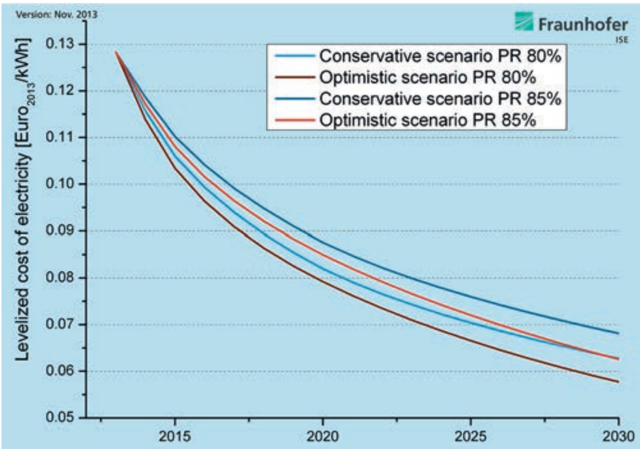

Figure 30: Sensitivity analysis for the forecast for LCOE CPV, investments 1800 Euro/kW, DNI=2000 kWh/(m2a)

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

The continuously falling LCOE of renewable energy technologies as well as increasing costs for fossil fuel power plants leads to a constantly improving competitive position for renewable energy technologies. This leads to rapidly growing market niches in which economically efficient operation of renewable energy technologies is possible even without subsidies so that renewable energy technologies will be able to make an essential contribution to the energy supply in the future.

This development is being supported politically in Germany by the federal government whose central objective is to reduce greenhouse gas emissions by 2050 by 80 – 95% compared to 1990 and at the same time cease using nuclear power by 2022.

With increasing installations of fluctuating electricity producers and therewith associated higher shares of power supply, the energy supply system, i.e. the interaction of the individual components and actors, will change fundamentally. In this, other factors beside the LCOE will also play a role in the analysis and evaluation of a technology in the energy system. For example, the "value" of the electricity will become more important, i.e. its availability at times of high demand and the ability to take on system services such as providing idle power or stabilizing frequency and voltage. There are a number of possible combinations for arranging such an energy system on the national, regional and community levels.

Under the requirement that it must be possible to cover demand at any time, a sector-spanning energy system can be developed with the help of an energy system model in order to reach a specified goal such as reduction of CO_2 (c.f. model ReMod-D, described in Henning and Palzer (2013)). Thereby t is essential that the energy system is regarded in its entirety since there are many interactions and interfaces between the different sectors (power, heat, transportation, etc.).

In order to answer the question of how to achieve such a target system, it is important that we estimate in which direction and in what speed the energy system is changing. Various factors are important to the change: Politically driven stimulus, framing conditions or restrictions as well as the efficiency of technologies. The actual core consists in analyzing under what conditions an investor is ready to invest in the various components of the energy system. The LCOE and its development play an important role in this decision.

The explorative energy system model E2S of Fraunhofer ISE, taking into account the LCOE and an economic efficiency analysis, attempts to answer the question of which investor groups invest in which technologies and at which locations these investments make sense for the system as a whole and the investors (investment decision model). The individual decisions are then combined in the model.

Figure 31 shows the schematic structure of the investment decision model. In it, the investments in new power generation capacity are illustrated in the investment decision model taking into account political, economic and technical framing conditions based on today's energy system. The reciprocating influence between investment decisions (for example, in renewable energy technologies and storages) and thus also the influence of the value of the electricity with the specific element must be taken into account explicitly.

In order to get a good representation of the development of investments in renewable energy technologies, the geographic distribution of resources must always be taken into account as an important factor as well, since there are different options for investment in technologies for every location for each investor group in Germany when observable investment behavior flows into the analysis. Thus, for example, energy supply companies cannot invest in rooftop PV power plants on private residential houses, but instead they have the know-how and the capacities for investing in storage solutions and in wind offshore power plants. Deciding reasons are the ROI expectations, shares of equity capital and external financing, as well as interest on loans for the various investor groups, which vary quite strongly, yielding different LCOE for each investor group and their preferred technologies.

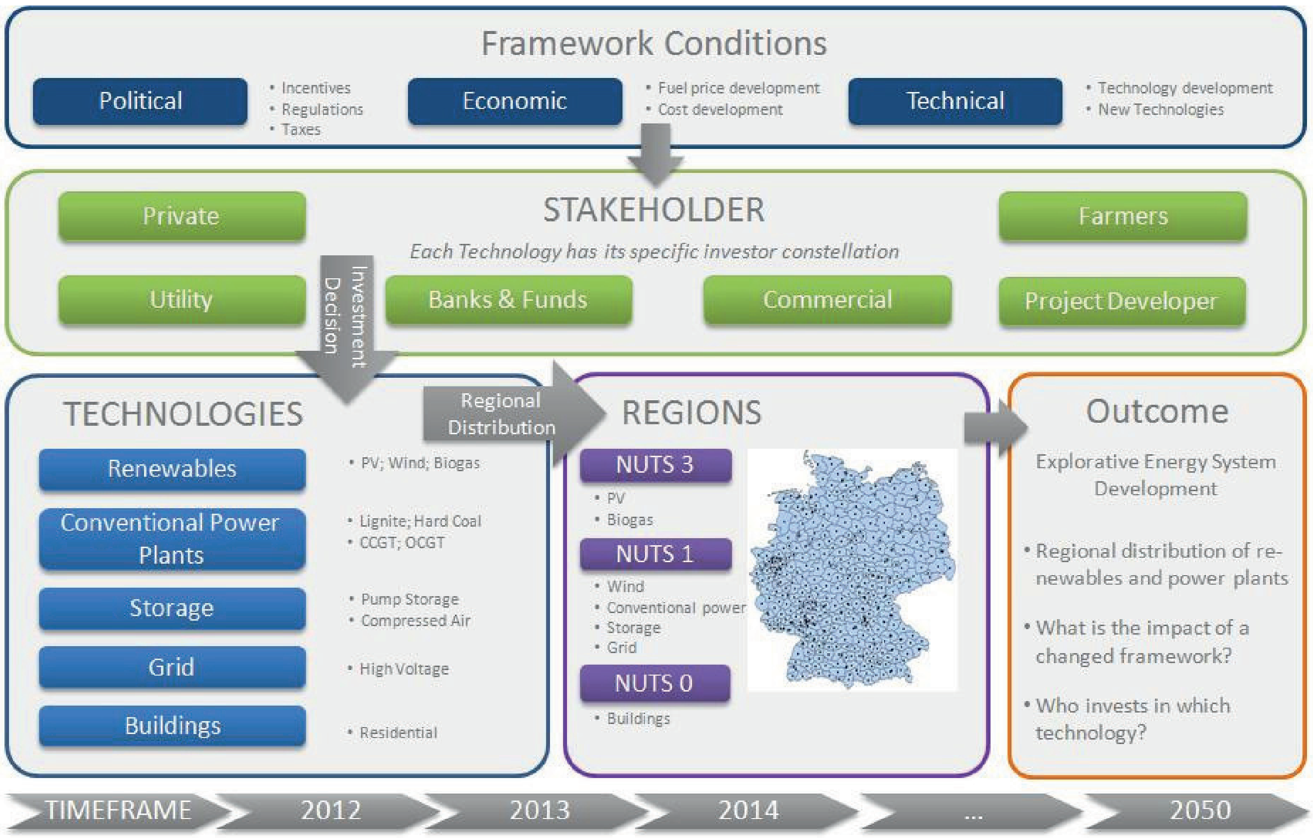

Figure 31: Schematic figure of the investment decision model (E2S-Invest) for the development of the energy system in Germany

Figure 32 shows examples of the regionally high differentiation in the LCOE of rooftop PV power plants for a private investor at a local district level. The figure on the left shows the costs for 2013 and the figure on the right those for 2020. The analysis of the LCOE helps to show what investments are made in what technologies at which locations within the investment decision model. It yields a possible developmental path for the energy system which shows the provisional development under the given framing conditions. Drawing on additional components in the analysis, one can determine how the overall structure can develop inexpensively. Additionally, one can determine whether the framing conditions are arranged in such a way that

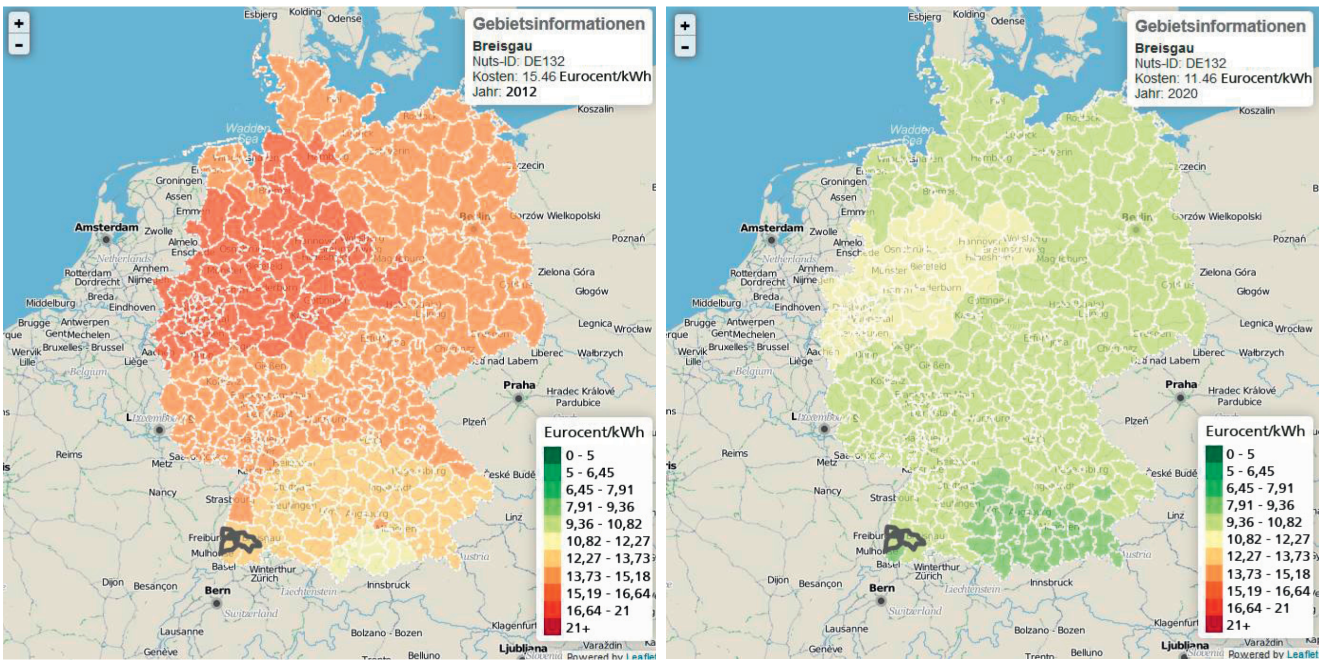

Figure 32: Model E2S at Fraunhofer ISE presents the development of regionally highly differentiated LCOE in combination with likewise regionally differentiated investor behavior for specific technology types. The figure shows as an example the LCOE of rooftop PV plants for private investors in 2012 (left) and 2020 (right)

a restructuring of the energy system was initiated in favorable terms macro-economically or whether and to what extent additional adjustments and market mechanisms (new business models, regulations on private use, grid expansion, expansion of storages) are needed to achieve the target system.

7. APPENDIX

Calculating the LCOE

The method of levelized cost of electricity (LCOE) makes it possible to compare power plants of different generation and cost structures with each other. The basic thought is that one forms the sum of all accumulated costs for building and operating a plant and comparing this figure to the sum of the annual power generation. This then yields the so-called LCOE in Euro per kWh. It is important to note that this method is an abstraction from reality with the goal of making different sorts of generation plants comparable. The method is not suitable for determining the cost efficiency of a specific power plant. For that, a financing calculation must be completed taking into account all revenues and expenditures on the basis of a cash-flow model.

The calculation of the average LCOE is done on the basis of the net present value method, in which the expenses for investment and the payment streams from earnings and expenditures during the plant's lifetime are calculated based on discounting from a shared reference date. The cash values of all expenditures are divided by the cash values of power generation. Discounting the generation of electricity seems, at first glance, incomprehensible from a physical point of view but is a consequence of accounting transformations. The idea behind it is, that the energy generated implicitly corresponds to the earnings from the sale of this energy. The farther these earnings are displaced in the future, the lower their cash value. The annual total expenditures over the entire operational lifetime are comprised of the investment expenditures and the operating costs accumulating over the operational lifetime. For calculating the LCOE for new plants, the following applies (Konstantin 2009):

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

LCOE	Levelized cost of electricity in Euro/kWh
I_0	Investment expenditures in Euro
A_t	Annual total costs in Euro in year t
$M_{t,el}$	Produced quantity of electricity in the respective year in kWh
i	Real interest rate in %
n	Economic operational lifetime in years
t	Year of lifetime (1, 2, ...n)

The annual total costs are comprised of fixed and variable costs for the operation of the plant, maintenance, service, repairs and insurance payments. The share of external financing and equity financing can be included in the analysis explicitly through the weighted average cost of capital (WACC) over the discounting factor (interest rate). It depends on the amount of equity capital, return on equity capital over lifetime, cost of debt and the share of debt used.

Also applicable to the formula for the annual total costs in the calculation of the LCOE:

Annual total 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 is therefore a comparative calculation on a cost basis and not a calculation of the level of feed-in tariffs. It can only be calculated by using additional influence parameters. Rules governing private use, tax law and realized operator earnings make the calculation of a feed-in tariff based on the results for the LCOE more difficult. An additional required qualification is that a calculation of the LCOE does not take into account the significance of the electricity produced within the energy system in any given hour of the year.

Learning Curve Models

In addition to the analysis of the LCOE for 2013 it is possible, with the help of market projections through 2020 and 2030, to generate learning curve models which in turn make possible statements about the future development of plant prices and therefore the LCOE as well. The learning curve concept presents a relationship between the cumulative produced quantity (market size) and the sinking unit costs (production costs) of a product. If the number of units doubles and the costs sink by 20%, one speaks of a learning rate of 20% (progress ratio PR = 1 – learning rate). The relationship between the quantity x_t produced at time t, the costs $C(x_t)$ compared to the output quantity at reference point x_0 and the corresponding costs $C(x_0)$ and the learning parameter b can be presented as follows:

The following applies to the learning rate:

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

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

compare Ferielli (2009), Wright (1936).

Through the forecast for plant prices $C(x_t)$ for the period studied by means of the learning curve model (assuming literature values for the learning rate and/or PR), it is possible to calculate the LCOE up to the year 2030.

In combination with market scenarios for the coming 20 years, it is possible to assign specific annual figures to the cumulative market units so that the development of the LCOE can be predicted on a chronological index. Changes in the terms of financing on the basis of changing framework conditions in the national economy are difficult to predict and are therefore not considered in this study. This would increase the forecast for the development of the LCOE with an additional, not-technology-specific uncertainty.

In a sensitivity analysis, the parameters for specific investments, operational lifetime, weighted average costs of capital (WACC), full load hours and operating costs can be studied with respect to their influence on the LCOE (see Chapter 4).

Data Appendix

Technology	PR	Market scenario	Variance of PR	Variance of scenarios
PV rooftop small	85%	Average value scenario	80%, 90%	IEA Roadmap, EPIA Policy Driven
PV rooftop large	85%	Average value scenario	80%, 90%	IEA Roadmap, EPIA Policy Driven
PV utility scale	85%	Average value scenario	80%, 90%	IEA Roadmap, EPIA Policy Driven
Wind Onshore	97%	Onshore Wind moderate	95%	Onshore Wind advanced
Wind Offshore	95%	Offshore Wind	-	-
CSP	90%	Greenpeace 2009	92-96%	Sarasin 2010, Trieb 2009
Biogas	-	-	-	-
CPV	85% auf Modul, BOS wie PV	Conservative scenario	-	Optimistic scenario
Brown coal	-	-	-	-
Hard coal	-	-	-	-
Combined cycle	-	-	-	-

Table 8: Summary of progress ratios and market scenarios for PV, CPV, CSP and wind power plants.

Technology	Scenario name	Source	2020 [GW]	2030 [GW]	Used in forecast
Wind offshore	Offshore Wind	ISE, EWEA	54	219	X
Wind onshore	Onshore Wind moderate	GWEC 2013, mod.	759	1617	X
Wind onshore	Onshore Wind advanced	GWEC 2013, adv.	1150	2541	
PV	IEA Roadmap Vision	IEA, 2010	390	872	
PV	average value scenario	ISE	581	2016	X
PV	EPIA Policy Driven	EPIA, 2013	759	2695	
PV	EPIA Business as Usual	EPIA, 2013	464	1591	
PV	Sarasin extrapolated	Sarasin 2011	710	1853	
CPV	ISE	ISE	3	10	X
CPV	ISE	ISE	5	50	
CSP	Sarasin 2010	Sarasin 2010	32	91	
CSP	Trieb 2009	Trieb 2009	15	150	X
CSP	Greenpeace 2009	Greenpeace 2009	68	231	
Biogas, brown coal, hard coal and combined cycle: No market scenarios required.					
The forecasts of fuel costs, carbon emission costs and full load hours are taken from external sources					

Table 9: Summary of scenarios and development goals for PV, CPV, CSP and wind power plants.

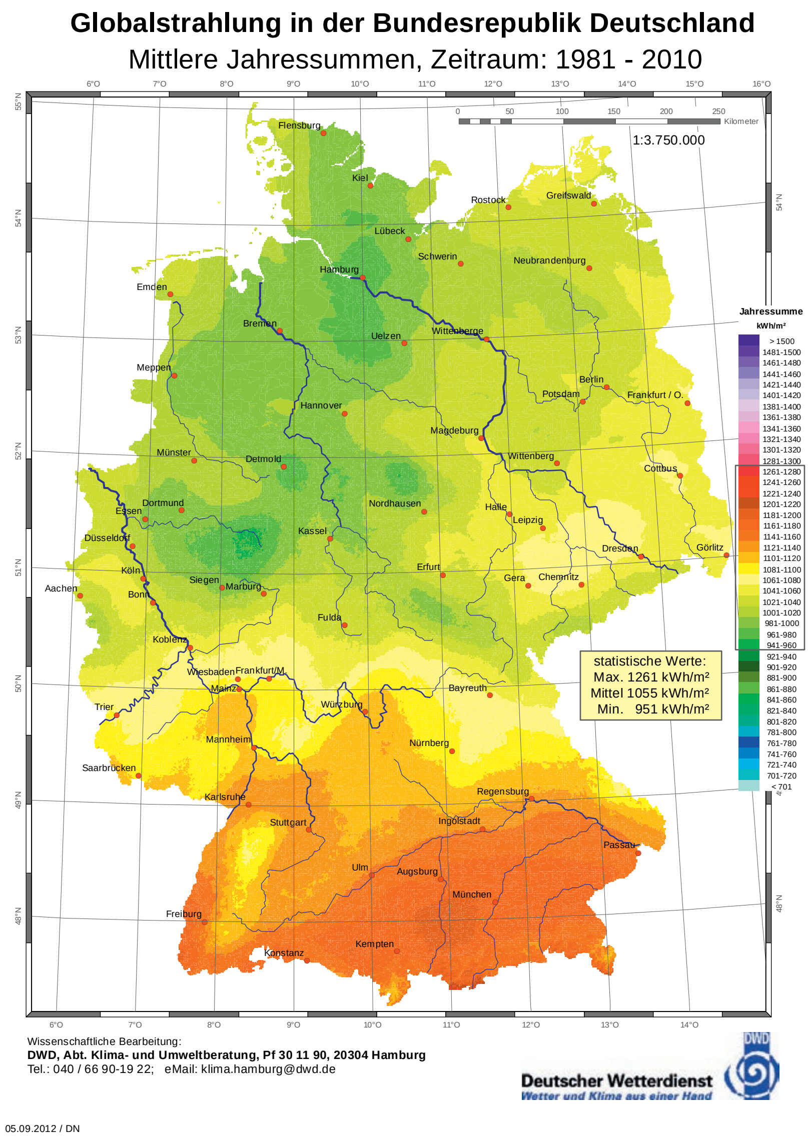

Figure 34: Global irradiation in Germany (average annual sum, DWD 2013).

8. OIL POWER PLANTS

Diesel power plants play only a minor role in Germany with a total installed capacity of less than 4.1 GW for power plants with a rated power greater 10 MW (BNA,2013). They produced 8.2 TWh or 1.3% of the total gross electricity production in Germany in 2012 (Destatis, 2013). No further installations of oil powered plants are planned in the next years (BNA, 2013a). However Diesel power plants play a very important role in the electricity system of some countries. The MENA region for example has a large amount of oil reserves. Especially countries like Saudi Arabia and others in the Middle East heavily rely on oil for power production. With an 88% share in the Saudi Arabian energy mix, the oil-based energy consumption is around 2300 TWh in the year 2013 (EIA, 2013). In order to support the economy and prevent social unrest, many countries subsidize mineral oil for local consumption, which leads to high budgetary loads on the governments. Even in oil-producing countries like Saudi Arabia, a subsidised domestic oil consumption results in lost revenues when compared to exporting the oil at world market price. This so-called opportunity costs have to be considered when comparing the costs of power production by different sources.

Assumptions

For the LCOE calculation, two classes of Diesel power generation units are selected. Small scale systems with less than 50 kW rated power output and utility scale systems with a rated power output between 1 and 10 MW. It is assumed that both systems run on Diesel or heating oil (which is chemically almost identical to Diesel). Large scale systems with a rated power of more than 10 MW normally run on heavy fuel oil or in bi-fuel mode with oil and gas combined and are not considered in this analysis. Heavy fuel oil is the rest material remaining after the distillation process in the refinery. It's very high viscosity requires heating before use and contains a lot of pollutants like sulfur and certain metals. Due to its more complicated usage and the high emissions it is less expensive than Diesel oil.

Diesel oil has an energy content of 11.85 kWh/kg and a density of 0.84 kg/liter, which results in a heating value of 14.11 kWh per liter (Fritsche, Schmidt 2012). The technical and economic assumptions for the calculation are summarized in table 10.

	Small scale Diesel (< 50 kW)		Utility scale Diesel (1 to 10 MW)	
Investment in Euro/kW	200	400	600	900
$WACC_{real}$	6.9%		6.9%	
O&M in Euro/kWh	0.02	0.02	0.03	0.03
Efficiency	30%	40%	40%	45%
FLH in h/a	2000	4000	7000	8000
Lifetime in years	20		20	
Fuel	Diesel		Diesel	
CO_2 price in Euro/t	0		0	

Table 10: Calculation parameters for small scale and utility scale Diesel systems.

The average world market price for Diesel in 2013 was 124.62 US$/bbl, which equals 0.579 Euro/liter (U.S. Gulf Coast Ultra-Low Sulfur No 2 Diesel Spot Price, EIA 2013a). The end consumer price for Diesel in a certain country highly depends on the local taxes or subsidies. In Saudi Arabia for example, the Diesel price is 0.053 Euro/liter, whereas in Germany the fuel price for stationary power applications (heat oil instead of Diesel, which is chemically identical but with lower tax) is 0.696 Euro/liter. The total opportunity costs for Saudi Arabia due to oil subsidies are estimated with 87.4 billion Euro per year. The total tax income in Germany based on the energy tax (Energiesteuer), which includes oil, gas, coal and other energy sources was app. 40 billion Euro in 2012 (BDS 2013). The projection of the Diesel price until 2033 was calculated according to the assumptions in the official network development plan 2013 from the German transmission system operators (NEP, 2013). This results in a world market Diesel price of 0.714 Euro/liter in 2023 and 0.768 Euro/liter in 2033, which is a very optimistic scenario, so the real Diesel price might be significantly higher.

Results

The LCOE of diesel generators vary according to the power plant specifications and fuel prices. Under consideration of the world market price small diesel generators have LCOE in the range of 0.13 - 0.17 Euro/kWh. Utility scale power plants have

LCOE in the range of 0.12 - 0.13 Euro/kWh. The range covers lower and higher efficient power plants with corresponding investment costs and full load hours.

As mentioned above oil-powered plants play a major role in the MENA region. Therefore the LCOE of solar technologies in locations with high solar irradiation are compared to the LCOE of oil-powered plants. In 2013 in locations with a DNI of 2000 kWh/(m²a) the LCOE of PV are in a range of 0.06 - 0.09 Euro/kWh and therefore lower than the LCOE of diesel-powered plants. The LCOE of CPV are between 0.08 and 0.15 Euro/kWh which means that this technology is also lower or equal to oil-powered plants. The LCOE of CSP however are between 0.14-0.19 Euro/kWh and lie on the upper level above the LCOE of diesel-fired plants.

Comparison to PV, CSP and c-PV

In several countries like UAE, Egypt, Saudi Arabia or Qatar the price of mineral oil is highly subsidized. A calculation of the LCOE based on local fuel prices is summarized in table 11. The highest subsidies can be found in Saudi Arabia, followed by Egypt and Qatar. Therefore a significant difference in the LCOE is the result. In Saudi Arabia for example the LCOE are six times lower than the LCOE with world market price but Saudi Arabia pays roughly 87 billion for oil subsidies. The subsidies are estimated by a comparison of costs, oil consumption based on world market price and the country specific diesel price taken from the EIA 2013. Morocco gains revenues from the use of mineral oil as they have a tax rate of 30% on mineral oil (forbes, 2013). In 2012 the country gains roughly 1.7 billion Euro. In other countries like Germany the LCOE would be significantly higher than the world market price, as mineral oil is highly taxed.

	Diesel price	Small Diesel < 50 kW	Utility Diesel > 10 MW	Subsidies/ taxes in bil. €
World Market	0.579	0.13 - 0.17	0.12 - 0.13	
United Arab Emirates	0.48	0.11 - 0.14	0.10 - 0.11	-3.6 (subsidy)
Egypt	0.135	0.04 - 0.05	0.04	-19.5 (subsidy)
Saudi Arabia	0.053	0.02	0.02 - 0.03	-87.4 (subsidy)
Qatar	0.203	0.05 - 0.07	0.05 - 0.06	-4.1 (subsidy)
Morocco	0.72	0.16 - 0.21	0.14 - 0.16	1.7 (tax)
Germany	0.696	0.15 - 0.20	0.14 - 0.16	40 (tax)

Table 11: LCOE of diesel generators in a set of choosen countries

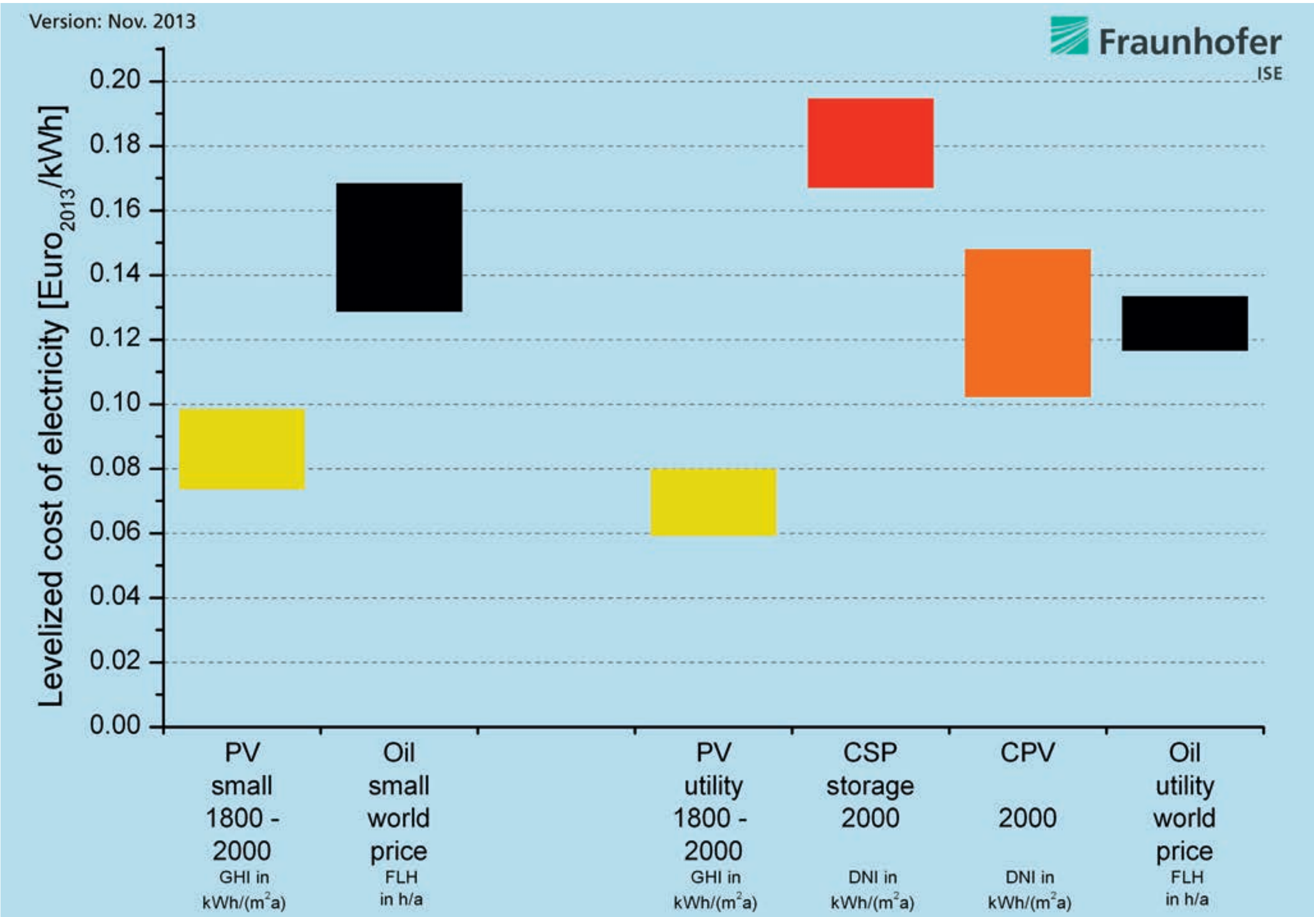

Figure 33: LCOE of oil power plants in comparison with solar technologies in regions with high solar irradiation.

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BUSINESS FIELD ENERGY SYSTEM ANALYSIS AT 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 starkly. Worldwide, renewable energy technologies, especially photovoltaics and wind power have not merely developed into 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 is a cost-effective use of renewable energy technologies to be achieved in various regions? How can different technologies be combined with each other 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 offers a variety of responses to these questions that are covered in the following business topics:

- 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, we analyze various energy technologies from technical and economic viewpoints, such as 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 field of Energy System Analysis studies the transformation of the energy system by very different methodological approaches: On the one hand, one can identify a multi-sector target system for a specific CO_2 reduction goal according to minimum costs to the national economy. On the other, one can use investment decision models to show how the system will develop under certain framing conditions and how the interaction of the components in the energy system works. This allows our models to offer a solid foundation for the decision concerning the framing conditions of any future energy supply.

An additional focus 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. In 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.

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