Recent Facts about Photovoltaics in Germany

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1 What purpose does this guide serve?
Germany is leaving the fossil-nuclear age behind, paving the way for photovoltaics (PV) to play a significant role in a future shaped by sustainable power production. This compilation of current facts, figures and findings is regularly updated. It aims to help in creating an overall assessment of PV growth in Germany.

2 Are we reaching our annual capacity target?
No.
In 2017, 1.75 GW of new PV power plant capacity was reported to the Federal Network Agency in Germany (as of 2018-31-01), which corresponds to almost 2% of total new PV capacity worldwide. In the German Renewable Energy Act EEG 2014 and 2017, the federal government set down an annual target of 2.5 GW PV [EEG]. The coalition agreement of March 2018 schedules increasing the share of renewable energies (RE) to 65 percent of gross electricity consumption by 2030. For this purpose, a steady annual PV expansion of about 5 GW is necessary [AGORA].
To meet most of or all of Germany’s energy demand with renewables by 2050, ca. 150-200 GW PV installed capacity is required by 2050 [ISE5, IWES2]. This means that an average of 4-5 GW PV must be installed annually up to 2050. With time, the older PV systems must be replaced. As of now, replacing installations have not played a large role. However, once the targeted capacity of 200 GW PV has been reached and assuming an operating life of 30 years, estimates show that 6-7 GW PV must be replaced each year.

3 Does PV contribute significantly to the power supply?
Yes.
According to estimates, PV-generated power amounted to about 40 TWh [BDEW5] and covered approximately 7.2 percent of Germany’s net electricity consumption including grid losses (final energy, see section 22.8) in 2017. Renewable energy as a whole (RE) accounted for ca. 39 percent of net electricity consumption, while PV and total RE in accounted for ca. 6.7 percent and 36 percent of Germany’s gross electricity consumption respectively. On sunny weekdays, PV power can cover 45 percent of the momentary electricity demand. On weekends and holidays the coverage rate of PV can reach 60 percent.
At the end of 2017, the total nominal PV power installed in Germany was ca. 43 GW, ([BNA2], installed capacity of all subsidized PV systems, as of 2018-31-01) distributed over 1.6 million power plants [BSW].
Is PV power too expensive?
It depends on the benchmark used.

It is difficult to compare the costs of PV electricity with fossil and nuclear electricity since the external costs are ignored (see section 22.9, [DLR1], [FÖS1], [FÖS2]). The marginal costs for nuclear power are in the order of only 1 €-ct/kWh, for coal-fired power 3-7 €-cts/kWh, for gas-fired power 6-9 €-cts/kWh. The fixed costs of power generation (e.g. investments, capital) are added on top of this. The cost of the fuel is included in the marginal costs but not the treatment of waste and waste gases. Although an EU-wide emissions trading (European Union Emissions Trading System, EU ETS) was introduced for the energy sector in 2005 to make CO₂ emissions more expensive and to internalize costs to some extent. Due to an overabundance of available certificates, however, the price had collapsed by the end of 2017. Estimates of the direct and indirect follow-up costs also facing Germany in the coming years due to global climate change are not yet known.

Expenditures for dismantling the nuclear power plants which have been shut down are most probably not covered by the operator’s reserves. The creation and maintenance of permanent storage sites for nuclear waste in Germany will probably cost much more than the 23 billion euros given to the German states for storing Germany’s nuclear waste. Damages from nuclear accidents are covered up to 250 million euros by the insurance company and up to 2.5 billion euros by an operator pool. For amounts above this, the nuclear power plant operator is liable with its assets. [ATW1]. As a comparison, damage caused by the Fukushima nuclear disaster amounted to ca. 100 billion euros, a value which is many times higher than the company value of the German nuclear power plant operators. The uncovered risks are carried by the tax payers.
In new MW power plants, PV electricity is produced at costs starting at 4-5 €-cts/kWh, under the condition that the produced electricity is directly fed into the grid. The power produced by the older, smaller power plants is much more expensive, due to the previously higher investment costs. In order to bring on the energy transformation and foster investments in PV systems of all sizes, the German Renewable Energy Sources Act RES (Erneuerbare Energien Gesetz EEG) was created in 2000. This instrument guarantees a fixed rate of purchase and enables plant operators to run their installations with an appropriate profit. The aim of the Renewable Energy Source Act is to effect a continual reduction in the cost of electricity generation from renewables by creating a market for RE systems. (See section 4.1).

Increasing PV capacity is only one of the costs in Germany’s energy transformation. For a long time, the costs associated with PV expansion stood in the forefront of the discussions. Over the past few years, PV and wind have an established place in Germany’s energy supply system, bringing new costs to the fore. Besides the costs for electricity generation, costs in the following areas are becoming increasingly significant:

- Expanding the north-south power lines for wind power
- Shutdown of nuclear power plants
- Dismantling and modification of fossil power plants to enable a more flexible operation during reduced utilization
- Build up storage and converter capacities i.e. for grid-stabilization (stationary batteries and electric mobility, pumped storage, heat pumps, heat storage, Power-to-X)

These costs are not caused by the increase in PV installations but rather, as with the expansion of PV itself, are associated with the normal progression of the energy transformation. All energy consumers for whom a long-term sustainable energy supply must be created are, in turn, responsible for the costs of its realization.

### 4.1 Levelized Cost of Energy

The levelized cost of energy (LCOE) for a PV power plant is the ratio between the total costs of the plant (€) and its total electricity production (kWh) over its economic lifetime. The LCOE for PV power plants [ISE1] is based primarily on:

1. purchase investments to construct and install the plant
2. financing conditions (return on investment, interest, plant lifetime)
3. operating costs over the lifetime of the plant (insurance, maintenance, repairs)
4. irradiance availability
5. lifetime and the annual degradation of the power plant

Thanks to technological progress, the learning curve and economies-of-scale, the investment costs for PV power plants, which make up the greatest outlay, have fallen an
average of 13 percent per year – in all, 75 % since 2006. Figure 2 shows the price development since 2006 for rooftop installations between 10 kWp to 100 kWp in Germany.

Module costs are responsible for almost half of the total investment costs of a PV power plant of this size. This percentage increases for larger power plants. The price development of PV modules follows a so-called «price learning curve,” in which doubling the total capacity installed causes prices to fall by a constant percentage. Figure 3 shows inflation-adjusted world market prices. At the end of 2017, approximately 400 GW of PV power had been installed worldwide. Provided that significant progress continues to be made in product development and manufacturing processes, prices are expected to keep dropping in accordance with this rule.

The average price includes all market-relevant technologies, i.e. crystalline silicon and thin film. The trend indicates a price reduction of about 24% with a doubling of the cumulative installed capacity. The module prices in Germany are 10-20% higher than on the world market, supported by anti-dumping measures of the European Commission. The tenders of the Federal Network Agency provide an orientation value for electricity generation costs from new PV ground-mounted systems (see following section).
The average price shown includes all market-relevant technologies in the fields of crystalline silicon and thin-film technology. The trend indicates that doubling the cumulative installed PV capacity results in a price reduction of 24 percent. In Germany module prices lie about 10-20% higher than on world market, due to anti-dumping measures of the European Commission. The licensing round of the Federal Network Agency (see following section) gives a benchmark for the electricity generation costs for new open-field PV systems (< 10 MW).

### 4.2 Feed-in Tariff

The German energy transformation requires large investments in solar and wind capacity. In order to build a PV power plant today, an investor needs a purchasing guarantee that stipulates a fixed price over the economic life of the power plant. Otherwise, the investor may delay his investment based on trends that show PV power plant costs continue to decline (deflation). Since all installed PV power plants produce electricity at the same time, the more expensive electricity from the older power plants would no longer be competitive in the future.

To delay PV expansion in hopes of lower costs in the future would not only be a cynical reaction with respect to the progressing climate change but would also slow down the dynamics of cost reductions. The first EEG in 2000 and the subsequent changes have shaped the growth of PV installments in Germany. The EEG 2017 specifies a fixed expansion corridor for RE as a share of gross electricity consumption, attempting to both support and restrict the growth in PV capacity.
• Self-consumed PV energy is taxed above a certain nominal power (approx. 10 kW) with 40% of the current EEG surcharge (Section 4.7), which means that the PV electricity generation costs increase by approx. 2.7 € ct / kWh
• New PV systems up to 100 kWp receive a fixed feed-in tariff
• New PV systems between 100 and 750 kWp must sell their energy by direct marketing.
• New PV systems over 750 kWp are required to partake in calls for tender and may not be used for self-production.
• Numerous other regulations exist regarding potential areas for installations, the capability of remote power control and power reduction, among others.

![Figure 4: Feed-in tariff for PV power as a function of commissioning date, average remuneration of the bidding rounds of the Federal Network Agency, electricity prices from [BMWi1] up to 2016 and with estimates thereafter, average compensation for PV power, partly estimated [BMWi5].](image)

Depending on the system size, the feed-in tariff for small roof systems put into operation by October 2018 can be up to **11,84 €-cts/kWh** and is guaranteed to the operator over the next twenty years. For medium-size systems from 750 kW up to 10 MW, the feed-in tariff is set by the licensing agreement. The last licensing round of the Federal Network Agency on the bid date February 1, 2018 set a mean value of **4.33 €-cts/kWh**.

To compare: The tender for electricity from onshore wind systems for the same bid date brought an average price of 4.60 €-cts/kWh. On the global scale PV electricity prices in locations with high radiation levels has been offered at record low levels between 1.5 –
2.5 cts/kWh (e.g. in Saudia Arabia for a 300 MW plant). In contrast, the negotiated strike price for the planned nuclear plant Hinkley Point C in England translates essentially to a feed-in tariff of 12 €-cts/kWh plus inflationary adjustment for a period of 35 years. The plant is planned to start operation in 2025.

The feed-in tariff for PV power drops faster than any other regenerative power source, in the last 15 years approx. 80% for small rooftop installations and 90% for systems of medium size.

The user who consumes self-generated electricity can by no means consider the difference between the gross electricity price (electricity from the grid) and the EEG feed-in tariff (estimated value of the electricity generation costs) as profit. For one, self-consumption increases the fixed costs per kilowatt-hour withdrawn. Considering that the same connection costs are distributed over a smaller amount of withdrawn electricity, the electricity purchased per kWh becomes more expensive. Also, the electricity withdrawn from a PV system for self-consumption may be subject to extra taxes and charges. These can reach appreciable values, depending on the tax classification of the system [SFV]. Electricity produced by PV systems > 10 kWp which were put into operation after August 2014 are subjected to a portion of the EEG levy.

After 2020, the feed-in tariff will gradually expire for the oldest plants, as their 20-year payment period is reached. However, these plants will continue to supply power at levelized costs that undercut those of all other fossil fuel and renewable energy sources, due to low operating costs and zero fuel costs.

### 4.3 Total Remunerations Paid

As stipulated in the EEG, the total costs for the remuneration of PV feed-in are determined each year by the transmission system operators (Figure 5). In 2017 the total costs amounted to an estimated **10.35 billion euros** [BMW45]. The already radical reduction in feed-in rates and system size in addition to the phase out of the EEG feed-in tariff for new PV systems at a threshold of 52 GW capacity ensures that total remunerations paid for PV are limited to 10 -11 billion euros per year [UNB]. Further PV expansion within the existing EEG will only moderately increase total remunerations (Figure 5). Additional measures to throttle PV expansion will not lead to a decrease in the total remuneration. Such a measure could, however, cause a slowdown in the construction of very inexpensive PV systems.
Figure 5: PV expansion and total feed-in tariff, data from [BMWi1] and [BMWi5]

4.4 Pricing on the energy exchange and the merit order effect

To estimate sales revenues from PV electricity, a mean electricity price is calculated based on the prices achieved on the European Energy Exchange. The running EEX price is determined by the merit order principle. Plant operators offer specific quantities of electricity, defined mostly by their marginal costs, and ranked in ascending order of price (Figure 6). The purchase offers of power consumers are arranged in descending order. The point of intersection of the two curves shows the energy exchange price of the entire quantity traded. The most expensive offer influences the profit margins of the cheaper suppliers.
PV power feed-in has legal priority, meaning that it is found at the start of the pricing scale due to the merit order effect. With fictitious marginal costs of zero, PV power is always sold when available. PV power is predominantly generated during the middle of the day when power consumption (and previously, but no longer, the electricity price) is at its midday peak. During these periods, PV power mainly displaces electricity from expensive peak-load power plants (especially gas-fired plants and pumped-storage). This displacement lowers the spot price of electricity on the market and leads to the merit order effect of PV feed-in (Figure 7). With sinking market prices, the profits of all conventional power plants (nuclear, coal, gas, hydro) also decrease. Further, solar PV electricity lowers the capacity utilization of the traditional peak-load power plants (gas and hydro in particular.)
The increasing amount of renewable electricity being fed into the grid, lower coal prices and surplus of CO2 allowances have drastically depressed prices on the EEX (Figure 8).

On the electricity market, PV power had an average market price factor of 1 over the course of the year. This means that the revenue per kWh is equivalent to the average electricity price on the exchange. The market price factor for wind was about 0.9 [ÜNB]. With the further expansion of volatile RE, the market price will decrease on the medium term because the electricity supplied increases with higher feed-in and the feed-in is controlled by the supply side.

With increasing feed-in of renewable electricity, the EEX becomes more and more a market for residual electricity, generating a price for the demand-related provision of renewable electricity and no longer reflecting the value of electricity.

4.5 Determining the Differential Costs
The differential costs shall cover the gap between the remunerations paid out according to the EEG promotion and the sales revenue collected from PV electricity. Following a peak of almost 7 ¢-cts/kWh, the spot price of electricity, used to determine the differential costs, has since fallen to below 4 ¢-cts/kWh. The amount of electricity from PV and wind that is fed into the grid is increasing. This reduces the spot market price through the merit order effect and thereby, paradoxically increases the calculated differential costs. According to this method, the more PV installed, the more expensive the kWh price of PV appears to be. Price drops in coal and CO2 allowances similarly reduce the spot price and thus increase the calculated differential costs.

![Figure 8: Development of the average spot electricity price and the calculated differential costs [BDEW2].](image-url)
4.6 Privileged Electricity Consumers

Policy makers determine who shall finance the transformation to renewable energy [BAFA]. They decided that energy-intensive industries, i.e. those who spend a high proportion of their costs on electricity, are to be exempted from the EEG surcharge to a large extent. In 2015, industries were relieved of costs totaling ca. 4.8 billion euros. The total electricity of 107 TWh falling under this exemption amounts to almost one-fifth of Germany’s entire power consumption. Figure 9 shows the estimated breakdown of the EEG surcharge paid by industry in 2015. This wide-scale exemption increases the burden on the other electricity customers, in particular, private households, who account for almost 30 percent of the total power consumed.

The surcharge exemption for privileged customers as set down in the EEG has further increased the nominal EEG surcharge per kilowatt hour (see Section 5.5). At the same time, energy-intensive industries are benefiting from the lower spot prices on during peak-power times. It is evident that part of the surcharge indirectly ends up in the pockets of these energy-intensive industries: «Energy-intensive companies, which are either largely exempt from the EEG surcharge or pay a reduced rate of 0.05 €-cts/kWh, benefit the most from the merit order effect. For these companies, the lower prices brought about by the merit order effect overcompensates for the costs incurred as a result of the EEG surcharge by far.» [IZES] Energy-intensive companies therefore benefit from the energy transformation without making a noteworthy contribution.

4.7 EEG Surcharge

The difference between the remunerations paid out and the sales revenues generated from renewable electricity (supplemented by other items) is compensated by the EEG surcharge (Figure 10). The cost of the surcharge is borne by those power consumers, who do not fall under the exemption scheme. For 2018, the EEG surcharge is set at
6.792 €-cts/kWh. End users must pay value added tax (19%) on this surcharge so that the costs imposed on private households increases to 8.08 €-cts/kWh.

Figure 10: Influential parameters and calculating method for the EEG surcharge [ÖKO]

Figure 11 shows the EEG surcharge in cts/kWh and the sum paid out for installed systems. Since the measure basing the surcharge on the EEX spot market price was introduced in 2010, the surcharge and the feed-in tariff have been drifting apart. The increasing amount of privileged consumers in energy-intensive industry and other measures have also contributed to this drift.
Based on the way it’s defined, the EEG surcharge would increase for the following reasons:

1. increasing quantities of power used by «privileged” consumers
   Because energy-intensive industries are virtually exempt from contributing to the surcharge, smaller-sized consumers, such as private households, small industry and commercial consumers must bear additional costs amounting to billions of euros.

2. merit order effect and PV feed-in during daytime.
   PV power feed-in during, for example, midday when the EEX spot price formerly peaked reduced the electricity price very effectively, benefitting electricity customers. (See section 4.4). At the same time, however, the difference between the feed-in tariff and the market price, the basis of calculating the EEG surcharge, increased. This disadvantages smaller customers bound to pay the EEG levy.

3. Merit order effect and electricity surplus
   For many years, increasingly more power has been produced in Germany than effectively consumed, and namely power from fossil and nuclear power plants with low marginal costs being used as expensive peak load power plants. Due to the merit order effect, this surplus reduces the market price, pushing peak power plants out of the energy mix.

4. declining electricity consumption through efficiency measures
   Initiatives supporting more efficient energy use (e.g. energy saving lamps) reduce the amount of electricity purchased, and thereby increase the surcharge per kWh consumed.

5. Additional expenditure from compulsory direct marketing
   The compulsory direct marketing creates additional administrative expense that power producers must compensate with a higher EEG remuneration.

6. Increasing production from RE power, without self-consumption
The expansion of RE drives the levy up at least on the short term both directly (because more feed-in remuneration is paid out) as well as indirectly (due to the reduced price of emission certificates leading to a cheaper price for energy from fossil fuel plants.)

5 Subventions and Electricity Prices

5.1 Is PV power subsidized?
No. The support is provided through a surcharge, which applies also to self-produced and self-consumed PV electricity. The investment incentives for PV power are not supported by public funds. While fragmentary reports often quote figures relating to past and future PV power feed-in tariff payments in the hundreds of billions and call these «subsidies”, a true subsidy is supported by public funds. The EEG, on the other hand, makes provisions for a surcharge in which energy consumers make a compulsory contribution towards the energy transformation, a necessary and agreed upon resolution. This interpretation is also supported by the European Commission. The EEG surcharge is not the total remuneration, but rather the differential costs, calculated as the difference between costs paid (remuneration) and revenues received (see section 4.5). The cumulative costs paid out for PV power fed into the grid up to and including 2016 amounted to ca. 70 billion euros.

To calculate the EEG surcharge, the financial benefits of PV power are determined according to the market clearing price on the European Energy Exchange (EEX) in Leipzig. By this method, the benefits of PV power are underestimated systematically. For one, PV power has long been having the desired effect on this market price, namely that of driving it downwards (see section 4.4). Second, the market price leaves out the heavy external costs of fossil fuel and nuclear power production (section 5.2). Considering total costs of fossil fuel and nuclear power production of ca. 10 €-cts/kWh, the additional costs of the PV feed-in tariff decline so quickly that the first intersection point occurs already in 2013 (see Figure 4). The marginal costs decrease to zero and thereafter are negative.

As it is expected that the external costs of fossil fuels and nuclear power shall soon become impossible to bear, the increase in RE shall ensure that electricity remains available at sustainable prices in the long term. Our industrial sector needs better prospects for a secure energy supply in the future, as do householders.

The electricity policy can learn from the bitter lessons experienced in housing construction policy. Because comprehensive measures to renovate the existing building stock have not been undertaken to date, many low-income households must apply for social funds to be able to pay for their heating fuel. These funds flow, in part, then to foreign suppliers of gas and oil.
What would be the price to pay if the German energy transformation fails? Without knowing this figure, it is difficult to make a statement as to the total costs required to transform our energy supply system.

5.2 Are fossil fuel and nuclear energy production subsidized?

Yes.

Policy makers also influence the price of electricity generated by fossil fuel and nuclear power plants. Political decisions determine the price of CO₂ emission allowances, conditions for filtering smoke and, where necessary, for the permanent storage of CO₂ (carbon capture and storage, CCS), the taxation of nuclear power as well as insurance and safety requirements for nuclear power plants. This means that policy makers decide to what extent today’s energy consumers must bear responsibility for the elusive risks and burden of producing electricity from fossil fuel and nuclear sources. As these aspects are more rigorously priced, it is very likely that PV power will make the electricity mix less expensive. Until this happens, fossil fuel and nuclear power will be sold at prices that conceal their external costs (see section 22.9, [DLR1], [FÖS1]) and pass the burden on to future generations.

Contrary to initial plans, and with costs of 5-15 euros per metric ton of CO₂, CO₂ emission allowances only have a minor effect on the costs of generating power from fossil fuels (see figure 12). Compared with estimated, realistic prices of 70 euros per metric ton [DLR1], this results in a subsidy of more than 20 billion euros per year for fossil fuel power plants.

Figure 12: Price of CO₂ allowances from 2008-2013 on the EEX spot market (http://www.finanzen.net/rohstoffe/co2-emissionsrechte/Chart)
It is currently impossible to pinpoint the actual costs and risks of generating power from fossil fuel and nuclear sources. The majority of these shall only emerge in the future (CO2-induced climate-related catastrophes, nuclear disasters, the permanent storage of nuclear waste, nuclear terrorism, permanently contaminated sites), making a comparison difficult. According to experts, the risks of nuclear power are so severe that insurance and reinsurance companies the world over are not willing to offer policies for plants generating energy of this kind. A study conducted by the Versicherungsforen Leipzig sets the limit of liability for the risk of the most serious type of nuclear meltdown at 6 trillion euros, which, depending on the time period over which this sum is accrued, would increase the electricity price per kilowatt hour to between 0.14 and 67.30 euros [VFL]. As a result, it is essentially the tax payers who act as the nuclear industry’s insurers. This is essentially forced upon them both against their wishes, since the majority of Germans have been opposed to nuclear energy for many years, and as an unspecified amount, because no fixed price has been established to date for damage settlements. This is a subsidy whose burden on the future cannot be predicted.

According to estimates by the IEA, power generated by fossil fuels received more than 544 billion dollars of subsidies worldwide in 2012 [IEA4]. According to a study by the International Monetary Fund, total subventions worldwide for coal, oil and natural gas in 2015 are estimated to be 5.1 billion US$ [IWF].

5.3 Do tenants subsidize well-positioned home owners?

No.

This notion, which makes a popular headline and in this instance is taken from the «Die Zeit” newspaper published on December 8, 2011 is a distorted image of reality. Except for the politically willed exception granted to energy-intensive industry, the costs of switching our energy system to RE are being borne by all consumers (including all households and thereby home owners and tenants) according to the cost-by-cause principle. In addition to PV, these costs also contribute funding to wind power and other renewables. All electricity customers can decrease their energy consumption by selecting and using energy efficient appliances. Many municipalities offer free consultations on energy saving advice and also grants to help pay for new, more efficient devices. Electricity tariffs that increase with consumption would be a suitable means to reduce the burden on low-income households and simultaneously to reward energy efficiency. PV systems installed by home owners are usually under 10 kWp. The systems within this power range make up less than 15% of the total installed PV power in Germany, while large systems above 500 kWp make up about 30 % (Figure 22). The larger systems are often financed with citizen participation or funds, in which tenants can also participate.
5.4 Does PV make electricity more expensive for householders?

Yes. However, private households bear many additional charges within their electricity bill. The German legislature sets the principles for calculating and distributing the EEG surcharge, and other taxes and fees, the effects of which are currently detrimental to householders.

Figure 13: An example showing components making up the domestic electricity price of 29,2 €-cts/kWh in 2017 (CHP: German Combined Heat and Power Act); German Electricity Grid Access Ordinance (Strom-NEV): easing the burden on energy-intensive industries; concession fee: fee for using public land; offshore liability fee; AbLa: Levy on interruptible loads), Data from [BDEW3].

A typical household has an annual power consumption of 3,900 kWh paid roughly 29,3 €-cts/kWh in 2016 [BMWi1]. Figure 13 shows a typical breakdown of this electricity price. The electricity levy was introduced in 1999. According to the law, the levy intends to make electricity more expensive; the proceeds go principally into the public pension fund. Private households must pay value added tax on the electricity levy and the EEG surcharge.
5.5 Does PV increase the electricity price for industry?

Yes and no. There are clear winners but also losers. According to the German Industrial Energy and Power Federation (VIK), the electricity price is at a ten year low for medium voltage customers—provided that they are exempted from the EEG-surcharges. (See VIK base index, Figure 15). Today the VIK final selling price index for non-privileged businesses is twice as high as the base index. This is mainly due to the EEG surcharge which makes up part of the final selling price.
Are we exporting large amounts of PV power to other European nations?

No, the increased export surplus comes primarily from coal power plants. Figure 16 shows the increase in electricity exports since 2011 [ISE4]. The monthly values of the Energy Charts (www.energy-charts.de) show that the export surplus was conspicuously high in winter, i.e. in months with a particularly low PV power production. The average price per kWh achieved in electricity exports has been somewhat below the average import price for some years.
Figure 16: Electricity export (negative values indicate export) for Germany [ISE4]

The fact that the German power plant park is increasingly producing for export should also be related to the low production costs for coal electricity, in particular the low CO₂ certificate prices (Section 5.2) of recent years.

7 Can new PV plants bring reasonable rates of return?
Yes.
In principle, new PV installations can bring profits through grid feed-in as well as self-consumption. Although the legislator curtails both business models through a package of measures (Section 4.7), good returns are possible due to the sharp drop in prices for PV modules. This also applies to PV systems without or with only low self-consumption.

Self-consumption becomes more worthwhile, the greater the difference is between the cost of delivering PV electricity and the LCOE of the PV system. For systems without energy storage, the self-consumption is dependent on coinciding supply and demand profiles. Independent of the system size, households generally consume 20-40 % of their self-produced electricity [Quasch]. Larger systems increase the percentage of PV coverage for the total power, however, reduce the percentage of self-consumption. Commercial or industry consumers achieve an particularly high rate of self-consumption as long as their consumption profile doesn’t collapse on the weekends (e.g. Refrigerated warehouses, hotels and restaurants, hospitals, server centers, retail). Energy storage and technologies for energy transformation offer a large potential for increasing the self-consumption (compare Section 17.1).

The PV system yield is higher in sunnier regions, however, regional irradiation differences do not transfer to specific yield in a one-to-one ratio (kWh/kWp). (See section 22.4.) Other parameters, such as the module operating temperature or the duration of snow cover, also affect the annual yield.
Figure 17: Rough estimate of levelized cost of electricity (LCOE) for PV power plants at different annual irradiances

To obtain a rough estimate of the discounted LCOE (not adjusted for inflation, see Figure 17), the following assumptions were used:

- optimal orientation of module (approximately 30° south)
- performance ratio (section 22.6) of 85 percent
- annual yield degradation of 0.5 percent
- lifetime of 20 years
- annual operating costs of 1 percent (of plant price)
- inflation rate of 0 percent
- nominal imputed interest rate of 5 percent (average of own and borrowed capital investments)

In Germany, the annual sum of average global irradiance on a horizontal surface is 1055 kWh/m² per year [DWD]. The levelized cost of energy (LCOE) is estimated using the net present value method, according to which, the running costs and LCOE are discounted by the interest rate given at the time the plant was commissioned. The LCOE values determined are not adjusted for inflation. This makes it easier to compare them with the feed-in tariff which is constant in nominal terms but declines in real terms.

In the event of a 100 percent equity investment, the imputed interest is equal to the rate of return. To compare, the Federal Network Agency (Bundesnetzagentur) set the return on equity at 9.05 percent (before corporate tax) for both new and further investments in the electricity and gas networks [BNA1].
It is currently not possible to calculate the energy yield beyond the twenty-first operating year of a PV system. It is likely, however, that many plants will continue to generate significant quantities of electricity at marginal running costs. However, the guidelines governing self-consumption and the future pricing and remuneration concept of ESCs as well as any interventions from policy makers also affect yield calculations. There is no guarantee on the PV plant’s rate of return during the EEG remuneration period. Neither the manufacturer’s guarantee nor plant insurance policies are able to remove the risk to the investor entirely.

8 Does installing PV only create jobs in Asia?

No, however over the last few years Germany lost many jobs in the PV industry. In 2016, the PV industry employed 36,000 people in Germany [BSW]. Businesses from the following sectors contribute to the German PV industry:

1. manufacture of materials (silicon, wafers, metal pastes, plastic films, solar glass)
2. manufacture of intermediate and final products, including solar cells, modules, inverters, supporting structures, cables and coated glass
3. construction of manufacturing plants
4. installation (especially trade)

Noteworthy shares in the global market in 2016 were the German inverter manufacturers (SMA, KACO and others with more than 10%), poly-silicon producers (Wacker world market leader), silver paste producers (Heraeus in second place worldwide) and the equipment manufacturers.

Many jobs were lost in Germany in the last few years as a result of company closures and insolvency, which affected cell and module manufacturers, the mechanical engineering industry and installers. In 2007, the plan that the combination of EEG, investment grants in the (new) eastern states of Germany and research support would help establish Germany as a worldwide leading production site for PV cells and modules appeared to work. A German company led the international rankings in production volume. Since then, however, the market share of German manufactures has decreased dramatically due to the industrial policy in Asia and the huge investments put into in production capacity there. The labor costs play a subordinate role in this development because PV production today is highly automated. An important aspect, however, is the low complexity associated with PV production as compared, for example, to the automobile or microelectronic industry. For several years, turn-key production lines that produce very good quality PV modules can be bought off-the-shelf, which enables fast technology transfer.

Effective laws for feed-in tariffs in Germany and Europe have spurred on massive investments in PV power plants. Alone in Germany, these amounted to investments of 90 billion euros through to 2014 [DLR2]. In these countries, however, the economic-political framework is missing for generating investments in production capacity within a
competitive format (e.g. on the gigawatt scale). Rather, China and other Asian countries have succeeded through the creation of attractive conditions for investments and credit to mobilize four billion euro investment capital from national and international sources for the construction of large-scale production lines.

In spite of the high import quota of PV modules, a large part of the value chain for PV power plants remains within Germany. Assuming that around 80 percent of PV modules installed in Germany come from Asia, that these modules comprise roughly 60 percent of the total PV plant costs (other 40 percent predominantly from inverter and installation costs) and that initial plant costs make up around 60 percent of the levelized cost of electricity (remainder: capital costs), then nearly 30 percent of the feed-in tariff goes to Asia for imported modules. Also to consider is that a share of all Asian PV products are produced on manufacturing equipment made in Germany.

Figure 18: Employees in the RE sector in Germany [DLR2]

In the long term, the falling costs of PV module manufacturing coupled with increasing freight costs and long delivery times shall improve the competitive position of manufacturing companies in Germany.
9 Are large power plant operators interested in PV?

For a long time, large German power plant operators have shown little interest in PV power production. In 2010, the majority of Germany’s installed PV capacity belonged to private individuals and farmers, while the remainder was divided between commercial enterprises, project planners and investment funds. The four big power plant operators EnBW, Eon, RWE and Vattenfall (called “big four” in Figure 19) owned a mere 0.2 percent. Where does their aversion to PV power come from?

1. The electricity consumption in Germany is showing a declining tendency since 2007. The construction of new renewable power plants will force either a reduction in the utilization rate of existing power plant parks or an increase in electricity export.

2. Because PV electricity is generated primarily during periods of peak load, conventional peak load power plants are required less often. This reduces their utilization and profitability in particular. Paradoxically flexible power plants with fast response times are increasingly in demand.

3. PV power plants deliver power during the day at times when demand is at a peak. Figure 43: Schematic representation of a residual load curve for Germany with power supply of 100% EE, with generators (+) and loads (-); Red: Converters that produce usable heat or waste heat (Figure 43). This lowers the market price of electricity on the EEX, which carries over to all plants presently producing electricity. (Section 4.4). Previously, the big power plant operators were able to sell inexpensive base load power at a lucrative price during midday. Since 2011, PV led to price reductions on the energy exchange and thus to dramatic slumps in profit.

4. Because PV power production fluctuates, the slow start-up and shut-down properties of nuclear of older coal-fired power plants cause difficulties with increasing PV expansion. One particularly striking example is negative electricity prices on the market. Coal is being burned and the consumers must pay for the electricity. This leads to system wear in places where controls are technically feasible but no provision in the necessary frequency exists.

5. Radically new business models are required for decentralized PV production as compared to largely centralized coal and nuclear power production. In the wind sector, especially offshore production, the transformation effect is less drastic.

While big power plant producers have shown little interest in PV up to now, large wind farms, especially offshore wind, fit much better into their business model.

As the balance sheets of the “BIG 4” German power producers began to worsen dramatically, they began to react: RWE transferred two-thirds of its staff to its daughter innogy, which handles all business related to the energy transformation, including PV electricity. In its mid-year report for 2017, it states that Innogy operated less than 100 MW PV at the end of 2016. Similarly, E.ON SE has formed Uniper to handle its traditional gas and electricity and is now concentrating on renewable energy, including PV. In 2013, EnBW stated that it is redirecting its activities to focus on the energy transformation. As of September 2016, the company operates 50 PV plants. Vattenfall is selling...
its lignite sector and plans to concentrate on renewable electricity production, and since 2016 also PV.

Figure 19: Division of ownership of the total installed capacity of PV plants at the end of 2010 [trend:research].

Many of the approximately 1000 municipal electricity suppliers in Germany recognized the challenges facing the energy transformation early on and have reacted by offering new products and integral concepts, e.g. «virtual power plants” (Figure 20).

Figure 20: Concept for a virtual power plant of the Stadtwerke München (Munich municipal works) [SWM]
10 Is PV research taking up high levels of funding?

Looking back at previous numbers, Figure 21 shows that it took time for renewable energy and energy efficiency to become a focal point of energy research. Figure 22 shows the funding granted for PV research by the federal ministries.

Figure 21: Germany's expenditure in the Energy Research Program of the Federal Government by topic in € million [BMWi6].

Figure 22: Funding for PV research categorized by technology in € million [BMWi6].
11 Does PV power overload our energy system?

11.1 Transmission and distribution

More than 98 percent of solar power systems in Germany are connected to the decentralized low-voltage grid (Figure 23) and generate solar power consumption [BSW]. As a result, solar power is mainly fed in decentrally and hardly demands to expand the German national transmission grid. High PV system density in a low voltage grid section may cause the electricity production to exceed the power consumption in this section on sunny days. Transformers then feed power back into the medium-voltage grid. At very high plant densities, the transformer station can reach its power limit. An even distribution of PV installations over the network sections reduces the need for expansion.

Figure 23: Left: Feed-in of PV power [BSW], Right: Distribution of installed PV power according to plant size [ISE10]

PV power plants are decentralized and well distributed thereby accommodating the feed-in and distribution of the existing electricity grid. Large PV power plants or a local accumulation of smaller plants in sparsely populated regions require that the distribution network and the transformer stations are reinforced at certain sites.

The further expansion of PV should be geographically even more consumption-friendly, in order to simplify the distribution of solar electricity. For example, Brandenburg or Mecklenburg-Vorpommern have installed 3 to 4 times more PV power per inhabitant than, for example, the Saarland, NRW, Saxony or Hesse [AEE2].

According to a study by the Agora Energiewende, the German electricity grid will be able to transport the required amounts of electricity even with an installed PV capacity of just under 100 GW in 2030 [AGORA]. In particular, measures to modernize and improve the use of existing networks are needed, but no significant development.
When there are currently network bottlenecks, PV power is rarely the reason (Figure 24). Due to surplus wind power in Northern Germany, electricity deficits due to power plant shutdowns (nuclear in Southern Germany) and a sluggish grid expansion, grid bottlenecks often occurred in the German transmission grid. Because the grid expansion – a necessary step to alleviate the bottlenecks – will still take some time, redispaching measures will be increasingly required in the foreseeable future. Redispaching means that the transmission operators (TSO) intervene in the market-based operation schedule of the power plants (dispatch) to redistribute the electricity feed-in, prevent power surges in the grid (preventative redispach) or to carry out fixes (curative redispach). Before a bottleneck occurs, the energy feed-in is reduced (negative redispach) and afterwards increased (positive redispach) [BDEW4]. In 2017, the total cost of redispach measures amounted to € 1.4 billion.

![Figure 24: Electronically limited electrical energy in GWh / year [BNA3]](image)

### 11.2 Volatility

11.2.1 Solar power production is predictable

Reliable national weather forecasts mean that the generation of solar power can now accurately be predicted (Figure 25). Because PV power generation is decentralized, regional changes in cloud cover do not lead to serious fluctuations in PV power production throughout Germany as a whole.
11.2.2 Peak production is significantly lower than installed capacity
Due to technical losses (performance ratio PR <= 90%, see section 22.6) and inconsistent weather conditions, a real generation of electricity above 70% of the installed rated output (see chapter 3) is very unlikely throughout Germany, cf. also Figure 26.

Limiting (‘’feed-in management’’) individual plants to 70 percent of their rated power leads to an estimated loss of revenue of between 2 and 5 percent. A statutory regulation that actually enforces this limit for small plants came into force in 2012.
11.2.3 Solar and wind energy complement each other

Climate-related high solar radiation and high wind forces are negatively correlated in Germany. With an installed capacity of 43 GW PV and 51 GW of wind power at the end of 2017, the total power supply rarely reached more than 45 GW of power (Figure 26). A balanced mix of solar and wind power generation capacities is clearly superior to the one-sided expansion that a competitive support model would produce.

Figure 26: Average power for the supply of solar and wind power in 2017, 15-minute values [ISE4].
Figure 27: Monthly production of PV and wind power for 2012 - 2014 [ISE4].

11.3 Controllability

With its ever greater capacity, PV increasingly fulfills the role as a stabilizing variable. The amended EEG dated January 1, 2012 stipulates that feed-in management in the form of remote control via the grid operator or an automatic cut off at 70 percent of real power is also performed to regulate plants connected to the low-voltage grid. In accordance with the Low Voltage Directive VDE AR-N-4105, which has been in force since January 1, 2012, inverters must perform functions that support the grid.

«...the predominantly decentralized way in which PV is fed into the distribution grid in close proximity to consumers reduces grid operating costs and in particular those relating to the transmission grid. A further advantage of feeding in PV is that in addition to
feeding in real power, PV plants are in principle able to offer extra grid services (e.g. local voltage regulation) at cost-effective prices. They are particularly suitable for integration in subordinate grid management systems and may contribute towards improving grid stability and quality.” [ISET2]

11.4 Conflicts with slow-response fossil and nuclear power plants
The PV power generation profile fits so well to the power grid’s load profile that at all times Germany’s entire electricity demand, which ranges between 40–80 GW, shall exceed the PV electricity available, even if PV capacity continues to expand in the coming years. However, conflicts with slow plant start-up are increasing. Due to the present technical and economic constraints, these types of power plants react to fluctuating residual loads only to a very limited extent. Older power plants, especially lignite, can not provide balance energy economically. Nuclear power plants are technically able to run with a power gradient of up to 2 %/min. and a power increment from 50 % to 100 % [ATW2]. For economic reasons, the power production was seldom reduced in nuclear plants. In principle, however, volatile producers with their negligible marginal costs must obtain priority.

These unresolved conflicts can briefly lead to significant overproduction and high electricity exports at low to negative stock market prices, as the example in Figure 28 shows. The entire week was sunny, with strong winds on Monday and Tuesday. On public holidays such as May 1st and weekends, the daily load is lower than on working days. Coal and nuclear power plants delivered electricity even when the price forecast the day before had negative values.

During past heat waves, the rivers used as cooling reservoirs for fossil fuel and nuclear power plants became critically warm. The PV installations in Germany were able to help relax this problem and can also help to reduce this problem in neighboring countries such as France. Especially during summer, the installed PV in Germany categorically reduces the load on the fossil fuel and nuclear power plants.
Figure 28: Example showing course of electricity trading price, conventional and renewable electricity in the 18th calendar week in May 2018 [ISE 4]
11.5 Does volatile solar power endanger security of supply?
No.
The security of supply for final consumers has even increased since 2006 in parallel with the expansion of photovoltaics (Figure 29). Increased investments in the expansion of transmission grids have contributed to this development.

![Figure 29: System Average Interruption Duration Index (SAIDI) for different network levels in minutes / year [BNA3]](image)

11.6 Does the expansion of PV have to wait for more storage?
No.
Investing in storage is first profitable when large differences in the electricity price frequently occur, either on the electricity exchange market EEX or at the consumer level. Currently investments in storage, specifically pumped storage, are even being deferred because cost-effective operation is not possible.

A continued expansion of PV and wind will first cause prices on the electricity exchange EEX to sink more often and more drastically. On the other hand, a reduced amount of nuclear electricity caused by the planned phase out and more expensive electricity from coal-fired plants due to the imposed CO₂ allowances or taxes will result in price increases on the EEX. This price spread creates the basis for a profitable storage operation. If the price difference is passed on to the final customer through a tariff structure, then storage also becomes an interesting alternative for them.

A study by AGORA Energiewende identifies 12 measures to modernize the grids to include among others, approximately 100 GW of installed PV power by 2030 [AGORA].
12 Does the manufacture of PV modules consume a lot of energy?

A solar plant’s energy payback time depends on the technology used and the plant’s location. For an annual global horizontal irradiance of 1055 kWh/m², which is the mean value for Germany, this takes approximately two years [EPIA]. The lifetime of solar modules is between 20 and 30 years, meaning that a solar plant constructed today would generate at least ten times as much energy during its lifetime as is used to manufacture it. What’s more, ever more efficient manufacturing processes mean that this value shall improve in the future. Wind power plants in Germany demonstrate even shorter energy payback times ranging from 2-7 months.

13 Do PV Power Plants Require Excessive Amounts of Area?

13.1 Will Germany be completely covered with PV modules?

No.
The nominal power of all PV modules installed in Germany is presently ca. 43 GW. Assuming an average efficiency of 14 percent for all installations, this translates to a module area of approximately 300 km². Some of these modules are installed in open fields, and some are installed on rooftops.

Projections show that to achieve its target of a carbon neutral and sustainable energy supply system, Germany requires 200 GW of installed PV in total. This is five times the installed power existing in 2016. If one assumes a mean module efficiency of 19 percent, then the required PV module installations to meet this goal add up to about 1000 km². This module area is equivalent to about 2 percent of the total area of settlements and roads or 8 percent of the net land area used for residential purposes in Germany. For modules installed on flat roofs and open spaces, the utilized area is actually about 2 to 2.5 times higher than the pure module area, due to the necessary spacing interval required between tilted modules mounted on horizontal planes.

A study commissioned by the Federal Ministry of Transport and Digital Infrastructure estimates that there is a potential for expansion of open spaces without restriction on more than 3000 km² of land, corresponding to 143 GW of PV. In addition there is an expansion potential on roof areas of 150 GW photovoltaic, without consideration of solar thermal use [BMVI].

13.2 Does new PV capacity compete with food production for land?

No.
The large-scale construction of PV systems on arable land has not been supported by the EEG since July 2010. As a result, the installation of such systems ground to a halt and new ground-mounted systems are only being constructed on specific redeveloped brownfield sites, low-quality sites or in the close vicinity of highways and railway lines.
Furthermore, expansion scenarios do not envisage a significant amount of PV installations being built on arable land. There are various methods under investigation in the area of Agro-PV that propose combined land use for both agricultural purposes and PV [Beck]. Reduced irradiance has not been found to stunt the growth of many crops; some crops even benefit from it.

14 Are PV plants in Germany efficient?
The nominal efficiency (see section 22.2) of commercial wafer-based PV modules (i.e. modules with silicon solar cells) in new production has risen in recent years by an annual rate of around 0.3 percentage points to an average of nearly 17 percent and a peak performance of over 20 percent. Each square-meter of module has a rated power of nearly 170 W, with premium modules reaching over 200 W.

Since additional losses occur during operation, PV plants do not actually operate at nominal module efficiency. These effects are combined in the performance ratio (PR). A well-designed PV plant installed today achieves a PR of 80–90 percent throughout the year. This takes into account all losses incurred as a result of higher operating temperature, varying irradiance conditions, dirt on the solar modules, line resistance and conversion losses in the inverter. Inverters convert the direct current (DC) generated by the modules to alternating current (AC) for grid feed-in. The efficiency of new PV inverters currently stands close to 98 percent.

Depending on irradiance and performance ratio (PR), specific yields of around 900-950 kWh/kWp are typically generated in Germany and in the sunnier regions up to 1000 kWh/kWp. This corresponds to around 150 kWh per square-meter module and for premium modules around 180 kWh. An average 4-person household consumes around 4400 kWh electricity per year, corresponding to the annual yield generated by 30 m² of new modules with today’s average market efficiency. Calculations show that a south-facing, tilted roof of a detached family home is typically expansive enough to accommodate about 20 PV modules. This would be sufficient to supply the equivalent of the family’s annual electricity needs. To increase yield, PV modules are optimally tilted on flat roofs and open land to achieve the highest yield. Tilted south-facing modules, positioned at suitable distance from one another to prevent shading, require an area approximately 2 to 2.5 times their own surface area.

In comparison, when converting energy crops into electricity, the efficiency value calculated on the basis of irradiance is significantly less than one percent. This amount falls further when organic fossil fuels such as coal, oil or natural gas are converted into electricity. The efficiency of combustion-based power plants is based on the chemical energy which already exists in fossil fuels. Based on this method of calculation, Germany’s coal-fired power plants report an average efficiency value of 38 percent, for example. Burning biofuels in vehicles also only results in mediocre levels of efficiency when these are determined on the basis of the irradiated energy and surface area used. Figure 30: compares the total driving distances of vehicles that burn various biofuels with that of
an electric vehicle (plug-in hybrid drive), whose required drive energy is provided by a PV array covering an area equivalent to the energy crop acreage needed for the fuel.

Figure 30: Vehicle range for an annual yield of 1 a = 100 m² of energy crops (2,3) or 40 m² of elevated PV modules constructed on 100 m² on flat, open ground, Sources: Photon, April 2007 (1) and Fachagentur Nachwachsende Rohstoffe (2), (3).

While southern Spain and North Africa are able to produce specific yields of up to 1600 kWh/kWp, the power transmission to Germany would result in energy losses and additional charges. Depending on the voltage level, transmission losses are between 0.5 and 5 percent per 100 kilometers. Not taking conversion losses into account, high-voltage direct current (HVDC) transmission lines reduce transportation losses to just under 0.3 percent per 100 kilometers. Based on this, an HVDC transmission line of 5000 kilometers in length would present transmission losses of around 14 percent.

14.1 Do PV plants degrade?
Yes, albeit very slowly.
Wafer-based PV modules age so slowly that detecting any output losses poses a challenge to scientists.
A study examining 14 plants in Germany fitted with multicrystalline and monocrystalline modules showed an average degradation of a 0.1 percent relative drop in efficiency per year across the entire plant, including the modules [ISE2]. In this context, the common assumption that plants experience annual output losses of 0.5 percent seems conservative. Typically the manufacturers guarantee holds for a period of 20 to 25 years and in some cases even 30 years, ensuring a maximal linear power loss of 20 % within this period.

The above figures do not take into account any losses arising as a result of manufacturing faults. Comprehensive tests conducted by Fraunhofer ISE have shown that light-induced degradation of between one and two percent occurs during the first few days
of operation depending on the material used in the solar cells. The indicated rated power of modules normally refers to output following this initial degradation.

Long-term data has not been collected for many types of thin-film modules. Depending on the type, degradation during the first few months of operation and seasonal fluctuations can be observed.

14.2 Can PV modules become soiled?
Yes, but any dirt that accumulates on the vast majority of plants in Germany is generally washed away the next time that it rains, so that virtually no yield losses occur. Problems only arise in modules installed at extremely shallow angles or those located in the vicinity of deciduous trees or sources of dust.

14.3 Do PV plants often operate at full capacity?
No.
The performance indicator «full-load hours» is the quotient of the actual energy generated by a power plant in the space of a year and its rated power (see section 22.3). Due to the fluctuating and cyclical solar irradiation patterns, PV plants actually operate for less than half of the 8760 total hours per year, and even when they are operating, the system generally operates at partial load. Based on a trend scenario, the transmission system operators (TSOs) assume an average of 980 full load hours per annum for PV systems in Germany and 892 hours per annum for roof-mounted systems [ÜNB]. Figure 31 gives the forecasted full load hours per annum for different renewable energy systems in Germany.

![Figure 31: Forecasted hours of full-load operation for renewable energy plants, mean values from 2012-2016 [ÜNB]](image)

The average total horizontal irradiance for Germany between 1981 and 2010 was 1055 kWh/m² per year and fluctuates between approximately 950 and 1260 kWh/m² per year.
according to location [DWD]. Figure 32 shows the irradiance distribution across Germany. In order to maximize yields, PV modules are oriented facing south and are installed with a tilt angle 30–40° to the horizontal. Tilting the PV modules increases the total incident irradiance on the modules by around 15 percent compared to the horizontal surface. This increases the average incident irradiation to roughly 1200 kWh/m² per year throughout Germany.

A performance ratio PR (see section 22.6) of 85 percent and an ideal orientation would result in a geographical average across Germany of more than 1030 full-load hours. Since some roof-mounted systems are not ideally oriented and many still have a PR of less than 85 percent, the actual average number of full-load hours is somewhat lower. Technical improvements in the module and installation can increase the incident irradiation, the performance ratio PR, the yield and thus the number of full-load hours of a PV system. The improvements entail:

- Tracking (see section 17.2)
- Bifacial PV technology
- Reducing losses caused by shading
- Reducing the temperature coefficient of the solar cells
- Reducing the operating temperature of the module by backside ventilation
- Increasing the module properties for weak light and askance light conditions
- Reducing module losses caused by snow cover and soiling
- Early detection and repair of reduced output
- Decrease degradation over the module lifetime

In wind power plants, the greater the hub height, the greater the number of full-load hours. When required, nuclear, coal and gas-fired power plants are capable of working almost continuously (one year = 8760 hours) at their rated power. In reality, according to [BDEW1], lignite-fired power plants reached 6640 full-load hours in 2007, while hard coal-fired power plants achieved 3550 hours.
Figure 32: Horizontal annual global irradiation in Germany averaged over 1981-2010
15 Does PV make relevant contributions to climate protection?

15.1 Do anthropogenic CO₂ emissions danger the climate?
Yes. Most experts see a substantial risk. It has been proven without a doubt that global warming is increasing [IPCC]. Compared to the preindustrial era, the mean global temperature has risen by 0.8 °C [IEA]. The majority of the scientific community assumes that anthropogenic CO₂ and other greenhouse gas emissions are most likely the main cause for the rising concentration of greenhouse gases in the atmosphere as well as for the increase in the mean global temperature. In May 2013, the atmospheric CO₂ concentration reached 400 ppm for the first time in 800,000 years. Figure 33 and Figure 34 show the development through today of the atmospheric CO₂ concentration and the global, or rather Antarctic, temperature.

Figure 33: Development of the atmospheric CO₂ concentration and the mean global temperature change based on the NASA Global Land-Ocean Temperature Index [IEA2].

A more rapid increase in global temperature dangers the stability of the global climate system to an extent that is not fully understood today. The temperature increase has far-reaching effects on the global food security, coastal settlements, diversity of species and numerous habitats.
15.2 Does PV make a significant contribution to reducing the CO₂ emissions?

Yes.

Presently PV is replacing electricity generated from natural gas and hard coal power plants on the market. Based on data from 2013 giving the proportional amount of power generated from each energy source and the primary energy factors, each kWh of PV-generated electricity saved about 2.2 kWh of primary energy. In 2013, total primary energy savings amounted to 65 TWh. The actual influence of PV electricity on the power plant operations in general is difficult to determine.
Extrapolated for the year 2016, 527 grams of CO₂ are produced as direct emissions [UBA2] in the production of one kWh of electricity on average (“German electricity mix”), while the production of solar power does not cause any direct CO₂ emissions. This figure does not take into account any further, direct climate-damaging emissions and decreases with the expansion of RES. A coal-fired power plant emits approx. 949 g CO₂ / kWh electric, a lignite power plant approx. 1153 g CO₂ / kWh electric.

New large PV power plant parks have an electricity generation cost of 5 €-cts/kWh with abatement costs of 10-12 euro-cts per kg CO₂-equivalent. Germany’s energy policy has influence on a global scale. Although only three percent of the global electricity consumption was due to Germany in 2008 (with consumption showing a downward trend), German policy makers are leading the way in terms of developing incentive programs for RE. The EEG is the best example of this. The EEG and its effect have been and continue to be closely observed around the world. It has been used by many countries (presently about 30) as a model for similar regulations. Meanwhile, China is leading in expanding its PV capacity and has surpassed Germany in annual installed power many times over.

The International Energy Agency (IEA) commends the EEG in their report «Deutschland 2013” as a very effective instrument for expansion, which has drastically reduced the costs for renewable energy production in the last years [IEA3]. Meanwhile, Germany’s break with nuclear energy has also caught people’s attention worldwide. An additional five European countries also have decided to phase out nuclear energy (Belgium, Switzerland, Spain) while other countries have already completed the phase-out (Italy, Lithuania).

In terms of avoiding CO₂ emissions, the EEG achieved the highest impact due to a side effect: The creation of the largest and most secure sales market for PV, which lasted many years and decidedly accelerated global expansion, technology development and
price reduction (Figure 36). Worldwide PV is reducing the use of fossil fuels for electricity production.

![Figure 36: Development of annually installed PV capacity for Germany and globally, or Rest of World, (RoW), (last year estimated) CAGR stands for the compound annual growth rate.](image)

The German EEG has made PV power affordable faster, also extending out to people in developing countries. In this context, the EEG is «possibly the most successful development program of all time when it comes to energy supply," says Bodo Hombach in the «Handelsblatt” newspaper on January 11, 2013, and also helps developing countries to save significant amounts of CO₂.

15.3 In addition to CO₂ are there other environmentally harmful gases released during the production of PV?

Yes, in the case of some thin film technologies. During the production of thin-film PV and flat screens, nitrogen trifluoride (NF₃) is still used, in part, to clean the coating systems. Residues of this gas can thereby escape into the atmosphere. NF₃ is more than 17,000 times as harmful to the environment as carbon dioxide. Current emission quantities are not known. As of 2013, however, NF₃ emissions are to be determined in 37 countries according to the revised Kyoto Protocol.

15.4 Do dark PV modules warm up the Earth through their absorption?

Solar radiation plays an important role in the Earth’s energy balance. Light-colored surfaces reflect a larger amount of incident solar radiation into the atmosphere, while dark surfaces absorb more sunlight causing the Earth to heat up. PV module installation alters the degree of reflection (albedo) of the ground on which the system is mounted. For example, the total thermal output of a PV module with 17 percent efficiency emits as much heat (locally) as an area with an albedo of ca. 20 per-
cent. (To compare, asphalt has an albedo of 15 percent, grass 20 percent, and the desert ca. 30 percent.) In consideration of the relatively low amount of area required by PV modules (Section 13.1), the albedo effect is marginal. Furthermore, PV electricity use replaces the power from fossil fuel plants, reduces carbon emissions and thus slows down the greenhouse effect.

16 Are PV systems capable of replacing fossil fuel and nuclear power plants?

No, not in the near future. PV and wind power may currently be capable of reducing the use of fossil fuels, imported energy consumption and CO₂ emissions but until considerable storage capacities for electricity or hydroelectric storage facilities are available in the grid, they are not capable of replacing capacities. Calm, dull winter days, when power consumption is at a maximum and no solar or wind power is available, present the most critical test. Despite this, PV and wind power are increasingly colliding with conventional power plants with slow start-up and shut-down processes (nuclear, old lignite power plants). These power plants, which are almost only capable of covering the base load, must be replaced by flexible power plants as quick as possible. The preferred power plant choice is multifunctional electrically powered CHP plants fitted with thermal storage systems (Section 17.3.2).

17 Are we capable of covering a significant proportion of our energy demand with PV power?

Yes, to the extent that we adapt our energy system and the energy-related structures to the requirements of the energy transition.

17.1 Energy demand and supply

The traditional energy industry promotes fossil and nuclear energy sources (primary energy), converts them and prepares them for end users (Figure 37).

The conversion and consumption are subject to dramatic efficiency deficits. For example, the end energy consumed in traffic is predominantly converted into waste heat via internal combustion engines; only a small part is transferred as mechanical energy to the drive train (load-dependent approx. 10-35%). Of the drive energy generated, a considerable part of the braking is still irreversibly burned, especially in city traffic, because internal combustion engines do not recuperate. Thus, motorized road traffic burns fossil fuels with a very low efficiency, based on the transport performance. Households, which use about 75% of the final energy consumed for heating, could halve this consumption through simple heat protection measures.
Germany is highly dependent on energy imports (Figure 38: Germany’s ), combined with the risk of political interference by producing and transit countries and the risk of disturbances in raw materials logistics, for example due to low water levels in the rivers.

Figure 37: Energy flow diagram for Germany 2017 in petajoules [AGEB2].
The costs of energy imports are shown in Figure 39. After deduction of import proceeds, the costs are on the order of 50-100 billion euros annually. Much of the money goes to autocratic regimes.

Figure 39: Cost development for the provision of primary energy in Germany [ÖKO3]

The majority of final energy (39 percent) is used to generate mechanical energy (force) for vehicles and stationary engines (Figure 40). For space heating and hot water, about 800 GWh of final energy is used annually [BMWi1].
Figure 40: Share of final energy in Germany, categorized by utilization 2014 [BMWi4].

Figure 41 provides an example of how energy demand is distributed throughout the course of the year. The energy consumption in road transportation is characterized by base load. The total electricity consumption and the energy needed for hot water drop only slightly in summer. The heating demand correlates negatively with global irradiance, with the highest point of intersection being found in spring.

The monthly distribution of solar and wind power generation is also shown. While around 69 percent of the PV power generated throughout the year is produced in spring and summer (April–September), 62 percent of wind power is generated in autumn and winter.

Figure 41 clearly shows that even without seasonal storage systems, solar power has the potential to cover significant amounts of the electricity, road transport and hot water requirements, provided that complementary energy sources hold the fort in autumn and winter. The potential for covering heating requirements is much lower, however, with spring being the only time of year where this is likely. Furthermore, a combination of solar and wind power may allow power to be generated using renewable sources throughout the year because the amount of wind energy produced falls significantly in spring and summer.

In addition to the regular seasonal fluctuations in PV power generation, irradiance changes significantly over the course of hours, days and weeks. On a local level, significant changes are seen as much as every minute or even second but these fluctuations do not have a bearing on Germany's power grid as a whole.
On the other hand, the energy load also fluctuates during the course of the day. More energy is required during the day than at night, and more on working days than over the weekend or on holidays. When considering load profiles, utilities distinguish between base, intermediate or peak load demands (see section 22.7). Base load corresponds to a power demand of 30–40 GW that remains virtually constant over a 24-hour period. Intermediate load fluctuates slowly and mostly in a periodic manner, while peak load comprises sudden, highly changeable above the basic and intermediate load.

On sunny days, PV power is already capable of covering most of the peak load seen around midday (Figure 28). The further expansion of PV capacity leads to the midday peak load being covered even on less sunny days, while the midday electricity production on sunny days will cover even part of the base load requirements, especially on the weekend.

When solar power is available, the energy demand is generally high. At high demand, the electricity price on the energy exchange used to be at its most expensive. Continuing to install new PV capacity over the coming years, there will never be a surplus of PV electricity.
17.2 Energy scenarios

Our current energy system, which is based on generating power from fossil fuel and nuclear sources, cannot survive in the long term. A variety of energy scenarios have been created for the coming decades, and they are increasingly incorporating the use of RE. The rapid expansion of PV witnessed in Germany, alongside the speed with which its costs have fallen, have already exceeded many of these studies’ expectations.

A study commissioned by the Federal Environment Agency has concluded that it is technically possible to generate all power renewably and in an environmentally friendly manner by 2050 [UBA]. While this study works on the assumption of a total installed PV capacity of 120 GW in 2050, conservative estimates suggest that this milestone shall be reached first with an installed capacity of 275 GW.

Researchers at the Fraunhofer Institute for Solar Energy Systems ISE have investigated an energy system for Germany in a simulation based on hourly time series (Figure 45). It is entirely based on renewable energies and includes the heating sector with its potential for storage and energetic building renovation. In an economically optimized generation mix PV contributes with an installed capacity of approx. 200 GW [ISE5].

Figure 42: Scenario of a German energy system, schematic representation of the system composition. [ISE5]
Figure 43 shows a schematic residual load curve for Germany with a 100% renewable power supply, based on 200 GW generator power PV and wind. Shown are the descending ordered hourly values of the residual load for one year. Residual load corresponds to the difference between the irreducible electricity load (from which all flexibility potentials are skimmed off) and the sum of electricity production from volatile renewable sources (PV, wind, run-of-river). Volatile power production can be limited at any time technically, but at the price of an economic loss of power of the corresponding amount of electricity.

Figure 43: Schematic representation of a residual load curve for Germany with power supply of 100% EE, with generators (+) and loads (-); Red: Converters that produce usable heat or waste heat

Load shifts and current-regulated generators such as the discharge of stationary battery and pumped storage, the operation of fuel cells, CHP generators (with synthetic fuel and bio-methane / bio-mass) and simple gas turbines are activated in order of their marginal costs to meet the electricity demand. For a few hours a year, the residual load reaches its maximum (left side of Figure 43: Schematic representation of a residual load curve for Germany with power supply of 100% EE, with generators (+) and loads (-); Red: Converters that produce usable heat or waste heat), for example, in case of lack of wind over large areas, in connection with darkness or closed snow cover. In these periods, all controllable generators are at maximum reduced load on the grid, even the less efficient, simple gas turbines. Batteries and pumped storage fail relatively fast as generators due to their very limited capacity. Vehicle batteries can only be charged to a limited load (load management) or operated as a battery in the grid because they primarily have to cover the mobility requirement. CHP generators burn hydrogen or methane from renewable energy or biomass and produce storable heat besides electricity. As an alternative to combustion, heat can also be
generated electrically via heating elements on the high-temperature side of the CHP generators and temporarily stored in high-temperature heat accumulators [VATT].

On the surplus side, the current-regulated consumers, such as flexible loads, charging of stationary batteries and pumped storage tanks, the operation of electrolyzers, heat pumps and heating elements, are activated in order of economic efficiency with decreasing electricity prices in order to absorb the current that is not required. As a last resort the electricity production is restricted, when insufficient power is consumed. This can occur, for example, on stormy nights or on sunny and very windy weekend days when low demand and very high power production meet. For these few operating hours, no further expansion of the acceptance performance is worthwhile. For batteries and pumped storage the aforementioned capacity restrictions apply. To operate heat pumps and heating rods current-regulated, they require large thermal storage. Electrolytically generated hydrogen can be stored in the gas network and used in the transport sector, it can be methanized and processed into synthetic fuels. The chemical industry requires hydrogen and hydrocarbons for the recovery of materials.

The waste heat from the operation of electrolyzers and fuel cells can contribute to covering the heat demand, just as in the case of classic CHP. Generators (eg simple gas turbines) and consumers (eg heating rods) with particularly low performance-related investment costs (€/W) are required for the two-sided extensions of the residual load curve. They are rarely operated and therefore do not have to be highly efficient.

A quick glance at global energy scenarios: Royal Dutch Shell’s study "New Lens Scenarios" [Shell] sees PV growing into the most important source of primary energy by 2060 (Figure 44: Primary energy consumption by sources [Shell]). Between 2018 and 2023, the International Energy Agency (IEA) forecasts a doubling of the worldwide installed PV capacity to about 1 TW [IEA1].
17.3 Compensatory measures

Despite there being no hard and fast rules for integrating intermittent PV power into our energy system on a large scale and in an economically as well as technologically feasible manner, a plethora of complementary measures exist that are suitable for this very purpose. The following sections examine the most important aspects of this in detail.

17.3.1 Keeping PV power production constant

How can the amount of PV power available in the grid be kept at a constant level? One of the simplest approaches is to increase the installation of roof- and ground-mounted PV modules with east/west orientation. Although in comparison to south orientation this results in lower annual yields per module, the availability of PV feed-in across Germany increases, meaning that complementary power plants do not need to be used until the late afternoon (compare Figure 45). Even more effective in achieving this aim are single and dual-axis tracking systems, which in addition to making power production more constant throughout the day, can increase the annual yield by between around 15-35 percent. Compared to non-tracking systems, these PV systems can reduce yield losses that occur due to higher operating temperatures or snow cover. Another option is vertically mounted, bifacial modules with north-south gradient.

Figure 45: Yield development throughout the course of a day of PV plants installed in a variety of different ways, calculated using the software PVsol on a predominantly clear July day in Freiburg.

Increased on-site consumption and the associated savings due to less purchased electricity mean that the somewhat higher costs of electricity production due to more elaborate systems pays off already, especially for commercial consumers. Also the measures given
in section 14.3 to increase the number of full-load hours contribute to the stability of the PV electricity supply.

17.3.2 Complementary operation of existing power plants
It is technically possible to operate, design or retrofit many fossil fuel power plants in a way that they are able to follow the residual load (Figure 46). Partial load operation, increased wear and any associated retrofitting increases the power production costs. Gas-fired power plants, in particular, are highly suitable to cover fluctuating loads. In combination with combined heat and power systems (CHP), natural gas power plants have a very high efficiency of 95 % [UBA3]. Gas power plants based on gas motors have only a fraction of the investment costs (€/kW) of combined cycle (gas and steam) power plants (CCPP).

However, since PV is already noticeably reducing the electricity demand and the mid-day price peak on the energy exchange, and the favorable CO₂ balance of gas power plants hardly comes to bear because of low emission costs, gas-fired plants are currently not a worthwhile investment. Most of the natural gas must be imported (about 95% in 2017 [AGEB6]), in particular, Russia and Norway deliver to Germany.

The existing run-of-river power plants (for pumped storage, see section 17.3.9) can only make small contributions to the complementary operation, taking into account the interests of shipping and environmental protection. While they contributed around 5.5 GW of rated power and roughly 20 GWh of production in 2017 [ISE4], there is little scope for these levels to be improved on in the future.

17.3.3 Decreasing energy consumption
Measures for improving the energy efficiency in households and in the industry are among the most cost-effective for reducing the residual load. The Stiftung Warentest found, for example, that a house, which is equipped solely with older appliances, uses

Figure 46: Power plant availability [VGB].
twice as much electricity as a comparable house with energy saving devices [TEST]. Especially effective are measures that reduce the nighttime electricity consumption. Particularly effective are measures that reduce the nocturnal power consumption, if solar power can only be made available through comparatively complex storage.

17.3.4 Load management

Electricity consumption by households (Figure 47), commerce and industry offers flexibility options with regard to supply-side management. Several studies have identified load management potential in the range of 20 GW and more for households and 14 GW for commercial consumers [AEE1]. However, the technical prerequisites and economic incentives for the development of these potentials still have to be created.

The basic requirements are variable electricity tariffs and electricity meters, which enable time-dependent billing. The self-consumption of solar power from newer PV systems has an analogous effect, because it significantly reduces the price of electricity, when obtained directly from your own roof.

Devices, whose operation can also start delayed, must technically be able to react to price signals. This often includes washing machine, tumble dryer or dishwasher in the household. Cooling and air conditioning units can be added if they have a significant thermal storage. For cold stores, food markets or air conditioning systems that already have a certain thermal storage capacity in the system, the storage expansion can be done relatively cheap.

![Figure 47: Energy consumption of an average household in Germany, not including hot water production [RWE].](image)

There are also potentials for the adaptation of consumption profiles in the power-intensive industry. However, they are activated only when very cheap daily electricity is available more frequently, ie when the installed PV output continues to increase. Open,
investments are required to increase the capacity of energy-intensive process steps, with decreasing capacity utilization, and to increase storage capacities for energy-intensive products. Electromobility will contribute a growing share to load management (17.3.8). Flexibility potentials due to electrical heat generation are addressed in Section 17.3.8.

17.3.5 Balanced expansion of PV and wind power capacities
In Germany, weather patterns show a negative correlation between the PV and onshore wind power generated on both the hourly and monthly scales (Figure 26 and Figure 27). In terms of hourly fluctuations, the total amount of electricity generated from PV and onshore wind rarely exceeds 50 percent of the total rated power, while in terms of monthly changes, the total electricity generated by both sources is distributed more evenly than the individual amounts generated by each source. If the installed PV and wind performance continues to be on a similar scale, this combination will reduce storage requirements.

17.3.6 Grid expansion

17.3.6.1 National grid expansion
Studies conducted by the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) and ECOFYS on behalf of BSW have shown that increasing the installed PV capacity to 70 GW by 2020 shall incur costs of approximately 1.1 billion euros in terms of grid expansion alone [IWES], [ECOFYS]. The equivalent annual costs of this grid expansion make up roughly ten percent of the routine yearly expenditure for grid strengthening. The studies took into account expanding the low-voltage grid using PV plants that provide ancillary services (e.g. voltage scheduling through reactive power compensation) and partially equipping local distribution transformers with regulating devices.

17.3.6.2 Strengthening the European grid
The German electricity grid is part of the larger European grid. All neighboring countries have some controllable power plants in their fleet and also experience high levels of demand during peak hours, e.g. midday. Strengthening cross-border interconnection capacity (presently ca. 20 GW) and thus European electricity trade will contribute significantly to smoothing out the fluctuations in PV production.

Switzerland has a hydroelectric capacity of around 2 GW, while Austria boasts roughly 4 GW and France approximately 25 GW of hydroelectric power. «As of June 27, 2012, a total of 9,229 MW of pumped storage capacity was connected to the German power grid (net rated power in generator mode). This comprised 6,352 MW in Germany, 1,781 MW in Austria and 1,096 MW in Luxembourg. The capacity of Germany’s pumped-storage power plants currently amounts to 37,713 MWh.” [Bundesreg]
Norway has about 30 GW hydroelectricity [Prognos] with potential for expansion. By 2018, an underwater cable with a length of 600 km and a transmission power of 1.4 GW will be installed to create a direct connection to the German electricity grid. The installed capacity of the hydroelectric power in Switzerland and Austria are 12 GW and 9 GW respectively.

Figure 48: Total power of hydroelectric stations in selected countries, status in 2010 [Prognos]. The capacity given for each of type of power plant differs according to the data source

17.3.7 Combined heat and power solution

Low-temperature heat for space heating and hot water, as well as industrial process heat, are still largely provided by the combustion of fossil resources and in conjunction with small heat storage capacities. In a renewable energy system, the provision of heat is closely linked to the transformation of electrical energy. Useful heat is obtained from the waste heat of CHP plants, fuel cells and electrolyzers, in times of surplus electricity via heat pump and heating element (17.3.9.1). Large heat storage capacities enable the current-controlled operation of the transformers.

The efficiency of a heat pump (electricity to heat) is given as an annual performance factor and is 300%, depending on technology and load. Heating rods convert electricity into heat at 100% efficiency, but in the case of low-temperature heat with low exergetic efficiency. Heating rods are worthwhile at very low electricity prices or infrequent use. Once converted into heat, the previously electrical energy can be stored efficiently and inexpensively (Section 17.3.9.1).

In Germany, at the end of 2014, about 33 GW of electrical CHP power was connected to the grid [ÖKO2], which mainly uses gas, biomass and coal. CHP plants achieve overall efficiencies of up to 90%, and gas CHPs as much as 95% [ÖKO2]. Even micro-CHPs for a single-family home can achieve electrical efficiencies of up to 25% and overall efficiencies of up to 90% [LICHTBLICK]. They use combustion or Stirling engines to generate mechanical power. As the energy transition progresses, CHP plants are being converted from fossil fuels to synthetic fuels, with some still burning biomethane / biomass. At the end of 2017 biomass power plants with 7.4 GW output were installed across Germany [ISE4].
17.3.8 Electromobility

Motorized road transport burns fossil fuels at an extremely low efficiency with respect to the transport performance. Most of the energy consumed disappears as waste heat in the motor and in the brake system. Electric vehicles use highly efficient motors (efficiency > 90%) and the mechanical energy generated can be used to a large extent (regeneration brake). Electric vehicles need batteries as electrochemical energy storage, possibly supported by internal combustion engines with fuel tank (plug-in hybrid) or fuel cell with hydrogen tank (hydrogen powered vehicles).

E-vehicles can contribute to load management if their battery is charged with power according to availability. In order to charge PV power, they must find charging stations at the parking spaces used during the day, e.g., at the workplace, in parking garages or other public car parks.
As soon as price signals become available, for example logistics companies with electric vehicles can take account of cheap charging times in their route planning.

Plug-in hybrids have an electric driving range of ca. 80 km. Many car manufacturers offer pure electric vehicles with standard ranges (NEDC) up to 380 km with 40 kWh of storage and up to 520 km with 60 kWh of storage. By 2020, one million electric cars should have been registered in Germany according to earlier plans of the Federal Government. With a charging capacity of ca. 40 kWh per vehicle in fast-charging mode, 25,000 vehicles plugged into the electricity grid would already mean one gigawatt of controllable consumption. However, revolutionizing our personal means of transport has really taken off on two wheels: At the end of 2017, several million e-bikes sold in Germany faced only 54,000 pure electric cars.

17.3.9 Energy storage

17.3.9.1 Thermal storage

Inexpensive low-temperature heat storage, especially hot water storage, enable the current-driven, highly efficient operation of CHP systems and fuel cells on the generator side, as well as heat pumps, electrolyzers and heating rods on the customer side. Heat storage systems are scalable from single-family house to multi-family houses and commercial enterprises to neighborhood supply. The proportionate storage losses and the specific costs decrease with the size of the storage.

Thermal storages increase the self-consumption of PV systems when they are loaded by heat pumps or heating rods, especially in the summer months. Seasonally, the PV system can heat up the domestic hot water, in particular when the PV modules with high inclination are mounted on steep south-facing roofs or on southern facades.

As soon as price signals become available, decentralized thermal storage units can also be charged from the power grid and, for example, use excess wind power. Latent heat
storage systems offer significantly higher storage densities compared to sensitive heat storage units such as the hot water storage tank.

17.3.9.2 Batteries
With small, stationary batteries in-house, the self-consumption of PV power can be extended into the evening hours and thus massively increased (typically doubling, see Figure 49: Percent of on-site consumption in dependence of the battery capacity and PV array power for a single-family home with an annual electricity consumption of 4,700 kWh. [Quasch]). In August 2018, the number of PV stores exceeded 100,000 in Germany.

![Figure 49: Percent of on-site consumption in dependence of the battery capacity and PV array power for a single-family home with an annual electricity consumption of 4,700 kWh. [Quasch]](image)

Systems with grid-optimized operation can reduce the grid load by decreasing the grid feed-in at peak times as well as the electricity purchased in the evenings (Figure 50). Storage systems thus promote the installation of PV systems. «Load flow calculations showed that a grid-optimized PV/battery operation reduces the feed-in peak of all systems by about 40%. Results indicate that 66 % more PV/battery could be installed as long as these systems also operate using a grid-optimized feed-in strategy." [ISE7]
Electric vehicles that are connected to the grid and must not be immediately available to drive, can also be operated as a power / electricity storage unit with the appropriate technical equipment. The load management potential of electric vehicles has already been mentioned (6217.3.8). Pilot projects are currently investigating the storage of electrical energy in large, stationary batteries [RWE2].

17.3.9.3 Pumped storage
The currently installed pumped storage capacity in the German grid stands at almost 38 GWh, while rated power is approximately 6.4 GW and the average efficiency value is 70 percent (without transmission losses). As a comparison, the aforementioned storage capacity corresponds to the yield generated by German PV power plants in the space of less than one full-load hour. If some projects are being planned or have been realized, the capacity of the pumped storage power plants can be increased to about 10 GW. The current market and price mechanisms do not allow economic operation of new power plants, although they are urgently needed for an efficient energy transition.

The storage of electrical energy in compressed air accumulators (adesabatic compressed air energy storage, CAES) is also being investigated.

17.3.9.4 Hydrogen and derivatives
The promising electrolytic conversion of excess solar and wind energy into hydrogen, with subsequent methanation and further processing into synthetic fuels, is under scaling and testing [AMP]. The conversion of renewable energy to storable energy sources gas ("Power-to-X") opens up huge, already existing storage possibilities. More than 200 TWh of energy (equivalent to 720 petajoules) can be accommodated in the existing gas network itself as well as in underground and above-ground storage facilities.
These synthetic energy sources can be reconverted, but they can also be used as fuels in the transport sector (for example, hydrogen for fuel cell vehicles, kerosene substitutes in aviation) or as starting materials for the chemical industry.

Figure 51 shows an overview of possible paths for the conversion and storage of PV power. For the practical relevance of these paths, in addition to the technical efficiency, the costs of the rated output (€ / W) for transformation and the costs of the stored energy (€ / kWh) for storage are also to be considered.

17.3.10 Overview

Time horizon until 2025: focus on "flexibilisation"

1. The energy efficiency of electricity consumers is increasing in all sectors.
2. The installed PV power is increased to 70-80 GW, close to consumption, for steadying of production in East / West orientation or with tracking, with grid-supporting inverter functions, for a production of approx. 60-70 TWh/a solar power at peak power up to approx. 50-55 GW. Wind power capacities are being expanded in similar dimensions.
3. Load management: Parts of household, industrial and e-mobility power consumption are adjusted to the availability of PV power (and wind power) through demand-side management (supply-based tariffs or signals).
4. Available pump storage capacity and capacity are being increased.
5. PV systems are provided with network-compatible battery storage; for heating and cooling supply, storage tanks are being expanded.
6. For the power utilization of occasional EE current spikes cheap (€/W) heating rods are built into thermal storage.
7. For the power utilization of frequent excess electricity surges, electric heat pumps with feed-in into thermal storage are constructed.
8. Low-cost (€/W) gas turbines are built to cover occasional residual load peaks (e.g., from the recycling of aircraft turbines).
9. To cover frequent residual load gaps, efficient CCGT/CHP power plants with feed-in into thermal storage are set up.
10. Existing coal-fired power plants will, if possible, be optimized for flexible operation, otherwise shut down.
11. The power grid connections to our neighboring countries will be strengthened.

Time frame until 2050: focus on "storage" 
1. The installed PV capacity will be gradually expanded to approx. 200 GW, for a solar power production of approx. 190 TWh/a 
2. The heat supply will be completely converted to RE, the structural thermal protection will be optimized 
3. The traffic will be completely converted to electricity or synthetic fuels from renewable sources 
4. The conversion and storage of RE (in particular electricity-to-electricity) via RE gas and batteries will be massively expanded 
5. Consumption of fossil fuels will be completely stopped 

In order to avoid costly undesirable developments and to keep pace with the above steps, incentives are needed: a stable EEG, investment incentives for energy efficiency measures, multifunctional power plants and pumped storage, price and investment incentives for supply-side electricity consumption and incentives for demand-based electricity supply. A further measure could be the reduction of the implicit subsidy for coal-fired power plants through a shortage of CO₂ allowances or, nationally, by a CO₂ tax.
From today’s perspective, an energy system based on almost 100% renewable energy is technically and economically feasible. Figure 52 shows the main elements connected to the grid, from extraction to transformation and storage down to consumption. In order to reduce the storage requirements, the power consumption in households and industry will be partially more flexible. ICT stands for information and communication technology. The dashed boxes indicate that currently very low performance (in the converters) or capacities (in the storages) are available.

In the “heat” sector (red), cogeneration units, heat pumps and - in the case of supply peaks on the electricity side - heating elements load the heat storage units. Wherever the acceptance density permits, for example in quarters, the efficient storage takes place centrally in large heat storages.

In the “gas” sector (green), biomass fermenters produce methane and electrolyzers hydrogen, which can also be methanized or processed into synthetic fuels. Partly biomass is burned directly in the CHP. When electricity is needed, combined gas and steam tur-
In the "battery" sector (black), stationary, central or decentralized electrochemical storage tanks are charged or discharged depending on the residual load. Mobile batteries in electric vehicles primarily serve the mobility needs, but can also support the network bidirectionally at standstill. In most electrochemical storage systems, the converter and the storage tank are structurally fused, only so-called redox flow batteries have external, scalable storage tanks.

In the mechanical sector (blue), water storage power plants are operated bidirectionally via pumps and turbines, similar to compressed air storage power plants via compressors and turbines.

**18 Do we need PV production in Germany?**

Yes, if we want to avoid new dependencies in energy supply.

As the energy transformation progresses, Germany will leave behind the «fossil fuel” century, in which we spent 90 billion euros for oil and gas imports annually and thus financed authoritarian governments.

The energy transformation offers the chance to escape from this dependency. Not only does the sun also shine in Germany but Germany has also made decisive contributions to technology development in the solar sector. In spite of the enormous slump in Germany’s solar market, the German PV sector with its material manufacturers, engineers, PV producers, R&D institutes and training facilities has held onto its leading position worldwide. A future energy system based on renewable energy sources with ca. 200 GW installed PV: For the construction and increasingly the up-keep of these power stations, annual installations of 6-7 GW are required. This corresponds to about 20 million PV modules at a cost of several billion euros. A PV production within Germany offers long-term security of supply at high ecological standards and quality.

**19 Do PV modules contain toxic substances?**

That depends on the technology and materials used.

**19.1 Wafer-based modules**

The silicon wafer-based modules (approximately 90 percent of the market share) produced by many manufacturers often contain lead in the cell metallization layer (around 2 grams of lead per 60-cell module) and in the solder used (approximately 10 grams of lead per 60-cell module). Lead, a toxic heavy metal, is soluble in certain, strongly acidic or basic environments, and lamination in the module does not permanently prevent mass transfer [IPV]. In wafer-based modules, lead can be completely substituted by
harmless materials at low additional costs. Other than lead, wafer-based modules do not usually contain any known toxic substances.

19.2 Thin-film modules
Cadmium telluride (CdTe) thin-film modules (approximately five percent of market share) contain cadmium (Cd) in salt form. The technology behind this type of module does not allow this material to be substituted. Metallic cadmium and cadmium oxide are classified as toxic; CdTe as harmful to health. Alternative thin-film modules containing little or no Cd are based on amorphous silicon or copper indium selenide (CIS). CIS solar cells contain selenium which can be toxic when oxidized (e.g. after a fire) independent of the amount. Many manufacturers declare the conformity of their CIS modules with the RoHS chemical regulation (Restriction of certain hazardous substances) and the EU chemicals ordinance REACH (Registration, Evaluation, Authorization and Restriction of chemicals). For a differentiated evaluation, reference is made to independent investigations of each module type.

19.3 Solar glass
All conventional solar modules require a front cover made of glass. The glass shall have a very low absorption in the spectral range between 380 and 1100 nm, conform to solar glass quality. Many glass manufactures increase the transmission by adding antimony (Sb) to the glass melt. If this glass is disposed of in waste dumps, antimony can seep into the ground water. Studies indicate that antimony compounds have a similar effect as arsenic compounds.

19.4 Take-back schemes and recycling
PV producers set up a manufacturer-independent recycling system in June 2010 (PV Cycle), which currently has more than 300 members. The version of the European WEEE Directive (Waste Electrical and Electronic Equipment Directive) which came into force on August 13, 2012 must be implemented in all EU states by the end of February 2014. This directive makes it compulsory for manufacturers to take back and recycle at least 85% of their PV modules free of charge. In October 2015, the electric and electronic device law came into effect. It classified PV modules as household devices and set down provisions for take-back obligations as well as financing.

20 Are there enough raw materials available for PV production?
20.1 Wafer-based modules
Wafer-based modules do not require any raw materials which could become limited in the foreseeable future. The active cells are fundamentally composed of silicon, aluminum and silver. Silicon accounts for 26 percent of the mass of the earth’s crust, meaning
that it is virtually inexhaustible. While aluminum is also readily available, the use of silver poses the most problems. The PV industry currently uses approximately \textbf{1,400 metric tonnes} of silver annually, corresponding to almost five percent of production in 2015. In the future, the silver in solar cells could be used more efficiently and replaced by copper as much as possible.

\textbf{20.2 Thin-film modules}

The availability of raw materials depends on the technology being used. Contradictory statements have been made concerning the availability of tellurium and indium for CdTe and CIS modules respectively. No raw material shortages have been foreseen for thin-film modules made from silicon.

\textbf{21 Do PV plants increase the risk of fire?}

\textbf{21.1 Can defective PV plants cause a fire?}

Yes, as is the case with all electric installations. Certain faults in the components of PV plants that conduct electricity may cause electric arcs to form. If flammable material, like roofing material or wood, lies in close vicinity to these arcs, then a fire may break out depending on how easily the material ignites. In comparison to AC installations, the DC power of solar cells may even serve as a stabilizing factor for any fault currents that occur. The current can only be stopped by disconnecting the circuit or preventing irradiation reaching any of the modules, meaning that PV plants must be constructed carefully.

With more than 1.4 million PV plants in Germany, the combination of all of these factors has been proven to have caused a fire to break out in just a few cases. The majority of the fires started as a result of faults in the cabling and connections.

«Using qualified skilled workers to ensure that existing regulations are adhered to is the best form of fire protection. To date, 0.006 percent of all PV plants have caused a fire resulting in serious damage. Over the past 20 years, 350 solar systems caught fire, with the PV system being at fault in 120 of these cases. In 75 cases, the damage was severe and in 10 cases, the entire building was burned to the ground.

The most important characteristic of PV systems is that they produce direct current. Since they continue to generate electricity for as long as light falls on their modules, they cannot simply be turned off at will. For example, if a low-quality or poorly installed module connector becomes loose, the current flow is not always interrupted immediately, potentially resulting in an electric arc, which, in the worst case scenario, may cause a fire to break out. Accordingly, investigations are being carried out on how to prohibit the occurrence of electric arcs. In addition, detectors are being developed that sound an alarm as soon as only a small electric arc occurs.
PV plants do not present a greater fire risk than other technical facilities. Sufficient regulations are in place that ensure the electrical safety of PV systems and it is imperative that these are followed. Fires often start when systems are fitted by inexperienced pieceworkers. Weak points are inevitable when solar module connectors are installed using combination pliers instead of tools designed especially for this purpose or when incompatible connectors are used, and system operators should not cut costs in the wrong places.

In addition to technical improvements, control regulations are vital. At present, system installers themselves are permitted to confirm that their installations were carried out in compliance with regulations but experts now recommend that acceptance tests be performed by third parties. It has also been suggested that privately owned PV systems are subjected to a compulsory, regular safety test similar to that performed on commercial plants every four years.” [ISE6]

21.2 Do PV plants pose a danger to firefighters?
Yes, as is also the case with many systems fitted with live cables.

Standing at least a few meters away from the fire when extinguishing a fire from outside of the building protects firefighters from electric shocks. This safe distance is normally given for all roof-mounted installations. The greatest risk for firefighters arises when extinguishing a fire from inside the building in areas where live, scorched cables connected to the PV plant come into contact with water or the firefighters themselves. To minimize this risk, the industry is developing emergency switches that use safety relays to separate the modules from their DC connection in close vicinity to the roof.

In Germany, no firefighter has to date been injured by PV power while putting out a fire. An incident widely reported in the press confused solar thermal collectors with PV modules and no PV plant was fitted to the house in question whatsoever.

«Comprehensive training courses for the fire brigade could eliminate any uncertainties firefighters may have. As with every electrical installation, depending on the type of electric arc it is also possible to extinguish a fire using water from a distance of one to five meters. Based on investigations to date, all of the claims stating that the fire brigade could not extinguish a house fire due to the PV system have been found to be false.” [ISE6]

21.3 Do PV modules prevent firefighters from extinguishing fires externally from the roof?
Yes.

The second «roof covering” created by the PV modules hinders the ability to extinguish the fire, as the water simply drains away. According to the fire brigade, objects damaged by a fire that needs to be extinguished in this way can rarely be saved, i.e. the
damage has to a large extent already been done and is irreversible before the PV plant impedes the firefighters’ ability to put out the fire.

21.4 Are toxic emissions released when PV modules burn?
The Bavarian Environment Agency (Bayerisches Landesamt für Umwelt) has calculated that the dispersion of fumes following a fire involving CdTe modules does not pose a serious risk for the surrounding area and general public [LFU]. For CIS modules, independent investigations for the different module types are referenced. For wafer-based modules, the rear side foils can contain fluoropolymers, which themselves are not poisonous. In a fire at high temperatures, however, they can decompose. Upon examination, the Bavarian Environment Agency came to the conclusion that during a fire, conflagration gases other than fluoropolymers play a more critical role in defining the potential danger.
22 Appendix: Terminology

22.1 EEG surcharge

«The EEG surcharge (EEG-Umlage in German) is the portion of the electricity price that must be paid by the end user to support renewable energy. It results from the equalization scheme for renewable energy sources, which is described in the Renewable Energy Act (EEG). The EEG provides incentives for plants that generate power from renewable energy and which otherwise could not be commissioned as a result of the market situation. Hydroelectric power plants, landfill gas, sewage gas, mine gas, biomass, geothermal energy, wind power and solar power are supported.

Several stages are used to determine how the costs associated with promoting renewable electricity are allocated to the end users. In the first stage, plant operators, who generate power from renewable energy, are guaranteed a fixed feed-in tariff for all power produced by their plant. “ [Bundestag]

The level of this feed-in tariff is based on the levelized cost of electricity (LCOE) for PV plants installed at that time and is guaranteed for 20 years.

«The grid operators, who connect these renewable plants to their grids and who also reimburse the plant operators for the fed-in power, transmit the power to the responsible transmission system operator (TSO), who reimburse them in turn (second stage). In the third stage, the renewable energy is distributed proportionally between Germany’s four transmission system operators (TSO), compensating regional differences in renewable energy generation.

The Equalization Scheme Ordinance (Ausgleichsmechanismusverordnung, AusglMechV) dated July 17, 2009 resulted in changes being made to the fourth step of the remuneration and reimbursement scheme for renewable energy. Until these amendments were adopted, the renewable power generated was simply transmitted (via the TSOs) at the price of the feed-in tariff to the energy supply companies, who sell the power. Now, however, TSOs are required to put the power generated from renewables onto the EEX (spot market). The energy supply companies, which ultimately transmit the power to the end customers, can obtain power from the market regardless of how much renewable energy is fed into the grid. This gives them greater planning security and also allows them to save costs. As a result, the costs of the EEG promotions remain first and foremost with the TSOs.

The costs related to the EEG promotion is calculated based on the difference between the rate of return generated by the renewable power put on the market (EEX) and the feed-in tariffs paid to plant operators. (...)” [Bundestag]

These costs are then distributed over the total energy consumption – the so-called EEG surcharge, which is apportioned to the end consumers by the electricity supply companies. «The Equalization Scheme Ordinance (AusglMechV) stipulates that the TSOs set the level of the EEG surcharge on October 15 of each year for the following year. The calculation of the surcharge is subject to review by the German Federal Network Agency. (...)»
The EEG surcharge is limited to 0.05 €-cts/kWh for energy-intensive companies.” [Bundestag].

As a result, energy-intensive industrial enterprises which spend a high proportion of their costs on power are largely exempt from the EEG surcharge.

22.2 Module efficiency

Unless stated otherwise, module efficiency is given in terms of nominal efficiency. Under standard test conditions (STC), it is calculated in terms of the relationship between the amount of electricity generated and the level of irradiation on the module’s total surface area. STC conditions imply a module temperature of 25 °C, vertical irradiance of 1000 W/m² and a standard solar irradiance spectrum. During actual operation, conditions are normally so different from these standard conditions that efficiency varies.

22.3 Rated power of a PV power plant

The rated power of a power plant is the ideal DC output of the module array under STC, i.e. the product of the generator surface area, standard irradiance (1000 W/m²) and nominal efficiency of the modules.

22.4 Specific yield

The specific yield [kWh/kWp] of a PV plant is the relationship between the useful yield (alternating current yield) over a certain period of time (often one year) and the installed (STC) module capacity. The useful yield is influenced by actual operating conditions, such as module temperature, solar radiation intensity, angle of solar incidence, spectral deviation from the standard spectrum, shading, snow cover, transmission losses, conversion losses in the inverter (and where applicable in the transformer) and operational failures.

Manufacturer data on module output under STC may vary from the actual values. Therefore, it is imperative that information on tolerances are checked. The specific yield is generally higher in sunny locations but it is not dependent on nominal module efficiency.

22.5 System efficiency

The system efficiency of a PV plant is the relationship between the useful yield (alternating current yield) and the total amount of irradiance on the surface area of the PV modules. The nominal module efficiency affects system efficiency.
22.6 Performance ratio
The performance ratio (PR) is often used to compare the efficiency of grid-connected PV plants at different locations with various module types.
Performance ratio is defined as the relationship between a plant’s useful yield (alternating current yield) and ideal yield (the product of the total amount of irradiance on the generator surface area and nominal module efficiency).
New, carefully planned plants achieve annual PR values of between 80 and 90 percent.

22.7 Base load, intermediate load, peak load, grid load and residual load
«Power demands fluctuate throughout the course of the day, generally peaking during the day and falling to a minimum at night between midnight and 6:00am. Power demand development is depicted as a load curve or load profile. In traditional energy technology, the load curve is divided into three sections as follows:
1. base load
2. intermediate load
3. peak load
Base load describes the load line that remains almost constant over a 24-hour period. It is covered by base-load power plants, such as nuclear power plants, lignite coal-fired power plants and, for the time being, run-of-the-river power plants. Intermediate load describes self-contained peaks in power demand which are easy to forecast and refers to the majority of power needed during the course of a day in addition to base load. Intermediate load is covered by intermediate-load plants, such as hard coal-fired power plants and combined cycle power plants powered by methane with oil-fired power plants being used now and again. Peak load refers to the remaining power demands, generally coming into play when demand is at its very highest. Peak load is handled by peak-load power plants, such as gas turbines and pumped-storage power plants. These can be switched to nominal output within an extremely short space of time, compensating for fluctuations and covering peaks in load.” (…) «Grid load refers to the amount of electricity taken from the grid, while residual load is the grid load less the amount of renewable energy fed in.” [ISET1]

22.8 Gross and nets power consumption
The gross power consumption is calculated as the sum of the national electricity production and the balance of power exchanged between bordering countries. It includes the self-consumption from power plants, storage losses, grid losses and unknowns. In 2017, the sum of all losses amounted to 13% of the gross power consumption [AGEB6].

Net power consumption is the amount of electrical energy (final energy) used by the end consumer. PV plants predominantly generate energy decentrally when electricity demand is at a peak and the PV plant’s self-consumption does not reduce the PV yield by a noteworthy amount. Instead of following the usual method of comparing output with gross power consumption, it is plausible for PV to compare power output with net power consumption.
22.9 External costs [DLR1]

«External costs, as defined within the context of the technological external effects, arise as a result of damage inflicted on the environment, climate and human health due to pollutants and noise emissions caused by economic activities. These include:

- damage to flora and fauna, materials and human health caused by air pollution; the majority of damage caused by air pollution is attributable to converting and using energy (including transportation).
- emerging effects of climate change caused by the increasing accumulation of CO₂ and other greenhouse gases in the atmosphere and its consequences; in Germany, 85 percent of these gases are emitted by the energy sector.
- damage caused by pollution to bodies of water, soil contamination, waste and noise pollution. As this study concentrates solely on classic airborne pollutants and greenhouse gases generated as a result of converting energy, these are not dealt with further.»
### Vorsätze und Vorzeichen

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<th>Symbol</th>
<th>Abkürzung</th>
<th>Multiplikator</th>
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<tr>
<td>k</td>
<td>Kilo</td>
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<tr>
<td>M</td>
<td>Mega</td>
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<tr>
<td>G</td>
<td>Giga</td>
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<td>Tera</td>
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<tr>
<td>P</td>
<td>Peta</td>
<td>10^15</td>
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<tr>
<td></td>
<td>Tausend</td>
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<td></td>
<td></td>
<td>Milliarde (Md.)</td>
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<tr>
<td></td>
<td></td>
<td>Billion (Bil.)</td>
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<td></td>
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### Umrechnungen

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<th>GWh</th>
<th>Mio. t SKE</th>
<th>Mio. t RÖE</th>
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<td>1 GWh</td>
<td>Gigawattstunde</td>
<td>0,0036</td>
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<td>1 Mio. t SKE</td>
<td>Mio. Tonnen Steinkohleanhe</td>
<td>20,31</td>
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<td>0,70</td>
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<td>1 Mio. t RÖE</td>
<td>Mio. Tonnen Rohölheinheit</td>
<td>41,87</td>
<td>11,630</td>
<td>1,43</td>
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### Typische Eigenschaften von Kraftstoffen

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<td>Rapsöl</td>
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<td>Benzin</td>
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<td>9,0</td>
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### Typische Eigenschaften von festen und gasförmigen Energieträgern

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<td>-</td>
<td>30,0 - 38,1</td>
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<td>Braunkohle</td>
<td>-</td>
<td>2,6 - 6,2</td>
<td>-</td>
<td>0,2 - 22,2</td>
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<td>Erdgas H</td>
<td>0,76</td>
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<td>8,8</td>
<td>41,7</td>
<td>31,7</td>
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<td>Biogas</td>
<td>1,20</td>
<td>4,2 - 6,3</td>
<td>5,0 - 7,5</td>
<td>15,0 - 22,5</td>
<td>18,0 - 27,0</td>
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<td>Holzpellets</td>
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<td>4,9 - 5,4</td>
<td>3,2 - 3,5</td>
<td>17,5 - 19,5</td>
<td>11,4 - 12,7</td>
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24 Appendix: Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>BMU</td>
<td>German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety</td>
</tr>
<tr>
<td>BSW</td>
<td>German Solar Industry Association</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon dioxide capture and storage – segregation of CO₂ from power plant emissions and storage in geological formations</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined heat and power – the principle of simultaneously generating mechanical energy (ultimately converted into electrical energy) and useful heat</td>
</tr>
<tr>
<td>CHP plant</td>
<td>Combined heat and power plant – a plant that uses combustion engines or gas turbines to generate electrical energy and heat</td>
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<tr>
<td>EEG</td>
<td>Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act, EEG)</td>
</tr>
<tr>
<td>ESC</td>
<td>Energy supply company</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and communications technology</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>RE</td>
<td>Renewable energy</td>
</tr>
<tr>
<td>Wₚ</td>
<td>Watt peak – rated power of a PV module or array</td>
</tr>
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25 Appendix: Sources

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<td>AEE1</td>
<td>Metaanalyse: Digitalisierung der Energiewende, Agentur für Erneuerbare Energien, August 2018</td>
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<td>AEE2</td>
<td>Bundesländer-Übersicht zu Erneuerbaren Energien, <a href="https://www.foederal-erneuerbar.de/uebersicht/bundeslaender">https://www.foederal-erneuerbar.de/uebersicht/bundeslaender</a>, Agentur für Erneuerbare Energien, October 2018</td>
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<td>AGEB1</td>
<td>Energieverbrauch in Deutschland - Daten für das 1.-3. Quartal 2011, Working Group on Energy Balances (Arbeitsgemeinschaft Energiebilanzen e.V.), November 2011</td>
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<td>AGEB2</td>
<td>Energieflussbild für die Bundesrepublik Deutschland in Petajoule, AGEB, May 2018</td>
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<td>AGEB6</td>
<td>Energieverbrauch in Deutschland in Jahr 2017, AGEB, February 2018</td>
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<td>AGORA</td>
<td>Stromnetze für 65 Prozent Erneuerbare bis 2030. Zwölf Maßnahmen für den synchronen Ausbau von Netzen und Erneuerbaren Energien, Agora Energiewende, July 2018</td>
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<tr>
<td>AMP</td>
<td>Sektorenkopplung: Amprion und Open Grid Europe geben Power-to-Gas in Deutschland einen Schub, Pressemeldung Amprion, June 2018</td>
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ATW2 Holger Ludwig, Tatiana Salnikova, Ulrich Wass; Lastwechselfähigkeiten deutscher KKW, ATW 55, Jg (2010), Heft 8/9


BDEW1 Durchschnittliche Ausnutzungsdauer der Kraftwerke im Jahr 2007 in Stund- en, as of September 2010

BDEW2 Erneuerbare Energien und das EEG: Zahlen, Fakten, Grafiken (2013); BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., 31 January 2013


BDEW4 Redispatch in Deutschland – Auswertung der Transparenzdaten, BDEW Bundesverband der Energie- und wasserwirtschaft e.B., 9. August 2016


BMVI Räumlich differenzierte Flächenpotentiale für erneuerbare Energien in Deutschland. BMVI (Hrsg.), BMVI-Online-Publikation 08/2015.

BMW1 Gesamtausgabe der Energiedaten - Datensammlung des BMWi, as of Jan. 12. 2016

BMW3 Forschungsförderung für die Energiewende, Bundesbericht Energieforschung 2016, Bundesministerium für Wirtschaft und Energie (BMWi)


BMW5 EEG in Zahlen: Vergütung, Differenzkosten und EEG-Umlage 2000 bis 2018, as of October 2017

BMW6 Bundesbericht Energieforschung 2018, Bundesministerium für Wirtschaft und Energie (BMWi), June 2018

BNA1 Bundesnetzagentur legt Eigenkapitalrenditen für Investitionen in die Strom- und Gasnetze fest, Pressemitteilung der Bundesnetzagentur vom 2. November 2011

BNA2 https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEG_Registerdaten/EEG_Registerdaten_node.html


BSW Statistische Zahlen der deutschen Solarstrombranche (Photovoltaik), German
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<td>BSW-Solar</td>
<td>Solar Industry Association (BSW-Solar), Februar 2018</td>
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<td>EEG-Umlage</td>
<td>EEG-Umlage 2010, German Parliament, Scientific Services, No. 21/10, March 25, 2010</td>
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<td>Antwort der Bundesregierung</td>
<td>Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Oliver Krischer, Hans-Josef Fell, Bärbel Höhn, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN – printed material 17/10018 –</td>
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<td>DEWI</td>
<td>Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020, Studie im Auftrag der Deutschen Energie-Agentur GmbH (dena), February 2005</td>
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<td>DLR1</td>
<td>Externe Kosten der Stromerzeugung aus erneuerbaren Energien im Vergleich zur Stromerzeugung aus fossilen Energieträgern, Gutachten im Rahmen von Beratungsleistungen für das Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, May 2007</td>
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<td>DLR2</td>
<td>M. O'Sullivan (DLR), U. Lehr (GWS), D. Edler (DIW), Bruttobeschäftigung durch erneuerbare Energien in Deutschland und verringerte fossile Brennstoffimporte durch erneuerbare Energien und Energieeffizienz, Zulieferung für den Monitoringbericht 2015, Stand: September 2015</td>
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<td>ECOFY</td>
<td>Wolfgang Riecke, Bereitstellung von historischen Globalstrahlungsdaten für die Photovoltaik, Second Symposium on Energy Meteorology, April 2011</td>
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<td>ECOFY</td>
<td>Abschätzung der Kosten für die Integration großer Mengen an Photovoltaik in die Niederspannungsnetze und Bewertung von Optimierungspotenzialen, ECOFY, March 2012</td>
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<td>EEG</td>
<td>Gesetz zur Einführung von Ausschreibungen für Strom aus erneuerbaren Energien und zu weiteren Änderungen des Rechts der erneuerbaren Energien (EEG 2017), Bundesrat Drucksache 355/16, 08.07.16</td>
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<td>EEX</td>
<td>Positionspapier der European Energy Exchange und EPEX SPTO, February 2014</td>
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<td>ENER</td>
<td>E-Mobility-Zukunft: ENERVIE an Meilenstein-Projekt beteiligt, Pressemeldung, Südwestfalen Energie und Wasser AG, October 2018</td>
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<td>EPIA</td>
<td>EPIA Sustainability Working Group Fact Sheet, May 13, 2011</td>
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<td>FINA</td>
<td>CO2 European Emission Allowances, <a href="http://www.finanzen.net/rohstoffe/co2-emissionsrechte/Chart">http://www.finanzen.net/rohstoffe/co2-emissionsrechte/Chart</a>, finanzen.net GmbH, October 2018</td>
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<td>FÖS1</td>
<td>Externe Kosten der Atomenergie und Reformvorschläge zum Atomhaftungsrecht, Hintergrundpapier zur Dokumentation von Annahmen, Methoden und Ergebnissen, Green Budget Germany (Forum Ökologisch-Soziale Marktwirtschaft e.V.), September 2012</td>
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<td>FÖS2</td>
<td>Was Strom wirklich kostet - Vergleich der staatlichen Förderungen und ge-</td>
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<td>FVEE1</td>
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