Recent Facts about Photovoltaics in Germany

Last update: **February 18, 2019**

Compiled by
Dr. Harry Wirth
Division Director Photovoltaics
Modules and Power Plants
Fraunhofer ISE

Contact:
Karin Schneider
Press and Public Relations
Phone +49 761 4588-5147
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstrasse 2
79110 Freiburg
Germany
info@ise.fraunhofer.de

Citation note: Recent Facts about Photovoltaics in Germany, Fraunhofer ISE, download from [https://www.pv-fakten.de](https://www.pv-fakten.de), version of February 18, 2019
Table of Contents

Inhaltsverzeichnis

1 What purpose does this guide serve? ................................................................. 5
2 Are we reaching our annual capacity target? .................................................. 5
3 Does PV contribute significantly to the power supply? ................................. 5
4 Is PV power too expensive? ............................................................................ 6
  4.1 Levelized Cost of Energy ........................................................................... 7
  4.2 Feed-in Tariff ............................................................................................. 9
  4.3 Pricing on the energy exchange and the merit order effect ....................... 11
  4.4 Determining the Differential Costs ............................................................ 13
  4.5 Privileged Electricity Consumers ............................................................... 14
  4.6 EEG Surcharge .......................................................................................... 15
5 Subventions and Electricity Prices ................................................................ 17
  5.1 Is PV power subsidized? ............................................................................ 17
  5.2 Are fossil fuel and nuclear power production subsidized? ......................... 18
  5.3 Do tenants subsidize well-positioned home owners? ................................. 19
  5.4 Does PV make electricity more expensive for householders? ................. 19
  5.5 Does PV increase the electricity price for industry? ................................ 21
6 Are we exporting large amounts of PV power to other European nations? 22
7 Can new PV plants bring reasonable rates of return? ................................ 22
8 Does installing PV only create jobs in Asia? .................................................. 24
9 Are large energy suppliers interested in PV? ............................................... 25
10 Is PV research taking up high levels of funding? ........................................ 28
11 Does PV power overload our energy system? ............................................ 29
  11.1 Transmission and distribution ................................................................. 29
  11.2 Volatility .................................................................................................. 30
    11.2.1 Solar power production is predictable ................................................ 30
    11.2.2 Peak production is significantly lower than installed PV capacity ...... 31
    11.2.3 Solar and wind energy complement each other ............................... 31
  11.3 Controllability .......................................................................................... 33
  11.4 Conflicts with slow-response fossil and nuclear power plants ............... 33
  11.5 Does volatile solar power endanger security of supply? ....................... 35
11.6 Does the expansion of PV have to wait for more storage? ........................................35
12 Does the manufacture of PV modules consume more energy than they can produce? ............................................................................................................. 36
13 Is there enough space for PV in Germany? ................................................................. 36
14 Are PV plants in Germany efficient? ........................................................................... 36
14.1 Do PV plants degrade? .......................................................................................... 38
14.2 Can PV modules become soiled? ........................................................................... 38
14.3 Do PV plants often operate at full capacity? ......................................................... 38
15 Does PV make relevant contributions to climate protection? ......................... 40
15.1 Do anthropogenic CO$_2$ emissions danger the climate? ...................................... 40
15.2 Does PV make a significant contribution to reducing the CO$_2$ emissions? ....... 42
15.3 In addition to CO$_2$ are there other environmentally harmful gases released during the production of PV? ............................................................. 44
15.4 Do dark PV modules warm up the Earth through their absorption? .................. 44
16 Are PV systems capable of replacing fossil fuel and nuclear power plants? 45
17 Are we capable of covering a significant proportion of our energy demand with PV power? ........................................................................................................ 45
17.1 Energy demand and supply .................................................................................. 45
17.2 Energy scenarios .................................................................................................... 49
17.3 Compensatory measures ....................................................................................... 54
17.3.1 Keeping PV power production constant ......................................................... 54
17.3.2 Complementary operation of thermal power plants .................................... 55
17.3.3 Increasing the energy efficiency .................................................................... 56
17.3.4 Load management ........................................................................................... 56
17.3.5 Balanced expansion of PV and wind power capacities .................................. 58
17.3.6 Grid expansion ............................................................................................... 58
17.3.7 Combined heat and power solution .............................................................. 59
17.3.8 Electromobility .............................................................................................. 60
17.3.9 Energy storage ............................................................................................... 61
17.3.10 Overview ...................................................................................................... 64
17.4 Does the energy transition have to wait for federal policy? .................................. 67
18 Do we need PV production in Germany? ................................................................. 67
19 Does it still need a Renewable Energy Sources Act (EEG)? ............................... 68
20 Do PV modules contain toxic substances? ............................................................... 68
20.1 Wafer-based modules .......................................................................................... 68
20.2 Thin-film modules ............................................................................................... 68
20.3 Solar glass ........................................................................................................... 69
20.4 Take-back schemes and recycling ...................................................................... 69
21 Are there enough raw materials available for PV production? ...................... 69
  21.1 Wafer-based modules ........................................................................ 69
  21.2 Thin-film modules ........................................................................... 70
22 Do PV plants increase the risk of fire? ..................................................... 70
  22.1 Can defective PV plants cause a fire? ............................................... 70
  22.2 Do PV plants pose a danger to firefighters? ...................................... 71
  22.3 Do PV modules prevent firefighters from extinguishing fires externally from the roof? ................................................................. 71
  22.4 Are toxic emissions released when PV modules burn? ................. 71
23 Appendix: Terminology ........................................................................ 73
  23.1 EEG surcharge ................................................................................ 73
  23.2 Module efficiency ........................................................................... 74
  23.3 Rated power of a PV power plant .................................................... 74
  23.4 Specific yield .................................................................................. 74
  23.5 System efficiency ........................................................................... 74
  23.6 Performance ratio ........................................................................... 74
  23.7 Base load, intermediate load, peak load, grid load and residual load .... 75
  23.8 Gross and nets power consumption ................................................. 75
24 Appendix: Conversion tables [EEBW] .................................................. 76
25 Appendix: Abbreviations ...................................................................... 77
26 Appendix: Sources ................................................................................ 77
27 Appendix: Figures .................................................................................. 84
1 What purpose does this guide serve?
Germany is leaving the fossil-nuclear age behind, paving the way for photovoltaics (PV) to play a central 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?
The annual expansion target of the Federal Government was reached in 2018, but the goals of the energy transition are still far away.

In 2018, PV power plants with a rated output of 3.59 GW were installed in Germany [ISE4], compared to 1.66 GW in the previous year. Newly registered at the BNA were 2.96 GW [BNA2]. The new German Energy Collective Energy Act, which came into force on 1.1.2019, has lowered the annual expansion target (*breathing lid*) from 2.5 GW to 1.9 GW.

The German coalition agreement of March 2018 envisages increasing the share of renewable energies (RES) to 65 percent of gross electricity consumption by 2030. For this purpose, a steady annual PV expansion of about 5 GW is necessary [AGORA].

In order to cover our entire energy needs mainly from renewable energies, various model-based scenarios require around 120-290 GW of installed PV power, in addition to a number of other measures [ISE5, IWES2]. If we assume a PV expansion of 200 GW by 2050, then an average of 5 GW of PV will have to be added annually. Increasingly, old systems also have to be replaced. These replacement installations are currently negligible, however, they rise to just under 7 GW per year in a fully exploited condition assuming a useful life of 30 years. An even, annual increase of 5-7 GW would steadily support the desired state.

3 Does PV contribute significantly to the power supply?
Yes.
In 2018, PV-generated power amounted to about 46 TWh [ISE4] and covered approximately 8.7 percent of Germany’s net electricity consumption including grid losses, based on the consumption figures of the previous year [BDEW3]. Renewable energy as a whole (RE) accounted for ca. 43 percent (Figure 1). In terms of gross electricity consumption, the shares are approx. 7.7% for PV and approx. 38% for all RE. 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 2018, the total nominal PV power installed in Germany was ca. 45.9 GW, ([ISE4], installed capacity of all
subsidized PV systems, as of 2018-31-01) distributed over 1.6 million power plants [BSW].

Figure 1: Percentage renewable energy in net electricity consumption ([BMW1], [AGEE]) for Germany, data from [BDEW3]

4 Is PV power too expensive?

It depends on the reference point.

It is difficult to compare the costs of PV electricity with fossil and nuclear electricity since external costs incurred by environmental, climate and health damage as a result of scheduled or accidental pollutant emissions are not included. ([UBA3], [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.

Whether the dismantling of the nuclear power plants is covered by reserves of the operators, and whether the final disposal of radioactive waste costs no more than the € 23 billion that the state gets from the operators for the takeover of the German nuclear waste is not foreseeable today. Accidental damage in the operation of nuclear power plants up to € 250 million is covered by the insurance market, up to € 2.5 billion by an operator pool; in the case of major damage, the operators of the nuclear power plants are only liable with their assets [ATW1]. By comparison, the nuclear catastrophe in Fukushima caused damage of around € 100 billion, which is many times higher than the value of German nuclear power plant operators.
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 2018, approximately 500 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 installations 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], [BDEW6] and average compensation for PV power [BMWi5].

Depending on the system size, the feed-in tariff for small roof systems put into operation until April 2019 can be up to 11,11 €-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 the lowest mean value of 4.33 €-cts/kWh ever.

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. In constrast, 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 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 5). 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.

![Figure 5: Pricing on the European Energy Exchange EEX](image)
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 6). 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.)

Figure 6: Influence of RE on the average spot price on the energy exchange (EEX) [BDEW2].

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 6).

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.
4.4 Determining the Differential Costs

The remuneration for PV power feed in accordance with the German EEG is determined annually by the transmission system operators. 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 reduced the spot price until 2017 and thus increased the calculated differential costs.

![Figure 7: Development of the average spot electricity price and the calculated differential costs [BDEW2].](image)

Figure 8 shows the development of the differential costs for the remuneration of the PV electricity generated. After a strong increase until 2014, the amount stabilized between € 9 and 10 billion.
4.5 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 2018, almost half of industrial consumption was privileged (Figure 9). 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.

Figure 8: PV expansion and remuneration amount [BMWi1],[BMWi5]

Figure 9: Electricity consumption of industry and EEG surcharge 2019 [BDEW6]
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 benefitting 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.

4.6 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 2019, the EEG surcharge is set at 6.405 €-cts/kWh. End users must pay value added tax (19%) on this surcharge so that the costs imposed on private households increases to 7.62 €-cts/kWh.

![Figure 10: Influential parameters and calculating method for the EEG surcharge [ÖKO]](image-url)

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 in-
creasing amount of privileged consumers in energy-intensive industry and other measures have also contributed to this drift.

Figure 11: Development of the EEG surcharge and the EEG differential costs [ISE9]

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 4.3). 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 selective 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 4.4). The cumulative costs paid out for PV power fed into the grid up to and including 2017 amounted to ca. 73 billion euros.

To calculate the EEG surcharge, the financial benefits of PV power are determined according to the market clearing price. 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 4.3). 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. The differential cost decrease to zero and thereafter are negative.

In this way, the development of renewable energy will secure a long-term supply of energy at a reasonable cost, since it is clear that we cannot afford fossil and nuclear energy for much longer. Our industry needs a supply perspective, as do households.

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 power 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 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 and pass the burden on to future generations.

Contrary to initial plans, and with costs of 5-25 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). According to calculations by the Federal Environment Agency, however, the emission of one ton of CO₂ causes damage of around 180 euros. In terms of Germany’s greenhouse gas emissions in 2016, this corresponds to costs of around 164 billion euros [UBA3].

![Figure 12: Price of CO₂ allowances [BDEW6]](image)

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 Versicherungsforsen 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 21). 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: Components of the average domestic electricity price in 2019 (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 [BDEW6].

A typical household with an annual power consumption of 3,900 kWh pays an electricity price of approx. 30.22 €-cts/kWh in 2019 [BDEW6]. 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.

Figure 14: Development of gross domestic electricity prices (2017, estimated at 3% increase), net electricity prices for large-scale industrial consumers [BMW1] and the EEG surcharge; about 55% of the gross domestic electricity price is made up of taxes and fees.
In many European countries, the electricity price for private households is much lower than in Germany. However, taking into account the purchasing power of the countries, Germany is in the European midfield. Germany has a very high level of security of supply: in low-price countries such as Romania or Bulgaria, power cuts are common.

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 for medium-voltage customers has developed since 2009. Winners were the companies that can be exempted from the EEG surcharge (see VIK base index, Figure 15). The VIK Retail Price Index for non-privileged companies is well above the base index. This is mainly due to the EEG surcharge which makes up part of the final selling price.

![Figure 15: VIK electricity price index for medium-voltage customers [VIK]](image-url)
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.

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.

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 17.3).

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 23.4.) 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](image)

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 23.6) 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 de-
termined 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]. By comparison, according to a study by the Ökoinstitut, about 21,000 people still worked in lignite mining and lignite-fired power plants in 2015. 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.

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 energy suppliers interested in PV?

In 2016, the majority of Germany’s installed PV capacity belonged to private individuals, farmers and commercial businesses. The four big power plant operators EnBW, Eon, RWE and Vattenfall (called «big four” in Figure 18) 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 to stable 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 42). This lowers the market price of electricity on the EEX, which carries over to all plants presently producing electricity. (Section 4.3). 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 core replacement 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.

According to its own statement, EnBW focused on the energy turnaround in 2013 and, as of February 2019, operates PV systems with a total nominal output of 70 MW. At the beginning of 2019, EnBW announced plans to build the first PV power plant in Germany without EEG support. Specifically, this is a 175 MW project in Brandenburg [EnBW]. Vattenfall would also like to install PV systems on land from the lignite opencast mine in the Lausitz PV without EEG support.
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 19).

Figure 18: Division of ownership of the total installed capacity of PV plants at the end of 2016 [AEE3].

Figure 19: 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 20 shows that it took time for renewable energy and energy efficiency to become a focal point of energy research. Figure 21 shows the funding granted for PV research by the federal ministries.

Figure 20: Germany’s expenditure in the Energy Research Program of the Federal Government by topic in € million [BMWi6].

Figure 21: 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.

![Diagram](image)

Figure 22: 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, redispatching measures will be increasingly required in the foreseeable future. Redispatching 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 redispatch) or to carry out fixes (curative redispatch). Before a bottleneck occurs, the energy feed-in is reduced (negative redispatch) and afterwards increased (positive redispatch) [BDEW4]. In 2017, the total cost of redispatch measures amounted to €1.4 billion.

![Figure 23: 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 24). 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 PV 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 25.

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 in Germany correlate negatively on all time scales of hours to months. On an hourly basis, with an installed capacity of 42 GW of PV and 56 GW of wind power at the end of the year, in total only rarely more than 45 GW of power was connected to the grid in 2017 (Figure 25).
Figure 25: Average power for the supply of solar and wind power in 2017, 15-minute values [ISE4].

Figure 26 shows the PV and wind power production for Germany in 2017 on an hourly basis. While the installed capacity of PV and wind at the end of the year was approximately 98 GW, only 3% of the electricity production was above a capacity of 30 GW.

Even on a daily basis, the combination of PV and wind power leads to a stabilization of the yield. While the relative mean absolute deviation of the daily flow production from the arithmetic mean in 2017 was 58% for PV and 56% for wind, the value for PV and wind was only 38%.

Figure 27: Monthly production of PV and wind power for 2014 - 2017 [ISE4]. Figure 27 shows the monthly values of electricity production from PV, wind power and their total, as well as the respective linear trend lines for the years 2014 - 2017. The relative deviations from the trend line for PV and wind in total are significantly lower than for the individual sectors.
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, cannot 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]](image-url)
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]

11.6 Does the expansion of PV have to wait for more storage?
No, not in the next few years.
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 more energy than they can produce?

No. The Energy Returned on Energy Invested (ERoEI or EROI) describes the relationship between the energy provided by a power plant and the energy spent on its construction. Energy payback time or energy payback time indicates the amount of time a power plant must run to provide the amount of energy invested.

Harvest factor and energy payback time of PV plants vary with technology and plant location. A recent study from 2017 [RAUG] found a harvest factor of 9-10 for PV power plants with wafer-based modules based on measured PV yields from Switzerland and an assumed lifetime of 25 years, corresponding to an energy payback period of 2.5 - 2.8 years. Wind power plants have significantly shorter energy payback times, usually less than a year.

13 Is there enough space for PV in Germany?

Yes, without any significant use of arable land. A study commissioned by the Federal Ministry of Transport and Digital Infrastructure estimates that the expansion potential of non-restriction open spaces is more than 3000 km² of land, corresponding to 143 GW PV [BMVI]. A study by the Federal Environmental Agency assumes a further 275 GW rated output, which can be installed on roofs, facades and other settlement areas [UBA].

Under the heading "Agrophotovoltaic" (APV), various approaches are being tested in order to use land at the same time for food and electricity production [Beck]. A number of crops show low to no yield loss under reduced irradiation, others even benefit. With an occupancy of only 1% of the arable land with APV an additional potential of 80 GW becomes usable. In total, there is an area potential for PV in the order of 500 GW.

14 Are PV plants in Germany efficient?

The nominal efficiency (see section 23.2) 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).](image)

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 23.3). 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].
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 23.6) 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 17.3.1)
- 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. Increasing global warming has been proven beyond doubt [IPCC]. Compared to the pre-industrial age, the mean global temperature has risen by 0.8° C [IEA2]. The vast majority of the scientific community believe that anthropogenic emissions of CO₂ and other
greenhouse gases significantly increase the growth of atmospheric greenhouse gas concentrations and, moreover, cause the increase of the average global temperature to become extremely likely. In May 2013, the atmospheric CO$_2$ 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 CO$_2$ concentration and the global, or rather Antarctic, temperature.

![Figure 33: Development of the atmospheric CO$_2$ concentration and the mean global temperature change based on the NASA Global Land-Ocean Temperature Index [IEA2].](image)

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.  
In 2017, the use of PV in Germany avoided around 24 million tons of greenhouse gas emissions (Figure 35).
Germany’s energy policy has influence on a global scale. Although less than three percent of the global electricity consumption was due to Germany (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 closely observed around the world. It has been used by dozens countries 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 35: Greenhouse gas emissions avoided by using renewable energy in 2017 [UBA1]
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 percent. (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 Fehler! Verweisquelle konnte nicht gefunden werden.), the al-
bedo 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 17.3.7).

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 transformation.

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 their consumption through simple heat protection measures.
Germany is highly dependent on energy imports (Figure 38) combined with the risk of political interference by mining 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 2017 for Germany in petajoules [AGEB2].

*) 1 million metric tonnes of coal equivalent (MtoE) = 29.308 petajoules (PJ)

Differences from the total amounts are due to rounding.
The total proportion of renewable energy sources of the primary energy consumption is 13.4 %.
### Table: Net Import Rate 2016 (Based on Primary Energy Consumption)

<table>
<thead>
<tr>
<th>Fuels</th>
<th>Net Import Rate 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown coal</td>
<td>-1.9 %</td>
</tr>
<tr>
<td>Hard coal</td>
<td>94.1 %</td>
</tr>
<tr>
<td>Uranium</td>
<td>100 %</td>
</tr>
<tr>
<td>Mineral oil</td>
<td>100 %</td>
</tr>
<tr>
<td>Natural gas</td>
<td>91.2 %</td>
</tr>
</tbody>
</table>

**Figure 38:** Germany’s import quotas for fossil and nuclear energy sources (www.umweltbundesamt.de)

The costs of energy imports are shown in Figure 39, minus their import revenues, which are around 50-100 billion euros per year. Much of the money goes to autocratic regimes.

![Cost Development Graph](image)

**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 TWh of final energy is used annually [BMWi1].
The electricity load fluctuates periodically: more electricity is needed during the day than at night, and on weekdays more than on weekends and public holidays. Electricity providers differentiate in the load profile between basic, medium and peak load, see Section 23.7. The base load is the load share of 30-40 GW, which barely changes over 24 hours. The intermediate load fluctuates slowly and predominantly periodically, the peak load comprises the rapidly changing load portion above the basic and intermediate load. Electricity consumption and the energy needed for hot water is slightly lower in summer than in winter. The heating demand correlates negatively with global irradiance, with the highest point of intersection being found in spring.

### 17.2 Energy scenarios

Our current energy system in Germany, 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 [UBA, ACA, ISE5].

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 41). 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]. A balanced bottom line was assumed for cross-border electricity trading.

**Figure 40: Share of final energy in Germany, categorized by utilization 2014 [BMWi4]**

![Energy Composition Diagram](image)

- **Space heating**: 27%
- **Mechanical energy**: 39%
- **Other process heat**: 22%
- **Hot water**: 5%
- **Air cooling**: 0%
- **Other process cooling**: 2%
- **ICT**: 2%
- **Lighting**: 3%

190218_Recent_Facts_about_PV_in_Germany.docx
Figure 41: Scenario of a German energy system, schematic representation of the system composition. [ISE5]

Figure 42 shows a schematic residual load curve for Germany with a 100% renewable power supply. Shown are the descending ordered hourly values of the residual load for one year. The residual load is the difference between the irreducible electricity load and the total 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. An electricity price with a useful control function would tend to fall from left to right in the illustration in Figure 42, and approach negative values at the right-hand edge, where it comes to a reduction.
On the demand side, load management and current-regulated generators such as the discharge of batteries and pumped storage, the operation of fuel cells, gas and steam generators, gas turbines and gas engines are activated in order of their marginal costs to cover the residual load. For a few hours a year, the residual load reaches its maximum (left side of Figure 42), for example, in case of lack of wind over large areas, in connection with darkness or closed snow cover. In these periods, all controllable power generators are at maximum reduced load on the grid, even the less efficient, simple gas turbines. Simple gas turbines and CCG burn hydrogen or methane from renewable sources to produce electricity. With sufficient utilization, they are designed as CHP generators and produce not only electricity but also heat.

On the surplus side, the current-carrying consumers, such as flexible loads, charging of batteries and pumped storages, the operation of electrolyzers, heat pumps and heating elements, are activated in order of economic efficiency with decreasing electricity prices to absorb the current that is not required. Gas turbines in CHP operation and heating elements can also provide high temperature heat for industrial processes.

In order to be able to operate heat-generating converters (Figure 42) on both sides of the curve in a current-regulated manner, they require thermal storage and heat consumers close to the location or a connection to heat distribution networks (Section 17.3.7). When power is needed, the operation of heat pumps or even heating rods should be avoided because inefficient and expensive. High-temperature heat for industrial processes can provide gas turbines in CHP operation when power is needed, but in the case of excess electricity, these are heating elements.

The electrolytically generated hydrogen can be stored in the gas network. In some cases a reconversion (gas turbine, gas, CHP, mobile / stationary fuel cell) takes place, as well as in some cases a methanation and further processing to synthetic fuels and raw materials for the chemical industry are carried out from the gas network.
Generators (e.g., simple gas turbines) and consumers (e.g., heating rods) with particularly low investment-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. Ultima ratio is the regulation of electricity production, if the energy demand is not sufficient for a few hours of the year. This can occur, for example, on stormy nights or on sunny and at the same time 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.

Because of their limited capacity, batteries and pumped storage drop out relatively fast in continuous operation as network operators (from minutes to a few hours), and so do many options for load management. Their benefit is the frequent change of operation between loading and unloading, which they implement quickly and efficiently. Vehicle batteries can only be charged to a limited load (load management) or operated bidirectionally as a battery in the network (storage), because they primarily have to meet the demand for mobility. Nevertheless, many millions of grid-connected electric vehicles can bidirectionally support the power grid for a few hours.

The storage capacity of the system must be designed for the worst case of a multi-week primary energy failure (sun, wind), for example, a prolonged lack of wind in winter. For this purpose, appropriate quantities of hydrogen and derived synthetic energy carriers and raw materials must be provided. The power generation capacity of the system must be able to take over the complete power supply whenever the hourly reserves (load management, pumped storage, battery) are exhausted. These are typically windless nights to several weeks of primary energy failure.

On the right side of Figure 42, the surplus power side, much more energy is converted than on the demand side due to a variety of reasons: electricity production also produces heat, the transport sector consumes electricity, and raw materials for the chemical industry (e.g., methane for polymers) are produced.

The power generation (left side of Figure 42) must provide enough power to take over the entire power supply when the hourly reserves (load management, pumped storage, battery) are exhausted. These are typically windless nights to several weeks of primary energy failure. On the right side of Figure 42, more energy is consumed than on the demand side because electricity production also generates heat, the transport sector consumes electricity and raw materials are produced for the chemical industry (e.g., methane for polymers).

A quick glance at global energy scenarios: The study “Shell Scenarios Sky - Meeting the goals of the Paris Agreement” by Shell International B.V. from March 2018 considers PV to be the world’s most important source of renewable energy (Figure 43). Global electricity consumption will rise from 22 PWh today to 100 PWh in 2100.
The International Energy Agency (IEA) has been trying for many years to predict the global expansion of PV (colored curves in Figure 44) and reliably underestimates the actual development (black curve).

Figure 43: Development of global power generation by technologies in the Sky-Scenario; the diameter of the pie charts corresponds to the global power requirement [Shell]

Figure 44: Forecasts of IEA and actual development of global annual PV construction (https://twitter.com/AukeHoekstra)
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? A constant level in the daily run reduces the compensation required, for example, through load management and batteries. One of the simplest approaches is the installation of roof- and ground-mounted PV modules with east/west orientation (Figure 43). This type of installation reduces the area consumption, but the specific annual yield per installed module capacity decreases compared with the south orientation. Single and dual-axis tracking systems not only make power production more constant throughout the day (Figure 43), they also increase the specific annual yield by approx. 15-30%. Compared to stationary systems, they can also reduce yield losses caused by snow cover or increased operating temperatures. Another option is vertically mounted, bifacial modules with north-south gradient, which provide more electricity in the morning and afternoon than at noon.

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.

The very pronounced seasonal fluctuation in PV power generation can be minimized by mounting south-facing modules with higher angles of inclination (Figure 45). As a result, the electricity yield in the winter half-year increased slightly, but at the cost of larger losses in the summer and in the total yield (in the calculation example -6%).
The slightly higher costs of electricity production for the alternative installation variants mentioned above can already be amortized in the context of increased self-consumption and the associated savings in electricity purchases, especially for commercial customers. Feed-in tariffs, which reward a higher value of electricity in the morning and evening hours, promote the construction of systemically advantageous PV power plants, which are not only optimized for maximum annual electricity yield. The measures to increase the number of full-load hours mentioned in section 14.3 also contribute to the stability of the PV electricity supply.

17.3.2 Complementary operation of thermal 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 47). 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 % [UBA2]. Simple 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 residual load 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.

Today, gas-fired power plants burn natural gas and biogas. Most of the natural gas must be imported (about 95% in 2017 [AGEB6]), in particular, Russia and Norway deliver to Germany. As part of the energy transformation, gas power plants will switch from natural gas to electrolytically generated hydrogen and methane.
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 TWh of production in 2017 [ISE4], there is little scope for these levels to be improved on in the future.

Depending on the type, biomass power plants can burn solid biomass (waste wood), liquid biomass (vegetable oil) or biogas (from agriculture or sewage treatment plants). At the end of 2017 biomass power plants with 7.4 GW output were installed across Germany [ISE4]. Power plants that burn solid or liquid biomass can be operated very easily guided due to the simple storage of fuel. Restrictions exist in biogas power plants, if the fermentation throughput can only be controlled to a limited extent and also the gas cannot be stored in the gas network. Economically, a complementary partial load operation is feasible if the feed-in tariff rises at times of increased electricity demand.

17.3.3 Increasing the energy efficiency

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 twice as much electricity as a comparable house with energy saving devices [TEST]. Especially effective are measures that reduce the nighttime electricity consumption, when solar power (and in windless nights even wind power) can be provided only by comparatively complex storage.

17.3.4 Load management

Load management ("Demand Side Management") allows an active, temporary shift of power consumption, without affecting the long-term consumption. Electricity consumption by households (Figure 48), 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 may also start delayed, must be technically enabled with appropriate approval by the user, to wait for the core time of the day when PV power production usually reaches its maximum value. This often includes washing machine, tumble dryer or dishwasher in the household. Cooling and air conditioners that have a significant thermal storage and a refrigerating unit with sufficient capacity can charge their cold storage in the core days’ time. The same applies to cold stores and food markets. Thermal storage capacity can be provided at relatively low cost compared to power storage devices such as batteries.

![Diagram](image)

**Figure 48: Energy consumption of an average household in Germany, not including hot water production [RWE].**

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. Often, 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. Electric heat generation in conjunction with thermal storage offers considerable potential for load management (Section 17.3.7), as does electromobility (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. If it is possible to keep the installed capacities for PV and wind power on the same scale, their combination reduces the need for equalization.

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. If you theoretically upscale the PV and wind power installed in 2017 with their hourly power production to 200 GW each, then the production curve from Figure 49 results.

![Figure 49: Fictitious annual electricity production (8760 hours) for 200 GW PV and 200 GW wind, extrapolated on the basis of installation and yield data for 2017](image)

In the dark and low wind, the production is close to 0. The amount of energy above 200 GW is below 1 per thousand, above 150 per cent below 1 per cent. If one ignores these storm peaks and one assumes a permanent power consumption of at least 50 GW, then a bandwidth of approx. 100 GW remains, for which technical solutions are needed for their integration.

On a monthly basis, the sum of PV and land wind power production over the year is more balanced than the output of the two sectors alone (Figure 27).

17.3.6 Grid expansion

17.3.6.1 National grid expansion
Studies conducted by Fraunhofer IWES and ECOFYS on behalf of the BSW have shown that an expansion of installed PV capacity to 70 GW by 2020 shall incur costs of this grid expansion of approximately 1.1 billion euros [IWES1], [ECOFYS]. The corresponding annual costs amount to approximately 10% of the routine annual expenditure for network upgrading. Consideration was given to expansion in the low-voltage grid with PV sys-
tems providing system services (e.g., voltage maintenance through reactive power compensation) and partial equipment of grid transformers with control equipment.

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.

<table>
<thead>
<tr>
<th>Capacity of hydroelectric power plants [MW]</th>
<th>AT</th>
<th>CH</th>
<th>DE</th>
<th>NO</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Hydro storage power plants</td>
<td>3,744</td>
<td>8,078</td>
<td>335</td>
<td>23,405</td>
<td>10,802</td>
</tr>
<tr>
<td>- Pumped-storage</td>
<td>3,781</td>
<td>1,839</td>
<td>6,521</td>
<td>1,344</td>
<td>108</td>
</tr>
<tr>
<td>- Run-of-river power plants</td>
<td>5,395</td>
<td>3,810</td>
<td>2,934</td>
<td>6,255</td>
<td>5,825</td>
</tr>
</tbody>
</table>

Figure 50: 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 at a high temperature level, are still largely obtained 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 preferably obtained from the waste heat of converters, in times of surplus electricity via heat pump and heating element (Figure 42).

Large heat storage capacities for low-temperature heat enable the current-controlled operation of the converters. Once converted to low-temperature heat, energy can be
stored efficiently and inexpensively (Section 17.3.9.1). However, if there is a lack of generously dimensioned thermal storage, then the thermosensitivity of the electricity load increases and larger power reserves must be maintained in power plants. Larger heat accumulators are connected to heat distribution networks. The expansion of heat distribution networks is much more limited by distance-dependent transport losses than in the electricity sector. Therefore, plants with electricity-heat coupling (Figure 42) have to be tailored in their performance and placement to the local heat consumption and existing or realizable heat networks. These can be local heating networks with heat transport between neighboring buildings or district heating networks that supply neighborhoods or entire cities.

High-temperature heat for industrial processes can be obtained from the waste heat of CHP gas turbines (up to approx. 550 °C) when electricity is needed, and when there is an excess of electricity with heating rods.

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 in terms of very low electricity.

In Germany, at the end of 2014, about 33 GW of electrical CHP power was connected to the grid [ÖKO2], which mainly uses natural gas, biomass and coal. CHP plants achieve overall efficiencies of up to 90%, and gas CHPs as much as 95% [UBA2]. 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 transformation progresses, CHP plants are being converted from fossil fuels to hydrogen and methane, with some still burning biomethane / biomass.

17.3.8 Electromobility

Electric vehicles use highly efficient motors (efficiency > 90%), and can recover a large part of braking energy (recuperation). Electric vehicles need batteries as electrochemical energy storage (battery electric vehicle, BEV), possibly supported by a fuel-cell internal combustion engine (plug-in hybrid electric vehicle, PHEV) or a fuel cell with hydrogen tank (fuel cell vehicle).

Vehicles with electric drive systems use highly efficient engines (efficiency> 90%), and can recover a large part of braking energy (recuperation brake). Electric vehicles need batteries as electro-chemical energy storage (battery electric vehicle, BEV), possibly supported by a combustion engine with fuel tank (plug-in hybrid electric vehicle, PHEV) or a fuel cell with hydrogen tank (fuel cell vehicle).

E-vehicles, in their role as consumers, can contribute to load management if the charging of their battery is power-driven if permitted by the vehicle use. In order to fill up
with PV power, they must find charging stations at the parking spaces used during the day, eg at the workplace, in parking garages or at public car parks. Crucial for the mobilization of the potential is the availability of price signals in real time and as a forecast. This will allow e-logistics companies to take into account cheap charging times in their route planning, as well as private persons in their charging stops.

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. Calculated, the total vehicle power of all cars registered in Germany in 2017 of 630 billion km [KBA] corresponds to an annual electricity consumption of e-vehicles in the order of 70 TWh. The number of 46 million cars [KBA] corresponds to a total storage capacity of the order of 1.8 TWh, with 40 kWh of battery storage per vehicle.

By 2020, one million electric cars should have been registered in Germany according to earlier plans of the Federal Government. With a charging power of approx. 40 kW per vehicle in fast-charging mode, 25,000 vehicles can already provide one gigawatt of bidirectionally controllable power for the primary, secondary and minute reserves on the power grid. However, the energy transformation in individual transport starts on two wheels: At the end of 2017 several million e-bikes sold in Germany faced only 69,000 pure electric cars (BEV) [NPE].

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. The same storage can be loaded simultaneously, for example, at high power surplus via heat pump and heating rod, in electricity demand by a CHP. 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. Large storage tanks (from several thousand m³) can be operated as seasonal heat storage (http://www.saisonalspeicher.de). They enable the transfer of useful heat from the summer to the winter half-year with its much higher heat requirement (Figure 41).

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. Elaborate high-
temperature heat accumulators, which are loaded by means of heating rods and used in CHP systems, enable the partial recovery of electricity [VATT].

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 51). In August 2018, the number of PV stores exceeded 100,000 in Germany.

![Graph showing 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.](image)

**Figure 51:** 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]

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 52). 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]

Pilot projects are also currently investigating the storage of electrical energy in large, stationary batteries [RWE2].
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 (Section 17.3.8). Pilot projects are currently investigating the storage of electrical energy in large, stationary batteries [RWE2].

As semi-flexible power consumers, electric vehicles are not only predestined for load management (Section 17.3.8); they will also act bidirectionally as carriers of battery storage systems [ENER]. Electric vehicles, which are currently connected to the network and do not have to keep the full range as a driving readiness, can be operated with the appropriate technical equipment as a power-current storage. With 10 million vehicles on the grid, each with 20 kWh of disposable capacity (with 40 - 60 kWh total capacity per vehicle), a battery capacity of 200 GWh is combined. Private cars park on average about 23 hours a day, even the limited capacity of traffic routes forces most cars to stop most of the time. Electric vehicles connected to the network can also generate economic benefits from their batteries even when stationary, unlike their predecessors with combustion engines.

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 transformation.
The storage of electrical energy in compressed air accumulators (adiabatic 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 via fuel cells or thermal power plants, 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. Reversible high-temperature electrolysers, which can also be operated as fuel cells, are currently being tested [salt].

### 17.3.10 Overview

Figure 53 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.

---

**Figure 53: Possible ways of converting and storing PV power with data on efficiencies**
From today’s perspective, an energy system based on almost 100% renewable energy is technically and economically feasible. Figure 54 shows the main elements connected to the grid, from extraction to transformation and storage to consumption. In order to reduce the storage requirements, the power consumption in households and industry is made more flexible sometimes. ICT stands for information and communication technology. The dashed boxes indicate that currently very low power (of converters) or capacities (in storages) are available.

Figure 54: Simplified scheme of a Renewable Energy System with the most important grid-related components of the categories production, conversion, storage and consumption.

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 collection density permits, for example in neighborhoods, efficient storage takes place centrally in large heat storage facilities.

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 turbines, fuel cells and, if demand peaks occur, even pure gas turbines are used. Hydrogen
electric vehicles refuel their fuel from stationary gas storage, vehicles for long distances (especially aircraft) refuel liquid synthetic fuels.

In the "battery" sector (black), stationary, central or decentralized electrochemical stores 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.

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 stabilizing 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. Thermal storage, local and district heating networks are being expanded.
5. PV systems and electric vehicles are provided with relevant network storage batteries.
6. Pumped storage performance and capacity are being expanded.
7. For the power utilization of occasional EE current peaks low-cost (€/W) heating rods are built into thermal storage.
8. For the power utilization of frequent excess electricity surges, electric heat pumps with feed-in into thermal storage are constructed.
9. Low-cost (€/W) gas turbines are built to cover occasional residual load peaks (eg from the recycling of aircraft turbines)
10. To cover frequent residual load gaps, efficient CCGT/CHP power plants with feed-in into thermal storage are set up
11. Existing coal-fired power plants will, if possible, be optimized for flexible operation, otherwise shut down.
12. 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.

17.4 Does the energy transition have to wait for federal policy?

No, even though federal politics can make things easier for everyone. In Germany the Bundestag, as legislator in Germany, sets the framework for the energy transformation. In addition, there are a number of important players who can make a difference in their fields of action, regardless of the regulatory framework. Support of these actors sends thus clear signals in the policy.

Consumers can demand renewables and energy efficiency from sources of electricity and heat, their choice of means of transport and their overall consumption. Investors are required to invest in the energy transition, be it on their own roof, in investment companies or funds. Decision-makers in commercial and industrial companies or municipal utilities can examine which measures are sustainable and at the same time advance the energy transition. Finally, federal states, cities and municipalities can promote the energy transition through a plethora of measures, from advising the stakeholders to promoting pilot projects, providing space and making investment decisions.

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. Despite the slowdown in national expansion of Germany’s solar market, the German PV sector with its material manufacturers, engineers, component manufacturers, 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 Does it still need a Renewable Energy Sources Act (EEG)?

Yes, with focusing on the energy transformation process.

Once the 52 MW limit has been reached, it will no longer be possible to subsidize new PV installations under the current EEG. The current market mechanisms would provide too little incentive for long-term investment in the energy transition without the support of the EEG or a successor. One of the main reasons is the sectoral gaping pricing of CO$_2$ emissions, which fluctuates with the stock market and is much too low overall. A socially balanced national carbon tax, such as that introduced in Sweden in 1991 and in Switzerland in 2008 as a "tax levy", can bridge these shortcomings.

As a rule, PV power plants of all sizes require a grid connection in order to deliver electricity that can neither be consumed on site nor saved economically. A legal framework must move the network operator to an uncomplicated connection.

Furthermore, PV power plants require a guaranteed long-term electricity purchase at a minimum price. This concerns electricity volumes that exceed the owner’s self-consumption or the storage capacity of the owner, or situations in which contractual customers, for example, fail due to insolvency. In view of the expected further decline in the cost of electricity generated by PV and the increasing PV power supply in the middle of the day, PV investments would otherwise be deferred (deflation effect).

20 Do PV modules contain toxic substances?

That depends on the technology and materials used.

20.1 Wafer-based modules

The silicon wafer-based modules (more than 90 percent of the market share) 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). 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. Some module manufacturers use backsheets containing fluoropolymers, for example polyvinyl fluoride.

20.2 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...
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.

20.3 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 of light 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.

20.4 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 had to 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.

21 Are there enough raw materials available for PV production?
21.1 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 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.
21.2 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.

22 Do PV plants increase the risk of fire?
22.1 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]

22.2 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]

22.3 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.

22.4 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 [LFU1]. 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 [LFU2].
23 Appendix: Terminology

23.1 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 calcu-
23.2 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.

23.3 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.

23.4 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.

23.5 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.

23.6 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.

23.7 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]

23.8 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.
24 Appendix: Conversion tables [EEBW]

Vorsätze und Vorzeichen

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>Kilo</td>
<td>(10^3)</td>
<td>Tausend</td>
</tr>
<tr>
<td>M</td>
<td>Mega</td>
<td>(10^6)</td>
<td>Million (Mio.)</td>
</tr>
<tr>
<td>G</td>
<td>Giga</td>
<td>(10^9)</td>
<td>Milliarde (Mrd.)</td>
</tr>
<tr>
<td>T</td>
<td>Tera</td>
<td>(10^{12})</td>
<td>Billion (Bll.)</td>
</tr>
<tr>
<td>P</td>
<td>Peta</td>
<td>(10^{15})</td>
<td>Billiarde (Brd.)</td>
</tr>
</tbody>
</table>

Umrechnungen

<table>
<thead>
<tr>
<th></th>
<th>PJ</th>
<th>GWh</th>
<th>Mio. t SKE</th>
<th>Mio. t RÖE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 PJ</td>
<td>Petajoule</td>
<td>1</td>
<td>277.78</td>
<td>0,034</td>
</tr>
<tr>
<td>1 GWh</td>
<td>Gigawattstunde</td>
<td>0,0036</td>
<td>1</td>
<td>0,00012</td>
</tr>
<tr>
<td>1 Mio. t SKE</td>
<td>Mio. Tonnen Steinkohleinheit</td>
<td>29,31</td>
<td>8,141</td>
<td>1</td>
</tr>
<tr>
<td>1 Mio. t RÖE</td>
<td>Mio. Tonnen Röhleinheit</td>
<td>41,87</td>
<td>11,630</td>
<td>1,43</td>
</tr>
</tbody>
</table>

Typische Eigenschaften von Kraftstoffen

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiesel</td>
<td>0,88</td>
<td>10,3</td>
<td>9,1</td>
<td>37,1</td>
<td>32,8</td>
</tr>
<tr>
<td>Bioethanol</td>
<td>0,79</td>
<td>7,4</td>
<td>5,9</td>
<td>26,7</td>
<td>21,1</td>
</tr>
<tr>
<td>Rapsöl</td>
<td>0,92</td>
<td>10,4</td>
<td>9,6</td>
<td>37,6</td>
<td>34,8</td>
</tr>
<tr>
<td>Diesel</td>
<td>0,84</td>
<td>12,0</td>
<td>10,0</td>
<td>43,1</td>
<td>35,9</td>
</tr>
<tr>
<td>Benzin</td>
<td>0,76</td>
<td>12,2</td>
<td>9,0</td>
<td>43,9</td>
<td>32,5</td>
</tr>
</tbody>
</table>

Typische Eigenschaften von festen und gasförmigen Energieträgern

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Steinkohle</td>
<td>-</td>
<td>8,3 - 10,6</td>
<td>-</td>
<td>30,0 - 36,1</td>
<td>-</td>
</tr>
<tr>
<td>Braunkohle</td>
<td>-</td>
<td>26 - 62</td>
<td>-</td>
<td>0,2 - 22,2</td>
<td>-</td>
</tr>
<tr>
<td>Erdgas H (in m³)</td>
<td>0,76</td>
<td>11,6</td>
<td>8,8</td>
<td>41,7</td>
<td>31,7</td>
</tr>
<tr>
<td>Heizöl EL</td>
<td>0,86</td>
<td>11,9</td>
<td>10,2</td>
<td>42,8</td>
<td>30,8</td>
</tr>
<tr>
<td>Biogas (in m³)</td>
<td>1,20</td>
<td>42 - 63</td>
<td>5,0 - 7,5</td>
<td>15,0 - 22,5</td>
<td>18,0 - 27,0</td>
</tr>
<tr>
<td>Holzpellets</td>
<td>0,65</td>
<td>4,9 - 5,4</td>
<td>3,2 - 3,5</td>
<td>17,5 - 18,5</td>
<td>11,4 - 12,7</td>
</tr>
</tbody>
</table>
25 Appendix: Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<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>
</tr>
<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>W_p</td>
<td>Watt peak – rated power of a PV module or array</td>
</tr>
</tbody>
</table>

26 Appendix: Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACA</td>
<td>Sektorkopplung – Optionen für die nächste Phase der Energiewende, acatech – Deutsche Akademie der Technikwissenschaften e. V. (Federführung), November 2017</td>
</tr>
<tr>
<td>AEE1</td>
<td>Metaanalyse: Digitalisierung der Energiewende, Agentur für Erneuerbare Energien, August 2018</td>
</tr>
<tr>
<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>
</tr>
<tr>
<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>
</tr>
<tr>
<td>AGEB2</td>
<td>Energieflussbild für die Bundesrepublik Deutschland in Petajoule, AGEB, May 2018</td>
</tr>
<tr>
<td>AGEB6</td>
<td>Energieverbrauch in Deutschland in Jahr 2017, AGEB, February 2018</td>
</tr>
<tr>
<td>AGEE</td>
<td>Monatsbericht zur Entwicklung der erneuerbaren Stromerzeugung und Leistung in Deutschland, Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat), December 2018</td>
</tr>
</tbody>
</table>
| AGO    | Stromnetze für 65 Prozent Erneuerbare bis 2030. Zwölf Maßnahmen für den
<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>Synchronen Ausbau von Netzen und Erneuerbaren Energien, Agora Energiewende, July 2018</td>
</tr>
<tr>
<td>AMP</td>
<td>Sektorenkopplung: Amprion und Open Grid Europe geben Power-to-Gas in Deutschland einen Schub, Pressemeldung Amprion, June 2018</td>
</tr>
<tr>
<td>ATW2</td>
<td>Holger Ludwig, Tatiana Salnikova, Ulrich Wass; Lastwechselfähigkeiten deutscher KKW, ATW 55, Jg (2010), Heft 8/9</td>
</tr>
<tr>
<td>BDEW1</td>
<td>Durchschnittliche Ausnutzungsdauer der Kraftwerke im Jahr 2007 in Stunden, as of September 2010</td>
</tr>
<tr>
<td>BDEW2</td>
<td>Presentation „Erneuerbare Energien EEG_2017“, BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., July 2017</td>
</tr>
<tr>
<td>BDEW3</td>
<td>Entwicklung des Nettostromverbrauchs in Deutschland, BDEW, February 2018 (<a href="https://www.bdew.de/service/daten-und-grafiken/entwicklung-nettostromverbrauch-deutschland/">https://www.bdew.de/service/daten-und-grafiken/entwicklung-nettostromverbrauch-deutschland/</a>)</td>
</tr>
<tr>
<td>BDEW4</td>
<td>Redispatch in Deutschland – Auswertung der Transparenzdaten, BDEW Bundesverband der Energie- und wasserwirtschaft e.B., August 9, 2016</td>
</tr>
<tr>
<td>BDEW6</td>
<td>BDEW-Strompreisanalyse Januar 2019 - Haushalte und Industrie, BDEW, Januar 2019</td>
</tr>
<tr>
<td>BMVI</td>
<td>Räumlich differenzierte Flächenpotentiale für erneuerbare Energien in Deutschland. BMVI (Hrsg.), BMVI-Online-Publikation 08/2015.</td>
</tr>
<tr>
<td>BWi1</td>
<td>Gesamtausgabe der Energiedaten - Datensammlung des BMWi, last update: 04.10.2017</td>
</tr>
<tr>
<td>BWi3</td>
<td>Forschungsförderung für die Energiewende, Bundesbericht Energieforschung 2016, Bundesministerium für Wirtschaft und Energie (BMWi)</td>
</tr>
<tr>
<td>BWi5</td>
<td>EEG in Zahlen: Vergütung, Differenzkosten und EEG-Umlage 2000 bis 2018, as of October 2018</td>
</tr>
<tr>
<td>BWi6</td>
<td>Bundesbericht Energieforschung 2018, Bundesministerium für Wirtschaft und Energie (BMWi), June 2018</td>
</tr>
<tr>
<td>Ref</td>
<td>Description</td>
</tr>
<tr>
<td>-----</td>
<td>-------------</td>
</tr>
<tr>
<td>BNA1</td>
<td>Bundesnetzagentur legt Eigenkapitalrenditen für Investitionen in die Strom- und Gasnetze fest, Pressemitteilung der Bundesnetzagentur vom 2. November 2011</td>
</tr>
<tr>
<td>BSW</td>
<td>Statistische Zahlen der deutschen Solarstrombranche (Photovoltaik), German Solar Industry Association (BSW-Solar), Februar 2018</td>
</tr>
<tr>
<td>Bundestag</td>
<td>EEG-Umlage 2010, German Parliament, Scientific Services, No. 21/10, March 25, 2010</td>
</tr>
<tr>
<td>Bundesreg</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>
</tr>
<tr>
<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>
</tr>
<tr>
<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>
</tr>
<tr>
<td>DWD</td>
<td>Wolfgang Riecke, Bereitstellung von historischen Globalstrahlungsdaten für die Photovoltaik, Second Symposium on Energy Meteorology, April 2011</td>
</tr>
<tr>
<td>ECOFY S</td>
<td>Abschätzung der Kosten für die Integration großer Mengen an Photovoltaik in die Niederspannungsnetze und Bewertung von Optimierungspotenzialen, ECOFYS, March 2012</td>
</tr>
<tr>
<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>
</tr>
<tr>
<td>EEX</td>
<td>Positionspapier der European Energy Exchange und EPEX SPTO, February 2014</td>
</tr>
<tr>
<td>EnBW</td>
<td>EnBW verstärkt Engagement im Bereich Solarenergie, Pressemeldung, Energie Baden-Württemberg AG, Februar 2019</td>
</tr>
<tr>
<td>ENER</td>
<td>E-Mobility-Zukunft: ENERVIE an Meilenstein-Projekt beteiligt, Pressemeldung, Südwestfalen Energie und Wasser AG, October 2018</td>
</tr>
<tr>
<td>Code</td>
<td>Title</td>
</tr>
<tr>
<td>------</td>
<td>-------</td>
</tr>
<tr>
<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>
</tr>
<tr>
<td>FÖS2</td>
<td>Was Strom wirklich kostet - Vergleich der staatlichen Förderungen und gesamtgesellschaftlichen Kosten von konventionellen und erneuerbaren Energien, Studie im Auftrag von Greenpeace Energy eG und dem Bundesverband WindEnergie e.V. (BWE), Forum Ökologisch-Soziale Marktwirtschaft e.V. (FÖS), August 2012</td>
</tr>
<tr>
<td>FVEE1</td>
<td>Energiekonzept 2050 - Eine Vision für ein nachhaltiges Energiekonzept auf Basis von Energieeffizienz und 100% erneuerbaren Energien, German Research Association for Renewable Energy (Forschungverbund Erneuerbare Energien, FVEE), June 2010, chart by B. Burger and updated on November 28, 2011</td>
</tr>
<tr>
<td>IEA1</td>
<td>Renewables 2018 - Market analysis and forecast from 2018 to 2023, International Energy Agency (IEA), October 2018</td>
</tr>
<tr>
<td>IEA3</td>
<td>Energiepolitik der IEA-Länder, Prüfung 2013, Deutschland, Zusammenfassung, International Energy Agency (IEA), April 2013</td>
</tr>
<tr>
<td>IPCC</td>
<td>Working Group I Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis, Summary for Policymakers, Intergovernmental Panel on Climate Change (IPCC), WGI AR5, Sept. 2013</td>
</tr>
<tr>
<td>IPV</td>
<td>Jessica Nover, Schadstofffreisetzung aus Photovoltaik-Modulen, Abschlussbericht, Universität Stuttgart, Institut für Photovoltaik, 2018</td>
</tr>
<tr>
<td>ISE1</td>
<td>Christoph Kost, Dr. Thomas Schlegl; Levelized Cost of Electricity Renewable Energies, study conducted by the Fraunhofer Institute for Solar Energy Systems ISE, December 2010</td>
</tr>
<tr>
<td>ISE4</td>
<td><a href="https://www.energy-charts.de">https://www.energy-charts.de</a>, Editor: Prof. Dr. Bruno Burger, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany</td>
</tr>
<tr>
<td>ISE5</td>
<td>Hans-Martin Henning, Andreas Palzer; Was kostet die Energiewende? Wege zur Transformation des deutschen Energiesystems bis 2050; Studie des Fraunhofer-Instituts für Solare Energiesysteme ISE, November 2015</td>
</tr>
<tr>
<td>ISE6</td>
<td>Fire Protection in Photovoltaic Systems – Facts replace Fiction, press release by Fraunhofer ISE, February 2013; more information on fire protection can be found at <a href="http://www.pvbrandsicherheit.de">www.pvbrandsicherheit.de</a></td>
</tr>
<tr>
<td>ISE7</td>
<td>Speicherstudie 2013 - Kurzgutachten zur Abschätzung und Einordnung energiewirtschaftlicher, ökonomischer und anderer Effekte bei Förderung von objektgebunden elektrochemischen Speichern, Studie des Fraunhofer-Instituts für Solare Energiesysteme ISE, January 2013</td>
</tr>
<tr>
<td>ISE9</td>
<td>Kurzstudie zur EEG-Umlage, Fraunhofer Insitute for Solar Energy Systems ISE, April 2015</td>
</tr>
<tr>
<td>------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>ISE10</td>
<td>Photovoltaics Report, Fraunhofer-Instituts für Solare Energiesysteme ISE, PSE Conferences &amp; Consulting GmbH, August 2018</td>
</tr>
<tr>
<td>ISET1</td>
<td>Yves-Marie Saint-Drenan et al. «Summenganglinien für Energie 2.0”, study conducted by the Institute for Solar Energy Technology (Institut für Solare Energieversorgungstechnik ISET e.V., April 2009</td>
</tr>
<tr>
<td>IWES1</td>
<td>Vorstudie zur Integration großer Anteile Photovoltaik in die elektrische Energieversorgung, study commissioned by the German Solar Industry Association (BSW) and the Fraunhofer Institute for Wind Energy and Energy System Technology IWES, November 2011</td>
</tr>
<tr>
<td>IWES2</td>
<td>Interaktion EE-Strom, Wärme und Verkehr, Studie im Auftrag des Bundesministerium für Wirtschaft und Energie, Projektleitung Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES), September 2015</td>
</tr>
<tr>
<td>IZES</td>
<td>Kurzfristige Effekte der PV-Einspeisung auf den Großhandelsstrompreis, Institut für ZukunftsEnergieSysteme (IZES), January 31, 2012</td>
</tr>
<tr>
<td>KBA</td>
<td>Zahlen im Überblick – Statistik, Kraftfahrt-Bundesamt, June 2018</td>
</tr>
<tr>
<td>LFU1</td>
<td>Berechnung von Immissionen beim Brand einer Photovoltaik-Anlage aus Cadmiumtellturid-Modulen, Bavarian Environment Agency (Bayerisches Landesamt für Umwelt), 11-2011</td>
</tr>
<tr>
<td>LFU2</td>
<td>Beurteilung von Kunststoffbränden, Az: 1/7-1515-21294, Bayerisches Landesamt für Umwelt, 1995</td>
</tr>
<tr>
<td>LICHTBLICK</td>
<td>Analyse des Beitrags von Mini-BHKW zur Senkung von CO2-Emissionen und zum Ausgleich von Windenergie, Gutachten zum geplanten »ZuhauseKraftwerk«, commissioned by LichtBlick AG, LBD-Beratungsgesellschaft mbH, 2009</td>
</tr>
<tr>
<td>MWV</td>
<td>Homepage of the Association of the German Petroleum Industry (Mineralölwirtschaftsverband e.V.), as of December 10, 2011</td>
</tr>
<tr>
<td>NPE</td>
<td>Fortschrittsbericht 2018 – Markthochlaufphase, Nationale Plattform Elektromobilität, May 2018</td>
</tr>
<tr>
<td>ÖKO</td>
<td>EEG-Umlage und die Kosten der Stromversorgung für 2014 – Eine Analyse von Trends, Ursachen und Wechselwirkungen, Kurzstudie im Auftrag von Greenpeace, June 2013</td>
</tr>
<tr>
<td>ÖKO2</td>
<td>Aktueller Stand der KWK-Erzeugung (Dezember 2015), Studie des Ökoinstituts e.V. im Auftrag des Bundesministerium für Wirtschaft und Energie, December 2015</td>
</tr>
<tr>
<td>ÖKO3</td>
<td>Eingesparte Kosten für Energieimporte im Jahr 2015 und die Innovationseffekte durch die Nutzung erneuerbarer Energien in Deutschland, Memo des Ökoinstituts e.V., October 2016</td>
</tr>
<tr>
<td>Source</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>ÖKO4</td>
<td>Beschäftigungsentwicklung in der Braunkohleindustrie: Status quo und Projektion, Öko-Institut Berlin, Juli 2018</td>
</tr>
<tr>
<td>Prognos</td>
<td>Bedeutung der internationalen Wasserkraft-Speicherung für die Energiewende, study conducted by Prognos AG and commissioned by the World Energy Council, Germany (Weltenergierat – Deutschland e.V.), October 9, 2012</td>
</tr>
<tr>
<td>QUASCHE</td>
<td>V. Quaschning, Solare Unabhängigkeitsklärung, Photovoltaik, Oktober 2012</td>
</tr>
<tr>
<td>Roon</td>
<td>S. von Roon, M. Huck, Merit Order des Kraftwerksparks, Research Center for Energy Economics (Forschungsstelle für Energiewirtschaft e.V.), June 2010</td>
</tr>
<tr>
<td>RWE</td>
<td>Die Energiewende, Daten und Fakten von RWE Deutschland, October 6, 2012</td>
</tr>
<tr>
<td>RWE2</td>
<td>RWE nimmt Batteriespeicher in Herdecke in Betrieb - Sechs Millionen Euro Investition, sieben MWh Kapazität, Pressemeldung RWE, Februar 2018</td>
</tr>
<tr>
<td>Salz</td>
<td>Project »GrInHy« – Green Industrial Hydrogen, Pressemeldung, Salzgitter AG, September 2016</td>
</tr>
<tr>
<td>Shell</td>
<td>Shell Scenarios Sky - Meeting the goals of the Paris agreement , Shell International B.V., March 2018</td>
</tr>
<tr>
<td>SWM</td>
<td>M-Partnerkraft - Das virtuelle Kraftwerk der SWM, Flyer der Stadtwerke München, January 2013</td>
</tr>
<tr>
<td>TEST</td>
<td>»Immer sparsamer«, Test 1/2012, Stiftung Warentest</td>
</tr>
<tr>
<td>UBA</td>
<td>Energieziel 2050: 100% Strom aus erneuerbaren Quellen, Umweltbundesamt, Juli 2010</td>
</tr>
<tr>
<td>UBA2</td>
<td>Artikel auf <a href="https://www.umweltbundesamt.de/daten/energie/kraft-waerme-kopplung-kw#textpart-1">https://www.umweltbundesamt.de/daten/energie/kraft-waerme-kopplung-kw#textpart-1</a>, October 2018</td>
</tr>
<tr>
<td>UBA3</td>
<td>Methodenkonvention 3.0 zur Ermittlung von Umweltkosten - Methodische Grundlagen, Federal Environment Agency, November 2018</td>
</tr>
<tr>
<td>UNB</td>
<td>Mittelfristprognose zur deutschlandweiten Stromerzeugung aus EEG-geförderten Kraftwerken für die Kalenderjahre 2017 bis 2021, Leipziger Institut für Energie GmbH, October 2016</td>
</tr>
<tr>
<td>VATT</td>
<td>CO₂-freie Energie fürs Quartier: Sektorenkoppelnder Stahlspeicher bringt Energiewende auf Hochtemperatur, Pressemeldung Vattenfall, October 2018</td>
</tr>
<tr>
<td>VFL</td>
<td>Berechnung einer risikoadäquaten Versicherungsprämie zur Deckung der Haftpflichtrisiken, die aus dem Betrieb von Kernkraftwerken resultieren, study conducted by the Versicherungsforsen Leipzig and commissioned by the German Renewable Energy Federation (Bundesverband Erneuerbare Energie e.V., BEE), April 1, 2011</td>
</tr>
<tr>
<td>VGB</td>
<td>Kraftwerke 2020+, opinion of the Scientific Council of VGB PowerTech e.V., 2010</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>VIK</td>
<td>VIK Strompreisindex Mittelspannung, Verband der Industriellen Energie- und Kraftwirtschaft e.V., September 2016</td>
</tr>
</tbody>
</table>
27 Appendix: Figures

Figure 1: Percentage renewable energy in net electricity consumption ([BMWi1], [AGEE]) for Germany, data from [BDEW3] ................................................................. 6
Figure 2: Average end customer price (net system price) for installed rooftop systems with rated nominal power from 10 - 100 kWp, data from BSW/EuPD, plotted by PSE AG. ........................................................................................................... 8
Figure 3: Historical price development of PV modules (PSE AG/Fraunhofer ISE, data from: Strategies Unlimited/Navigant Consulting/EuPD). The straight line shows the price development trend. ................................................................. 9
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], [BDEW6] and average compensation for PV power [BMWi5] .... 10
Figure 5: Pricing on the European Energy Exchange EEX [Roon]. ........................................ 11
Figure 6: Influence of RE on the average spot price on the energy exchange (EEX) [BDEW2] ................................................................. 12
Figure 7: Development of the average spot electricity price and the calculated differential costs [BDEW2]. ............................................................................... 13
Figure 8: PV expansion and remuneration amount [BMWi1],[BMWi5] ........................................ 14
Figure 9: Electricity consumption of industry and EEG surcharge 2019 [BDEW6]........ 14
Figure 10: Influential parameters and calculating method for the EEG surcharge [ÖKO] 15
Figure 11: Development of the EEG surcharge and the EEG differential costs [ISE9] ..... 16
Figure 12: Price of CO2 allowances [BDEW6] ........................................................................ 18
Figure 13: Components of the average domestic electricity price in 2019 (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) [BDEW6], ............................................................................... 20
Figure 14: Development of gross domestic electricity prices (2017, estimated at 3% increase), net electricity prices for large-scale industrial consumers [BMWi1] and the EEG surcharge; about 55% of the gross domestic electricity price is made up of taxes and fees. ............................................................................... 20
Figure 15: VIK electricity price index for medium-voltage customers [VIK] ......................... 21
Figure 16: Electricity export (negative values indicate export) for Germany [ISE4] ............ 22
Figure 17: Rough estimate of levelized cost of electricity (LCOE) for PV power plants at different annual irradiances. ............................................................................... 23
Figure 18: Division of ownership of the total installed capacity of PV plants at the end of 2016 [AEE3]. ............................................................................... 27
Figure 19: Concept for a virtual power plant of the Stadtwerke München (Munich municipal works) [SWM] ............................................................................... 27
Figure 20: Germany’s expenditure in the Energy Research Program of the Federal Government by topic in € million [BMWi6] ............................................................................... 28
Figure 21: Funding for PV research categorized by technology in € million [BMWi6] .... 28
Figure 22: Left: Feed-in of PV power [BSW], Right: Distribution of installed PV power according to plant size [ISE10] ............................................................................... 29
Figure 23: Electronically limited electrical energy in GWh / year [BNA3] ......................... 30
Figure 24: Actual and predicted hourly generation of power in 2014 [ISE4].................. 31
Figure 25: Average power for the supply of solar and wind power in 2017, 15-minute
values [ISE4].................................................................................................................... 32
Figure 26: Electricity production of PV and wind in ascending hourly values for the year
2017 ........................................................................................................................................ 32
Figure 27: Monthly production of PV and wind power for 2014 - 2017 [ISE4].......... 33
Figure 28: Example showing course of electricity trading price, conventional and
renewable electricity in the 18th calendar week in May 2018 [ISE 4]............................ 34
Figure 29: System Average Interruption Duration Index (SAIDI) for different network
levels in minutes / year [BNA3].......................................................................................... 35
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). .............. 37
Figure 31: Forecasted hours of full-load operation for renewable energy plants, mean
values from 2012-2016 [ÜNB].......................................................................................... 39
Figure 32: Horizontal annual global irradiation in Germany averaged over 1981-2010 40
Figure 33: Development of the atmospheric CO₂ concentration and the mean global
temperature change based on the NASA Global Land-Ocean Temperature Index
[IEA2]. ........................................................................................................................................ 41
Figure 34: Estimate of the atmospheric CO₂ concentration and the temperature in
Antarctica based on ice core data [EPA], CO₂ concentration for 2016 has been added
.................................................................................................................................................. 42
Figure 35: Greenhouse gas emissions avoided by using renewable energy in 2017
[UBA1]................................................................................................................................... 43
Figure 36: Development of annually installed PV capacity for Germany and globally, or
Rest of World, (RoW), numbers from EPIA (up to 2010), IHS (up to 2017), PV Market
Alliance (estimate for 2018) and Trendforce (forecast for 2019)................................. 44
Figure 37: Energy flow diagram 2017 for Germany in petajoules [AGEB2].................. 47
Figure 38: Germany’s import quotas for fossil and nuclear energy sources
(www.umweltbundesamt.de).............................................................................................. 48
Figure 39: Cost development for the provision of primary energy in Germany [ÖKO3] 48
Figure 40: Share of final energy in Germany, categorized by utilization 2014 [BMWi4] 49
Figure 41: Scenario of a German energy system, schematic representation of the system
composition. [ISE5] .............................................................................................................. 50
Figure 42: Schematic representation of a residual load curve for Germany with power
supply with 100% EE, with generators (+) and loads (-); Red: Delivering of usable
heat or waste heat.................................................................................................................. 51
Figure 43: Development of global power generation by technologies in the Sky-Scenario;
the diameter of the pie charts corresponds to the global power requirement [Shell] 53
Figure 44: Forecasts of IEA and actual development of global annual PV construction
(https://twitter.com/AukeHoekstra).................................................................................. 53
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 ................................................................................................. 54
Figure 46: Calculation example for the specific monthly yield of a PV system at Freiburg for south-oriented modules with 30° inclination (maximum annual yield) and 60° inclination.............................................................. 55

Figure 47: Power plant availability [VGB].......................................................... 56

Figure 48: Energy consumption of an average household in Germany, not including hot water production [RWE].......................................................................................... 57

Figure 49: Fictitious annual electricity production (8760 hours) for 200 GW PV and 200 GW wind, extrapolated on the basis of installation and yield data for 2017 ............ 58

Figure 50: 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 .................................................................................................................. 59

Figure 51: 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].............................................................................................................. 62

Figure 52: Comparison of the conventional and grid-optimized system operation [ISE7] ................................................................................................................................. 63

Figure 53: Possible ways of converting and storing PV power with data on efficiencies 64

Figure 54: Simplified scheme of a Renewable Energy System with the most important grid-related components of the categories production, conversion, storage and consumption. ................................................................. 65