Recent Facts about Photovoltaics in Germany

Current version available at https://www.ise.fraunhofer.de/en/publications/studies/recent-facts-about-pv-in-germany.html

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, Harry Wirth, Fraunhofer ISE, download from https://www.ise.fraunhofer.de/en/publications/studies/recent-facts-about-pv-in-germany.html, version of May 15, 2021

Table of Contents

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 Will we achieve the expansion targets?

The annual target of the German Federal Government for PV capacity increase of 2.5 GW was exceeded in 2020, but the goals of the energy transformation are still far away.
On May 12, 2021, the German government approved climate targets that call for a balanced national greenhouse gas footprint by 2045 at the latest.

In order to cover all of our energy needs from renewable energies (RE), a massive expansion of the installed PV power is necessary, along with a number of other measures. More recent model-based scenarios calculate a reduction of energy-related greenhouse gas emissions alone of at least 90% in relation to 1990, with a PV expansion corridor of 130-650 GW_p nominal capacity ([Prog], [BCG], [ESYS], [ISE11], [UBA8], [IRENA], [ISE12]). The scenarios make different assumptions about boundary conditions, e.g. for energy imports and questions of acceptance. Based on the scenarios "reference" and "inacceptance" [ISE12], a magnitude of 500 GW_p installed PV capacity seems to be plausible.

If we calculate a PV expansion to 500 GW_p by 2045, an average of 18 GW_p of PV will have to be added annually. Increasingly, old systems must also be replaced. These replacement installations are currently still of little importance, but they will increase to around **17 GW_p per year** when fully expanded, assuming a lifetime of 30 years.

The German Renewable Energy Sources Act [EEG2021] defines an interim target for 2030 of a share of renewable energies (RE) of 65 percent of gross electricity consumption. This requires an average annual PV addition of at least 5-10 GW_p, depending on the development of electricity demand and the expansion of wind power ([AGORA1], [BEE]). The German Renewable Energy Sources Act EEG, on the other hand, sets the PV expansion target at 100 GW_p, corresponding to an average addition of just under **5 GW_p per year**.

From 2013-2018, power plants with a nominal output of only 1.9 GW_p/a were installed on average in Germany [BMWi1], in 2020 the figure was 4.9 GW_p [ISE4].

3 Does PV contribute significantly to the power supply?

Yes.

PV covered 9.2% of gross electricity consumption in Germany in 2020, with electricity generation of **50,6 TWh** [UBA1]; all renewables (RE) combined came to 45% (Figure 1: Percentage renewable energy in net electricity consumption for Germany, data from [BMWi1], [UBA1], [ISE4]). Gross electricity consumption includes grid, storage, and self-consumption losses (Section 25.8). On sunny days, PV electricity can temporarily cover more than two-thirds of our current electricity consumption. At the end of 2020, PV modules with a nominal capacity of **54 GW_p** were installed in Germany [ISE4], distributed over **2 million systems** [BSW1].

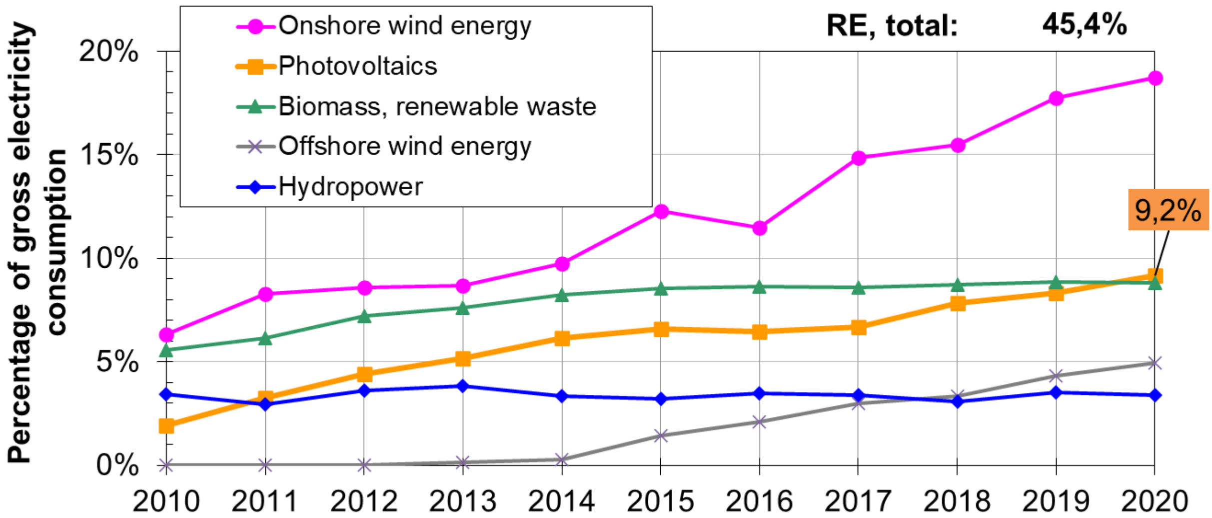


Figure 1: Percentage renewable energy in net electricity consumption for Germany, data from [BMWi1], [UBA1], [ISE4]

4 Is PV power too expensive?

It depends on the reference point.

The cost comparison with fossil and nuclear power generation is made more difficult by the fact that their external costs and risks in terms of environmental, climate and health damage are largely not taken into account in pricing ([UBA3], [FÖS1], [FÖS2]). Hiding these external costs represents a massive subsidy to the energy sources involved (Section 5.2).

The marginal costs for nuclear power are in the order of 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 marginal costs essentially cover the provision of the fuel, but not the neutralization of the radiating waste or polluting emissions (CO_2, NO_x, SO_x, Hg).

New MW power plants produce PV electricity at a cost of 3-5 ct/kWh in Germany, provided that the volatile electricity is sold in full. The lowest bid price to date for power plants up to 10 MW is 3.55 ct/kWh. Newly built, larger power plants that are operated directly by utilities outside the German Renewable Energy Sources Act (RES) or supply their electricity via offtake agreements are likely to produce at costs well below 4 ct/kWh. Newly constructed, smaller power plants have higher LCOE, in the order of 10 ct/kWh for rooftop installations of a few kW nominal capacity. Older PV power plants produce solar electricity much more expensively due to the previously very high investment costs.

To promote the energy turnaround and to stimulate investments in PV systems of various sizes, in the year 2000 the instrument of the German Renewable Energy Sources Act was created. It is intended to enable the plant operator to run the plant at a reasonable profit with a guaranteed purchase. Furthermore, the German Renewable Energy Sources Act aims at continuously reducing the LCOE from RE by securing a substantial market for RE systems (see section 4.1).

Building PV generation capacity is only a part of the transformation costs associated with the energy turnaround. For a long time, this part was at the forefront of the discussion. In recent years, PV has become increasingly system-relevant, bringing new types of costs into focus. In addition to the pure generation costs for electricity from RE, there are the development of grid-serving storage and conversion capacities (e-mobility and stationary batteries, heat pumps and heat storage, Power-To-X, flexible gas-fired power plants, pumped storage) as well as the dismantling of nuclear and coal-fired power plants. These costs are not caused by the PV expansion, they go - just like the PV expansion itself - on the account of the energy turnaround. The costs of the energy turnaround are incurred by all energy consumers, for whom a sustainable energy supply must be created. Without knowing the costs of an omitted energy turnaround, it is difficult to evaluate the costs of the turnaround.

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 total costs 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. deconstruction costs

The annual operating costs of a PV power plant are comparatively low at about 1% of the investment costs, and the financing costs are also favorable due to the current low interest rates. 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 12 percent per year – in all, 75 % since 2008. Figure 2 shows the price development since 2006 for rooftop installations between 10 kW_p to 100 kW_p in Germany.

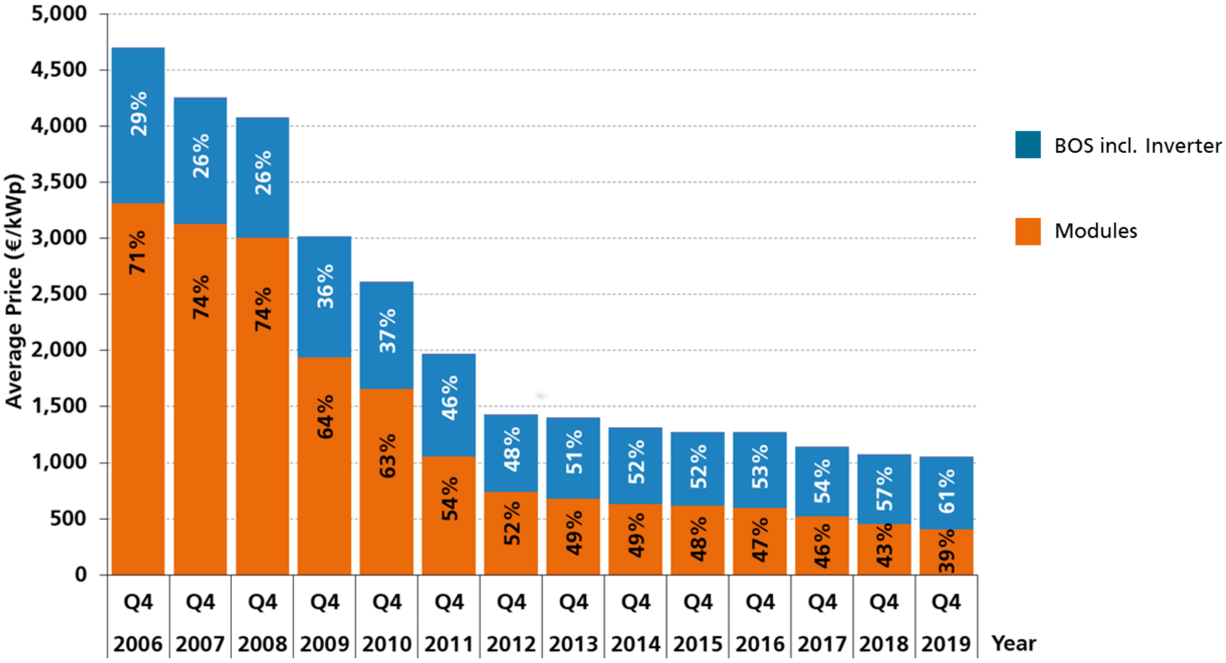


Figure 2: Average end customer price (net system price) for installed rooftop systems with rated nominal power from 10 - 100 kW_p [ISE10], data BSW-Solar.

Module costs are responsible for almost half of the total investment costs of a PV power plant of this size. 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 2020, more than 700 GW_p 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 tenders of the Federal Network Agency provide an orientation value for electricity generation costs from new PV ground-mounted systems (see following section).

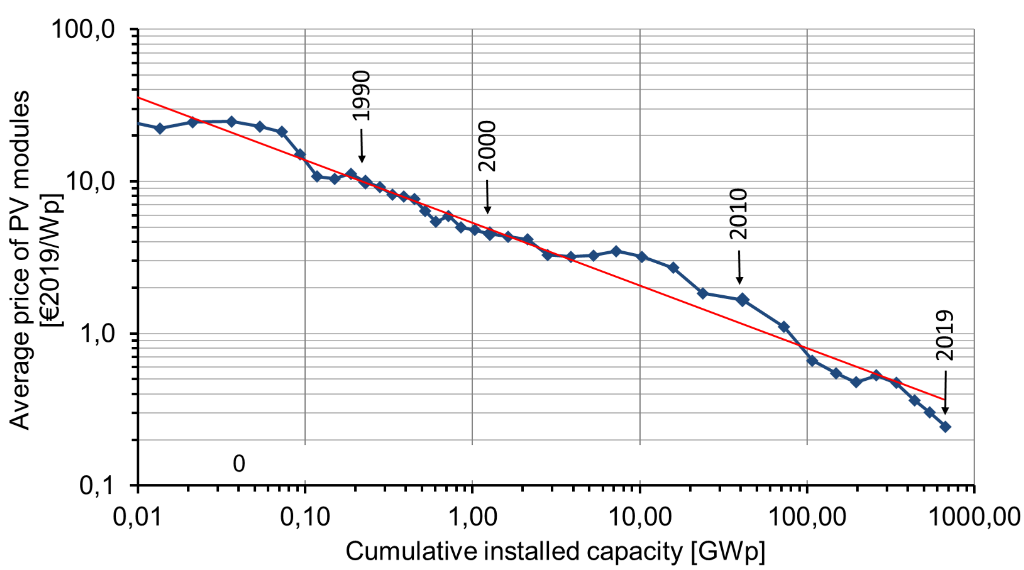


Figure 3: Historical price development of PV modules (PSE AG/Fraunhofer ISE, data from: Strategies Unlimited/Navigant Consulting/EuPD). The straight line shows the price development trend.

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 largely simultaneously, 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 German Renewable Energy Sources Act in 2000 and the subsequent changes have shaped the growth of PV installments in Germany.

The German Renewable Energy Sources Act [EEG2021] tries to promote and constrain PV expansion at the same time:

- PV systems may only be constructed on arable land in 200 m corridors along federal motorways and railways

- The size of PV ground-mounted systems has been limited to 20 MW
- The power of PV systems must either be able to be reduced to 70% of their nominal capacity or be regulated by the grid operator
- Self-consumed PV energy is taxed above a certain nominal power (approx. 30 kW nominal system power) with 40% of the current German Renewable Energy Sources Act surcharge (Section 4.6), which means that the PV electricity generation costs increase by approx. 2.6 € ct / kWh
- Plants only receive a fixed feed-in tariff up to a nominal power of 100 kW; For plants with a rated output of 100-750 kW, the PV energy must be marketed directly
- New plants with a rated output of more than 750 kW are required to partake in calls for tender and must not contribute to self-consumption; the annual tender volume is limited

Depending on the system size, the feed-in tariff for small roof systems put into operation until **January 2021** can be up to **8,16 €-cts/kWh** and is guaranteed to the operator over the next twenty years. For medium-size systems from 750 kW up to 20 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 from 1.75 (Brasilia) to 2 $cts/kWh (USA). 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.

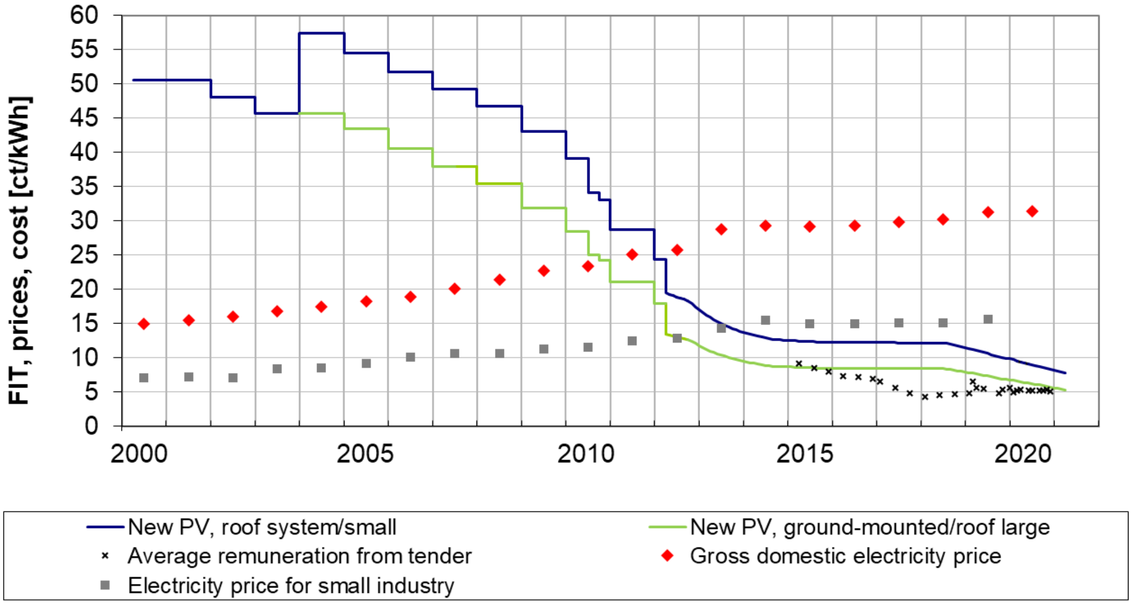


Figure 4: Feed-in tariff for PV power as a function of commissioning date, average remuneration of the bidding rounds of the Federal Network Agency, electricity prices and average compensation for PV power, data from [BMWi1], [BDEW6].

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 feed-in tariff of the German Renewable Energy Sources Act (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 >30 kW_p which were put into operation after 2021 are subjected to a portion of the levy according to the German Renewable Energy Sources Act.

After 2021, 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 (Figure 5).

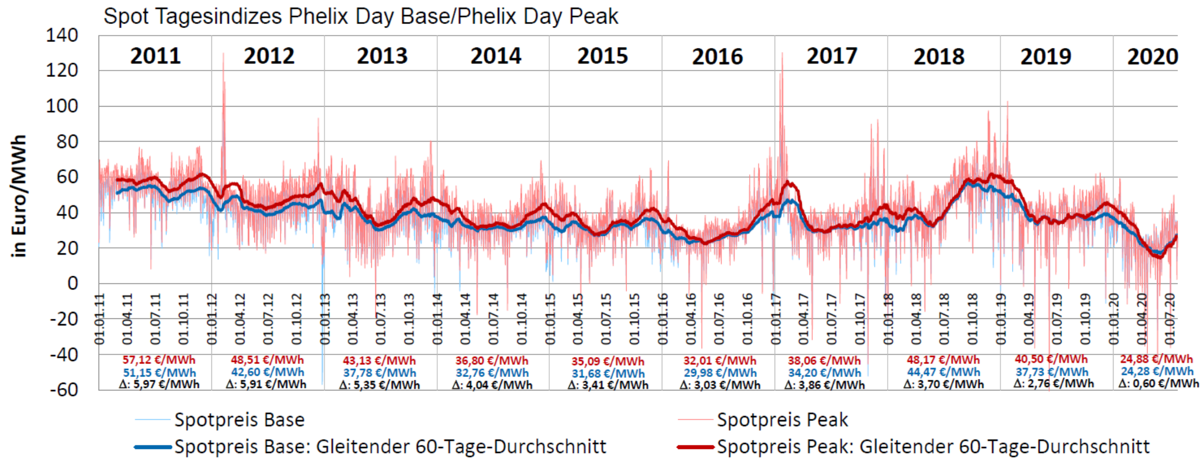


Figure 5: Electricity price development on the day-ahead spot market [BDEW6]

The running EEX price is determined by the merit order principle (Figure 6). The electricity producers' sales offers for certain quantities of electricity, usually defined by the respective marginal costs, are sorted by price in ascending order. The purchase offers of the power consumers are sorted in descending order. The intersection of the curves gives the exchange price for the total traded quantity. The most expensive offer that is accepted thus determines the profit margins of the less expensive suppliers.

PV power feed-in has legal priority, meaning that it is found at the start of the pricing scale due to the merit order effect. With fictitious marginal costs of zero, PV power is always sold when available. PV power is predominantly generated during the middle of the day when power consumption (and previously, but no longer, the electricity price) is at its midday peak. During these periods, PV power mainly displaces electricity from expensive peak-load power plants (especially gas-fired plants and pumped-storage). This displacement lowers the spot price of electricity on the market and leads to the merit order effect of PV feed-in (Figure 7). Together with the prices the revenues of all conventional power producers (nuclear power, coal, gas) sink. However, the revenues for electricity from RES (solar power, wind power, hydropower) are also falling accordingly. Furthermore, solar power reduces the utilization of conventional peak load power plants (gas, water).

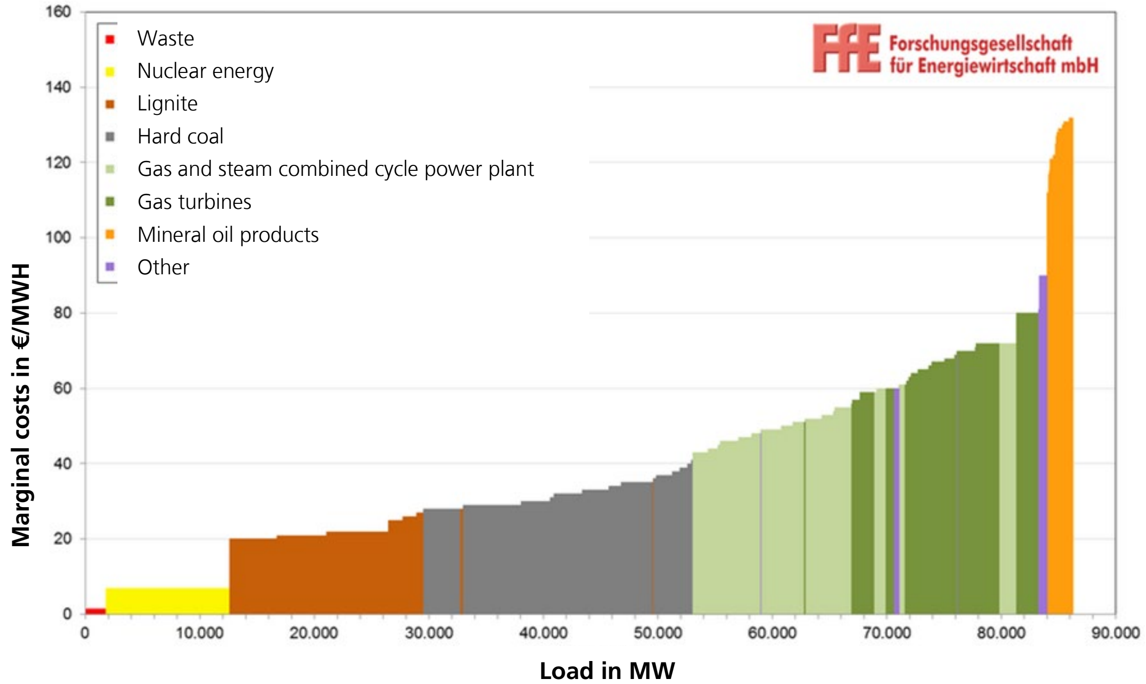


Figure 6: Merit order for conventional power plants in 2018 with an average CO_2 certificate price of € 16 per ton [FFE].

The increasing amount of renewable electricity being fed into the grid, lower coal prices and surplus of CO_2 allowances have drastically depressed prices on the EEX (Figure 8). PV electricity achieves over several years a market value factor of approx. 0.85 - 0.9 [ÜNB] on the electricity exchange on an annual average, i.e. the revenue generated per kWh is slightly below the average exchange electricity price. The market price factor for on-shore wind power was about 0.8 - 0.9 [ÜNB].

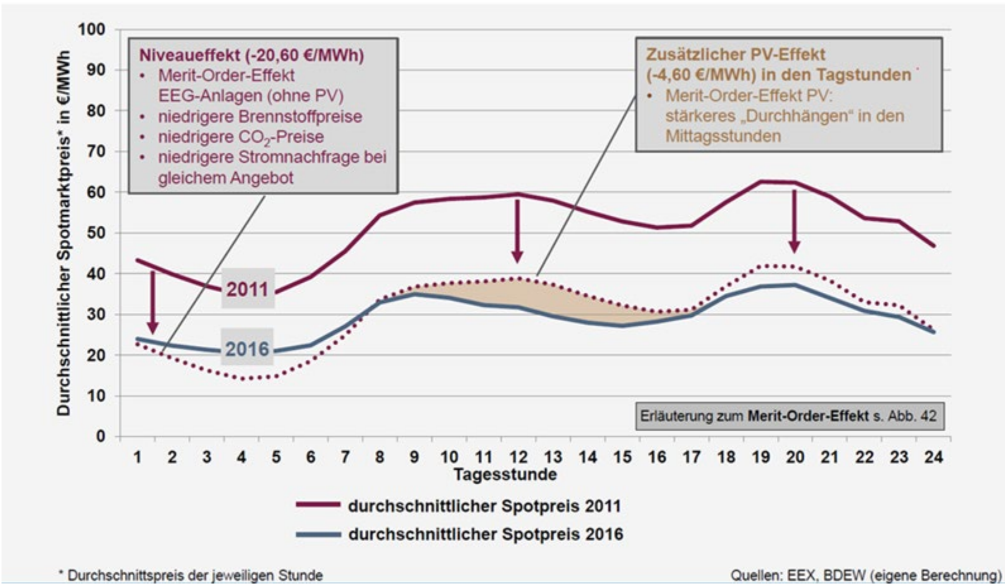


Figure 7: Influence of RE on the average spot price on the energy exchange (EEX) [BDEW2].

With further expansion of volatile renewables, their market value factor will decline in the medium term, because the supply of electricity increases at times of high feed-in and both PV and wind power have a high simultaneity. For PV, a decrease of the market value factor to 0.8 by 2030 is expected [ZSW].

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 3 €-cts/kWh in 2020. 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 support of PV appears to be.

Figure 8 shows the development of the differential costs for the yearly remuneration of the PV electricity generated. After a strong increase until 2014, the amount stabilized between € 9 and 10 billion.

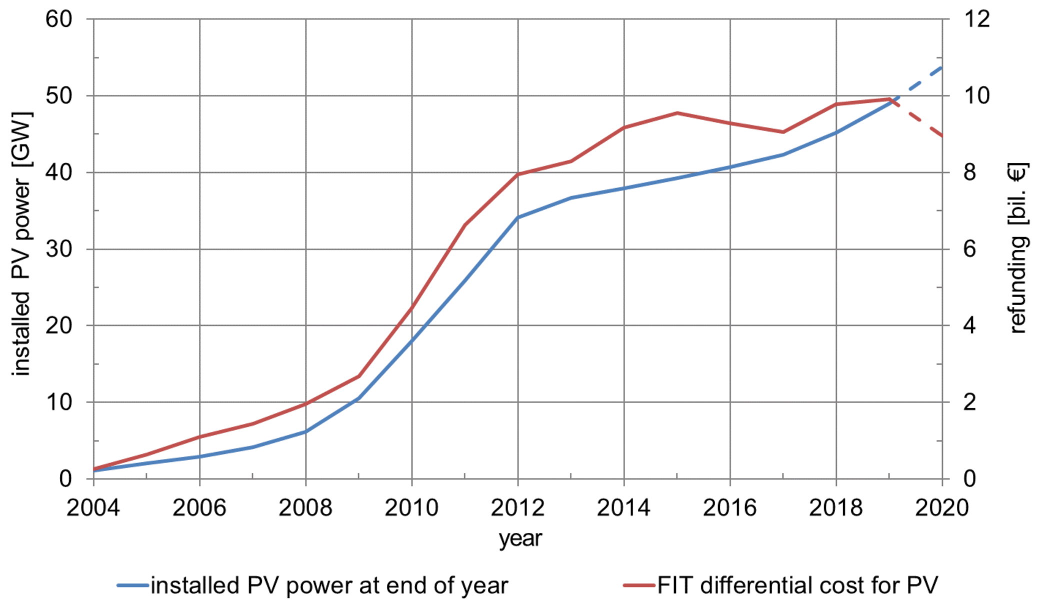


Figure 8: PV expansion and remuneration amount, data from [BMWi1], [BMWi5]

A study by the Friedrich-Alexander-University in Erlangen-Nürnberg, Germany has shown that in the years 2011 to 2018 a total of € 157 billion in EEG differential costs has been incurred, while in the same time cost savings of € 227 billion due to the feed-in of PV and wind power were realized [FAU]. On balance, consumers thus saved € 71 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 2019, a share of 44% 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.

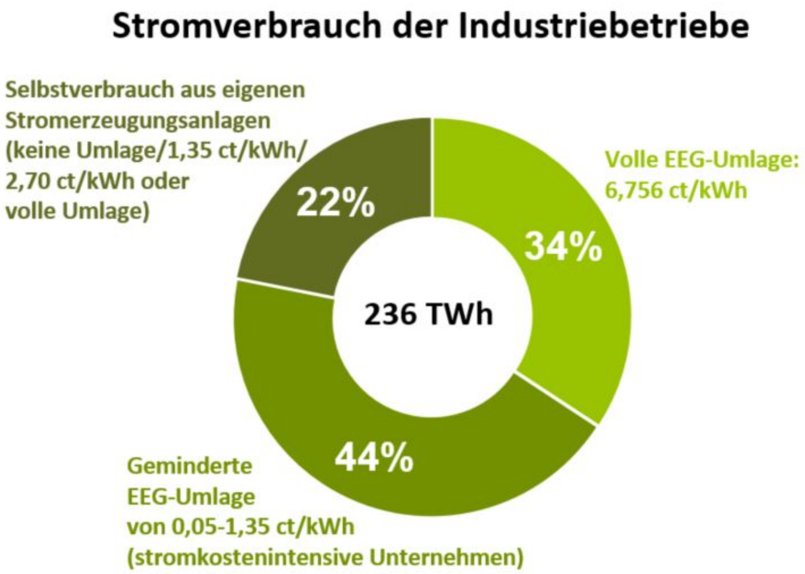


Figure 9: Electricity consumption of industry and EEG surcharge 2019 [BDEW6]

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 benefiting from the lower spot prices on during peak-power times. It is evident that part of the surcharge indirectly ends up in the pockets of these energy-intensive industries: «Energy-intensive companies, which are either largely exempt from the EEG surcharge or pay a reduced rate of 0.05 €-cts/kWh, benefit the most from the merit order effect. For these companies, the lower prices brought about by the merit order effect overcompensates for the costs incurred as a result of the EEG surcharge by far." [IZES] Energy-intensive companies therefore benefit from the energy transformation without making a noteworthy contribution.

4.6 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. In 2021 there will be a grant from the federal budget (Energy and Climate Fund) of €10.8 billion for the first time. For 2021, the EEG surcharge is set at **6.5 €-cts/kWh**. End users must pay value added tax (19%) on this surcharge.

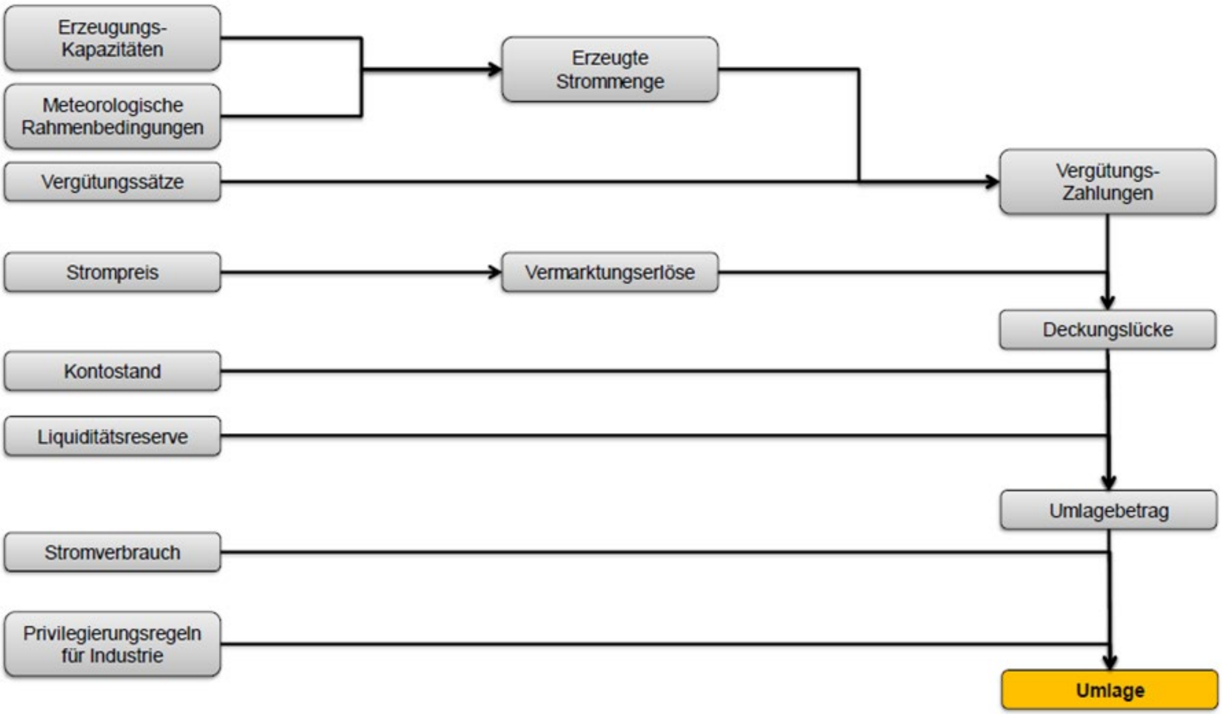


Figure 10: Influential parameters and calculating method for the EEG surcharge [ÖKO]

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 also disadvantages smaller customers bound to pay the EEG levy.
3. Merit order effect and electricity surplus
   For years, Germany has been producing more electricity than necessary from fossil and nuclear power plants (see Section 6). This oversupply also lowers the exchange electricity price via the merit order effect and 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 which must be compensated by increased EEG remuneration for electricity producers.
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?

Yes, since the year 2021.
A subsidy is defined as a benefit from public funds. Up to and including 2020, the subsidy for PV electricity generation did not come from public funds, but from a selective consumption levy, which applies also to self-produced and self-consumed PV electricity. Energy consumers make a compulsory contribution for the - necessary and approved - transformation of our energy system. This interpretation is also supported by the European Commission. The amount of the levy also does not correspond to the total remuneration, but to the differential costs. The cumulative costs paid out for PV power fed into the grid up to and including 2020 amounted to ca. 100 billion euros [BMWi5]. In 2021, for the first time there will be a contribution from the Federal Government's Energy and Climate Fund (section 4.6). The revenues of the Energy and Climate Fund come from emissions trading and from federal subsidies, thus there is a partial subsidy since 2021.

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). On the other hand, the exchange price still largely ignores important external costs of fossil and nuclear power generation (Section 5.2).

5.2 Are fossil fuel and nuclear power production subsidized?

Yes, the future costs of the subsidy are still difficult to estimate.

Policy makers influences the price of electricity from fossil and nuclear power plants. Political decisions define the price of CO_2 emission allowances, the conditions for filtering smoke or for the permanent storage of CO_2, the taxation of nuclear power or the insurance and safety requirements for nuclear power plants. Policy makers thus determine the extent to which electricity consumers bear the elusive risks and burdens of fossil and nuclear power generation. These largely arise in the future, through the CO_2-induced climate crisis, the final disposal of nuclear waste and eternal liabilities from hard coal mining. If these costs are priced in more consistently, PV power generation will end up making the electricity mix cheaper. Until we get to that point, fossil and nuclear power will be sold at prices that mask its external costs and pass the burden on to future generations.

5.2.1 Fossil energy sources

Fossil power generation is hardly burdened by costs for CO_2 certificates. It is true that EU-wide emissions trading (European Union Emissions Trading System, EU ETS) was introduced in 2005 to make CO_2 emissions more expensive and to begin internalizing the costs. However, due to an oversupply of certificates, the price had collapsed by the end of 2017. Across Europe, certificate trading also covers only 45% of greenhouse gas emissions because important sectors beyond industry and energy are excluded [UBA5]. Even with certificate prices of up to **€30/t CO_2** [Figure 11], the EU ETS still has little steering effect. In Germany, a national emissions trading system for the heat and transport sectors started in January 2021 with a CO_2 price of **25 €/t** [NEHS].

The direct and indirect consequential costs of global climate change, which will also affect Germany, are difficult to estimate. According to calculations by the Federal Environment Agency, the emission of one ton of CO_2 causes damages of around **195 €/t** with a - questionable - higher weighting of the welfare of current versus future generations and **680 €/t** with the - more plausible - equal weighting [UBA3]. In Germany, nearly 810 million tons of carbon dioxide and CO2 equivalents were emitted in 2019, causing corresponding damages of €157 billion or €551 billion, depending on the welfare weighting. For lignite-fired electricity generation with an emission factor of 1075 g CO2/kWh (Figure 38), the derived CO2 price premiums are 21 and 73 ct/kWh, respectively.

Taking externalities into account, the total societal costs for lignite-based electricity were thus many times higher than the pure electricity production costs of 3.4-4.7 ct/kWh [FÖS2]. For comparison: The recycling of CO_2 from the atmosphere via direct air Capture Pilot Plants currently costs about **550 €/t**. A study by the International Monetary Fund estimates global subsidies for coal, oil and natural gas, including external costs, at US$5.1 trillion in 2015 [IMF].

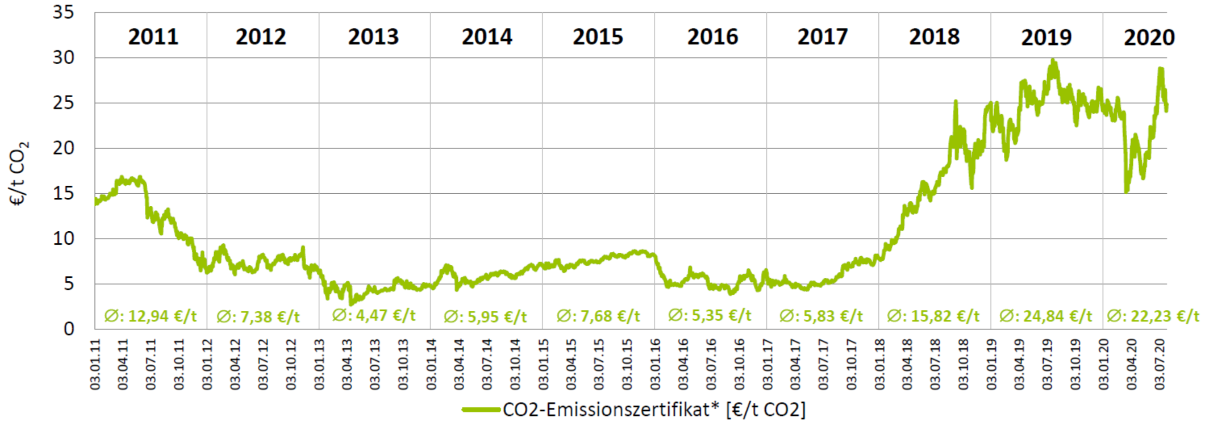


Figure 11: Price of CO_2 allowances [BDEW6]

5.2.2 Nuclear power

According to experts, the risks of nuclear power are so severe that no insurance or reinsurance company in the world dares to offer policies. Accidental damage during the operation of nuclear power plants is only covered up to € 250 million by the insurance market, up to € 2.5 billion by an operator pool; in the case of larger damage, the operators of the nuclear power plants are only liable with their assets [ATW1]. By way of comparison, the nuclear catastrophe at Fukushima caused damage of around €100 billion, which is many times higher than the enterprise value of German nuclear power plant operators. A study by Versicherungsforen Leipzig sets the limit of liability for the risk of the most serious type of nuclear meltdown at 6 trillion euros, which, depending on the time period over which this sum is accrued, would increase the electricity price per kilowatt hour to between 0.14 and 67.30 euros [VFL]. As a result, it is essentially the tax payers who act as the nuclear industry's insurers. This is essentially forced upon them both against their wishes, since the majority of Germans have been opposed to nuclear energy for many years, and as an unspecified amount, because no fixed price has been established to date for damage settlements. Taking externalities into account, the total societal cost of nuclear power in 2019 was around **24-28 ct/kWh** [FÖS1]. Studies that exclude accident risks due to their high indeterminacy conclude significantly lower values.

Germany will shut down its remaining nuclear power plants by 2022. This will stop the chain reactions in the fuel rods and eliminate the risk of a nuclear GSA (greatest supposed accident).

Whether the operators' financial reserves for dismantling the nuclear power plants will be sufficient is not foreseeable today. The state has received €24 billion from the power plant operators for taking over Germany's nuclear waste, which has been paid into a fund. It is equally uncertain whether the income from this fund will be sufficient to pay for the construction and commissioning of a disposal site by 2050; according to calculations by the Commission on the Final Disposal of Nuclear Waste, the total costs are estimated at €176 billion.

The EURATOM Treaty of 1957 allows EU Member States to subsidize nuclear power plants, which is not allowed in other sectors for competitive reasons. This derogation has played an important role in financing the UK nuclear power plant Hinkley Point C through generous guaranteed feed-in tariffs from taxpayers' money [FÖS3]. The project was calculated for a return of 9% over a period of 60 years.

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 home owners, and there including owners and renters) 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 kW_p. The systems within this power range make up less than 15% of the total installed PV power in Germany, while large systems above 500 kW_p make up about 30 % (Figure 19). 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.

Fraunhofer ISE

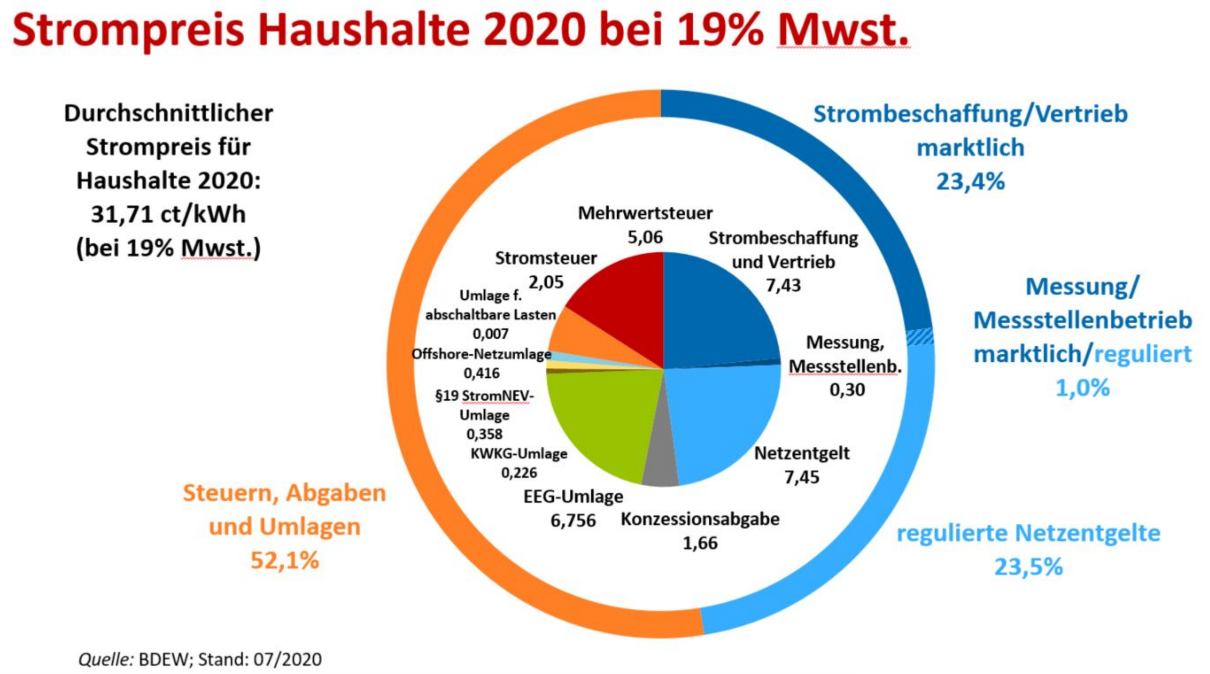


Figure 12: Components of the average domestic electricity price in 2020 (CHP: German Combined Heat and Power Act); German Electricity Grid Access Ordinance (Strom-NEV): easing the burden on energy-intensive industries; concession fee: fee for using public land) [BDEW6].

In 2020 a typical household with an annual power consumption of 3,500 kWh pays an electricity price of approx. **31,71 €-cts/kWh** in 2019 [BDEW6]. Figure 12 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.

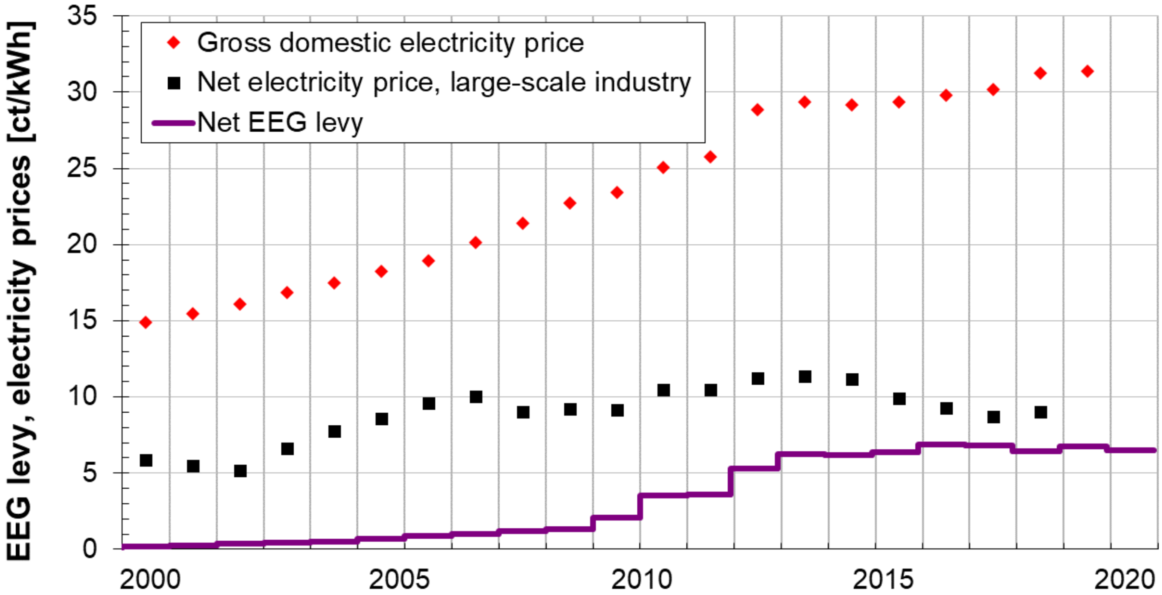


Figure 13: Development of gross domestic electricity prices, net electricity prices for large-scale industrial consumers and the EEG surcharge, data from [BMWi1]

The price of electricity for private households in Germany is approx. 50% higher than the European average (source: stromreport.de, year under review 2020), but the purchasing power per German inhabitant is also 60% higher (source: statista.de, year under review 2019). If electricity prices and purchasing power are taken into account, Germany is in the European middle range. 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 14). 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.

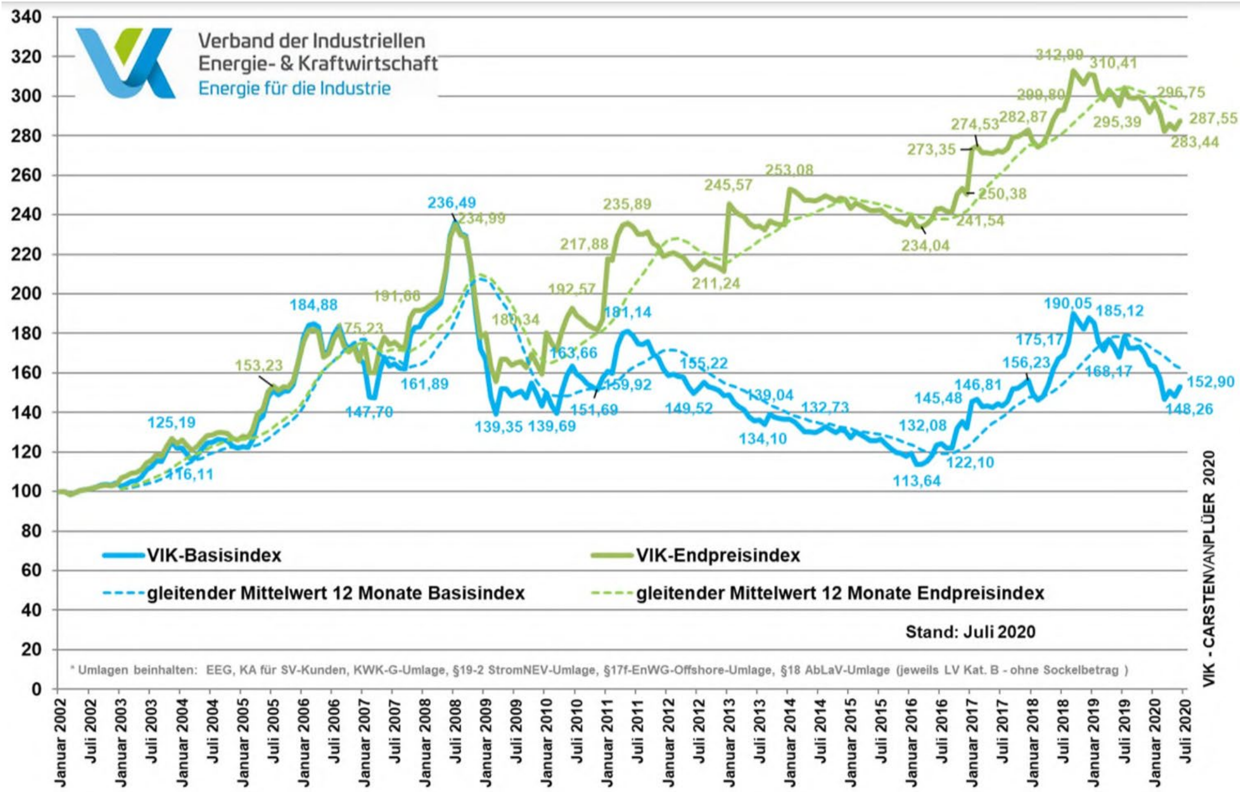


Figure 14: VIK Verband der Industriellen Energie- und Kraftwirtschaft e.V., electricity price index for medium-voltage customers [VIK]

6 Are we exporting large amounts of PV power to other European nations?

No, the increased export surplus comes primarily from coal power plants.

Figure 15 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 export price per kWh of electricity differs slightly from the average import price.

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 CO_2 certificate prices (Section 5.2) of recent years.

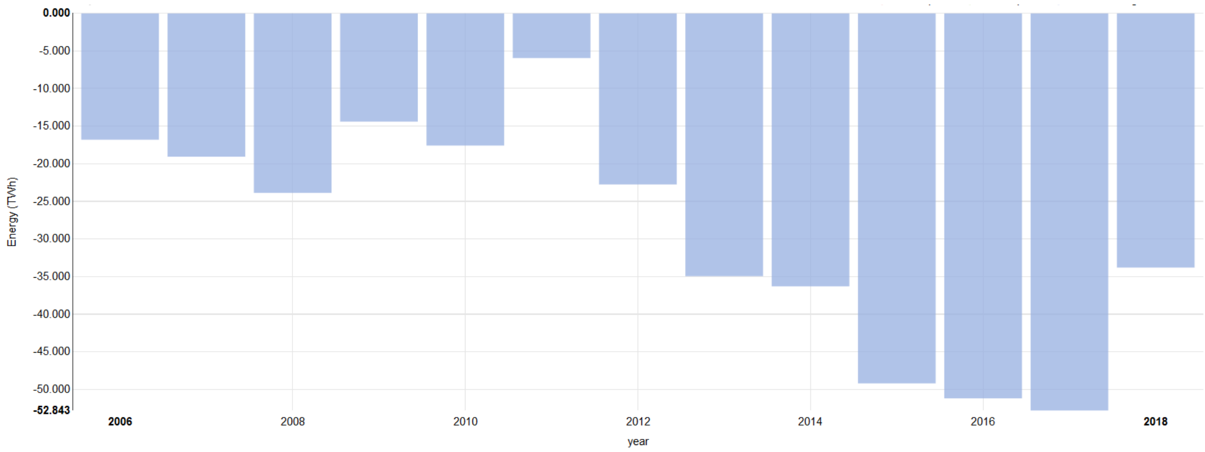


Figure 15: Electricity export (negative values indicate export) for Germany [ISE4]

7 Can small PV systems generate attractive returns?

Yes.

In principle, small PV systems can generate returns both via the EEG remuneration for feeding electricity into the grid and via the reduction in electricity consumption thanks to self-consumption. Due to the sharp drop in prices for PV modules, attractive returns are possible. The Solar Cluster Baden-Württemberg has estimated returns of up to 5% for small systems without battery storage and with self-consumption of around 25% [SCBW].

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 a 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 19.3).

The PV system yield is higher in sunny regions. In fact, the regional difference in the annual sum of irradiation is not transferred in a one-to-one ratio to the specific yield (kWh/kW_p, see section 25.4.), because, for example, the operating temperature of the modules, pollution effects or the duration of the snow cover also play a role.

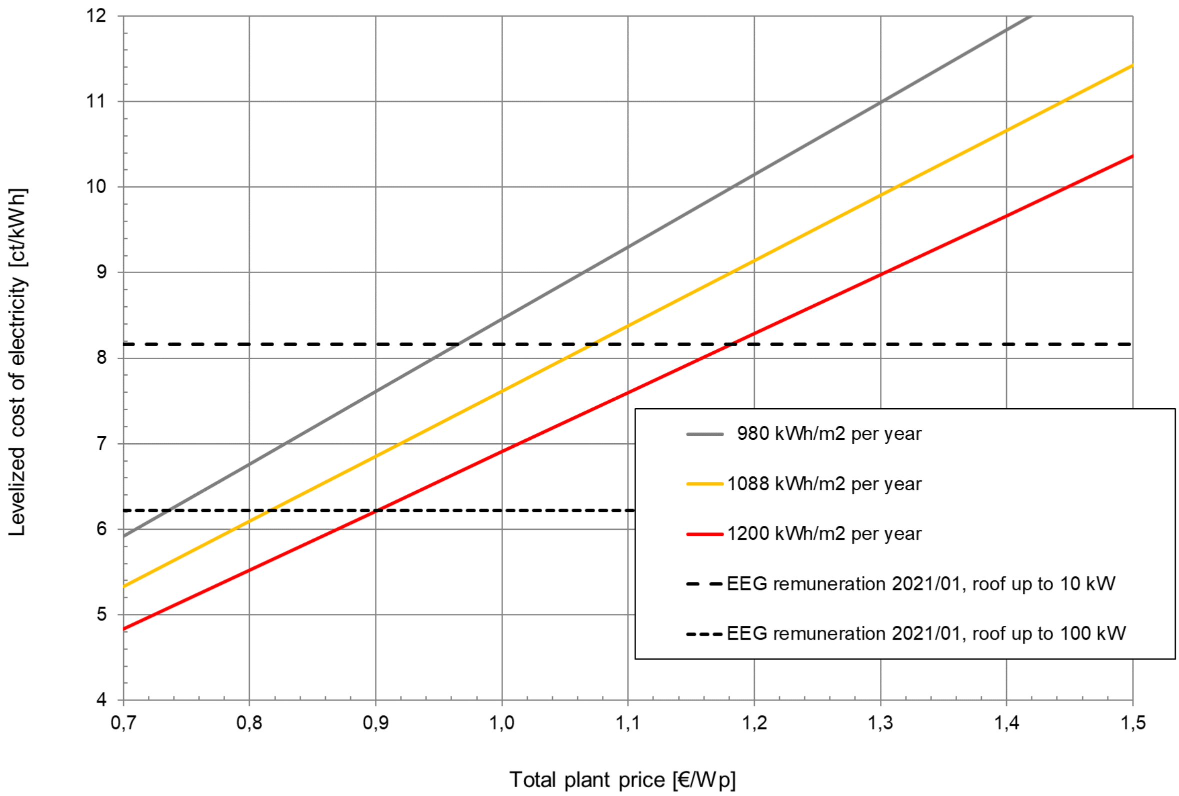


Figure 16: Rough estimate of levelized cost of electricity (LCOE) for PV power plants at different annual irradiances

To obtain a rough estimate of the discounted LCOE (not adjusted for inflation, see Figure 16), the following assumptions were used:

- optimal orientation of module (approximately 30° south)
- average annual total of horizontal global irradiation in Germany 1088 kWh/m²/a
- performance ratio (section 25.6) 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)

The levelized cost of energy (LCOE) is estimated using the net present value method, according to which, the running costs and LCOE are discounted by the interest rate given at the time the plant was commissioned. The LCOE values determined are not adjusted for inflation. This makes it easier to compare them with the feed-in tariff which is constant in nominal terms but declines in real terms.

In the event of a 100 percent equity investment, the imputed interest is equal to the rate of return. To compare, the Federal Network Agency (Bundesnetzagentur) set the return on equity at 9.05 percent (before corporate tax) for both new and further investments in the electricity and gas networks [BNA1].

Neither the manufacturer's guarantee nor plant insurance policies are able to remove the risk to the investor entirely. The use of electricity from the 21st year of operation will be regulated for the first time by the German Renewable Energy Act 2021 [EEG2021]. It is expected that many plants will still produce considerable amounts of electricity at marginal running costs. The self-consumption capability plays a major role in calculating the continued operation of "de-subsidized" plants [SCBW1].

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 2018, the PV industry employed 24,000 people in Germany [BSW]. By comparison, about 21,000 people still worked in lignite mining and lignite-fired power plants in 2015 [ÖKO1]. Businesses from the following sectors contribute to the German PV industry:

1. manufacture of materials: solar silicon, metal pastes, bus bars, plastic films, solar glass, coated glass
2. manufacture of intermediate and final products: modules, cables, inverters, mounting structures, tracker systems
3. mechanical engineering for cell and module production
4. installation (especially trade)
5. power plant operation and maintenance

In 2019, the German inverter manufacturers held notable shares of the global market with approx. 10%, silicon manufacturers (Wacker), silver paste manufacturers (Heraeus) and manufacturers of production systems.

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. For several years, turn-key production lines that produce very good quality PV modules can be bought off-the-shelf, which enabled fast technology transfer.

Effective laws for feed-in tariffs in Germany and Europe have spurned 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 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 50 percent of the total PV plant costs (other 40 percent predominantly from inverter and installation costs) and that initial plant costs make up around 70 percent of the levelized cost of electricity (remainder: capital costs, maintenance), 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.

According to a study by EuPD Research, an annual expansion of 10 GW of PV requires almost 70,000 full-time direct employees, with a focus on installation and maintenance [EuPD].

9 Are large energy suppliers interested in PV?

The PV capacity operated in Germany is predominantly owned by private individuals, farmers and commercial enterprises (Figure 17). No other power generation technology enables such a high degree of decentralization and participation. The traditional electricity suppliers, especially the "big four" (E.ON, RWE, EnBW and Vattenfall), have been reluctant to invest in PV for a very long time. Where did this reluctance come from?

1. Until a few years ago, the electricity production costs for solar power were much higher than for electricity from other renewable or fossil sources, CO_2 emission costs did not play a role.
2. The electricity consumption in Germany is showing a declining to stable tendency since 2007. The construction of new PV power plants will force either a reduction in the utilization rate of existing power plant parks or an increase in electricity export.
3. 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 for the energy transformation.
4. PV power plants deliver power during the day at times when demand is at a peak (Figure 46). This lowers the market price of electricity on the EEX, which carries over to all plants presently producing electricity. (Section 4.3). In the past, the large

power plant operators were therefore able to sell base load electricity at lunchtime very lucratively. Since 2011, PV led to price reductions on the energy exchange and thus to dramatic slumps in profit for the "big four".
5. Because PV power production fluctuates, the slow start-up and shut-down properties of nuclear of older coal-fired power plants cause difficulties with increasing PV expansion. One particularly striking example is negative electricity prices on the market. Coal is being burned and the consumers must pay for the electricity. This leads to system wear in places where controls are technically feasible but no provision in the necessary frequency exists.
6. 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.

The annual report for 2019 shows that at the end of 2019, Innogy, a spin-off of RWE, operated 3.1 GW of wind power plants and 550 MW of other electricity generation plants based on renewables, including PV.

Vattenfall has sold its German lignite division in Lusatia and intends to concentrate on electricity from renewables. According to its 2019 annual report, Vattenfall operates 30 MW of PV. E.On transferred its renewables business to RWE in September 2019.

According to its own account, EnBW has refocused its activities in 2013 towards an energy turnaround. In the 2019 annual report, an installed rated capacity of 1.7 GW for wind power and 225 MW for other renewable energies including PV in total is stated. In early 2019 EnBW announced plans to build the first PV power plant in Germany without EEG support. This refers to a 187 MW project in Brandenburg [EnBW]. In the meantime, the electricity production costs for PV power have fallen to such an extent that energy suppliers have increasingly been building large PV power plants independently of the EEG since 2020.

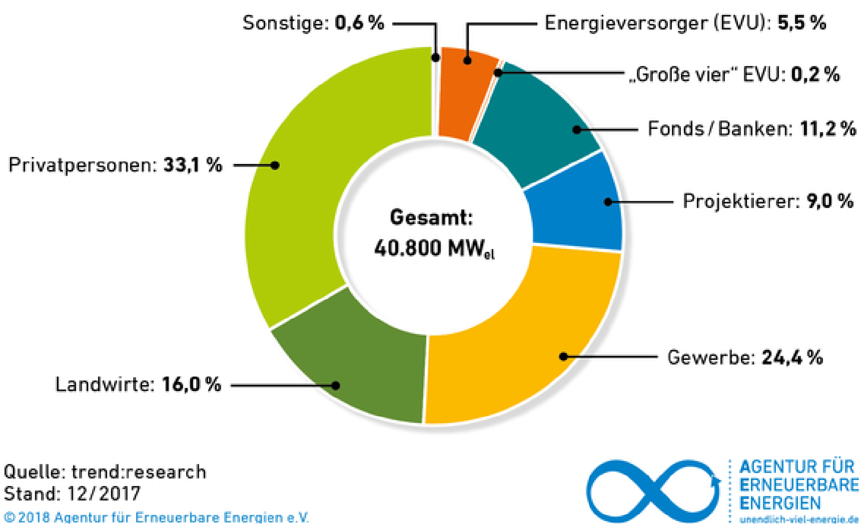


Figure 17: PV power plant capacity by owner group [AEE3].

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 18).

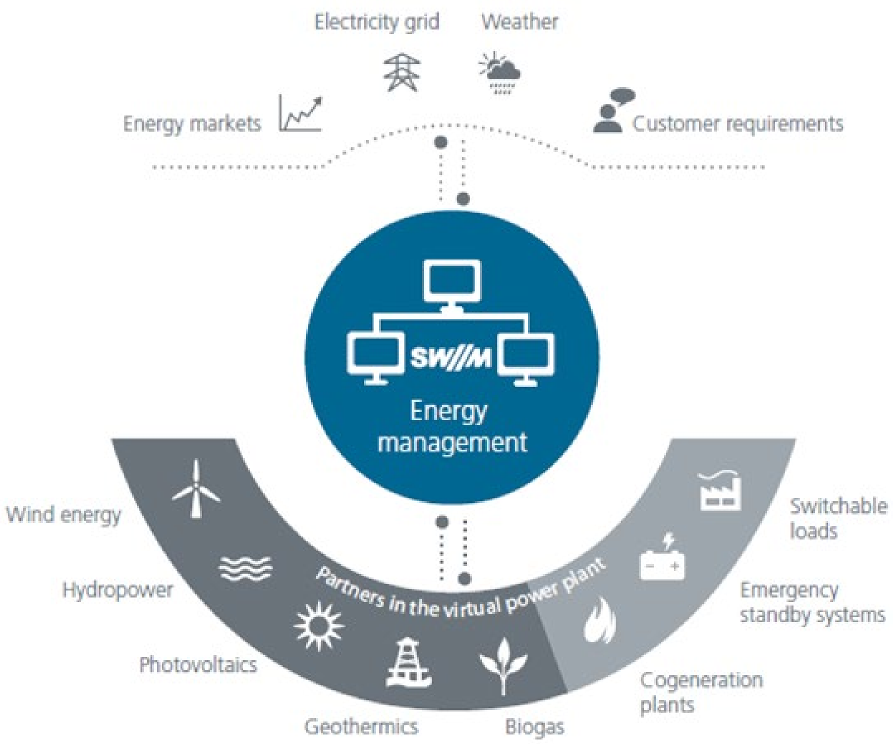


Figure 18: Concept for a virtual power plant of the Stadtwerke München (Munich municipal works) [SWM]

Fraunhofer ISE

10 Is PV research taking up high levels of funding?

In 2020, the German government has invested 1.2 billion euros in energy research. Of this, 86 million euros went to support photovoltaic research (Figure 19).

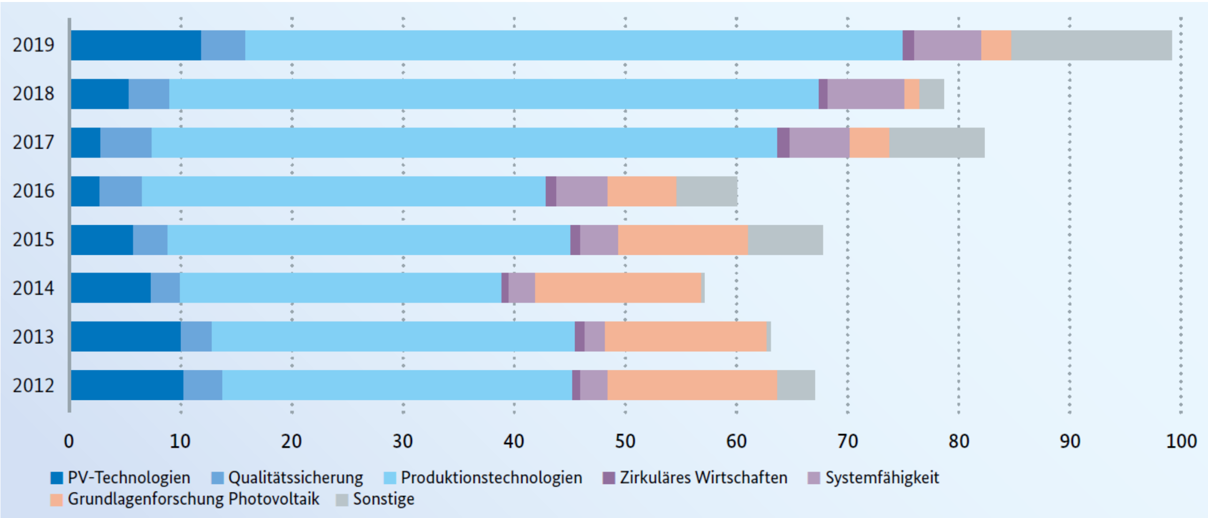


Figure 19: Funding for PV research categorized by technology in € million [BMWi7].

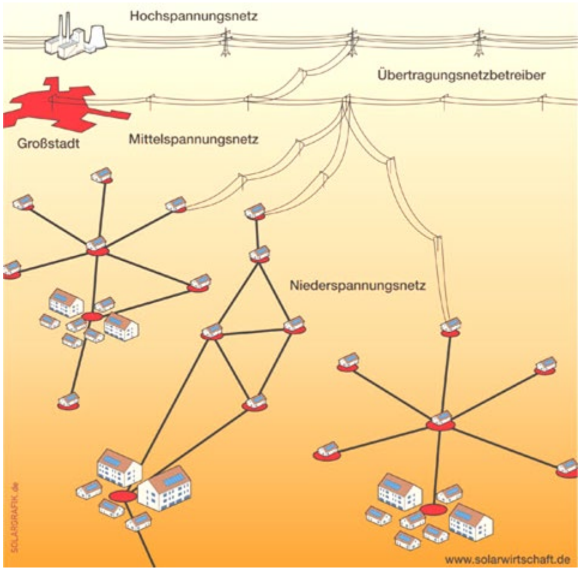
By way of comparison: even after the decision to phase out nuclear power, European treaties are still forcing Germany to finance the EURATOM program with high double-digit million amounts each year, in 2019 with around 80 million euros [FÖS3]. Most of the EURATOM funds are spent on fusion research.

11 Does PV power overload our energy system?

11.1 Transmission and distribution

Most solar power systems in Germany are connected to the decentralized low-voltage grid (Figure 20) and generate solar power consumption.

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¸ due to the high simultaneity factor. Transformers then feed power back into the medium-voltage grid. At very high plant densities, the transformer station can reach its power limit. An even distribution of PV installations over the network sections reduces the need for expansion.



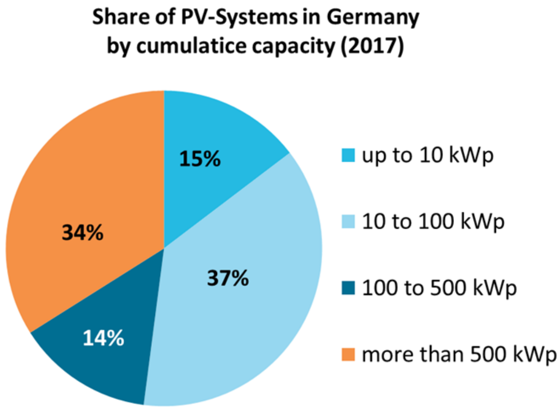


Figure 20: Left: Feed-in of PV power [BSW], Right: Distribution of installed PV power according to plant size [ISE10]

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 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_p in 2030 [AGORA1]. 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 21). 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]. According to provisional figures from the German Federal Network

Agency, a quantity of electricity from renewable energies of 6.5 TWh was regulated in 2019, of which 2.7% was solar power and 96.7% wind power.

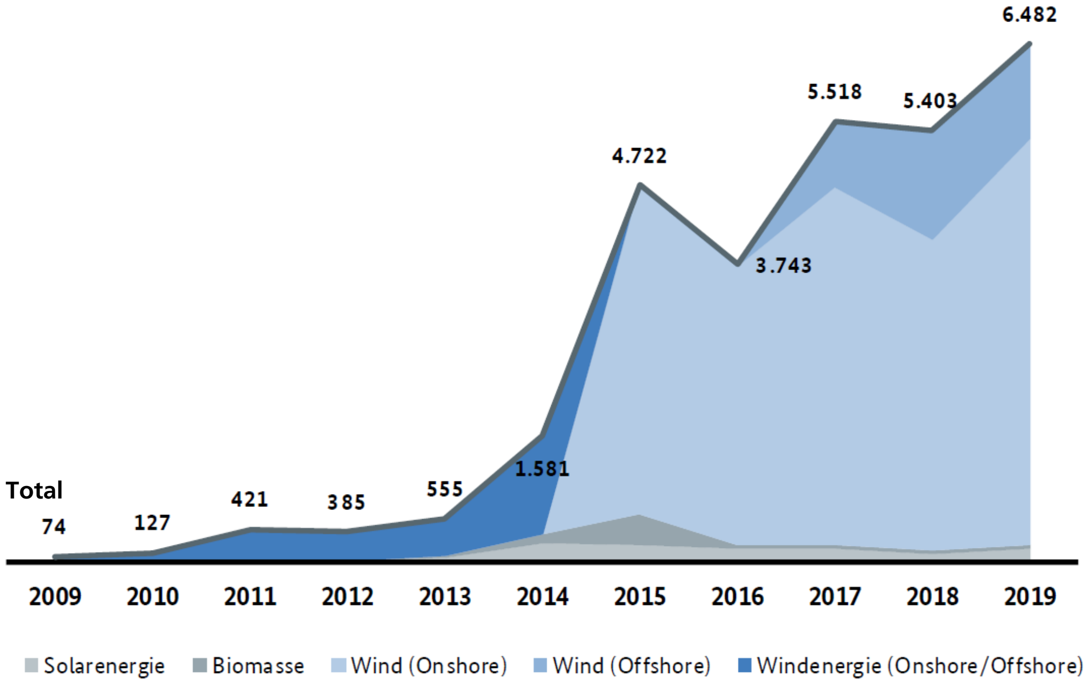


Figure 21: Electronically limited electrical energy in GWh/year [BNA]

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 22). 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.

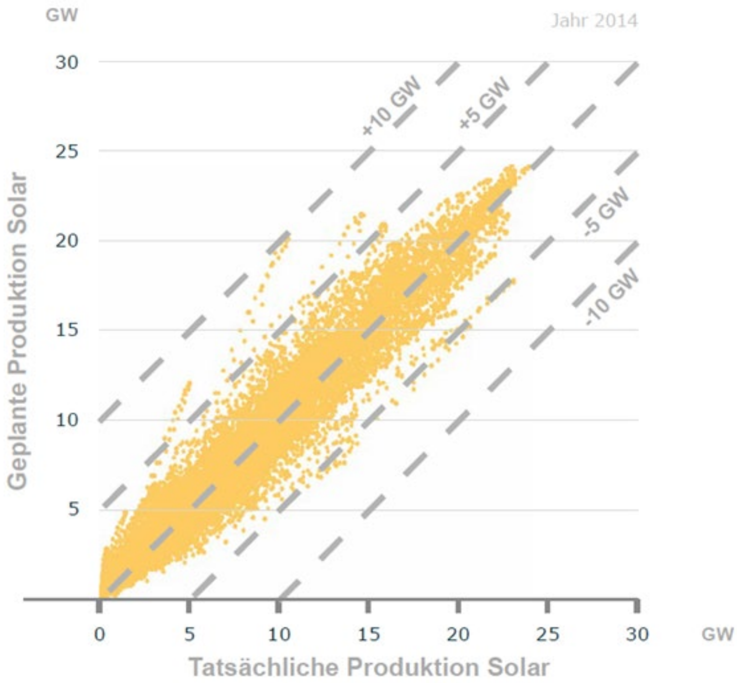


Figure 22: Actual and predicted hourly generation of power in 2014 [ISE4].

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 rare throughout Germany, cf. also Figure 23.

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 legal regulation prescribing this curtailment or, alternatively, remote controllability 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_p of PV and 56 GW_p of wind power at the end of the year, in total only rarely more than 45 GW_p of power was connected to the grid in 2017 (Figure 23).

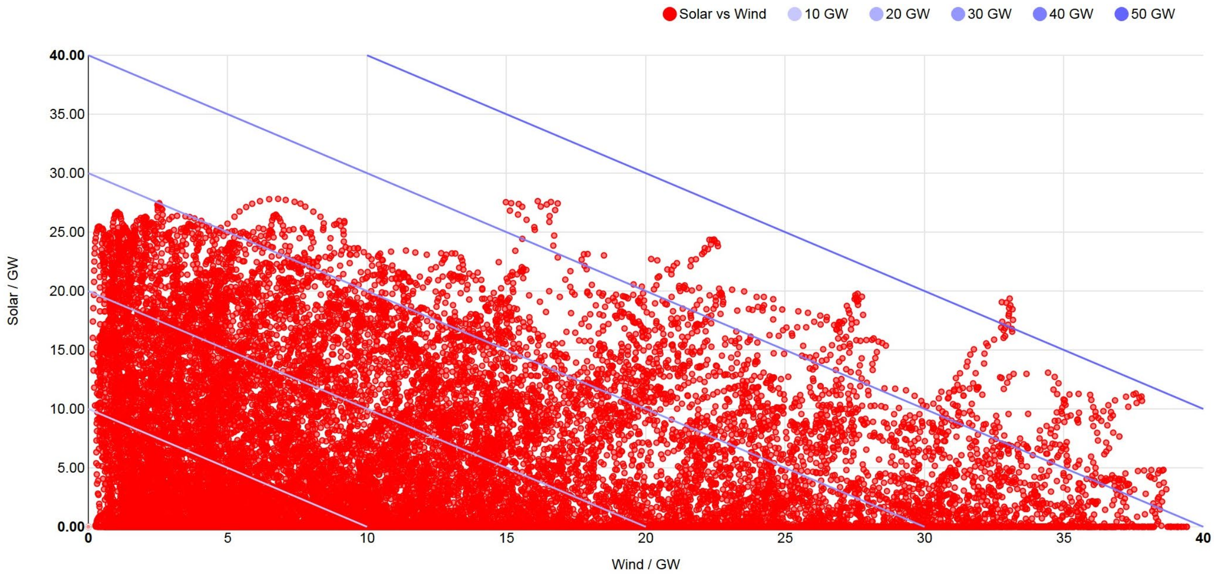


Figure 23: Average power for the supply of solar and wind power in 2017, 15-minute values [ISE4].

Figure 24 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.

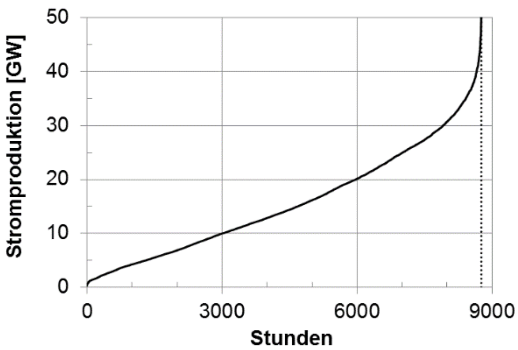


Figure 24: Electricity production of PV and wind in ascending hourly values for the year 2017

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 25: Monthly production of PV and wind power for 2014 - 2017 [ISE4].Figure 25 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.

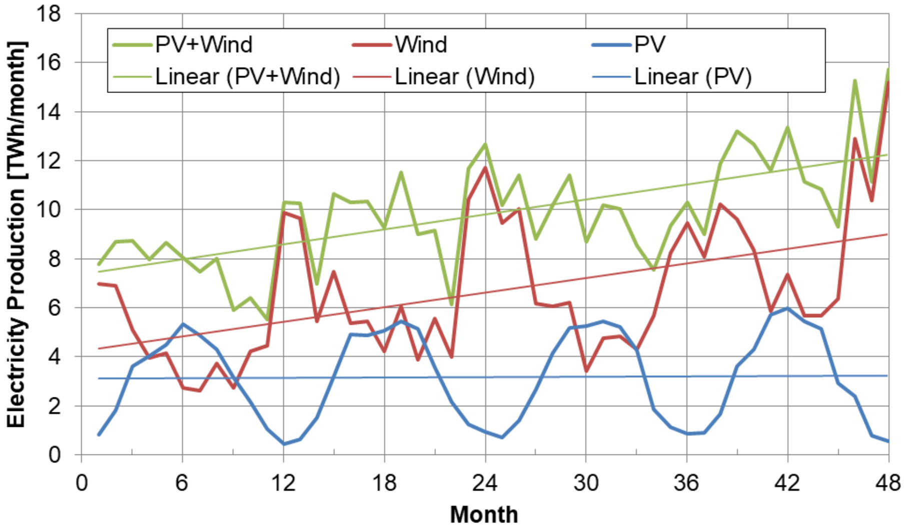


Figure 25: Monthly production of PV and wind power for 2014 - 2017 [ISE4].

11.3 Controllability

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

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

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. The residual load is the difference between the electricity load and the electricity production from volatile renewable sources (PV, wind, run-of-river). 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.

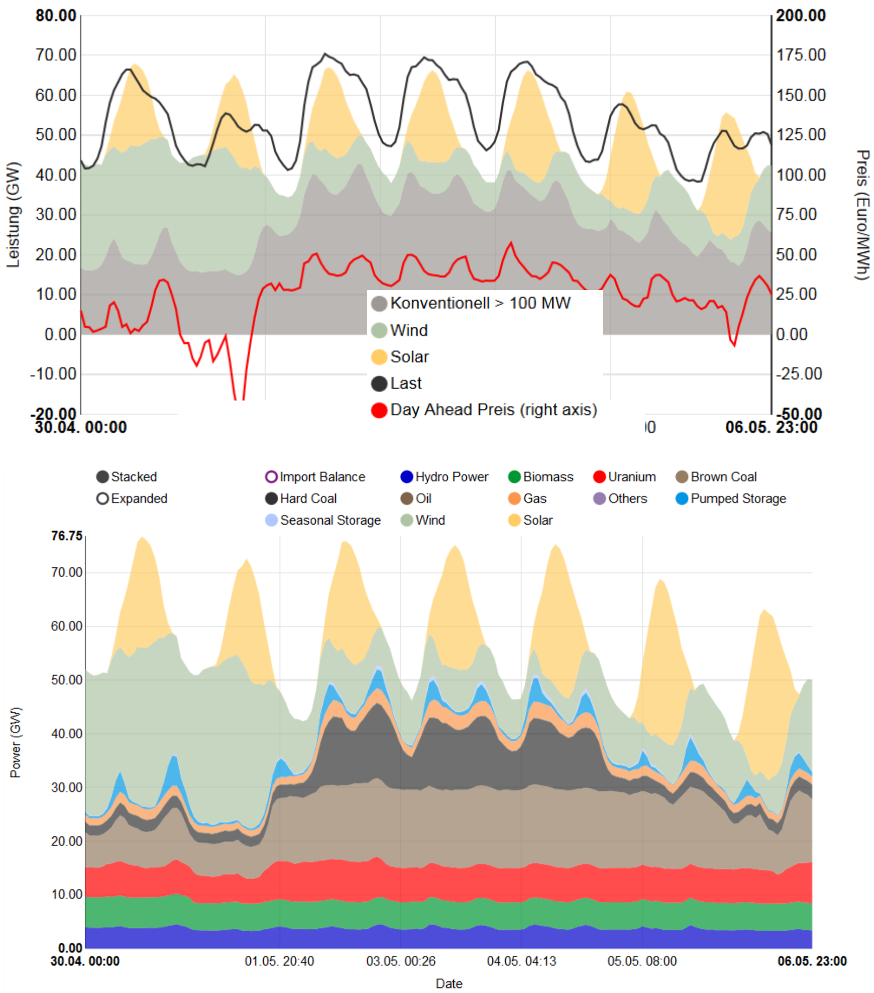


Figure 26: Example showing course of electricity trading price, conventional and renewable electricity in the 18th calendar week in May 2018 [ISE 4]

11.5 Does volatile solar power endanger security of supply?

No.

The security of supply for final consumers has even increased since 2006 in parallel with the expansion of photovoltaics (Figure 29). Increased investments in the expansion of transmission grids have contributed to this development.

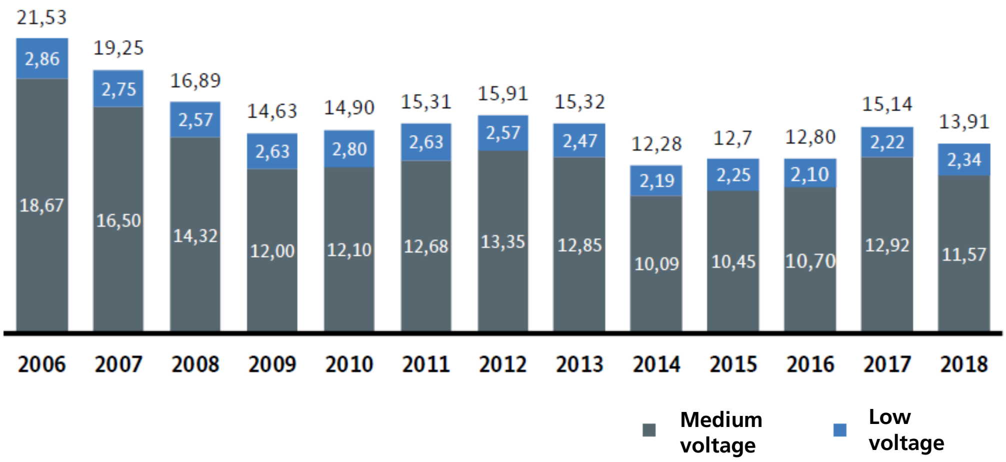


Figure 27: System Average Interruption Duration Index (SAIDI) for different network levels in minutes / year [BNA]

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 CO_2 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_p of installed PV power by 2030 [AGORA1].

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 (Energy Payback Time, EPBT) 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 study by Fraunhofer ISE on PV power plants with current PV technology (monocrystalline PERC modules) has determined energy payback times of about one year for European production and operating sites. With a life span of 25-30 years, this results in yield factors greater than 20.

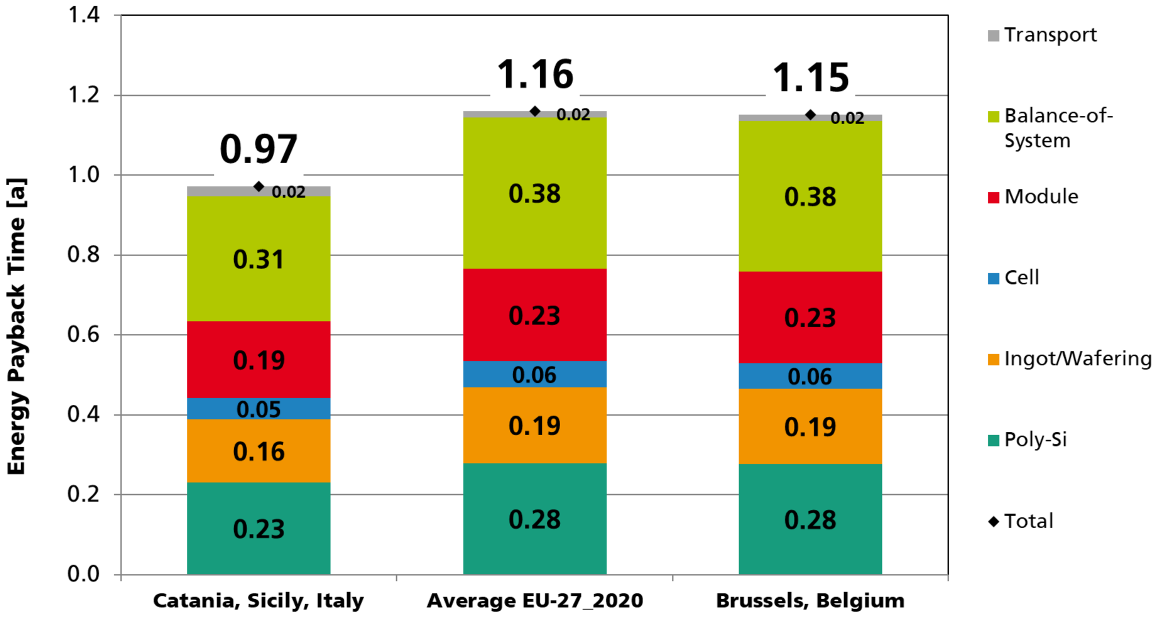


Figure 28: Calculated energy payback times of PV power plants for European production and operating sites [ISE10], data: Lorenz Friedrich

13 Is there enough space for PV in Germany?

Yes, without any significant conflicts with agriculture.

An important concept for the development of significant land potential is integration. Integrated photovoltaics enables double land use, additional land consumption for new PV power plants is significantly reduced or completely avoided. For this purpose, PV systems specially tailored to the application are combined with agriculture, erected on artificial lakes, used as envelopes for buildings, parking lots, traffic routes and vehicles, or they provide ecosystem services on renaturalized biotope and moorland areas (Figure 29).

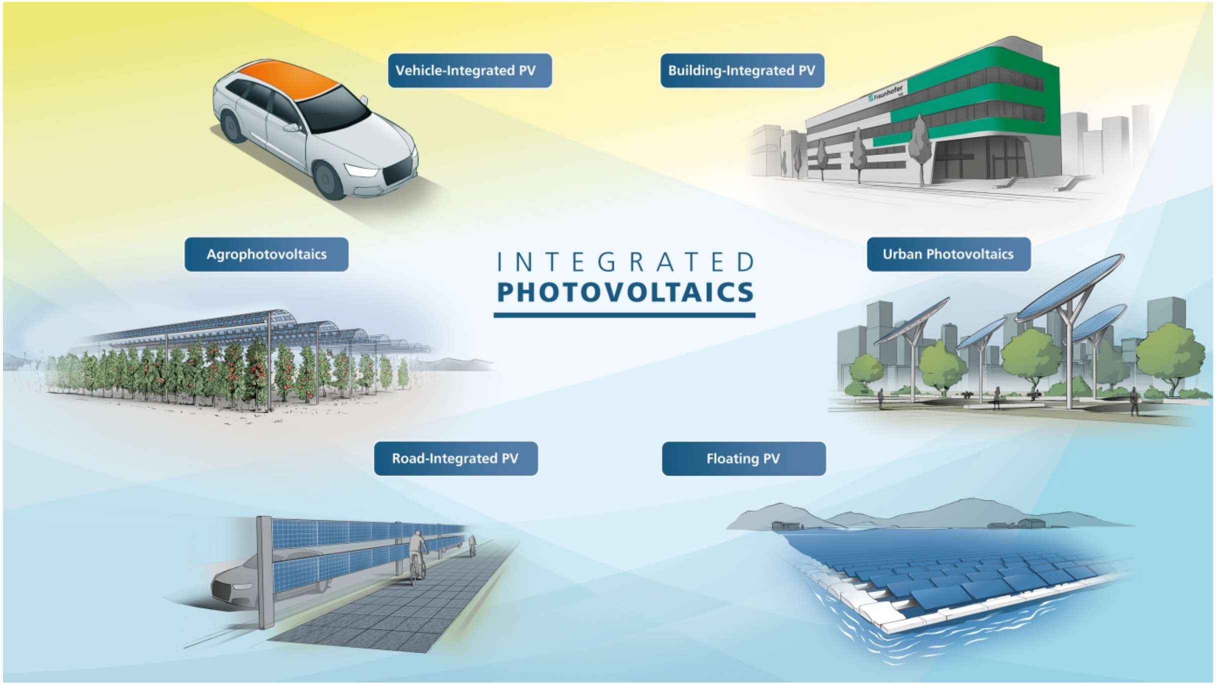


Figure 29: Applications for the integration of photovoltaic

In the following analysis of potential, a distinction is made between a theoretical, a technical and an economic-practical, feasible or exploitable potential. The **theoretical potential** considers the maximum possible implementation of a technology on the basis of the total supply (physical rough calculation). The **technical potential** is lower because it already takes basic technical constraints into account (technical rough calculation). The **economic-practical potential** takes into account all relevant boundary conditions, in particular legal (including nature conservation), economic (including infrastructure), sociological (including acceptance), as well as competing uses (e.g. solar thermal energy and PV on roofs). Different sources draw somewhat different boundaries between the categories.

The agriculturally used area in Germany is just under 17 million hectares (theoretical potential, Figure 29). **Agri-Photovoltaics** (APV, see www.agri-pv.org) uses land simultaneously for agricultural crop production (photosynthesis) and PV electricity production (photovoltaics). APV covers a wide spectrum in the intensity of agriculture and in the additional cost of PV system construction. It ranges from intensive crops with dedicated PV mounting systems to extensive grassland with marginal adaptations on the PV side and high potential for ecosystem services. APV increases land efficiency and enables massive expansion of PV power, while preserving fertile soils for agriculture or in combination with the creation of species-rich biotopes on lean soils. Worldwide, APV is already used on a GW scale; in Germany, there are only a few systems.

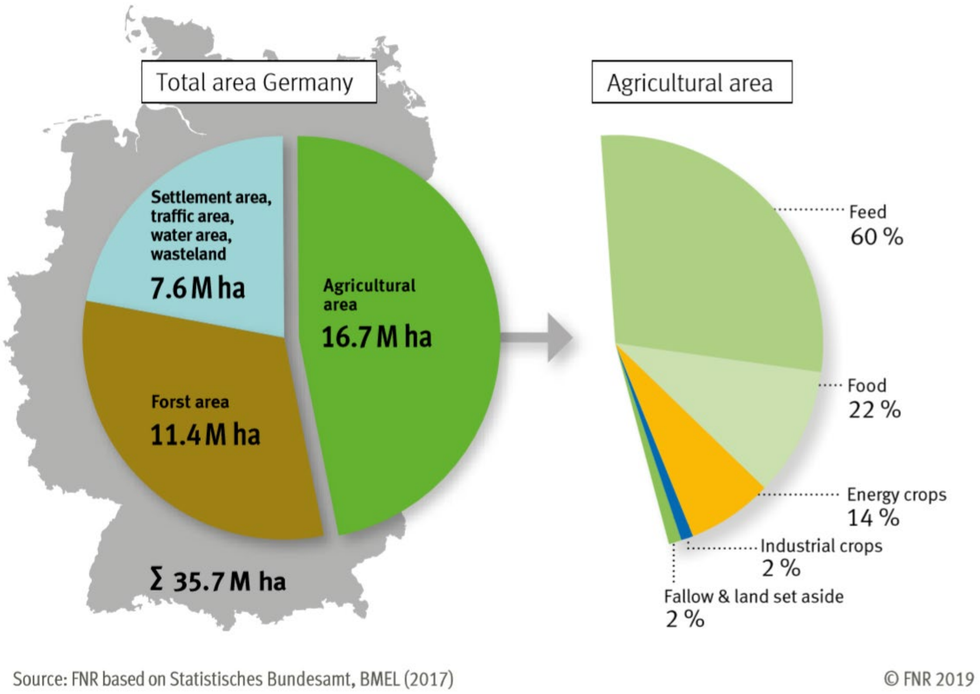


Figure 30: Land use in Germany [FNR]

Agrivoltaics with highly elevated modules allows crops to be grown partially shaded under the modules. A number of crops show hardly any yield loss with reduced irradiation, some even benefit. If permanent crops (e.g., orchards and vineyards) are considered in their entirety and arable land (excluding corn crops) is considered one-third of the technical potential, an occupancy density of 0.6 MW_P/ha results in a technical potential of **1.7 TW_P**. Modules mounted close to the ground with wide row spacing allow cultivation between rows. At an occupancy density of 0.25 MW_P/ha, the cultivation of forage crops on permanent grassland alone opens up a technical potential of a further **1.2 TW_P**.

Energy crops are grown on 14% of agricultural land (Figure 30), especially for the production of biogas, biodiesel, vegetable oil and bioethanol [FNR]. Comparing the efficiency of land use for electricity production, Agrivoltaics performs better than energy crops by a **factor of 32**. Silage corn, grown on about 1 million ha in Germany, yields 18.7 MWh_{el}/ha of electricity [FNR], compared to about 600 MWh_{el}/ha for high elevation APV. Silage corn alone is grown on 1 million ha; this area is equivalent to **600 GW_P** of rated power when converted to APV with suitable crops (or to solar biotopes, see Section 15).

Brown coal mining has destroyed an area of 1773 km² [UBA4] in Germany, more than three times the area of Lake Constance (theoretical potential). If one quarter of this area is flooded and covered with **Floating PV** (FPV) this opens up a technical potential of **44 GW_p**. Worldwide, more than 1 GW_p of floating PV systems is already installed.

Building envelopes, i.e. roofs and facades, offer a technical potential in the order of **1000 GW_p** [Eggers]. Only surfaces that receive at least 500 kWh/(m^2a) of irradiation were considered. PV modules can not only be mounted on existing flat or pitched roofs, but products for building integration (BIPV, "**Building-integrated PV**") are also commercially available. These include PV roof tiles, PV roof sheets, modules for cold facades, external thermal insulation composite systems (ETICS) with PV, opaque and transparent PV insulating glass.

A study by the German Federal Environmental Agency assumes 670 km^2 of sealed settlement areas [UBA], corresponding to **134 GW_p** of technical potential for PV installations. These include structurally characterized settlement areas, but without building and traffic areas such as roads or railways. Part of this area can be covered with PV modules as a shade dispenser or can be covered with PV modules that can be walked on (UPV, from "**Urban PV**"). The more than 300,000 larger parking spaces in Germany alone would open up a technical potential of **59 GW_P** if covered with PV modules.

Further potential on a GW scale is offered by the integration of PV into traffic routes (RIPV, from "**Road Integrated PV**"), including PV noise barriers, horizontal surfaces (as PV roofing or pavement) and rail tracks. With the shift to electric mobility, the envelope surfaces of electric vehicles are being added as vehicle integrated PV (VIPV, from "**Vehicle Integrated PV**").

Whatever part of the above-mentioned technical potential is economically and practically usable depends on complex economic, regulatory and technical constraints, in addition to questions of acceptance. In general, integrated PV - which merges with the shell of buildings, traffic routes and vehicles, or uses areas together with agriculture or water surfaces in flooded opencast mines - will have slightly higher electricity generation costs than simple open-space power plants. For this purpose, integrated PV avoids conflicts of land usage and creates synergies by replacing a building façade, using the substructure of a noise barrier or increasing the range of electric vehicles.

From a current, energy law perspective, the available potential for open space PV includes verges along highways and railways, conversion areas, and, if a state uses the state opening clause of the EEG, also disadvantaged agricultural areas. In Baden-Württemberg alone, the restriction-free area suitable for open space PV plants according to these criteria is 3850 km^2 (https://www.energieatlas-bw.de/sonne/freiflachen/potenzialanalyse). This is predominantly permanent grassland and arable land according to the state-specific "Open Space Opening Ordinance" (German FFÖ-VO). At an occupancy density of 0.6 MW_P/ha, this area absorbs 230 **GW_P** of PV, for example as agrivoltaics (Section **Fehler! Verweisquelle konnte nicht gefunden werden.**) or as a solar biotope (Section 14). Current figures for all of Germany are not yet available. A study commissioned by the German Federal Ministry of Transport and Digital Infrastructure with figures from 2014 had still estimated the expansion potential of restriction-free open spaces for PV at 3164 km2 [BMVI].

14 Do PV systems destroy ecologically valuable areas?

No, on the contrary, usually they promote renaturation.
If an area is taken out of intensive agriculture, e.g. energy crop cultivation, converted into grassland and a ground mounted PV system is installed on it, then biodiversity increases in principle [ESD]. In ground mounted PV system, no fertilizer is used, so that less demanding plants have a chance. The fencing of a ground mounted PV system protect the area against unauthorized access and free-range dogs, which is good for ground breeders, among other aspects.

Further improvements can be achieved by making small adjustments to the PV system. Enlarged row spacing of the module tables, slightly elevated mounting of the modules, sowing of wild plant mixtures instead of grass monoculture and careful maintenance of the greenery create a **biotope solar park**.

According to the German Federal Agency for Nature Conservation, peatland soils cover 1.4 million hectares in Germany, of which about 50% is used as grassland and 25-30% as arable land. The draining of peatlands for intensive agricultural use leads to a dramatic increase in their CO_2 emissions. Alternatively, on already used peatland, adapted PV power plants with reduced occupancy density could provide an area yield without intensive agriculture. The partial shading by PV counteracts the drying out of peatlands or supports the rewetting. Based on the agriculturally used peatland area of 1.1 million ha and an occupancy density of 0.25-0.6 MW_P/ha, technical potentials of **270-660 GW_P** result.

15 Do PV power plants find acceptance in the population?

Yes. The free scalability of PV power plants enables decentralized expansion, even down to so-called "balcony modules" ("plug-in PV") with a few hundred watts rated power. The high number of more than 1.7 million PV systems in Germany, of which about 60% are small systems with outputs below 10 kW, shows that extensive use is made of these technical possibilities.

According to a representative survey by Lichtblick, solar systems are among the most popular power plants [Licht2]. Figure 31 shows the distribution of the answers to the question "If you think of the construction of new plants for energy generation in Germany: What types of plants should the focus be on?”

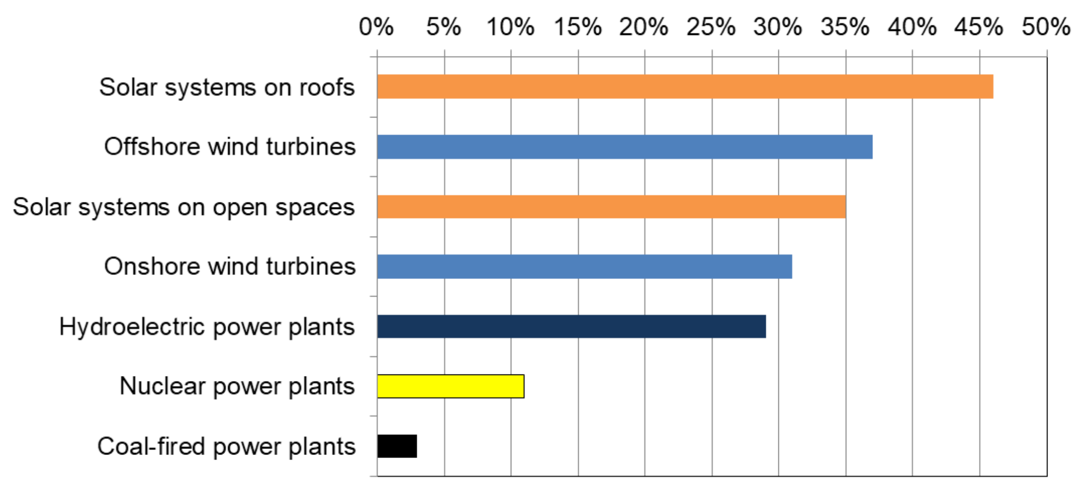


Figure 31: Results of the survey on the construction of new power plants, data from [Licht2]

Also from a residents' perspective, PV power plants are by far the most popular power plants, according to a survey by the Renewable Energy Agency (Figure 31). The popularity increases when such power plants in their own neighborhood are practically experienced.

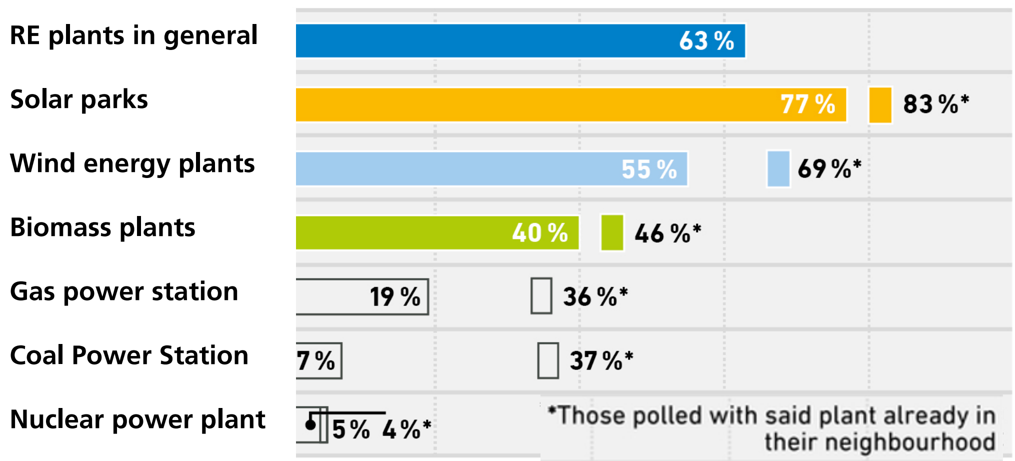


Figure 32: Survey results on the acceptance of different types of power plants [AEE4]

From the point of view of non-privileged electricity consumers, the acceptance of PV expansion is less favorable. This is not surprising, since the design of the EEG allocation mechanism means that predominantly private households and smaller companies have to bear the costs of the energy transformation (see Section 4).

16 Are PV plants in Germany efficient?

The efficiency of PV systems as energy converters is comparatively low, but the sun shines for free. The impact on efficiency in terms of cost, land use, resource use, CO_2 savings, etc. is relevant.
The nominal efficiency (see section 25.2) of commercial wafer-based PV modules (i.e. modules with silicon solar cells) in new production increased by an average of about 0.3 percentage points per year in recent years to average values of about **20%** [ITRPV]. Per square meter of module, they thus provide a nominal power of 200 W, top-class modules are 10% above this value.

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** annual average. This takes into account all losses incurred as a result of higher operating temperature, varying irradiance conditions, dirt on the solar modules, line resistance, conversion losses in the inverter and downtime. 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.

In 2018, the average household electricity consumption for electrical appliances, lighting, hot water (for hygienic purposes) and domestic heating was **1.6 MWh** per household member [DESTATIS]. Average values for 1-person households are slightly higher per capita, for multi-person households significantly lower. On average, PV roof systems achieve **910 full load hours** [TSO] (Section 16.3.). From a south-facing and moderately inclined roof surface of a house, 22 m^2 are thus sufficient to generate an amount of electricity with 12 PV modules of 360 W, which corresponds to the average annual electricity demand of a family (4 MWh).

To increase yield, PV modules are optimally tilted on flat roofs and open land to achieve the highest yield. Because of the spacing required for this, they occupy several times their own area when oriented south, depending on the angle of installation. Today, PV ground-mounted systems are usually built with reduced tilt angles (approx. 20°-25°) and row spacing, resulting in an occupancy density of around 1 MW/ha at module efficiencies of 20%. In 2010, this value was still 0.35 MW/ha [ZSW]. With regard to an optimal development of biodiversity, larger row spacing is advantageous (Section 14).

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 results in modest efficiencies in relation to the irradiated energy and land use.

A passenger car with a diesel combustion engine consuming 5.5 l biodiesel per 100 km travels approx. 32000 km with the annual yield of a 1 hectare rapeseed field of 1775 l/(ha*a) [FNR]. With the annual yield of a new PV plant (1 MW/ha, 980 MWh/MW) on the same area, a battery electric vehicle (e-car, consumption 16 kWh per 100 km) travels approx. 6.1 million km, the range is higher by a **factor of 190**.

While southern Spain and North Africa are able to produce specific yields of up to 1600 kWh/kW_p, the power transmission to Germany would result in energy losses and additional charges. With 800 kV high-voltage lines, line losses can be reduced to about 0.5 % per 100 km. 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.

16.1 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 by Fraunhofer ISE of 44 larger, quality-tested rooftop systems in Germany has shown an average annual degradation of the nominal output of about 0.15% [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 e.g. 20 % within this period.

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

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.

16.2 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 (approx. 10° and less) or those located in the vicinity of deciduous trees or sources of dust. In regions that are increasingly suffering from drought due to climate change, it may be worthwhile to clean the modules from time to time.

16.3 Do PV plants often operate at full capacity?

No. 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.

The performance indicator «full-load hours" or "full hours of use" is the quotient of the actual energy generated by a power plant in the space of a year and its rated power (kWh/kW_P, see section 25.3). Based on a trend scenario, the transmission system operators (TSOs) assume 980 full load hours on a multi-year average for PV ground-mounted systems in Germany and 910 hours per annum for roof-mounted systems with less optimal southern orientation [ÜNB].

The complete overview of the forecasts for electricity generation from RE, adjusted for loss quantities due to feed-in management (Section 11.1), is shown in Figure 33. Due to the low full utilization hours, growing shares of solar electricity in the grid increasingly require accompanying measures (Section 19).

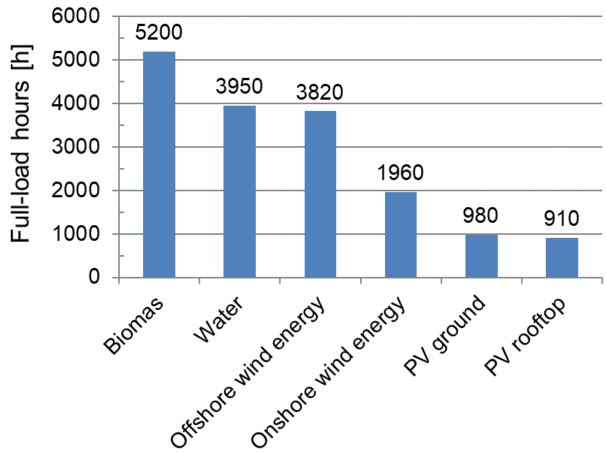


Figure 33: Forecasted hours of full-load operation for renewable energy generation in 2020, data from [ÜNB]

The average annual sum of horizontal global irradiance in Germany for the years 1998-2018 is 1088 kWh/m²/a with a linear trend of +0.3% per year according to figures from the German Weather Service. Figure 34 shows the irradiance distribution across Germany for an earlier period, with an average annual sum of 1055 kWh/m² at that time. In order

to maximize yields, PV modules are oriented facing south and are installed with a tilt angle 30–40° to the horizontal. This increases the average incident irradiation to roughly 1250 kWh/m^2 per year throughout Germany.
A performance ratio PR (see section 25.6) of 85 percent and an ideal orientation would result in a geographical average across Germany of more than 1060 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 19.3.1)
- 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, as far as there is sufficient cooling water available.

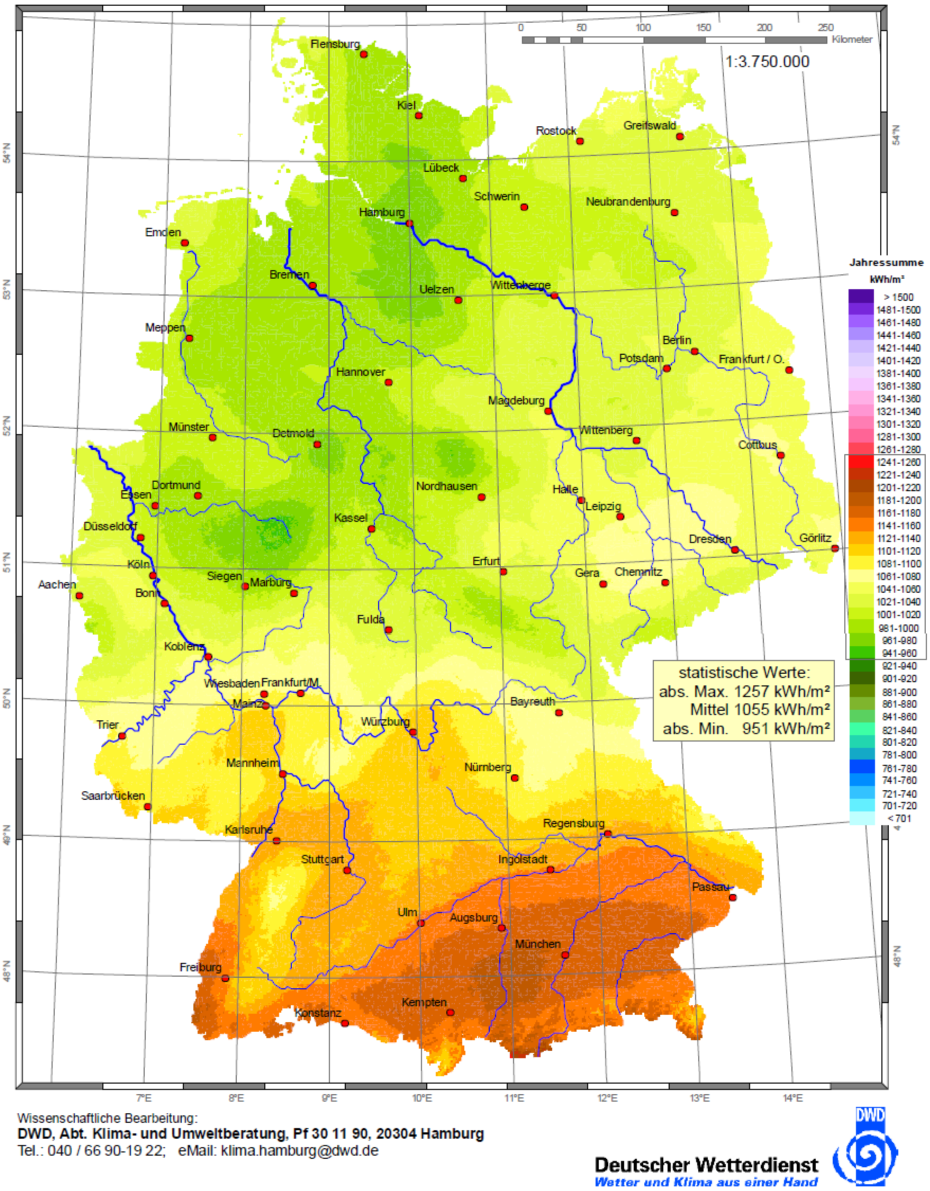


Figure 34: Horizontal annual global irradiation in Germany averaged over 1981-2010

17 Does PV make relevant contributions to climate protection?

17.1 Do anthropogenic CO_2 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 CO_2 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 35 and
Figure 36 show the development through today of the atmospheric CO_2 concentration and the global or Antarctic temperature to date.

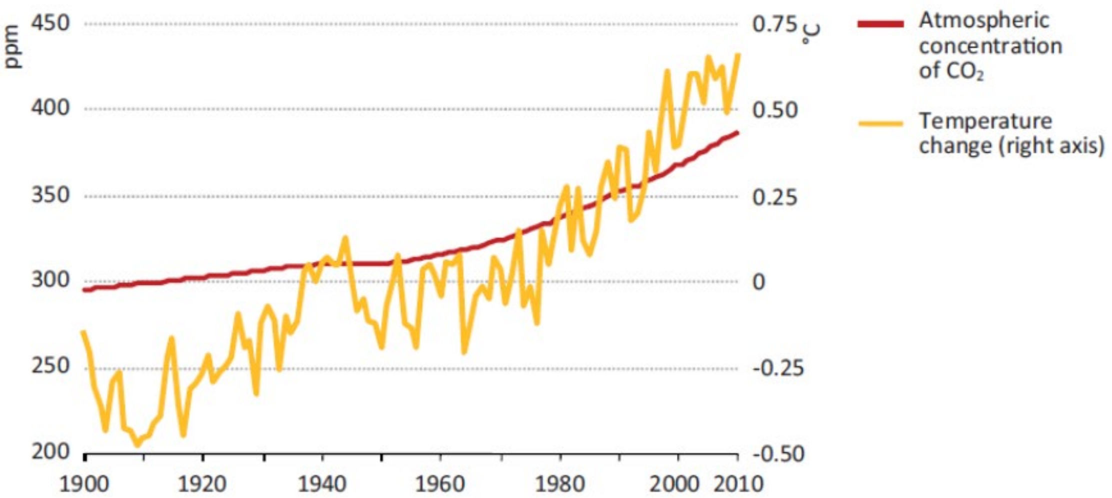


Figure 35: Development of the atmospheric CO_2 concentration and the mean global temperature change based on the NASA Global Land-Ocean Temperature Index [IEA2].

A more rapid increase in global temperature dangers the stability of the global climate system to an extent that is not fully understood today. The temperature increase has far-reaching effects on the global food security, coastal settlements, diversity of species and numerous habitats.

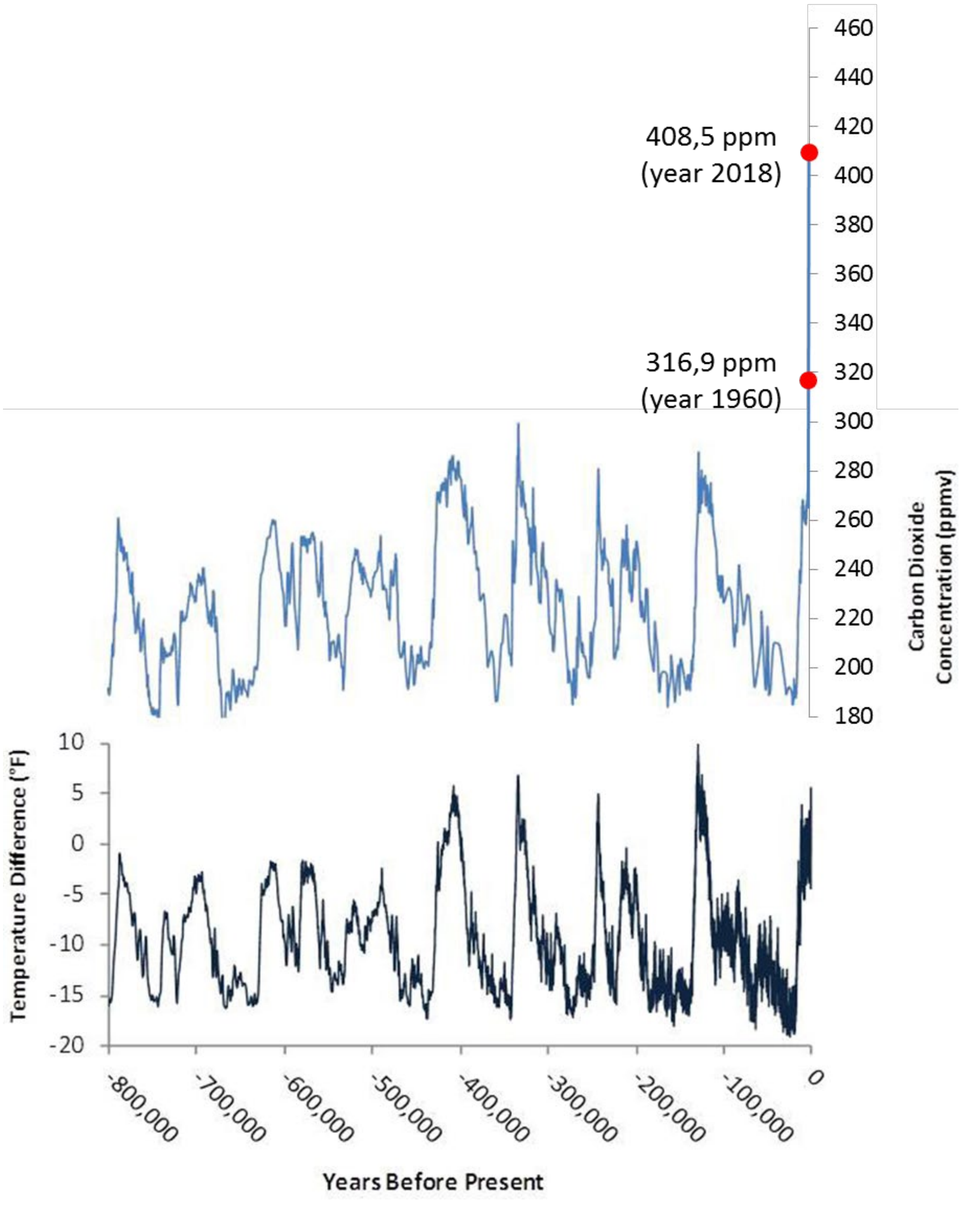


Figure 36: Estimate of the atmospheric CO_2 concentration and the temperature difference in Antarctica based on ice core data [EPA]; red dots: two recent measures of CO_2 concentration from Mauna Loa Observatory [https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html]

17.2 Does PV make a significant contribution to reducing the CO_2 emissions?

Yes.

While PV systems do not release CO_2 during operation, a holistic view must also take into account the manufacture of the system and its disposal. If one considers the life cycle of a photovoltaic roof system operated in Germany, plausible estimates lie between approx. 50 (Figure 37, [EnAg]) and 67 g CO_2 eq./KWh solar power [UBA7]. With increasing efficiency and the spread of new technologies such as diamond wire saws, greenhouse gas emissions from PV production have continued to decrease in the recent past.

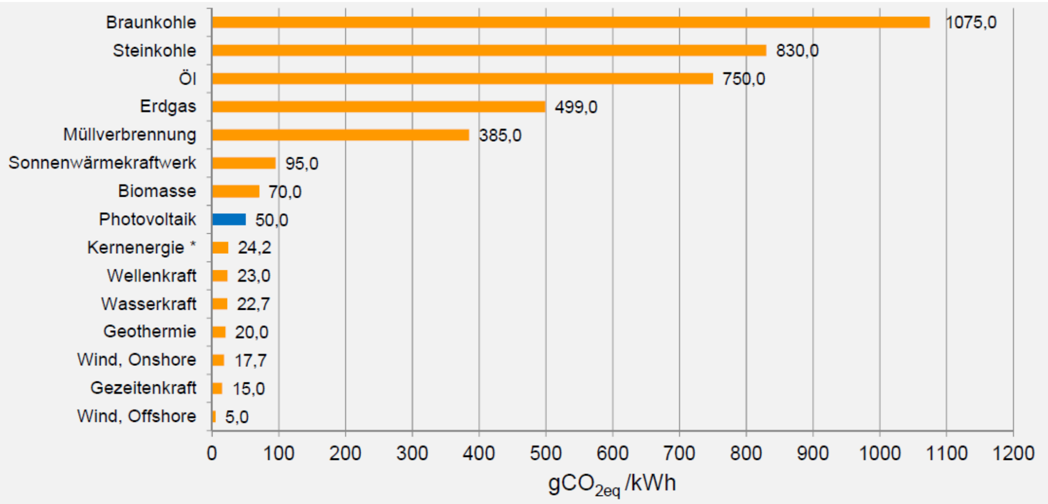


Figure 37: Average CO_2 equivalent emissions of various power generation technologies [EnAg]

By expanding RE, the CO_2 emission factor for electricity generation in Germany could be reduced to 474 g CO_2/kWh by 2018 (Figure 38).

The expansion of RES has reduced the CO_2 emission factor for the German electricity mix from 764 g CO_2/kWh in 1990 to 474 g CO_2/kWh in 2018 (Figure 38). The emission factor describes the ratio of the direct CO_2 emissions of the entire German electricity generation (including electricity export) to the net to electricity consumption in Germany [UBA6].

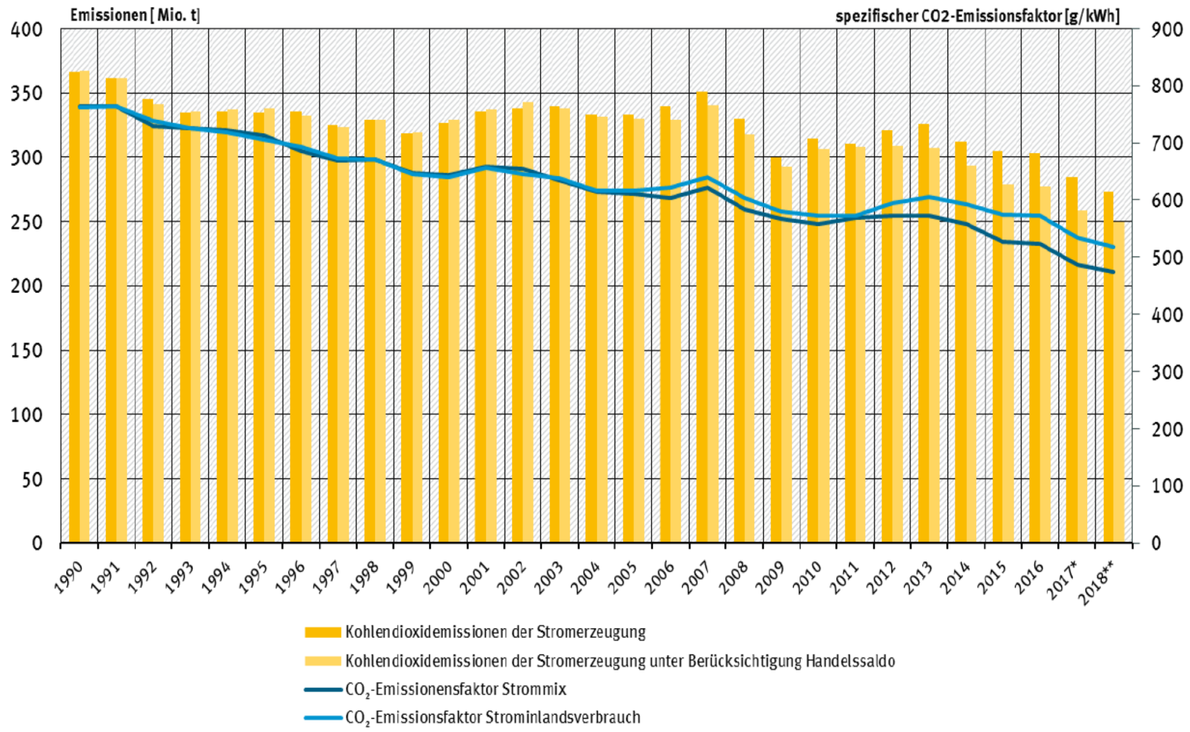


Figure 38: Specific and absolute CO_2 emissions of electricity generation in Germany [UBA6]

In 2020, the use of PV in Germany avoided a net 34.9 million tons of greenhouse gas emissions (Figure 39), i.e. approx. 690 g/kWh of PV electricity from 50.6 TWh of generated electricity. In the calculations, the emissions from the production of PV system components were taken into account approximately [UBA7].

Germany's energy policy has influence on a global scale. With a production volume of 171 million tonnes in 2016, Germany was the number 1 international lignite mining company, ahead of China. 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.

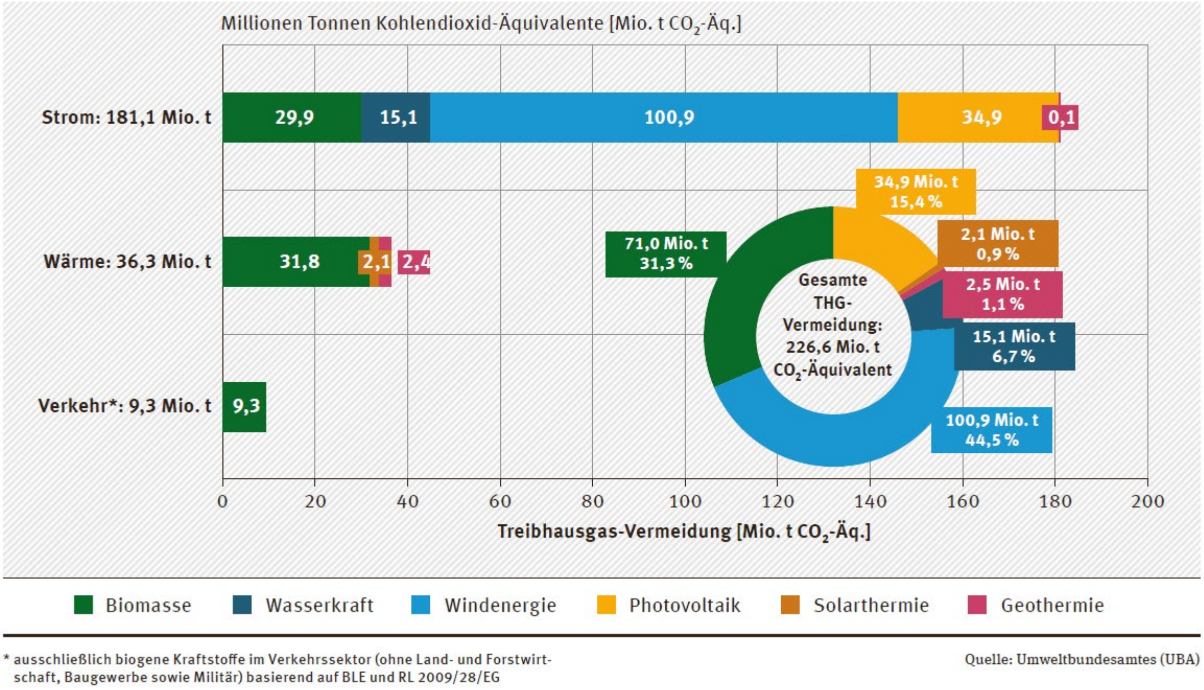


Figure 39: Greenhouse gas emissions avoided by using renewable energy in 2020 [UBA1]

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 CO_2 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 40). Worldwide PV is reducing the use of fossil fuels for electricity production.

Fraunhofer ISE

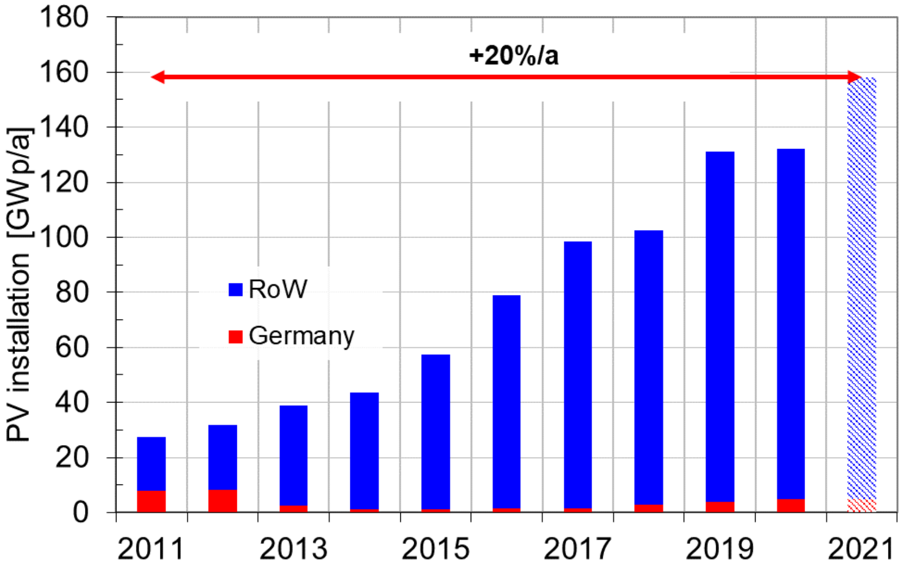


Figure 40: Development of annually installed PV capacity for Germany and the Rest of World, (RoW), figures from EPIA , IHS, Solar Power Europe, with forecast for 2021.

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 CO_2.

17.3 In addition to CO_2 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 (NF_3) is still used, in part, to clean the coating systems. Residues of this gas can thereby escape into the atmosphere. NF_3 is more than 17,000 times as harmful to the environment as carbon dioxide. Current emission quantities are not known. As of 2013, however, NF_3 emissions are to be determined in 37 countries according to the revised Kyoto Protocol.

17.4 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, meadow below 20 percent, and the desert ca. 30 percent (http://wiki.bildungsserver.de/klimawandel/index.php /Albedo). In consideration of the relatively low amount of area required by PV modules (Section 13), the albedo effect is marginal. Furthermore, PV electricity use replaces the power from fossil fuel plants, reduces carbon emissions and thus slows down the greenhouse effect.

18 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 CO_2 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 can reach 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 19.3.6).

19 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.

19.1 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 41).

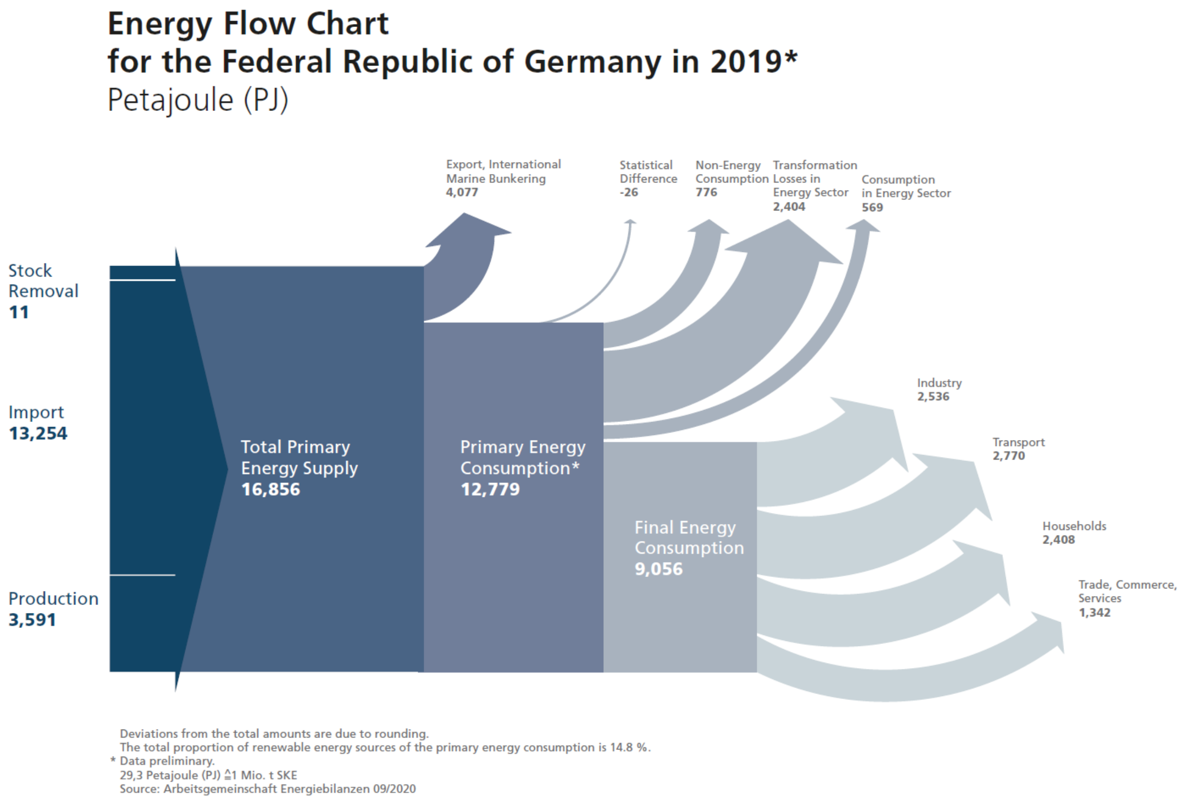


Figure 41: Energy flow diagram 2019 for Germany in petajoules [AGEB].

There are dramatic efficiency deficits in conversion and final energy consumption (cf. Section 19.3.3). Our future energy demand is by no means the same as today's primary energy consumption, neither in terms of quantities nor in terms of energy carriers.

Until now, Germany has been highly dependent on energy imports (Figure 42), associated with the risk of volatile prices, political interference by mining and transit countries, and the risk of disruptions in raw material logistics, for example due to low water in rivers.

Fuels	Net import rate 2016 (based on the primary energy consumption)
Brown coal	-1.9 %
Hard coal	94.1 %
Uranium	100 %
Mineral oil	100 %
Natural gas	91.2 %

Figure 42: Germany’s import quotas for fossil and nuclear energy sources (www.umweltbundesamt.de)

The costs of energy imports are shown in Figure 43, minus their import revenues, which are around 50-100 billion euros per year. Much of the money goes to autocratic regimes.

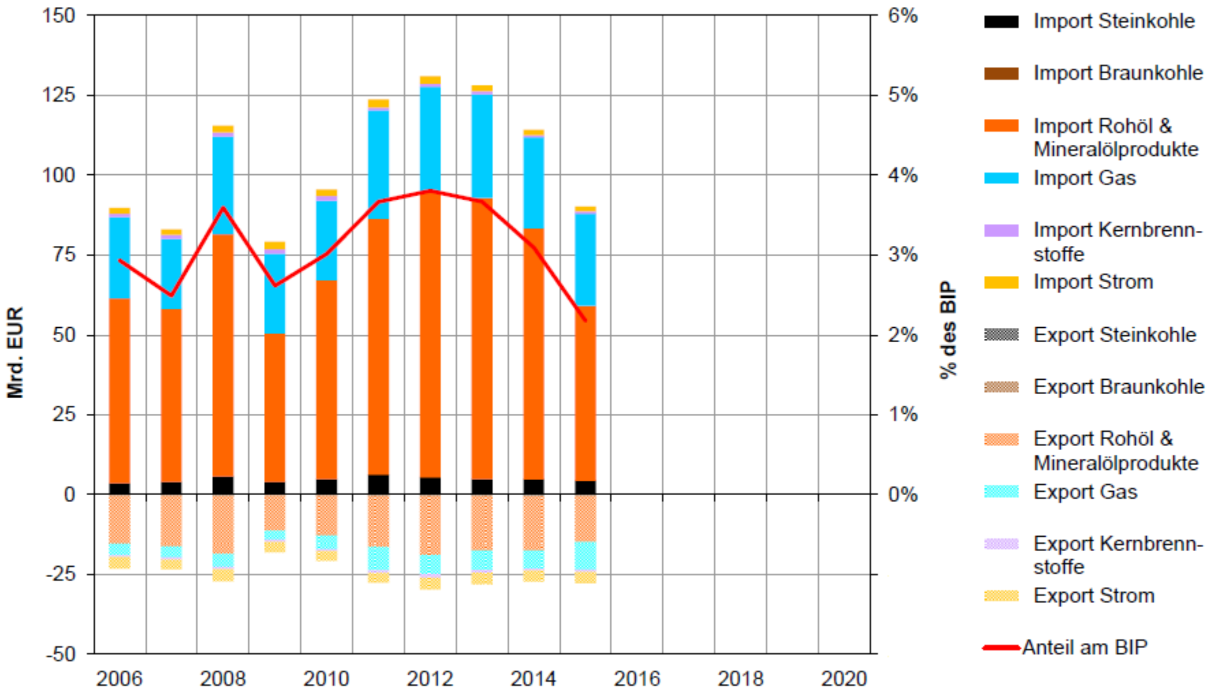


Figure 43: Cost development for the provision of primary energy in Germany [ÖKO3]

The majority of final energy (39 percent) is used to generate mechanical energy (force) for vehicles and stationary engines (Figure 44). For space heating and hot water, about 800 TWh of final energy is used annually [BMWi1].

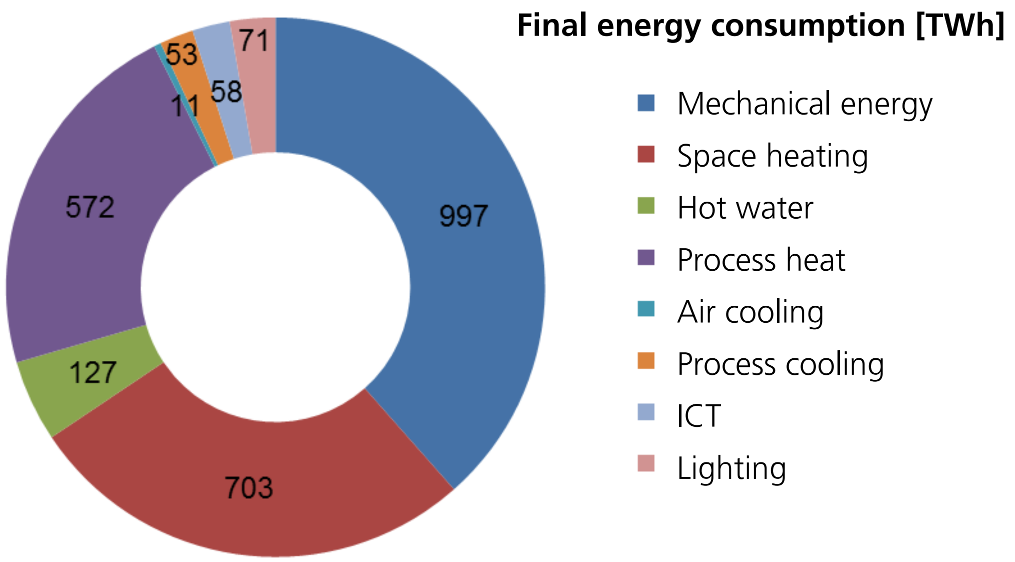


Figure 44: Share of final energy in Germany, categorized by utilization 2017, Figures by [BMWi1]

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 25.7. 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 petroleum sales (petrol and diesel fuel) show very low seasonal fluctuations [MWV]. The heating demand correlates negatively with global irradiance, with the highest point of intersection being found in spring.

19.2 Energy scenarios

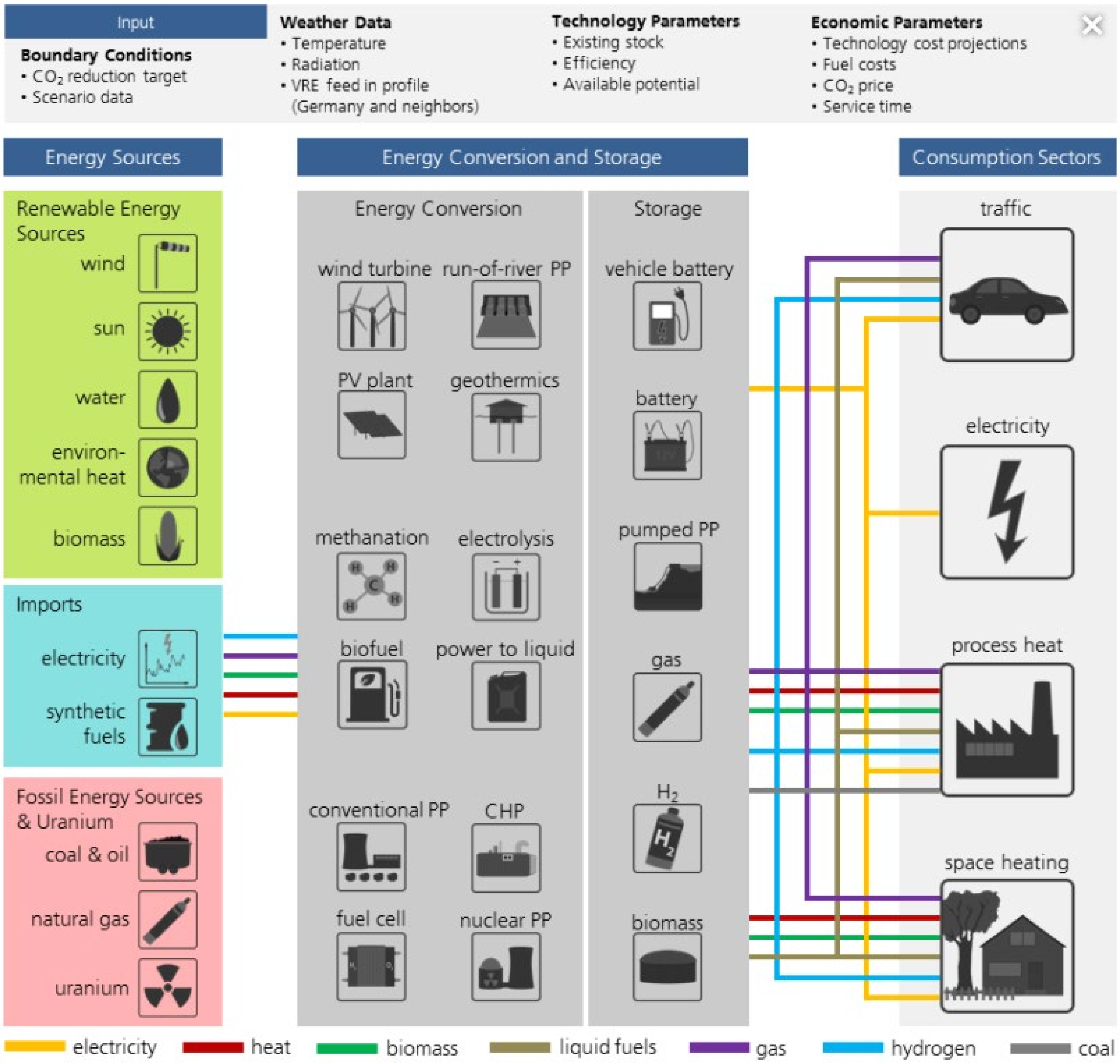


Figure 45: Schematic representation of the REMod model [ISE12]

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, ISE12]. Researchers at the Fraunhofer Institute for Solar Energy Systems ISE have used simulations, based on hourly time series and taking into account sector coupling, to investigate various transformation paths to a renewable energy system for Germany (Figure 45). The goal was to reduce the energy-related CO_2 emissions by 95-100% compared to the reference year 1990. In an economically optimized generation mix, the PV contributes with an installed capacity of 300-645 GW depending on the boundary conditions [ISE12].

Figure 46 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 (section 11.4) for one year. 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 reasonable tax function would fall from left to right along the residual load curve in Figure 46.

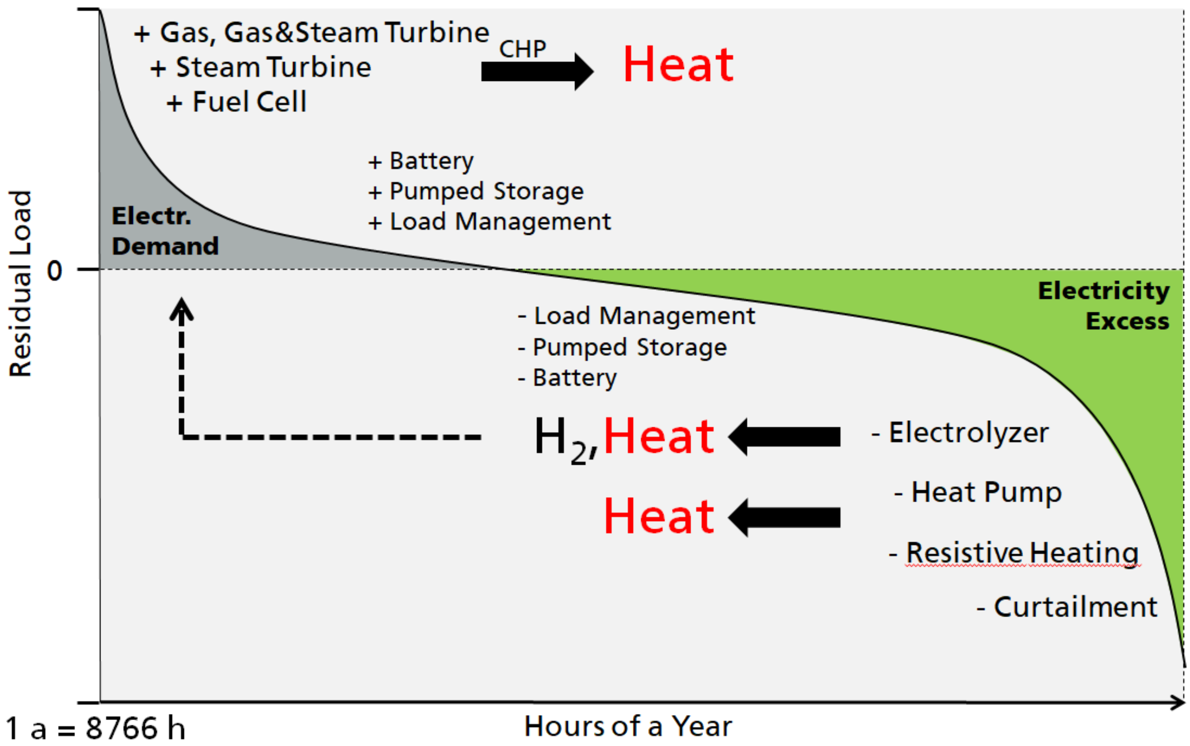


Figure 46: Schematic representation of a residual load curve for Germany with power supply with 100% EE, with generators (+) and loads (-)

On the **demand side**, flexible loads are reduced, batteries and pumped storage are discharged, fuel cells, steam turbines, gas and steam generators (CCGT) and gas turbines are activated in the order of their marginal costs to cover the residual load. Hydrogen or methane, produced with EE, is used as an energy source. When there is local demand for heat, power generators are designed with combined heat and power (CHP) and produce usable waste heat. CHP gas turbines provide high-temperature heat for industrial processes.

On the **surplus side**, flexible loads are increased, batteries and pumped storage are loaded, electrolysers, heat pumps and resistance heating ("heating elements") are activated when electricity prices are falling in order to decrease the electricity that is not currently required. Electrolysers can also be operated as CHP systems and produce usable waste heat. Resistance heaters and high-temperature heat pumps can supply heat for industrial processes. Ultima ratio is the regulation of electricity production, if the installed purchase capacity or the network capacities are not sufficient for a few hours of the year. In order to be able to operate heat-generating converters (Figure 46) 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 networks (Section 19.3.6). Generators (eg simple gas turbines) and consumers (eg resistance heating systems) with particularly low performance-related investment and reserve costs (€ / W) are needed for the two-sided extensions of the residual load curve. Being rarely in operation, they do not have to be highly efficient.

The electrolytically generated **hydrogen** can be stored directly or after methanation in pressure tanks or in the gas network. From there, a back-flow takes place (gas turbine, CHP, fuel cell), a further processing to synthetic fuels or a material use in the chemical industry.

The **storage capacity** of the system must be designed for the worst case of a primary energy failure (sun and wind) lasting several weeks, i.e. a prolonged winter slack, possibly worsened by a closed snow cover. For this, sufficient quantities of hydrogen and derived synthetic energy sources and feedstocks must be kept on hand. If there were no wind power support for PV, the worst case would last months, not weeks, in winter, and it would require many times more storage capacity. Because of their limited capacity, stationary batteries and pumped storage fail relatively quickly (minutes to a few hours) as power suppliers in continuous operation. The same applies to vehicle batteries, which can be operated bidirectionally on the grid but must primarily meet mobility needs. The benefit of these storage systems lies in the frequent change of operation between charging and discharging, which they implement more quickly and, above all, more energy-efficiently compared with the power-to-power path via hydrogen. Many load management options also only have a short effect in the hourly range.

The **power generation capacity** of the system on the left side of Figure 46 must be sufficient to take over the entire supply in the order of 100-150 GW when the hourly reserves (load management, pumped storage, battery) are exhausted. This situation occurs frequently for example on nights with little wind and may in some cases last over several weeks (see above).

The **power consumption** of the system on the right side of Figure 46 in the order of several 100 GW must be sufficient to largely absorb the production of electricity from volatile RE minus the current power consumption. The power consumption starts as soon as the capacity of the hourly reserves (load management, pumped storage, battery) has been exhausted. This requires, among other things, an electrolysis capacity in the range of 50-120 GW [ISE12]. If the power consumption is insufficient for rare production peaks, power generation must be regulated. This can happen, for example, on stormy nights or on sunny and at the same time very windy weekend days, when low demand and very high electricity production come together. For these few operating hours, no further expansion of the acceptance performance is worthwhile.

Converter, that allow a reversible operation work on both sides of the curve in Figure 46 and thus achieve a higher utilization. In addition to batteries and pumped storage, this also includes reversible fuel cells that are operated as electrolysers when there is an excess of electricity. They are currently under development.

Converters that allow reversible operation operate on both sides of the curve in Figure 46 and achieve high utilization. In addition to batteries, this also includes reversible fuel cells that can operate electrolysis in the event of excess electricity. The technologies and measures mentioned in Figure 46 are scalable, with the exception of turbines and pumped storage. They can not only be operated centrally on a multi-MW scale, but also on a single-digit kW scale. Appropriate devices are commercially available as domestic technology.

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 47). Global electricity consumption will rise from 22 PWh today to 100 PWh in 2100.

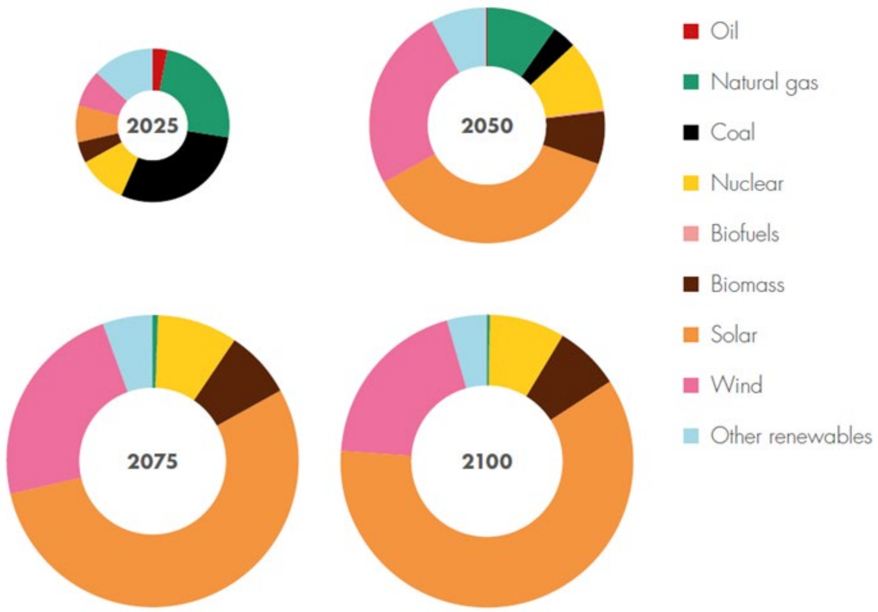


Figure 47: Development of global power generation by technologies in the Sky-Scenario; the diameter of the pie charts corresponds to the global power requirement [Shell]

The International Energy Agency (IEA) has been publishing scenarios for the worldwide expansion of PV (
Figure 48) for years and reliably underestimates the actual development (black curve). IEA expects that the worldwide installed PV output will overtake wind power in 2020, hydropower in 2027, coal power in 2032, gas power in 2035 and reach an order of magnitude of over 3 TW by 2040 [IEA5].

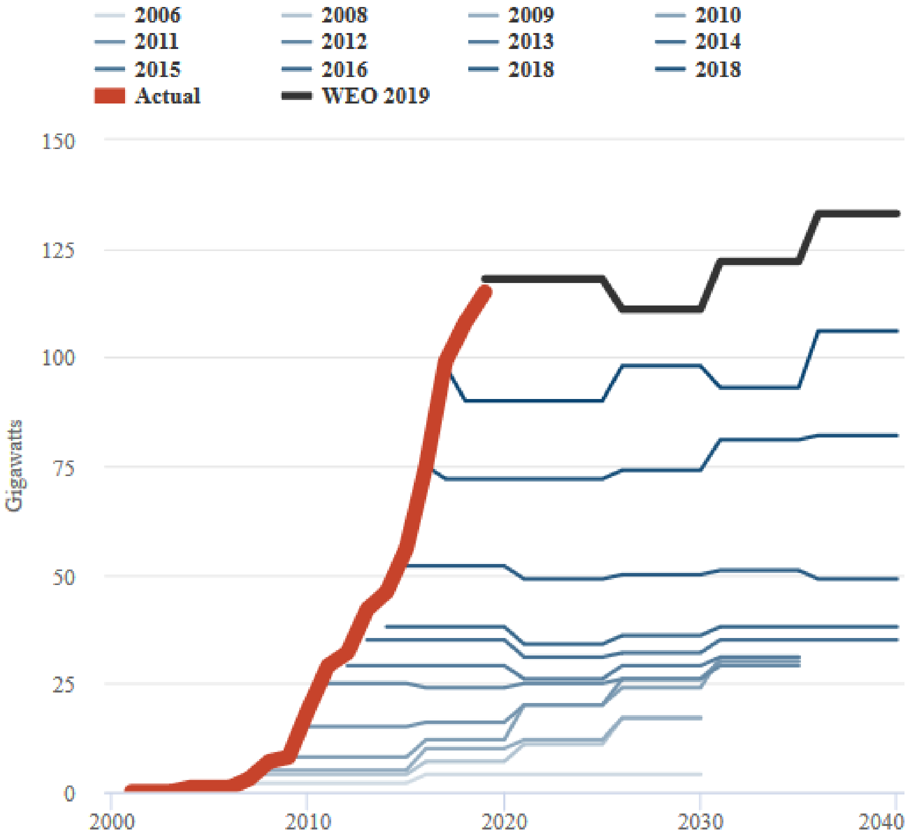


Figure 48: Forecasts of IEA since 2006 and actual development of global annual PV construction [Carb]

19.3 Transformation 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.

19.3.1 Keeping PV power production constant

How can we keep the PV power supply constant in the grid?

A constant level in the daily run increases the full load hours of a PV power plant and reduces the need for compensation, 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 47). 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 47), 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.

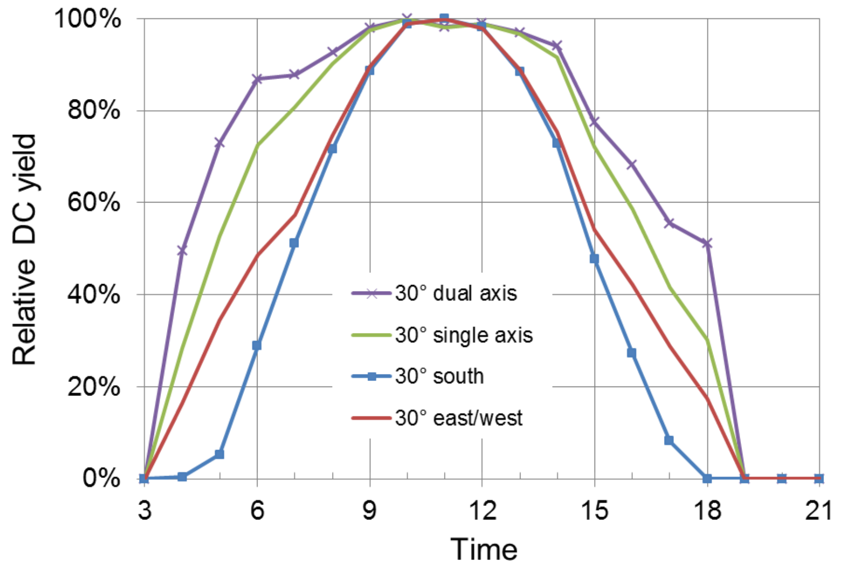


Figure 49: Yield development throughout the course of a day of PV plants installed in a variety of different ways, calculated using the software PVsol on a predominantly clear day in July in Freiburg, Germany.

The very pronounced seasonal fluctuation in PV power generation can be minimized by mounting south-facing modules with higher angles of inclination (Figure 49). 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%).

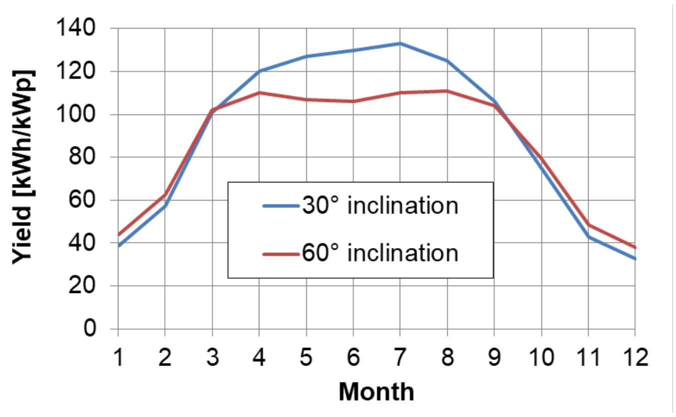


Figure 50: Calculation example for the specific monthly yield of a PV system at Freiburg for south-oriented modules with 30° inclination (maximum annual yield) and 60° inclination.

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 16.3 also contribute to the stability of the PV electricity supply.

19.3.2 Complementary operation of 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 51). 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 have only a fraction of the investment costs (€/kW) of combined cycle (gas and steam) power plants (CCPP).

Today, gas-fired power plants burn natural gas and biogas. Most of the natural gas must be imported (about 95% in 2017 [AGEB1]), in particular, Russia and Norway deliver to Germany. As part of the energy transformation, gas power plants will switch from natural gas to mixed gases with increasing proportions of electrolytically generated hydrogen.

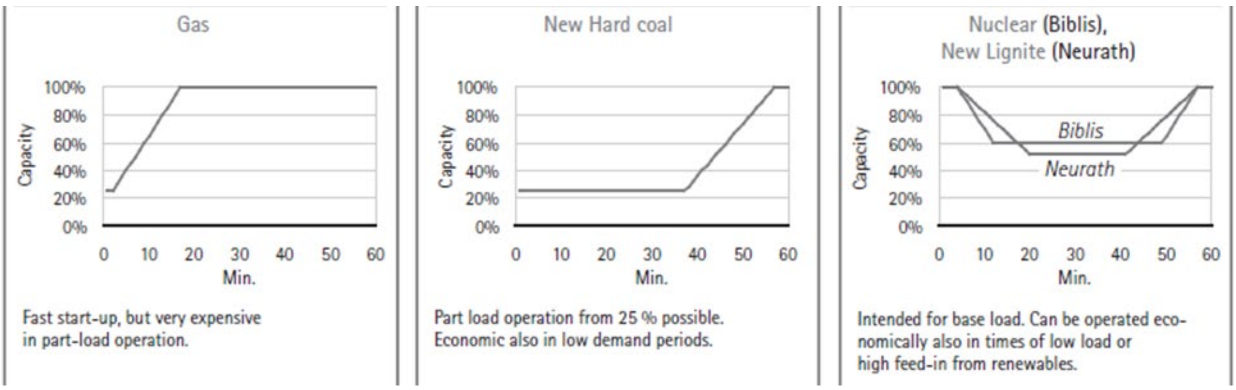


Figure 51: Power plant availability [VGB].

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 2019 biomass power plants with 8 GW_p 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. An agricultural cultivation of biomass for the purpose of energetic usage will decrease due to the low efficiency of area, the usage will concentrate on residues of agriculture. Economically, a complementary partial load operation is feasible if the feed-in tariff rises at times of increased electricity demand.

Power plants for complementary operation must meet the following criteria:

- high efficiency, also in partial load operation
- fast load changes
- increasing hydrogen percentage in gas-fired power plants
- decreasing shares of biomass from associated agricultural cultivation

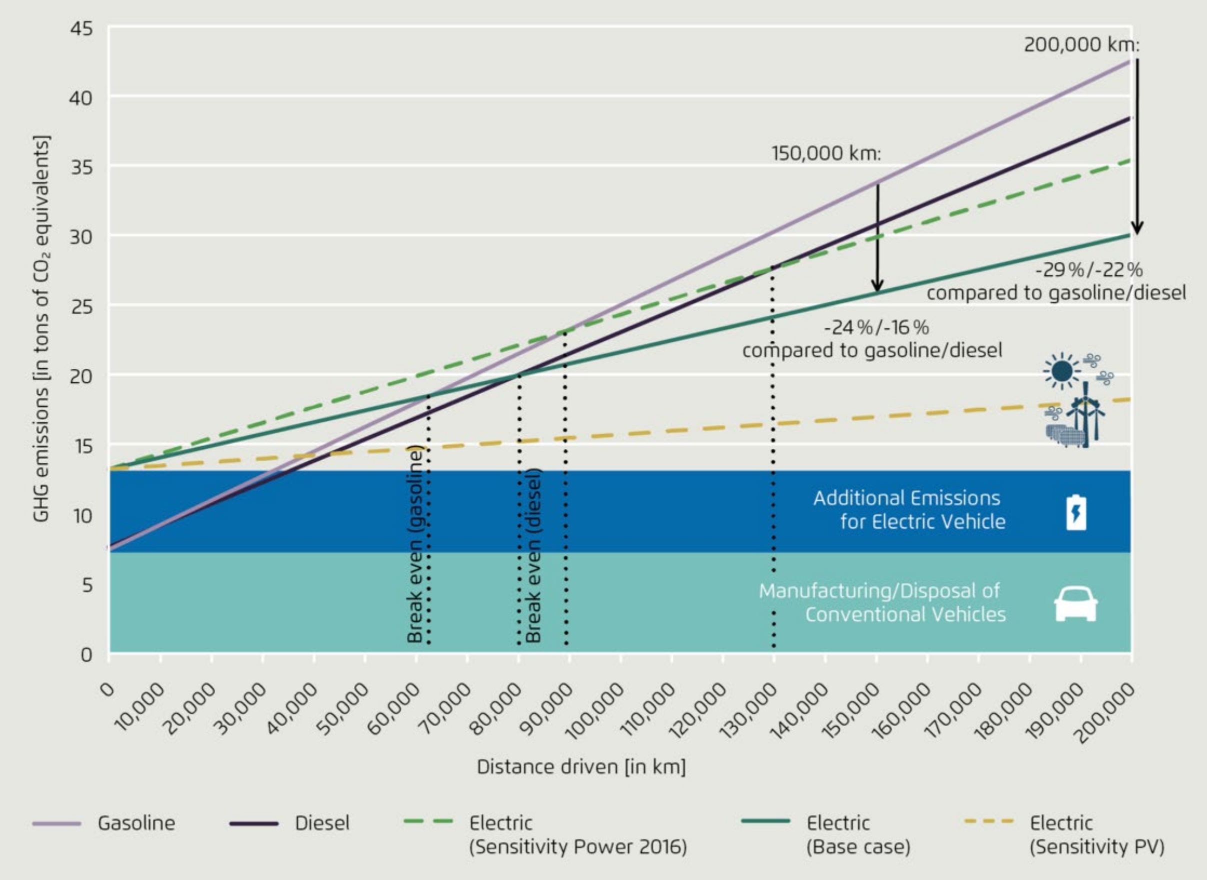
19.3.3 Increasing the energy efficiency

19.3.3.1 Traffic

Most of the final energy consumed in traffic is converted into waste heat by combustion engines; only a small part reaches the drive train as mechanical energy. Diesel engines for passenger cars achieve an efficiency of up to approx. 42% at their best, while in urban traffic the average efficiency is only approx. 20% due to partial load operation [Sprin]. The values for gasoline engines in passenger cars are even lower, at up to 37% at the peak and approx. 10-15% in city traffic. Particularly in urban traffic, a considerable portion of the drive energy gained is irreversibly wasted during braking, because vehicles with internal combustion engines can hardly recuperate via their alternators. Thus, motorized road transport burns fossil fuels with a very low efficiency in relation to the transport performance.

Electric vehicle drives use highly efficient motors with an effective efficiency of around 90%. Losses during charging of the vehicle battery are in the order of 15% and are particularly high during fast (DC) charging. Electric vehicle drives can recover a large proportion of kinetic energy; according to the manufacturer, the efficiency of recuperation for the BMW i3, for example, is around 63%. For reasons of energy efficiency alone, it makes sense to switch to electric drives, in addition to the considerable storage potential (Section 19.3.7.6).

Figure 52 shows the complete greenhouse gas emissions of a battery electric vehicle (BEV) with a 35 kWh battery over the mileage for mixed urban/rural use, compared with a gasoline and a diesel car, with 3 variants for the electricity mix.



Note: Power generation mix based on Pehnt et al. (2018); Consumption data: electric vehicle: 16 kWh/100 km (without charging losses); gasoline car: 5.9 l/100 km; and diesel car: 4.7 l/100 km.
IFEU calculations

Figure 52: Greenhouse gas emissions of today's compact-class vehicles as a function of mileage [AGORA2]

Preferred charging with solar or wind power (see Section 19.3.7.5) leads to a particularly flat course of the BEV emission line (yellow). If the BEV is purchased together with a small PV system of 3 kW_p nominal power, the vehicle runs on 100% solar power, with an average annual mileage of over 15000 km, a specific annual yield of 950 kWh/kW_p and 15% charging losses. Considering pure city driving with typical stop-and-go operation, consumption and GHG emissions per km decrease for BEVs thanks to recuperation, while they increase for internal combustion vehicles due to braking losses and inefficient partial load operation. For city driving, smaller batteries of e.g. 15-20 kWh capacity are usually sufficient, which further reduces GHG emissions for production and operation.

Recent studies show an interim reduction of battery-related GHG emissions to values of 61-106 kg CO_2-eq/kWh battery capacity [IVL], compared to the 145 kg CO_2-eq/kWh from 2017 on which Figure 52 is based. In perspective, the production of BEVs will use increasing shares of RE with correspondingly decreasing GHG emissions.

The CO_2 balance in comparison with gasoline and diesel cars can be evaluated as follows: an electric car with a small battery, which mostly drives in towns, prefers to charge renewable electricity and covers many (necessary) km per year, has a particularly clear advantage in terms of the GHG balance. For weekend drivers with a large battery and a high share of highway trips, the advantage shrinks.

19.3.3.2 Households

Private households consume about 75% of final energy for heating. This consumption can be halved by simple thermal insulation measures. The German consumer organization Stiftung Warentest has determined that a household completely equipped with old appliances consumes twice as much electricity as one that uses only efficient appliances [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 via comparatively costly storage.

19.3.4 Load management

Demand side management aims at a supply-oriented, temporal shift of electricity consumption. When the residual load is high (section 11.4), consumption is temporarily reduced or stopped; when the residual load is low, demand is made up.

Requirements for load management are flexibility options through **material storage** or reserves on the demand side. A washing machine can often wait a few hours or even days, while a passenger train must depart on time. In addition, electrical systems in continuous operation require **power reserves** that allow a compensating increase above normal power after a reduction below normal power. Energy storage systems are considered in Section 19.3.7. They are charged in a way that serves the grid (e.g., pumped-storage power plants) or at least takes grid service into account (in the future, e.g., car batteries).

Several studies have identified load management potentials in the order of 20 GW and more for private households and up to 14 GW for commercial consumers [AEE1]. Household appliances, whose operation is allowed to start with a delay in a defined time interval according to the user's decision, must be technically enabled to wait for grid-serving operating times. The electricity supplier can offer time-based tariffs for this purpose, but direct control is even more effective. Some appliances with particularly high output, such as washing machines, dishwashers and tumble dryers, could be considered for this.

For the most part, the technical prerequisites and economic incentives for tapping this potential have yet to be created. Dynamic electricity tariffs and electricity meters that enable time-based billing ("smart meters") are of crucial importance. In the best case, dynamic tariffs reflect the current residual load. The current composition of electricity prices for households (Figure 12), with very high fixed costs per kWh, would hardly create incentives for load management given the usual price fluctuations on the electricity exchange. According to the EU Electricity Market Directive 2019/944, end customers with smart meters should be able to choose dynamic electricity tariffs from Jan. 1, 2021.

In electricity-intensive industry, for example electrolytic aluminum production, there is also potential for adjusting consumption profiles. Companies that accept temporary power cuts in electricity supply announced at short notice can already receive a contractually agreed compensation payment from their transmission system operator (Verordnung über abschaltbare Lasten – AbLaV, Ordinance on Disconnectable Loads). The electrolytic production of green hydrogen as a raw material for metallurgy, e.g. for the direct reduction of iron ore, and the chemical industry, e.g. via methanation and ammonia synthesis, will also contribute to load management.

As soon as particularly cheap daily electricity is available more frequently, because the installed PV capacity grows and variable electricity tariffs are offered, flexibility on the part of industry and consumers will also increase. Self-consumption of solar power has an analogous effect to dynamic electricity tariffs because it significantly reduces the price of electricity when purchased directly from one's own roof. Promoting PV self-consumption for households and businesses is a highly effective means of incentivizing load management.

19.3.5 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. The amount of energy that would have to be curtailed above 50% of the total rated output is less than 1 per mille of the total annual generation. Curtailment beyond 40% of the total rated power would affect less than 1% of electricity production. Even on a monthly basis, the sum of electricity production from PV and onshore wind over the year is more even than the production of the two sectors alone (Figure 25).

19.3.6 Cogeneration of power and heat

Low-temperature heat for space heating and hot water, as well as industrial process heat at a high temperature level are still largely obtained today through the combustion of fossil resources and in conjunction with small heat storage capacities. In a renewable energy system, large amounts of useful heat are generated during the transformation of electrical energy from the waste heat of converters. Large heat storage capacities for low temperature heat (Section19.3.7.1) enable the current-driven operation of the converter. The expansion of heat distribution networks is limited to a much greater extent by distance-dependent transport losses than in the electricity sector. For this reason, systems with combined heat and power (Figure 44) must be tailored in their performance and placement to local heat consumption and existing heating networks. These can be local heating networks with a heat transfer between neighboring buildings or district heating networks that supply districts or entire cities.

High-temperature heat for industrial processes can be obtained from the waste heat of cogeneration gas turbines (up to approx. 550 ° C). 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% [LICHT]. 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 or biomass.

19.3.7 Energy storage

Energy storage devices are components that can absorb energy and deliver usable energy. Energy converters such as water or heat pumps, electrolysers, or fuel cells are used in charging and discharging. In some energy storage systems, the energy is extracted in a converted form, such as in the case of heat storage systems that are charged with electricity. A hydrogen storage unit is used as an energy storage unit when hydrogen or its derivatives serve as an energy source, otherwise it is used as a **material storage unit**, for example for the chemical industry. The loading of material storage by energy-intensive processes, e.g. aluminum production, can serve the grid via load management (Section 19.3.4).

19.3.7.1 Low-temperature heat storage

Electric heat pumps consume electricity to provide useful heat from ambient heat (heating) or to dissipate heat into the environment (cooling). In the building sector, the efficiency of a heat pump is specified as the annual performance factor (APF) and is around 300% in heating mode, depending on the technology and load. An efficient operation is achieved by heat pumps with surface heating systems, mostly underfloor heating systems, which manage with low feed temperatures. Resistance heaters (heating rods) convert electricity into heat with 100% efficiency, but with low exergetic efficiency when producing low temperature heat. At the end of 2020, 1 million heat pumps were installed in Germany.

Thermal storage capacity can be provided much more cheaply than electricity-to-electricity storage capacity. If the thermal storage capacity and the heat pump capacity are sufficiently dimensioned, their loading can be supply-oriented, depending on the current residual load. For this purpose, thermal storage units and cold storage units, e.g. of air-conditioning systems, refrigerated warehouses and food markets, are preferably charged during the core time of the day or according to electricity price signals. However, in the absence of generously dimensioned thermal heat storage facilities, the thermosensitivity of the electricity load increases and larger power reserves have to be kept available at power plants.

Low-temperature heat storage, especially hot water storage, enable the current-driven, highly efficient operation of CHP systems on both sides of the residual load curve (Figure 46), as well as heat pumps 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.

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.

19.3.7.2 High-temperature heat storage

Excess electricity can be very efficiently converted into high-temperature heat (order of magnitude 650 °C) by means of resistance heaters. The high-temperature heat can be stored as latent heat in liquid salt storage or as sensitive heat in rock fill [Siem] or steel bodies [Vatt]. In the case of electricity demand, the heat is used for industrial processes or for driving a conventional steam turbine, possibly with further use of the low-temperature heat. The first pilot plants are currently being tested, and the manufacturer Lumenion states a current-to-current efficiency of 25%.

19.3.7.3 Cooling Storage

At the location of cooling generation and consumption, e.g. in air-conditioning systems for buildings or in refrigerated warehouses, cooling can be stored by comparatively simple means. A further requirement for grid-serving operation is a sufficiently dimensioned capacity of the cooling generator.

At very low temperatures, power-to-power operation is also possible. Liquid air energy storage (LAES) systems based on liquid air (-195°C) are currently being tested. Depending on the use of additional components, power-to-power efficiencies of approx. 25-50% are planned.

19.3.7.4 Stationary batteries

Lithium-ion batteries have followed a similar steep price learning curve as PV modules and have reached a price level of approx. 110 €/kWh in 2020 (without energy management system, https://de.statista.com/statistik/daten/studie/534429/umfrage/weltweite-preise-fuer-lithium-ionen-akkus/). With 2000 charging cycles, this battery price corresponds mathematically to a surcharge of 5.5 ct/kWh on the electricity price, plus charging losses.

With small, stationary batteries, households can extend their self-consumption of PV electricity into the evening hours and thus massively increase it (typically doubling it, see Figure 53). At the end of 2020, there were approximately **285,000** PV electricity storage systems installed in Germany, with a total capacity of **2.3 GWh** [BVES]. A grid-serving system management of the batteries relieves the grid by specifically reducing the midday feed-in peak (Figure 54). Storage would thus enable increased PV addition [ISE7]. Pilot projects are also currently investigating the storage of electrical energy in large, stationary batteries [RWE].

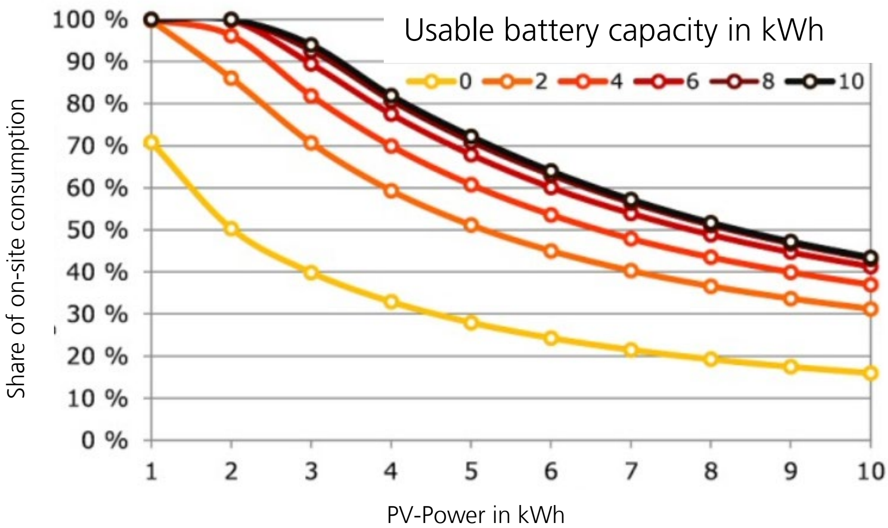


Figure 53: Percent of on-site consumption in dependence of the battery capacity and PV array power for a single-family home with an annual electricity consumption of 4,700 kWh. [Quasch]

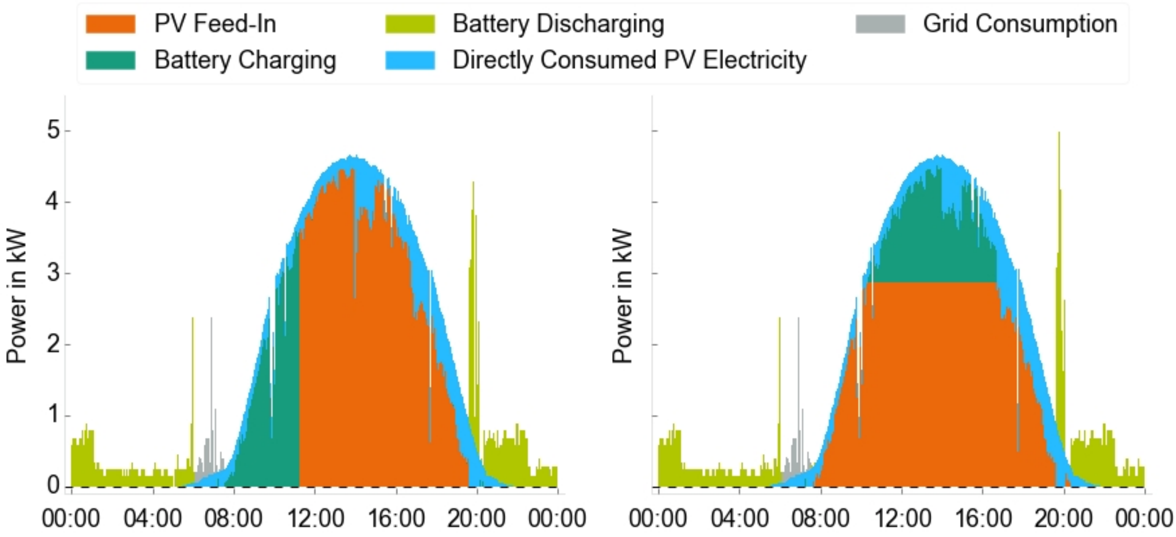


Figure 54: Comparison of the conventional and grid-optimized system operation [ISE7]

19.3.7.5 Fahrzeugbatterien

Electric vehicles use batteries as electro-chemical energy storage devices, in hybrid vehicles supported by an internal combustion engine or a fuel cell. At the end of 2020, 330,000 all-electric cars (BEVs, excluding plug-in hybrids) were registered in Germany, out of a total of approximately 48 million passenger cars (de.statista.com, www.kba.de). Mathematically, the total mileage of passenger cars in Germany of 645 billion km in 2019 [KBA] at a consumption of 160 W/km [AGORA2] corresponds to an annual electricity consumption by e-cars of 100 TWh. Additional consumption arises from electric utility vehicles, as well as approx. 15% charging losses and conversion losses to bridge periods of high residual load using hydrogen. Several measures are necessary to activate vehicle batteries as grid-serving energy storage devices.

Supply-dependent electricity prices will motivate residential and business customers to choose low-cost charging times with a high share of RE in the electricity mix. Variable fuel prices are not new; gas stations also vary their prices depending on the time of day.
In 2020, the share of electricity from renewables in net electricity generation in Germany varied between 15% and 85%. Those who already want to supply their e-car with particularly green electricity from the grid prefer to charge at night in winter, and around midday in summer and on sunny spring and fall days. At any time of year, the weekend is usually advantageous. The significantly lower power consumption on weekends and winter nights tends to improve the carbon footprint. In spring, summer and autumn, a lot of solar power is often produced at midday. Precise information on the current and planned share of RE in the German electricity mix is shown in the Energy Charts [ISE4]. In order to be able to supply PV electricity for direct consumption, charging stations must be located at typical daytime sites, e.g. at the workplace, in parking garages, or at public parking lots.

Remote control of the charging power, taking into account the mobility needs in individual cases, allows grid operators to stabilize the grid.

Bidirectional energy management systems enable electric vehicles to operate as electricity storage systems when they are connected to the grid and do not have to maintain full driving range on standby at all times. With ten million e-vehicles on the grid, each with 20 kWh of dispatchable storage capacity, this adds up to 200 GWh of battery capacity. Private vehicles park for an average of 23 hours per day, and the limited capacity of traffic routes alone forces most cars to be parked for most of this time. E-vehicles connected to the grid can also provide an economic benefit when stationary via their batteries, unlike their combustion engine predecessors. With a charging capacity of about 40 kW per vehicle in fast charging mode, 25000 vehicles on the grid can already provide a gigawatt of bidirectionally controllable power for primary, secondary and minute reserve.

19.3.7.6 Mechanical storage

The currently installed pumped storage capacity in the German grid stands at almost 38 GWh, while rated power is approximately 10 GW and the average efficiency value is 70 percent (without transmission losses). As a comparison, the mentioned storage capacity corresponds to the yield of the German PV power plant park from less than one operating hour under full load. Run-of-river power plants can hardly make regular contributions in complementary operation due to the lack of stowage capacity. Their contribution of approx. 3,8 GW nominal output [ISE4] is not very expandable. The mechanical storage of electrical energy in compressed air accumulators (adiabatic compressed air energy storage, CAES) is currently being tested.

19.3.7.7 Hydrogen and synthesis products

The electrolytic conversion of excess solar and wind energy into hydrogen, with subsequent methanation and further processing into synthetic liquid fuels (e.g. methanol) or to produce ammonia, is currently being scaled up and tested [AMP].

Commercial alkaline electrolyzers achieve efficiencies of up to 80%, high-temperature electrolyzers even more than 80%. Additional energy is required for gas compression, possibly liquefaction (20-30% loss) and subsequent synthesis steps. In April 2019, electrolyzers with a total capacity of about 30 MW were connected to the German grid, 273 MW were planned [DVGW]. Figure 55 shows current and forecast investment costs for various electrolysis technologies.

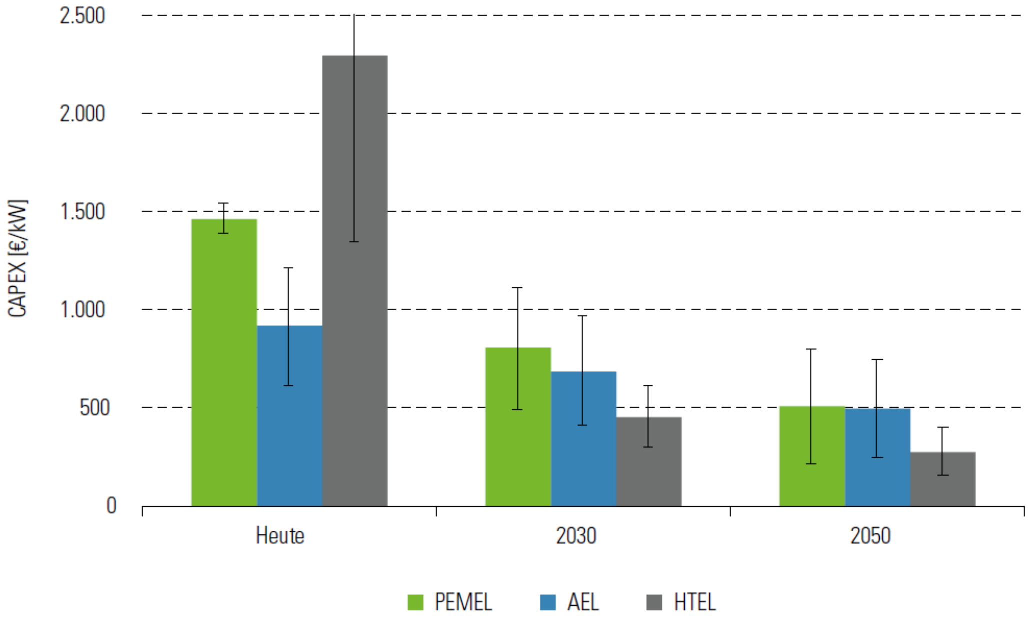


Figure 55: Specific investment costs for different electrolyzer technologies (PEMEL: Membrane electrolysis, AEL: Alkaline electrolysis, HTEL: High-temperature electrolysis, [NOW])

The conversion of renewable energy to storable energy sources gas ("Power-to-X") opens up huge, already existing storage possibilities. It is already technically possible today to increase the hydrogen content in the gas network to up to 20%. In total, around 230 TWh of working gas (equivalent to 820 petajoules) can be stored in existing underground gas storage facilities. Underground cavern storage facilities account for about two thirds of the volume of German gas storage facilities and can store up to 100 percent hydrogen.

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, diesel substitutes for shipping, kerosene substitutes in aviation) or as starting materials for the chemical industry. Reversible high-temperature electrolyzers, which can also be operated as fuel cells, are currently being tested [salt].

Synthetic energy sources can be converted back into electricity via stationary fuel cells (efficiency up to approx. 65%) or thermal power plants. They can also be used as fuels in the transport sector (e.g. hydrogen for fuel cell vehicles, diesel substitutes for shipping, kerosene substitutes in air traffic) or as raw materials for the chemical industry. Reversible high-temperature fuel cells (rSOC, "reversible Solid Oxide Cell"), which can also be operated as electrolyzers are under development and currently achieve a current-to-current efficiency of 43% [FZJ]. Compared to a combination of pure electrolyzers with pure fuel cells, these bidirectional converters as stationary power plants in the power grid promise a high number of full load hours and lower investment costs per installed total capacity.

19.3.7.8 Overview

Figure 56 shows paths for storing and converting PV and wind power. In addition to the technical efficiency, the practical relevance of these paths includes to consider the costs of the nominal power of converters to be installed (€/W) and the capacity of storage systems (€/Wh).

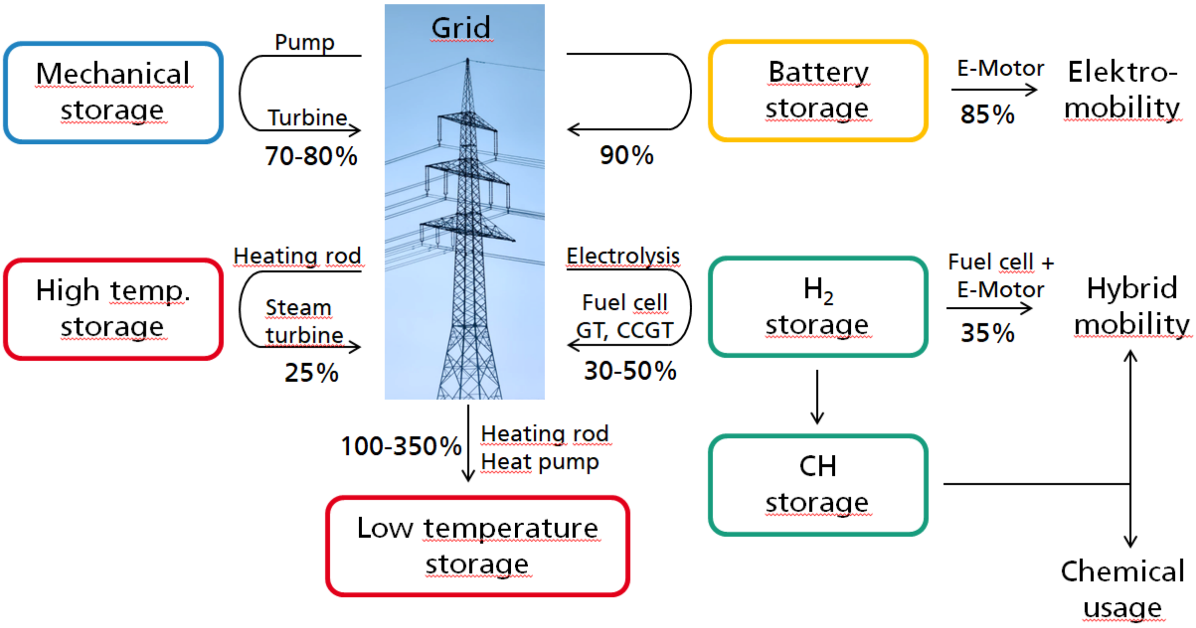


Figure 56: Technologies for energy storage and converters with today's achievable efficiencies at the end of the converter chain, without combined heat and power

19.3.8 Grid expansion

19.3.8.1 National grid expansion

The energy flows in an energy system with 100% renewables are fundamentally different from the situation at the turn of the millennium. A study by AGORA Energiewende shows the most important steps for grid modernization for a RE share of 65% in 2030 [AGORA1]. PV is ideally suited for a decentralized expansion close to consumption. With a spatially distributed development of batteries and converters (e.g. electrolysis, fuel cell, heat pump), which is also close to consumption, the need for expansion of electricity and gas transmission lines can be minimized. On the other hand, a strong concentration of wind power generation in the north or offshore leads to a high demand for transmission line capacity.

PV power production is characterized by a high simultaneity factor. In order to avoid local grid overloads due to generation peaks, battery storage is sometimes considered an economically interesting alternative to grid expansion.

19.3.8.2 Strengthening the European grid

The German power grid is part of the European network. An increase in the cross-border dome capacity of currently around 20 GW enables a better compensation of volatile PV electricity production via European electricity trading.

Figure 57 shows the installed capacity of run-of-river and storage hydro power plants as well as of pumped storage power plants. Storage power plants can be operated as a complement to PV generation, pumped storage can act as efficient electricity-to-electricity storage.

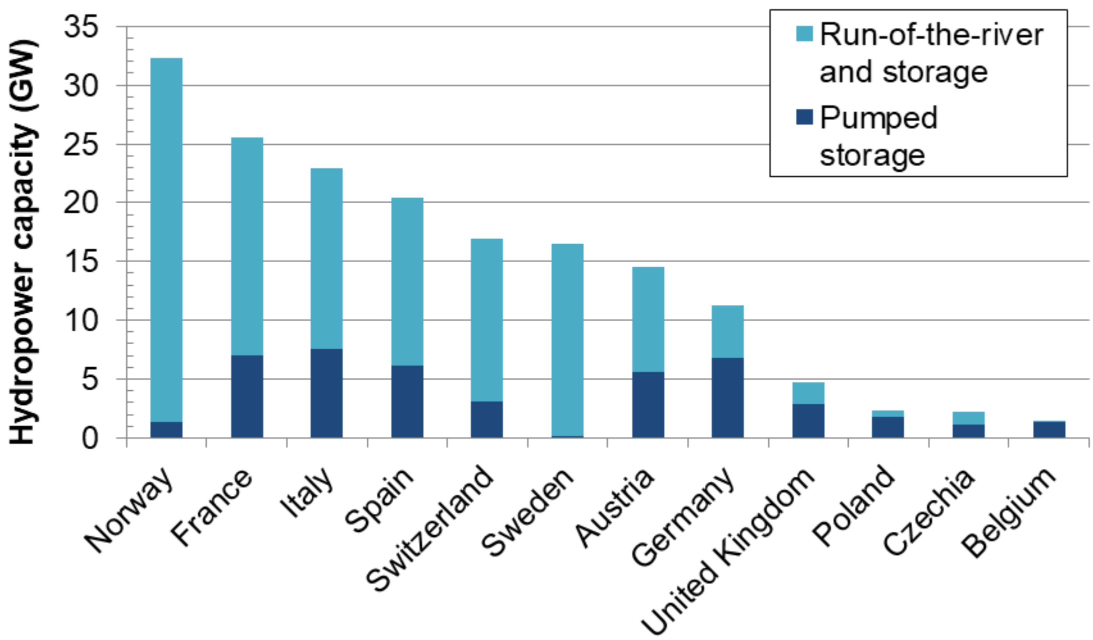


Figure 57: Installed capacity of hydroelectric power plants in neighboring countries, figures from [IHA]

19.3.9 Overview

From today's perspective, an energy system based on almost 100% renewable energy is technically and economically feasible. Figure 58 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.

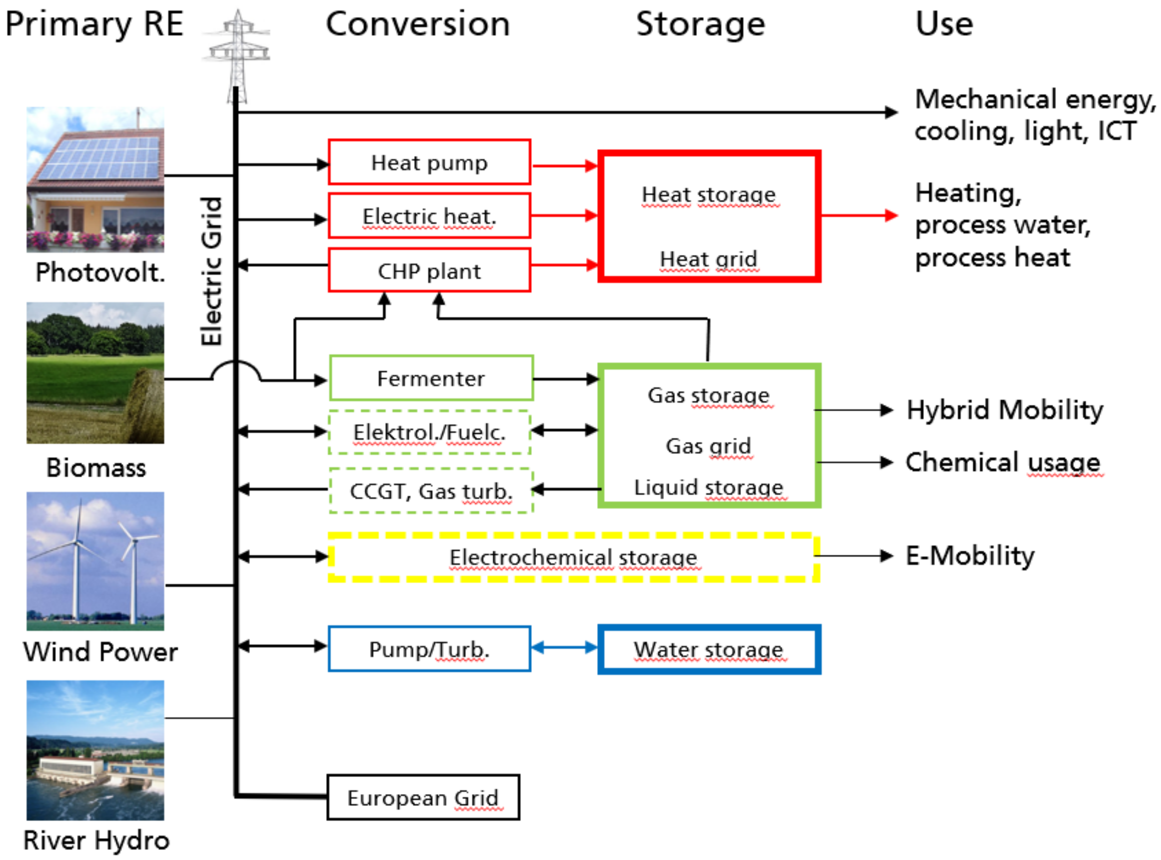


Figure 58: Simplified scheme of a Renewable Energy System with the most important grid-related components of the categories production, conversion, storage and consumption.

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 (yellow), 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 2030: focus on "**flexibilisation**"

1. The energy efficiency of electricity consumers is increasing in all sectors.
2. The installed PV power is increased to 150-200 GW, close to consumption, for steadying of production in East / West orientation or with tracking, with grid-supporting inverter functions.
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 are equipped with grid-serving battery storage, vehicle charging stations with grid-serving functions.
6. Pumped storage performance and capacity are being expanded.
7. Inexpensive heating rods are installed in thermal storage units to take occasional RE power peaks.
8. Electric heat pumps with feed-in to thermal storage units will be set up and e-mobility will be expanded in order to take advantage of frequent surpluses of renewable energy.
9. Low-cost (€/W) gas turbines are built to cover occasional residual load peaks.
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. 400-500 GW, for a solar power production of approx. 400-450 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 CO_2 allowances or, nationally, by a CO_2 tax.

19.4 Does the energy transformation 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 transformation. Finally, federal states, cities and municipalities can promote the energy transformation through a plethora of measures, from advising the stakeholders to promoting pilot projects, providing space and making investment decisions.

20 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. The prices of these imports are influenced by cartels, the revenues largely finance authoritarian regimes, and there are often political costs as well as monetary ones.

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.

An energy system converted to renewables is based, among others, on 400 GW of installed PV power. Annual installations of 12-15 GW are required for the construction and increasingly for the ongoing renewal of these power stations, corresponding to approx. 40 million PV modules at a cost of several billion euros. A PV production in Germany offers long-term security of supply at high ecological and quality standards.

21 Does it still need a Renewable Energy Sources Act (EEG)?

Yes, with focusing on the energy transformation process.

The current market mechanisms would provide too little incentive for long-term investment in the energy transformation without the support of an EEG. 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. In order to maintain the diversity of actors involved in PV generators, a legal framework must entice the grid operator to make connections easily.

Furthermore, PV power plants require a guaranteed long-term **electricity purchase** at a minimum price. This also applies to self-consumers who can not consume or store their entire electricity production. The investment costs of PV power plants dominate the electricity generation costs, and curtailment saves no operating costs. It would also be far too expensive to move an existing PV power plant to another location in order to supply new customers there. In addition, a PV power plant that is being built today is competing with PV power plants of later years, which will deliver solar power at the same time as the electricity production cost is expected to continue to decline (deflationary effect for LCOE, declining market value factor).

Innovative technologies, such as integrated PV, have slightly higher electricity generation costs in direct comparison with simple PV open-space systems, but they do not take up any additional space. In order to accelerate their market entry and thus defuse conflicts of use at an early stage, they need start-up funding.

22 Do PV modules contain toxic substances?

Often yes, so PV modules do not belong in the residual waste.

22.1 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

22.2 Thin-film modules

Cadmium telluride (CdTe) thin-film modules (approximately five percent of market share) contain cadmium (Cd) in salt form. The technology behind this type of module does not allow this material to be substituted. Metallic cadmium and cadmium oxide are classified as toxic; CdTe as harmful to health. Alternative thin-film modules containing little or no Cd are based on amorphous silicon or copper indium selenide (CIS).

CIS solar cells contain selenium which can be toxic when oxidized (e.g. after a fire) independent of the amount. Many manufacturers declare the conformity of their CIS modules with the RoHS chemical regulation (Restriction of certain hazardous substances) and the EU chemicals ordinance REACH (Registration, Evaluation, Authorization and Restriction of chemicals). For a differentiated evaluation, reference is made to independent investigations of each module type.

22.3 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. Some glass manufacturers refine the molten glass and increase the light transmission by adding antimony (Sb). 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. Alternative refining processes without antimony addition are available.

22.4 Take-back schemes and recycling

In June 2010, PV producers launched a cross-manufacturer recycling system (PV Cycle), with currently more than 300 members. The version of the European WEEE Directive (Waste Electrical and Electronic Equipment Directive) that came into force on August 13, 2012 had to be implemented in all EU countries by the end of February 2014. It obliges producers to take back PV modules free of charge and to return them to the material cycle. In October 2015, the act on the distribution, return and environmentally sound disposal of electrical and electronic equipment (Electrical and Electronic Equipment Act - ElektroG) came into force in Germany. It classifies PV modules as large appliances and regulates take-back obligations and financing. The proportion of recovery (collection rate) must be at least 85 percent and the proportion of preparation for reuse and recycling at least 80 percent (recycling rate).

In the recycling process, the aluminum frame, junction box and glass are separated from the laminate. Aluminum and glass are recycled. Material separation processes for the remaining laminate are being tested. Its valuable components include silicon, silver on the solar cells and the copper of the cell connectors.

In its White Paper, Deutsche Umwelthilfe shows clear potential for improvement in the reuse and recycling of PV modules [DUH].

23 Are there enough raw materials available for PV production?

23.1 Wafer-based modules

Wafer-based modules do not require any raw materials which could become limited in the foreseeable future. The main components by weight are glass, aluminum, polymers and silicon, with silicon and aluminum among the most important components of the earth's crust by weight. Most critical is silver consumption for cell production. The PV industry currently consumes about 1,500 metric tonnes of silver annually, corresponding to almost 6 % of production in 2020. The silver on the solar cell can be technically substituted by copper to the greatest possible extent, and some manufacturers already use copper.

23.2 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.

24 Do PV plants increase the risk of fire?

24.1 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 2 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]

24.2 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]

24.3 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.

24.4 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].

25 Appendix: Terminology

25.1 EEG surcharge

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

Several stages are used to determine how the costs associated with promoting renewable electricity are allocated to the end users. In the **first stage**, plant operators, who generate power from renewable energy, are guaranteed a fixed feed-in tariff for all power produced by their plant." [Bundestag]
The level of this feed-in tariff is based on the levelized cost of electricity (LCOE) for PV plants installed at that time and is guaranteed for 20 years.

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

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

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

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

25.2 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/m^2 and a standard solar irradiance spectrum. During actual operation, conditions are normally so different from these standard conditions that efficiency varies.

25.3 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/m^2) and nominal efficiency of the modules.

25.4 Specific yield

The specific yield [kWh/kW$_p$] 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.

25.5 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.

25.6 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.

25.7 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]

25.8 Electricity generation and 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.

Figure 59 shows the energy path from the primary energy source, e.g. solar irradiation (irradiance [W/m^2]), wind or natural gas (energy density during combustion [J/kg]), down to the net energy that is important to the consumer. Large gas turbines show conversion losses of 60-65%. PV power plants have conversion losses of 80-85%, with practically free and unlimited primary energy. The gross electricity generation, adjusted for the import balance, corresponds to the gross electricity consumption. Storage losses occur during the operation of pumped storage power plants or batteries. Losses from pumped storage power plants amount to approx. 25% of the stored amount of electricity, with Li-ion batteries it is 5-10%, plus the losses in the battery management system. If hydrogen is used as a power store via stationary electrolysers and fuel cells, the losses are around 50%. Storage losses will increasingly play a role for PV electricity as the installed PV capacity is expanded.

The in-house consumption of fossil and nuclear power plants is approx. 7% of their gross generation, for PV power plants it is marginal. Grid losses, in particular line and transformer losses, amount to almost 6% in the German power grid. The decentralized nature of the PV installations reduces the grid losses for PV electricity. The amount of electricity consumed by the consumer is the net consumption (final energy). The efficiency of the consumers devices determines the conversion losses up to the final useable energy, e.g. power or light.

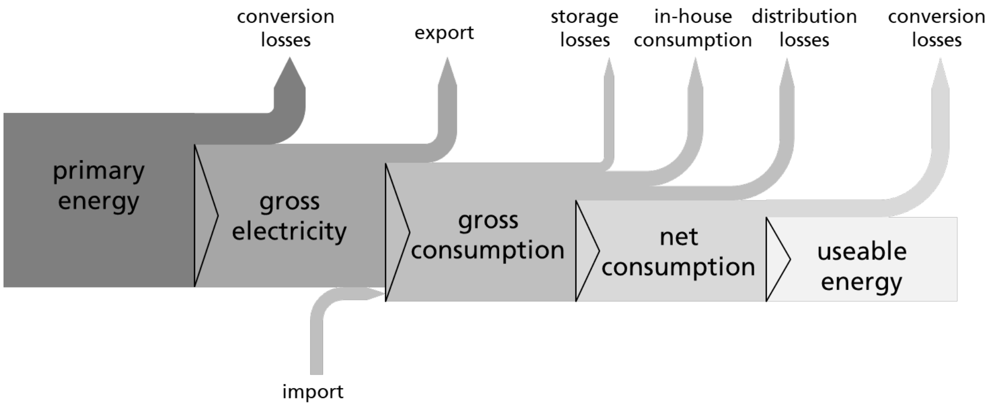


Figure 59: Terms of electricity generation and consumption

26 Appendix: Conversion tables [EEBW]

Vorsätze und Vorzeichen

k	Kilo	10^3	Tausend
M	Mega	10^6	Million (Mio.)
G	Giga	10^9	Milliarde (Mrd.)
T	Tera	10^{12}	Billion (Bill.)
P	Peta	10^{15}	Billiarde (Brd.)

Umrechnungen

		PJ	GWh	Mio. t SKE	Mio. t RÖE
1 PJ	Petajoule	1	277,78	0,034	0,024
1 GWh	Gigawattstunde	0,0036	1	0,00012	0,000086
1 Mio. t SKE	Mio. Tonnen Steinkohleeinheit	29,31	8.141	1	0,70
1 Mio. t RÖE	Mio. Tonnen Rohöleinheit	41,87	11.630	1,43	1

Typische Eigenschaften von Kraftstoffen

	Dichte [kg/l]	Heizwert [kWh/kg]	Heizwert [kWh/l]	Heizwert [MJ/kg]	Heizwert [MJ/l]
Biodiesel	0,88	10,3	9,1	37,1	32,6
Bioethanol	0,79	7,4	5,9	26,7	21,1
Rapsöl	0,92	10,4	9,6	37,6	34,6
Diesel	0,84	12,0	10,0	43,1	35,9
Benzin	0,76	12,2	9,0	43,9	32,5

Typische Eigenschaften von festen und gasförmigen Energieträgern

	Dichte [kg/l] bzw. [kg/m³]	Heizwert [kWh/kg]	Heizwert [kWh/l] bzw. [kWh/m³]	Heizwert [MJ/kg]	Heizwert [MJ/l] bzw. [MJ/m³]
Steinkohle	-	8,3 - 10,6	-	30,0 - 38,1	-
Braunkohle	-	2,6 - 6,2	-	9,2 - 22,2	-
Erdgas H (in m³)	0,76	11,6	8,8	41,7	31,7
Heizöl EL	0,86	11,9	10,2	42,8	36,8
Biogas (in m³)	1,20	4,2 - 6,3	5,0 - 7,5	15,0 - 22, 5	18,0 - 27,0
Holzpellets	0,65	4,9 - 5,4	3,2 - 3,5	17,5 - 19,5	11,4 - 12,7

27 Appendix: Abbreviations

BEV	Battery Electric Vehicle
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BSW	German Solar Industry Association
CCGT	Gas and steam generators
CHP plant	Combined heat and power plant – a plant that uses combustion engines or gas turbines to generate electrical energy and heat
EEG	Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act, EEG)
ESC	Energy supply company
GHG	Greenhouse Gas
ICT	Information and communications technology
IEA	International Energy Agency
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaics
RE	Renewable energy
W_p	Watt "peak", unit for nominal output of a PV module, a module array or a power plant

28 Appendix: Sources

AEE1	Metaanalyse: Digitalisierung der Energiewende, Agency for Renewable Energies (Agentur für Erneuerbare Energien), August 2018
AEE2	Bundesländer-Übersicht zu Erneuerbaren Energien, https://www.foederal-erneuerbar.de/uebersicht/bundeslaender, Agency for Renewable Energies (Agentur für Erneuerbare Energien), October 2018
AEE3	https://www.unendlich-viel-energie.de/mediathek/grafiken/eigentuemerstruktur-erneuerbare-energien, Agency for Renewable Energies (Agentur für Erneuerbare Energien), January 2021
AEE4	https://www.unendlich-viel-energie.de/themen/akzeptanz-erneuerbarer/akzeptanz-umfrage/klares-bekenntnis-der-deutschen-bevoelkerung-zu-erneuerbaren-energien, Agency for Renewable Energies (Agentur für Erneuerbare Energien), October 2018
AGEB	Energy flow diagram 2019 for the Federal Republic of Germany in petajoules, German Working Group on Energy Balances, September 2020
AGEB1	Energieverbrauch in Deutschland im Jahr 2017, AGEB, February 2018
AGEE	Monatsbericht zur Entwicklung der erneuerbaren Stromerzeugung und Leistung in Deutschland, Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat), February 2019

AGORA1	Stromnetze für 65 Prozent Erneuerbare bis 2030. Zwölf Maßnahmen für den synchronen Ausbau von Netzen und Erneuerbaren Energien, Agora Energiewende, July 2018
AGORA2	Klimabilanz von Elektroautos - Einflussfaktoren und Verbesserungspotenzial, Study commissioned by Agora Verkehrwende, ifeu - Institute for Energy and Environmental Research, April 2019
AMP	Sektorenkopplung: Amprion und Open Grid Europe geben Power-to-Gas in Deutschland einen Schub, Pressemeldung Amprion, June 2018
ATW1	Weis M, van Bevern K, Linnemann T; Forschungsförderung Kernenergie 1956 bis 2010: Anschubfinanzierung oder Subvention?, ATW 56, Edition 2011, Volume 8/9
ATW2	Ludwig H, Salnikova T, Waas U; Lastwechselfähigkeiten deutscher KKW, ATW 55, Jg (2010), Volume 8/9
BAFA	Hintergrundinformationen zur Besonderen Ausgleichsregelung, Antragsverfahren 2013 auf Begrenzung der EEG-Umlage 2014, Ed.: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and Federal Office of Economics and Export Control (BAFA), 15 October 2013
BCG	Klimapfade für Deutschland, Studie, The Boston Consulting Group (BCG) und Prognos, on behalf of the Federal Association of German Industry (BDI), January 2018
BDEW2	Presentation „Erneuerbare Energien EEG_2017", BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., July 2017
BDEW3	Stromerzeugung und -verbrauch in Deutschland, Mitteilung des BDEW (https://www.bdew.de/presse/presseinformationen/aktuelle-berechnungen-von-zsw-und-bdew-2020), December 2020
BDEW4	Redispatch in Deutschland – Auswertung der Transparenzdaten, BDEW Bundesverband der Energie- und wasserwirtschaft e.B., August 9, 2016
BDEW5	BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. Press conference 20.12.2017 https://www.bdew.de/media/documents/20171220_PI_Anlage_Zahlen-Fakten.pdf (in German)
BDEW6	BDEW-Strompreisanalyse Januar 2019 - Haushalte und Industrie, BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., July 2020
Beck	Beck M, Bopp G, Goetzberger A, Obergfell T, Reise C, Schindele S; Combining PV and Food Crops to Agrophotovoltaic – Optimization of Orientation and Harvest, 27th European Photovoltaic Solar Energy Conference, Frankfurt, Germany, September 24–28, 2012
BEE	BEE-Szenario 2030 - 65% Erneuerbare Energien bis 2030; Ein Szenario des Bundesverbands Erneuerbare Energie e.V. (BEE), May 2019
BMEL	Daten und Fakten, Land-, Forst- und Ernährungswirtschaft mit Fischerei und Wein- und Gartenbau, Federal Ministry of Food and Agriculture (BMEL), December 2017
BMVI	Räumlich differenzierte Flächenpotentiale für erneuerbare Energien in Deutschland. BMVI (Hrsg.), BMVI-Online-Publication 08/2015.
BMWi1	Gesamtausgabe der Energiedaten - Datensammlung des BMWi, Federal Ministry of Economics and Energy, last update: 22.06.2020

BMWi3	Forschungsförderung für die Energiewende, Bundesbericht Energieforschung 2016, Federal Ministry of Economics and Energy (BMWi)
BMWi4	Energiegewinnung und Energieverbrauch, Federal Ministry of Economics and Energy (BMWi), Download as of 28.8.2016 https://www.bmwi.de/DE/Themen/Energie/Energiedaten-und-analysen/Energiedaten/energiegewinnung-energieverbrauch.html
BMWi5	Vergütungen, Differenzkosten und EEG-Umlage 2000 bis 2021, https://www.erneuerbare-energien.de/EE/Navigation/DE/Recht-Politik/Das_EEG/DatenFakten/daten-und-fakten.html#doc95662bodyText2, Federal Ministry of Economics and Energy (BMWi), as of December 2020
BMWi6	Bundesbericht Energieforschung 2021, German Federal Ministry of Economics and Energy (BMWi), March 2021
BMWi7	Bundesbericht Energieforschung 2020, S. 29, Federal Ministry of Economics and Energy (BMWi), June 2020
BNA	Monitoringbericht 2020 von Bundesnetzagentur und Bundeskartellamt, Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railways, as of January 2021
BNA1	Bundesnetzagentur legt Eigenkapitalrenditen für Strom- und Gasnetze fest, Press release of the German Federal Network Agency, as of October 2016
BNE	Solarparks – Gewinne für die Biodiversität, Studie des Bundesverbands Neue Energiewirtschaft (bne) e.V., November 2019
BSW	50.000 neue Jobs durch Photovoltaik und Speicher, Press release from German Solar Industry Association, Berlin, December 5, 2019
BSW1	Statistische Zahlen der deutschen Solarstrombranche (Photovoltaik), German Solar Industry Association (BSW-Solar), Bundesverband Solarwirtschaft e. V., Berlin, February 2021
Bundestag	EEG-Umlage 2010, German Parliament, Scientific Services, No. 21/10, March 25, 2010
BVES	BVES Branchenanalyse 2021, Bundesverband Energiespeicher Systeme e.V., Pressekonferenz, März 2021
Carb	https://www.carbonbrief.org/profound-shifts-underway-in-energy-system-says-iea-world-energy-outlook, Carbon Brief, 2019
DESTATIS	Environmental economic calculations, private households and the environment, DESTATIS, Federal Statistical Office, September 2020
DLR	O'Sullivan M, Lehr U, Edler D; Bruttobeschäftigung durch erneuerbare Energien in Deutschland und verringerte fossile Brennstoffimporte durch erneuerbare Energien und Energieeffizienz, Zulieferung für den Monitoringbericht 2015, as of September 2015
DUH	Kreislaufwirtschaft in der Solarbranche stärken - Alte Photovoltaik-Module für den Klima- und Ressourcenschutz nutzen, Deutsche Umwelthilfe e.V., March 2021
DVGW	Deutscher Verein des Gas- und Wasserfaches e. V., Press release dated April 24, 2019

DWD	Wolfgang Riecke, Bereitstellung von historischen Globalstrahlungsdaten für die Photovoltaik, Second Symposium on Energy Meteorology, April 2011
ECOFYS	Abschätzung der Kosten für die Integration großer Mengen an Photovoltaik in die Niederspannungsnetze und Bewertung von Optimierungspotenzialen, ECOFYS, March 2012
EEBW	Erneuerbare Energien in Baden-Württemberg 2011, Ministry of the Environment, Climate Protection and the Energy Sector of Baden-Württemberg, November 2012
EEG 2017	Gesetz zur Einführung von Ausschreibungen für Strom aus erneuerbaren Energien und zu weiteren Änderungen des Rechts der erneuerbaren Energien (EEG 2017), Bundesrat Printed matter 355/16, July 2016
EEG 2021	Gesetz zur Änderung des Erneuerbare-Energien-Gesetzes und weiterer energierechtlicher Vorschriften (EEG 2021), Bundesrat Printed matter 763/20, December 2020
EGGERS	Eggers J-B, Behnisch M, Eisenlohr J, Poglitsch H, Phung W-F, Münzinger M, Ferrara C, Kuhn T, PV-Ausbauerfordernisse versus Gebäudepotenzial: Ergebnis einer gebäudescharfen Analyse für ganz Deutschland, 2020 (currently under print)
EnAg	Klimabilanz Photovoltaik - Wie groß ist der CO_2-Fußabdruck von Solarstrom, EnergieAgentur.NRW, 2017
EnBW	EnBW verstärkt Engagement im Bereich Solarenergie, Press release, Energie Baden-Württemberg AG, February 2019
ENER	E-Mobility-Zukunft: ENERVIE an Meilenstein-Projekt beteiligt, Press release, Südwestfalen Energie und Wasser AG, October 2018
ESYS	Ausfelder et al., Sektorkopplung – Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems, Series of Energy Systems of the Future, November 2017
EPA	United States Environmental Protection Agency, Download as of 9.7.2013 von http://www.epa.gov/climatechange/science/causes.html#GreenhouseRole
EuPD	ENERGIEWENDE im Kontext von Atom und Kohleausstieg, Perspektiven im Strommarkt bis 2040, Studie der EuPD Research Sustainable Management GmbH, November 2019
FAU	Deutschland ohne erneuerbare Energien?“ – Ein Update für die Jahre 2014 bis 2018, Discussion paper commissioned by EWS Elektrizitätswerke Schönau, Friedrich-Alexander University Erlangen-Nuremberg, October 2019
FFE	Download of https://www.ffegmbh.de/aktuelles/veroeffentlichungen-und-fachvortraege/828-merit-order-der-konventionellen-kraftwerke-in-deutschland-2018, February 2020
FNR	Basisdaten Bioenergie Deutschland 2021, Fachagentur Nachwachsende Rohstoffe e.V., September 2020
FÖS1	Gesellschaftliche Kosten der Atomenergie in Deutschland, Eine Zwischenbilanz der staatlichen Förderungen und gesamtgesellschaftlichen Kosten von Atomenergie seit 1955, Studie des Forums Ökologisch-Soziale Marktwirtschaft e.V. (FÖS) im Auftrag von Greenpeace Energy eG, September 2020

FÖS2	Was Braunkohlestrom wirklich kostet, Studie des Forums Ökologisch-Soziale Marktwirtschaft e.V. (FÖS) im Auftrag von Greenpeace Energy eG, June 2018
FÖS3	Brief analysis of government expenditure for EURATOM, study commissioned by Greenpeace Energy eG, Forum Ökologische-Soziale Marktwirtschaft e.V. (FÖS), October 2019
FZJ	Reversible Brennstoffzelle bricht Wirkungsgrad-Rekord, Pressemeldung, Forschungszentrum Jülich, December 2018
HTW	Sinnvolle Dimensionierung von Photovoltaikanlagen für Prosumer, Short Study, University of Applied Sciences (HTW) Berlin, March 2019
Hydro	Caglayan D, Weber N, Heinrichs H, Linßen J, Robinius M, Kukla P, Stolten D, Technical potential of salt caverns for hydrogen storage in Europe, International Journal of Hydrogen Energy, Volume 45, Issue 11, 2020
IEA1	Renewables 2018 -Market analysis and forecast from 2018 to 2023, International Energy Agency (IEA), October 2018
IEA2	Redrawing the Energy-Climate Map, World Energy Outlook Special Report. International Energy Agency (IEA), June 2013
IEA3	Energiepolitik der IEA-Länder, Prüfung 2013, Deutschland, Summary, International Energy Agency (IEA), April 2013
IEA5	World Energy Outlook, International Energy Agency (IEA), November 2019
IHA	Hydropower status report, International Hydropower Association, May 2019
IPCC	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
IPV	Jessica Nover, Schadstofffreisetzung aus Photovoltaik-Modulen, Final Report, University of Stuttgart, Institute of Photovoltaics, 2018
IRENA	Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects, Study of International Renewable Energy Agency (IRENA), Abu Dhabi, 2019
ISE1	Kost C., Schlegl T.; Levelized Cost of Electricity Renewable Energies, study conducted by the Fraunhofer Institute for Solar Energy Systems ISE, December 2010
ISE2	Kiefer K, Farnung B, Müller B, Degradation in PV Power Plants: Theory and Practice. 36th European Photovoltaic Solar Energy Conference and Exhibition, Marseille, 2019.
ISE4	https://www.energy-charts.de, Editor: Prof. Dr. Bruno Burger, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany
ISE6	Fire Protection in Photovoltaic Systems – Facts replace Fiction, press release by Fraunhofer ISE, February 2013; more information on fire protection can be found at www.pvbrandsicherheit.de
ISE7	Speicherstudie 2013 - Kurzgutachten zur Abschätzung und Einordnung energiewirtschaftlicher, ökonomischer und anderer Effekte bei Förderung von objektgebunden elektrochemischen Speichern, Study by Fraunhofer Institute for Solar Energy Systems ISE, January 2013

ISE10	Photovoltaics Report, Fraunhofer Institute for Solar Energy Systems ISE, PSE Conferences & Consulting GmbH, September 2020
ISE11	Meta Study on Future Crosssectoral Decarbonization Target Systems in Comparison to Current Status of Technologies, Discussion Paper, Fraunhofer ISE, March 2018
ISE12	Wege zu einem klimaneutralen Energiesystem - Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen, Study of Fraunhofer ISE, February 2020
ISET	Rolle der Solarstromerzeugung in zukünftigen Energieversorgungsstrukturen - Welche Wertigkeit hat Solarstrom?, Investigation commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, May 2008
ITRPV	International Technology Roadmap for Photovoltaic, VDMA Photovoltaic Equipment, 11th ed., October 2020
IVL	Lithium-Ion Vehicle Battery Production, Status 2019 on Energy Use, CO_2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling, Study by the Swedish Environmental Research Institute on behalf of the Swedish Energy Agency, November 2019
IWES1	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
IWF	How Large Are Global Energy Subsidies? IMF Working Paper by David Coady, Ian Parry, Louis Sears and Baoping Shang, 2015
KBA	Zahlen im Überblick – Statistik, German Federal Motor Vehicle Office, June 2018
LFU1	Berechnung von Immissionen beim Brand einer Photovoltaik-Anlage aus Cadmiumtellurid-Modulen, Bavarian Environment Agency (Bayerisches Landesamt für Umwelt), 11-2011
LFU2	Beurteilung von Kunststoffbränden, Az: 1/7-1515-21294, Bavarian Environment Agency (Bayerisches Landesamt für Umwelt), 1995
Licht	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
Licht2	Repräsentative Umfrage zu erneuerbaren Energien, Marktforschungsinstitut YouGov, commissioned by LichtBlick AG, February 2020
MWV	Annual Report 2018, Association of the German Petroleum Industry (Mineralölwirtschaftsverband e.V.), July 2018
NEHS	Nationales Emissionshandelssystem – Hintergrundpapier, Deutsche Emissionshandelsstelle (DEHSt) im Umweltbundesamt, November 2020
NOW	IndWEDe - Industrialisierung der Wasserelektrolyse in Deutschland, Study commissioned by the German Federal Ministry of Transport and Digital Infrastructure (BMVI), 2018

ÖKO	EEG-Umlage und die Kosten der Stromversorgung für 2014 – Eine Analyse von Trends, Ursachen und Wechselwirkungen, Short study commissioned by Greenpeace, June 2013
ÖKO1	Beschäftigungsentwicklung in der Braunkohleindustrie: Status quo und Projektion, Öko-Institut Berlin, July 2018
ÖKO2	Aktueller Stand der KWK-Erzeugung (Dezember 2015), Study by the Ökoinstitut e.V. on behalf of the German Federal Ministry for Economic Affairs and Energy, December 2015
ÖKO3	Eingesparte Kosten für Energieimporte im Jahr 2015 und die Innovationseffekte durch die Nutzung erneuerbarer Energien in Deutschland, Memo of Ökoinstitut e.V., October 2016
Prog	Klimaneutrales Deutschland, Prognos, Öko-Institut, Wuppertal-Institut, Summary, commissioned by Agora Energiewende, Agora Verkehrswende and Climate Neutrality Foundation, October 2020
Quasch	Quaschning V, Solare Unabhängigkeitserklärung, Photovoltaik, October 2012
SCBW	Photovoltaik: Neue Solarstromanlagen lohnen sich auch 2021, Press Information Solar Cluster Baden-Württemberg, January 2021
SCBW1	Weiterbetrieb von Ü20-Photovoltaikanlagen - Möglichkeiten nach Ende ner EEG-Förderdauer, Faktenpapier, Solar Cluster Baden-Württemberg, January 2021
Sprin	Motorentechnik - Im Fokus, online article, December 2010 https://www.springerprofessional.de/motorentechnik/pkw-antriebe-im-ueberblick-vergangenheit-gegenwart-und-zukunft/6561052
RWE	RWE nimmt Batteriespeicher in Herdecke in Betrieb - Sechs Millionen Euro Investition, sieben MWh Kapazität, Pressemeldung, RWE, Februar 2018
Shell	Shell Scenarios Sky - Meeting the goals of the Paris agreement, Shell International B.V., March 2018
Siem	Weit mehr als nur heiße Luft, Pressemeldung, Siemens AG, March 2017
SWM	M-Partnerkraft - Das virtuelle Kraftwerk der SWM, Flyer of Stadtwerke München, January 2013
Test	»Immer sparsamer«, Test 1/2012, Stiftung Warentest
UBA	Energieziel 2050: 100% Strom aus erneuerbaren Quellen, German Federal Environment Agency, July 2010
UBA1	Erneuerbare Energien in Deutschland, Daten zur Entwicklung im Jahr 2020, German Federal Environment Agency, March 2021
UBA2	Article at https://www.umweltbundesamt.de/daten/energie/kraft-waerme-kopplung-kwk#textpart-1, German Federal Environment Agency, October 2018
UBA3	Methodenkonvention 3.1 zur Ermittlung von Umweltkosten – Kostensätze Stand 12/2020, German Federal Environment Agency, December 2020
UBA4	Daten und Fakten zu Braun- und Steinkohlen, German Federal Environment Agency, December 2017
UBA5	Der Europäische Emissionshandel, https://www.umweltbundesamt.de/daten/klima/der-europaeische-emissionshandel#textpart-1, Download on June 2019

UBA6	Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 – 2018, German Federal Environment Agency, April 2019
UBA7	Emissionsbilanz erneuerbarer Energieträger - Bestimmung der vermiedenen Emissionen im Jahr 2018, German Federal Environment Agency, November 2019
UBA8	Wege in eine ressourcenschonende Treibhausgasneutralität – RESCUE Kurzfassung, German Federal Environment Agency, November 2019
ÜNB	Mittelfristprognose zur deutschlandweiten Stromerzeugung aus EEG-geförderten Kraftwerken für die Kalenderjahre 2021 bis 2025, prepared on behalf of 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, enervis energy advisors GmbH, October 2020
Vatt	CO_2-freie Energie fürs Quartier: Sektorenkoppelnder Stahlspeicher bringt Energiewende auf Hochtemperatur, Pressemeldung, Vattenfall, October 2018
VFL	Berechnung einer risikoadäquaten Versicherungsprämie zur Deckung der Haftpflichtrisiken, die aus dem Betrieb von Kernkraftwerken resultieren, study conducted by the Versicherungsforen Leipzig and commissioned by the German Renewable Energy Federation (Bundesverband Erneuerbare Energie e.V., BEE), April 1, 2011
VGB	Kraftwerke 2020+, opinion of the Scientific Council of VGB PowerTech e.V., 2010
VIK	VIK Strompreisindex Mittelspannung, Verband der Industriellen Energie- und Kraftwirtschaft e.V., July 2020
ZSW	Untersuchung zur Wirkung veränderter Flächenrestriktionen für PV-Freiflächenanlagen, Short study by the ZSW on behalf of innogy SE, January 2019

29 Appendix: Figures