Recent Facts about Photovoltaic in Germany

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

Contact:
Sophia Judith Bächle
Communications
Telefon: +49 (0) 7 61 / 45 88 — 5215
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstrasse 2
79110 Freiburg, Germany
presse@ise.fraunhofer.de

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1 What purpose does this guide serve?

Germany is leaving the fossil-nuclear age behind, paving the way for photovoltaics (PV) to play a 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 create an overall assessment of the progress in the PV expansion in Germany.

2 How much photovoltaics is needed for the energy transition?

In order to cover our entire energy demand from renewable energies (RE), a massive expansion of installed PV capacity is necessary, in addition to a number of other measures. Figure 1 shows the required nominal PV power according to a selection of studies and scenarios from the year of publication 2021 ([ISE3], [ISI], [DIW], [ARIA], [BDI], [ESYS], [Prog], [IEE], [HTW2], [ÜNB2], [AGORA2]).

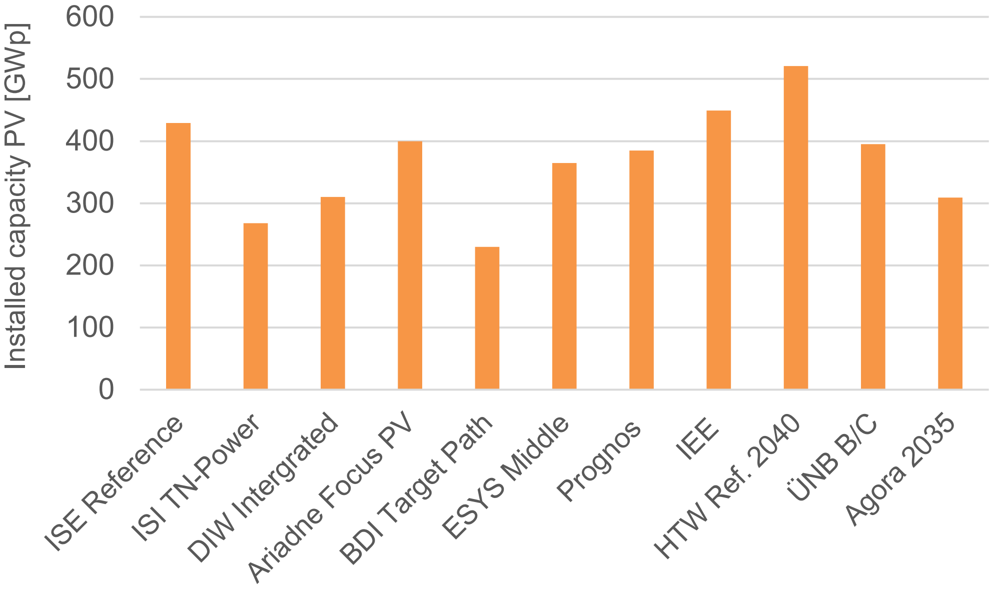


Figure 1: Installed PV capacity necessary to reach climate neutrality as determined by different studies. (The studies are named according to the institutions and, if applicable, the scenario).

The scenarios make different assumptions on boundary conditions, e.g., for energy imports, efficiency increases and acceptance. Some studies only consider the electricity system, others the entire energy system.

The EEG 2023 envisages a PV expansion to 215 GW_p by 2030 and to 400 GW_p by 2040. The annual net addition is to climb to a maximum of 22 GW_p within a few years. Increasingly, old installations also need to be replaced.

These replacement installations are currently of little significance, but they will increase to approx. 15 GW_p per year in fully developed condition with an assumed useful life of just under 30 years. In the years 2013–2018, an average of only 1.9 GW_p/a was installed (Figure 2). With the deployment of approx. **14 GW_p** in 2023, the total number of **systems** is now **3.7 million** including plug-in solar units [BSW1], with a total capacity of **81 GW_p** [ISE4].

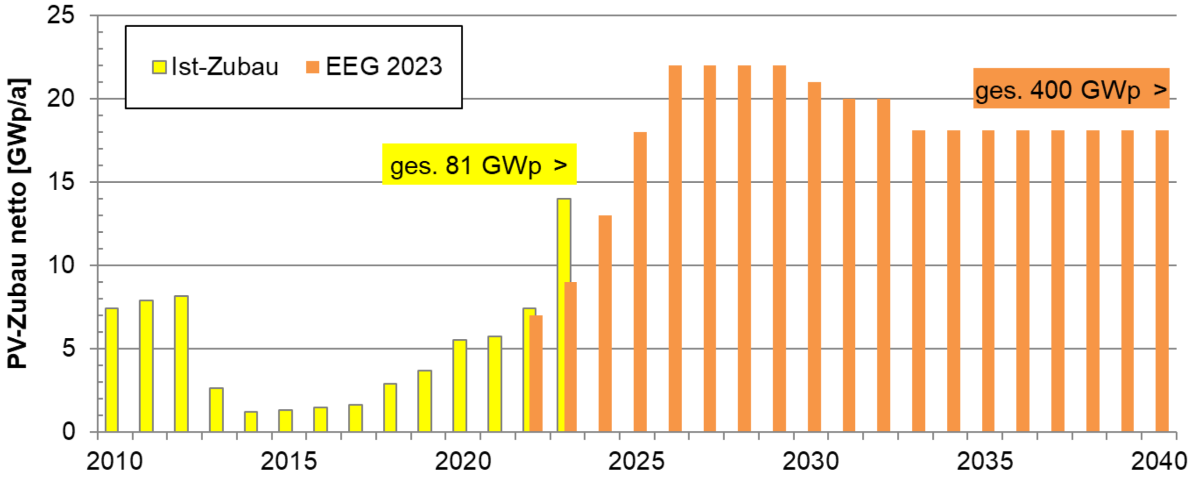


Figure 2: Net PV additions: actual values until 2022, expansion path to achieve the legal targets [BMWK1], [EEG2023].

3 Does PV contribute significantly to the power supply?

Yes.
With an estimated electricity generation of **61.1 TWh** in 2023, photovoltaics covered **12 percent** of gross electricity consumption [AGEE] in Germany (Figure 3). All renewable energies (RE) together came to **52 percent**.

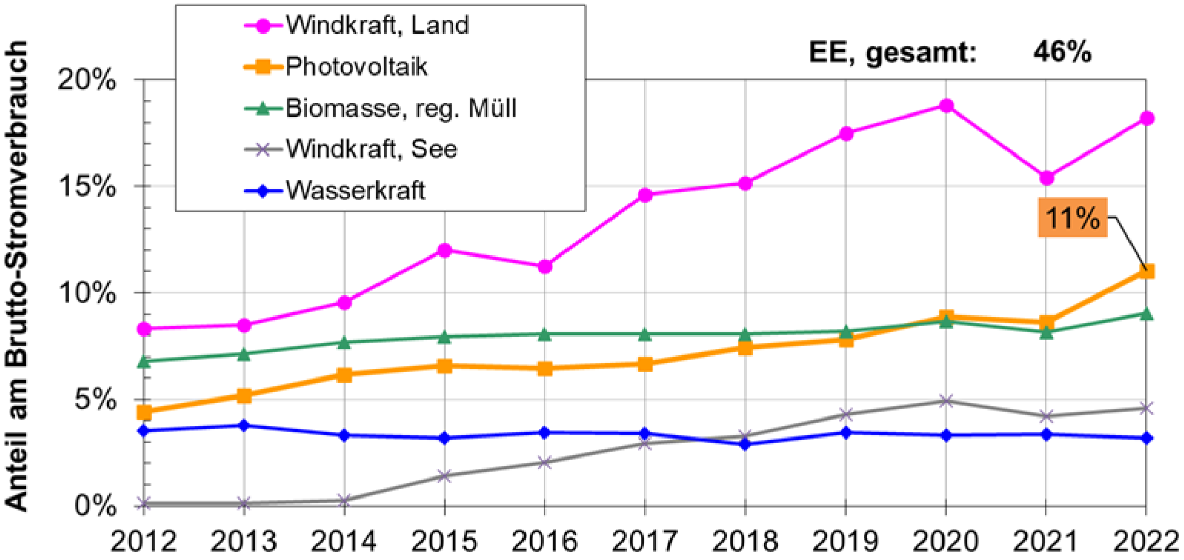


Figure 3: Development of the share of renewable energies in gross electricity consumption in Germany [ISE4], [UBA1], [AGEE].

Gross electricity consumption is the reference value for the statutory expansion targets of the energy transition and includes grid, storage, and self-consumption losses (Section 27.9). On sunny days, PV electricity may temporarily cover more than two thirds of our electricity demand. Based on a forecasted gross electricity consumption of 658 TWh in 2030, the planned PV expansion to 215 GW_p would lead to a PV power share of about 30 percent, with renewable energies generally covering 80 percent.

4 Is PV power too expensive?

PV electricity was once very expensive.

If one compares the electricity production costs of new power plants of different technologies, PV comes off very favorably [ISE1]. Large PV power plants in particular produce unrivaled cheap electricity. However, the cost comparison is still considerably distorted as long as the supply costs for fuels are considered, but neither the full cycle costs with CO_2 recovery nor the follow-up costs of interrupted cycles, i.e., the costs of the climate crisis.

The marginal costs for nuclear power are in the order of 1 ct/kWh, for coal-fired power 3–7 ct/kWh, for gas-fired power 6–9 ct/kWh, plus the fixed costs of the power plants (e.g., investment, capital). The marginal costs essentially cover the provision of the fuel, but not the neutralization of the radiating waste or environmentally harmful emissions (CO_2, NOx, SOx, Hg). So far, external costs and risks relating to environmental, climate and health damage have largely been disregarded in pricing ([UBA3], [FÖS1], [FÖS2]). The ignoring of these external costs represents a massive subsidization of the energy sources concerned (Section 5.2).

In order to promote the energy transition and to stimulate investments in PV systems of various sizes, the Renewable Energy Sources Act (EEG) came into force on 1 April 2000. It is intended to enable plant operators to operate economically at a reasonable profit with guaranteed power purchase. The aim of the Renewable Energy Sources Act is to continuously reduce the LCOE from RE by securing a substantial market for RE systems (see Section 4.1).

The development of PV generation capacities is only one part of the transformation costs associated with the energy transition. For a long time, this part was at the forefront of the discussion. In recent years, PV has become increasingly system-relevant, which means that other transformation steps and cost types have come into focus. In addition to the pure generation costs for electricity from RE, there are also the costs of building 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). These costs are not caused by the PV expansion, they go — just like the PV expansion itself — to the account of the energy transition. The costs of the energy transition are incurred by all energy consumers, for whom a sustainable energy supply must be created. Without knowing the costs of an omitted energy transition, it is difficult to assess the costs of the transition.

4.1 Levelized Cost of Electricity

The levelized cost of electricity (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 are 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

Investment costs are the dominant cost component of PV power plants. The price of the PV modules is only responsible for about one third of the investment costs, and the share is higher for large PV ground-mounted systems (PV FFA) than for small rooftop systems. History shows that the price development for PV modules follows a so-called “price-experience curve", i.e., when cumulative production doubles, prices fall by a constant percentage. Figure 4 shows the inflation-adjusted world market prices. Between the years 2010 and 2020, PV module prices have decreased by 90 percent. In the long term, module prices [€/W_P] are expected to continue to fall in line with this regularity, provided that major efforts continue to be made in the further development of products and manufacturing processes.

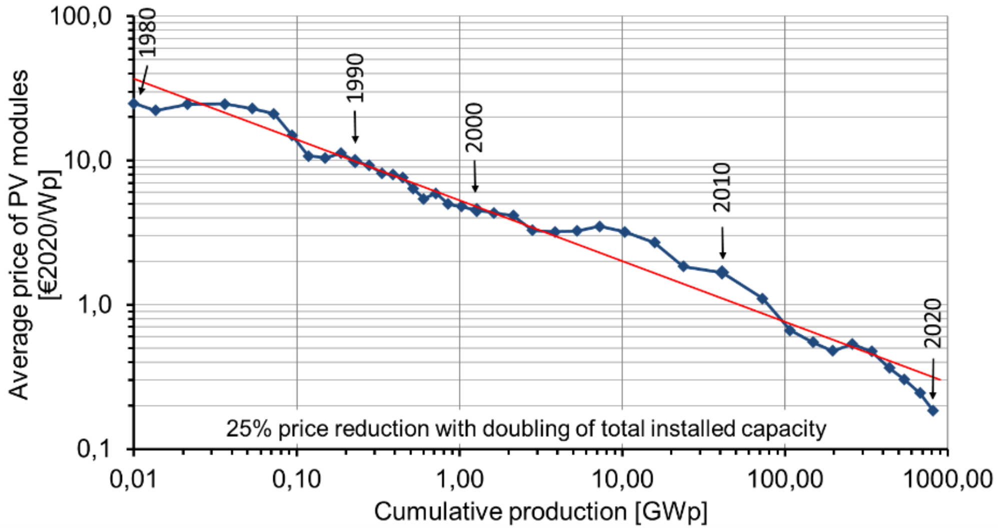


Figure 4: Historical development of prices for PV modules (PSE Projects GmbH/Fraunhofer ISE, data source: Strategies Unlimited/Navigant Consulting/EuPD). The straight line shows the trend in price development.

Prices for PV power plants have fallen by over 75 percent since 2006 thanks to technological progress, economies of scale and learning effects. Figure 5 shows the price development for rooftop systems of 10 to 100 kW_p nominal power in Germany. The annual operating costs of a PV power plant are comparatively low at approx. 1-2 percent of the investment costs; the financing costs increase as interest rate levels rise.

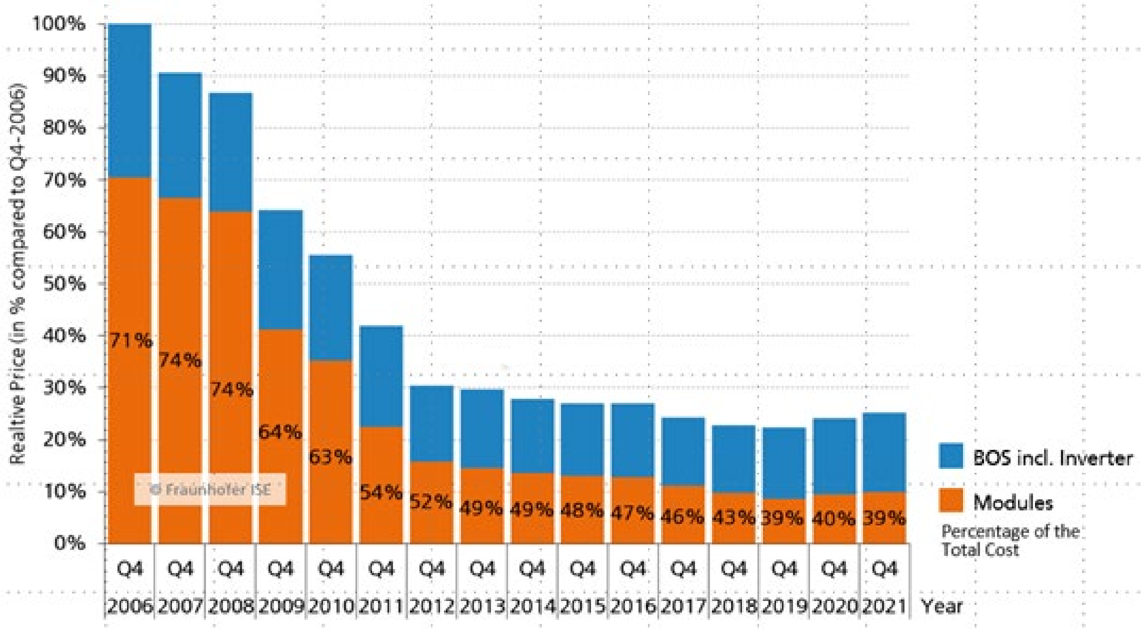


Figure 5: Development of the average end customer price (net system price) for installed rooftop systems with rated nominal power from 10–100 kW_p [ISE5], data BSW-Solar.

New MW-sized power plants produce PV electricity at costs of approx. 5–7 ct/kWh (estimated on the basis of current BNA tender results). For small rooftop plants the costs range from 11–13 ct/kWh. These cost estimates always assume that the volatile electricity is completely purchased. Over the long term, further decreases in the LCOE can be expected. Due to the very high investment costs in the past, older PV power plants are significantly more expensive. An orientation value for the development of the electricity generation costs from new PV ground-mounted plants is provided by the tenders of the German Federal Network Agency (following Section).

4.2 Feed-in Tariff

The energy transition requires massive investments in renewable generation capacities for solar power, among other things. However, given the cost reduction dynamics to date (Section 4.1), there is a risk that investments will be postponed in anticipation of a continued trend (deflation effect). Moreover, since PV power plants largely produce electricity at the same time, the more expensive electricity from the power plant built today would no longer be competitive in the future (crowding-out effect). To nevertheless mobilize actors beyond the classic energy suppliers, in particular homeowners, businesses and small and medium-sized companies, a purchase guarantee for electricity that cannot be used by the investor is necessary for the economic service life of the power plant at a fixed remuneration or a minimum remuneration. The basis for the expansion of PV has been the various versions of the Renewable Energy Sources Act since 2000. The various amendments have increasingly tried to promote and hinder PV expansion at the same time. The "breathing cap" (e.g., 1.5 GW_p according to the EEG 2017) limited the annual expansion, while low tendering volumes slowed down the free-field segment. In addition, there were a number of restrictions, e.g., with regard to area coverage, system sizes and self-consumption.

There are three basic EEG remuneration models, depending on the size and type of the PV power plant: fixed tariff [BNA3] or market premiums (*Marktprämie*) for direct marketing. For large-scale power plants, the remuneration is determined by the bidding rounds for the German Federal Network Agency's tender [BNA4]. The purpose of the market premium is to balance negative differences between the market price of solar electricity (monthly average day-ahead exchange electricity price) and a legally defined reference value (*der anzulegende Wert*) [BNA3]. Surcharges are provided for certain cases of full feed-in, for landlord-to-tenant electricity supply and for elevated agrivoltaic installations.

The feed-in tariff for small rooftop systems with self-consumption that go into operation in January 2024 is up to **8.2 ct/kWh** for 20 years, depending on the size of the system. The Federal Network Agency's bidding round for the bidding deadline of 1 February 2018 determined the lowest average surcharge value to date of 4.33 ct/kWh, and the lowest individual surcharge of 3.55 ct/kWh dates from February 2020.

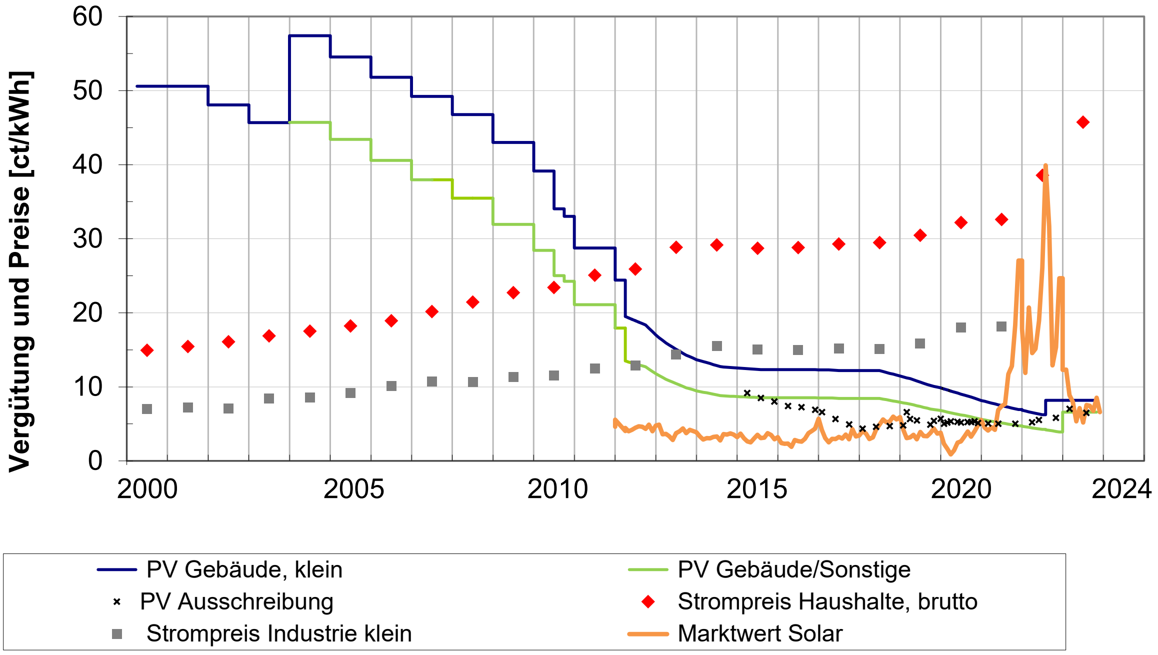


Figure 6: Fixed EEG feed-in tariff for PV power as a function of commissioning date according to system types „Building PV with up to 10 kW_P excess feed-in" and „Other systems up to 100 kW" from [Netz2] and [BNA3], average remuneration of the bidding rounds of the German Federal Network Agency [BNA3], electricity prices [BMWK1], [BDEW1] and average compensation for PV power [NETZ1].

Since the introduction of the EEG in 2000, the remuneration for PV electricity from new power plants has fallen by approx. 85–90 percent (Figure 6). The average fixed tariff for PV electricity is expected to have fallen to **21.3 ct/kWh** by 2022 (source: statista). Internationally, PV electricity at locations with high solar radiation has already been offered at rock-bottom prices of up to 1.12 €ct/kWh (Portugal) and 0.87 €ct/kWh (Saudi Arabia). For comparison: for the planned nuclear power plant "Hinkley C", which is to go into operation in the UK in 2025, a feed-in tariff of the equivalent of 12 ct/kWh plus inflation compensation has been guaranteed for a period of 35 years.

4.3 Pricing on the energy exchange and the merit order effect

PV electricity purchased under the EEG must be traded on the day-ahead market of the exchange. Because this turns it into "gray electricity", the supplier cannot put a price on the sustainable quality of the green electricity. To estimate sales revenues from PV electricity, a mean electricity price ("market value solar" in Figure 6) is calculated based on the prices achieved on the European Energy Exchange (Figure 7).

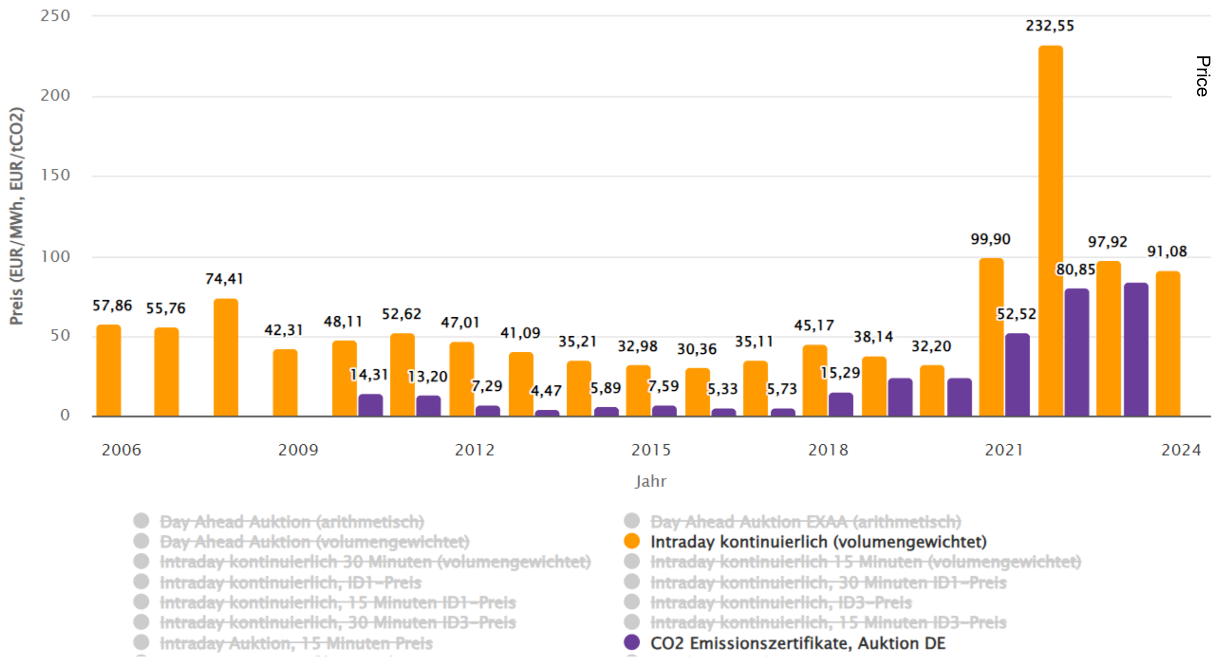


Figure 7: Exchange electricity and certificate prices in Germany [ISE4].

Ongoing price determination on the exchange takes place according to the "merit order" principle (Figure 8). The electricity producers' sales offer for certain quantities of electricity, usually defined by the respective marginal costs, are sorted by price in ascending order. The electricity buyers' purchase offers are sorted in descending order. The intersection of the curves results in the exchange price for the entire traded quantity. The most expensive offer that comes into play thus determines the profit margins of all cheaper suppliers.

The feed-in of solar electricity has legal priority, so it is at the beginning of the offer price scale. With fictitious marginal costs equal to zero, solar power always comes into play. But when solar power comes on, it comes on a massive scale in the core time of the day, when the load — and with it the electricity price in the past — reaches its midday peak. There it predominantly displaces expensive peak-load power plants (especially gas-fired power plants and pumped storage). This displacement lowers the total resulting exchange electricity price and leads to the merit order effect of PV feed-in. With the prices, the revenues of all fossil electricity producers (gas, coal, oil) fall, but also the revenues for electricity from RE (solar power, wind power, hydropower). Furthermore, solar power reduces the utilization of the classic peak load power plants (gas, hydro) in particular.

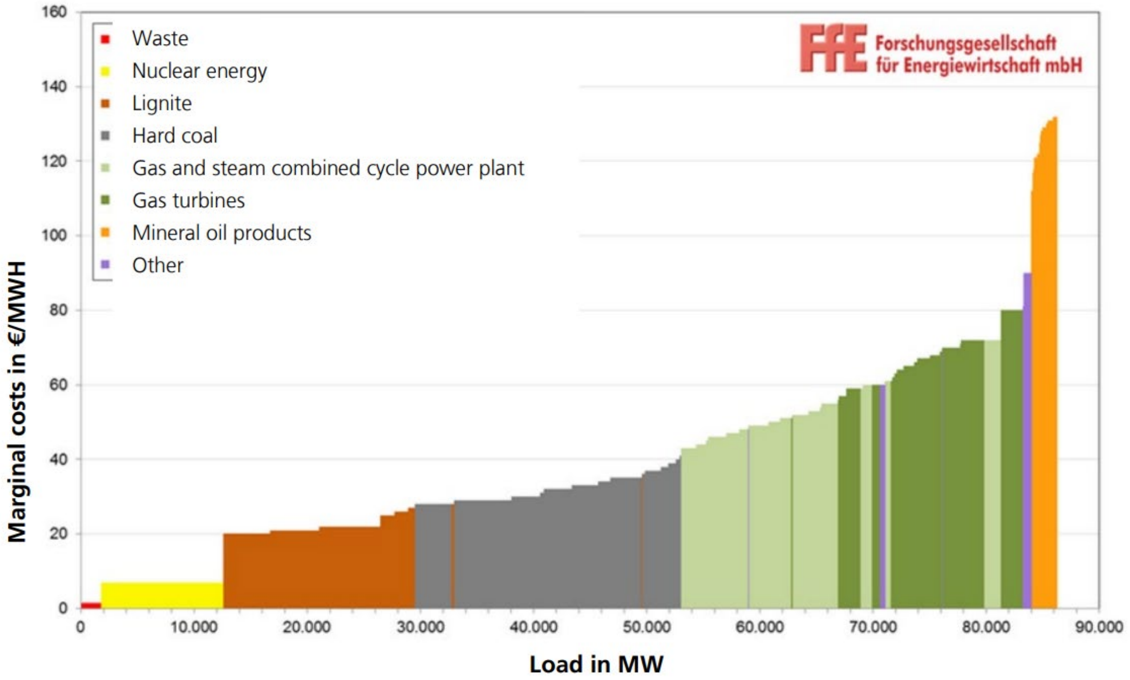


Figure 8: Merit order for conventional power plants in 2018 with an average CO_2 certificate price of €16 per ton [FFE].

With further expansion of volatile RE, their market value factor will decrease in the medium term, because the electricity supply grows at times of high feed-in and both PV and wind electricity have a high simultaneity. For PV, the market value factor is expected to drop to just under 0.8 by 2026 [UNB1].
With the increasing feed-in of RES-E, the Leipzig power exchange has become a residual power exchange. It generates a price for the demand-based supplementation of renewable electricity generation and no longer reflects the value of the electricity.

4.4 Determining the differential costs

The remuneration for PV electricity feed-in according to the EEG is determined annually by the transmission grid operators. The differential costs are intended to cover the gap between remuneration and revenues for PV electricity. The increasing feed-in of PV electricity and wind power lowers the market prices via the merit order effect and thus paradoxically increases the calculated differential costs; the more PV is installed, the more expensive the kWh of PV electricity appears in the subsidy according to this method.
Figure 9 shows the development of the differential costs for the annual remuneration of the PV electricity generated. After a strong increase until 2014, the amount has stabilized between 9 and 10 billion euros.
The value of PV electricity is measured via the electricity exchange price. According to this method, its value was systematically underestimated: on the one hand, PV electricity has long since influenced the exchange price in the intended direction, namely downwards.

On the other hand, the exchange price still largely ignores important external costs of fossil and nuclear power generation (Section 5.2).
A study by the Friedrich-Alexander University Erlangen-Nuremberg has shown that in the years 2011 to 2018 a total of 157 billion euros in EEG differential costs were incurred, while in the same period cost savings of 227 billion euros were realized through the feed-in of PV and wind power [FAU]. The bottom line is that consumers saved 71 billion euros in costs.

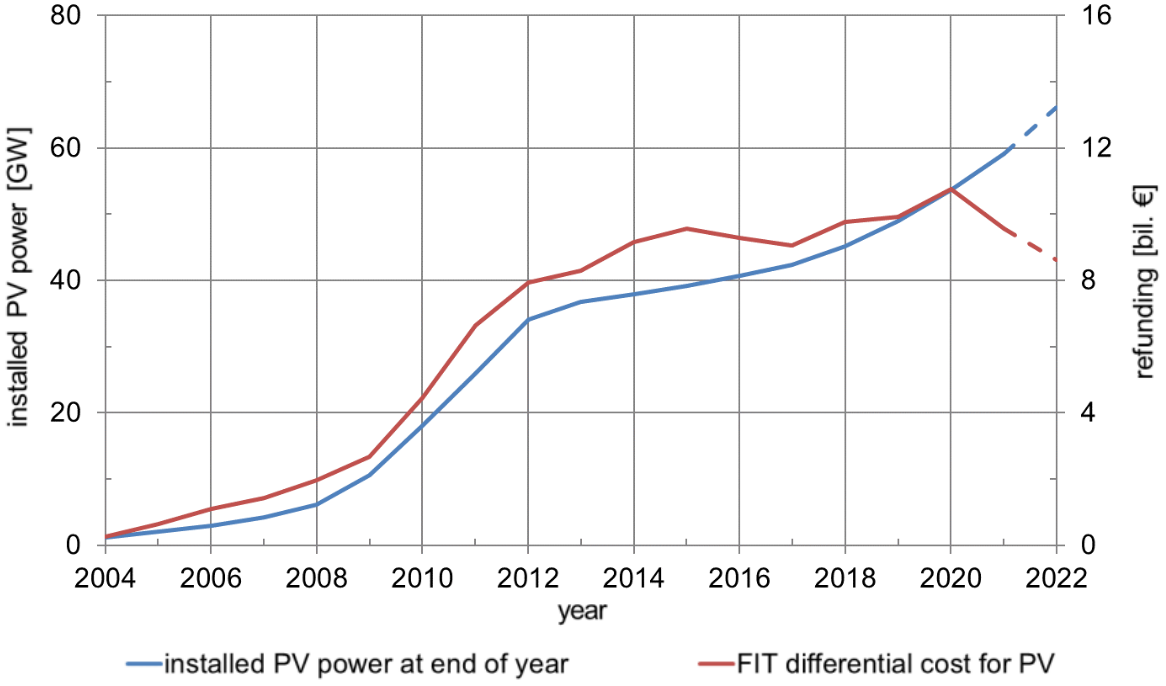


Figure 9: PV expansion and differential costs, data from [BMWK1], [BMWK3].

4.5 EEG levy

The difference between remuneration payments and sales revenues for RES-E, supplemented by other items, was compensated by the EEG levy until June 2022. The levy was borne by those electricity consumers who could not be exempted. Politicians had defined who had to finance the switch to renewable energies [BAFA]. It had decided to largely exempt energy-intensive industrial companies with a high share of electricity costs from the EEG levy. In 2021, 44 percent of industrial consumption was thus privileged. This comprehensive exemption increased the burden for other electricity customers, especially private households. Final consumers had to pay an additional 19 percent VAT on the levy. In 2021, there was a subsidy from the federal budget (Energy and Climate Fund, EKF) of 10.8 billion euros for the levy account for the first time. From July 2022, the EEG levy was abolished, and the differential costs will be covered by the EKF.

5 Subventions and Electricity Prices

5.1 Is PV power subsidized?

Yes, since 2021.

A subsidy is defined as a benefit from public funds. Up to and including 2020, however, the subsidy for PV electricity generation did not come from public funds, but from a selective consumption levy (Section 4.5), which was also partly levied on PV electricity produced and consumed by the consumer. Part of the energy consumers paid a compulsory levy for the necessary transformation of our energy system. This view was also confirmed by the EU Commission. The amount of the levy did not correspond to the total remuneration, but to the differential costs. On the cost side, the cumulative differential costs of the feed-in tariff for PV electricity amount to approximately 100 billion euros up to and including 2020 [BMWK3]. In 2021, there was a contribution from the EKF for the EEG account for the first time (Section 4.5). The revenues of the EKF come from emissions trading and federal subsidies, thus a subsidy will take effect from 2021. In 2020, EnBW built the "Weesow-Willmersdorf" solar park, the first large-scale PV power plant in Germany without electricity purchase via the EEG. This is a 187 MW_P project in Brandenburg [EnBW1].

5.2 Is fossil fuel power production subsidized?

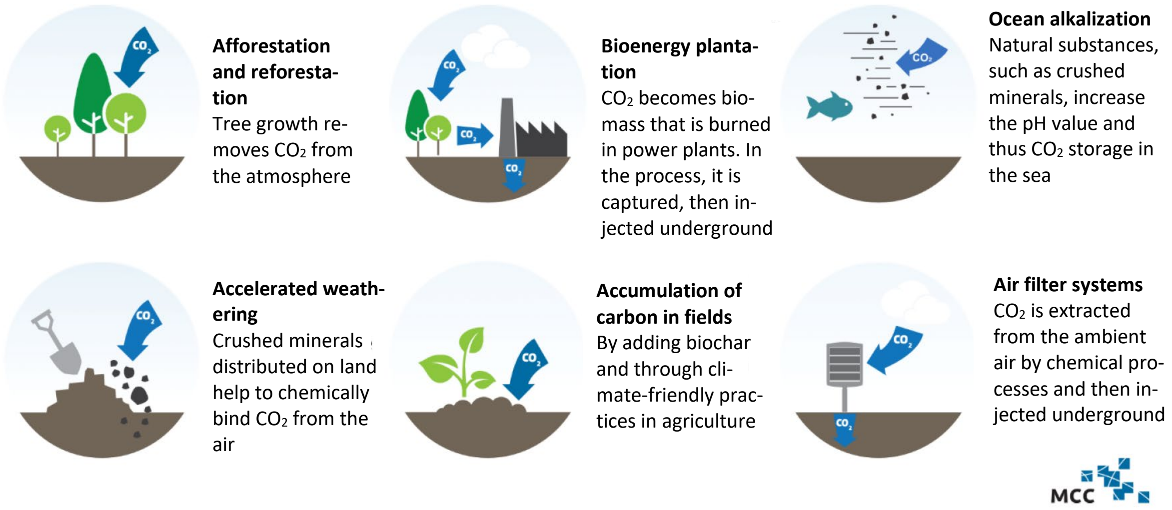
Yes, the future costs of the subsidy are still difficult to estimate.

Policy makers influence the electricity price of fossil and nuclear power plants. Policy decisions define the price of CO_2 emission allowances, the conditions for smoke filters, the permanent storage of CO_2, the taxation, 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 effects largely arise in the future through CO_2-induced climate crisis, the final disposal of nuclear waste and the perpetual loads of hard coal mining. If these costs are consequently priced, PV power generation will make the electricity mix cheaper. Until we get to that point, fossil power will be sold at prices that mask their external costs and pass the burden on to future generations.

In 2005, an EU-wide emissions trading scheme (European Union Emissions Trading System, EU ETS) was introduced to make CO_2 emissions more expensive and to begin internalizing the costs. However, due to an oversupply of allowances, the price had collapsed by the end of 2017 and was thus practically ineffective (Figure 7). Across Europe, certificate trading also covers only 45 percent of greenhouse gas emissions, because important sectors beyond industry and the energy sector are excluded [UBA5]. An expansion to about 85 percent of emissions has now been decided.

In Germany, a national emissions trading system for the heating and transport sectors was launched in January 2021 with the Fuel Emissions Trading Act (BEHG). Initially, only heating oil, natural gas, petrol, and diesel were considered, from 2023 coal and waste fuels will be included. A fixed price per emission allowance of EUR 45 in 2024 and EUR 55 in 2025 has been in place since 01.01.2024. These prices are offset by considerably higher costs caused by climate damage and the necessary recycling of CO_2 from the atmosphere:

1) 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 195–680 €/t, depending on the higher or equal weighting of the welfare of current versus future generations [UBA3]. In Germany, almost 810 million tons of carbon dioxide and CO_2 equivalents were emitted in 2019, with corresponding damages of 157 billion euros or 551 billion euros, depending on the welfare weighting. For lignite-based electricity generation with an emission factor of 1075 g CO_2/kWh (Figure 10), the derived CO_2 price premiums are 21 and 73 ct/kWh, respectively. Considering the external effects, the costs to society as a whole for lignite-based electricity are thus many times higher than the pure electricity generation costs of 3.4–4.7 ct/kWh [FÖS2].
2) All climate protection scenarios assume that direct carbon capture (DCC) will be necessary to contain the climate crisis. Direct Air Carbon Capture and Sequestration (DACCS) with air filtration systems offers potential for permanent recapture without further intervention in the biosphere (Figure 10). In pilot plants, recapture via DACCS currently costs about 550 €/t, the cost potential with successful scaling is estimated at 90–260 €/t [MCC]. Some questions about the final storage of the recycled CO_2 are still open.



Afforestation and reforestation
Tree growth removes CO_2 from the atmosphere

Bioenergy plantation
CO_2 becomes biomass that is burned in power plants. In the process, it is captured, then injected underground

Ocean alkalization
Natural substances, such as crushed minerals, increase the pH value and thus CO_2 storage in the sea

Accelerated weathering
Crushed minerals distributed on land help to chemically bind CO_2 from the air

Accumulation of carbon in fields
By adding biochar and through climate-friendly practices in agriculture

Air filter systems
CO_2 is extracted from the ambient air by chemical processes and then injected underground

Figure 10: Process for removing CO_2 from the atmosphere and storing carbon [MCC].

A study by the International Monetary Fund estimates that global subsidies for coal, oil and natural gas, including external costs, will amount to 5.9 trillion US dollars in 2020 [IMF].

5.3 Do tenants subsidize well-positioned homeowners?

No.
This popular headline, quoted here from the "Zeit" of 8 December 2011, is a distorted portrayal. The costs of the conversion of our energy system to RE have been passed on to all electricity consumers until 2021 - with the politically intended exception of electricity-intensive industry — according to the polluter-pays principle, including households of homeowners and tenants. These costs cover not only PV but also wind power and other RE. All electricity customers can influence their electricity consumption through the choice and use of their appliances; many municipalities offer free energy-saving advice and subsidies for the purchase of efficient new appliances (examples at https://www.stromspiegel.de/beratung/foerderung-und-zuschuesse/).
Systems in the power class below 10 kW_p, which are often purchased by homeowners, account for approx. 15 percent of the total installed capacity (Figure 18). Larger systems are often financed through citizen participation or funds, in which tenants can, of course, also participate.

5.4 Does PV increase electricity consumption costs?

No, since the abolishment of the EEG levy in mid-2022, the electricity price does not include any components for the remuneration of PV electricity.
A sample household with an annual consumption of 3,500 kilowatt hours will pay an average gross electricity price of **47 ct/kWh** in 2021 [BDEW1]. Figure 11 shows an exemplary price structure. The electricity tax was introduced in 1999 in order to make energy more expensive through higher taxation; the revenues flow mainly into the pension fund. Private households pay value-added tax on electricity tax. The concession levy is a charge for the use of public roads. The Electricity Grid Charges Ordinance (Section 19 Strom-NEV) is designed to reduce the burden on electricity-intensive industrial companies at the expense of other final consumers. The Combined Heat and Power Act (KWKG) promotes the operation of combined heat and power plants for electricity generation.

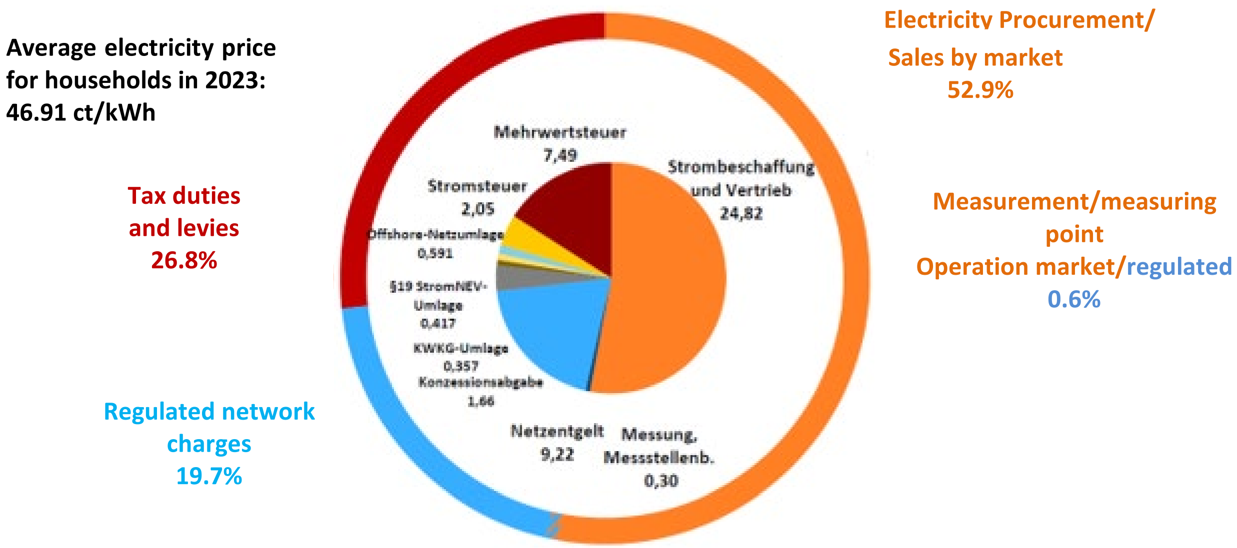


Figure 11: Composition of the average household electricity price in 2023 [BDEW1].

The electricity price for private households in Germany is about 50 percent higher than the European average (source: stromreport.de, reference year 2020), but the purchasing power per inhabitant is also 60 percent higher here (source: statista.de, reference year 2019). If electricity prices and purchasing power are taken into account, Germany is in the middle of the European field. Added to this is the high security of supply. In low-price countries, power outages are commonplace.

With an average price of 27 ct/kWh net excluding electricity tax for new contracts, electricity consumption for small and medium-sized industrial customers will not become more expensive as a result of the expansion of PV in Germany.

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

No.
The monthly values of the Energy Charts (www.energy-charts.de) show that electricity imports are conspicuously high in summer, i.e. in months with particularly high PV electricity production (Figure 12).

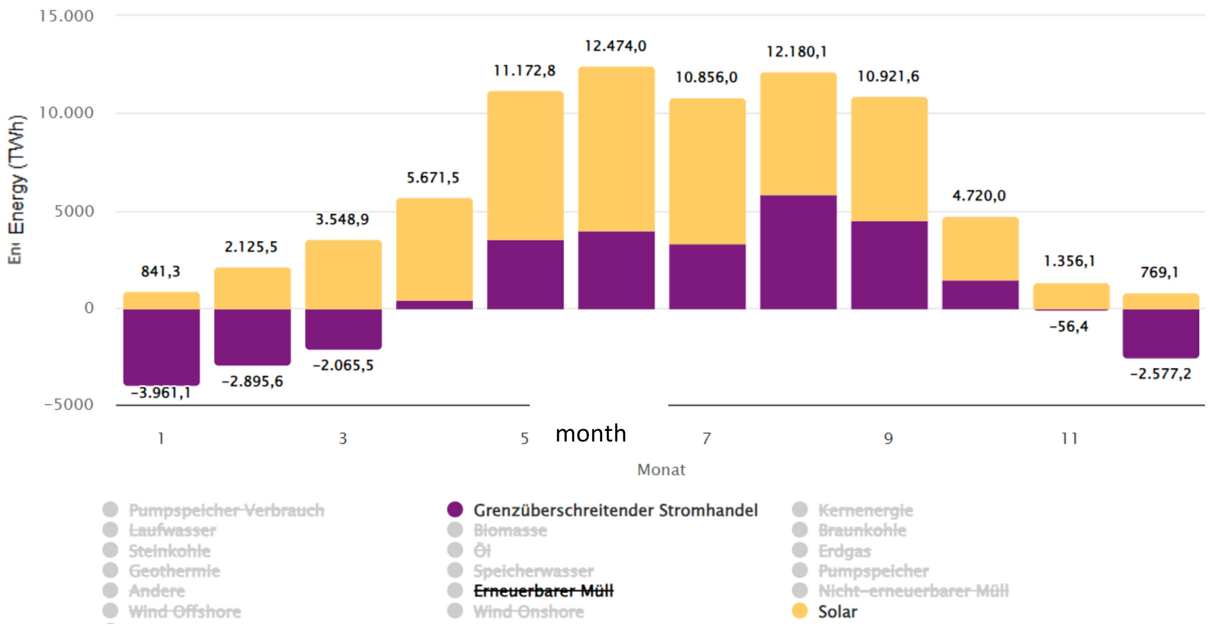


Figure 12: Net Electricity import (purple) and solar electricity production (yellow) in 2023 for Germany [ISE4].

7 Can small PV systems generate attractive returns?

Yes.
In principle, small PV systems can generate income via the EEG remuneration for feeding into the grid and via the reduction in electricity consumption thanks to self-consumption. Systems without self-consumption ("full feed-in") receive higher remuneration than systems with self-consumption ("partial feed-in", Figure 13). Attractive returns are possible due to the sharp drop in prices for PV modules, the sharp rise in electricity consumption costs and the increased remuneration for full feed-in.
The greater the difference between the purchase costs for electricity and the electricity production costs of the PV system, the more worthwhile self-consumption becomes. In systems without storage, the potential for self-consumption depends on the coincidence between the generation and consumption profiles. Depending on the size of the system, households achieve 20–40 percent self-consumption in relation to the electricity generated [Quasch]. Larger systems increase the degree of coverage of the total electricity demand with PV electricity but reduce the share of self-consumption. Commercial or

industrial consumers achieve particularly high self-consumption values if their consumption profile does not drop significantly at the weekend (e.g., cold stores, hotels and restaurants, hospitals, server centers, retailers). Energy storage and transformation technologies offer considerable potential for increasing self-consumption (see Section 21.3). The yield of a system is higher in sunny regions. In fact, the regional difference in the annual sum of irradiation is not transferred 1:1 to the specific yield (kWh/kW$_p$, Section 27.5) because, for example, the operating temperature of the modules, pollution effects or the duration of snow accumulation also play a role.

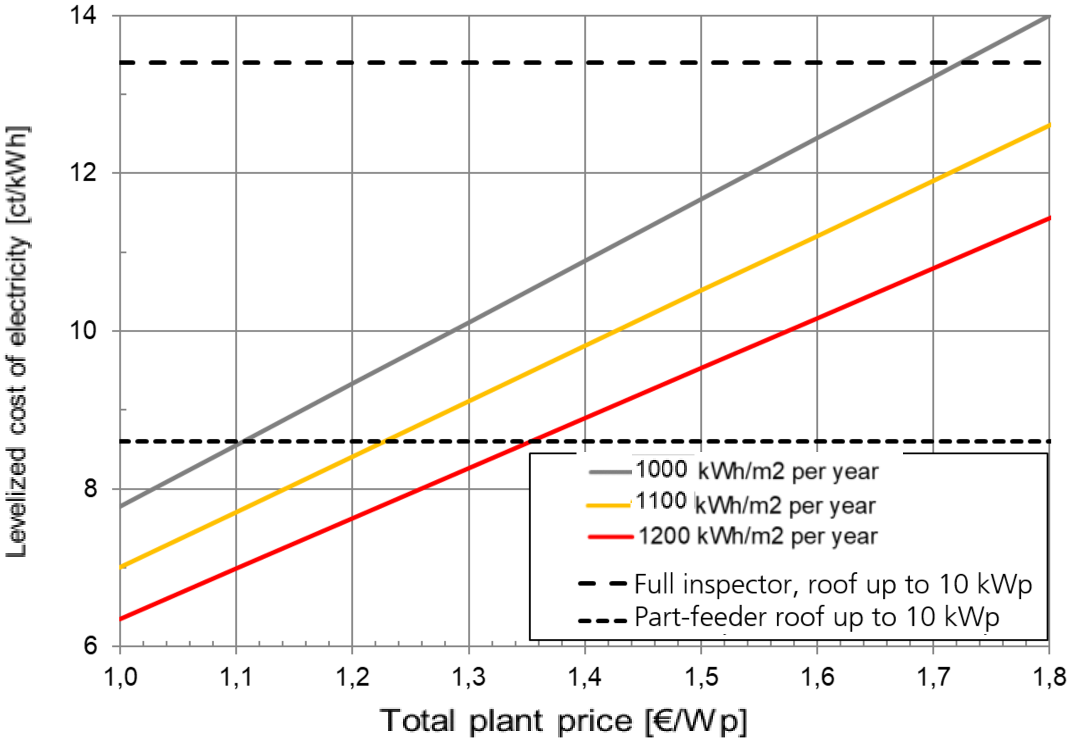


Figure 13: Estimation of the LCOE for small PV systems under different irradiation conditions, plus remuneration according to [EEG2023].

- Performance Ration of 85 percent (see Section 27.7)
- Annual yield degradation of 0.5 percent
- Lifetime of 20 years
- Annual operating costs of 1 percent (of plant price)
- Inflation rate of 2 percent
- Nominal imputed interest rate of 4 percent (average of own and borrowed capital investments)

The Levelized Costs of Electricity (LCOE) are estimated on the basis of the net present value method. The current expenditure and the LCOE are discounted to the time of commissioning using the specified interest rate. In the case of full financing through equity, the imputed interest rate corresponds to the achievable return. For comparison: the

Federal Network Agency has set the return on equity for investments in electricity and gas grids for new plants at 6.91 percent before corporate income tax [BNA1].
The return on a PV system is not risk-free during the EEG remuneration period. Neither manufacturer guarantees nor plant insurance reduce the investor risk to zero. The utilization of electricity from the 21st year of operation is regulated for the first time by the [EEG2021]. Self-consumption capability plays a major role in calculating the continued operation of "de-subsidized" plants [SCBW].

8 Is the supply of solar components ensured?

No, China has built up a critical monopoly.
The complete PV value-added cycle based on silicon wafer technology (Figure 14) begins with the production of high-purity polysilicon and continues with the crystallization of silicon ingots and the sawing of silicon wafers. This is followed by cell production and module production. If the coverage of more than one stage is to be emphasized, one speaks of (vertically) integrated PV production.

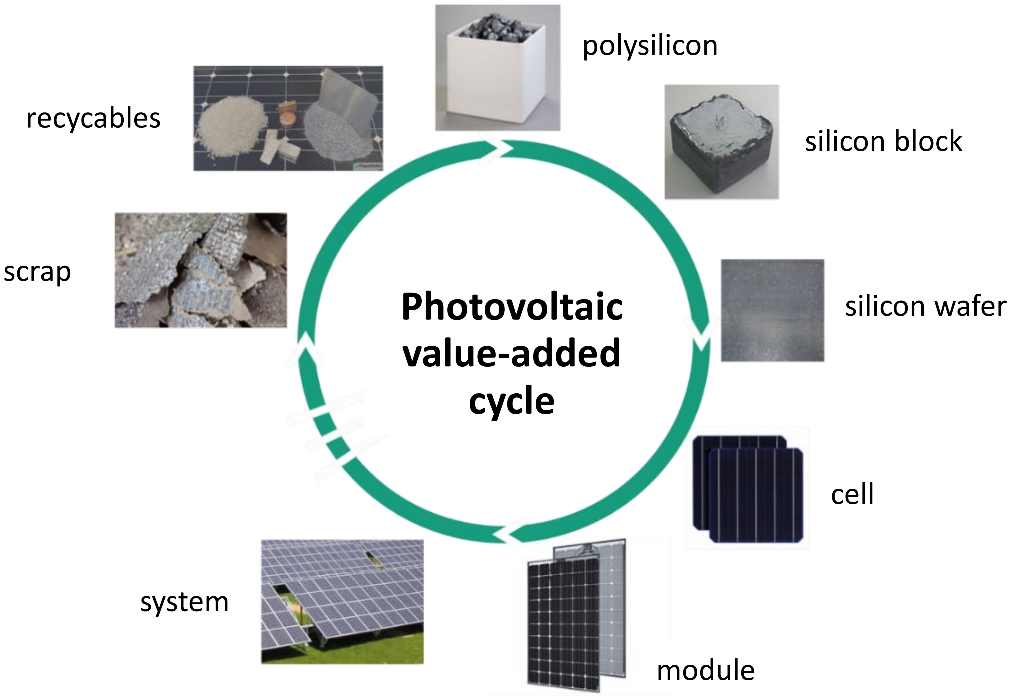


Figure 14: Value Chain for Photovoltaics.

Many material and component manufacturers are part of the extended PV value cycle. These include suppliers of silver pastes for solar cells, special films, wires, solar glass, and junction boxes for solar modules. Other players complete the cycle with additional components for power plants through to recycling:

1. Material production: solar silicon, metal pastes, connector wires, plastic foils, solar glass, glass coating

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
6. Recycling

In 2022, China's market share in the production of polysilicon and silicon wafers was around 85 %, for solar cells just under 60 % and for solar modules around 70 % [IEA4]. While there was still a complete PV supply chain in Germany and Europe around 2010, the production of some feedstocks has been discontinued due to the regional demand that has decreased in the meantime. Figure 15 shows the current production landscape in Germany for the most important components and intermediate products. Notable shares of the global market are held by inverter manufacturers and silicon manufacturer Wacker. In Europe, there are small module production facilities and hardly any cell or wafer production. A slump in trade with China would seriously jeopardize the expansion of PV in Germany and also severely impair local module production due to a lack of intermediate products.

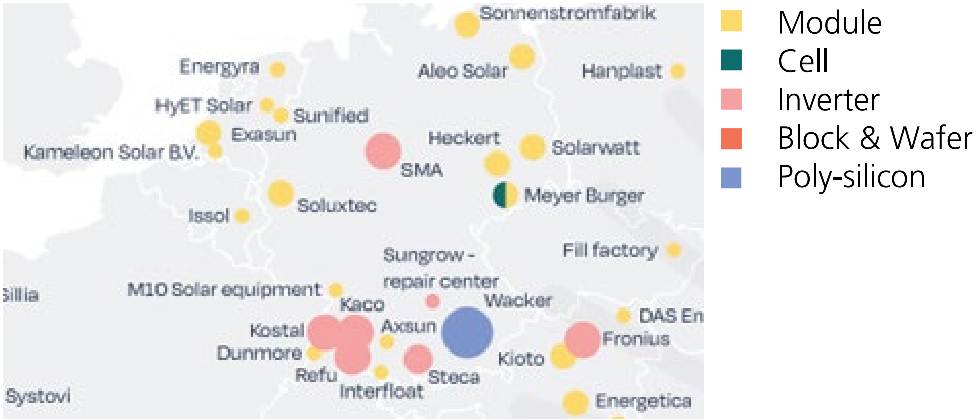


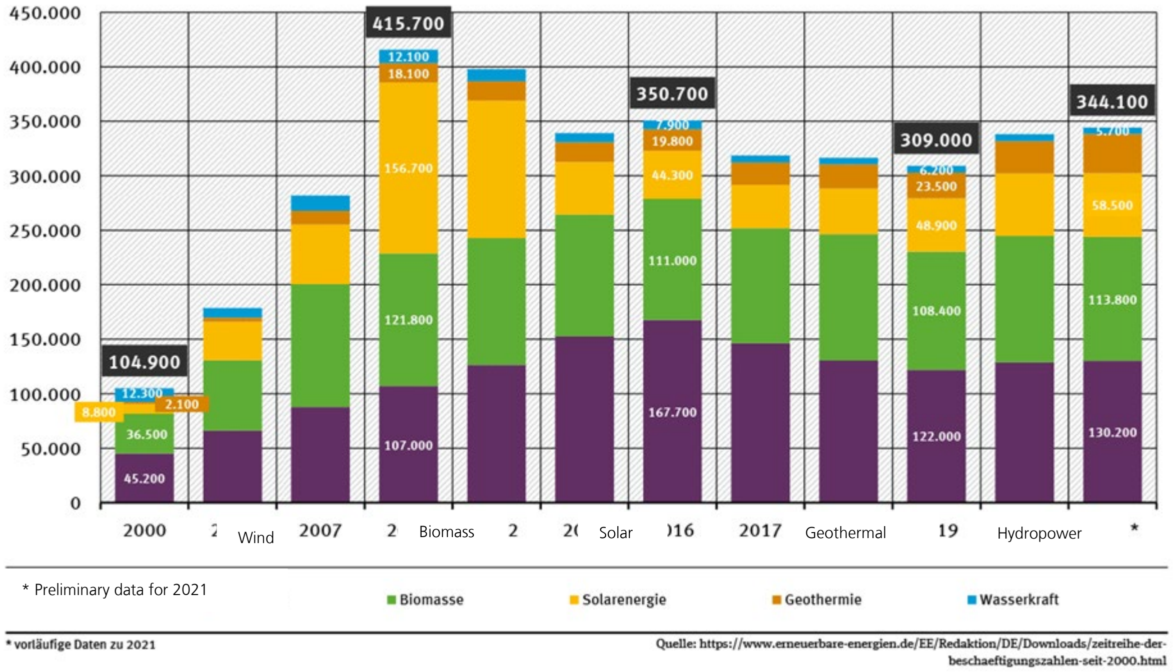
Figure 15: PV production sites, circular area represents production capacity [SPE].

9 Does installing PV only create jobs in Asia?

No, but Germany has lost many jobs in the PV industry in the last decade.
Figure 16 shows the number of jobs in the renewable energies sector. By comparison: in 2015, just under 21,000 people were still working in lignite mining and in lignite-fired power plants [ÖKO1]. In the decade, many jobs were lost in Germany due to company closures and insolvencies, affecting not only cell and module producers but also mechanical engineering and installers.
According to calculations by Fraunhofer ISE, a vertically integrated 10 GW production from silicon ingot via wafer and cell to module creates approx. 7500 full-time jobs [ISE8].

According to a study by EuPD Research based on figures from 2018, around 46,500 full-time employees are needed to install 10 GW of PV [EuPD].

The hope that the combination of the Renewable Energy Sources Act (EEG), investment subsidies in the new federal states and research funding would be enough to establish Germany as a world-leading production location for PV cells and modules seemed to be fulfilled as recently as 2007, when a German company topped the international rankings in terms of production volume. Since then, German manufacturers have dramatically lost market share because of the decisive industrial policy in the Asian region and the massive investments in production capacities generated there. Labor costs play a subordinate role in this development, as PV production has reached a very high degree of automation. Turnkey production lines that deliver very good PV modules have been available “off the shelf” for several years, which has enabled a rapid transfer of technology.



* Preliminary data for 2021

* vorläufige Daten zu 2021

Quelle: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/zeitreihe-der-beschaeftigungszahlen-seit-2000.html

Figure 16: Number of jobs in the renewable energy sector [UBA11]

Effective laws on feed-in tariffs have triggered massive investments in PV power plants in Germany and Europe. However, there was a lack of economic policy support to ensure that production capacities remained competitive. On the other hand, China and other Asian countries have succeeded in mobilizing many billions of domestic and foreign capital for the construction of large-scale production lines by creating attractive investment and credit conditions.

Despite the high import quota for PV modules, a large part of the value added associated with a PV power plant remains in the country. In the long term, falling manufacturing costs of PV modules on the one hand and rising freight costs and long freight times on the other will improve the competitive position for module production in Germany.

10 What funding is being directed to PV research?

In 2022, the German government invested almost 70 million euros to support photovoltaic research (Figure **17**), mostly in production technologies.

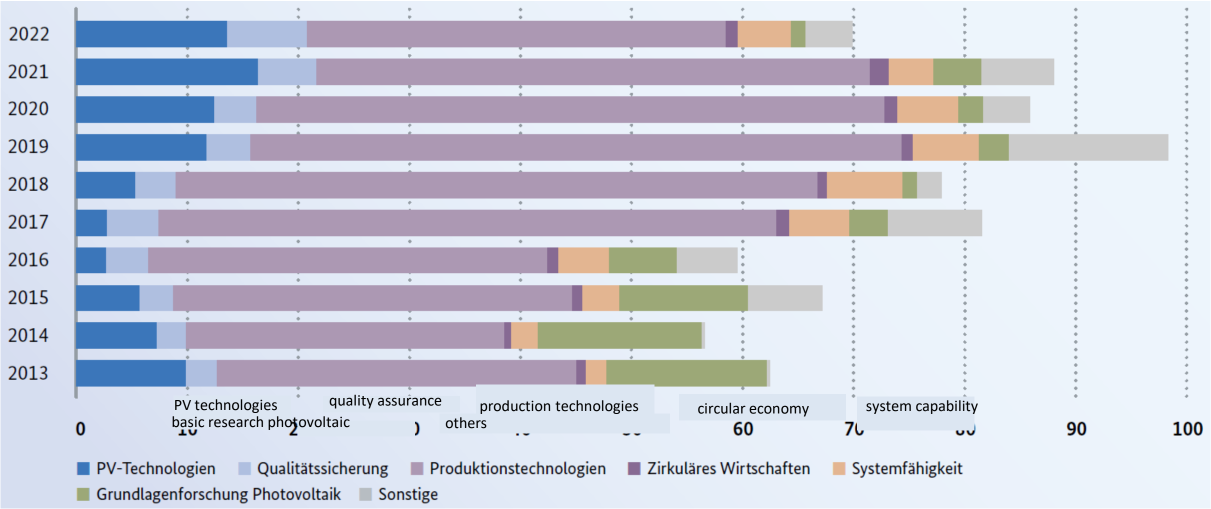


Figure 17: Funding for PV research categorized by technology in € million [BMWK2].

11 Does PV power overload our energy system?

11.1 Transmission and distribution

Most solar power plants in Germany are connected to the low-voltage grid; Figure 18 illustrates how they are distributed according to plant size. Many systems generate solar power decentralized and close to consumption; they hardly place any demands on the expansion of the transmission or medium-voltage grid. On sunny days, a high density of PV systems in a low-voltage grid can lead to electricity production exceeding electricity consumption locally due to the high simultaneity factor. Transformers then feed power back into the medium-voltage grid. With very high system densities, the transformer station can reach its capacity limit. Large-scale PV power plants or local clusters of systems in sparsely populated areas sometimes require an enhancement of the power grid and/or transformer stations, or the installation of storage capacities.

An even distribution of PV installations across the grid sections reduces the need for grid expansion. PV expansion should be geographically even more consumption-based to facilitate the distribution of solar power. Per inhabitant, Brandenburg or Mecklenburg-Western Pomerania, for example, have four to five times more PV capacity installed than North Rhine-Westphalia or Hesse [AEE2].

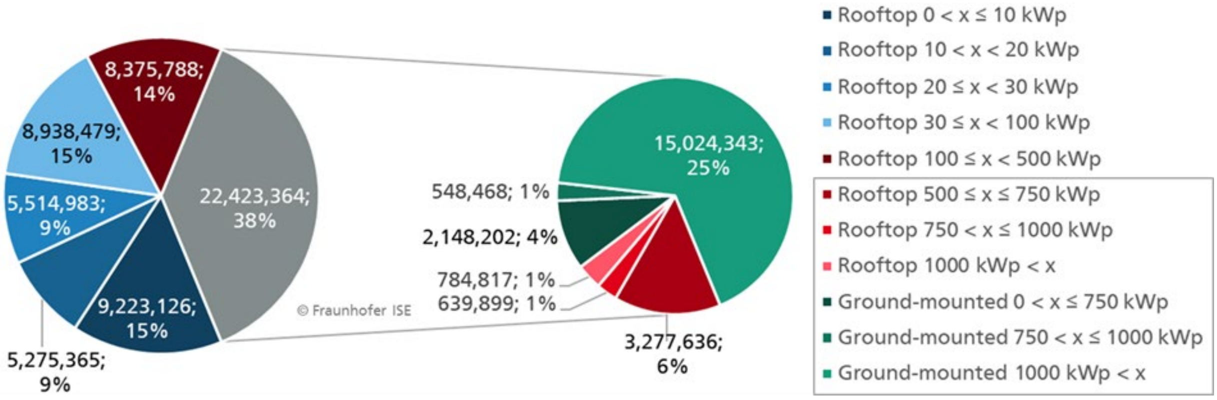


Figure 18: Distribution of installed PV power according to plant size in 2021 [ISE4].

When grid bottlenecks are currently discussed, photovoltaics are rarely mentioned (Figure 19). In 2021, 5.8 TWh of electricity from renewable energies was regulated, corresponding to around 1 percent of total electricity consumption. Solar power only made up 4 percent of the regulated electricity [BNA2]. The derating mainly affects wind power, which is mostly produced in the north and for which there is not yet sufficient transmission capacity to southern Germany. When wind levels are high, the remuneration for regulated power in the north and the procurement of the missing power in the south (redispatch measures) lead to significant costs.

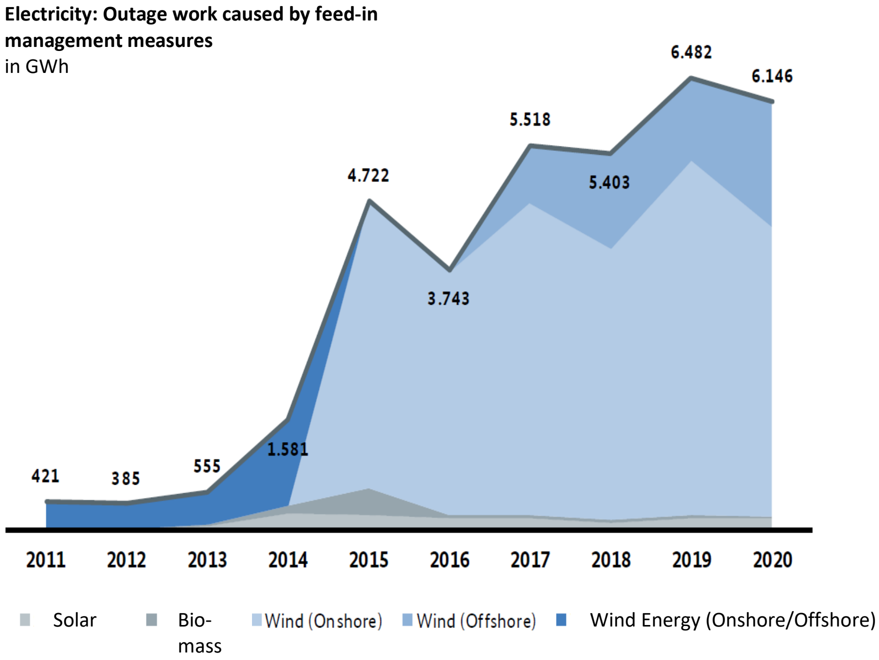


Figure 19: Regulated electrical energy [BNA2].

11.2 Volatility

11.2.1 Solar power production is predictable

Reliable performance forecasts based on satellite data can be created for individual power plants or regional clusters, with local sky imagers or monitoring stations being added as needed. On a national level, the generation of solar electricity can also be planned very well thanks to reliable national weather forecasts and yield models (Figure 20). Due to decentralized generation, regional changes in cloud cover cannot lead to serious fluctuations in Germany-wide PV electricity production. Even the effects of a solar eclipse with a high, trans-regional simultaneity factor can be reliably forecasted.

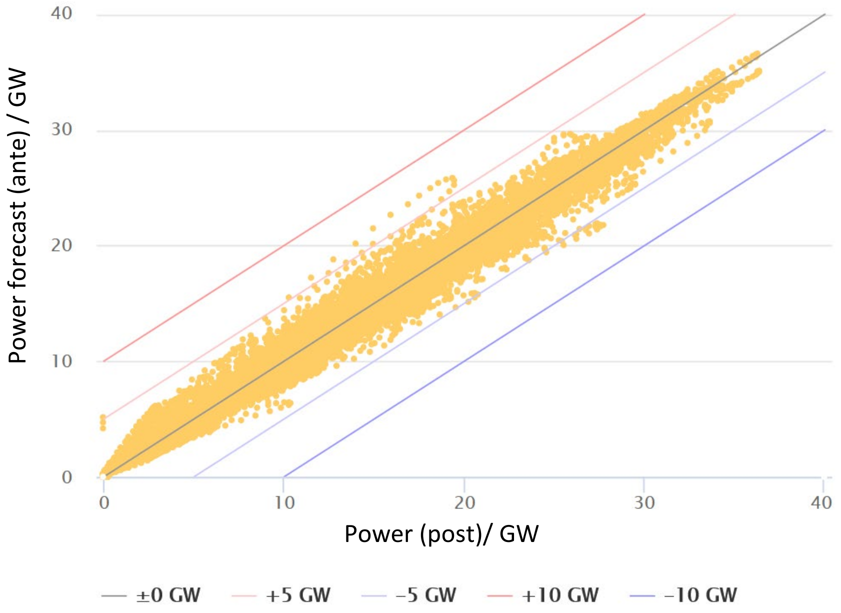


Figure 20: Actual and predicted hourly generation of power in 2021 [ISE4].

11.2.2 Peak production is significantly lower than installed PV capacity

Due to technically induced losses with performance ratio values below 90 percent, (cf. Section 27.7) and often inconsistent weather conditions, real electricity generation above 65 percent of the installed nominal capacity is very rare throughout Germany (cf. Section 3 and Figure 21).

11.2.3 Solar and wind energy complement each other

Due to the climate, solar radiation and wind strength in Germany correlate negatively on time scales of hours to months.

On a **quarter-hourly basis**, with an average installed capacity of approx. 57 GW# PV and 63 GW$_P$ wind power at the end of the year, in 2021 practically never more than 60 GW of capacity (i.e., 50 percent of the nominal PV + wind capacity) entered the electricity grid (Figure 21). Viewed on an **hourly basis**, less than 1 percent of the electricity generated would have been lost if the combined PV + wind capacity had been limited to a maximum of 40 GW (i.e., 33 percent of the nominal PV + wind capacity).

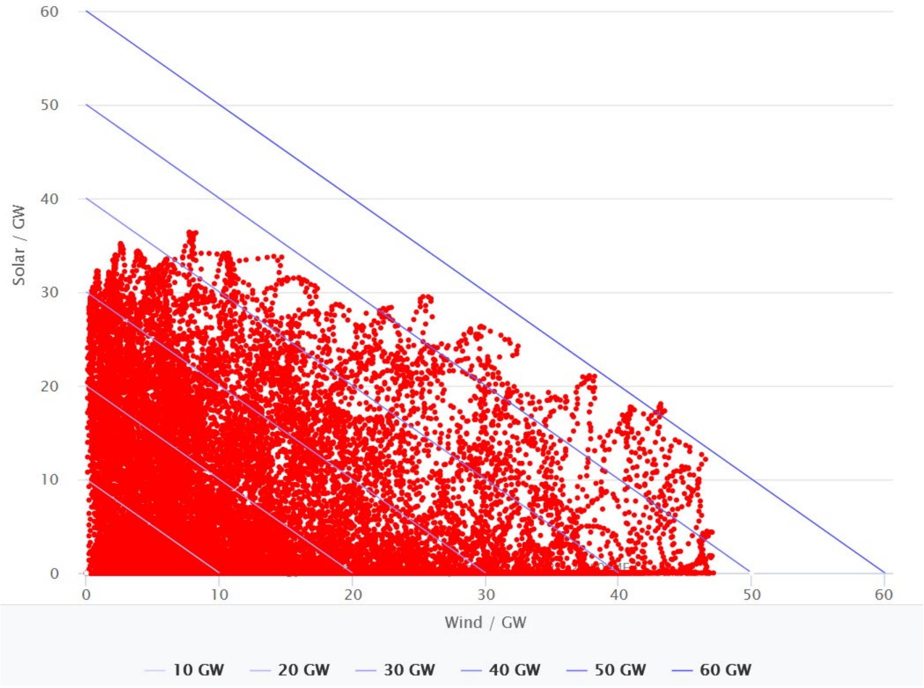


Figure 21: Average power for the supply of solar and wind power in 2021, 15-minute values [ISE4].

On a **daily basis**, the combination of PV and wind power also leads to a stabilization of the yield. While the relative mean absolute deviation of daily electricity production from the arithmetic mean in 2021 was 55 percent for PV and 56 percent for wind, the value for PV + wind was only 37 percent.

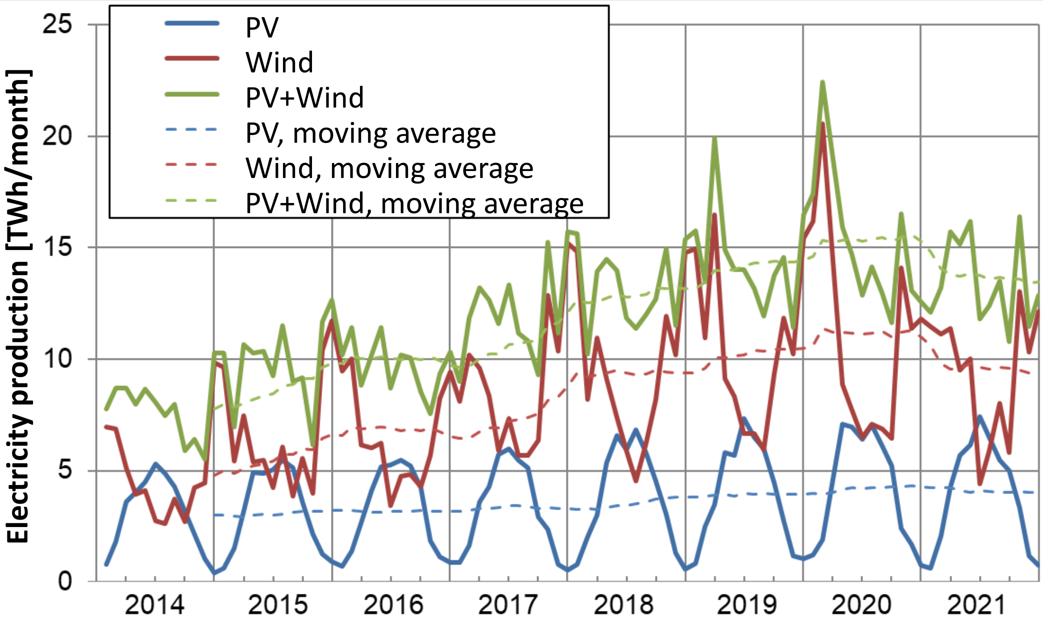


Figure 22: Monthly totals of PV and wind power production, data from [ISE4].

Figure 22 shows the **monthly totals** of electricity production from PV and wind power, as well as the moving annual averages. The average relative deviation of the monthly values from the moving annual value is 53 percent for PV and 30 percent for wind. The sum of PV and wind power is significantly more stable than the individual sectors, with a value of 14 percent.

11.3 Controllability

With increasing output, PV is increasingly being called upon as a stabilizing control variable. The amendment to the Renewable Energy Sources Act (EEG) on 1 January 2012 also requires systems connected to the low-voltage grid to participate in feed-in management via remote control by the grid operator or via automatic derating at 70 percent of the active power, except in the case of small systems. According to the Low Voltage Directive VDE AR-N-4105, in force since 1 January 2012, inverters must provide grid support functions.

11.4 Conflicts with slow-response power plants

The generation profile of PV electricity with peaks around noon matches the load profile of the power grid well. However, conflicts are increasing with sluggish power plants that can only follow a fluctuating residual load to a very limited extent for technical and economic reasons. Older coal-fired power plants, especially lignite-fired power plants, cannot contribute balancing power in an economically justifiable way. Run-of-river hydro and current biomass power plants also offer little flexibility. In principle, however, volatile generators with their negligible marginal costs must be given priority.

These unresolved conflicts can briefly lead to significant overproduction and negative exchange electricity prices, as the example in Figure 23 shows.
During hot spells in the past, fossil and nuclear power plants caused critical heating of the rivers used as cooling reservoirs. Photovoltaics installed in Germany have eliminated this problem and can also ease such situations in neighboring countries such as France, because they fundamentally reduce the load on fossil and nuclear power plants, especially on summer days.

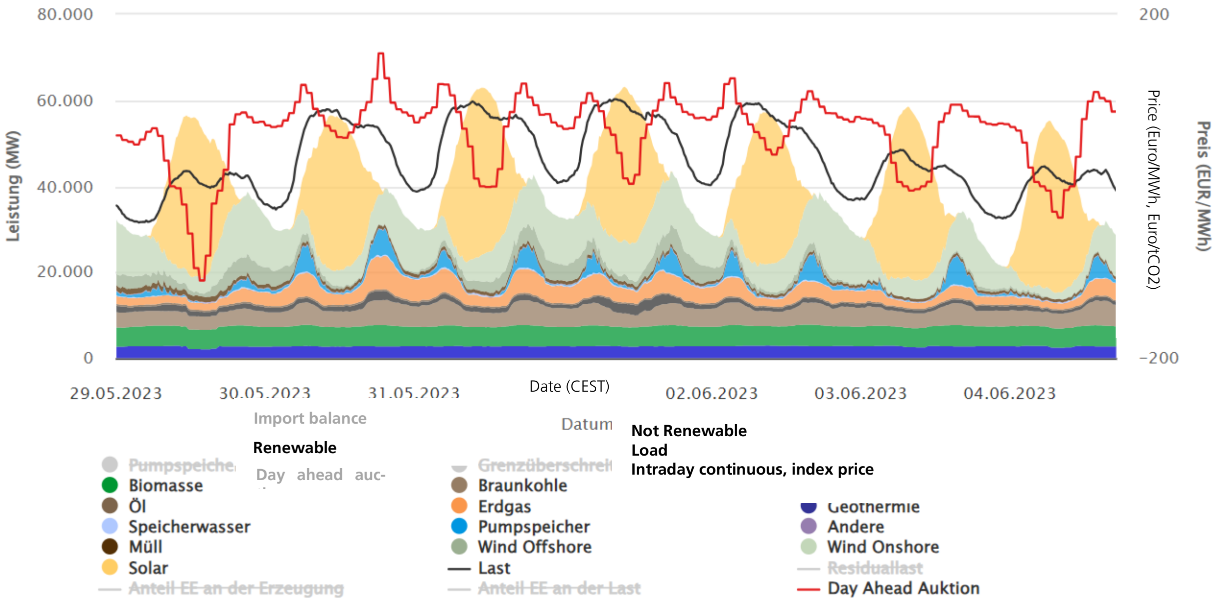


Figure 23: Example showing the course of electricity trading price, conventional and renewable electricity in the 22th calendar week in 2023 [ISE 4].

11.5 Does volatile solar power endanger security of supply?

No.
The security of supply for end consumers actually improved with the photovoltaic expansion (Figure 24).

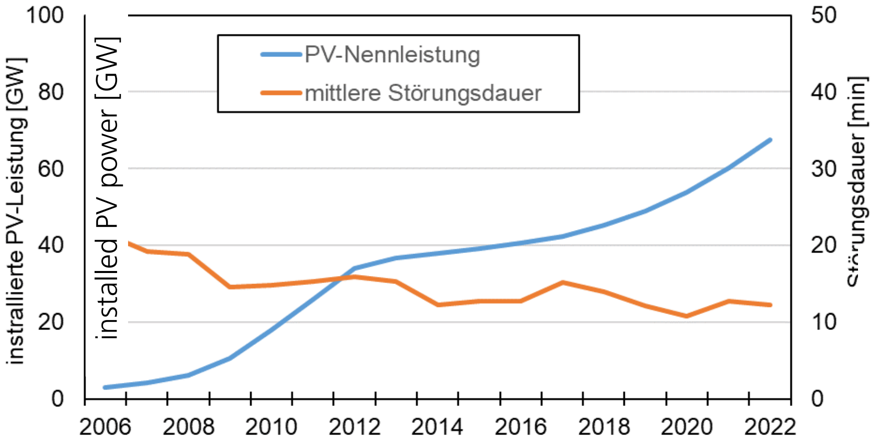


Figure 24: System Average Interruption Duration Index (SAIDI) for low and medium. Data from [BNA2].

11.6 Does the expansion of PV have to wait for more storage?

No, not in the next few years.
When price differences in electricity consumption are large and frequent enough, it is worth investing in load management measures, stationary battery storage systems or pumped-storage power plants. The 2010s saw postponements in investments in storage – specifically pumped storage – because their operation was not financially feasible.
Further expansion of PV and wind power will lower the energy exchange prices more frequently and massively. On the other hand, an increase in the price of electricity generated from fossil fuels due to CO2 certificates or taxes, will increase EEX prices during periods of high residual load. Price spreads create the basis for load shifting, profitable storage operations and the production of green hydrogen. If the price spread is passed on to the end user through tariffs, storage facilities also become interesting for them. This would increase the capacity to absorb the volatile energy from the sun and the wind.

12 Is there enough space for PV in Germany?

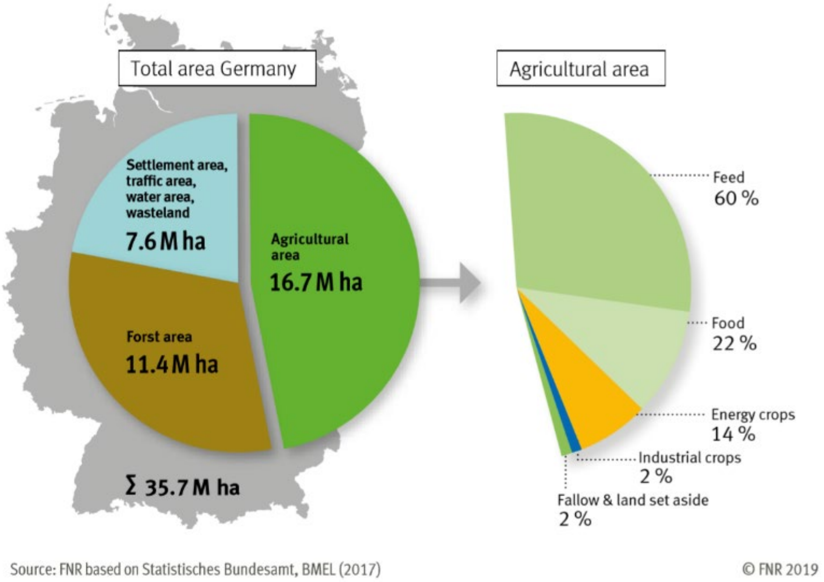
Yes, and without any significant conflicts with agriculture or nature conservation.
An important concept for the development of significant land potential is integration. Integrated photovoltaics (www.integrierte-pv.de) enables double land use, additional land consumption for new PV power plants is significantly reduced or avoided altogether. PV systems specially tailored to the application are combined with agriculture, erected on artificial lakes, used as the shell of buildings, car parks, traffic routes and vehicles, or they provide ecosystem services on re-naturalized biotopes and moorland (Figure 25).

Figure 25: Applications for the integration of photovoltaics.

Relying exclusively on one or a few of these possible applications today does not do justice to the urgency of the energy transition. We no longer have the time to try out options one after the other. All technically and socio-economically promising application options must be tested quickly and promoted in a dedicated start-up phase to explore optimization and cost reduction potentials through scaling and learning effects. Only after this broad start-up phase can well-founded decisions be made in favor of certain applications and technologies.
In the following analysis of potentials, a distinction is made between a theoretical, a technical and an economic-practical or realizable or developable potential. The **theoretical potential** considers the maximum possible implementation of a technology based on the entire supply (physical rough calculation). The **technical potential** is lower because it already considers basic technical boundary conditions (technical rough calculation). The **economic-practical potential** considers all relevant boundary conditions, legally (incl. nature conservation), economic (incl. infra-structure), sociological (incl. acceptance), and

e.g., competing uses (e.g., solar thermal and PV on roofs). Different sources draw slightly different boundaries between the categories.

The area used for agriculture in Germany is just under 17 million hectares (Figure 26). **Agrivoltaics** (APV) uses land simultaneously for agricultural crop production (photosynthesis) and PV electricity production (photovoltaics). APV covers a broad spectrum in the intensity of agriculture and in the additional effort required for PV system construction. It ranges from intensive crops with special PV mounting systems to extensively used grassland with marginal adaptations on the PV side and high potential for eco-system services. APV increases land efficiency and enables a massive increase in PV power, while preserving fertile soils for agriculture or in combination with the creation of species-rich biotopes on poor soils. APV is already being used on a GW scale worldwide, but there are only a few systems in Germany.



Source: FNR based on Statistisches Bundesamt, BMEL (2017)

Figure 26: Land use in Germany [FNR].

Agri-PV with high-mounted modules allows cultivation in partial shade under the modules. A number of crops show hardly any yield losses with reduced irradiation, some even benefit. If permanent crops (e.g., orchards and vineyards) are considered in their entirety and one-third of arable land (without maize) as 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 enable cultivation between the 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 13 percent of agricultural land, especially for the production of biogas, biodiesel, vegetable oil and bioethanol [FNR]. The land efficiency is significantly below what would be possible with Agri-PV plants (Section 15). Energy maize alone is cultivated on 1 million ha; this area corresponds to **600 GW$_p$** of nominal capacity if converted to APV with suitable crops (or to solar biotopes, see Section 13).

Opencast lignite mining has destroyed an area of 1773 km^2 [UBA4] in Germany, more than three times the area of Lake Constance. Parts of this mining area have already been flooded or are still being flooded, and there are many more artificial lakes. In total, this opens up a technical potential of **44 GW$_p$** for **floating PV** (FPV). In the case of active quarry lakes, the PV can contribute to the self-sufficiency of the production facilities. Worldwide, more than 3 GW$_p$ of floating PV systems have already been installed.

In Germany, there are about 40 million buildings (Figure 27). Building envelopes, i.e., roofs and façades, offer a technical potential in the order of **1000 GW$_p$** [Eggers]. The analysis only includes areas that receive a minimum of 500 kWh/(m^{2}a) of irradiation and have a connected minimum size. Today, less than 10 percent of the rooftop potential and less than 1 per mille of the façade potential is used.

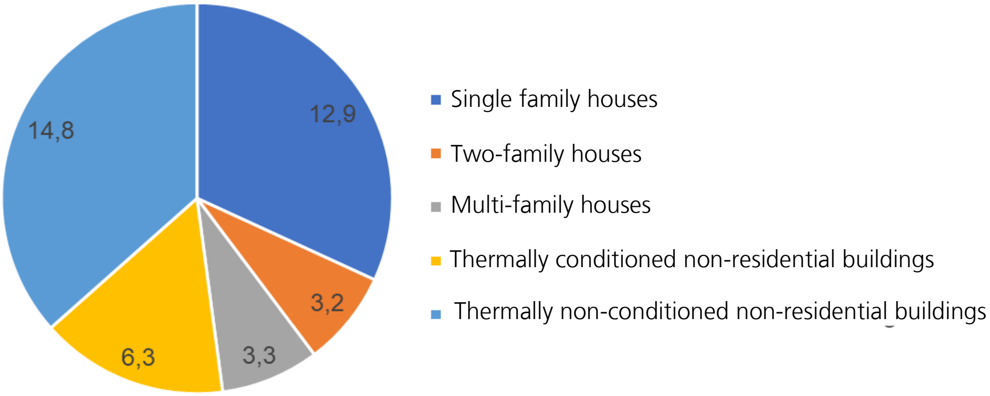
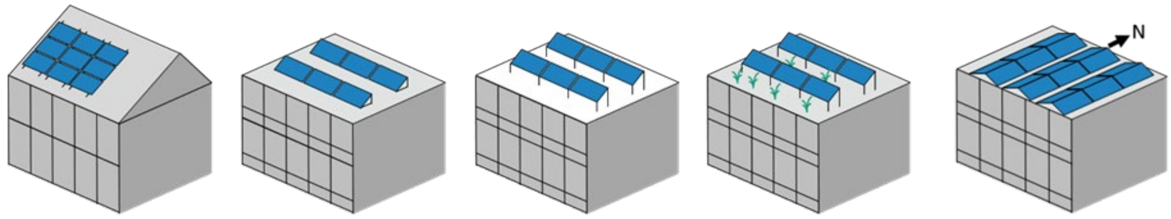
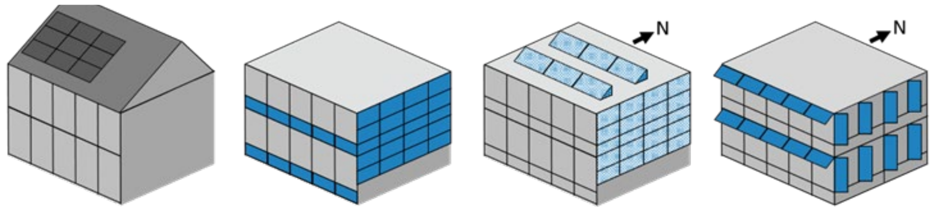


Figure 27: Building stock in millions, data from [DENA], [IWU].

As yet, PV use is largely limited to rooftop systems, even though numerous building-integrated products (BIPV, "**building-integrated PV**") are certified and commercially available. These include PV panels and PV tiles for pitched roofs, lightweight PV systems for roofs with low load-bearing capacity, PV systems for green roofs, PV modules for cold façades (curtain-type, rear-ventilated façades), external thermal insulation composite systems (ETICS) with PV, opaque and semi-transparent PV insulating glass and PV solar control louvres (Figure 28). BIPV offers material-efficient solutions for high-pitched rooftops, enabling surface areas to be used that would not be suitable for roof-mounted systems for aesthetic reasons. The advantage of roof-mounted systems is that they are less tied to construction and renovation cycles.



Roof-mounted: high-pitched roof   Flat roof   Flat roof, bifacial   Flat roof, green roof   Flat roof, east/west-fac-



Integrated PV: high-pitched   Cold façades, opaque   (Opaque and semi-transparent) PV insulating glass for façades, shed   PV solar control louvres (fixed or adjustable)

Figure 28: PV solutions for roofs and façades (top row: roof-mounted systems, bottom row: integrated PV).

A study by the Federal Environment Agency assumes 670 km^2 of sealed settlement areas [UBA10]. This includes built-up settlement areas, but not building areas or traffic areas such as roads or railways. Part of this area can be covered with PV modules to provide shade or can be covered with PV modules that can be walked on (UPV, "**urban PV**"). The more than 300,000 large car parks in Germany alone would open up the 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 canopies or road surfaces) and rail tracks. PV canopies are particularly suitable for tunnel entrances and for highly emitting motor roads in urban areas. With the switch to electric mobility, the envelope surfaces of electric vehicles are being added as **vehicle-integrated PV** (VIPV).

Which part of the aforementioned technical potential can be used economically and practically depends on complex economic, regulatory and technical boundary conditions, as well as questions of acceptance. In principle, integrated PV, which merges with the envelope of buildings, traffic routes and vehicles, uses land together with agriculture or occupies water surfaces in flooded opencast mines, will have somewhat higher electricity generation costs than simple open-space power plants. On the other hand, integrated PV avoids conflicts of use and creates synergies, for example 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 ground-mounted PV includes verges along motorways and railway lines, conversion areas and, if a federal state uses the state opening clause of the EEG, also disadvantaged agricultural areas. In Baden-Württemberg alone, the restriction-free area suitable for PV FFA according to these criteria amounts to 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 Ordinance" (FFÖ-VO). With an occupancy density of 0.6 MW_P/ha, this area absorbs 230 GW_P PV, for example as agri-photovoltaics or as a solar biotope (Section 13). Current figures for the whole of Germany are not yet available. A study commissioned by the Federal Ministry of Transport and Digital Infrastructure with figures from 2014 estimated the expansion potential of restriction-free open spaces for PV at 3164 km^2 [BMVI].

13 Is PV electricity a privilege reserved for homeowners?

No.

There are various operator models for PV systems that are suitable for co-owned roofs of condominium buildings, individual owners and construction companies [EAFR]. Tenants can install plug-in solar panels (balcony modules), on their balcony balustrades, walls or terraces. These solar modules can be plugged into the tenant's household grid to supply electricity for self-consumption, lowering the tenant's electricity bills (https://www.pvplug.de/). Depending on the intended location of the module, the landlord's permission may be required. At the end of 2021, nearly **200,000** plug-in solar panels were operating in Germany.

If a building is not suited for a PV installation, community energy cooperatives provide the opportunity to contribute to the construction of PV power plants. Anyone who is not interested in investing can still choose a utility company with a sizable portfolio of PV power plants, for example, Elektrizitätswerke Schönau (EWS) or Energie Baden-Württemberg (EnBW).

14 Do PV systems destroy ecologically valuable areas?

No, quite the opposite, they usually promote renaturation.

If an area is taken out of intensive agriculture, e.g., from energy crop cultivation, converted into grassland and an open space PV plant (PV FFA) is built on it, then biodiversity basically increases [ESD]. In PV-FFAs, fertilizer is not used, so that less demanding plants are given a chance. The fencing of the PV-FFA protects the area against unauthorized access and free-roaming dogs, which is good for ground-nesting birds, among others.

Further improvements can be achieved through small adjustments to the PV plant. Increased row spacing of the module tables, slightly higher elevation of the modules, sowing of wild plant mixtures instead of grass monoculture and careful green maintenance create a solar biotope. The larger row spacing also allows a greater module inclination, with higher electricity yields in the winter half-year at higher market value factors of solar electricity and lower yield losses due to pollution and snow cover.

According to the Federal Agency for Nature Conservation, peatland soils cover 1.4 million ha in Germany, of which about 50 percent is used as grassland and 25–30 percent 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 produce an area yield without intensive agriculture. The partial shading by PV counteracts the drying out of peatlands or supports rewetting. Based on an agriculturally used peatland area of 1.1 million ha and an occupancy density of 0.25–0.6 MW_P/ha, the technical potential is 270–660 GW_p.

15 Do PV power plants find acceptance in the population?

Yes.
The free scalability of PV power plants enables decentralized expansion, down to so-called "balcony modules" ("plug-in PV") with a few hundred watts of nominal power. The high number of more than 2 million PV systems in Germany, of which about 64 percent are small systems with outputs below 10 kW [ISE5], shows that these technical possibilities are being used extensively. Photovoltaics is ideal for implementing the concept of community energy and promoting acceptance of the energy transition through participation. According to a representative survey by Lichtblick, solar systems are among the most popular power plants. Figure 29 shows the distribution of answers to the question "When you think about the construction of new energy generation plants in Germany, on which types of plants should the focus be?

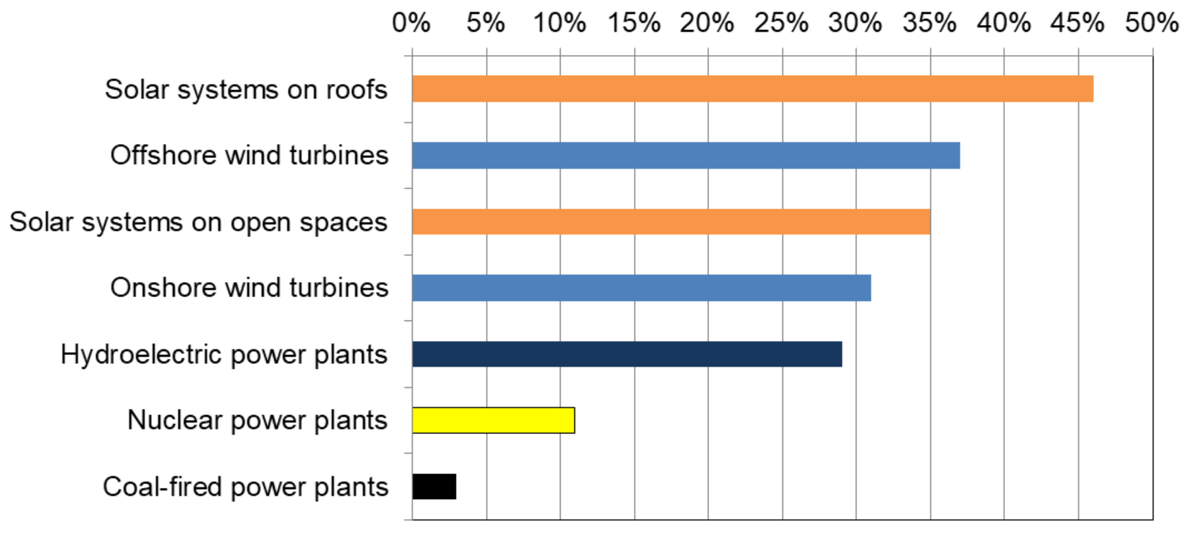


Figure 29: Survey results on the construction of new power plants, data from [Licht2].

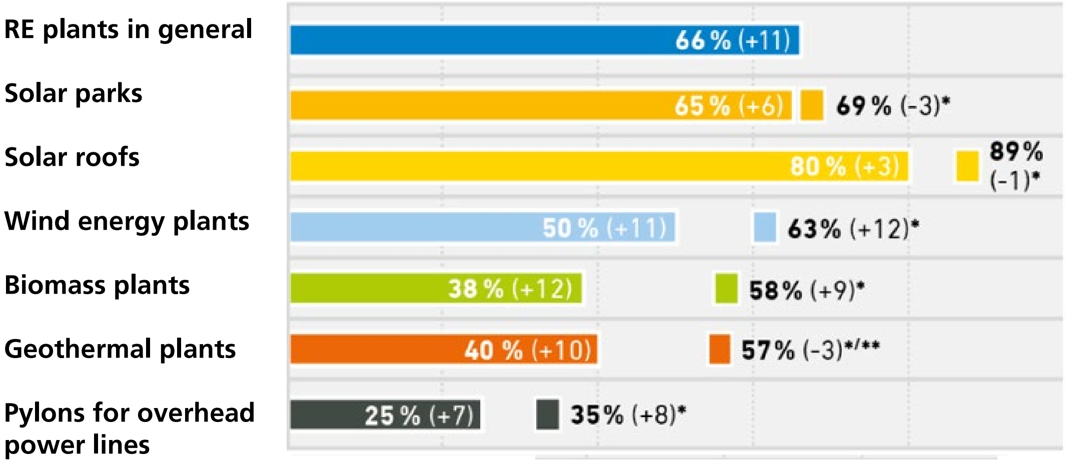


Figure 30: Survey results on the acceptance of different types of power plants [AEE2].

PV power plants are also by far the most popular power plants from the point of view of residents, as a survey by the Renewable Energy Agency shows (Figure 30). The popularity increases when such power plants can be practically experienced in one's own neighborhood.

16 Are PV plants in Germany efficient?

Yes and no, depending on the reference value.
For newer installations, the effective energy conversion efficiency is around 17–19 percent in relation to the irradiated solar energy, but the sun shines for free. The effects of efficiency on electricity production costs, space requirements, use of resources and CO2 savings are the deciding factors.
The nominal efficiency (see Section 27.1) of commercial wafer-based PV modules (i.e., modules with solar cells based on silicon wafers) from new production has increased in recent years by an average of approx. 0.3–0.5 percentage points per year to **21 percent** [ISE5]. Per square meter of module, they thus produce a nominal output of 210 W; peak modules are 10–15 percent higher.
PV systems do not work with the nominal module efficiency because losses occur during operation and because the initial efficiency of the modules degrades (Section 15.2). These effects are summarized in the so-called performance ratio (PR). A PV system installed today achieves PR values of 80–90 percent on an annual average (typical value), including all losses due to increased operating temperature, unfavorable irradiation conditions in terms of intensity, spectrum and angle of incidence, soiling, shading, snow accumulation, line resistance, conversion losses in the inverter, peak capping of the inverter (DC/AC ratio typically > 1) and, in some cases, downtimes due to malfunctions. Additional yields increase the PR of bifacial modules through rear-side irradiation, as the reference value of the PR only factors in front-side irradiation. Yield assessments provide information on the performance and yields that can be expected from PV power plants

for concrete locations, components and system designs based on historical irradiation data.

The DC current delivered by the modules is adapted by inverters for grid feeding. The efficiency of new PV inverters is around 98 percent. Ground-mounted PV systems usually show slightly higher PR than systems on pitched roofs, thanks to better convective cooling, optimal orientation, better maintenance, less of shading, more efficient inverters, and possibly bifacial additional yields. In terms of irradiation, newly installed PV power plants therefore operate with average efficiencies of around **18 percent**.

The average electricity consumption in households for electrical appliances, lighting, hot water (hygiene purposes) and space heating was 1.6 MWh per household member in 2018 [DESTATIS]. Average values for 1-person households are slightly higher per capita, for multi-person households significantly lower. On average, rooftop PV systems achieve **922 hours of full** use in 2021 in the trend scenario [ÜNB1], cf. Section 15.4. 21 m^2 of a roof area of a house facing roughly south and with a moderate slope are thus sufficient to generate an amount of electricity with 12 370 W_P modules that corresponds to the average annual electricity demand of a family (4 MWh).

On flat roofs and in open spaces, modules are elevated to increase their yield. Because of the spacing required for this, they occupy several times their own area when oriented to the south, depending on the angle of installation. Today, PV FFAs 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 21 percent. In 2010, this value was still 0.35 MW/ha [ZSW]. With a view to optimal development of biodiversity, larger row spacing is advantageous (Section 13).

By way of comparison, the efficiency of electricity generation from energy crops based on irradiation is well below 1 percent; for electricity generation from energy maize, for example, it is 0.2 percent. The efficiency related to irradiation for the conversion of fossil organic matter such as coal, oil or natural gas into electricity is likely to be in a similar order of magnitude. However, corresponding combustion power plants normally only relate their efficiency figures to the conversion of the chemical energy already present in the fossil energy source. For coal-fired power plants in Germany, for example, an average efficiency of around 38 percent is given.

When biofuels are burnt in vehicles, modest efficiencies are achieved in relation to the energy radiated and the land use. A passenger car with a diesel combustion engine that consumes 5.5 l of biodiesel per 100 km can travel about 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 system (1 MW_P/ha, 980 MWh/MW_P) 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** (Figure 31). Even an agri-PV system (Section 11), which allows simultaneous agricultural use of the land, would take an e-car a **factor of 116** further. This comparison does not take into account charging losses for e-cars, energy consumption for rapeseed cultivation or energy supply from by-products of rapeseed use.

If one compares the efficiency of land use for electricity production, then agri-PV performs better than maize by a **factor of 32**, for example. Silage maize, which is cultivated on an area of approx. 0.9 million ha in Germany, yields 18.7 MWhel/ha of electricity [FNR], whereas the figure for high altitude APV (Section 11) is approx. 600 MWh_{el}/ha. This comparison does not consider waste heat utilization (CHP) from methane combustion.

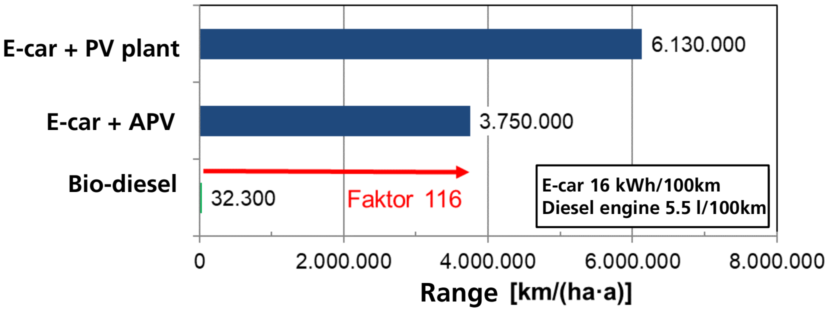


Figure 31: Range of electric and biodiesel vehicles per hectare of land used.

In southern Spain or North Africa, specific yields of up to 1600 kWh/kW_p can be achieved, but long transmission lines to Germany would lead to energy losses and cost surcharges. With 800 kV extra-high voltage lines, power losses can be reduced to about 0.5 percent per 100 km. Lines for high-voltage direct current transmission (HVDC) reduce transport losses to just under 0.3 percent per 100 km, plus conversion losses. A 5000 km HVDC line would thus have about 14 percent pure line losses.

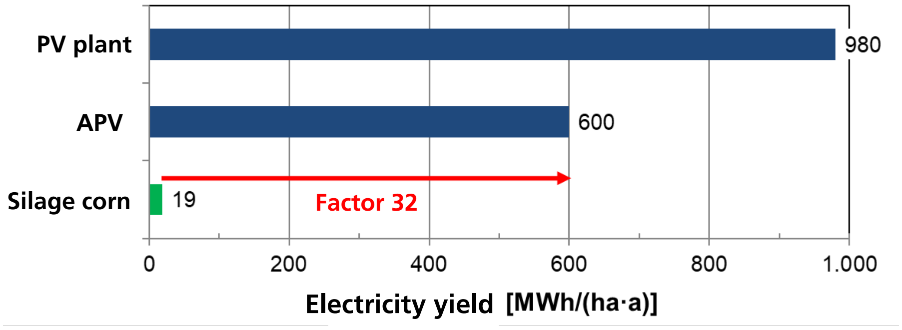
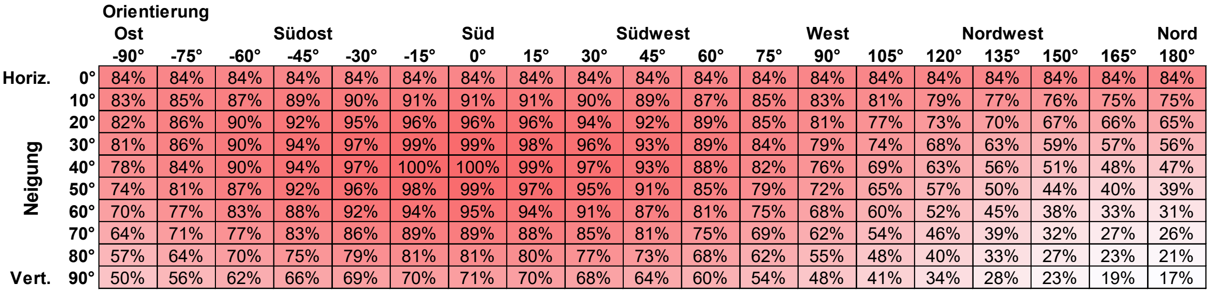


Figure 32: Electricity yields of PV power plants and silage maize per hectare of land used.

16.1 Are PV systems only viable on roofs that are optimally oriented?

No, it is worth considering the overall profitability.
Figure 33 shows the relative annual yield potential in Freiburg in relation to the orientation of the roof or façade area. The maximum yield with a south orientation and an inclination of 40° shows a flat line, with small deviations having little effect on the yield. Installations located in more northern latitudes require a steeper inclination to achieve their maximum yield.



		Orientierung																		
		Ost			Südost			Süd			Südwest			West			Nordwest			Nord
		-90°	-75°	-60°	-45°	-30°	-15°	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
Horiz.	0°	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%
	10°	83%	85%	87%	89%	90%	91%	91%	91%	90%	89%	87%	85%	83%	81%	79%	77%	76%	75%	75%
	20°	82%	86%	90%	92%	95%	96%	96%	96%	94%	92%	89%	85%	81%	77%	73%	70%	67%	66%	65%
Neigung	30°	81%	86%	90%	94%	97%	99%	99%	98%	96%	93%	89%	84%	79%	74%	68%	63%	59%	57%	56%
	40°	78%	84%	90%	94%	97%	100%	100%	99%	97%	93%	88%	82%	76%	69%	63%	56%	51%	48%	47%
	50°	74%	81%	87%	92%	96%	98%	99%	97%	95%	91%	85%	79%	72%	65%	57%	50%	44%	40%	39%
	60°	70%	77%	83%	88%	92%	94%	95%	94%	91%	87%	81%	75%	68%	60%	52%	45%	38%	33%	31%
	70°	64%	71%	77%	83%	86%	89%	89%	88%	85%	81%	75%	69%	62%	54%	46%	39%	32%	27%	26%
	80°	57%	64%	70%	75%	79%	81%	81%	80%	77%	73%	68%	62%	55%	48%	40%	33%	27%	23%	21%
Vert.	90°	50%	56%	62%	66%	69%	70%	71%	70%	68%	64%	60%	54%	48%	41%	34%	28%	23%	19%	17%

Figure 33: Relative yield potential, no shade, located in Freiburg, calculated online using https://re.jrc.ec.europa.eu/pvg_tools/en/.

16.1.1 High-pitched rooftops facing east/west

In a direct comparison, PV on a west-facing roof with an inclination of 40°, for example, produces about 24 percent less electricity than an optimal south-facing roof, which increases the levelized cost of electricity accordingly. A PV installation on a west-facing roof can still be worth-while, in particular when electricity prices are high and self-consumption is employed.

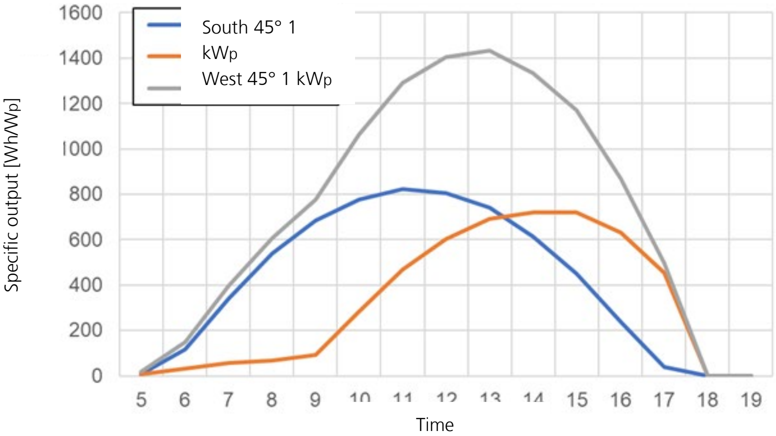


Figure 34: Power yield profile by hour for different roof orientations and a 45° roof slope on a sunny day in April, no shade, located in Freiburg, calculated online using https://re.jrc.ec.europa.eu/pvg_tools/en/.

The question of whether a west-facing roof should be used in addition to a south-facing roof can be answered by reviewing marginal costs. Additional PV modules can be expected to come at comparatively lower installation costs, and their orientation towards the west and late-afternoon generation profile should increase the self-consumption potential (Figure 34).

16.1.2 Vertical south-facing façade

A PV system on a south-facing façade produces about 29 percent less electricity per year than an installation with a module inclination of 30° on a south-facing roof (Figure 35). A vertical installation's monthly fluctuation between the summer and winter yield is considerably smaller when compared to horizontal installations, making it much easier to integrate PV electricity into the system. The lower yield of vertical systems is only a concern during the sunny half of the year, when installations on south-facing roofs often "overproduce", which leads to a lower share of self-consumption, or when the market value factor of solar energy decreases (Section 4.3). The financial viability of a façade installation is therefore only marginally affected by the reduction of the annual electricity yield.

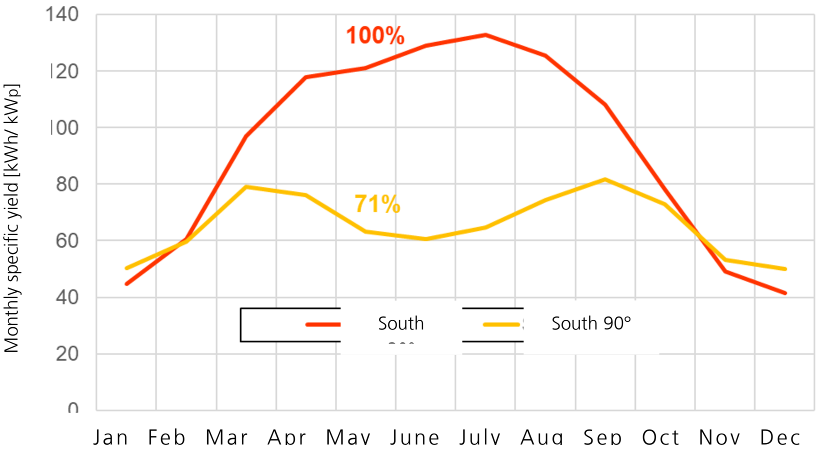


Figure 35: Monthly specific yield potential for different inclinations, no shade, located in Freiburg, calculated online using https://re.jrc.ec.europa.eu/pvg_tools/en/; the percentages provide the relative annual yield in relation to an inclination of 30°.

16.2 Do PV plants degrade?

Yes, but normally very slowly.

Wafer-based PV modules age so slowly that it can be a challenge for scientists to even prove power losses. A study by Fraunhofer ISE on 44 larger, quality-tested rooftop systems in Germany showed an average annual degradation of the nominal power of the modules of approx. 0.15 percent [ISE2]. Manufacturers' guarantees for a maximum power loss of their PV modules of 10–15 percent over 25–30 years of operation are common.

These values do not take into account failures due to production defects. Faults in the material composition or defects that arise during production, transportation or mounting may accelerate degradation or even lead to the modules failing altogether. Degradation may affect the appearance of the modules (e.g., delamination), their yield and/or their electrical safety. A damage analysis serves to quantify deviations, identify causes and create forecasts for further degradation dynamics.

The declared nominal power of modules usually refers to operation after initial degradation. Depending on the material of the solar cells, light-induced degradation (LID) of 1–2 percent occurs in the first days of operation, as extensive measurements at Fraunhofer ISE have shown.

For systems with quality assurance for component selection, design, installation and operation, the frequently made assumption of 0.5 percent average yield loss per year seems very conservative in this context.

16.3 Can PV modules become soiled?

Yes*.*

In many cases, this keeps the resulting yield loss during the modules' service life at a manageable level. Local effects such as leaf litter, bird droppings, dust from construction sites or agriculture, soot from nearby chimneys, regional effects such as pollination or trans-regional effects such as Saharan dust events may cause problematic soiling. While heavy rain will mostly clean the modules, soiling does accumulate over the years, increasing yield losses. This especially applies to regions experiencing longer periods without rainfall as a result of the climate crisis.

Modules with a very flat inclination (less than 15°) are particularly affected. The bottom edge and especially the bottom corners of modules are the areas that collect the most dirt. When solar cells are connected in series, extreme soiling of partial surfaces can cause yield losses that are much higher than should be the case in relation to the surface area. Whether, when and how frequently it pays to have the modules cleaned varies depending on many influential parameters.

16.4 Do PV plants seldom operate at full capacity?

Yes.

Due to the irradiation conditions, PV plants only operate for slightly less than half of the total 8760 annual hours, and then mostly at partial load. The key figure "full load hours", also "full utilization hours" (VBh) or specific yield is determined as the quotient of the amount of electricity actually generated in the course of a year and the nominal output of the power plant (kWh/kW$_p$). In their 2021 trend scenario, the transmission system operators assume **987 VBh** for ground-mounted PV systems in Germany, and **922 VBh** for roof systems [TSO1]. The values correspond to annual utilization rates ("capacity factors") of **11.1 percent** and **10.3 percent**, respectively, calculated as the ratio of VBh to total annual hours. The specific annual yield is usually higher in sunny, south-facing locations when the module has a slight inclination, but it does not depend on the nominal module efficiency. Figure 36 shows the overview of the projections for electricity generation from RE, adjusted for losses due to feed-in management (Section 10.1). Due to the low VBh, increasing shares of solar electricity in the grid increasingly require accompanying measures (Section 21).

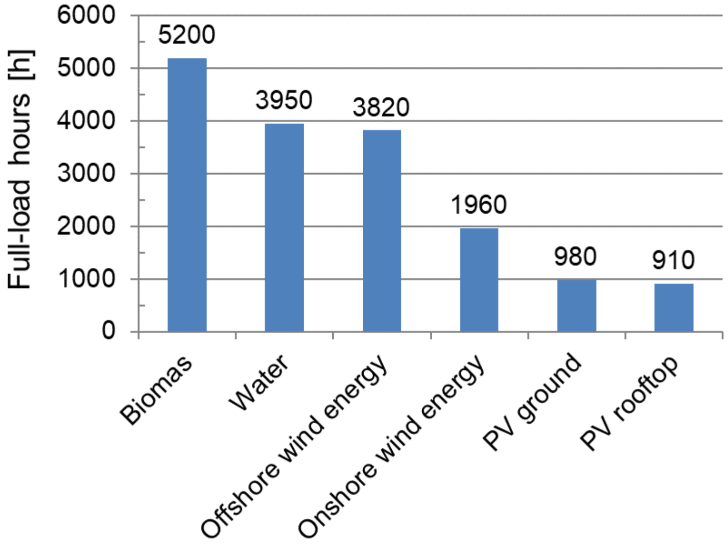


Figure 36: Forecast full utilization hours for electricity generation from EE, data from [ÜNB1].

The mean annual sum of horizontal global radiation in Germany for the years 2001-2020 (Figure 37) is **1102 kWh/m²/a** with a linear trend of +0.3 %/a between 1991 and 2020, according to figures from the German Weather Service. Between 1981 and 2010, the average value was still at 1055 kWh/m²/a. To maximize the annual electricity yield, PV modules are often mounted with an inclination of approx. 30° to the horizontal and oriented to the south. This increases the irradiation sum in relation to the module level by approx. 15 percent in relation to the horizontal irradiation sum and results in a geographical average for Germany of approx. 1270 kWh/m²/a.

With a performance ratio (PR, see Section 27.7) of 85 percent for a new, unshaded system with yield-optimized alignment, a geographical average of 1077 full-load hours could be achieved across Germany. Because not all rooftop systems are aligned to optimize yield, partial shading occurs and because the PR decreases slightly with age, the actual average number of full load hours is somewhat lower.

Technical improvements to the modules and the installation can increase the usable irradiation, the PR, the yield and thus the number of full load hours of a PV system. These include:

- Tracking (Section 21.3.1)
- bifacial PV technology
- Reduction of losses due to shading
- Reducing the temperature coefficient of the solar cells
- Reducing the operating temperature of the modules through good rear ventilation
- Improvement of the modules' low-light and oblique light behavior
- Reduction of losses due to snow cover and soiling
- early detection and correction of underperformance
- Reduction of degradation over the lifetime

Unlike wind power plants, where the hub height is a decisive factor, the size of a PV power plant has no direct influence on the number of full load hours.

Nuclear, coal and gas-fired power plants can produce almost continuously at their rated output if sufficient fuel and cooling water are available.

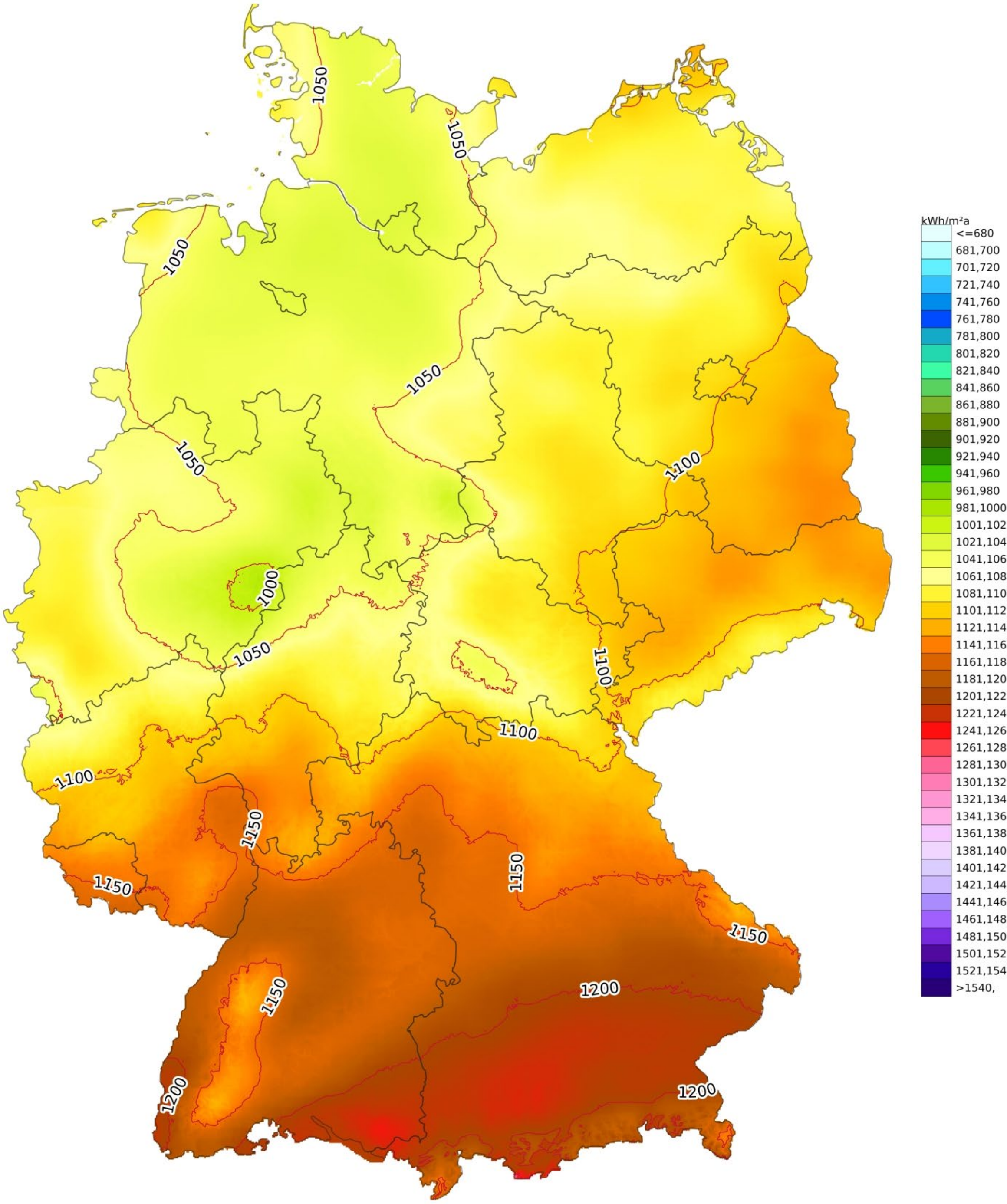


Figure 37: Horizontal annual global radiation total in Germany, averaged over the period 2001-2020 [DWD].

17 Does PV make relevant contributions to climate protection?

17.1 Do anthropogenic CO_2 emissions danger the climate?

Yes.
Increasing global warming has been proven beyond doubt [IPCC]. Compared to the pre-industrial era, the average global temperature has risen by 1.1 °C, and by as much as 1.6 °C over the land surface. The vast majority of scientists are convinced that anthropogenic emissions of CO_2 and other greenhouse gases are causing the increase in atmospheric greenhouse gas concentrations and thus the global temperature rise.

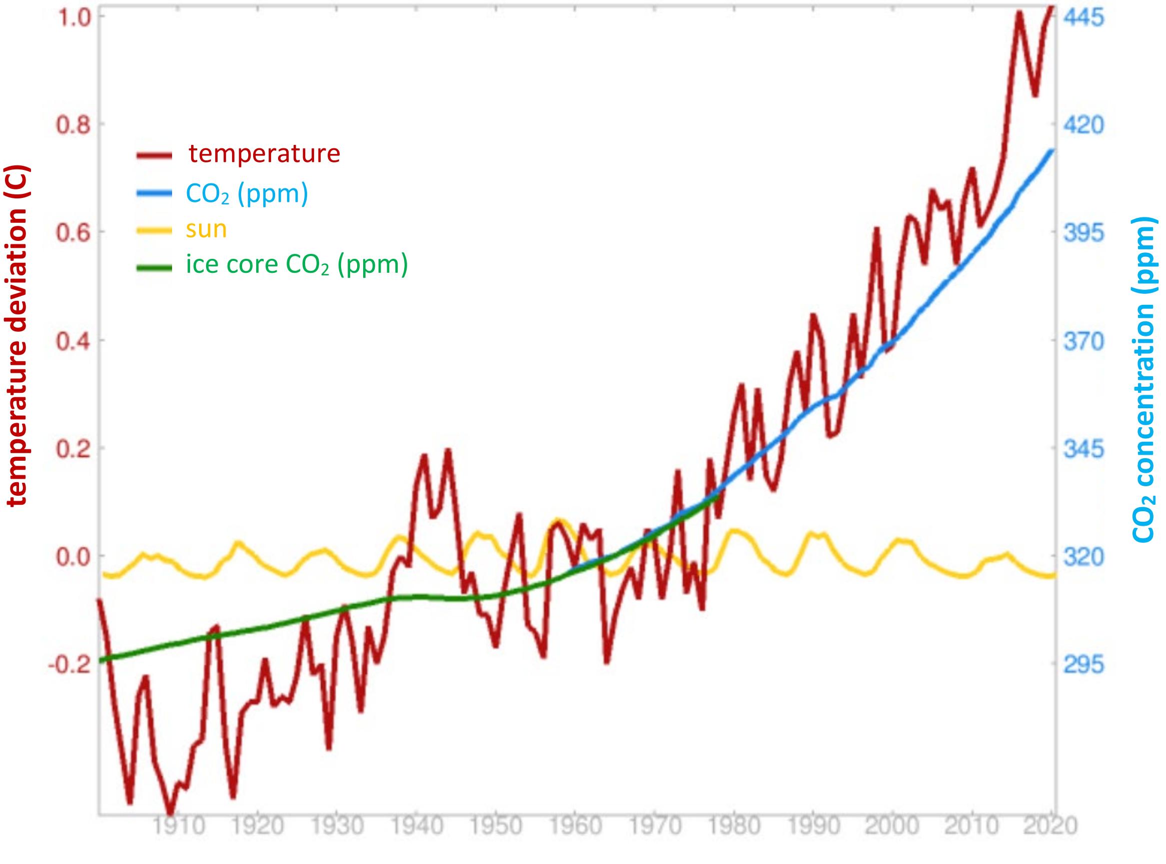


Figure 38: Development of atmospheric CO_2 concentration, mean global temperature change and solar activity (http://herdsoft.com/climate/widget/).

In May 2013, the atmospheric CO_2 concentration reached 400 ppm for the first time in at least 800,000 years. Figure 38 and Figure 39 show the development of the atmospheric CO_2 concentration alongside the global, or rather, the Antarctic temperature up to this point.
A fast and global temperature rise endangers the stability of the global climate system to a hitherto little understood extent, with effects on the lives of people threatened by extreme weather conditions, the word population's primary food production,

infrastructures, populated coastal zones, adding additional pressure on biodiversity and the preservation of biotopes.

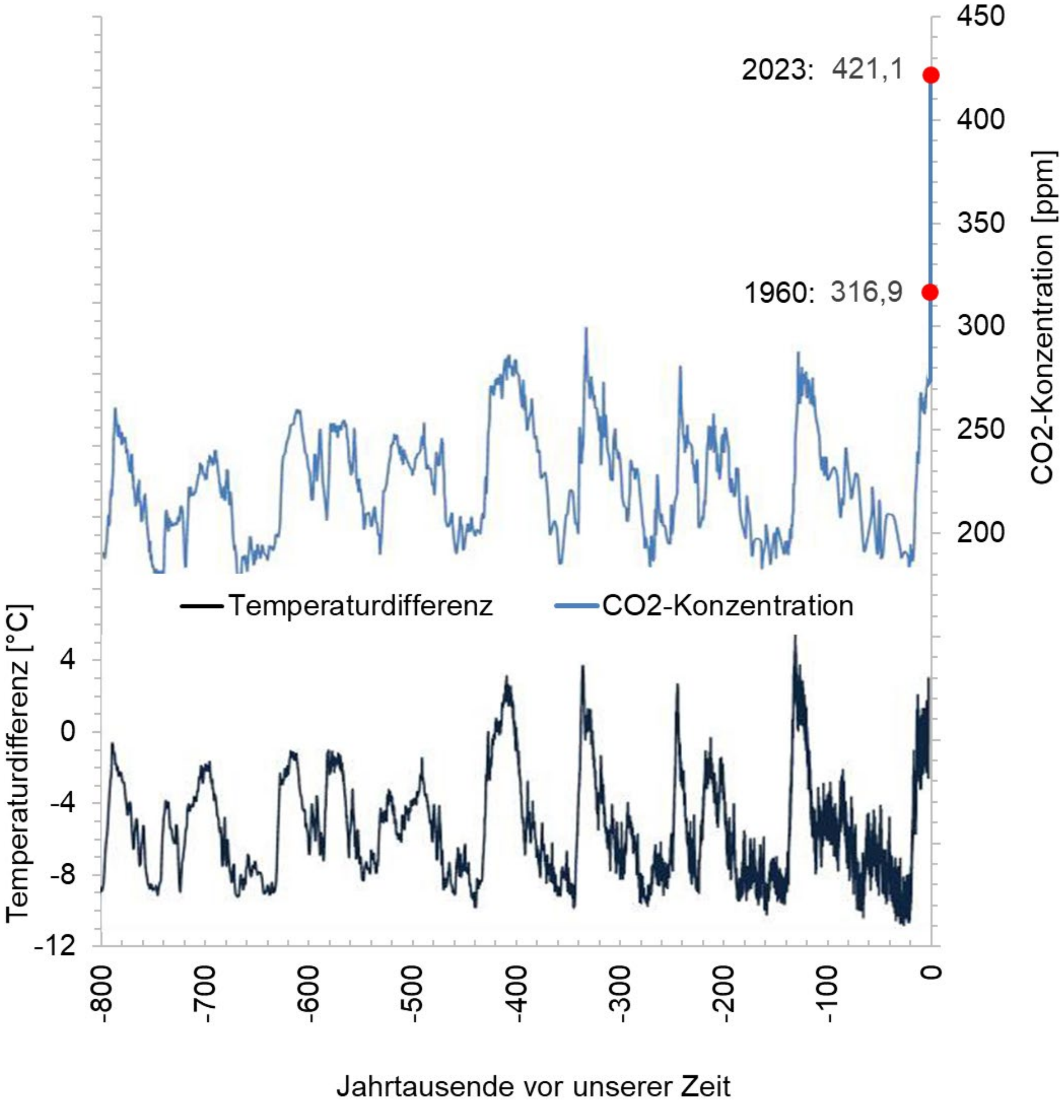


Figure 39: Estimates of atmospheric CO_2 concentration and temperature difference in Antarctica based on ice cores [EPA]; red: two recent CO_2 measurements from Mauna Loa Observatory [https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html].

17.2 Does PV make a significant contribution to CO_2 emission reduction?

Yes.

The CO_2 equivalent (GHG) emission factor for the electricity mix in Germany, including upstream emissions, has dropped from 860 g CO_2 e/kWh in 1990 to about **498 g**

CO_2/kWh in 2022 [UBA6]. The expansion of RE has been a major contributor to this reduction.

To estimate the overall emission factors of individual fuels for electricity generation, it is necessary to differentiate, amongst other factors, between the country of origin, the materials handling technology used, the primary energy concentration, the primary energy content of the raw material deposits, methane leaks during natural gas production, as well as the total (for combined heat and power) and the effective electrical efficiency of power plants.

While PV systems do not release any CO_2 during operation, a holistic assessment must also take into account the production (upstream) and disposal of the system. The German Federal Environment Agency estimates the greenhouse gas potential for PV electricity during system operation in Germany at 56 g CO_2 eq./kWh (primary energy-related emission factor according to [UBA9], see Figure 40).

PV modules produced in Europe together with their feedstocks are particularly favorable because the electricity mix here contains a higher share of renewable energy and the transport distances are significantly shorter. Glass-glass modules are favorable due to their lower degradation and the absence of aluminum frames [LCA]. With the continued increase in efficiency and the share of RE in production, GHG emissions per kWh of PV electricity will continue to decrease.

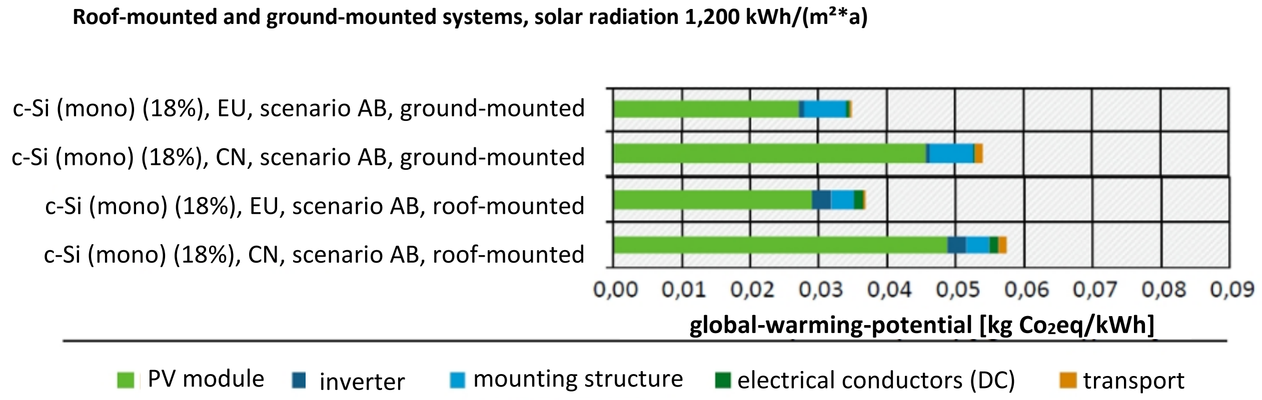


Figure 40: Global warming potential of electricity generation with mono c-Si PV for roof-mounted and ground-mounted systems [UBA7].

Figure 41 shows the GHG potential of PV compared with coal, natural gas and nuclear power. The emission factor of power generation from biogas with energy crops is around 160–184 g CO_2-Eq./kWh [UBA9].

In 2022, the use of PV in Germany avoided a net 41,7 million tons of greenhouse gas emissions (Figure 42). In the calculations, the emissions from the production of the PV system components were taken into account approximately.

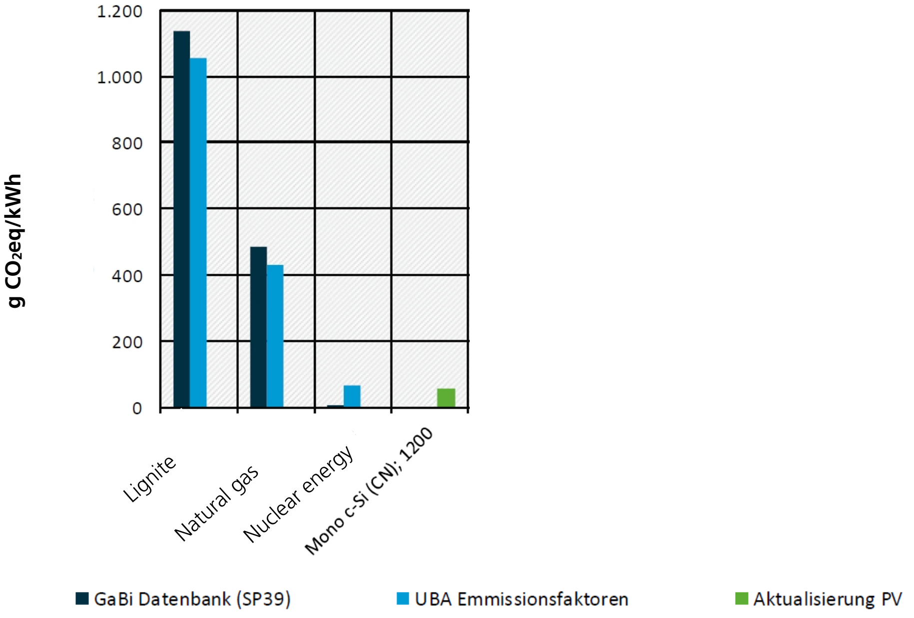
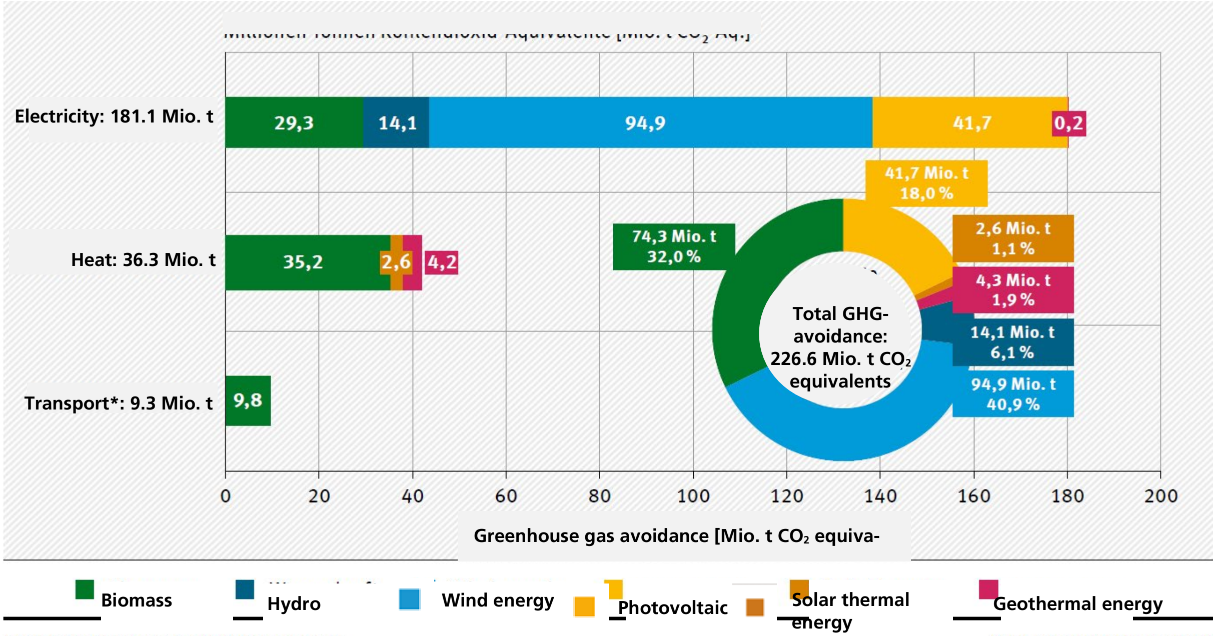


Figure 41: Global warming potential of different electricity generation technologies [UBA7].



¹ ohne Berücksichtigung des Holzkohleverbrauchs
² ausschließlich biogene Kraftstoffe im Verkehrssektor (ohne Land und Forstwirtschaft, Baugewerbe sowie Militär und ohne Stromverbrauch des Verkehrssektors), basierend auf vorläufigen Daten der Bundesanstalt für Landwirtschaft und Ernährung (BLE) für das Jahr 2021 sowie den fossilen Basiswerten gemäß § 3 und § 10 der 38. BImSchV

Source: Umweltbundesamt (UBA)

Figure 42: Avoided greenhouse gas emissions through the use of renewable energies in 2022 [UBA1].

German energy policy also has a high international relevance. With a production volume of 171 Mt in 2016, Germany was number one internationally in the extraction of lignite, ahead of China. Germany accounts for less than 3 percent of global electricity consumption, and the trend is still downwards. However, German policy has played a pioneering

role in the development of instruments to promote RE, first and foremost the EEG. The EEG instruments have received considerable international attention and have served as a model for similar regulations in dozens of countries. China has now become a pioneer in PV expansion and has overtaken Germany many times over in terms of annual installed capacity. In its country report "Germany 2013", the International Energy Agency (IEA) praised the Renewable Energy Sources Act (EEG) as a very effective expansion instrument that has significantly reduced the costs of generating renewable energy in recent years [IEA1]. The Germans' departure from nuclear energy has also attracted international attention. Other European countries have decided to phase out nuclear power (e.g., Belgium, Switzerland, Spain) or have already done so (Italy, Lithuania).
However, the EEG achieved the highest impact in terms of CO_2 avoidance in its early years through a "side effect": by creating the largest and most secure international sales market for PV over several years, it has significantly accelerated global scaling, technology development and price reduction (Figure 43). PV reduces the consumption of fossil raw materials for electricity generation worldwide.

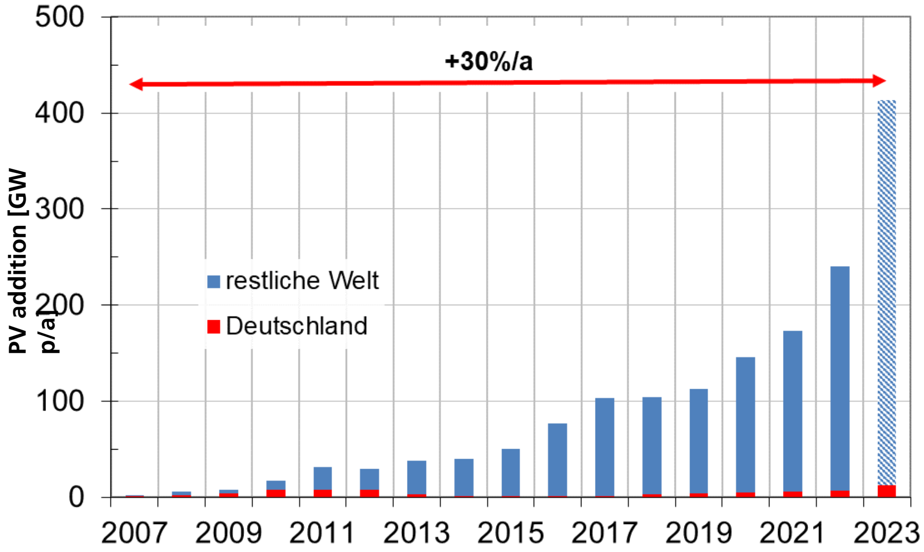


Figure 43: Development of annual PV additions [IEA3], estimations by BloombergNE and average annual growth rate.

The German EEG has thus made PV electricity more affordable for many people in developing countries. From this perspective, the EEG is also "probably the most successful development aid program of all time in this area" (Bodo Hombach in Handelsblatt 11.1.2013), which also saves considerable amounts of CO_2 in developing countries.

17.3 Does the production of PV modules use more energy than they can deliver during operation?

No.

The Energy Payback Time (EPBT) indicates the period of time that a power plant has to be operated in order to replace the primary energy invested. The harvest factor (Energy Returned on Energy Invested, ERoEI or EROI) describes the ratio of the energy provided by a power plant and the energy expended for its life cycle.
The energy return time and harvest factor of PV plants vary with technology and plant location. An analysis commissioned by the Federal Environment Agency has determined EPBT for PV power plants for a plant operation in Germany (assumed average annual irradiation sum at the module level of 1200 kWh/(m2-a)) of 1.6 years for multi- and 2.1 years for monocrystalline Si modules [UBA7]. With a lifetime of 25-30 years and an annual yield degradation of 0.35 percent, this results in harvest factors of 11-18. Calculations by Fraunhofer ISE based on the latest production data indicate an EPBT of under **1.3 years** for systems with commercially available monocrystalline Si modules in Germany [ISE5]. Component production in Europe further reduces the EPBT due to the higher share of green electricity compared to imported components from China.

17.4 Are there other environmentally harmful gases released during the production of PV?

Yes, for some thin-film technologies.
In the production of thin-film PV and flat screens, nitrogen trifluoride (NF3) is still sometimes used to clean coating systems. Residual amounts of this gas can escape into the atmosphere. NF3 is more than 17,000 times more harmful to the climate than carbon dioxide. Current emission levels are not known, but NF3 emissions will be determined in 37 countries from 2013 in accordance with the amended Kyoto Protocol.

18 Do PV modules heat up their environment significantly?

Locally, it depends on what is being compared. Globally, the indefinite cooling effect is decisive in terms of avoided greenhouse gas emissions in electricity production.

17.1 Solar reflection and absorption

Light-colored surfaces reflect more of the incident solar radiation, while dark surfaces absorb more and thus heat up more. The **solar albedo (solar reflectance**) of a surface indicates the percentage of incoming solar radiation that is reflected. Asphalt has an albedo of 12–25 percent, concrete 14–22 percent, a grey wall 20–45 percent, roof tiles 10 (dark)–30 (light) percent, green grass 26 percent (https://www.stadtklima-stuttgart.de/index.php?klima_klimaatlas_5_grund).

The latest designs of conventional PV modules have a solar reflectance in the order of 5–10 percent, depending on the choice of material and module design. Light-colored frames and back sheet foils increase reflection. PV modules are optimized to absorb as much solar radiation as possible in the active layer. Thermal insulation glazing, especially solar control

glazing, reflects many times more (in the order of 10–30 percent). If one compares a glass building façade with a PV façade, the PV façade reflects significantly less solar radiation downwards to the street level. Ordinary PV modules can be blinding, but they reflect extremely little solar radiation.
For example, when new PV modules convert solar radiation into electrical energy on a hot day with an operating efficiency of 18 percent, and also reflect part of the irradiation (approx. 5–10 percent), they generate as much local heat as a comparable surface with an albedo of 23–28 percent. When it comes to PV modules in operation, this is referred to as **effective albedo**. In the example above, it ranges from 23 to 28 percent. Only when PV modules are not supplying electricity does their effective albedo drop to the value of their solar reflectance of 5–10 percent.

17.2 *Evaporative cooling*

Although the difference between the albedo of a green area and the effective albedo of a PV module is not very large during operation, the green area remains significantly cooler than the PV modules on hot days due to evaporative cooling. This is true at least as long as the plants can draw enough water from the soil. After that, evaporative cooling stops and the plants dry out. Conversely, partial shading of plants by PV modules can reduce the water demand of the plants and the soil remains moist longer. This effect argues for a combination of PV with, for example, agriculture, dry moorland soils and green roofs (Sections 11 and 13).

17.3 *Heat storage*

The heat storage capacity of ordinary PV modules is significantly lower compared to, for example, a solid concrete wall. As a result, the PV module heats up faster than a concrete wall under solar radiation with the same effective albedo, but also cools down faster in the evening. The actual impact of PV modules on the urban climate, compared to other building materials, depends on numerous factors and may need to be analyzed on a case-by-case basis.

17.4 Greenhouse effect

PV electricity in particular replaces electricity from fossil-fuel power plants, which not only generate waste heat during operation (order of magnitude 2 kWh waste heat per kWhel), but also release up to 1.1 kg CO_2/kWhel, depending on the fuel. The CO_2 is released into the atmosphere, where it acts as a greenhouse gas for an unlimited period of time (Section 16.1). Compared to fossil power plants, electricity generation via PV massively reduces the release of CO_2 and thus effectively slows down the greenhouse effect (Section 16).

19 Can PV modules cause glare?

Yes.
Similar to window glass, the cover glass of PV modules can cause glare, depending the sun's position, the orientation of the module, glass texture and the observer's field of vision. The effect will only occur at certain times of the day and on certain days in the year. A glare analysis can provide details. When it comes to PV modules, it is usually not about a measurable impairment of vision (disability glare) but a sense of disturbance due to high luminance (discomfort glare). The cover glass of PV modules only has a one boundary surface that may cause glare, which usually has a slight surface texture and an additional antiglare (AR) coat, the maximum luminance of its reflection is significantly lower than that of windows with up to 6 smooth boundary surfaces that lack AR coating. In particularly critical cases, for instance, when a PV system is located near an airport, PV modules with special, more strongly textured cover glass can reduce the risk of glare.

20 Do PV modules emit irradiation that is harmful to health?

No, provided the components are certified and have been mounted properly.
The term "electromagnetic pollution" includes static, electric and magnetic fields as well as electromagnetic (EM) fields that are generated by technological devices.
Static electric fields are caused by charge imbalances (potential) between two objects, for instance between module string cables, or between live and grounded components. The field strength depends on the voltage and the distance between the live objects. A module string typically provides voltages between 400 – 1000 V, depending on the number of modules connected in series. There is now knowledge of cases of damage to health from static electric fields associated with PV systems.
Static magnetic fields surround electrical currents, for instance in live cables. A rooftop PV module typically produces a current in the range of 10 – 15 A. While magnetic fields can magnetize certain materials, the magnetic field strength decreases rapidly with increasing distance from the cables, and is further weakened by the usual paired arrangement of the wires carrying currents in opposite directions. The live wires of a PV system should not be routed through living or bedrooms. There is now knowledge of cases of damage to health from static magnetic fields associated with PV systems.
Electromagnetic fields ("waves", "radiation") are created by accelerating or decelerating electrical loads. Solar cells produce a direct current (DC) that does not generate EM fields, neither within the PV modules nor in the DC power lines. Inverters convert the direct current from the module string or individual module to 50 Hz alternating current (AC) for grid feeding. Most small PV systems use a central inverter, though some use module-integrated inverters located on the rear side of the modules.
Currents in the kilohertz frequency range flow through such inverters, and these alternating currents generate EM fields. The law requires manufacturers to shield inverters so that the EM value near the device stays below the threshold value. Inverters must be mounted outside living and bedrooms, with the distance and shielding effect of the material between the inverter and the dwelling area being the determining factor. During operation,

inverters can feed a portion of high-frequency electricity back into the DC circuit, and therefore also into the PV modules. Transformerless inverters transmit low-frequency (e.g., 50 Hz or 150 Hz) voltages to the DC side. There is now knowledge of cases of damage to health from electromagnetic fields associated with PV systems. A study commissioned by EnergieSchweiz [BFE] provides numerical values and comparisons with typical domestic electrical appliances. Low- and high-frequency currents in inverters may also produce audible sound during operation and although this may cause disturbance depending on the inverter's location, this is not EM radiation.

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

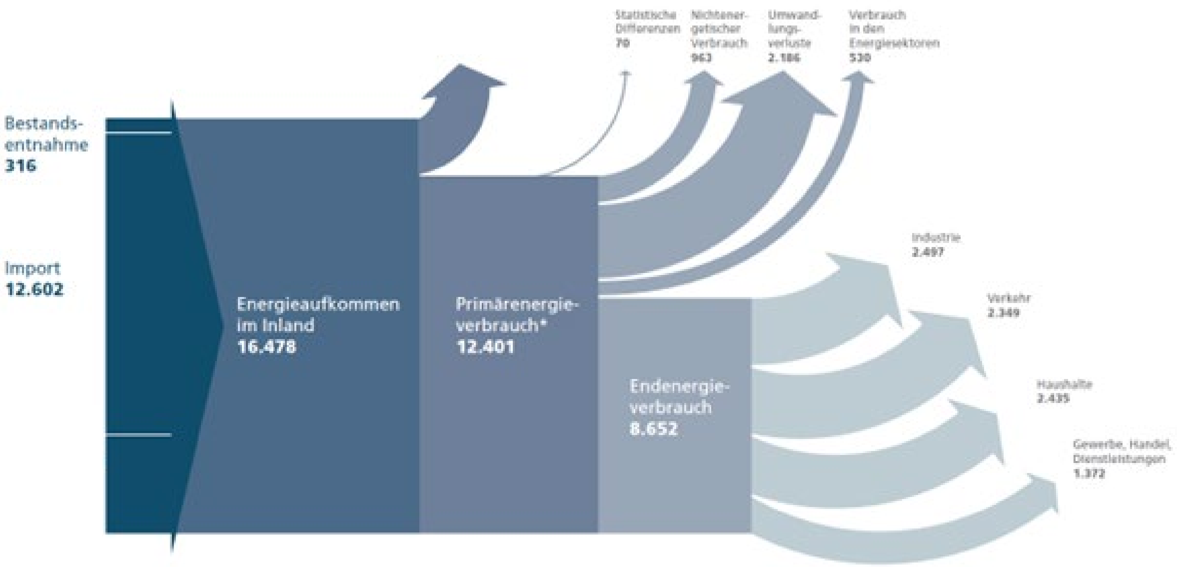
No, at least not in the next few years.
As long as no significant power-to-power storage capacities or storage power plants are available in the grid, PV and wind power will reduce fossil fuel consumption, energy imports and CO_2 emissions, but they will not replace power capacities. The acid test is windless, cloudy winter days, when electricity consumption can reach maximum levels without solar or wind power being available. On the other hand, PV and wind power increasingly collide with inert conventional power plants (nuclear power, old lignite). These — almost exclusively base-load capable — power plants must therefore be replaced as quickly as possible by flexible power plants, preferably in multifunctional, electricity-led CHP technology with thermal storage (Section 21.3.6).

22 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.

22.1 Starting point: energy demand and energy supply

The traditional energy industry extracts fossil and nuclear energy sources (primary energy), converts them and prepares them for end consumers (Figure 44).



Der Anteil der erneuerbaren Energieträger am Primärenergieverbrauch liegt bei 15,7 %.
Abweichungen in den Summen sind rundungsbedingt.
* Alle Zahlen vorläufig/geschätzt.
29,3 Petajoule (PJ) ≙ 1 Mio. t SKE
Quelle: Arbeitsgemeinschaft Energiebilanzen 05/2022

Figure 44: Energy flow diagram 2021 for Germany, figures in petajoules [AGEB2].

There are dramatic efficiency deficits in conversion and final energy consumption (cf. Section 21.3.3). 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.

Up to now, Germany has been highly dependent on energy imports, associated with the risk of volatile prices, political influence by producing and transit countries and the risk of disruptions in raw material logistics, e.g., pipeline blockages or low water in rivers.

The costs of fossil energy imports are in the order of 40–130 billion euros annually (Figure 45). A large part of the money went to supporting autocratic regimes.

		2017	2018	2019	2020	2021	2022
Coal, coke and briquettes		5,2	5,0	4,1	2,3	4,7	12,6
Oil, oil products and related products		36,1	43,8	42,8	26,9	36,6	60,7
Natural gas		15,0	18,0	15,9	12,3	28,4	63,3
Total fossil-based energies		**56,3**	**66,8**	**62,9**	**41,4**	**69,6**	**136,7**
Electrical power		-1,8	-1,9	-1,6	-0,9	-2,3	-5,2
Total		**54,5**	**64,9**	**61,3**	**40,6**	**67,4**	**131,5**

1) *Including in-transit quantities*

Figure 45: Balance of Germany's foreign trade in energy sources from 2017 to 2022 [AGEB1].]

Most final energy (36 percent) is used to generate mechanical energy ("power") for transport and in stationary engines (Figure 46). Approximately 800 TWh of final energy is used annually for space heating and hot water [BMWK1].

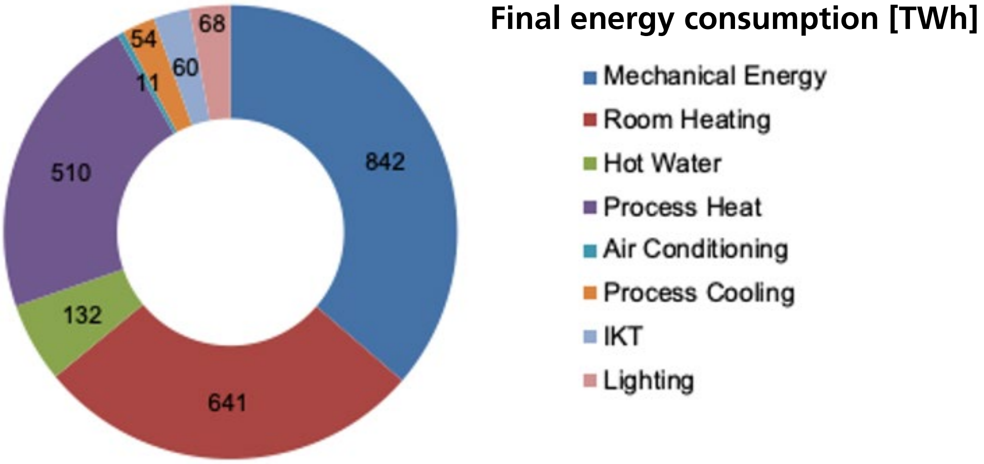


Figure 46: Structure of final energy consumption by application area for Germany in 2020, figures from [BMWK1].

The electricity load fluctuates periodically: less electricity is needed at night, on weekends and holidays. Electricity suppliers distinguish in the load profile between base, medium and peak load, cf. Section 27.8. The base load is the load share around 30–40 GW, which hardly changes over 24 h. The medium load fluctuates slowly, the peak load comprises the rapidly changing load share above the base load. The medium load fluctuates slowly, the peak load comprises the rapidly changing load share above the base and medium load. Electricity consumption and energy demand for water heating are slightly lower in summer than in winter. Mineral oil sales (petrol and diesel fuel) show very little seasonal fluctuation [MWV]. The heating demand correlates negatively with global radiation, with the highest coincidence in spring.

22.2 Energy scenarios

Our current energy system in Germany, based on fossil and nuclear generation, is a discontinued model. There is a plethora of energy scenarios for the coming decades, and they increasingly count on RE [UBA, ACA, ISE3]. Researchers at the Fraunhofer Institute for Solar Energy Systems ISE have investigated different transformation paths to a climate-neutral energy system for Germany in simulations based on hourly time series with consideration of sector coupling (Figure 47). In an economically optimized generation mix, PV contributes an installed capacity of 300–450 GW, depending on the boundary conditions [ISE3].
Figure 48 shows a schematic residual load curve for Germany with a 100 percent renewable electricity supply. The hourly values of the residual load (Section 10.4) for one year are shown in descending order. Although volatile electricity production can be technically

shut down at any time, this is at the price of a total economic loss of the corresponding electricity quantity. An electricity price with a meaningful control function would fall from left to right along the residual load curve of Figure 48.

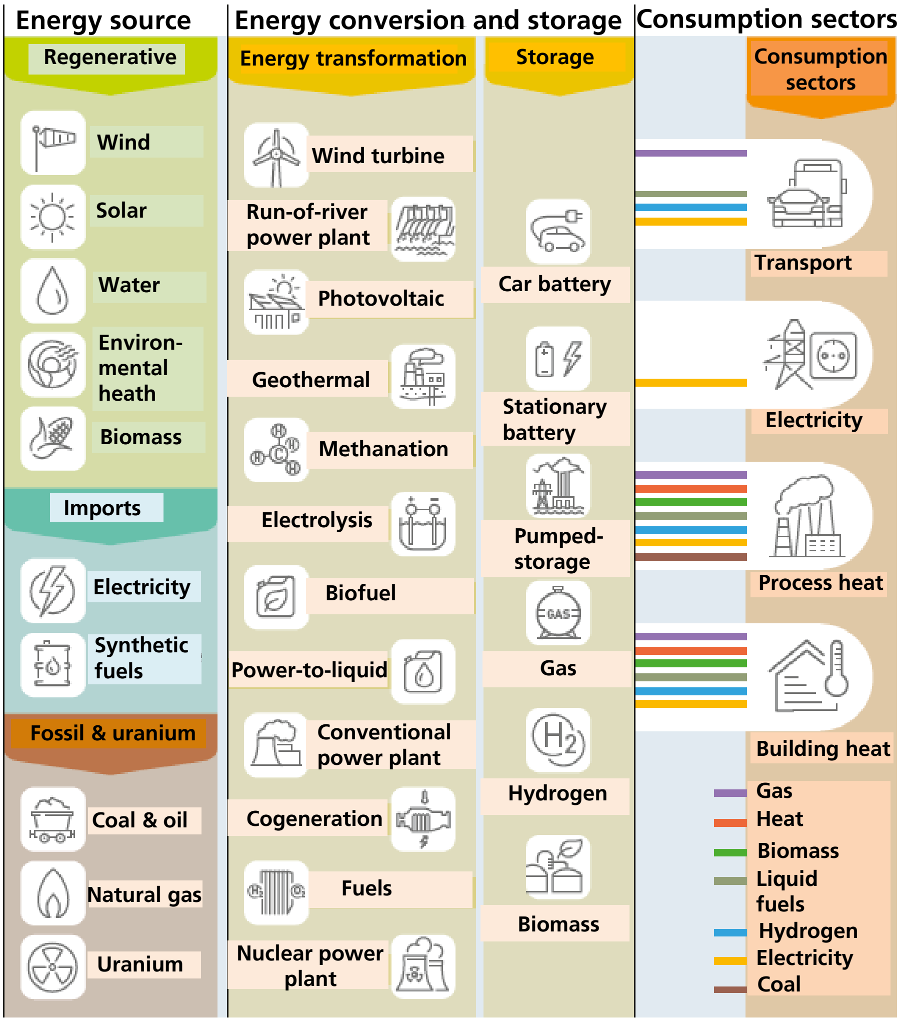


Figure 47: Schematic representation of the REMod model (KW: power plant, KWK: combined heat and power, [ISE3]).

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 RE, serve as energy carriers. In the case of local heat demand, electricity 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 charged, electrolyzers, heat pumps and resistance heaters ("heating rods") are activated when electricity prices increasingly fall in order to take the electricity that is not currently needed. Electrolyzers can also be operated as CHP plants and produce usable waste heat. Resistance heaters and high-temperature heat pumps can provide heat for industrial processes. The last resort is to shut down electricity production if the installed output or the grid capacities are not sufficient for a few hours of the year.

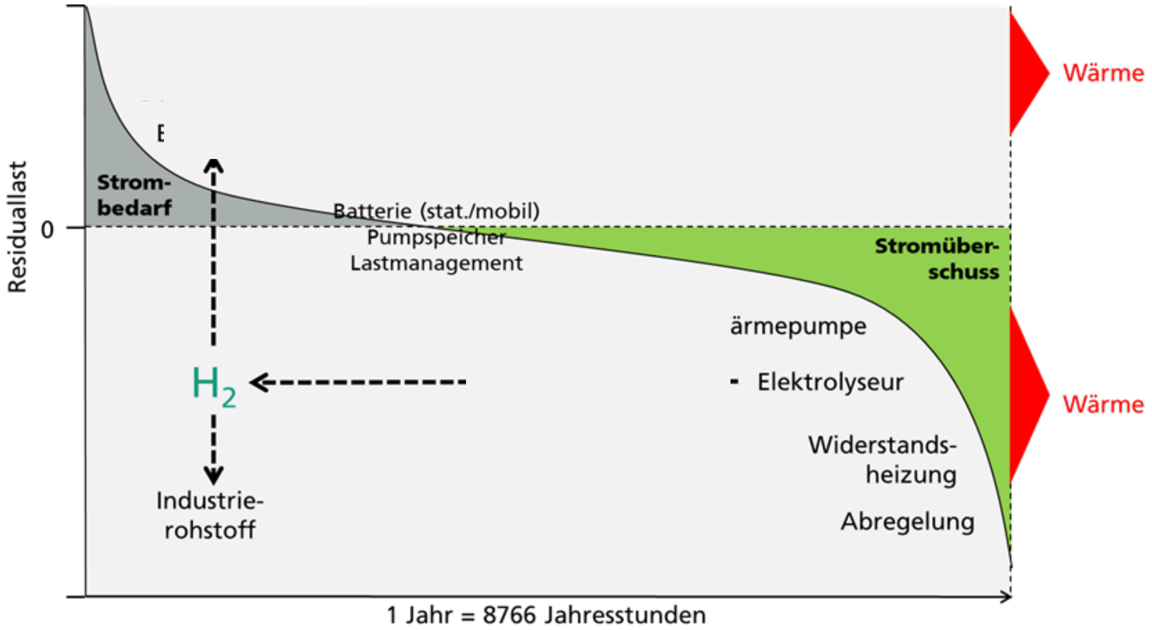


Figure 48: Schematic representation of a residual load curve for Germany with electricity supply with 100 percent RE, with generators (+) and loads (-).

In order for heat-generating converters on both sides of the curve to be operated with electricity, they require local thermal storage and heat consumers or connection to heat grids (Section 21.3.6). Generators (e.g., simple gas turbines) and consumers (e.g., resistance heaters) with particularly low performance-related investment and maintenance costs (€/W) are required for the two-sided spurs of the residual load curve. Since they are rarely in operation, they do not have to be highly efficient. The electrolytically produced hydrogen can be stored directly or after methanization in pressure tanks or in the gas grid. From there, it can be converted back into electricity (gas turbine, combined cycle gas turbine, fuel cell), further processed into synthetic fuels or used as a material 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 lull in winter, possibly exacerbated by a closed snow cover. For this, sufficient quantities of hydrogen and synthetic energy carriers and raw materials derived from it must be kept in stock. If there were no support for PV from wind power, then the worst case in winter would last months, not weeks, and many times more storage capacity would be needed.

Due to their limited capacity, stationary batteries and pumped storage fail relatively quickly as generators in continuous operation (minutes to a few hours). The same applies to vehicle batteries, which can be operated bidirectionally on the grid, but primarily have to cover the mobility demand. 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 to the electricity-to-electricity 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 48 must be sufficient to take over the complete supply in the order of 100–150 GW when the hourly reserves (load management, pumped storage, battery) are exhausted. This situation occurs frequently, e.g., on low-wind nights, and can last for several weeks in a worst-case scenario.

The **power purchase capacity** of the system on the right-hand side of Figure 48 in the order of several 100 GW must be sufficient to absorb the electricity production from volatile RE minus the current electricity consumption as far as possible as soon as the hourly reserves (load management, pumped storage, battery) are exhausted. If the power demand is not sufficient during rare production peaks, the system must be regulated. This can happen, for example, on stormy nights or on sunny and very windy weekend days, when low demand and very high electricity production coincide. For these few hours of operation, it is not worthwhile to further expand the power output.

Converters that allow reversible operation work on both sides of the curve in Figure 47 and thus achieve a higher utilization. In addition to batteries and pumped storage, these may also include reversible fuel cells that operate electrolysis in the case of excess electricity and are currently under development.

The technologies and measures mentioned in Figure 48 are scalable, except for turbines and pumped storage. They can not only be operated centrally on a multi-MW scale, but also on a single-digit kW scale. Corresponding devices are commercially available as domestic technology.

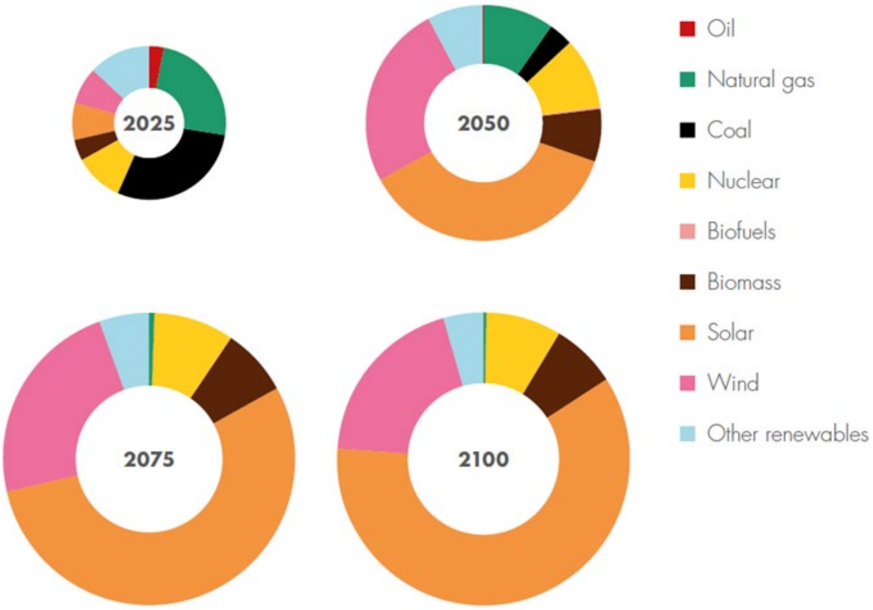


Figure 49: Development of global electricity generation by technologies in the Sky scenario; the diameter of the pie charts corresponds to global electricity demand [Shell].

A brief sideways 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 sees PV growing to become the most important source of electricity globally (Figure 49). Global electricity consumption increases from 22 PWh today to 100 PWh in 2100.
The International Energy Agency (IEA) has been publishing scenarios on the global expansion of PV for years (Figure 50), reliably underestimating the actual development (red curve).

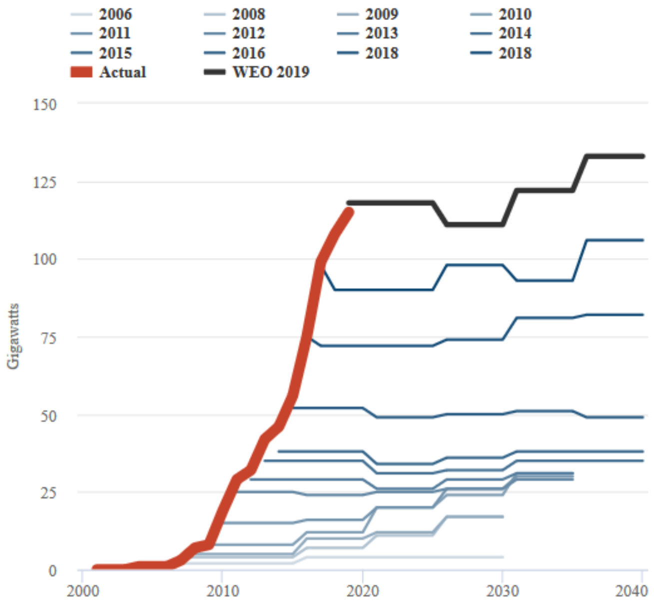


Figure 50: IEA forecasts since 2006 and actual development of global annual PV additions [Carb].

In the meantime, the IEA also predicts that photovoltaics will play a major role in the global primary energy supply: in its report “Net Zero by 2050: A Roadmap for the Global Energy Sector”, the IEA assumes a 20-fold expansion of the currently installed PV capacity to over 14,000 GW_P [IEA2].

22.3 Transformation steps

For a massive, technologically, and economically controllable integration of volatile PV electricity into our energy system, there is no single patent solution, but a multitude of complementary measures. The most important steps are addressed in the following sections.

21.3.1 Steady PV power generation

How can the PV power supply be stabilized in the grid?
Stabilization during the day increases the full load hours of a PV power plant and reduces the need for balancing, e.g., through load management and batteries. One of the simplest measures is to install PV modules with an east/west orientation, either on roofs or on open

spaces (Figure 51). This mounting variant reduces land consumption, but the specific annual yield per installed module output decreases compared to the south orientation. 1- or 2-axis tracking systems not only stabilize the electricity production over the course of the day (Figure 51), they also increase the specific annual yield by approx. 15–30 percent. Compared to stationary installation, they can also reduce losses caused by snow cover or increased operating temperatures. Another option is vertically mounted, bifacial modules with a north-south orientation, which deliver more electricity in the morning and afternoon than at noon.

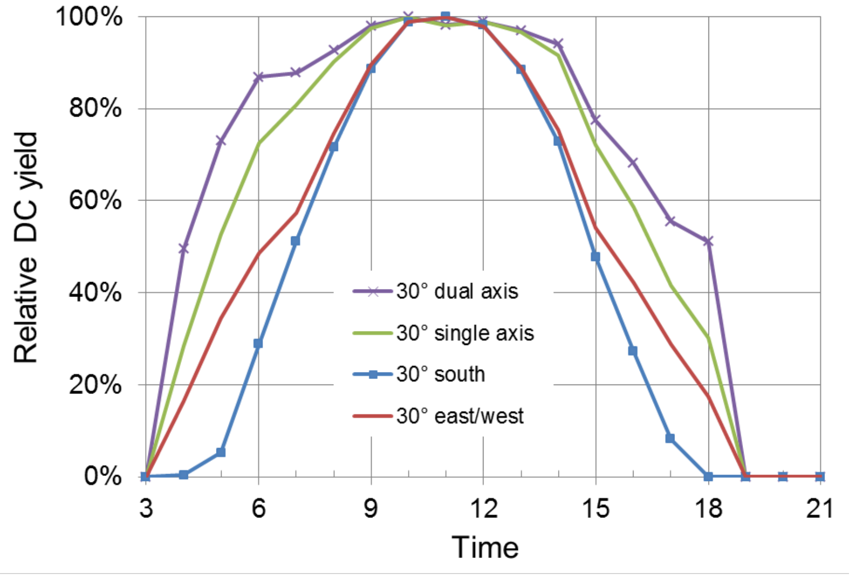


Figure 51: Power yield profiles of PV systems in different mounting variants, calculated with the PVsol software for a predominantly clear July day at the Freiburg site.

The very pronounced seasonal fluctuation of PV electricity generation can be dampened by mounting south-facing modules with higher tilt angles; vertical south-facing façades are particularly effective (Figure 35).

The somewhat higher electricity production costs for the alternative installation variants mentioned can pay off in the context of increased self-consumption and the associated savings on electricity purchases, especially for commercial customers. Feed-in tariffs that reward a higher value of electricity in the morning and evening hours promote the construction of systemically advantageous PV power plants that are not only optimized for maximum annual electricity yield. The measures to increase the number of full-load hours mentioned in Section 15.4 also contribute to the stabilization of PV electricity generation.

21.3.2 Complementary operation of power plants

Power plants for complementary operation must also be highly efficient in partial load operation, allow for rapid load changes and, in the case of gas-fired power plants, be able to cope with increasing hydrogen shares.

Gas-fired power plants are very well suited to cover fluctuating loads. In combination with combined heat and power (CHP), high overall efficiencies of up to 95 percent are achieved [UBA2]. Simple gas power plants based on gas engines have an investment cost (€/kW) that is a fraction of the cost of combined cycle power plants. Today, gas-fired power plants burn natural gas and biogas. Natural gas must be imported for the most part (approx. 95 percent in 2017 [AGEB1]), especially from Russia and Norway. In the course of the energy transition, gas-fired power plants will switch from natural gas to mixed gases with increasing proportions of electrolytically produced hydrogen.
It is technically possible to operate, design or retrofit many coal-fired power plants so that they can partially follow the residual load (Figure 52). The partial load operation itself, the increased wear and the possibly necessary retrofitting increase the production costs for electricity. In some coal-fired power plants, steam generation can be converted from coal to gas burners (fuel switch) so that the steam turbine and generator can continue to be used [EnBW2].

Figure 52: Availability of power plants [VGB].

Depending on the type, biomass power plants can burn solid biomass (residual wood, waste wood), liquid biomass (vegetable oil) or biogas (from agriculture or sewage treatment plants). At the end of 2019, biomass power plants with a capacity of over 8 GW_p were installed throughout Germany [ISE4]. Power plants that burn solid or liquid biomass are very easy to operate as electricity-generating plants due to the simple storage of the fuel material. There are limitations with biogas power plants when the fermentation throughput can only be controlled to a limited extent and the gas cannot be stored in the gas grid. The cultivation of biomass for the purpose of energy use will decrease due to low land efficiency (Section 15), and use will concentrate on agricultural residues (biogenic waste).

21.3.3 Increasing energy efficiency

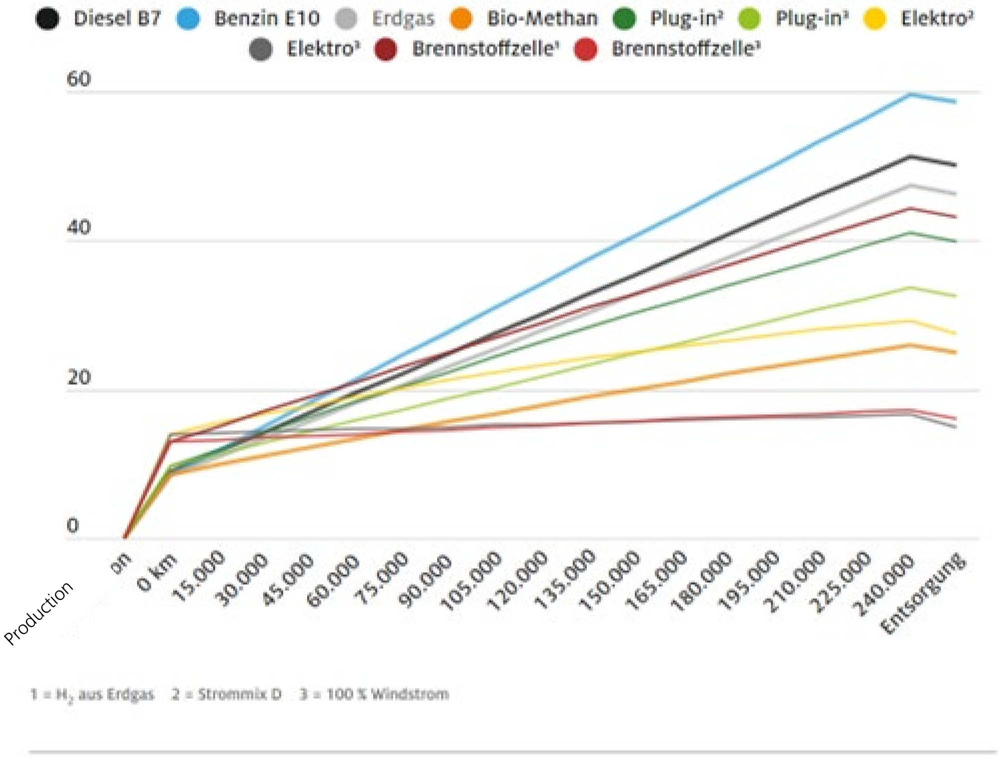
21.3.3.1 Transport

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 percent at their peak, while in urban traffic the average efficiency is only approx. 20 percent due to partial load operation [Sprin]. For passenger car petrol engines, the values are even lower, at up to 37 percent at the peak and approx. 10–15 percent in urban traffic. In urban traffic in particular, a considerable proportion of the drive energy gained is irreversibly burnt up during braking, because vehicles with internal combustion engines can hardly recuperate via their alternator. Thus, motorized road traffic burns fossil fuels with a very low efficiency, related to the transport performance.

Electric vehicle drives use highly efficient motors with an effective efficiency of around 90 percent. Losses during charging of the vehicle battery are in the order of 15 percent and are particularly high during fast (DC) charging. Electric vehicle drives can recover a large part of the kinetic energy; according to the manufacturer, the efficiency of recuperation for the BMW i3, for example, is around 63 percent. For reasons of energy efficiency alone, it makes sense to switch to electric drives, in addition to the considerable storage potential (Section 21.3.7.5). Figure 53 shows the accumulated greenhouse gas emissions of average compact cars (Volkswagen Golf) with different drives in relation to their total mileage in 2022 [ADAC].

Preferred charging with solar or wind power (cf. Section 21.3.7.5) leads to a particularly flat course of the emission line (Elektro3). If the BEV is sold together with a small PV system of 3 kW_p nominal power, the vehicle runs on 100 percent solar power on a bi-lobal basis, with an average annual mileage of over 15000 km, a specific annual yield of 950 kWh/kW_p and 15 percent charging losses. Especially in city traffic with its typical stop-and-go operation, consumption and GHG emissions per km for BEVs decrease thanks to recuperation, while they increase for internal combustion vehicles due to braking losses and inefficient partial load operation.

For city operation, smaller batteries are usually sufficient, which further reduces GHG emissions for production and operation. In the future, the production of BEVs will use increasing shares of RE with correspondingly decreasing greenhouse gas emissions.



Quelle: Joanneum Research, Graz

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Figure 53: Greenhouse gas emissions (CO_2-Eq. in tons) of an average compact car with different drives in 2022, in relation to the total mileage [ADAC].

The CO_2 balance can be evaluated as follows: an electric car with a small battery, which mostly drives in town, prefers to charge with renewable electricity and covers many (necessary) km per year, has a particularly clear advantage in terms of the GHG balance. The advantage shrinks for Sunday drivers with a large battery, a high proportion of car journeys and gray charging current.

21.3.3.2 Private households

Private households use about 75 percent of the final energy consumed for heating. On average, this consumption can be halved by simple thermal insulation measures.
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]. Measures that reduce night-time electricity consumption are particularly effective when solar power (and wind power when there is a night-time lull) can only be made available through comparatively expensive storage.

21.3.4 Load management

Grid-serving load management ("demand side management") aims at a supply-oriented, temporal shift of electricity consumption. When the residual load is high (Section 10.4), consumption is temporarily reduced or stopped, but is made up for when the residual load is low. If the CO_2 price is sufficiently high to determine the merit order (Section 4.3), load management can already save CO_2 emissions today, because the dirtiest power plants are then needed less often.

Prerequisites for load management are flexibility options through **material storage** or reserves on the demand side. A washing machine can often wait a few hours, while a passenger train must depart on time. For electrical systems in continuous operation, **power reserves** are necessary that enable a compensatory increase above normal power after a reduction below normal power. The interaction between load management and energy storage systems is discussed in Section 21.3.7. They are charged in accordance with their intended use for the grid (e.g., pumped-storage power plants) or with consideration for grid efficiency (in the future, e.g., heat pumps and batteries for electric cars).

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, but direct control is even more effective. Some appliances with particularly high output, such as washing machines, dishwashers, and tumble dryers, come into question.

The technical prerequisites and economic incentives for tapping this potential still must be created for the most part. Dynamic electricity tariffs and electricity meters that enable time-dependent billing ("smart meters") are of decisive importance. In the best case, dynamic tariffs reflect the current residual load. The current composition of electricity prices for households (Figure 11) 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 1.1.2021, and the German federal government's plan is to make these electricity tariffs mandatory by 2025 at the latest.

In the electricity-intensive industry, e.g., 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 (Ordinance on Disconnectable Loads — AbLaV). The electrolytic production of green hydrogen as a raw material in metallurgy, e.g. for the direct reduction of iron ore, and in the chemical industry, e.g. via methanization 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 it is purchased directly from one's own roof. The promotion of PV self-consumption for households and businesses is a highly effective means of incentivizing load management.

21.3.5 Balanced addition of PV and wind power capacities

Due to the weather conditions, there is a high degree of complementarity between the hourly and monthly generation of PV and wind power in Germany (Section 10.2.3). If the installed capacities for PV and wind power can be expanded to similar levels, their combination will reduce the need for balancing.

21.3.6 Combined heat and power generation

Low-temperature heat for space heating and hot water, as well as industrial process heat at a high temperature level, are still mainly produced by burning fossil resources and in connection 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 (Section 21.3.7.1) enable the current-controlled operation of the converters. The expansion of heat distribution networks is limited by distance-dependent transport losses to a much greater extent than in the electricity sector. For this reason, plants with electricity-heat coupling (Figure 48) must be tailored in their output and placement to local heat consumption and usable heat grids. These can be local heating networks with heat transport between neighboring buildings or district heating networks that supply city districts or entire cities. High-temperature heat for industrial processes can be generated from the waste heat of CHP gas turbines (up to approx. 550°C) if electricity is required.

In Germany, about 39 GW of electrical CHP capacity was on the grid at the end of 2020 ([ÖKO2], statista.com), using mainly natural gas, biomass, and coal. CHP plants achieve overall efficiencies of up to 90 percent, and as gas CHPs even up to 95 percent [UBA2]. Even micro-CHP units for single-family homes can achieve electrical efficiencies of up to 25 percent and overall efficiencies of up to 90 percent [Licht1]. They use combustion or Stirling engines to generate mechanical power. As the energy transition progresses, CHP plants are being converted from fossil fuels to hydrogen and methane; some continue to burn bio methane/mass from biogenic waste.

21.3.7 Energy storage

Energy storage systems are components that can absorb energy and release it again as usable energy. Energy converters such as water or heat pumps, electrolyzers or fuel cells are used for charging and discharging. In some energy storage systems, energy can only be extracted in a converted form, e.g., in the case of heat storage systems 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 as a material storage unit, e.g., 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 21.3.4).

21.3.7.1 Low-temperature heat accumulator

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 indicated as the annual performance factor (APF) and is around 300 percent in heating mode, depending on the technology and load. Efficient operation is achieved by heat pumps with surface heating systems, mostly underfloor heating systems, which manage with low flow temperatures. Resistance heaters (heating rods) convert electricity into heat with 100 percent efficiency, but with a low exergetic efficiency when generating low-temperature heat.
Thermal storage capacity can be provided much more cheaply than electricity-to-electricity storage capacity. If the thermal storage capacity and the heat pump or heating system output are sufficiently dimensioned, the storage load can be supply-oriented, depending on the current residual load. For this purpose, heat storage units and cold storage units, e.g., of air-conditioning systems, cold stores, and food markets, are preferably charged during the core time of the day or according to electricity price signals. However, if generously dimensioned thermal heat storage systems are lacking, the thermosensitivity of the electricity load increases and larger power reserves must be kept available at power plants.

Low-temperature thermal storage, especially hot-water thermal storage, enables the electricity-led, highly efficient operation of CHP plants on both sides of the residual load curve (Figure 48), as well as of heat pumps and heating rods on the electricity consumer side. The same storage unit can, for example, be charged simultaneously by heat pump and heating rod when there is a high electricity surplus, and by a CHP when there is a demand for electricity. Heat storage systems are scalable from single-family homes to multi-family homes and commercial enterprises to neighborhood supply. The relative storage losses and the specific costs decrease with the size of the storage tank. Large storage facilities of several thousand m3 or more, e.g., neighborhood storage facilities, can be operated as seasonal heat storage facilities (http://www.saisonalspeicher.de). They enable the transfer of useful heat from the summer to the winter half-year with its much higher heat demand.
For the estimation of the maximum electrical load that can be switched on (peak load) via remote-controlled heat pumps, partly combined with heating rods, an average thermal rated output of 15 kW$_P$,th per unit is assumed. With a coefficient of performance (COP) of 3, this corresponds to an nominal electrical capacity of 5 kW$_P$,el. In normal operation, heat pumps usually work with a COP of 3–5. By the end of 2021, more than 1.2 million

heat pumps were in use [BWP], which, under the same assumptions, is equivalent to an electrical nominal capacity of 6 GW_p.
Heat storage systems increase the self-consumption of PV systems if they are charged via the heat pump and the heating rod, especially in the summer half-year. The PV system can take over the domestic hot water heating seasonally, all the more so if the PV modules are mounted with a high inclination on steep south-facing roofs or on south-facing façades. As soon as price signals become available, decentralized heat storage systems can also be selectively charged with surplus wind power from the grid.

21.3.7.2 High-temperature heat storage

Surplus electricity can be converted very efficiently into high-temperature heat (order of magnitude 650 °C) via resistance heaters. High-temperature heat can be stored as latent heat in liquid salt storage tanks or as sensible heat in rock fill [Siem] or steel bodies [Vatt]. If required, the heat can be used for industrial processes or to drive a conventional steam turbine, possibly with further utilization of the low-temperature heat. The first pilot plants are currently being tested; the manufacturer Lumenion states an electricity-to-electricity efficiency of 25 percent.

21.3.7.3 Cold accumulator

At the point of cold generation and use, e.g., in building air conditioning or in refrigerated warehouses, cold can be stored with comparatively simple means. Another prerequisite for grid-friendly operation is a sufficiently dimensioned output 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. The planned power-to-power efficiency is approx. 25 percent; it can be significantly increased by adding further thermal system components.

21.3.7.4 Stationary batteries

Lithium-ion batteries have followed a similarly 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.

The installed capacity of large-scale stationary batteries reached **0.6 GW_p** by the end of 2021 (ISE4). With small, stationary batteries, households can extend their own consumption of PV electricity into the evening hours and thus massively increase it (typically doubling it, see Figure 54). At the beginning of April 2022, approximately **500,000** PV electricity storage systems were installed in Germany, with a total capacity of **4.4 GWh** and a nominal capacity of **2.5 GW** [BVES]. A grid-serving system management of the batteries relieves the grid by selectively reducing the midday feed-in peak (Figure 55). Speakers would thus enable an increased PV expansion [ISE7]. Pilot projects are also currently investigating the storage of electrical energy in large, stationary batteries [RWE].

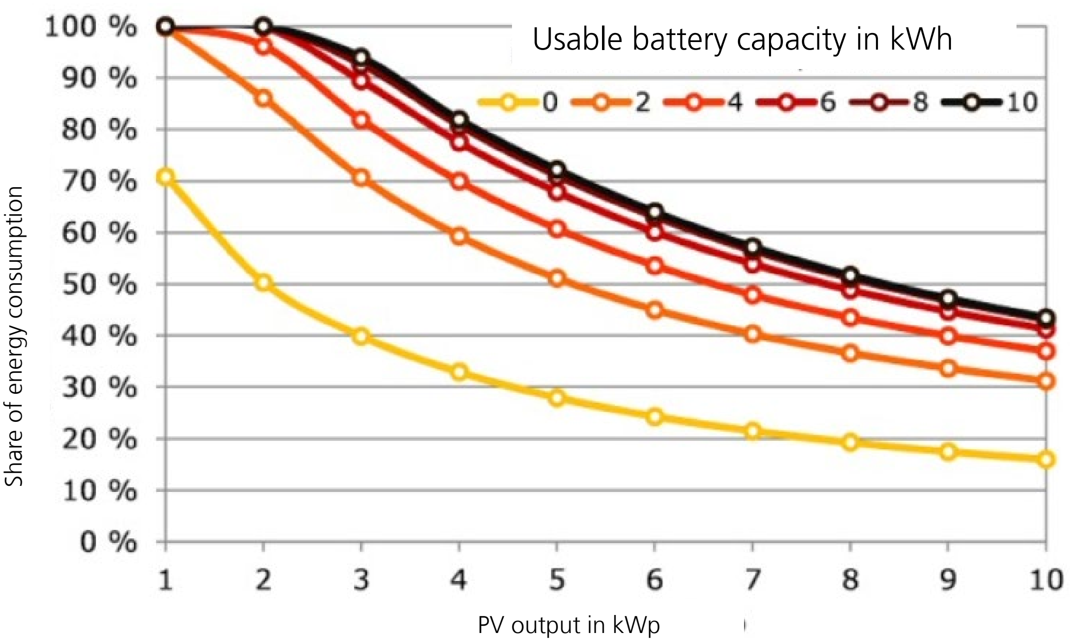


Figure 54: Self-consumption share as a function of battery capacity and power of the solar generator for a single-family household with an annual electricity consumption of 4,700 kWh. [Quasch].

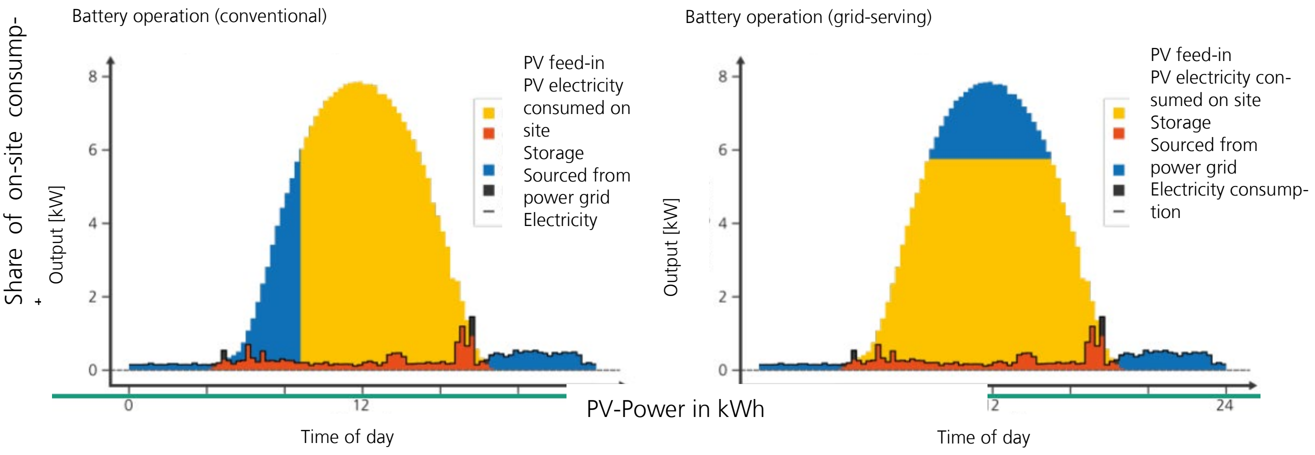


Figure 55: Comparison of conventional and grid-serving operation [ISE7].

21.3.7.5 Vehicle batteries

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 2022, around **1 million** purely electric cars (BEV, without plug-in hybrid) were registered in Germany, out of a total of approx. 48 million passenger cars (de.statista.com, www.kba.de). The total mileage of passenger cars in Germany of 645 billion km in 2019 [KBA] with a consumption of 160 Wh/km corresponds to an annual electricity consumption by electric cars of 100 TWh, plus approx. 15 percent charging losses. If 10 percent of the fully electric vehicles that are currently registered had a switchable connection to the power grid at a fast charging power of 50 kW, this would create a balancing power of 5 GW_p. In fact, at the end of 2021, there were only about 7,000 fast charging stations with more than 22 kW. The RWTH Aachen University estimates Germany's total capacity of vehicle batteries at about 50 GWh by the end of 2022.

E-buses are state of the art in urban transport, along with small electric cargo vans for distribution logistics. The use of larger commercial vehicles with electric drives and reasonable battery capacities is still limited today by their short range. For e-trucks, solutions are currently being tested for recharging the batteries while driving on sections of track with overhead lines.

Several measures are necessary to activate vehicle batteries as grid-serving energy storage systems. **Supply-dependent electricity prices** will motivate private 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; petrol stations also vary their prices depending on the time of day.

The current share of electricity from renewable sources covering the grid load in Germany fluctuated between 13 and 112 % in 2022 [ISE4]. Those who already want to supply their e-car with especially green electricity from the grid prefer to charge on sunny days around midday, otherwise on windy nights. Weekends are usually advantageous because the lower electricity consumption tends to improve the CO_2 balance. Unfortunately, most e-cars are charged at home in the evening, adding to the evening peak demand while also not using any direct PV electricity. Precise information on the current and planned share of RE in the German electricity mix is shown in the Energy Charts [ISE4]. Actual CO_2 savings through supply-side charging are achieved when:

- the CO_2 price is sufficiently high to determine the merit order of fossil-fuel power plants (Section 4.3), or
- when surplus RES-E is used, which would otherwise have to be regulated or consumed in heating plants.

In order to be able to supply PV electricity for direct consumption, charging stations must be located in typical daytime parking areas, e.g., at the workplace, in multi-story car parks or in public car parks. **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 allow electric vehicles to be operated as electricity storage units when they are connected to the grid and do not have to keep the full range on standby at all times. Private cars 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, unlike their predecessors with combustion engines. In the expansion scenarios [ISE3], it is assumed that at least 10 percent of the mobile batteries are connected to the grid at all times via bidirectional remote control. This means that with 40 million e-cars (reference scenario), at least 4 million would be available for grid service, provided there are enough fast charging stations. With 50 kW fast charging capacity per charging point, this would provide 200 GW_p of bidirectional controllable capacity. The German federal government has set the goal of bringing at least 15 million e-cars to the streets by 2030.

21.3.7.6 Mechanical storage facilities

The currently installed **pumped storage** capacity in the German electricity grid is just under **38 GWh,** the nominal capacity is **10 GW_P**, and the average efficiency is around 70 percent, excluding electrical supply and discharge losses. For size comparison: the storage capacity mentioned corresponds mathematically to the yield of the German PV power plant park from less than one operating hour under full load.
Due to a lack of storage capacity, run-of-river power plants can hardly make any control contributions in complementary operation. Their contribution of approx. **3.8 GW_P** nominal output [ISE4] is only slightly expandable, their electricity production (annual full load hour) is generally declining due to the increasing drought. The mechanical storage of electrical energy in compressed air storage (Compressed Air Energy Storage, CAES) is currently being tested.

21.3.7.7 Hydrogen and synthesis products

The electrolytic conversion of surplus solar and wind power into hydrogen, possibly with subsequent methanation and further processing into synthetic liquid fuels (e.g., methanol) or for the production of ammonia, is currently being scaled up and tested [AMP]. Commercial alkaline electrolyzers achieve efficiencies of up to 80 percent, high-temperature electrolyzers over 80 percent. Additional energy is required for gas compression, possibly liquefaction (20–30 percent loss) and subsequent synthesis steps. By the end of 2021, **electrolyzers** with a total capacity of around **80 MW_P** were connected to the grid, with 273 MW_P in planning [DVGW]. Figure 56 shows current and projected investment costs for various electrolysis technologies.
The conversion of renewable electricity into storable energy sources ("Power-to-X") opens up huge, already existing storage possibilities. It is already technically possible today to increase the proportion of hydrogen in the gas grid to up to 20 percent. In German salt caverns, 9.4 PWh of energy can be stored in the form of hydrogen [Hydro], which corresponds to 2.6 times Germany's primary energy consumption.
Synthetic energy carriers can be converted back into electricity via stationary fuel cells (efficiency up to approx. 65 percent) or thermal power plants, used as fuels in the transport sector (e.g., hydrogen for fuel cell vehicles, diesel substitutes for shipping, paraffin substitutes in aviation) or as feedstock for the chemical industry.

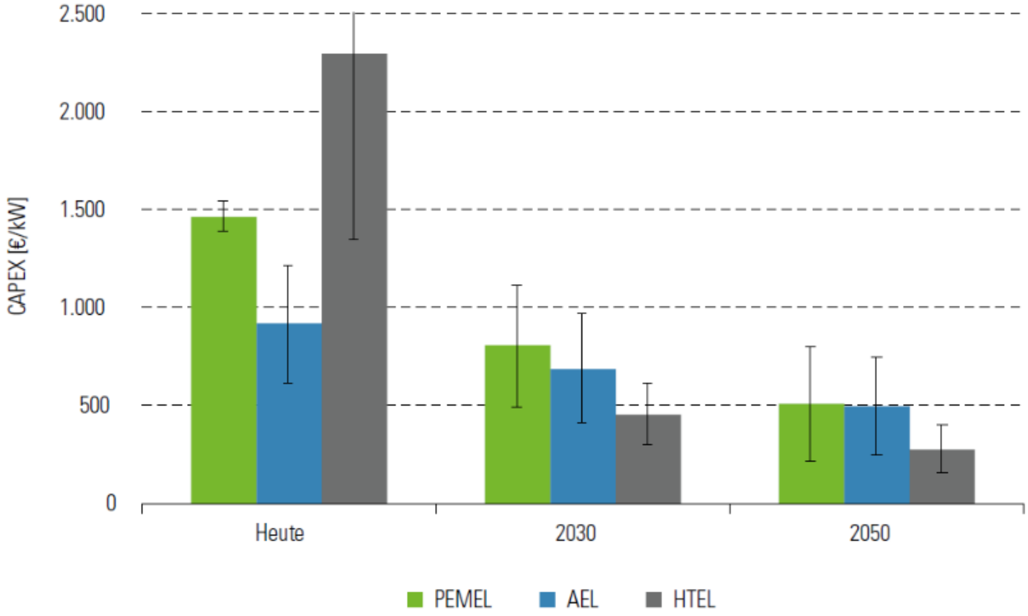


Figure 56: Specific investment costs for different electrolyzers technologies (PEMEL: membrane electrolysis, AEL: alkaline electrolysis, HTEL: high-temperature electrolysis, [NOW]).

Reversible high-temperature fuel cells (rSOC), which can also be operated as electrolyzers, are currently being developed and currently achieve a current-to-current efficiency of 43 percent [FZJ]. Compared to a combination of pure electrolyzers with pure fuel cells, these bidirectional converters promise a higher number of full load hours and lower investment costs per total installed capacity as stationary power plants in the electricity grid.

21.3.7.8 Overview

Figure 57 shows paths for storage and conversion of PV and wind electricity. For the practical relevance of these paths, the costs of the nominal power of converters to be installed (€/W) and capacity of storage (€/Wh), among others, must be considered in addition to the technical efficiency.

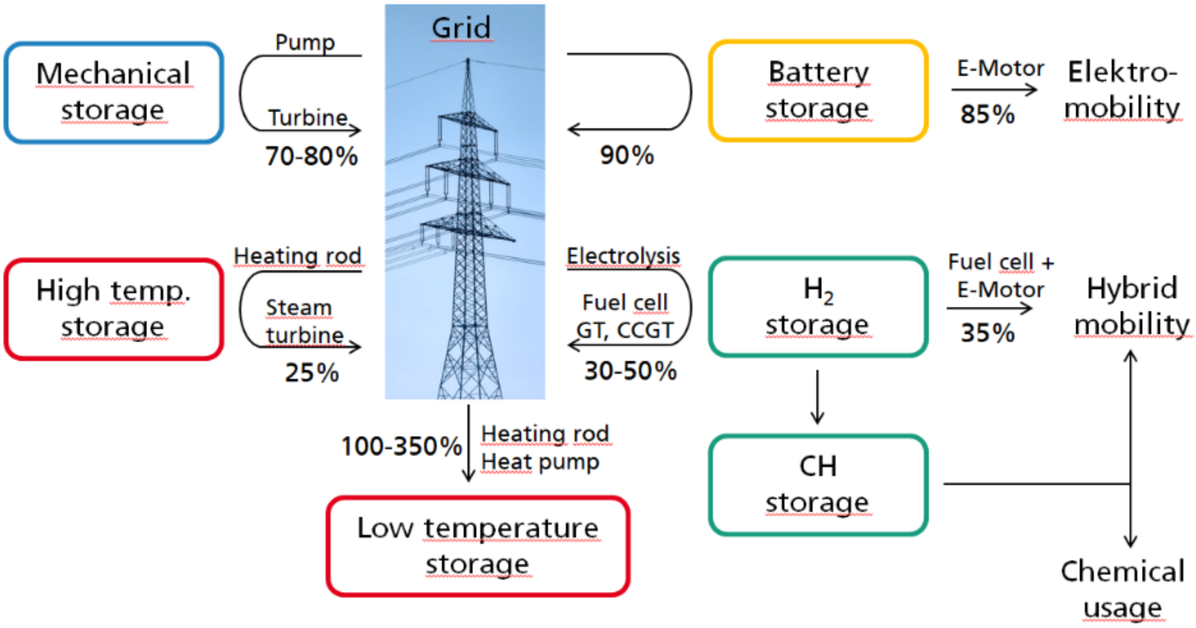


Figure 57: Technologies for energy storage devices and inverters with current efficiency at the end of the inverter chain, without co-generation (GT: gas turbine, CCGT: combined cycle gas turbine).

21.3.8 Grid expansion

Grid-bound, supra-regional energy transport takes place via the extra-high voltage grid and the gas transmission grid. In the course of the energy transition, the gas transmission grid will increasingly transport renewable gases (hydrogen or methane). Gas transport with reconversion in the target region reduces the need for expansion of the electricity grid.

21.3.8.1 National grid expansion

The energy flows in an energy system with 100 percent renewables are fundamentally different from the situation at the turn of the millennium. PV is ideally suited for decentralized expansion close to consumption. The need for expansion of electricity and gas transmission lines can be minimized with a spatially distributed development of batteries and converters (e.g., electrolysis, gas power plants, fuel cells, heat pumps) that is also close to consumption. A strong concentration of wind power generation in the north or offshore, on the other hand, leads to a high demand for transmission line capacity (electricity or gas).
The production of PV electricity is characterized by a high simultaneity factor. In order to avoid local grid overloads due to generation peaks, battery storage is considered an economically interesting alternative to grid expansion in some places.

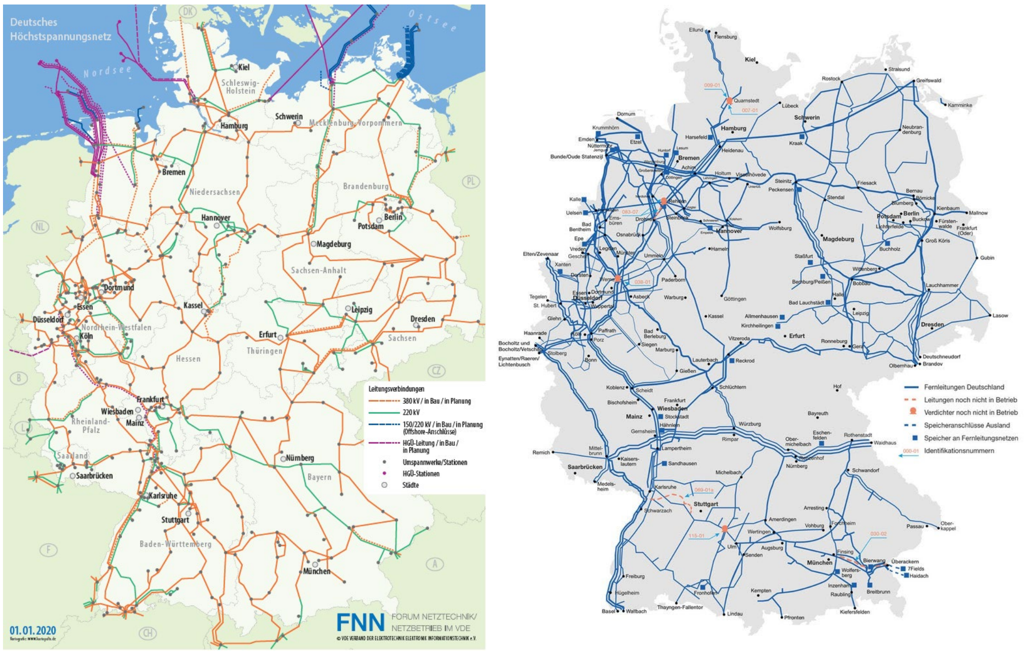


Figure 58: Extra-high voltage grid [VDE] and gas transmission grid [Fern].

21.3.8.2 Strengthening the European interconnected grid

The German electricity grid is part of the European interconnected grid. Strengthening the cross-border interconnection capacity of currently approx. 20 GW enables a better balancing of volatile PV electricity production via European electricity trading.

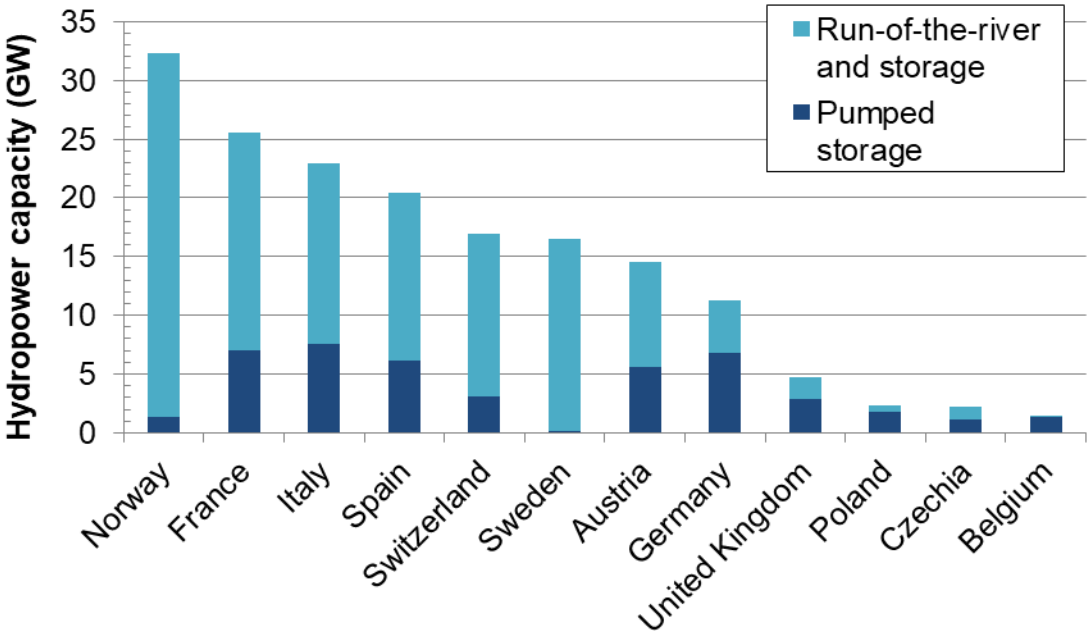


Figure 59: Installed capacity of hydropower plants in neighboring countries, figures from [IHA].

Figure 59 shows the installed capacity of run-of-river and storage hydropower plants as well as pumped storage power plants. Storage power plants can be operated as a complement to PV generation, while pumped storage plants act as efficient power-to-power storage.

21.3.9 Importing energy sources

For some applications, such as aviation and shipping, there are no alternatives to liquid fuels in the longer term. The production of synthetic fuels from PV electricity requires a lot of energy. Liquid fuels can be produced particularly cheaply in sun-rich countries and imported by sea; the logistics chain required for this is in principle in place.

21.3.10 Overview

From today's perspective, an energy system based on 100 percent RE is technically and economically feasible. Figure 60 shows the most important elements connected to the electricity grid, from generation to conversion and storage to consumption. To reduce the need for storage, electricity consumption in households and industry is partly made more flexible.

In the **"heat"** sector (red), combined heat and power plants, heat pumps and — in the event of supply peaks on the electricity side — heating rods load the heat storage facilities with electricity. Where the density of demand permits, e.g., in neighborhoods, efficient storage takes place centrally in large heat storage facilities.

In the "**Gas**" sector (green), biomass fermenters produce methane from biogenic waste and electrolyzers produce hydrogen, which can also be methanized or processed into synthetic fuels. In some cases, biomass is burned directly in the CHP unit. When electricity is needed, combined gas and steam turbines, fuel cells and — at peak demand — pure gas turbines are used. Hydrogen electric vehicles fill up their fuel from stationary gas storage, vehicles for long ranges (especially aircraft) fill up with liquid synthetic fuels.

In the "**Battery**" sector (yellow), stationary, centralized, or decentralized electrochemical storage facilities are charged or discharged depending on the residual load. Mobile batteries in electric vehicles primarily serve the mobility demand but can also provide bidirectional support for the grid if a connection exists. In most electrochemical storage systems, the converter and storage are structurally fused; only so-called redox flow batteries have external, independently scalable storage tanks.

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

Figure 61 summarizes the most important expansion measures for an energy transition in the electricity sector with coupling to the transport and heat sectors.

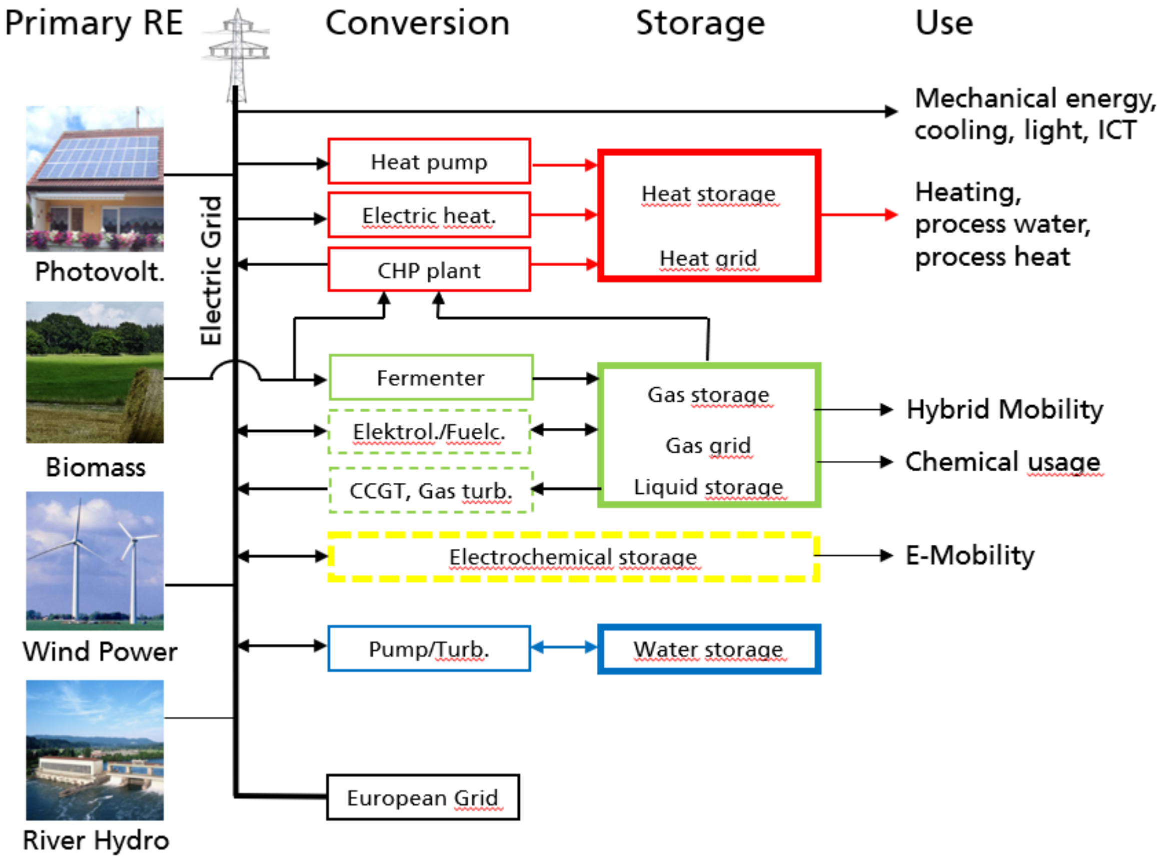
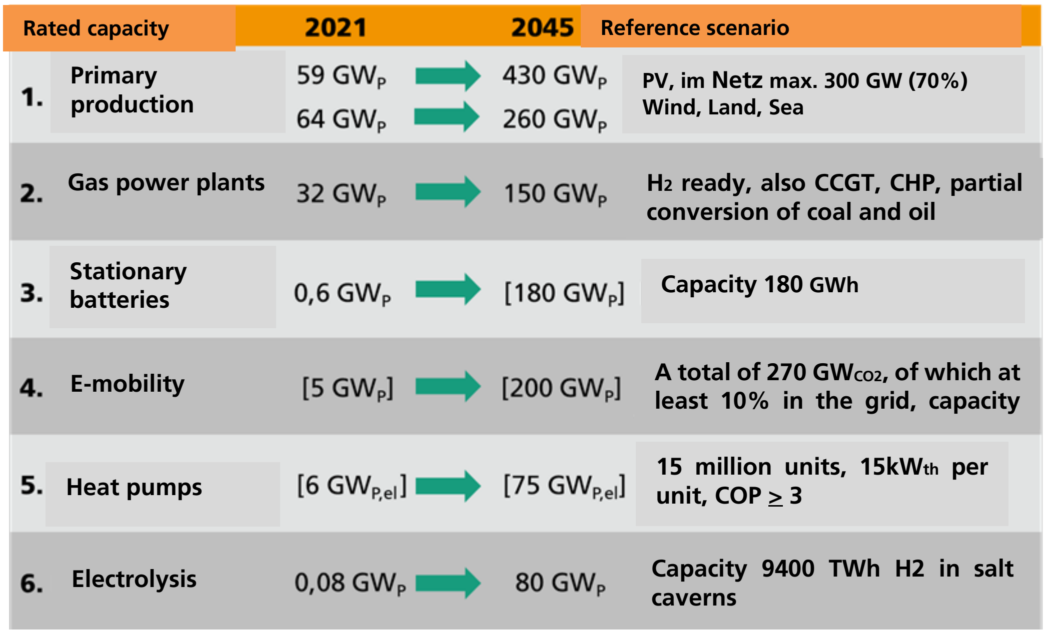


Figure 60: Simplified schematic representation of a renewable energy system with the most important electricity grid-related components of generation, conversion, storage, and consumption; ICT: information and communication technology, CHP: combined heat and power, CCGT: combined cycle gas and steam power plant.



	Rated capacity	2021		2045	Reference scenario
1.	Primary production	59 GW_p 64 GW_p	➡ ➡	430 GW_p 260 GW_p	PV, im Netz max. 300 GW (70%) Wind, Land, Sea
2.	Gas power plants	32 GW_p	➡	150 GW_p	H_2 ready, also CCGT, CHP, partial conversion of coal and oil
3.	Stationary batteries	0,6 GW_p	➡	[180 GW_p]	Capacity 180 GWh
4.	E-mobility	[5 GW_p]	➡	[200 GW_p]	A total of 270 GW_{CO2}, of which at least 10% in the grid, capacity
5.	Heat pumps	[6 $GW_{P,el}$]	➡	[75 $GW_{P,el}$]	15 million units, 15kW_{th} per unit, COP ≥ 3
6.	Electrolysis	0,08 GW_p	➡	80 GW_p	Capacity 9400 TWh H2 in salt caverns

Figure 61: Important power generators, converters and storage units, COP: Coefficient of Performance,

Sources: [ISE3], [ISE4], additional estimates and assumptions in square brackets.

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

No, even if federal policy can make it easier for everyone.
As legislator, the Bundestag determines the framework for the energy transition.
In addition, there are several important actors who can move a lot in their fields of action, even independently of the regulatory framework. Action by these actors also sends clear signals to politicians. Consumers can demand renewable energies and energy efficiency when purchasing electricity and heat, when choosing their means of transport and in their overall consumption. Investors are called upon to invest in the energy transition, whether on their own roofs, in investment companies or funds. Decision-makers in commercial and industrial enterprises or in municipal utilities can examine which measures pay off sustainably and at the same time advance the energy transition. Finally, federal states, cities and municipalities can promote the energy transition through a wide range of measures, from advising stakeholders, providing investment grants and other forms of support for projects, providing land, obliging building owners to install solar panels, and even making their own investment decisions.

23 Do we need PV production in Germany?

Yes, if we want to avoid new dependencies in energy supply.
As the energy transition progresses, Germany will leave the "fossil" century behind, a century in which we spend up to 90 billion euros a year on oil and gas imports. The prices of these imports are influenced by cartels, the revenues largely finance authoritarian regimes, and often there are political costs as well as monetary ones. The energy transition offers a historic opportunity to break out of this economic and political dependency: the sun shines in Germany too, raw materials for PV production are available and technologies for solar power generation were significantly co-developed in Germany. The German PV sector, with its material producers, mechanical engineering, component manufacturers, R&D facilities, and teaching, still occupies a leading position worldwide despite the slowdown in national expansion. An energy system converted to renewables is based, among other things, on approx. 300–450 GW of installed PV capacity. Annual installations of 12–20 GW are required for the construction and increasingly for the ongoing renewal of this plant park, corresponding to approx. 40 million PV modules at a cost of several billion euros. PV production in Germany offers long-term security of supply with high environmental, social, and quality standards.

23 Do we need a Renewable Energy Sources Act (EEG)?

Yes, whereby the energy transition legislation as a whole must come into focus.

The current market mechanisms would provide too little incentive for long-term investments in the energy transition if they were not accompanied by an EEG. The main reason is the far too low pricing of **CO_2 emissions across all sectors**, measured against the actual recovery costs or the currently foreseeable follow-up costs of the climate crisis. This de-facto subsidy for fossil energy supply must be dismantled, also in order to secure the market value of solar power with increasing PV expansion. A rapid reduction in EU-ETS certificates and a rapid increase in the national CO_2 tax, combined with compensation measures, are necessary.

For the social acceptance of the energy transition, a broad participation and diversity of actors is beneficial, which can be realized especially in the decentralized generation of PV electricity. Therefore, the **regulatory hurdles**, especially for small plants, must be lowered or smoothed out by a law such as the EEG. PV power plants of all sizes generally need a **grid connection** to deliver electricity that can neither be consumed nor stored on site. A legal framework must move the grid operator towards uncomplicated connection of even smaller plants.

Furthermore, PV power plants for electricity production beyond self-consumption require a long-term **purchase agreement**. Small private investors in particular can neither control the price risks on the electricity exchange nor keep up with the electricity production costs of large PV power plants. They must be able to sell surplus electricity at secured conditions. A PV power plant built today will soon be competing with PV power plants built in later years, which will supply solar power at the same time as the cost of electricity is expected to fall further. The deflationary effect is compounded by the long-term decline in the market value factor for solar power.

In order to better match the daily profiles of PV electricity production and electricity consumption, **transformation** incentives are necessary for the steps described in Section 21.3. They aim, among other things, at supply-oriented electricity consumption, demand-oriented electricity feed-in, and overall grid efficiency in the electrification of the heat and transport sectors.

Innovative technologies such as integrated PV (Section 11) have slightly higher LCOE in direct comparison with simple PV ground-mounted systems. However, they do not require additional land and create synergies. In order to accelerate their market entry and thus mitigate land conflicts at an early stage, they require targeted start-up support, e.g., in the form of dedicated feed-in tariffs or tender segments.

24. Do PV modules contain toxic substances?

Often yes, which is why PV modules do not belong in the residual waste.

Toxic substances can leach out of modules over long periods of time if the cover glass is broken, the edge seal is damaged, or the module is fragmented [IPV]. The leaching rate depends in particular on the pH value and temperature. Because of the above-mentioned risks, disused PV modules should not be disposed of in residual waste or landfills, and damaged modules should not be left exposed to the weather for long periods of time.

24.1 Wafer-based modules

Modules based on silicon wafers (over 90 percent market share) often still contain lead in the cell metallization (approx. 2 g lead per 60-cell module) and in the solders used (approx. 10 g 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 cost. Some module manufacturers use backsheet foils that contain fluoropolymers, e.g., polyvinyl fluoride.

24.2 Thin-film modules

Thin-film modules based on CdTe (approx. 5 percent market share) contain cadmium in salt form; it cannot be substituted in this technology. The metallic cadmium and cadmium oxide are classified as very toxic, CdTe as harmful to health. There are alternative thin-film technologies based on amorphous silicon or copper indium selenide (CIS) that contain no or very little Cd.
CIS solar cells contain selenium, which can have a toxic effect, especially as an oxide (e.g., after fires), depending on the amount absorbed. Some manufacturers explain the conformity of their CIS solar modules with the RoHS Directive (Restriction of certain Hazardous Substances) and the EU chemicals regulation REACH (Registration, Evaluation, Authorization and Restriction of Chemicals). For a differentiated assessment, reference is made to independent investigations of the respective module type.

24.3 Solar glass

Common solar modules require a glass with a very low absorption (solar glass quality) as a front panel. Some glass manufacturers purify the molten glass and increase the light transmission by adding antimony (Sb). When this glass is disposed of in landfills, antimony can enter the groundwater. Alternative refining processes without antimony addition are available.

24.4 Take-back and recycling

In June 2010, PV producers launched a cross-manufacturer recycling system (PV Cycle), which currently has over 300 members. The version of the European WEEE Directive (Waste Electrical and Electronic Equipment Directive) that came into force on 13 August 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 return them to the recycling system. In October 2015, the Act on the Marketing, 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. Processes for separating materials 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 (German Environmental Aid) shows clear potential for improvement in the reuse and recycling of PV modules [DUH].

25. Are raw materials for the production of PV modules sufficiently available?

Wafer-based modules do not require raw materials for which limited availability is foreseeable. 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 the consumption of silver for the production of solar cells. The PV industry consumes about 1500 t of silver per year worldwide, which corresponds to just under 6 percent of the production volume in 2020. The silver for solar cell metallization can be technically substituted by copper to the greatest possible extent, and some manufacturers are already using this technology.

For thin-film modules, which account for about 5 percent of the world market, CdTe technology dominates. There are contradictory statements about the long-term availability of tellurium and indium for CdTe modules.

26. Do PV systems increase the risk of fire?

26.1 Can defective PV systems cause a fire?

Yes, like all electrical installations.
Certain defects in current-conducting components of a PV system can lead to the formation of electric arcs. If there is flammable material in the immediate vicinity, for example roofing felt or wood, a fire can occur. The current source characteristics of the solar cells can even stabilize a fault current compared to alternating current installations. The current can only be stopped by interrupting the circuit or irradiating all modules. For this reason, PV systems must be installed with special care.
In some cases — with currently approx. 2 million PV systems in Germany — the combination of these factors has demonstrably led to a fire. The starting point of the fires was usually faults in the cabling and connections.

Here is a quote from a press release by Fraunhofer ISE from 2013: "Compliance with the existing rules by qualified specialists is the best fire protection. 0.006 percent of photovoltaic systems have caused a fire with major damage to date. In the last 20 years, there have been 350 fires in which the solar system was involved, in 120 of which it was the cause of the fire. In 75 cases the damage was greater, in 10 of these cases a building burned down.

The most important special features of photovoltaic systems: They work with direct current, and you cannot simply switch them off, because as long as light falls on the modules, they produce electricity. If, for example, an inferior or poorly installed plug connection comes loose, this does not always interrupt the flow of current. An electric arc can occur, which in the worst case can directly cause a fire. Accordingly, research is being done on how to prevent arcing. In addition, work is being done on detectors that give an early alarm if even a small arc occurs.

Compared to other technical systems, photovoltaic systems do not pose a particularly high fire risk. There are also sufficient rules for electrical safety — it is important that they are observed. Fires often occur when inexperienced installation crews install systems on a piecework basis. If the solar plugs are attached with combination pliers instead of special tools, or if incompatible plugs are used, then the weak spot is pre-programmed. System operators must not save money in the wrong place.

In addition to technical improvements, it is therefore also important to have control regulations. At present, the installer of a system can confirm that it has been properly installed. One recommendation of the experts is therefore to make acceptance by an independent third-party mandatory. It is also under discussion to prescribe a recurring safety inspection for private photovoltaic systems, as is mandatory for commercial systems every four years." [ISE6]

26.2 Do PV systems endanger firefighters?

Yes, but this is true for many live lines.

When fighting fires from the outside, a minimum distance of a few meters protects firefighters from electric shocks; this safety distance is generally given for roof systems. The greatest risk for firefighters when fighting fires from the inside arises when they enter rooms where live, scorched cables of the PV system come into contact with water or the firefighting force itself. To reduce this risk, the industry is working on emergency switches that disconnect the modules from the descending DC cable via safety relays while they are still near the roof.

So far, no firefighters in Germany have been injured fighting fires caused by PV electricity. A case report that went through the press had confused solar thermal collectors with PV modules. No PV system had been installed on the house in question at all. "Initial uncertainties could be eliminated through comprehensive training measures for the fire brigades. As with any electrical installation, depending on the type of jet, water can also be used to safely extinguish photovoltaic systems from a distance of one to five meters. All claims that the fire brigade did not extinguish a burning residential building because of photovoltaics turned out to be false in the research carried out so far." [ISE6]

26.3 Do PV modules hinder direct firefighting access via the roof?

Yes, the second "roof skin" created by the PV modules impedes the success of the extinguisher because the water simply runs off. From the fire brigade's point of view, however, an object exposed to fire in this way can usually no longer be saved, i.e., the damage is already largely present and irreversible even before the PV system impedes the extinguishing activity.

26.4 Do toxic emissions occur when PV modules burn?

With regard to CdTe modules, a dispersion calculation by the Bavarian State Office for the Environment states that in the event of a fire, a serious danger to the surrounding neighborhood and the general public can be safely ruled out [LFU1]. For CIS modules, reference is made to independent investigations of the respective product.

In the case of wafer-based modules, the backsheet foils may contain fluoropolymers, which are not toxic themselves but can decompose at high temperatures in the event of a fire. In a study, the Bavarian State Office for the Environment concludes that when plastics containing fluorine burn, the hazard potential is not largely determined by hydrogen fluoride, but by the other fire gases [LFU2].

27 Appendix: Technical terms

27.1 Module efficiency

Unless otherwise stated, module efficiency refers to nominal efficiency. It is determined under standardized conditions ("STC", standard test conditions) as the ratio of the electrical power output to the irradiated power on the module surface. The standard conditions stipulate a module temperature of 25° C, vertical irradiation of 1000 W/m2 and a specific irradiation spectrum. In real operation, the conditions usually deviate significantly, so that in many cases the STC efficiency is not achieved.

27.2 Nominal power of a PV power plant

The nominal power of a power plant [kW$_p$, MW$_p$] is the idealized DC power of the module array under STC conditions, i.e. the product of the generator area, standard irradiation (1000 W/m2) and the nominal efficiency of the modules. During operation, the generation capacity of a PV power plant is usually below 70 percent of its nominal capacity.

27.3 Annual full load hours (annual full operating hours)

Number of hours a PV power plant would need to generate at its nominal capacity in order to reach its actual annual yield with frequent partial load operation and energy standstill at night (see Section 15.4).

27.4 Annual utilization rate (capacity factor)

Ratio of annual full load hours and the 8,760 hours in a 365-day-year.

27.5 Specific yield

The specific yield [kWh/kW$_p$] of a PV power plant is the ratio of the user yield (alternating current yield) over a certain period of time, often a year, and nominal power. The specific annual yield corresponds to the number of full load hours.

27.6 System efficiency

The system efficiency of a PV system is the ratio of the useful yield (alternating current yield) and the total irradiation on the generator surface. The nominal module efficiency is included in the system efficiency.

27.7 Performance Ratio

The term "performance ratio (PR)" refers to the ratio of the useful yield (alternating current yield) and the idealized yield (product of the total irradiation on the generator surface and the nominal module efficiency) of a system over a certain period of time, usually one year. PR is often used to compare the efficiency of grid-connected PV systems at different locations with various PV technologies.
New, carefully planned systems achieve annual PR values between 80 and 90 percent.

27.8 Base load, medium load, peak load, grid load and residual load

"The power demand fluctuates depending on the time of day. As a rule, maxima occur during the day and the minimum at night between 0 and 6 o'clock. The course of the power demand is described as a load curve or load pattern. In classical energy technology, the load curve is divided into three areas:
(i) The base load
(ii) The medium load
(iii) The peak load
The base load describes the load band that is almost constant over 24 hours. It is covered by so-called base load power plants such as nuclear power plants, lignite-fired power plants and currently also run-of-river power plants.
The medium load describes predictable, closed power blocks that cover most of the daily demand in addition to the base load. The medium load is covered by so-called medium load power plants such as hard coal-fired power plants and methane-fired combined cycle power plants. Oil-fired power plants are also used in rare cases. The peak load covers the remaining power demand, which is usually the daily maximum. The peak load is covered by so-called peak-load power plants such as gas turbine power plants and pumped-storage power plants. These can be run at nominal power within a very short time and thus compensate for load fluctuations and cover peak loads.
(...) The grid load (is) the power value of the electricity demand that is taken from the grid. The residual load results from the grid load minus the feed-in from renewable energies" [ISET].

27.9 Electricity generation and consumption

Figure 62 shows the energy path from the primary energy source, e.g., solar radiation (irradiance [W/m2]), wind or natural gas (energy density during combustion [J/kg]), to the useful energy that is important to the end user. Large gas turbines show conversion losses of 60–65 percent. PV power plants show conversion losses of 80–85 percent, with virtually free and unlimited primary energy. The gross electricity generation, adjusted for the import balance, corresponds to the gross electricity consumption.
Storage losses occur in the operation of pumped storage power plants or batteries. Losses from pumped storage power plants amount to approx. 25 percent of the amount of

electricity stored, for Li-ion batteries it is 5–10 percent, plus the losses in the battery management system. If hydrogen is used to store electricity via stationary electrolyzers and fuel cells, the losses are about 50 percent. With the expansion of installed PV capacity, storage losses will also play an increasingly important role for PV electricity.
The self-consumption of fossil and nuclear power plants is about 7 percent of their gross power generation; for PV power plants it is marginal. Grid losses, especially line and transformer losses, amount to just under 6 percent in the German electricity grid. The decentralized nature of PV installations reduces grid losses for PV electricity.
The amount of electricity purchased from the end user is the net consumption (final energy). The efficiency of the devices determines the conversion losses to the final useful energy, e.g., power or light.

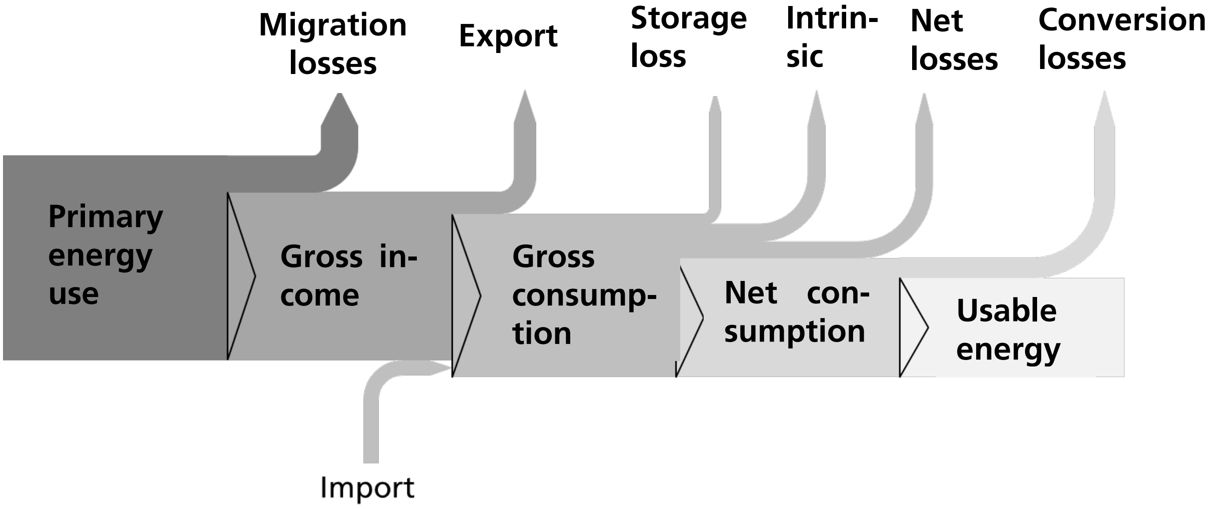


Figure 62: Electricity generation and consumption terms.

28 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	Combined heat and power, the simultaneous generation of mechanical (ultimately electrical) energy and usable heat
CHP plant	Combined heat and power plant – a plant that uses combustion engines or gas turbines to generate electrical energy and heat
COP	Coefficient of Performance (heat pumps)
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

29. Appendix: conversion tables [EEBW]

Vorsätze und Vorzeichen

k	Kilo	10^3	thousand
M	Mega	10^6	million (m)
G	Giga	10^9	billion (bn)
T	Tera	10^{12}	trillion (tn)
P	Peta	10^{15}	quadrillion (qa)

Conversions

		PJ	GWh	Mio. t tce	Mio. t toe
1 PJ	petajoule	1	277,78	0,034	0,024
1 GWh	gigawatt hours	0,0036	1	0,00012	0,000086
1 Mio. t tce	million tonnes of coal equivalent	29,31	8.141	1	0,70
1 Mio. t toe	million tonnes of oil equivalent	41,87	11.630	1,43	1

Typical Fuel Properties

	Density [kg/l]	Heating value [kWh/kg]	Heating value [kWh/l]	Heating value [MJ/kg]	Heating value [MJ/l]
Biodiesel	0,88	10,3	9,1	37,1	32,6
Bioethanol	0,79	7,4	5,9	26,7	21,1
Rapeseed oil	0,92	10,4	9,6	37,6	34,6
Diesel	0,84	12,0	10,0	43,1	35,9
Petrol	0,76	12,2	9,0	43,9	32,5

Typical Properties of Solid and Gaseous Energy Yields

	Density [kg/l] bzw. [kg/m^3]	Heating value [kWh/kg]	Heating value [kWh/l] bzw. [kWh/m^3]	Heating value [MJ/kg]	Heating value [MJ/l] bzw. [MJ/m^3]
Hard coal	-	8,3 - 10,6	-	30,0 - 38,1	-
Brown coal	-	2,6 - 6,2	-	9,2 - 22,2	-
Natural gas H (in m^3)	0,76	11,6	8,8	41,7	31,7
Heating oil EL	0,86	11,9	10,2	42,8	36,8
Biogas (in m^3)	1,20	4,2 - 6,3	5,0 - 7,5	15,0 - 22, 5	18,0 - 27,0
Wooden pellets	0,65	4,9 - 5,4	3,2 - 3,5	17,5 - 19,5	11,4 - 12,7

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