Recent Facts about Photovoltaics in Germany

Current version available: www.pv-fakten.de

Compiled by:
Dr. Harry Wirth
Division Director Power Solutions
Fraunhofer ISE

Contact:
Sophia Judith Bächle
Communications
Telefon: +49 (0) 7 61 / 4588 5215
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstrasse 2
79110 Freiburg, Germany
presse@ise.fraunhofer.de

Please cite as: Recent Facts about Photovoltaics in Germany, Harry Wirth, Fraunhofer ISE, Download from https://www.pv-fakten.de/, Version update 18.08.2025.

Fraunhofer ISE

Table of Contents

1 What purpose does this guide serve? 5
2 How much photovoltaics is needed for the energy transition? 5
3 Does PV contribute significantly to the power supply? 6
4 Is PV power too expensive? 7
4.1 Levelized Cost of Electricity 8
4.2 Feed-in Tariff 9
4.3 Pricing on the energy exchange and the merit order effect 11
4.4 Determining the differential costs 12
4.5 EEG levy 13
5 Subventions and Electricity Prices 13
5.1 Is PV power subsidized? 13
5.2 Is fossil fuel power production subsidized? 13
5.3 Is PV development raising the cost of electricity? 15
6 Are we exporting large amounts of PV power to other European nations? 16
7 Can small PV systems generate attractive returns? 17
8 Is the supply of solar components ensured? 19
9 Does installing PV only create jobs in Asia? 21
10 What funding is being directed to PV research? 22
11 Does PV power overload our energy system? 22
11.1 Transmission and distribution 23
11.2 Volatility 24
11.2.1 Can solar power production be predicted? 24
11.2.2 Do solar and wind power complement each other? 25
11.3 Does the grid feed-in reach the installed capacity? 27
11.4 Is a significant amount of PV electricity lost through redispatch? 28
11.5 Conflicts with slow-response power plants 28
11.6 Does the PV expansion have to wait for increased storage? 29
11.7 Does volatile solar power endanger security of supply? 30
11.8 Does the expansion of PV have to wait for more storage? 30
12 Is there enough space for PV in Germany? 31
13 Is PV electricity a privilege reserved for homeowners? 35
14 Do PV systems destroy ecologically valuable areas? 35

15 Do PV power plants find acceptance in the population? 36

16 Are PV plants in Germany efficient? 37

16.1 Are PV systems only viable on roofs that are optimally oriented? 39

16.1.1 High-pitched rooftops facing east/west 40

16.1.2 Vertical south-facing façade 40

16.2 Do PV plants degrade? 41

16.3 Can PV modules become soiled? 41

16.4 Do PV plants seldom operate at full capacity? 41

17 Does PV make relevant contributions to climate protection? 45

17.1 Do anthropogenic CO_2 emissions danger the climate? 45

17.2 Does PV make a significant contribution to CO_2 emission reduction? 46

17.3 Does the production of PV modules use more energy than they can deliver during operation? 49

17.4 Are there other environmentally harmful gases released during the production of PV? 50

18 Do PV modules heat up the earth? 50

18.1 Local effects 51

18.1.1 Do PV modules heat up their environment? 51

18.1.2 Do PV modules reflect solar radiation into the surrounding environment? 51

18.1.3 Do PV modules store solar heat? 51

18.2 Global effects 52

18.2.1 Does solar power production contribute to the greenhouse effect? 52

18.2.2 Do PV modules heat up the earth's atmosphere? 52

19 Can PV modules cause glare? 52

20 Do PV modules emit irradiation that is harmful to health? 53

21 Are PV systems capable of replacing thermal power plants? 54

22 Are we capable of covering a significant proportion of our energy demand with PV power? 54

22.1 Starting point: energy demand and energy supply 54

22.2 Energy scenarios 56

22.3 Transformation steps 60

22.3.1 Keeping PV power generation constant 60

22.3.2 *Expending flexible generation capacity 63*

22.3.3 *Increasing energy efficiency 63*

22.3.4 *Load management 65*

22.3.5 Balanced addition of PV and wind power capacities 68

22.3.6 Combined heat and power generation 68

22.3.7 Electrical energy storage 69

22.3.8 Grid expansion 72

22.3.9 Importing energy sources 74

22.3.10 Overview 74

22.4 Does the energy transition have to wait for federal policy? 76
23 Do we need PV production in Germany? 77
24 Do we need a Renewable Energy Sources Act (EEG)? 77
25 Do PV modules contain toxic substances? 78
25.1 Wafer-based modules 78
25.2 Thin-film modules 78
25.3 Solar glass 79
25.4 Take-back and recycling 79
26 Are there sufficient raw materials available for the production of PV modules? 80
27 Do PV systems increase the risk of fire? 80
27.1 Can defective PV systems cause a fire? 80
27.2 Do PV systems endanger firefighters? 81
27.3 Do PV modules hinder direct firefighting access via the roof? 82
27.4 Do toxic emissions occur when PV modules burn? 82
28 Appendix: Technical terms 83
28.1 Module efficiency 83
28.2 Nominal power of a PV power plant 83
28.3 Annual full load hours (annual full operating hours) 83
28.4 Annual utilization rate (capacity factor) 83
28.5 Specific yield 83
28.6 System efficiency 83
28.7 Performance Ratio 84
28.8 Base load, medium load, peak load, grid load and residual load 84
28.9 Electricity generation and consumption 84
29 Appendix: Abbreviations 86
30 Appendix: conversion tables [EEBW] 87
31 Appendix: Sources 88
32 Appendix: Figures 96

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], [AGORA], [Aurora]).

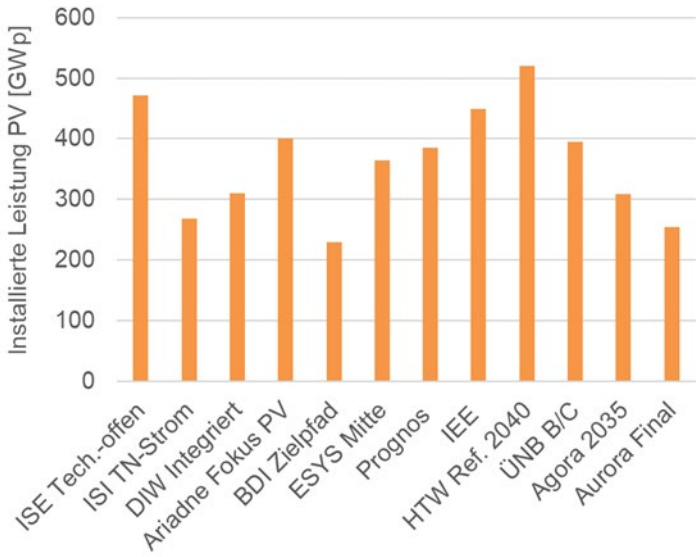


Figure 1: Installed PV capacity necessary to reach climate neutrality as determined by different studies. (The studies are named according to the institutions and, if applicable, the scenario).

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 by 2026. 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. **16.9 GWp** in 2024, the total number of

systems is now over **4.8 million** (including plug-in solar units) with a total capacity of approximately **100 GWp** [BSW].

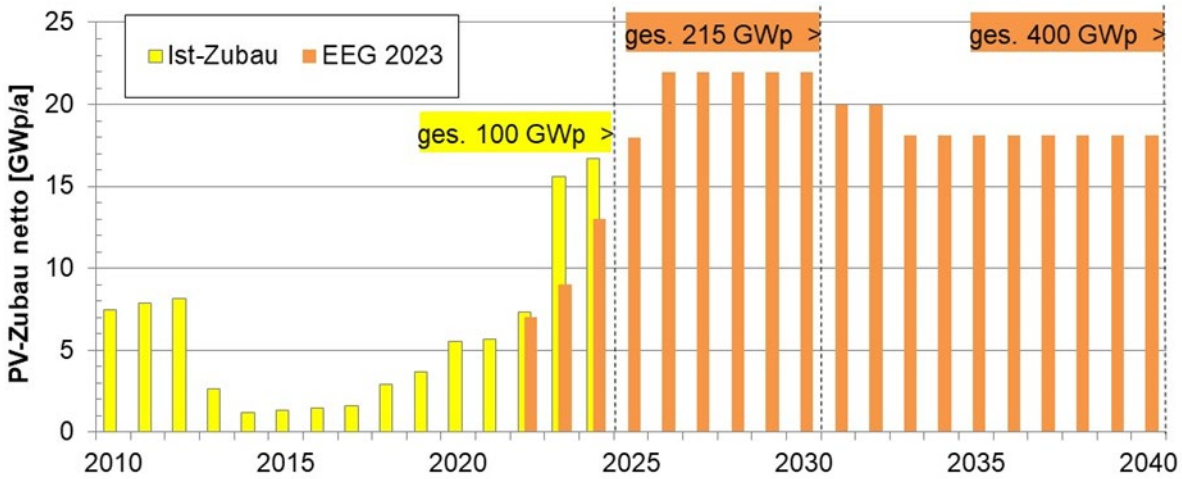


Figure 2: Net PV additions: Actual values until 2024 (yellow) , Expansion path to achieve the legal targets shown in orange [ISE4], [BSW], [EEG2023].

3 Does PV contribute significantly to the power supply?

Yes.
With an electricity generation of **72.6 TWh** in 2024, photovoltaics covered nearly **14 percent** of gross electricity consumption [AGEE] in Germany (Figure 3). All renewable energies (RE) together came to **53 percent**.

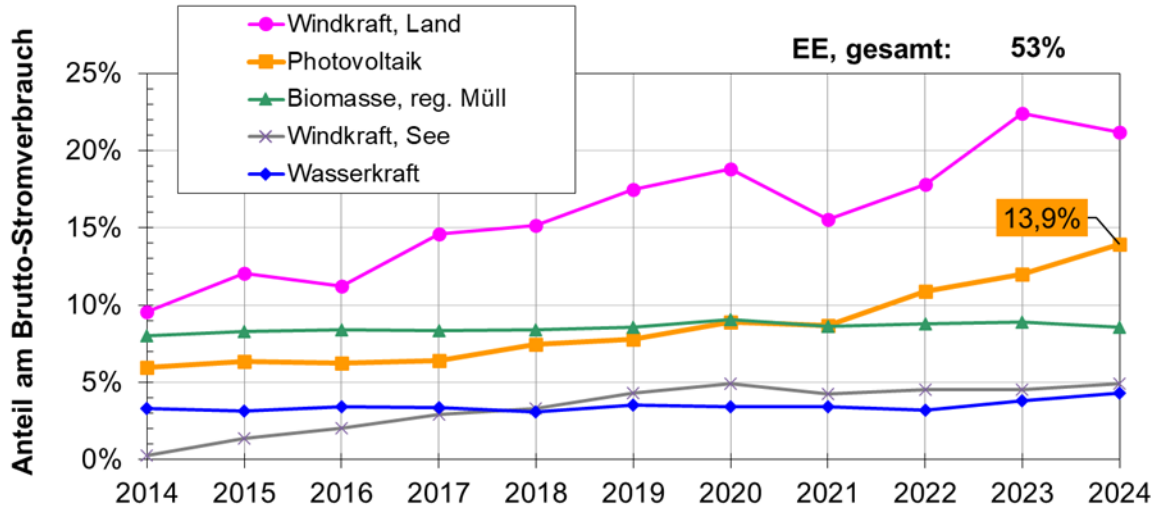


Figure 3: Development of the share of renewable energies in gross electricity consumption in Germany [ISE4], Status 12.03.2025 [AGEE].

Gross electricity consumption is the reference value for the statutory expansion targets of the energy transition and includes grid and self-consumption losses (Section 28.9). On

sunny days, PV electricity may temporarily cover more than 90 percent 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 capacity 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. Besides the electricity generation from RE, other measures to enact are:

- Demand-side flexibility
- Electrification of the heat and transport sectors
- Expansion of grid-serving storage (stationary batteries, heat storage, pump storage) and electrolyzers
- Expansion of electricity grids
- Transfer from coal to gas-fired power plants.

The associated costs are not caused by the PV expansion but belong, like the PV expansion itself, to the cost 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.

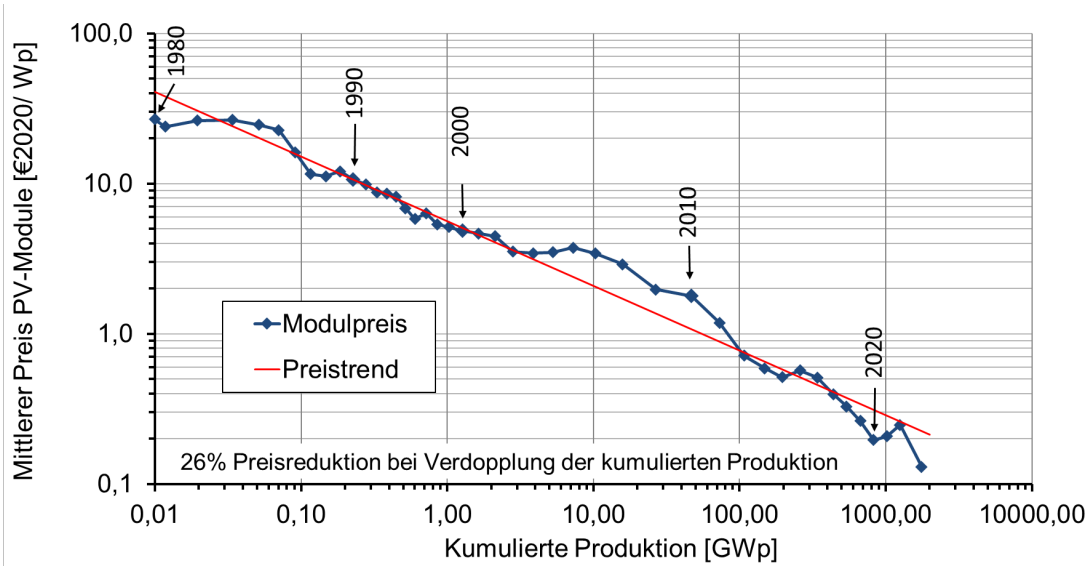


Figure 4: Historical development of prices for PV modules (PSE Projects GmbH/Fraunhofer ISE, data source: Strategies Unlimited/Navigant Consulting/EuPD). The straight line shows the trend in price development.

Prices for PV power plants have fallen by 70 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.

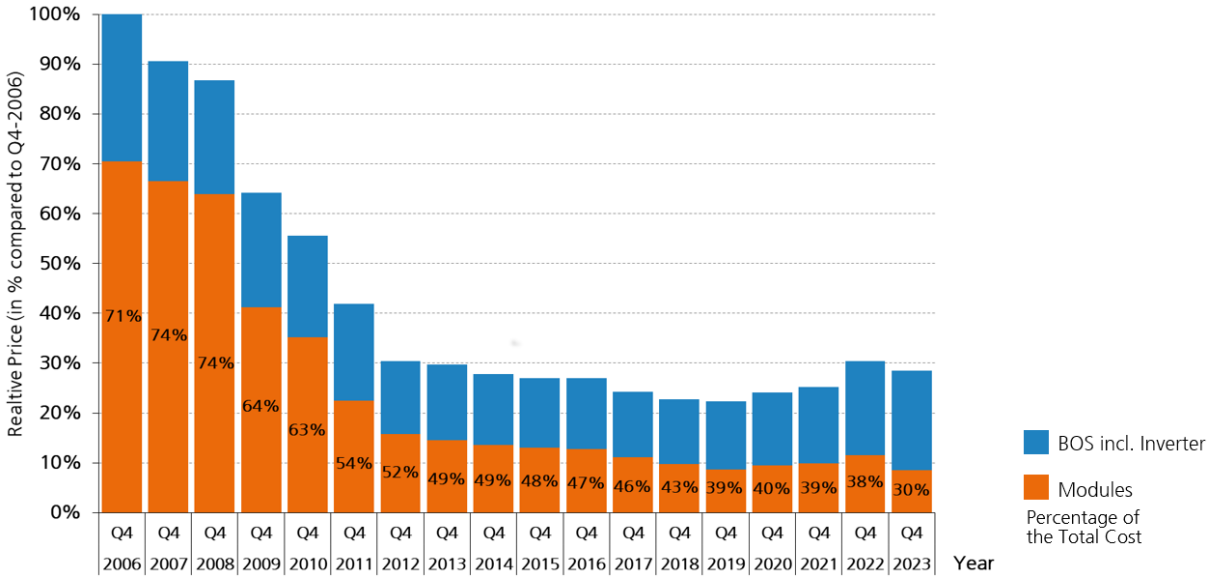


Figure 5: Development of the average end customer price (net system price) for installed rooftop systems with rated nominal power from 10–100 kW_p, data: BSW [ISE5].

New MW-sized power plants produce PV electricity at costs of approx. 4–7 ct/kWh. For small rooftop plants the costs range from 6–14 ct/kWh [ISE1]. 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 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 [BNA3]. Surcharges are provided for certain cases of full feed-in or for landlord-to-tenant electricity supply.
The feed-in tariff for small rooftop systems with self-consumption that go into operation by Dec. 31, 2025 is up to **7.86 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.

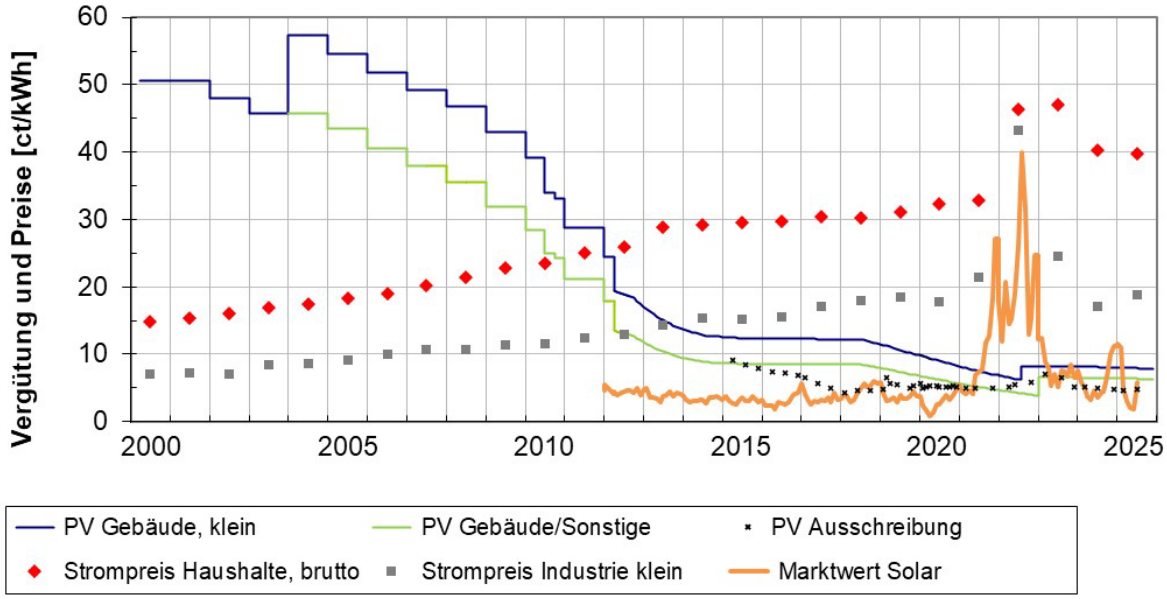


Figure 6: Fixed EEG feed-in tariff for PV power as a function of commissioning date according to system types "Building PV with up to 10 kW_P excess feed-in" and "Other systems up to 100 kW" from [Netz2] and [BNA3], average remuneration of the bidding rounds of the German Federal Network Agency [BNA3],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

Since the introduction of the EEG in 2000, the nominal remuneration for PV electricity (without inflation adjustment) from new power plants has fallen by approx. 85–90 percent (Figure 6). The average fixed tariff for PV electricity has fallen to approx. 21.3 ct/kWh by 2022 (source: statista) and continues to fall.
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).

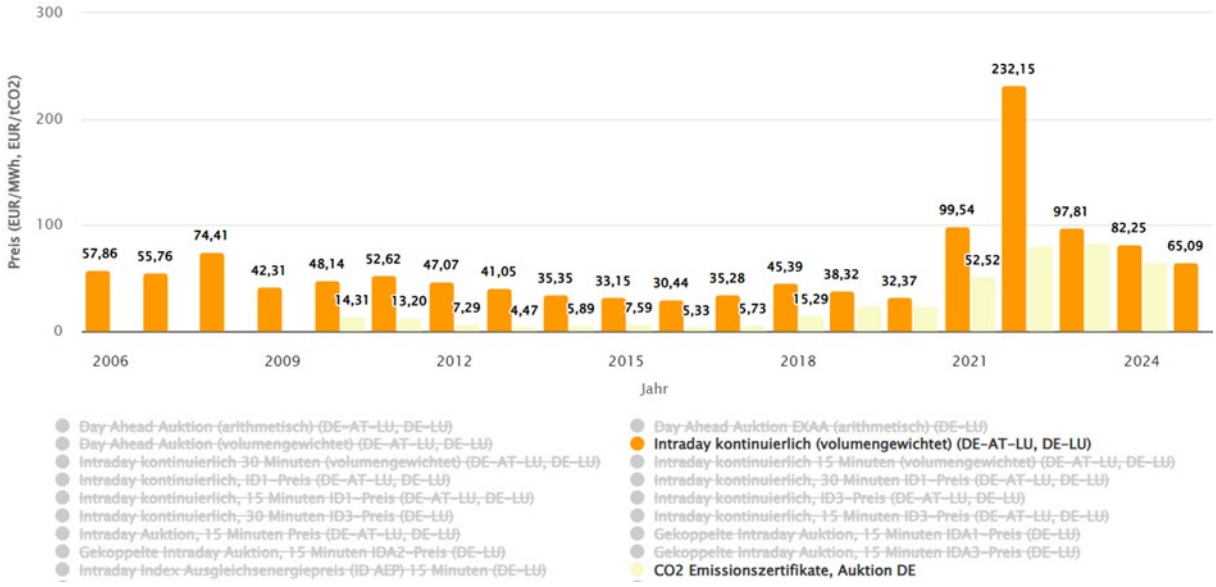


Figure 7: Exchange electricity and certificate prices in Germany [ISE4].

Ongoing price determination on the exchange takes place according to the "merit order" principle. 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.

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 8 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.

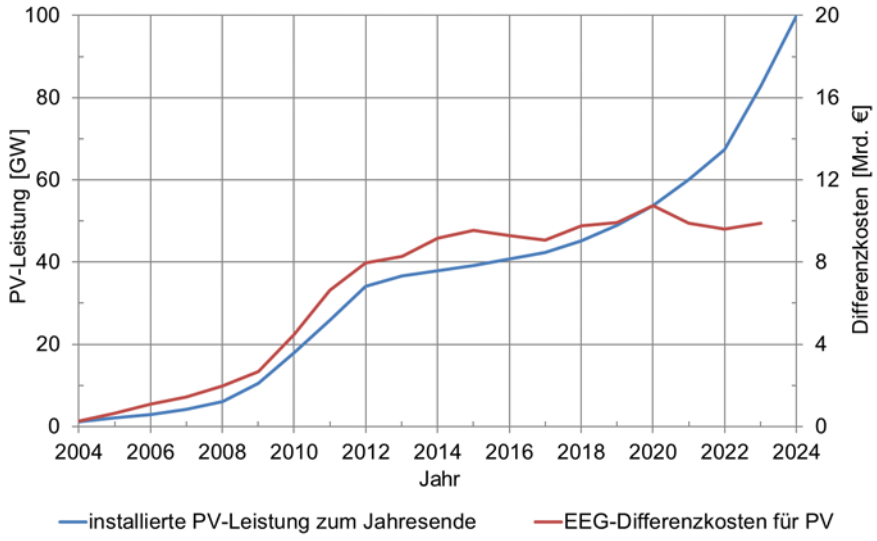


Figure 8: PV expansion and differential costs, data from [BMWK1], [BMWK3]. Medium-term prognoses of the ÜNB.

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 and the German federal budget.

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.
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 9), 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 9). In pilot plants, recapture via DACCS currently costs about 350-640 €/t, the cost potential with successful scaling is estimated at 210-330 €/t [ECTI]. Some questions about the final storage of the recycled CO_2 are still open.

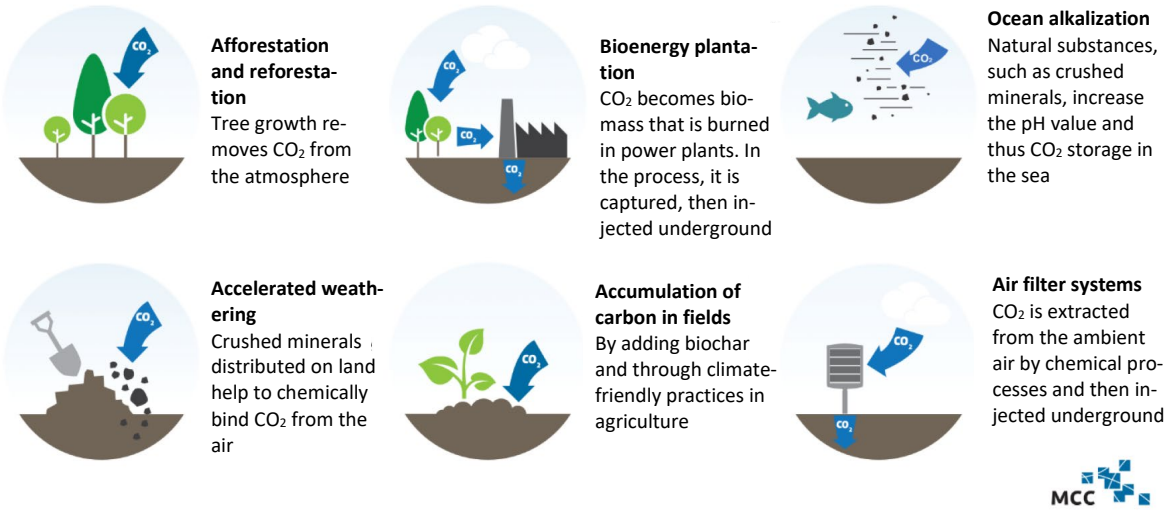


Figure 9: Process for removing CO_2 from the atmosphere and storing carbon [MCC].

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 Is PV development raising the cost of electricity?

Not directly. 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 **39.8 ct/kWh** in 2025, including base price [BDEW1]. Figure 10 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. Grid charges have risen sharply over the last few years. They also include the cost of local grid upgrades that benefit PV deployment.



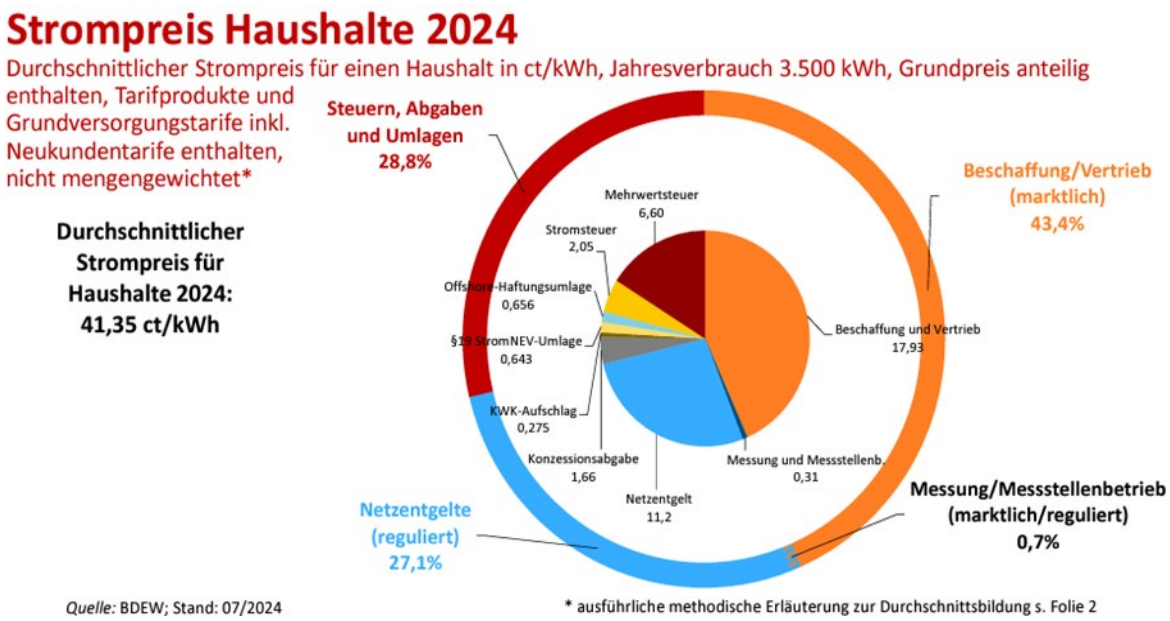


Figure 10: Composition of the average household electricity price in 2024 [BDEW1].

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.

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 net electricity imports are conspicuously high in summer, i.e. in months with particularly high PV electricity production (Figure 11).

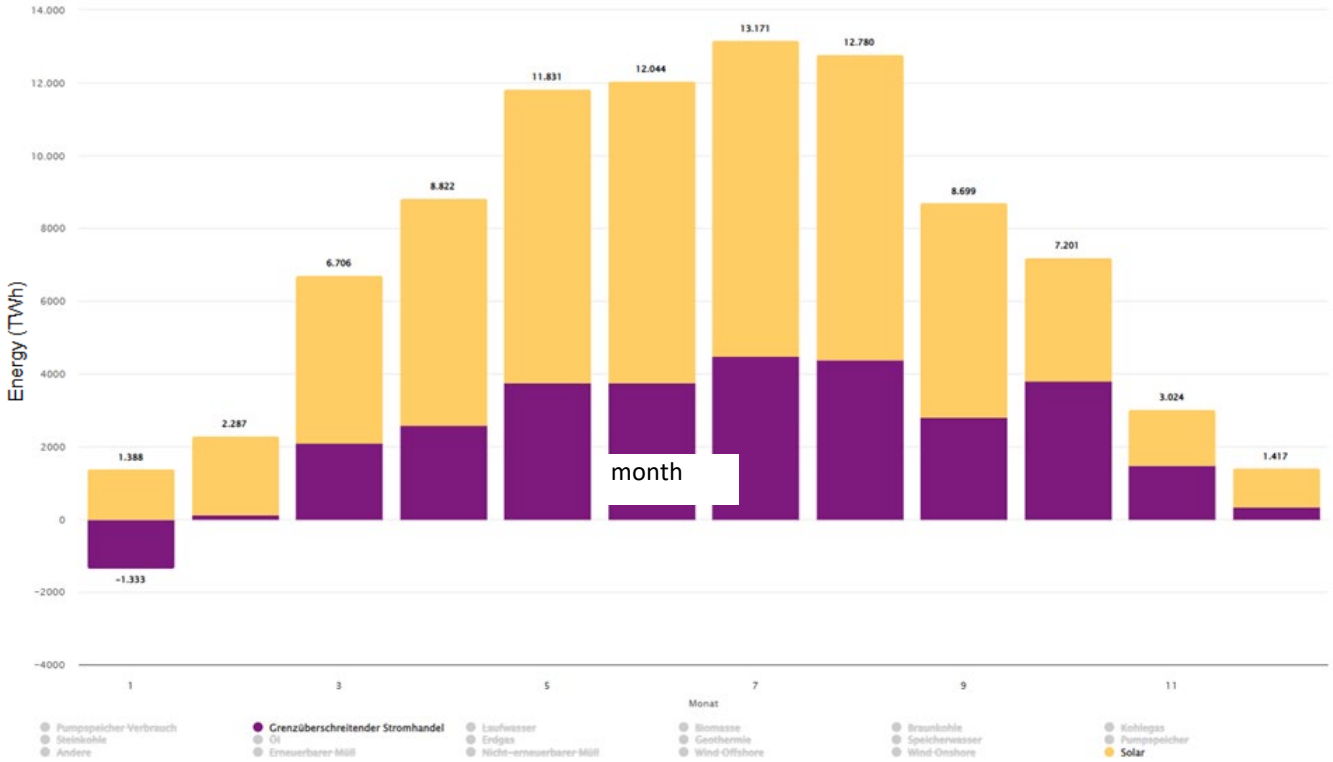


Figure 11: Net Electricity import (purple) and solar electricity production (yellow) in 2024 for Germany [ISE4].

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 12). Attractive returns are possible due to the 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 [HTW1]. 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 22.3).

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 28.5) because, for example, the operating temperature of the modules, pollution effects or the duration of snow accumulation also play a role. To obtain a rough estimate of the discounted levelized cost of electricity LCOE (not adjusted for inflation, see Figure 12: Estimation of the LCOE for small PV systems under different irradiation conditions, plus remuneration according to [EEG2023]), the following assumptions were made:

- optimal orientation of module with regard to annual yield (approximately 30° south)
- average annual total of horizontal global irradiation in Germany 1100 kWh/m2/a
- Performance Rati of 85 percent (see Section 28.7)
- 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].

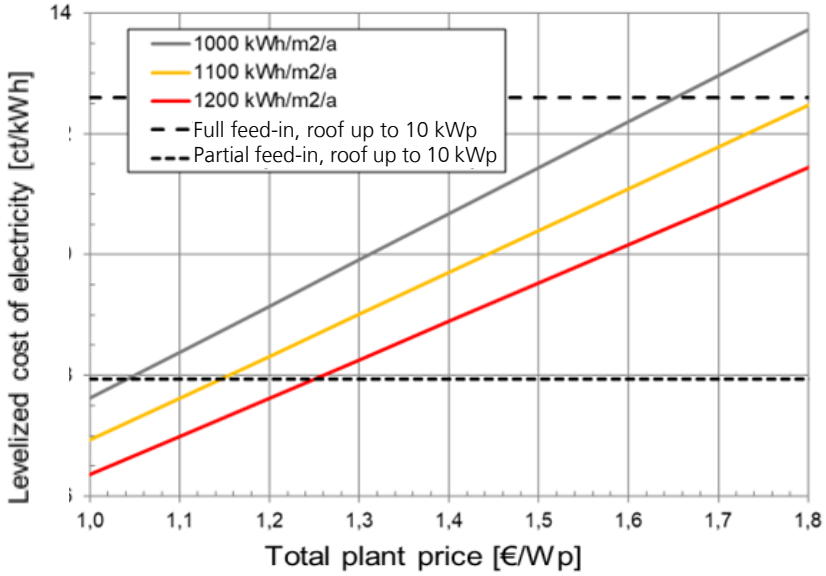


Figure 12: Estimation of the LCOE for small PV systems under different irradiation conditions, plus fixed remuneration according to EEG.

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 13) 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.

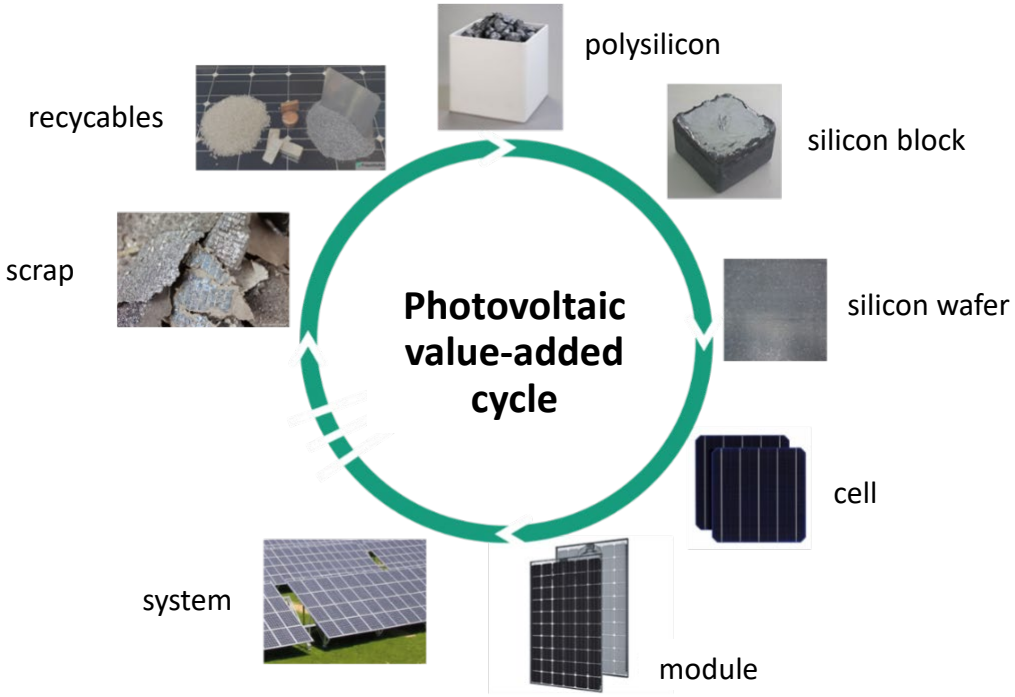


Figure 13: Value Chain for Photovoltaics.

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 2023, China was dominating all value chain stages with market shares of more than 80 percent (
Figure 14).

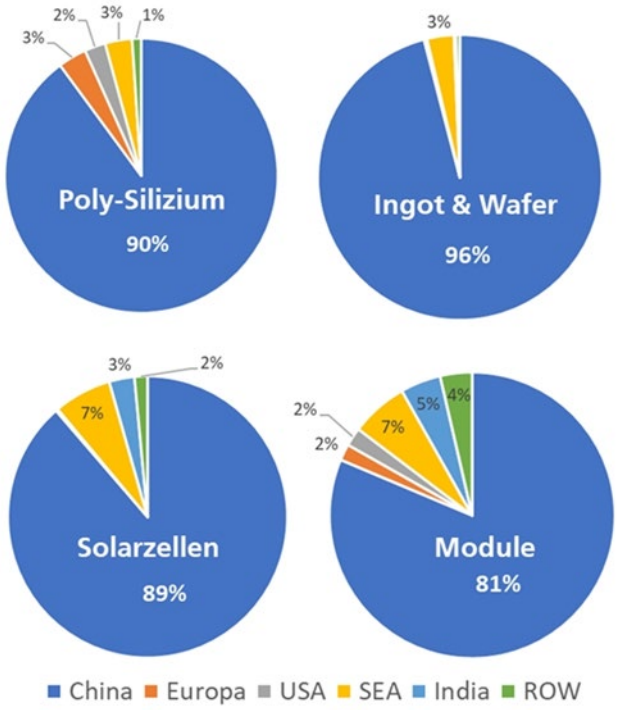


Figure 14: Production capacity according to value chain stage and country, data: Wood Mackenzie, 2023

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.

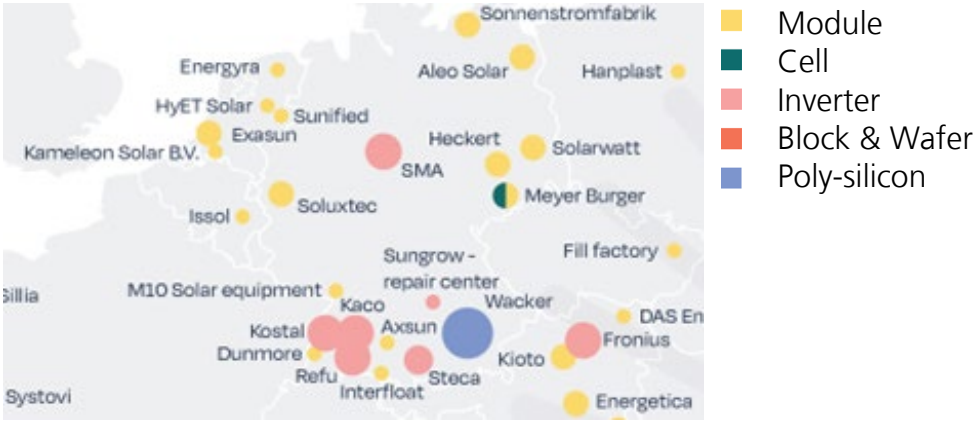


Figure 15: PV production sites in Germany and other European countries [SPE].

9 Does installing PV only create jobs in Asia?

No, but Germany has lost many jobs in the PV production industry in the last decade. In 2023, gross employment in the PV industry was about 98,600 [GWS]. Germany lost many jobs in the 2010s due to companies closing and experiencing bankruptcy. First the PV cell and module production were affected, then companies involved in PV machine engineering followed.

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]. In 2022, the solar industry (PV and thermal) employed 84,100 people [BMWK press report from January 24, 2024].
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.

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 2023, the German government invested 73 million euros to support photovoltaic research (Figure 16) with production technology accounting for the largest share.

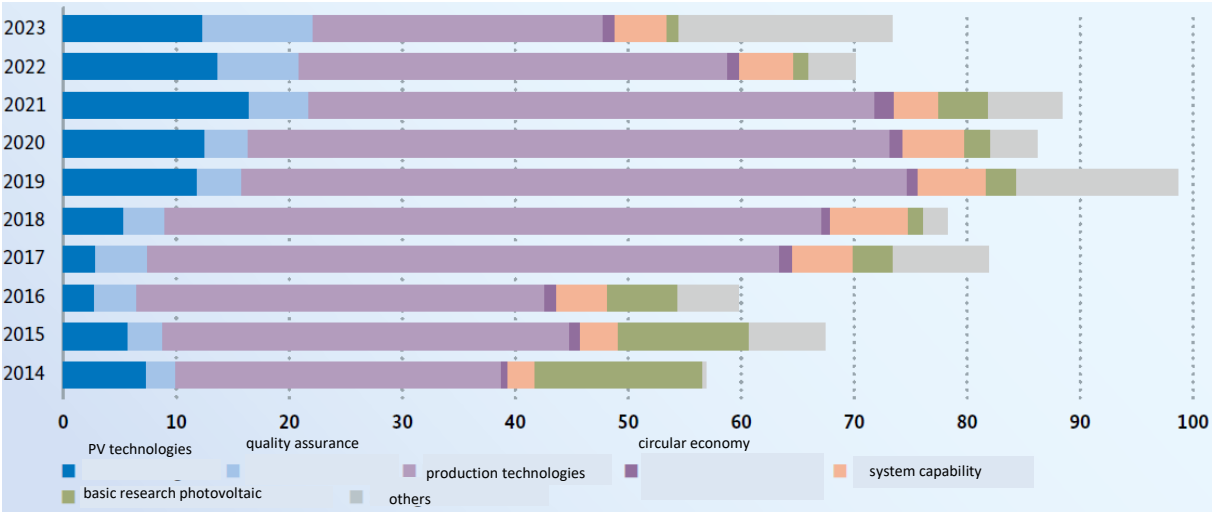


Figure 16: Funding for PV research categorized by technology in € million [BMWK2].

11 Does PV power overload our energy system?

At times, yes.
The energy transition is driving change in many different areas, but they are all moving at different speeds. Photovoltaic expansion is on track, but the restructurization of the energy system and the adjustment of the electricity market have not kept pace for years. In many areas, there is a lack of price signals and technical and/or regulatory requirements, including for the following grid-friendly and stabilizing measures:

- stabilization of solar power production
- load flexibility and the installation of smart meters
- expansion and operation of stationary battery storage systems
- bidirectional operation of charging infrastructure for e-mobility
- electrification and smart operation of the heating sector
- flexibilization of electricity production from biomass.

Due to these omissions, yield losses are becoming increasingly common during the sunny months around midday as a result of active curtailment or permanent power limitation of PV systems. Because many small PV systems cannot be actively controlled, their storage facilities are not operated in a grid-friendly manner. Some of the large systems are incorrectly controlled. Due to this, negative electricity prices frequently occur on the Leipzig Stock Exchange.
The necessary measures to deter this are explained in section 22.3 Transformation Steps.
Until our energy system is able to accept more feed-in of solar power locally, regionally, and nationally, it is necessary to reduce the feed-in from PV systems more consistently during periods of insufficient absorption capacity, combined with a corresponding extension of the purchase agreements. The technical and regulatory requirements are often lacking.

11.1 Transmission and distribution

Most solar power plants in Germany are connected to the low-voltage grid; Figure 17 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 and do not require long connection lines. 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 use of stationary battery storage systems.
Battery storage systems allow generation peaks to be leveled out at the feed-in point or the feed-in volume to be reduced through increased self-consumption.
An even distribution of PV installations across the grid sections reduces the need for additional capacity. PV should be expanded in locations where it is needed most 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 [ISE4].

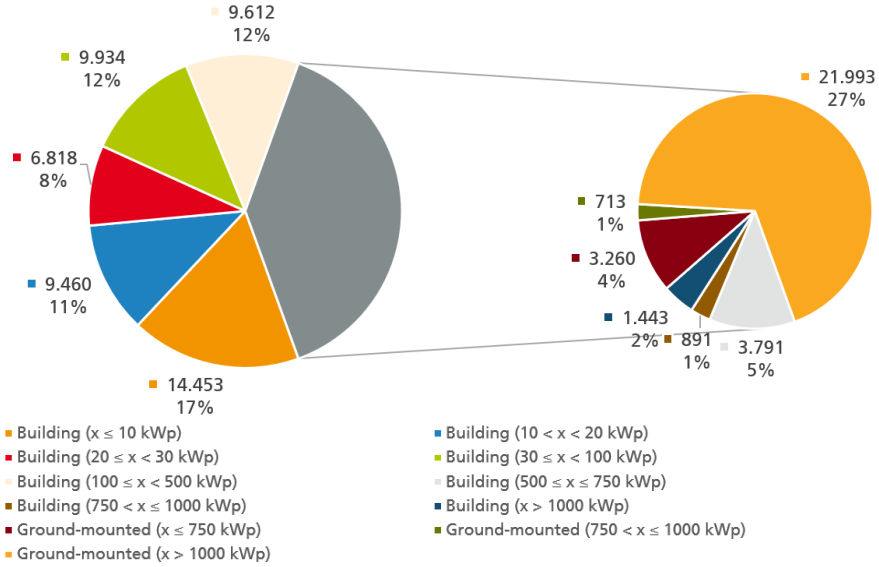


Figure 17: Distribution of installed PV power according to plant size by the end of 2023 [ISE5].

Since solar radiation and wind often occur in the same locations (11.2.3), it makes sense to connect them to the same feed-in point. Hybrid power plants, i.e. the combined installation of solar and wind power plants, ideally along with a battery storage system, can significantly reduce the requirements for grid-expansion and transformer capacity. This combination ensures an improved utilization of the feed-in infrastructure.

11.2 Volatility

11.2.1 Can solar power production be predicted?

Yes.
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 18).

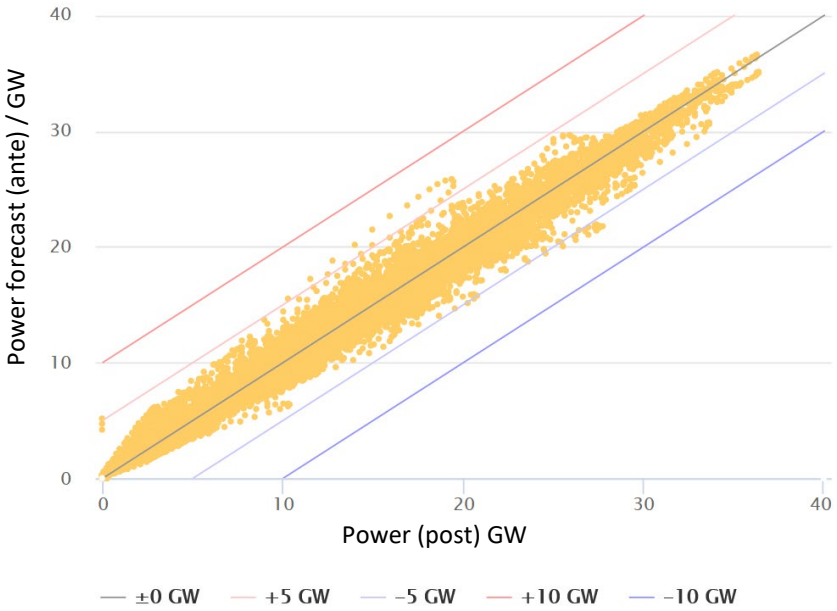


Figure 18: Actual and predicted hourly generation of power in 2021 [ISE4].

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 and compensated.

11.2.2 Do solar and wind power complement each other?

Yes.
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 19). 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).

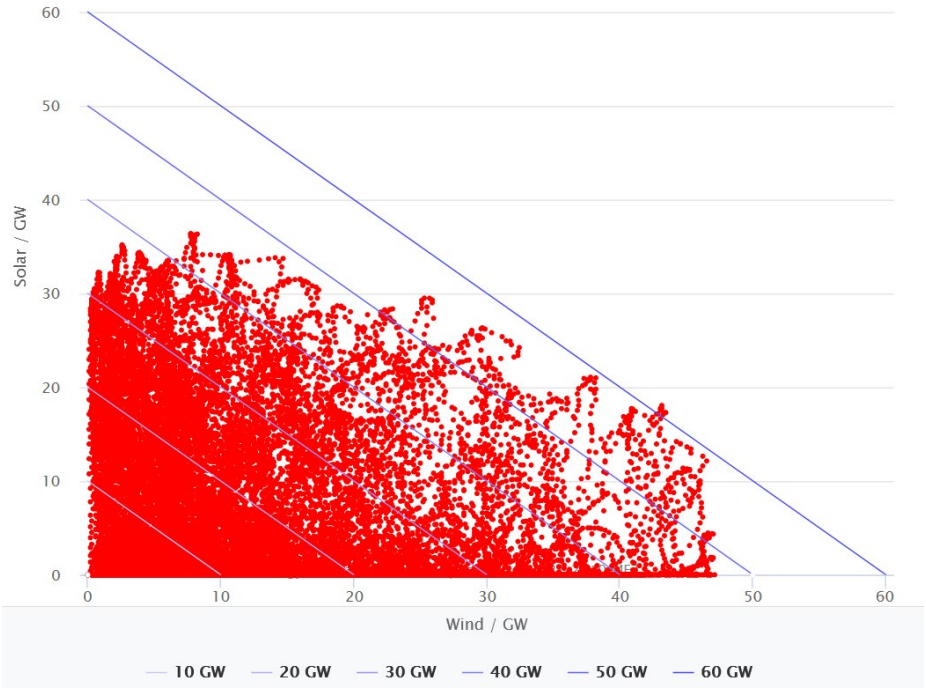


Figure 19: Average power for the supply of solar and wind power in 2021, 15-minute values [ISE4].

The combination of PV and wind power also leads to a stabilization of the yield on **a daily basis.** 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 20 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. For the sum of PV and wind the deviation is 14 percent and thus significantly more stable than the sectors alone.

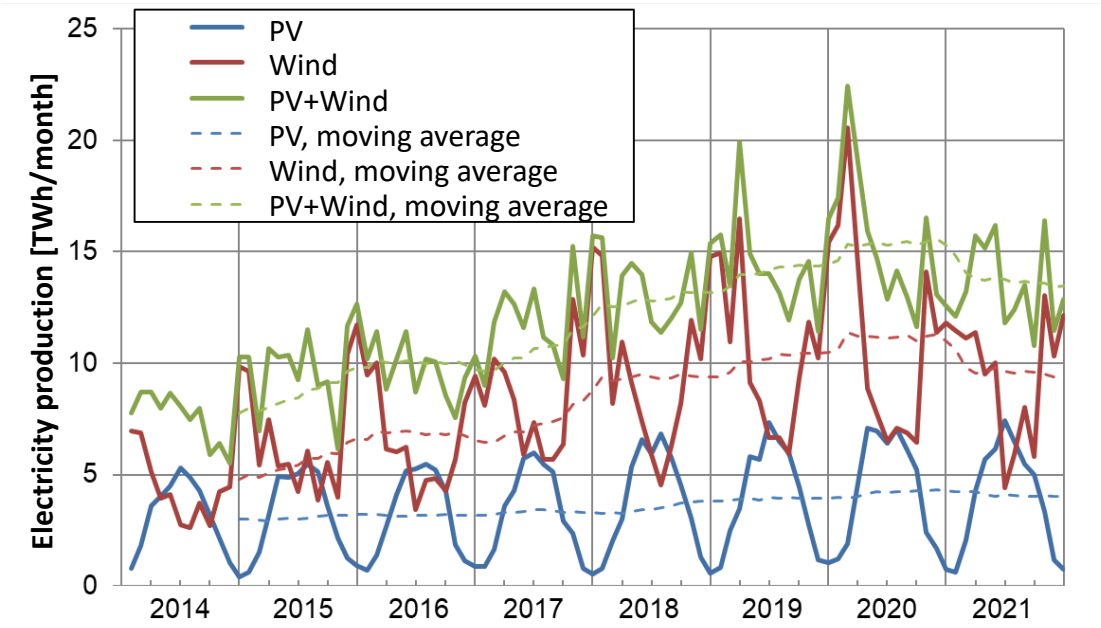


Figure 20: Monthly totals of PV and wind power production, data from [ISE4].

11.3 Does the grid feed-in reach the installed capacity?

No, at least not across Germany.
Information on the installed PV capacity of an individual power plant or a region refers to the DC side of the PV system, i.e. to the nominal power of the modules (https://www.clearingstelle-eeg-kwkg.de/haeufige-rechtsfrage/221). However, inverters are often undersized for better utilization, so that their nominal AC power is significantly lower than the nominal DC power of the connected PV modules. For large PV power plants with a southern orientation, the AC/DC ratio is typically around 85%. When batteries are added on the DC-side, this ratio can fall to 50%. As a rule, small rooftop systems must be reduced to 70% capacity at times, or sometimes even 60%. The systematic undersizing of inverters, or also curtailment, already creates a significant gap between installed capacity (DC) and maximum feed-in.
This gap is widened by technically induced losses with performance ratio values below 90% (see Section 28.7 Performance Ratio) and often inconsistent weather conditions across Germany. Self-consumption also reduces feed-in, even if its potential for load flexibility has not yet been fully exploited. The same applies to the charging of DC-coupled batteries. Figure 21 shows the trend in recent years in the ratio of maximum feed-in to the public grid to installed PV capacity. In 2024, the peak PV feed-in across Germany was 53%, just over half of the installed PV capacity. Even with the addition of PV power plants away from the dominant south-facing, flat-roofed locations, the ratio will continue to fall.

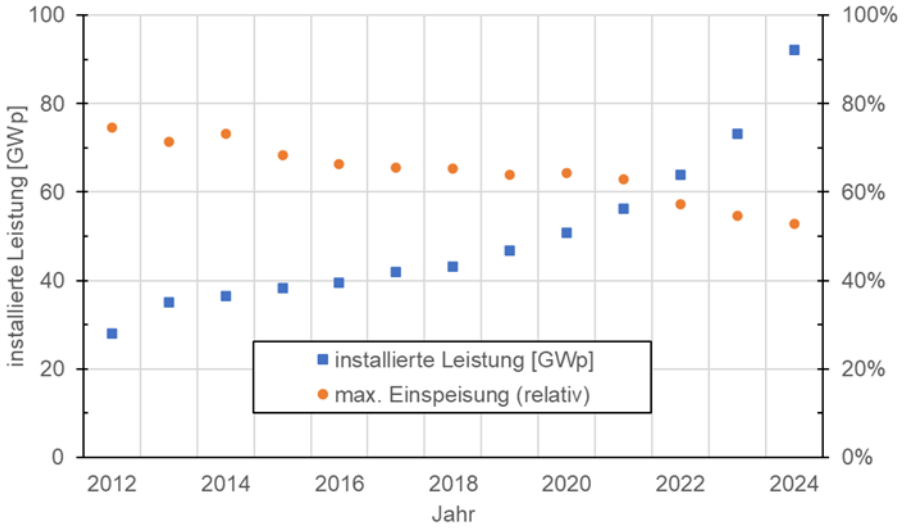


Figure 21 Annual maximum of the grid feed-in compared to installed PV capacity at the end of the corresponding month, data from [ISE4].

11.4 Is a significant amount of PV electricity lost through redispatch?

No, but the amount lost has clearly increased in 2024.
In the event of bottlenecks in the transmission or distribution grid, generation plants on one side of the bottleneck must be throttled down and those on the other side ramped up in order to serve the load (redispatch). In 2024, 1.4 TWh of PV electricity was curtailed in redispatch [SMARD], which is 1.9% of the PV grid feed-in [ISE4] for that year.

For the most part, curtailment (7.9 TWh) mainly affects wind power, which is mostly produced in the north and for which there is not yet sufficient transmission capacity to southern Germany (Figure 18). When wind levels are high, the remuneration for curtailed power in the north and the procurement of the missing power in the south (redispatch measures) lead to significant costs.

11.5 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 most 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 22 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.

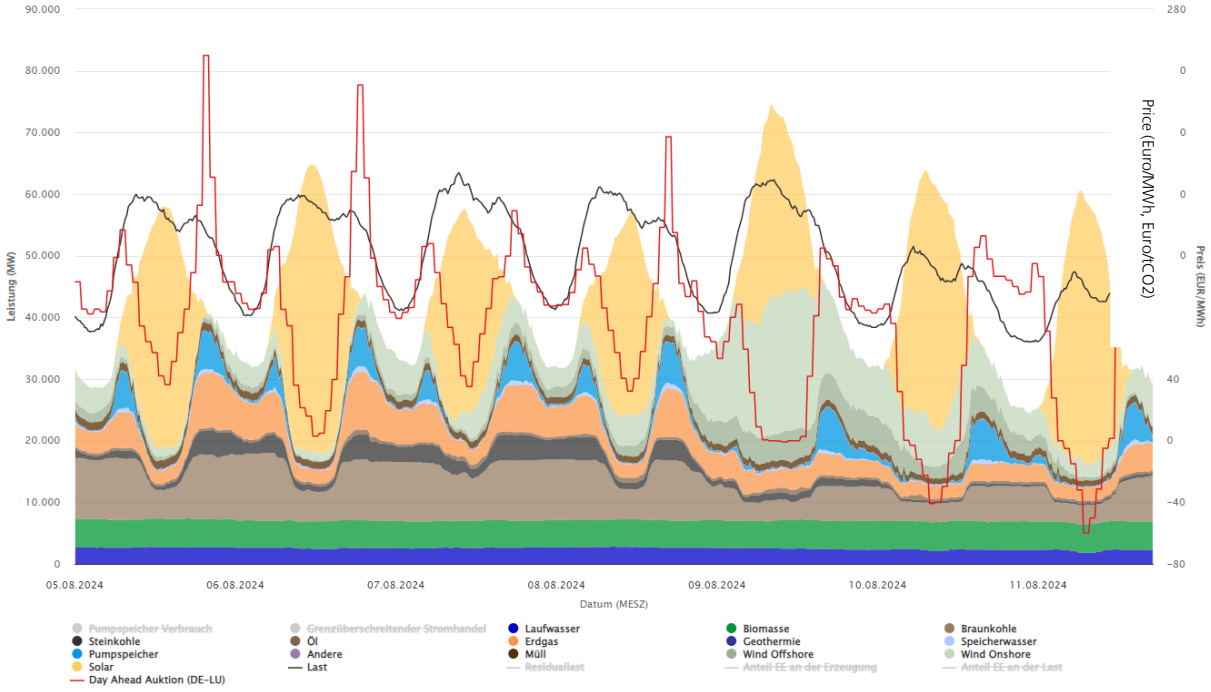


Figure 22: Example showing the course of electricity trading price, conventional and renewable electricity in the 32th calendar week in 2024 [ISE 4].

11.6 Does the PV expansion have to wait for increased storage?

No, but electrical energy storage systems make it much easier to integrate PV electricity into the grid.

Investments in load management measures, stationary battery storage systems, or pumped storage power plants are worthwhile if frequent and large differences in the price of electricity procurement exist. In the 2010s, investments in new pumped storage systems were put on hold because their operation was not economically viable at that time.

Further expansion of PV and wind power will cause prices on the electricity exchange to fall more frequently and more sharply. On the other hand, CO2 certificates or taxes will make fossil-generated electricity more expensive, pushing up EEX prices at times of high residual load. Price differentiation creates the incentive for load shifting, storage operation, and the temporary production of green hydrogen. If the differentiation is passed on to end consumers via tariff structures, load shifting and storage operation will become attractive for them. As a result, the capacity for volatile solar and wind power will increase.

11.7 Does volatile solar power endanger security of supply?

Not yet, however, it is becoming increasingly important to reduce midday peak production through load shifting, storage, or curtailment. As PV output increases, it will increasingly be called upon to act as a stabilizing control variable.

The security of supply for end consumers has actually improved with the photovoltaic expansion (Figure 23).

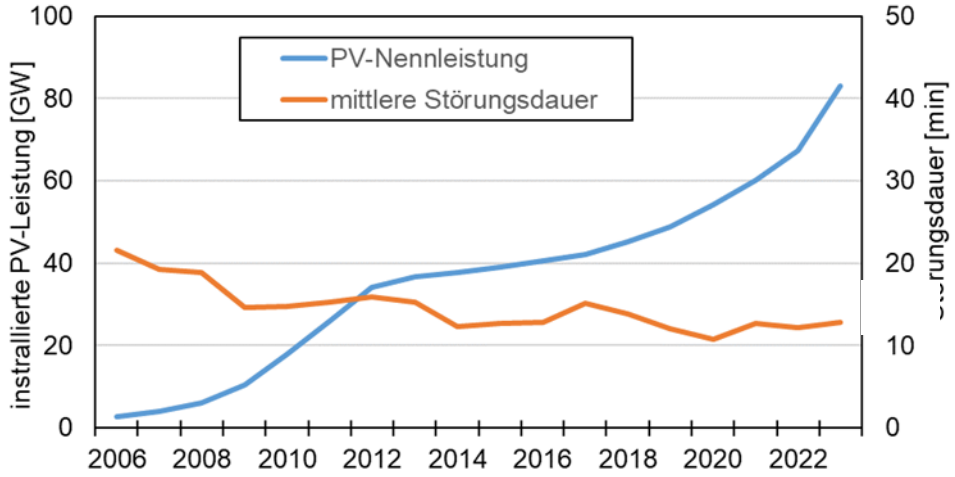


Figure 23: System Average Interruption Duration Index (SAIDI) for low and medium voltage grid. Data from [BNA2].

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

No, but storage systems are increasingly expanding alongside PV.
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 and load shifting 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 24).



Figure 24: 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 **regulatory potential** considers additional, non-monetary legal restrictions and exclusion criteria. The **economic-practical potential** considers all relevant boundary conditions, in

particular economic (incl. infrastructure), sociological (incl. acceptance), and 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 25). **Agrivoltaics** (Agri-PV) uses land simultaneously for agricultural crop production (photosynthesis) and PV electricity production (photovoltaics). Agri-PV 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. Agri-PV 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. Agri-PV is already being used on a GW scale worldwide, but there are only a few systems in Germany.

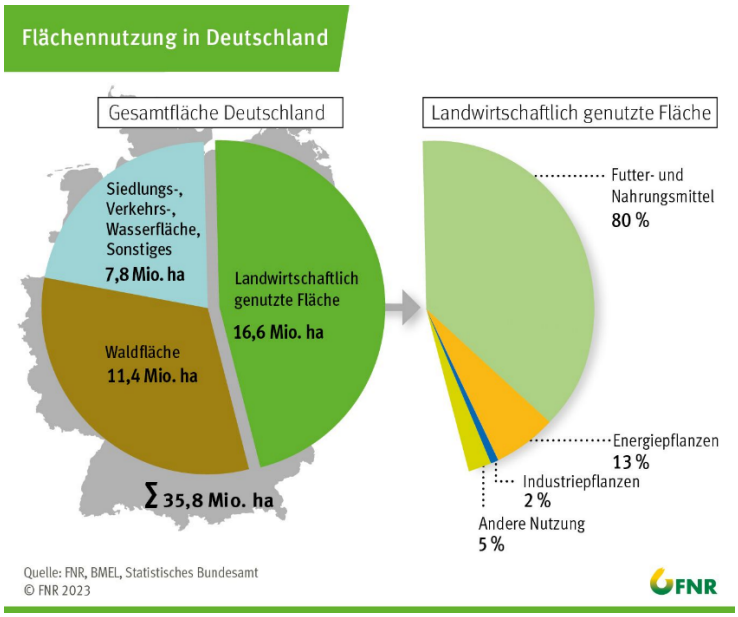


Figure 25: Land use in Germany [FNR].

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 with vertical modules, 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 16). 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 in **biodiversity PV**, see Section 4).
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 **45 GW_p** for **floating PV** (FPV, [ISE9]). In the case of active quarry lakes, the PV can contribute to the self-sufficiency of the production facilities and use existing grid connection points, if available. Worldwide, there are already several gigawatts of floating PV installed.
In Germany, there are about 40 million buildings (Figure 26). 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^2a) 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.

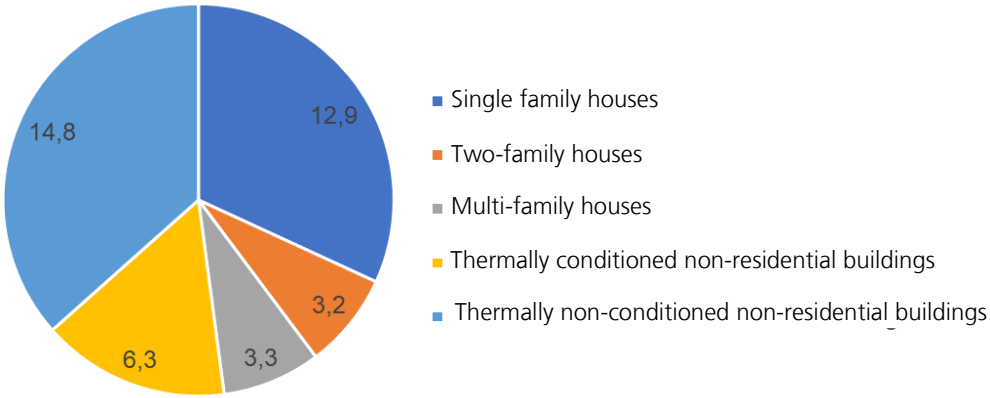


Figure 26: Building stock in millions, data from [DENA], [IWU].

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. BIPV products 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 27). 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.

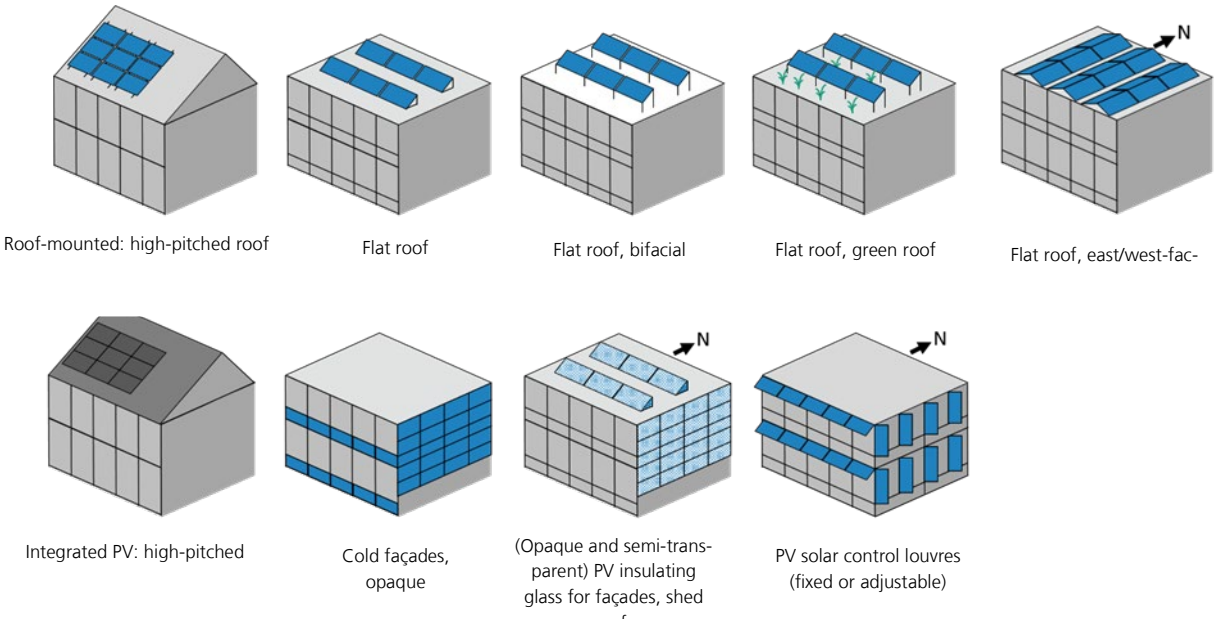


Figure 27: PV solutions for roofs and façades (top row: roof-mounted systems, bottom row: integrated PV).

A study by the Federal Environment Agency assumes 670 km² 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 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 km² (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 **biodiversity PV** (Section 14). 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]. In its brochure from 2020, the German Golf Association (DGV) estimates the area of golf courses in Germany at 48,000 hectares. In a report, the German Federal Environment Agency estimated that the total area used for ground-mounted PV systems was around 32,000 hectares by the end of 2021.

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]. Red tape has been reduced and the EEG has created incentives for landlord-to-tenant electricity supply. In addition, 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. In 2024 more than 780,000 plug-in solar systems were registered. It is estimated that the actual number is two or three times higher.

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 (OSPP) is installed on it, then biodiversity basically increases [ESD]. Fertilizer is not used and less demanding plants are given a chance to thrive. The fencing of the OSPP 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 (**biodiversity PV**). 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 hectares 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. Around 7 percent of the greenhouse gas emissions in Germany come from drained peatland (Source: Umweltbundesamt 2022). Alternatively, if PV power plants with reduced occupancy density were installed on such peatlands, a yield without intensive agriculture could be achieved. The partial shading by the PV system counteracts the drying out of peatlands or even can support 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 of PV on peatland 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 small balcony module or plug-in PV systems with a nominal power of a few hundred watts. At the end of 2024, 4.8 million PV systems were installed in Germany, of which 66 percent are small systems with outputs below 10 kW_P [ISE5]. This high number shows that the 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 28 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?

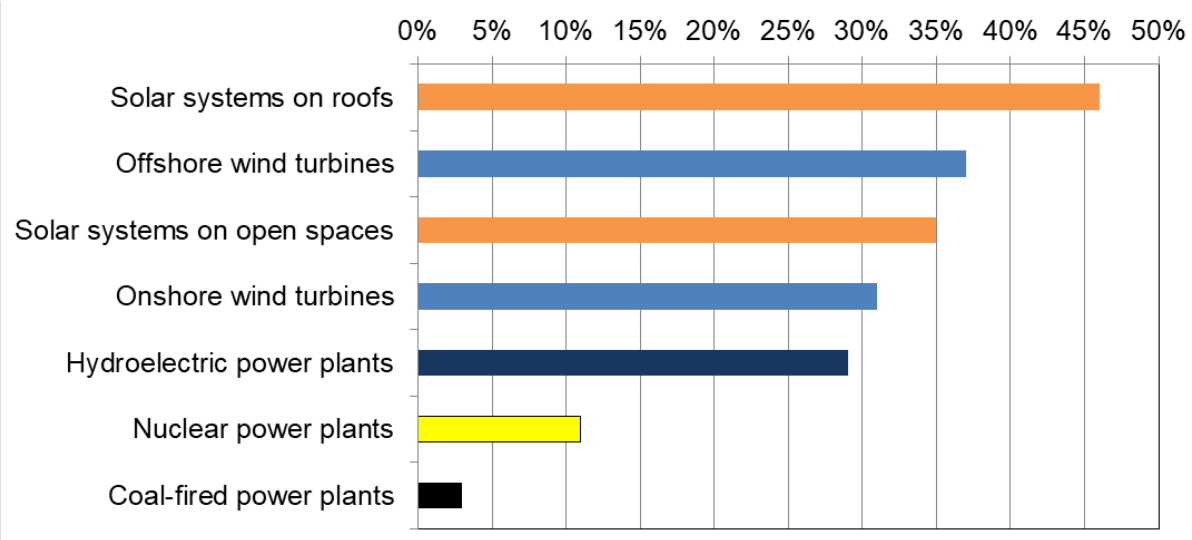


Figure 28: Survey results on the construction of new power plants, data from [Licht2].

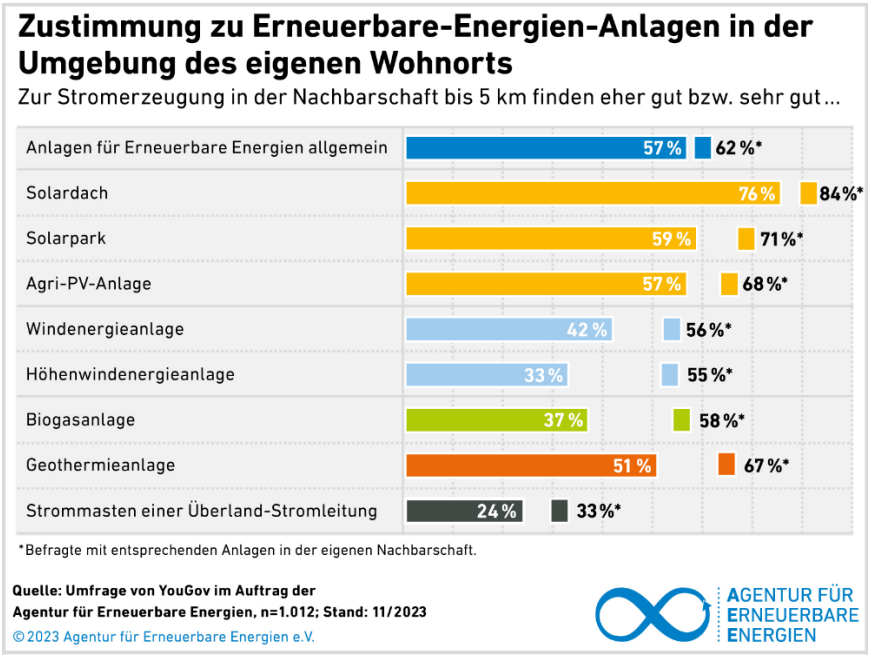


Figure 29: Survey results on the acceptance of different types of power plants [AEE].

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 29). The popularity increases when such power plants can be practically experienced in one's own neighborhood.

16 Are PV plants in Germany efficient?

That depends on the reference value.
For newer installations, the effective energy conversion efficiency is around 18–19 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 28.1) 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. 0.4–0.6 percentage points per year to **21.6 percent** [ISE5]. Per square meter of module, they thus produce a nominal output of 216 W; peak modules are approx. 10 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 **18–19 percent**.

The average electricity consumption of a two-person household for electrical appliances, lighting, hot water (hygiene purposes) and space heating was 3.5 MWh in 2021 [DESTATIS]. The per capita values for one-person households are higher, for multi-person households it is lower. On average, rooftop PV systems achieve **922 hours of full** use in 2021 in the trend scenario [ÜNB1], cf. Section 16.4. 18 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 10 390 W_P modules that corresponds to the average annual electricity demand of a two-person household (3.5 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 30). 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.

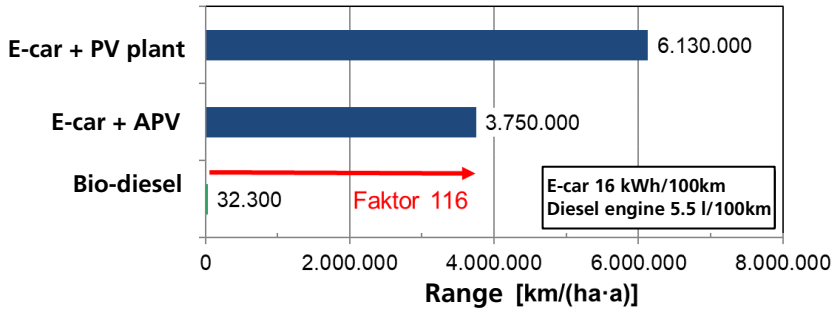


Figure 30: Range of electric and biodiesel vehicles per hectare of land used.

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.

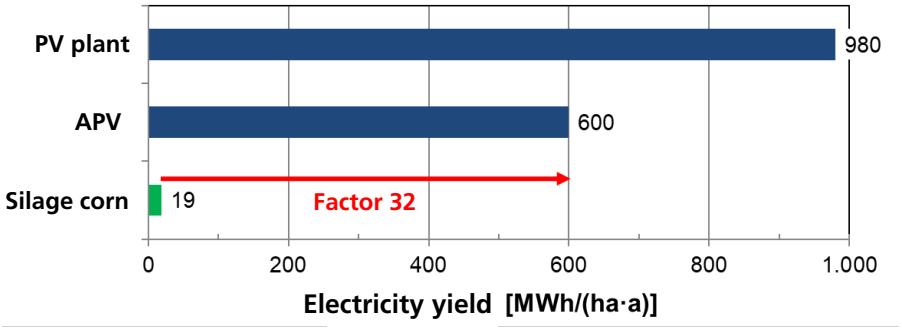


Figure 31: Electricity yields of PV power plants and silage maize per hectare of land used.

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

No, it is worth considering the overall profitability.
Figure 32 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%
Neigung	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%
	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 32: 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 45°, for example, annually produces about 26 percent less electricity than a south-facing roof with the same angle of inclination (Figure 32), which increases the levelized cost of electricity accordingly. A PV installation on an east or west-facing roof can still be worth-while, in particular when electricity prices are high and self-consumption is employed.

The question of whether an east or 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 48).

16.1.2 Vertical south-facing façade

A PV system on a vertical south-facing façade produces about 29 percent less electricity per year than an installation with a module inclination of 45° on a south-facing roof (Figure 32). The same applies to vertically mounted, south-facing plug-in solar panels. A vertical installation's seasonal fluctuation between summer and winter yield is considerably smaller when compared to horizontal installations (Figure 49), making it much easier to integrate PV electricity into the system and to use it for self-consumption. 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 PV installation is therefore only marginally affected by the reduction of the annual electricity yield.

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 33 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 22).

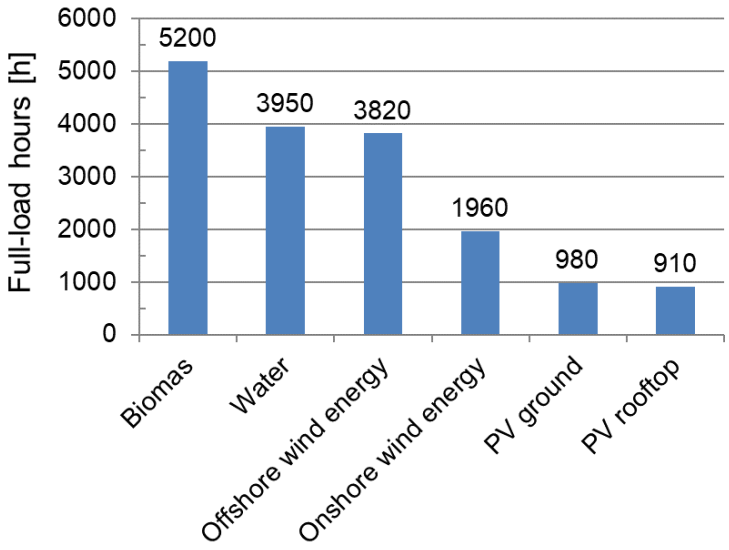


Figure 33: Forecast full utilization hours for electricity generation from EE, data from [ÜNB1].

The mean annual sum of horizontal global radiation in Germany for the years 2001-2020 (Figure 34) 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. 25° 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 22.3.1)
- 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.

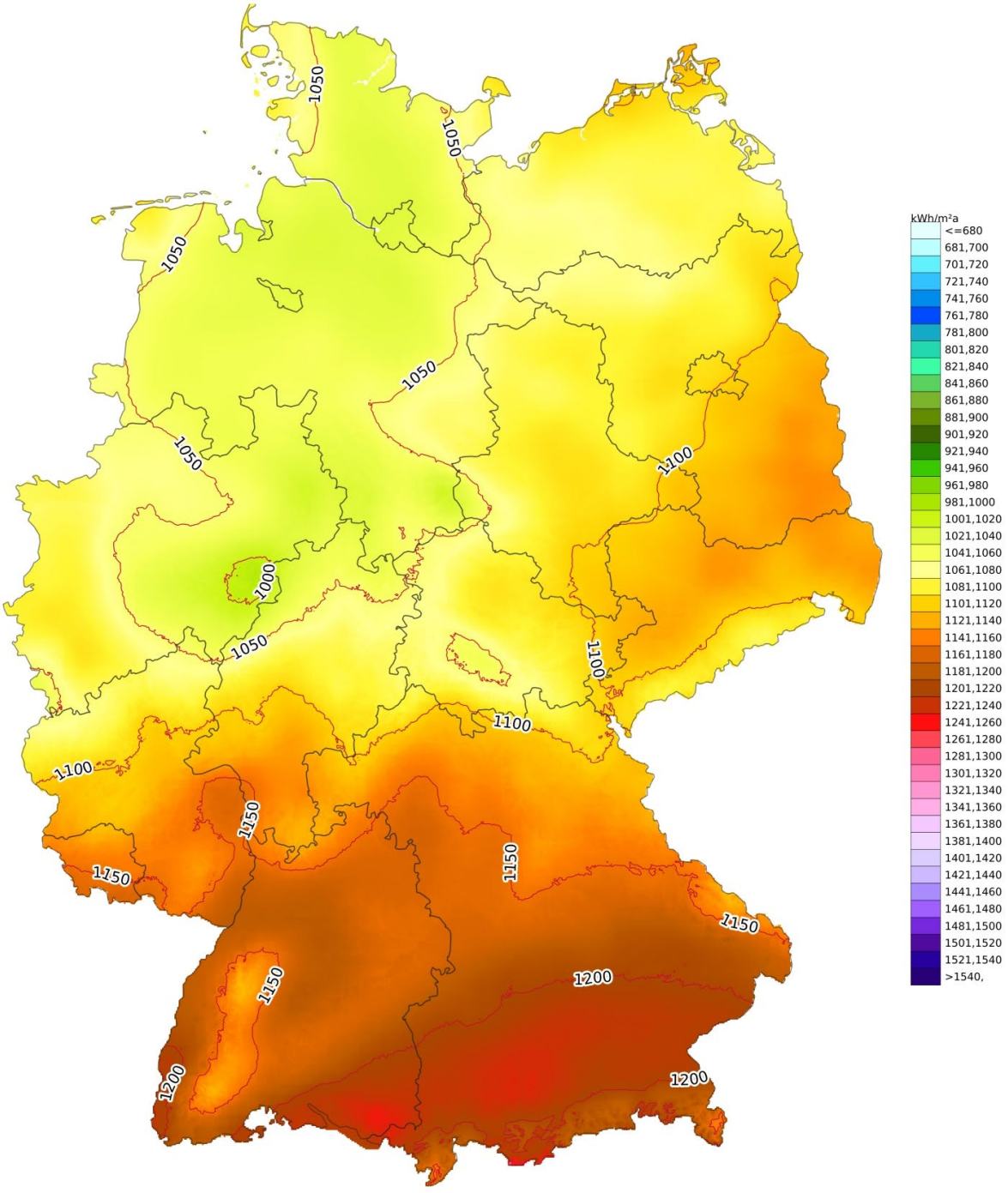


Figure 34: Horizontal annual global radiation total in Germany, averaged over the period 2001-2020 [DWD].

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.

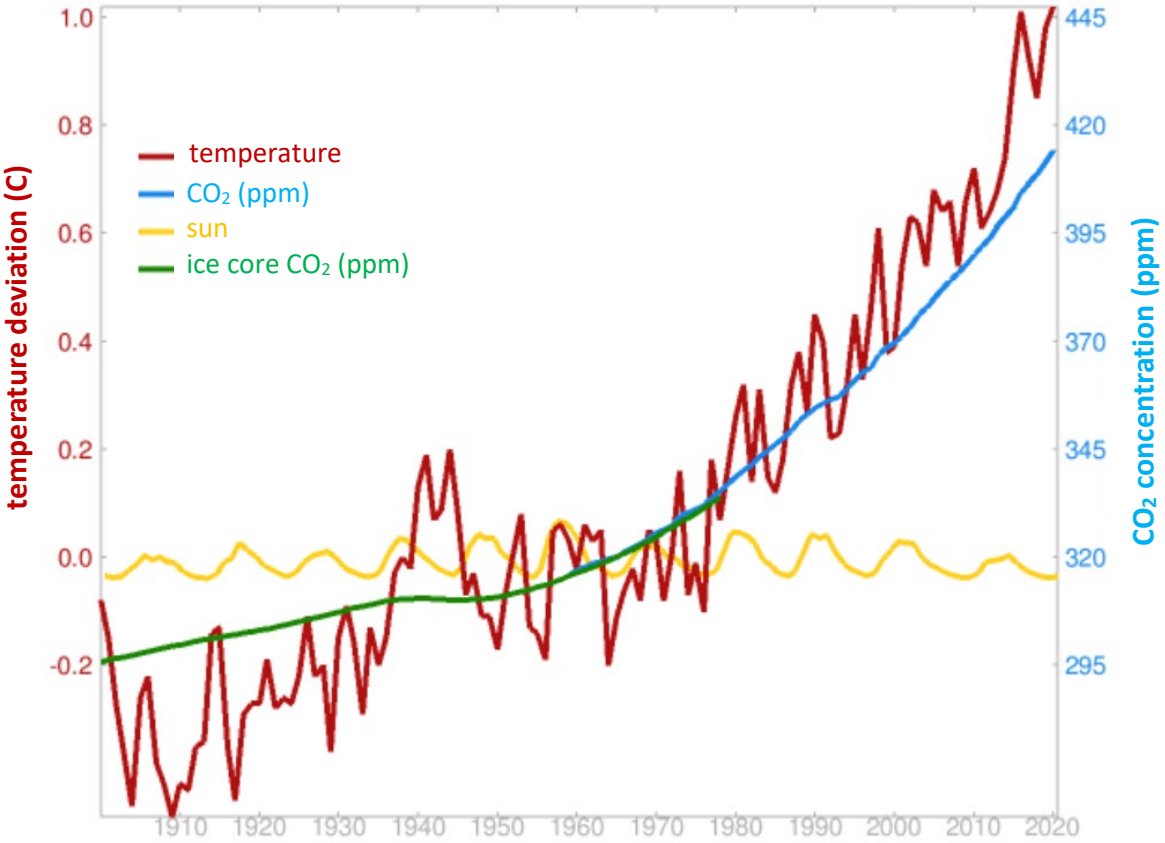


Figure 35: Development of atmospheric CO_2 concentration, mean global temperature change and solar activity (http://herdsoft.com/climate/widget/).

In May 2013, the atmospheric CO_2 concentration reached 400 ppm for the first time in at least 800,000 years. Figure 35 and Figure 36 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.

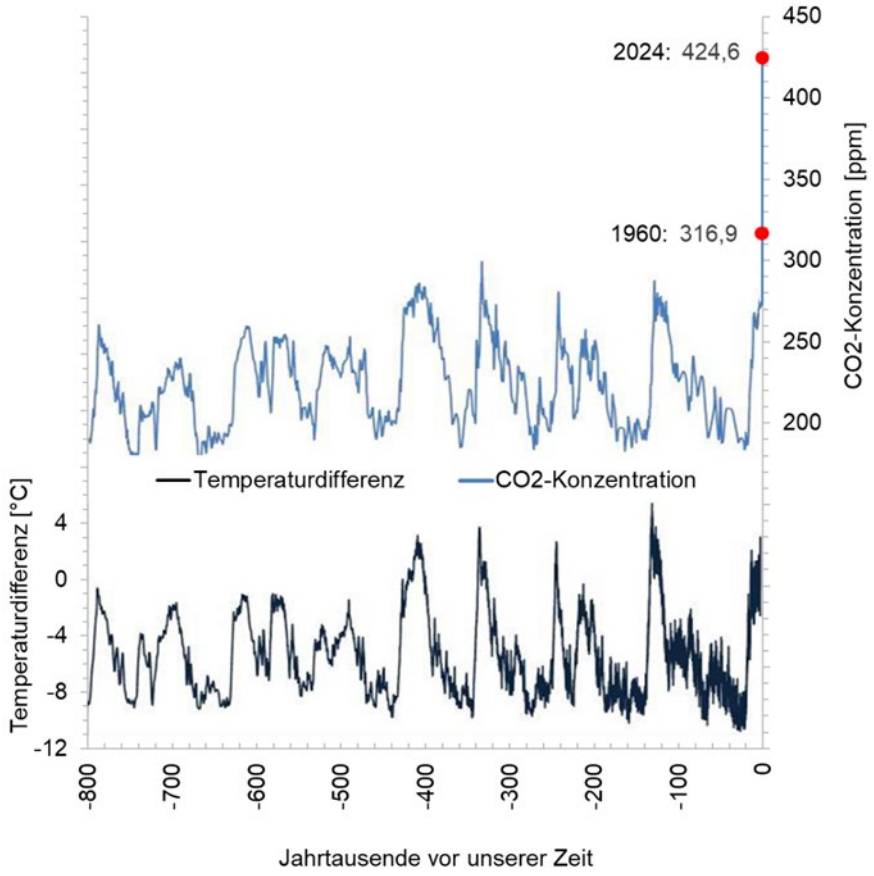


Figure 36: Estimates of atmospheric CO_2 concentration and temperature difference in Antarctica based on ice cores [EPA]; red: CO_2 measurements from Mauna Loa Observatory [https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html].

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 and disposal of the system. The specific yield

[kWh/(kWP·a)] and thus the annual irradiation sum at the operation site play a major role, as does the lifetime of the PV system. Thanks to advances in production and efficiency, the carbon footprint of PV electricity has been dramatically reduced in recent decades. It is therefore important to consider life cycle assessments (LCAs) of current technologies when evaluating new systems.

The IEA PVPS Task 12 has found that a large ground-mounted PV system in Piacenza in Northern Italy (GHI 1,368 kWh/(m2·a) with 85 MWP, modern PERC technology and 21.2 percent module efficiency, has an emission factor of 25.7 g CO2-eq/kWh [IEA5]. In Germany, only about **30–35 g CO2-eq/kWh** could potentially be achieved due to the somewhat lower solar radiation (approx. 20 percent lower on average).

The German Federal Environment Agency has compared the greenhouse gas potential of PV electricity from ground-mounted and pitched roof mounted PV systems based on older data and only found little difference between the two ([UBA9], see Figure 37). 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.

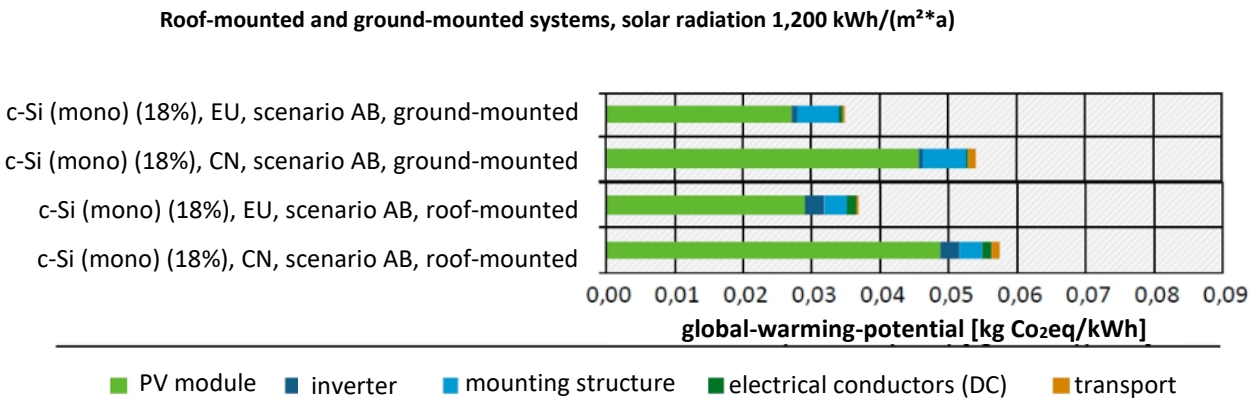


Figure 37: Global warming potential of electricity generation with mono c-Si PV for roof-mounted and ground-mounted systems [UBA7].

Figure 38 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 39). In the calculations, the emissions from the production of the PV system components were taken into account approximately.

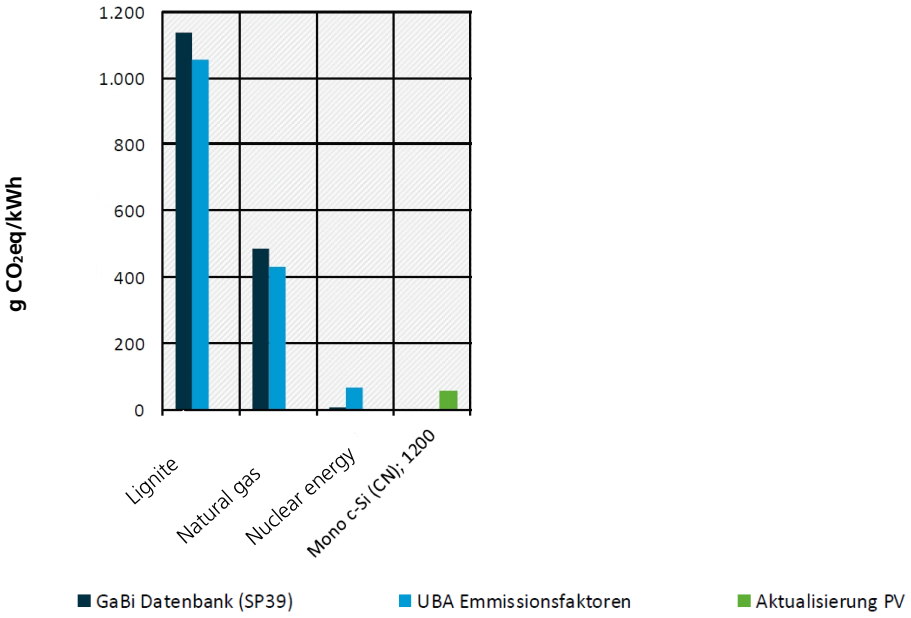


Figure 38: Global warming potential of different electricity generation technologies [UBA7].

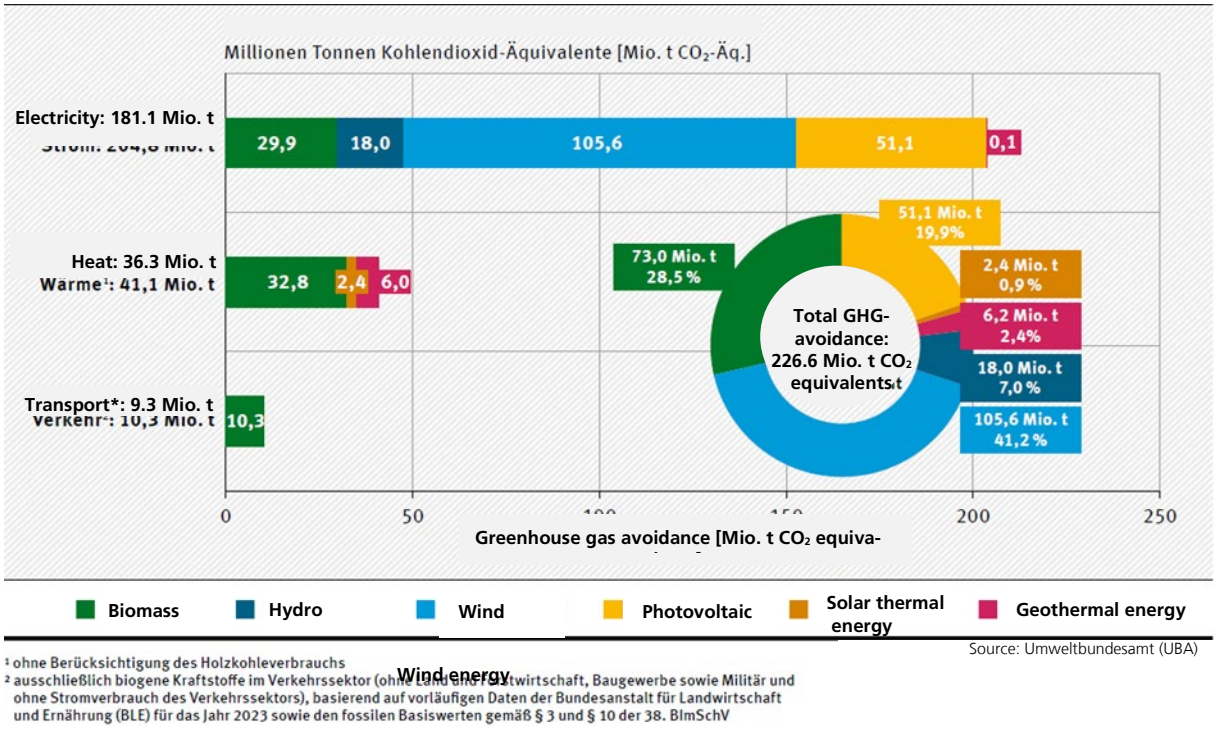


Figure 39: Avoided greenhouse gas emissions through the use of renewable energies in 2024 [AGEE].

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 40). PV reduces the consumption of fossil raw materials for electricity generation worldwide.

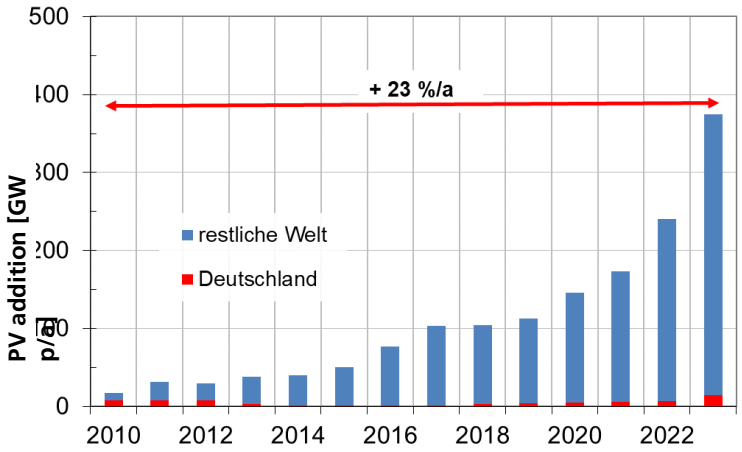


Figure 40: Development of annual PV additions [IEA3] and average annual growth rate.

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, but their market share is below 5 percent.
In the production of thin-film PV, 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 the earth?

Light-colored surfaces reflect a large portion of the incident solar radiation while dark surfaces absorb more. As a result, they heat up more and radiate more heat into the surrounding air. The **solar albedo** (solar reflectance) of a surface indicates the percentage of incoming solar radiation that is reflected. The rest is absorbed or transmitted. In addition to the visible spectrum, the solar albedo also includes the UV and IR parts of the spectrum. Albedo values found in literature vary widely from surface to surface. According to the Swiss Federal Office of Meteorology and Climatology MeteoSwiss, arable land has an albedo of 7–17 percent, grassland 12–30 percent and forests 5–20 percent. The Thuringian Ministry of Environment estimates roof tiles to reflect 10–35 percent, light-colored roofs 60–70 percent.

18.1 Local effects

18.1.1 Do PV modules heat up their environment?

That depends on the reference material.
As most materials, PV modules absorb a large portion of the incident solar radiation. However, because they convert part of the absorbed radiation into electrical energy rather than heat, their effective albedo and thus the local generation of heat is similar in magnitude to that of typical surrounding materials or vegetation.
For example, when new PV modules convert solar radiation into electrical energy with an actual efficiency of 18 percent, and also reflect approx. 5–10 percent of the irradiation, 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. Comparing the effective albedo of PV modules with the albedo of the surface area they cover helps determine whether the installation increases or reduces waste heat generation. Another important influential parameter is evaporative cooling, which plants use to cool themselves and their surroundings. 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, green roofs and degraded moorland soils that are to be rewetted (Sections 12 and 14).

18.1.2 Do PV modules reflect solar radiation into the surrounding environment?

Only very little.
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, or better yet, 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. Although PV modules can cause glare (Section 19), they reflect very little solar radiation.

18.1.3 Do PV modules store solar heat?

Only very little.
The heat storage capacity of ordinary PV modules is low compared to a solid concrete wall, for example. As a result, the PV module heats up much faster than a concrete wall under solar radiation, 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.

18.2 *Global effects*

18.2.1 Does solar power production contribute to the greenhouse effect?

Yes, but much less than the electricity production of fossil fuel power plants and it will stop once the production of PV components is fully powered by green electricity.
In particular, PV electricity replaces electricity from fossil fuel power plants, which release up to 1.1 kg CO2/kWh$_{el}$, depending on the fuel. The CO2 is released into the atmosphere, where it acts as a greenhouse gas for an unlimited period of time (Section 17.1). Compared to fossil power plants, electricity generation via PV massively reduces the release of CO2 and thus effectively slows down the greenhouse effect (Section 17).

18.2.2 Do PV modules heat up the earth's atmosphere?

That depends on the albedo of the area they cover.
When PV modules are installed, their effect on local warming corresponds to the change in albedo. Dark PV modules with an actual efficiency of 18 percent and an albedo of 5 percent covering a light-colored tile roof with an albedo of 30 percent (unfavorable combination) generate 400 Wh additional waste heat, or 40 percent of the produced electricity. To compare, thermal power plants (coal, nuclear) produce around 2 kWh of waste heat per kWh of electricity, or 200 % of the produced electricity. Solar power production generates less waste heat than thermal power production, even when the modules are installed on relatively light-colored surface areas.

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 no 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 thermal power plants?

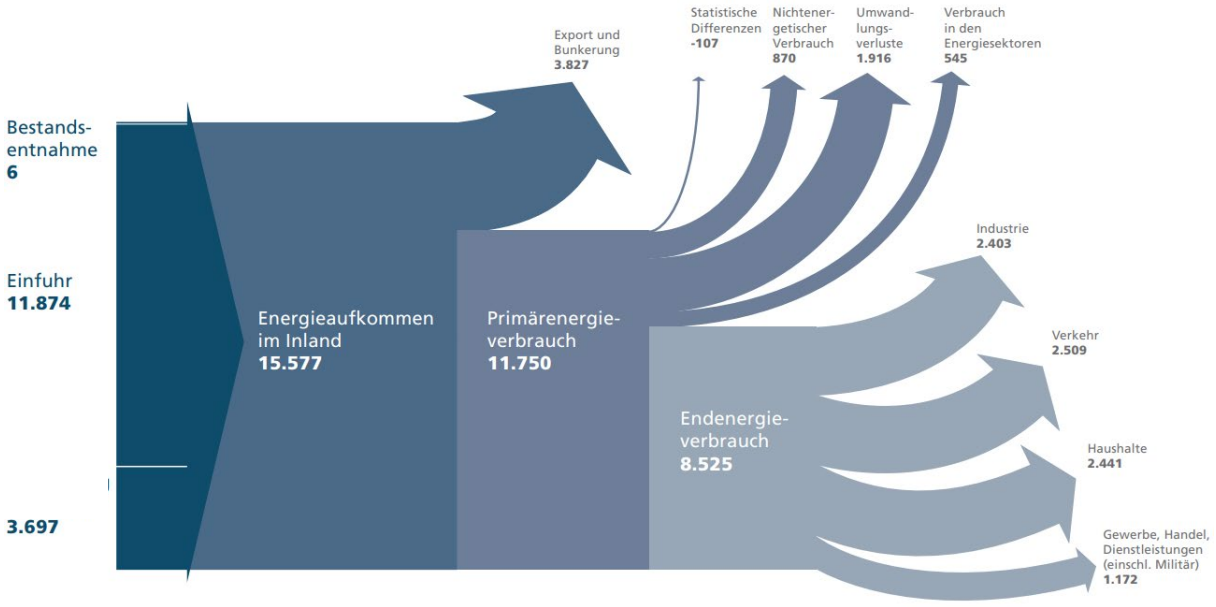
No.
Although PV power plants reduce the consumption of fossil fuels, energy imports and CO2 emissions, they do not replace controllable generation capacities, not even in combination with wind power, battery storage and pumped storage, which can only be expanded to a limited extent in Germany. Windless nights and especially windless, cloudy winter weeks without significant PV or wind power production are critical. Only by adding flexible thermal power plants, fueled by natural gas, biogas and, in the future, hydrogen, can generation gaps be covered all year round.

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 41).



Der Anteil der erneuerbaren Energieträger am Primärenergieverbrauch liegt bei 17,6 %.
Abweichungen in den Summen sind rundungsbedingt.
29,3 Petajoule (PJ) ≙ 1 Mio. t SKE
Quelle: Arbeitsgemeinschaft Energiebilanzen 09/2023

Figure 41: Energy flow diagram 2022 for Germany, figures in petajoules [AGEB2].

There are dramatic efficiency deficits in conversion and final energy consumption (cf. Section 22.3.3). 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 40-135 billion euros annually (Figure 42). A large part of the money went to supporting autocratic regimes.

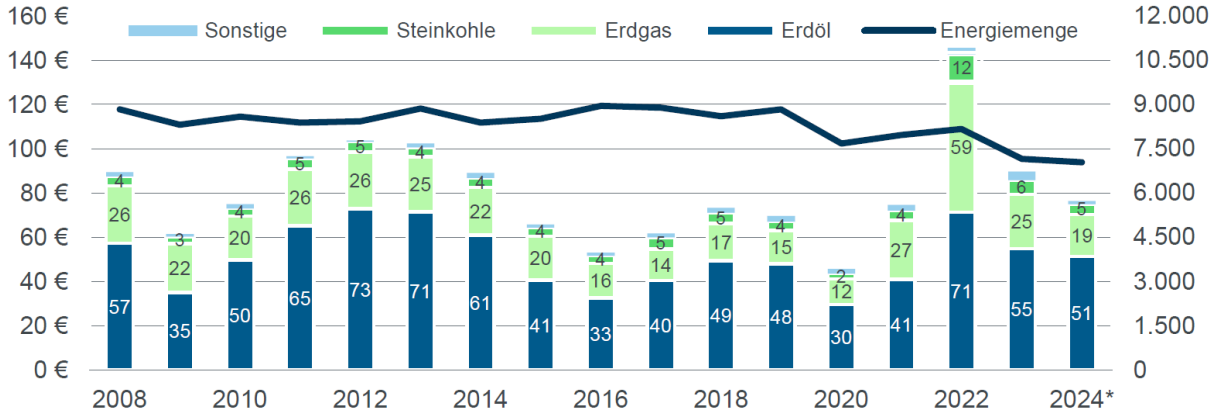


Figure 42: Value and energy volume of net imports of fossil fuels (left axis: value in EUR billion, nominal; right axis: energy volume in PJ) [KFW].

Most final energy (36 percent) is used to generate mechanical energy ("power") for transport and in stationary engines (Figure 43). Approximately 800 TWh of final energy is used annually for space heating and hot water [BMWK1].

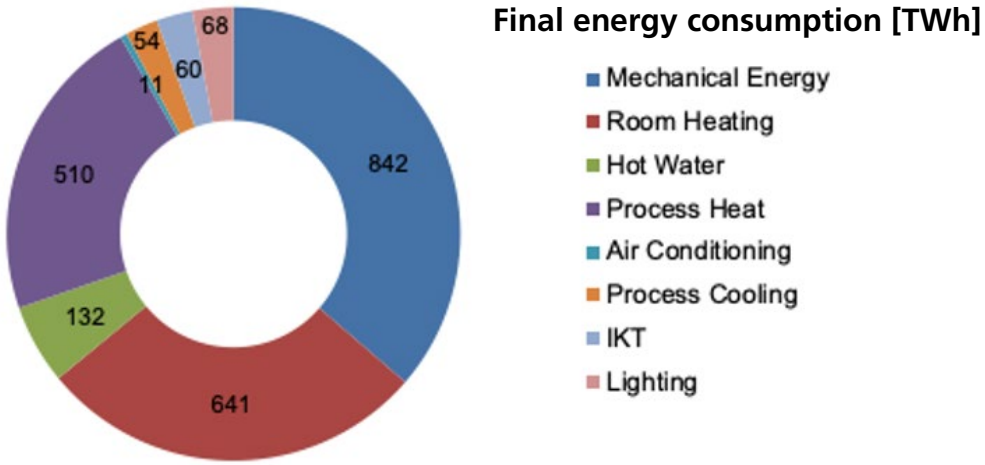


Figure 43: Structure of final energy consumption by application area for Germany in 2020, figures from [BMWK1].

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 44). In an economically optimal scenario, PV must contribute an installed capacity of 471 GW [ISE3].

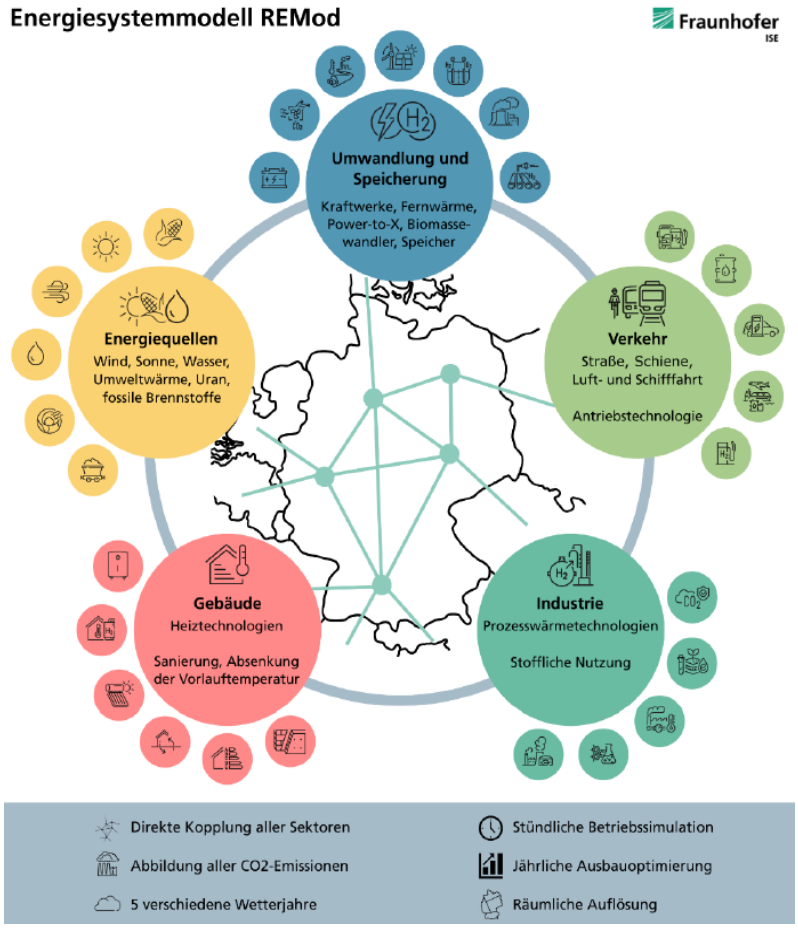


Figure 44: Schematic representation of the REMod model [ISE3].

Figure 45 shows a schematic residual load curve for Germany with a 100 percent renewable electricity supply. The hourly values of the residual load (Section 11.4) 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 45.

On the **demand side**, flexible loads are reduced, batteries and pumped storage are discharged, combined cycle gas turbine (CCGT) generators and gas turbines are activated and other measures are taken in order to cover the residual load. The thermal power plants use green hydrogen and are designed with combined heat and power (CHP) for local heat demand.

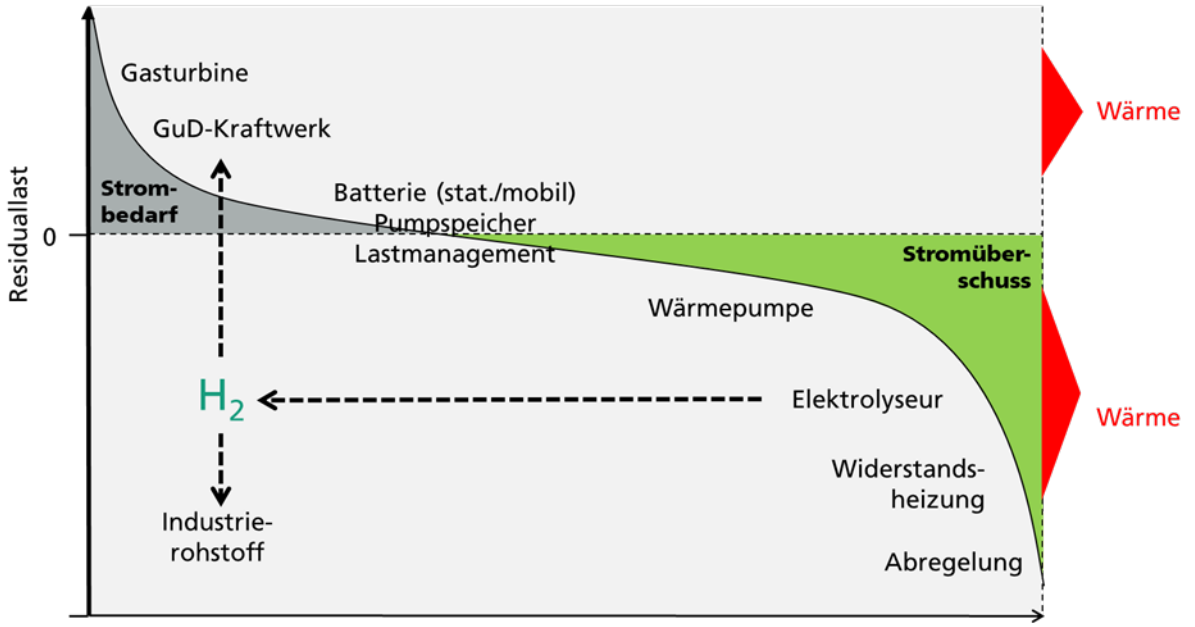


Figure 45: Schematic representation of a residual load curve for Germany with electricity supply with 100 percent RE.

On the **surplus** side, flexible loads are increased, batteries and pumped storage are charged, heat pumps, electrolyzers and resistance heaters (heating rods, electrode boiler) 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.

Before the occurrence of foreseeable, particularly high residual load peaks, storage and flexible loads are also operated atypically to reduce both the required maintained capacity of thermal power plants and curtailment.

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.

Hydrogen, produced by electrolysis, serves as an industrial raw material (direct reduction, organic chemistry, ammonia synthesis). Hydrogen and its derivatives can be converted back into electricity in gas-fired power plants and can power vehicles with the highest

energy densities, e.g. aircraft. A hydrogen network is planned for Germany, and hydrogen can also be added to the existing natural gas network.

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 45 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 45 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 45 and thus achieve a higher utilization. In addition to batteries and pumped storage, these may prospectively include reversible fuel cells, which carry out electrolysis in the case of excess electricity. These are currently under development.

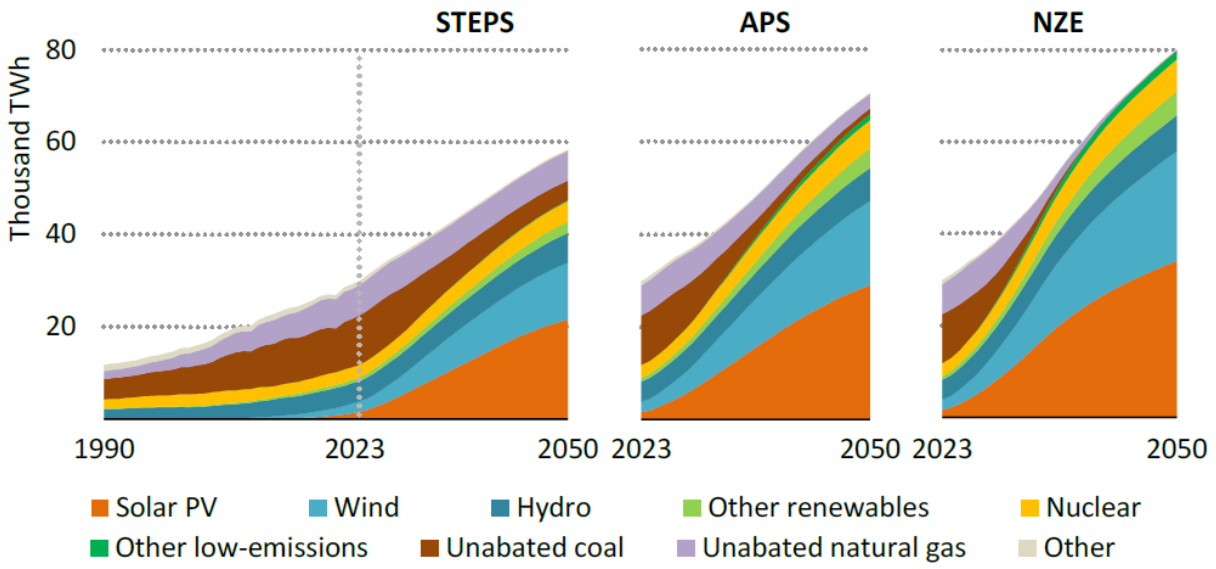


Figure 46: Development of the global electricity generation by technology and scenario [IEA2].

Taking a brief glance at global energy scenarios brings us to the International Energy Agency (IEA) that predicts that photovoltaics will play a major role in the global energy supply across all three scenarios of the global energy transition (Figure 46).

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.

22.3.1 Keeping PV power generation constant

Elevated modules installed on fields and flat roofs have mainly been oriented towards the south and have a 25° inclination to maximize the specific annual electricity yield (Wh/W_P). For the same reason, PV has mainly been installed on pitched roofs facing south. This uniform module orientation increases the hourly spread of solar power generation around midday, especially on clear days, and the seasonal spread during the summer months.
As a result, the maximum PV electricity yield in Germany is mainly reached around noon, while less power is generated in the morning and evening due to flat angles of incidence. This situation is increasing the need to stabilize power generation, for example through curtailment, load management and storage. In addition, the market value of electricity tends to drop more and more around noon. Alternative mounting methods can stabilize PV electricity generation.

Vertically mounted, bifacial modules with an east-west orientation supply significantly more electricity with direct sunlight during the mornings and afternoons than around noon. Their generation profile optimally complements the large number of existing PV power plants, most of which are south-facing (Figure 47). **Uni-/biaxial tracking systems** stabilize the electricity production on clear sunny days and increase it on cloudy days by orienting the modules to the brightest point in the sky. The trackers can increase the specific annual yield by approx. 15–30 percent. Vertically oriented and moveable modules are additionally advantageous since their impact on the agricultural use of the land is minimal (Section 12).

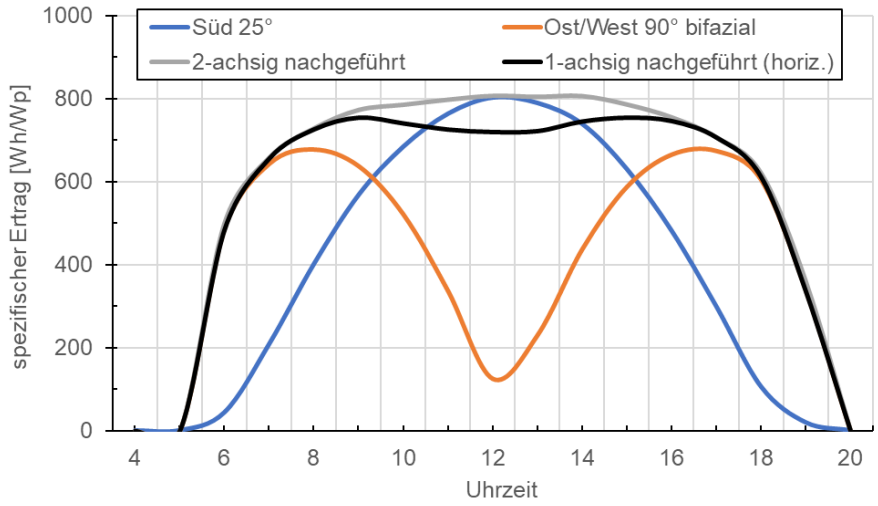


Figure 47: Electricity yield profiles of PV power plants in different mounting variants, calculated online with https://re.jrc.ec.europa.eu/pvg_tools for a predominantly clear day in May at the Freiburg site, no shading, bifaciality factor 100 %.

PV on **pitched roofs facing other directions than south** also helps extend power generation into the morning and evening, while modules facing east or west on flat roofs broaden the daily generation profile (Figure 48).

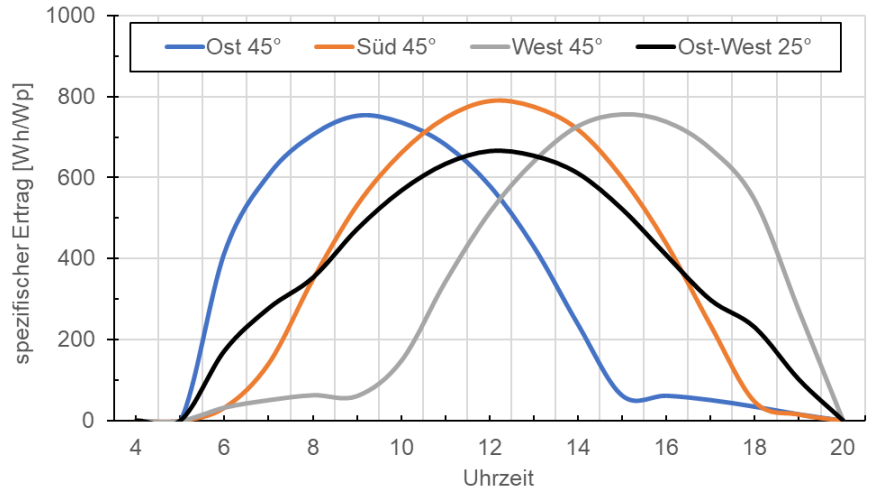


Figure 48: Electricity yield profiles of PV systems mounted in various ways on a predominantly sunny day in May, no shade, located in Freiburg, calculated online using https://re.jrc.ec.europa.eu/pvg_tools.

The very pronounced seasonal fluctuation of PV power generation can be dampened by south-facing modules, especially on vertical façades (Figure 49). Yield losses due to restricted rear ventilation were not considered in the comparison calculations.

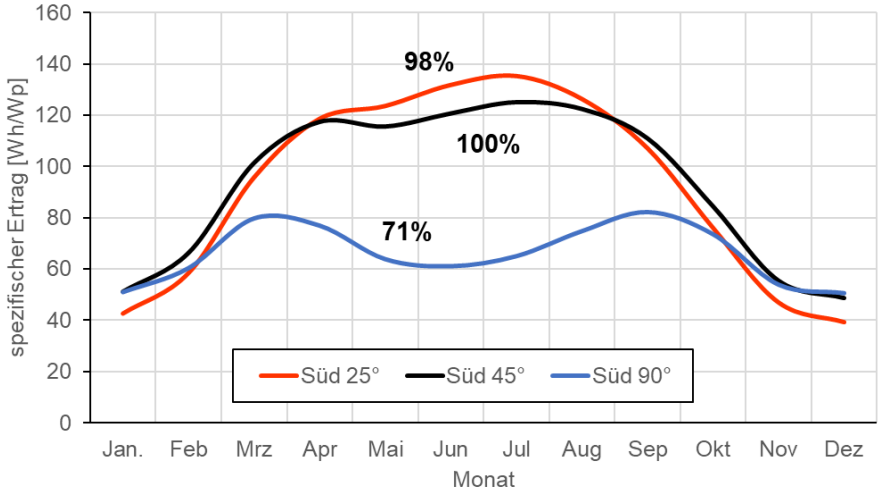


Figure 49: Electricity yield profiles of PV systems mounted in various ways, no shade, located in Freiburg, calculated online using https://re.jrc.ec.europa.eu/pvg_tools; the percentages provide the relative annual yield in relation to the 45° inclination.

The somewhat higher electricity production costs for the alternative installation variants can pay off in the context of increased self-consumption or higher market values for electricity. Feed-in tariffs that reward a higher value of electricity in the morning and evening hours, as well as in the winter months, 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 16.4 also contribute to the stabilization of PV electricity generation.

22.3.2 *Expending flexible generation capacity*

The energy transition will require a dramatic increase in the generation capacity of hydrogen-compatible gas-fired and biomass power plants, with decreasing full load hours and higher market values for the electricity generated.
Gas-fired power plants are particularly 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. They will switch from natural gas to mixed gases with increasing proportions of electrolytically produced hydrogen ("H2-ready"). Germany has decided to phase out fossil fuels. 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].
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 2024, biomass power plants with a capacity of over 9 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 that only allow limited control over the fermentation throughput. For large plants near gas grids, investments in grid connection and the processing of biogas to biomethane are often profitable. Smaller plants require local biogas storage systems and higher generator output to focus power generation on times of peak demand. The cultivation of biomass for the purpose of energy use will decrease due to low land efficiency (Section 16), and use will concentrate on agricultural residues (biogenic waste).

22.3.3 *Increasing energy efficiency*

22.3.3.1 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. Even 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 50 shows the greenhouse gas emissions of average medium range cars with different drives in in 2025. Preferred charging with solar or wind power (cf. Section 21.3.7.2) 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.

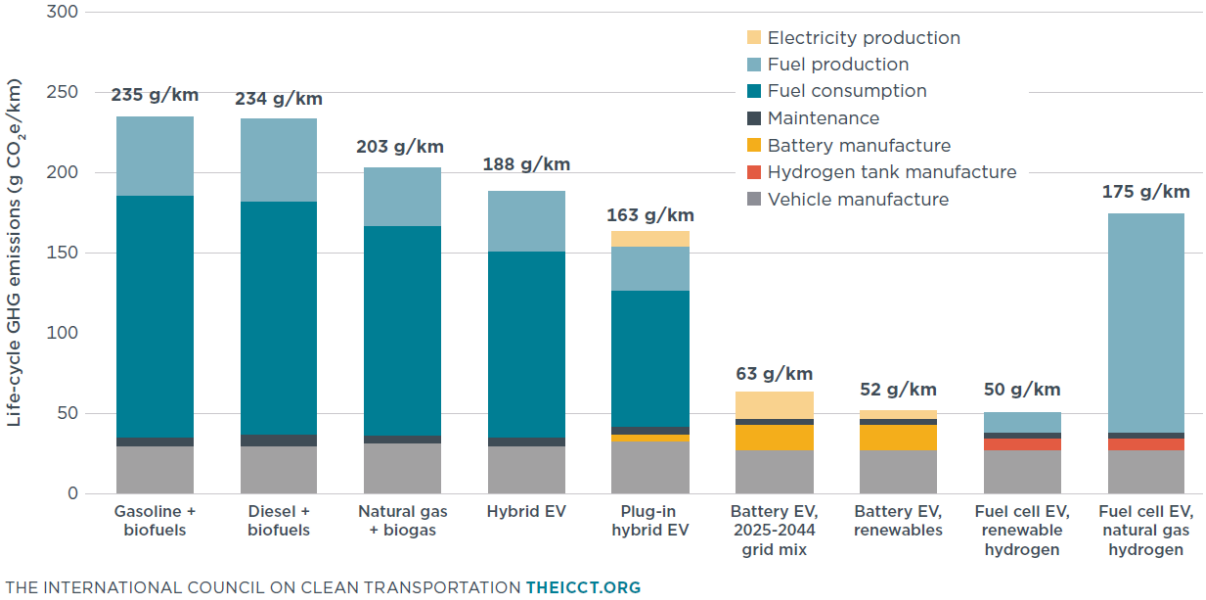


Figure 50: Greenhouse gas emissions (CO_2-eq in tons) for the life cycle of a mid-range car with different drives in 2025. Average values based on sales figures in the EU

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.

22.3.3.2 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.

22.3.4 *Load management*

Grid-serving load management, or demand side management, aims at a supply-oriented, temporal shift of electricity consumption. When the residual load is high (Section 10.4), consumption is 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 save CO_2 emissions, because the most harmful power plants are then needed less often.
Prerequisites for load management are flexibility options through **energy or material storage** on the demand side. A washing machine can often wait a few hours or even days, 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. Grid-serving operation reduces full load hours.

A study has calculated the theoretical load management potential of 15.6 TWh for private households in the year 2024 [EON], taking into account heat pumps, electric cars, home storage units, washing machines, dryers and dishwashers. This amount of electricity corresponds to around a third of public electricity generation from gas-fired power plants and is likely to double by 2030.

The technical prerequisites and economic incentives for tapping into this potential still need to be created for the most part. Household appliances that are allowed to operate within a user-defined time interval must be technically enabled to select optimal operating times with regard to electricity and grid shortages. Dynamic electricity tariffs and electricity meters that enable time-dependent billing ("smart meters") are of crucial importance.
The current composition of electricity prices for households (Figure 10) 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. A cross-industry survey of 400 companies in Germany has shown that there is potential for increasing flexibility by around 10 to 15% of peak load, i.e. around 5 to 7 GW [MCK]. 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).

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.
As transportation and heating become increasingly electrified, the potential for load management grows significantly. Electric vehicles, heat pumps and heating rods consume large volumes of electricity and offer high flexibility potentials through integrated electricity, heat and cold storage systems.

22.3.4.1 Electric vehicles

In 2023, passenger cars registered in Germany had an average annual mileage of 12,320 km. The total mileage of passenger cars in Germany of 591 billion km in 2023 [KBA] with a consumption of 180 Wh/km and a complete transition to e-cars corresponds to an annual electricity consumption of 106 TWh, plus approx. 15 percent charging losses. The large on-board battery capacity of electric passenger cars (30–100 kWh) and e-vehicles in general opens up massive potential for load management by shifting the charging times hours to days later or earlier, or by limiting charging capacity. At the end of 2024, around 1.6 million purely electric cars (BEV, without plug-in hybrid) were registered in Germany, out of a total of approx. 49 million passenger cars (de.statista.com, www.kba.de). E-buses for urban transport are commercially available, along with electric cargo vans for distribution logistics and increasingly 40-ton electric trucks for long-distance transport.
Supply-dependent electricity prices 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 continuously change their prices. 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.
The current share of electricity from renewable sources covering the grid load in Germany fluctuated between 11 and 137 percent in 2024 [ISE4]. Those who already want to supply their e-car with especially green electricity from the grid preferably charge on sunny days around midday, otherwise on windy nights. Weekends and public holidays are usually advantageous because the lower electricity consumption tends to improve the CO2 balance. Unfortunately, many 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].

22.3.4.2 Heat pumps

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. 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 a 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 2024, around 2 million heat pumps were in use [BWP], which, under the same assumptions, is equivalent to an electrical nominal capacity of 9 GWp. 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 m^3 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. 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.
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.

22.3.4.3 Heating rods and electrode boilers

Resistance heaters can be used to convert excess electricity into low-temperature heat for hot water and heating in buildings, and into high-temperature heat for industrial processes. When used in low and high-temperature heat storage systems, heating rods offer load flexibility potentials at a comparatively low cost of investment.

22.3.4.4 Electrolysis

With the transformation of the electricity sector and industry, the demand for green hydrogen and its derivatives will increase massively, from 55 TWh in 2023 to 290–440 TWh in 2025 [NWS]. Some of the hydrogen will be stored for reconversion into electricity (section 22.3.7.5 Hydrogen storage with reconversion), while the rest will be used for chemical reduction and synthesis processes. Electrolysis capacities operated in Germany for supplying hydrogen to industry create significant capacities for load management in conjunction with hydrogen storage facilities.

22.3.5 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 (11.2.2). If the installed capacities for PV and wind power can be expanded to similar levels, their combination will reduce the need for balancing.

22.3.6 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 45) 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.

22.3.7 Electrical energy storage

Electrical energy storage (EES) refers to storage systems that can absorb energy via electricity and release it later in the form of electricity. EES includes, in particular, stationary batteries, vehicle batteries (when stationary) and pumped-storage power plants. It will increasingly also include H2-based systems with electrolysis, H2 storage systems and re-conversion via thermal power plants or fuel cells. There are also experiments with systems consisting of a heating element, a high-temperature heat storage system and a thermal power plant.

22.3.7.1 Stationary batteries

At the end of 2024, the installed capacity of stationary batteries (large-scale, commercial and residential storage systems) was **18 GWh**, with a capacity of **12 GW$_P$** (ISE4, https://battery-charts.rwth-aachen.de/). Stationary batteries can be used to:

- Adjust local generation profile of PV power plant to
  - reduce costs of external electricity procurement through self-consumption
  - increase revenues by selling electricity
  - eliminate bottlenecks in connections and in grid capacity
- Adjust local load profile to
  - Reduce costs of external electricity procurement and make use of flexible or power-limited tariffs
  - Eliminate bottlenecks in connections/grid capacity (e.g. fast charging stations)
- Counteract grid-wide disruptions by providing
  - balancing power, instantaneous reserve
  - Emergency electricity supply
- Balance generation and load across the grid by electricity trading

With 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 51). A grid-serving system management of the batteries relieves the grid by selectively reducing

the midday feed-in peak (Figure 52). Storage systems would thus enable an increased PV expansion [ISE7].

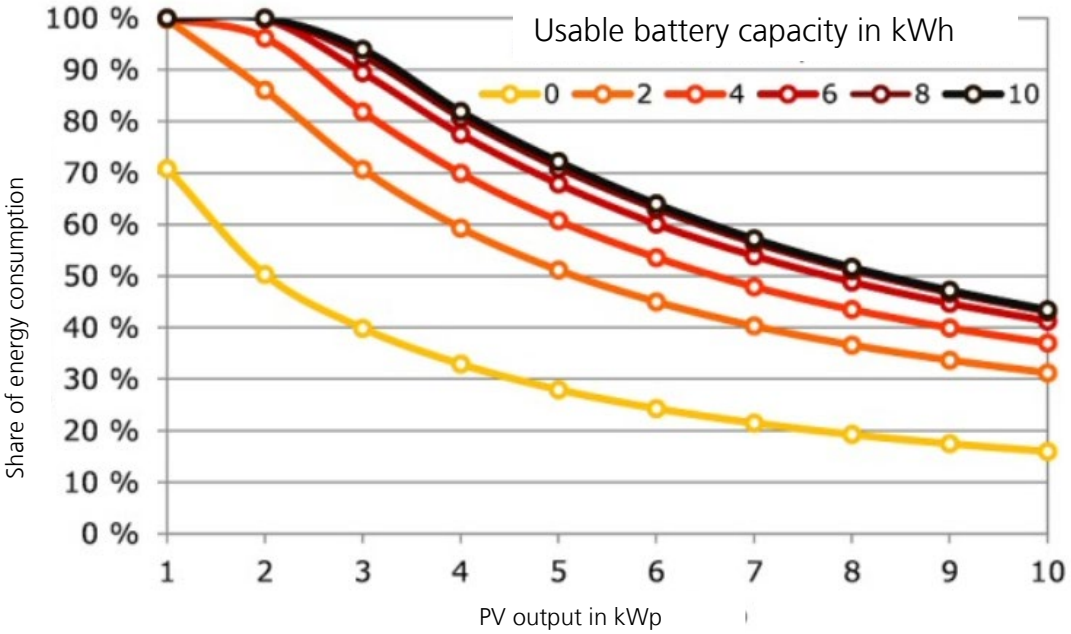


Figure 51: Self-consumption share as a function of battery capacity and power of the solar generator for a single-family household with an annual electricity consumption of 4,700 kWh. [Quasch].

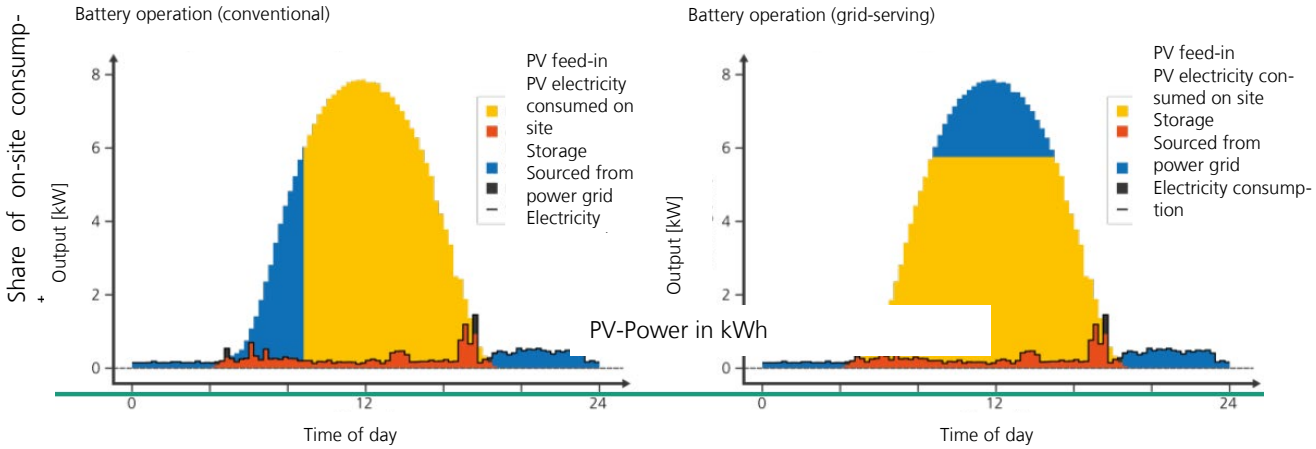


Figure 52: Comparison of conventional and grid-serving operation [ISE7].

22.3.7.2 Vehicle batteries in stationary operation

Thanks to their high consumption and storage capacity, electric vehicles already offer enormous potential as flexible loads through grid-serving charging. (Section 22.3.4).
With **bidirectional energy management** they can also be used 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. Assuming an average peak power capacity of 20 kW per charging point, the bidirectional controllable capacity would be 80 GWp. The German federal government has set the goal of bringing at least 15 million e-cars to the streets by 2030.
If each electric car has an average battery capacity of 40 kWh, there would be around 64 GWh of storage capacity on Germany's roads and parking lots by the end of 2024, spread across 1.6 million vehicles.

22.3.7.3 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 nominal capacity.
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.

22.3.7.4 High-temperature heat storage with reconversion

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 to drive a conventional steam turbine, possibly with further utilisation 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.

22.3.7.5 Hydrogen storage with reconversion

For longer periods with low PV and wind power generation, our future energy system will require additional hydrogen generation, storage and reconversion capacities. Depending on production costs and geostrategic factors, part of the production will take place outside Germany.
9.4 PWh of energy in the form of hydrogen could theoretically be stored in German onshore salt caverns [Hydro], which corresponds to 3.2 times the primary energy consumption in 2024. It is already technically possible today to increase the proportion of hydrogen in the gas grid to up to 20 percent.
Hydrogen can be reconverted via thermal power plants or stationary fuel cells (up to approx. 65 percent efficiency). 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 the combined use of electrolyzers and fuel cells, these bidirectional converters promise a higher number of full load hours.

22.3.7.6 Overview

Figure 53 shows important paths for storage of PV and wind electricity. For the practical relevance of these paths, the costs of the nominal power of converters (€/W) and the capacity of storage (€/Wh), among others, must be considered in addition to the technical efficiency. The water reservoirs of pumped-storage power plants serve as mechanical storage systems. Battery storage systems, on the other hand, include stationary and mobile storage systems that allow bidirectional charging.

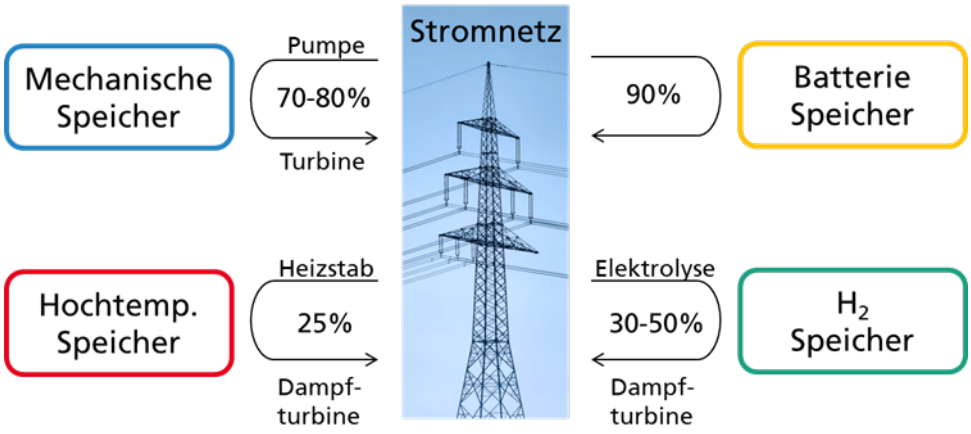


Figure 53: Technologies for the storage of electrical energy at efficiencies achievable today.

22.3.8 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.

22.3.8.1 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, 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.

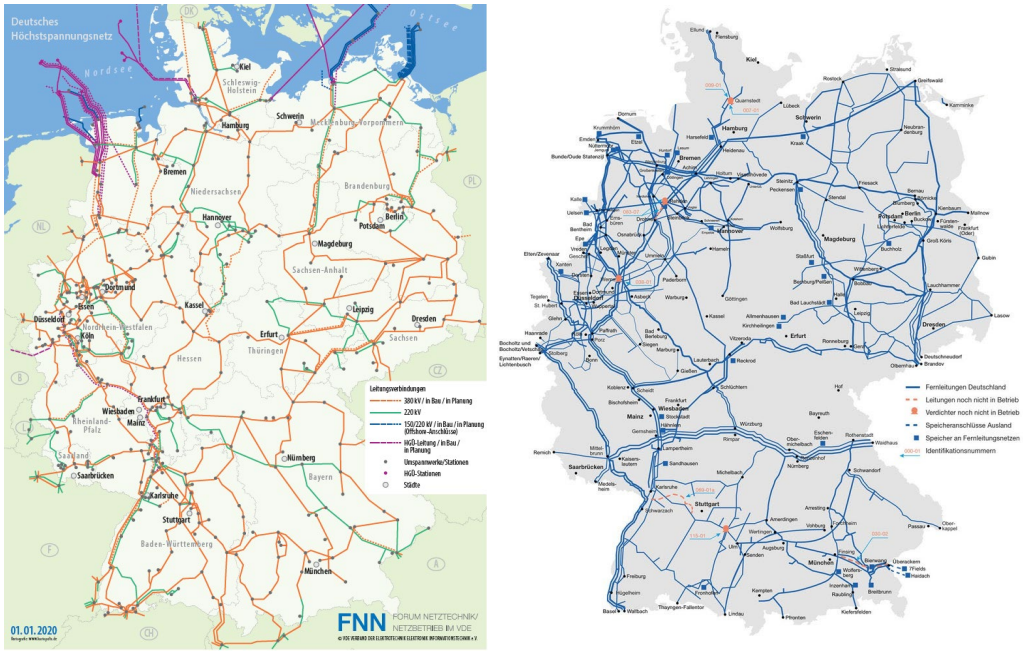


Figure 54: Extra-high voltage grid [VDE] and gas transmission grid [Fern].

22.3.8.2 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.

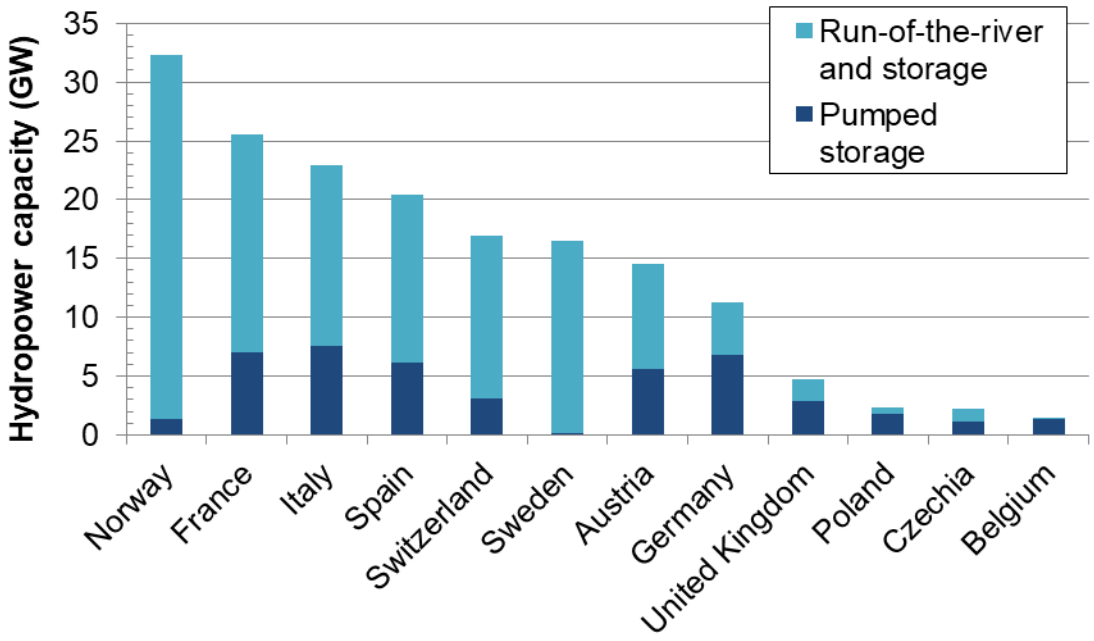


Figure 55: Installed capacity of hydropower plants in neighboring countries, figures from [IHA].

Figure 55 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.

22.3.9 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.

22.3.10 Overview

From today's perspective, an energy system based on 100 percent RE is technically and economically feasible. Figure 56 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 and gas turbines are used.
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 57 summarizes the most important expansion measures for an energy transition in the electricity sector with coupling to the transport and heat sectors.

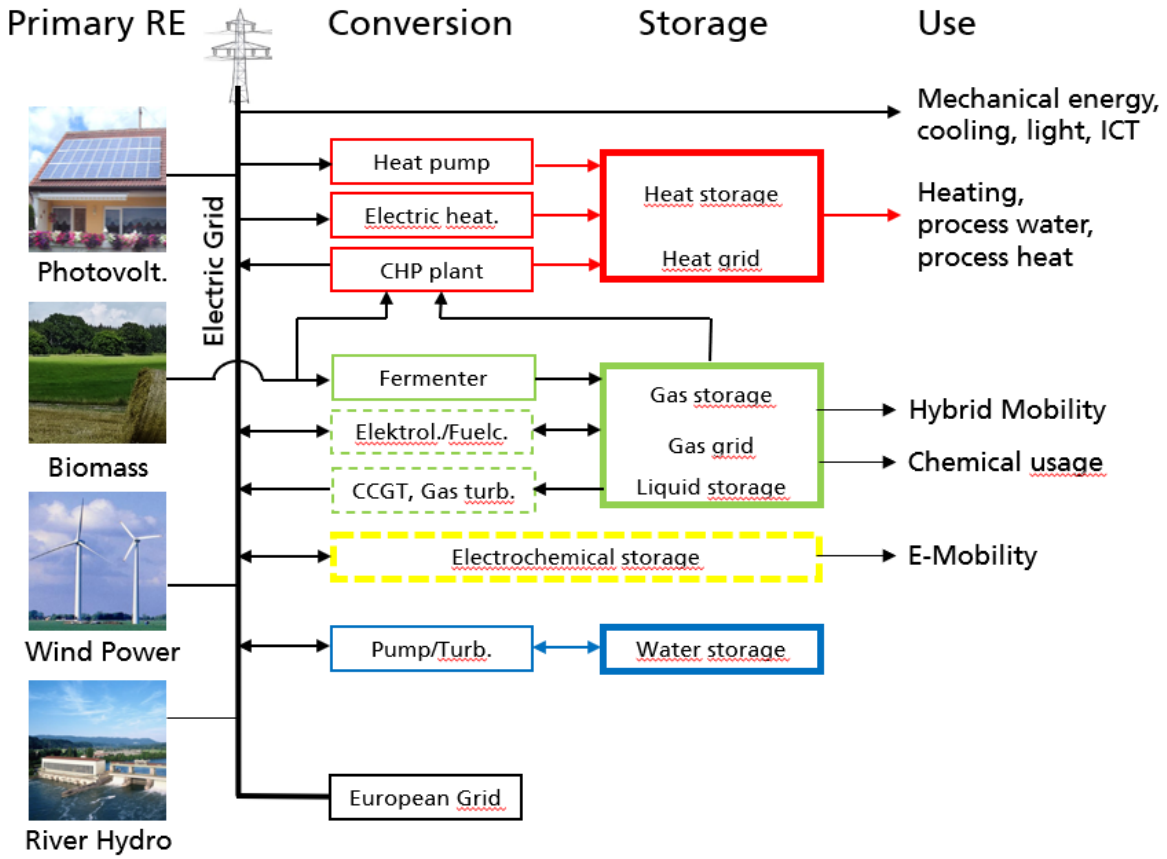


Figure 56: Simplified schematic representation of a renewable energy system with the most important electricity grid-related components of generation, conversion, storage, and consumption; ICT: information and communication technology, CHP: combined heat and power, CCGT: combined cycle gas and steam power plant.

Nennleistung	2024		2045 Szenario „Technologieoffen“	
1. Primärerzeugung	99 GW_P	→	471 GW_P	PV, im Netz max. 329 GW (70%)
	72 GW_P	→	308 GW_P	Wind, Land + See
2. Gaskraftwerke	37 GW_P	→	146 GW_P	H_2-ready, auch GuD, KWK
3. Batterien	12 GW_P	→	[397 GW_P]	[Nennleistung ≈ Kapazität / 1 h]
4. Wärmepumpen	[10 $GW_{P,el}$]	→	[75 $GW_{P,el}$]	[im Mittel 5 kWh_{el} für 15 kW_{th}, COP = 3)]
5. Elektrolyse	0,25 GW_P	→	68 GW_P	Kapazität 9400 TWh H_2 in Salzkavernen

Figure 57: Important power generators, converters and storage units, additional estimates and assumptions in square brackets ([ISE3], see also Section 22.3.7).

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, controlling their own investment decisions, through to mandatory solar installation. Many federal states have introduced so-called solar obligations for residential and commercial construction, public buildings, and large parking lots. The solar obligation sets an example for the responsibility to make maximum use of already developed areas to cover the energy needs of their users, thereby reducing the use of open spaces. The solar obligation reminds builders of the installation of a solar system at an economically optimal time (the roof is being redone, tradespeople are nearby, wiring can be planned). Ultimately, the solar obligation defines a new normality: solar systems are as much a part of the roof as a gutter.

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.

24 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.

25 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.

25.1 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. 15 g lead [Li]). 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.

25.2 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.

25.3 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.

25.4 Take-back and recycling

In June 2010, PV producers launched a cross-manufacturer recycling system (PV Cycle). 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).

Recycling centers accept small quantities of old solar modules free of charge, and there are industrial processes for separating and recycling the materials. The aluminum frame, cables, and connection boxes are simply removed and the metals recycled. Mechanical separation processes are then used to separate the glass, connectors, silicon, and plastic. The glass fraction is used to manufacture glass wool. Trials are currently underway to process the glass on an industrial scale for higher-value melting applications, including new solar glass. The copper is recovered from the solder-coated connectors in the melt. The silicon fraction is reused as a metallurgical raw material. Here, too, attempts are being made to serve higher-value applications, including new solar cells. Silver accounts for less than one-tenth of one percent by weight but makes up almost half of the material value. There are processes for recovering silver in pure form (by the company Solar Materials). The plastic fraction is often thermally recycled.
Figure 58 shows the mass fractions of the most important materials in PV modules and the relative material value of the recycled materials. In its white paper, Deutsche Umwelthilfe (German Environmental Aid) highlights potential for improvement in the reuse and recycling of PV modules [DUH].

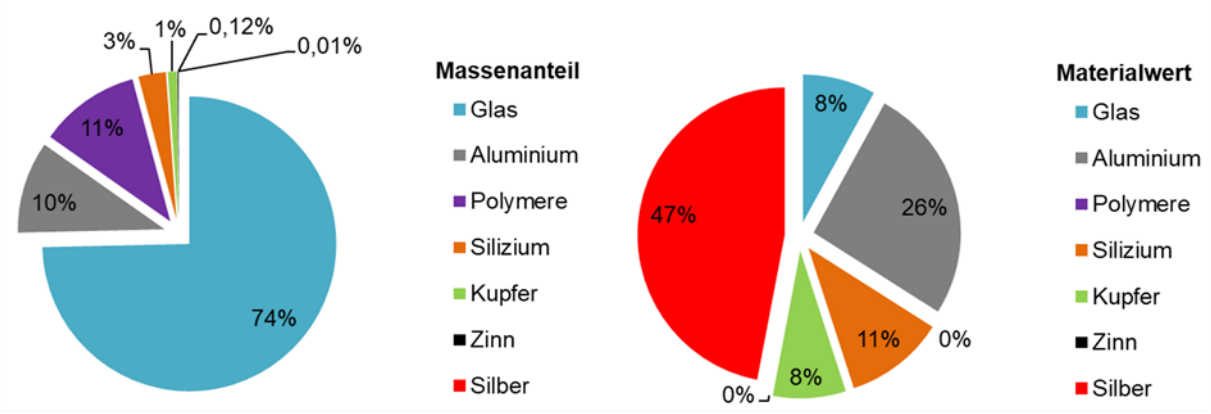


Figure 58: PV Module: Share of mass and value of the recovered materials [Peters]

26 Are there sufficient raw materials available for the production of PV modules?

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.

27 Do PV systems increase the risk of fire?

27.1 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]

27.2 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]

27.3 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.

27.4 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].

28 Appendix: Technical terms

28.1 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.

28.2 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.

28.3 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).

28.4 Annual utilization rate (capacity factor)

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

28.5 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.

28.6 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.

28.7 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.

28.8 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 [ISET].
The residual load results from the net load minus the feed-in from renewable energies.

28.9 Electricity generation and consumption

Figure 59 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.
Gross electricity generation is the total amount of electricity produced, equal to the difference between primary energy consumption and conversion losses in electricity production. 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. **Net electricity generation** (not shown in the figure) is the difference between

gross electricity generation and self-consumption. **Gross electricity consumption** equals gross electricity generation minus import balance and storage. Gross electricity consumption accounts for the power plants' self-consumption. The self-consumption of fossil and nuclear power plants is about 7 percent of their gross power generation; for PV-only power plants it is marginal. Battery storage systems are increasingly used in connection with PV power plants ("behind-the-meter"). Their storage losses are included in the self-consumption of such PV-battery power plants. Battery storage systems that only exchange energy with the power grid ("front-of-meter") are balanced in the same way as pumped-storage power plants. Storage losses of Li-ion batteries amount to approx. 5–10 percent of the amount of electricity stored, plus the losses in the battery management system. For pumped-storage power plants it is around 25 percent. When hydrogen is used to store electricity using stationary electrolyzers and fuel cells, for example, the losses are in the order of 50 percent.
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.

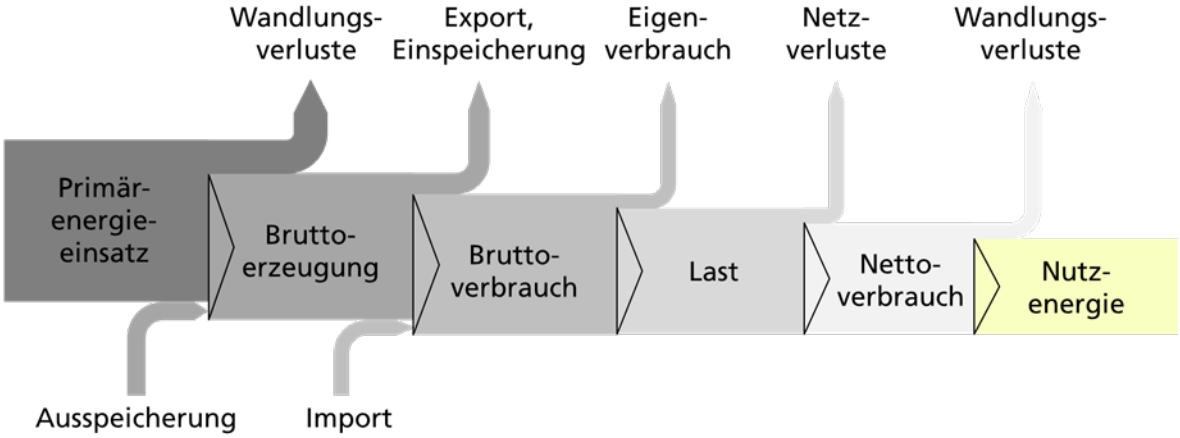


Figure 59: Electricity generation and consumption terms.

29 Appendix: Abbreviations

BEV	Battery Electric Vehicle
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BSW	German Solar Industry Association
BMWK	Federal Ministry for Economic Affairs and Climate Action
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

30 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/m³]	Heating value [kWh/kg]	Heating value [kWh/l] bzw. [kWh/m³]	Heating value [MJ/kg]	Heating value [MJ/l] bzw. [MJ/m³]
Hard coal	-	8,3 - 10,6	-	30,0 - 38,1	-
Brown coal	-	2,6 - 6,2	-	9,2 - 22,2	-
Natural gas H (in m³)	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 m³)	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

31 Appendix: Sources

AEE2	https://www.unendlich-viel-energie.de/presse/pressemitteilungen/ erneuerbare-energien-in-deutschland-zwischen-akzeptanz-und-unsicherheit, Download im Dezember 2023
AGEB1	Energieverbrauch in Deutschland im Jahr 2023, Arbeitsgemeinschaft Energiebilanzen e.V., März 2024
AGEB2	Energieflussbild 2020 für die Bundesrepublik Deutschland in Petajoule, Arbeitsgemeinschaft Energiebilanzen, September 2023
AGEE	Erneuerbare Energien in Deutschland, Daten zur Entwicklung im Jahr 2024, Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat), März 2025
AGORA	Klimaneutrales Stromsystem 2035. Wie der deutsche Stromsektor bis zum Jahr 2035 klimaneutral werden kann; Agora Energiewende, Prognos, Consentec (2022)
ARIA1	Deutschland auf dem Weg zur Klimaneutralität 2045 — Szenarien und Pfade im Modellvergleich, Kopernikus-Projekt Ariadne, Oktober 2021
ARIA2	Wasserstoff und die Energiekrise: fünf Knackpunkte, Kopernikus-Projekt Ariadne, Potsdam-Institut für Klimafolgenforschung (PIK), September 2022
ATW	Weis M, van Bevern K, Linnemann T. Forschungsförderung Kernenergie 1956 bis 2010: Anschubfinanzierung oder Subvention? — ATW 56. Jg. (2011) Heft 8/9
Aurora	Systemkostenreduzierter Pfad zur Klimaneutralität im Stromsektor 2040, Aurora Energy Research im Auftrag der EnBW, 2025
BAFA	Hintergrundinformationen zur Besonderen Ausgleichsregelung, Antragsverfahren 2014 auf Begrenzung der EEG-Umlage 2014, Hrsg.: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) und Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), 15. Oktober 2013
BCG	Klimapfade für Deutschland, Studie, The Boston Consulting Group (BCG) und Prognos, im Auftrag des Bundesverbandes der Deutschen Industrie (BDI), Januar 2018
BDEW1	BDEW-Strompreisanalyse, Bundesverband der Energie- und Wasserwirtschaft e.V., Juli 2024
BDEW3	Stromerzeugung und -verbrauch in Deutschland, Mitteilung des BDEW (www.bdew.de/presse/presseinformationen/erneuerbare-energien-deckten-im-jahr-2021-rund-42-prozent-des-stromverbrauchs), Dezember 2021
BDEW4	Redispatch in Deutschland — Auswertung der Transparenzdaten, BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., 9. August 2016
BDI	Handlungsempfehlungen zur Studie Klimapfade 2.0 — Wie wir unser Industrieland klimaneutral gestalten, Bundesverband der Deutschen Industrie, Oktober 2021
BFE	Grundlagen zu Vorurteilen gegenüber der Solarenergie, Schlussbericht, Studie im Auftrag der EnergieSchweiz, Bundesamt für Energie, 2021

BMEL	Daten und Fakten, Land-, Forst- und Ernährungswirtschaft mit Fischerei und Wein- und Gartenbau, Bundesministerium für Ernährung und Landwirtschaft (BMEL), Dezember 2017
BMVI	Räumlich differenzierte Flächenpotentiale für erneuerbare Energien in Deutschland. BMVI (Hrsg.), BMVI-Online-Publikation 08/2015.
BMWK1	Gesamtausgabe der Energiedaten — Datensammlung des BMWK, letzte Aktualisierung: Januar 2022
BMWK2	Bundesbericht Energieforschung 2024, Bundesministerium für Wirtschaft und Klimaschutz (BMWK), Juli 2024
BMWK3	EEG: Daten und Fakten: Vergütungen, Differenzkosten und EEG-Umlage 2000 bis 2022, Stand Oktober 2021 https://www.erneuerbare-energien.de/EE/Navigation/DE/Recht-Politik/Das_EEG/DatenFakten/daten-und-fakten.html#doc95662bodyText2
BNA1	Bundesnetzagentur legt Eigenkapitalrenditen für Strom- und Gasnetze fest, Pressemeldung der Bundesnetzagentur vom Oktober 2016
BNA2	Monitoringbericht 2024, Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen und Bundeskartellamt, Februar 2025
BNA3	https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/ErneuerbareEnergien/ZahlenDatenInformationen/EEG_Registerdaten/start.html, Stand September 2022
BNA4	https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Ausschreibungen/start.html
BNE	Solarparks – Gewinne für die Biodiversität, Studie des Bundesverbands Neue Energiewirtschaft (bne) e.V., November 2019
BNEF	Interview mit Bloomberg NEF Analyst Jenny Chase, Dezember 2022 https://www.pv-magazine.com/2022/12/23/global-solar-capacity-additions-hit-268-gw-in-2022-says-bnef/
BSW	Statistische Zahlen der deutschen Solarstrombranche (Photovoltaik), Bundesverband Solarwirtschaft e. V., Dezember 2024
Bundestag	EEG-Umlage 2010, Deutscher Bundestag, Wissenschaftliche Dienste, Nr. 21/10, 25.03.2010
Bub	Buberger J, Kersten A, Kuder M, Eckerle R, Weyh T, Thiringer T. Total CO_2-equivalent life-cycle emissions from commercially available passenger cars, Renewable and Sustainable Energy Reviews, Volume 159, 2022
BVES	BVES Branchenanalyse 2022, Bundesverband Energiespeicher Systeme e.V., April 2022
BWP	Starkes Wachstum im Wärmepumpenmarkt, Pressemitteilung des Bundesverband Wärmepumpe (BWP), Januar 2022
DENA	DENA-Gebäudereport 2022 — Zahlen, Daten, Fakten; Deutsche Energie-Agentur (Hrsg.), Oktober 2021
DESTATIS	Umweltökonomische Gesamtrechnungen, Private Haushalte und Umwelt, DESTATIS, Statistisches Bundesamt, September 2020

DIW	Göke L, Kemfert C, Kendziorski M, von Hirschhausen C. 100 Prozent erneuerbare Energien für Deutschland: Koordinierte Ausbauplanung notwendig, DIW Wochenbericht Nr. 29+30, Juli 2021
DUH	Kreislaufwirtschaft in der Solarbranche stärken — Alte Photovoltaik-Module für den Klima- und Ressourcenschutz nutzen, Deutsche Umwelthilfe e.V., März 2021
DWD	Rasterdaten der Jahressumme für die Globalstrahlung auf die horizontale Ebene für Deutschland basierend auf Boden- und Satellitenmessungen, Version V003, Climate Data Center (CDC), Deutscher Wetterdienst, 2022
EAFR	Betriebskonzepte für Photovoltaik auf Mehrfamilienhäusern, Leitfaden der Energieagentur Regio Freiburg, Juli 2022
ECTI	The role of Direct Air Capture technologies in the EU's decarbonisation effort, Directorate-General for Economy, Transformation and Industry, June 2025
EEBW	Erneuerbare Energien in Baden-Württemberg 2011, Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg, November 2012
EEG 2021	Gesetz zur Änderung des Erneuerbare-Energien-Gesetzes und weiterer energierechtlicher Vorschriften (EEG 2021), Bundesrat Drucksache 763/20, Dezember 2020
EEG 2023	Gesetz zu Sofortmaßnahmen für einen beschleunigten Ausbau der erneuerbaren Energien und weiteren Maßnahmen im Stromsektor, Bundesrat Drucksache 315/22, Juli 2022
EGGERS	Eggers J-B, Behnisch M, Eisenlohr J, Poglitsch H, Phung W-F, Münzinger M, Ferrara C, Kuhn T. PV-Ausbauerfordernisse versus Gebäudepotenzial: Ergebnis einer gebäudescharfen Analyse für ganz Deutschland, 35. PV-Symposium, ISBN 978-3-948176-09-9, September 2020
EnBW1	EnBW verstärkt Engagement im Bereich Solarenergie, Pressemeldung, Energie Baden-Württemberg AG, Februar 2019
ENBW2	EnBW will Kraftwerk Altbach/Deizisau bis 2026 kohlefrei und langfristig klimaneutral machen, Pressemeldung, Energie Baden-Württemberg AG, Oktober 2021
ENER	E-Mobility-Zukunft: ENERVIE an Meilenstein-Projekt beteiligt, Pressemeldung, Südwestfalen Energie und Wasser AG, Oktober 2018
EON	Flexibilitäts-Check, Studie von E.ON und der Forschungsstelle für Energiewirtschaft (FfE) zum Potenzial flexibler Energienutzung in deutschen Haushalten, Juni 2025
ESYS	Wenn nicht jetzt, wann dann – wie die Energiewende gelingt, Nationale Akademie der Wissenschaften Leopoldina, acatech – Deutsche Akademie der Technikwissenschaften, Union der deutschen Akademien der Wissenschaften, Oktober 2021
EPA	United States Environmental Protection Agency, heruntergeladen am 9.7.2013 von http://www.epa.gov/climatechange/science/causes.html#GreenhouseRole

EUPD	Energiewende im Kontext von Atom und Kohleausstieg, Perspektiven im Strommarkt bis 2040, Studie der EUPD Research Sustainable Management GmbH, Update Mai 2020
FAU	Deutschland ohne erneuerbare Energien? – Ein Update für die Jahre 2014 bis 2018, Diskussionspapier im Auftrag der EWS Elektrizitätswerke Schönau, Friedrich-Alexander-Universität Erlangen-Nürnberg, Oktober 2019
Fern	Download am 13.11.2021 von https://www.bmwi.de/Redaktion/DE/Artikel/Energie/gas-erdgasversorgung-in-deutschland.html
FFE	Homepage der Forschungsgesellschaft für Energiewirtschaft mbH, Download https://www.ffegmbh.de/aktuelles/veroeffentlichungen-und-fachvortraege/828-merit-order-der-konventionellen-kraftwerke-in-deutschland-2018, Februar 2020
FNR	Basisdaten Bioenergie Deutschland 2022, Fachagentur Nachwachsende Rohstoffe e.V., Juli 2022
FÖS1	Gesellschaftliche Kosten der Atomenergie in Deutschland, Eine Zwischenbilanz der staatlichen Förderungen und gesamtgesellschaftlichen Kosten von Atomenergie seit 1955, Studie des FÖS im Auftrag von Greenpeace Energy eG, September 2020
FÖS2	Was Braunkohlestrom wirklich kostet, Studie des Forums Ökologisch-Soziale Marktwirtschaft e.V. (FÖS) im Auftrag von Greenpeace Energy eG, Juni 2018
FZJ	Reversible Brennstoffzelle bricht Wirkungsgrad-Rekord, Pressemeldung, Forschungszentrum Jülich, Dezember 2018
HTW1	Sinnvolle Dimensionierung von Photovoltaikanlagen für Prosumer, Kurzstudie, Hochschule für Technik und Wirtschaft Berlin, März 2019
HTW2	Solarstromausbau für den Klimaschutz, Studie, Hochschule für Technik und Wirtschaft Berlin, November 2021
Hydro	Caglayan D, Weber N, Heinrichs H, Linßen J, Robinius M, Kukla P, Stolten D. Technical potential of salt caverns for hydrogen storage in Europe, International Journal of Hydrogen Energy, Volume 45, Issue 11, 2020
ICCT	Life-cycle greenhouse gas emissions from passenger cars in the European Union, International Council on Clean Transportation, 2025
IEA1	Energiepolitik der IEA-Länder, Prüfung 2013, Deutschland, Zusammenfassung, International Energy Agency (IEA), April 2013
IEA2	World Energy Outlook 2024, International Energy Agency, Oktober 2024.
IEA3	Snapshot of Global PV Markets 2023, International Energy Agency PVPS, , 2023.
IEA4	Special Report on Solar PV Global Supply Chains, International Energy Agency, 2022.
IEA5	Environmental Life Cycle Assessment of Passivated Emitter and Rear Contact (PERC) Photovoltaic Module Technology, IEA Task 12 PV Sustainability, 2024
IEE	Neues Strommarktdesign für die Integration fluktuierender Erneuerbarer Energien, Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik IEE, Fraunhofer-Institut für Solare Energiesysteme ISE, Becker Büttner Held Rechtsanwälte, November 2021

IHA	Hydropower status report, International Hydropower Association, May 2019
IMF	Parry I, Black S, Vernon N. Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies, International Monetary Fund, 2021
IPCC	Climate Change 2021: The Physical Science Basis, Intergovernmental Panel on Climate Change (IPCC), Working Group I report as contribution to the Sixth Assessment Report (AR6), August 2021
IPV	Nover J, Zapf-Gottwick R, Feifel C, Koch M, Werner JH. Leaching via Weak Spots in Photovoltaic Modules. Energies. 14(3):692 2021; https://doi.org/10.3390/en14030692
IRENA	Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects, Studie der International Renewable Energy Agency (IRENA), Abu Dhabi, 2019
ISE1	Kost C, Müller P, Schweiger J S, Fluri V, Thomsen J. Stromgestehungskosten Erneuerbare Energien; Studie des Fraunhofer-Instituts für Solare Energiesysteme ISE, Juli 2024
ISE2	Kiefer K, Farnung B, Müller B. Degradation in PV Power Plants: Theory and Practice. 36th European Photovoltaic Solar Energy Conference and Exhibition, Marseille, 2019.
ISE3	Thelen C, Nolte H, Kaiser M, Jürgens P, Müller P, Senkpiel C, Kost C: „Wege zu einem klimaneutralen Energiesystem: Bundesländer im Transformationsprozess“, 2024, Fraunhofer ISE.
ISE4	https://www.energy-charts.de, Verantwortlicher Redakteur: Prof. Dr. Bruno Burger, Fraunhofer-Institut für Solare Energiesysteme ISE
ISE5	Photovoltaics Report, Fraunhofer-Institut für Solare Energiesysteme ISE, PSE Photovoltaics Projects GmbH, Juli 2024
ISE6	Photovoltaik-Brandschutz – Fakten statt Phantome, Pressemeldung, Fraunhofer ISE, Februar 2013 (Näheres zum Brandschutz unter www.pv-brandsicherheit.de)
ISE7	Speicherstudie 2013 — Kurzgutachten zur Abschätzung und Einordnung energiewirtschaftlicher, ökonomischer und anderer Effekte bei Förderung von objektgebunden elektrochemischen Speichern, Studie des Fraunhofer-Instituts für Solare Energiesysteme ISE, Januar 2013
ISE8	Sustainable PV Manufacturing in Europe – An Initiative for a 10 GW GreenFab, Studie des Fraunhofer ISE, Juli 2020
ISE9	Deutschland hat großes Potenzial für Schwimmende Photovoltaik, Presseinfo des Fraunhofer-Instituts für Solare Energiesysteme ISE, Juli 2024
ISET	Saint-Drenan Y-M et al. „Summenganglinien für Energie 2.0“, Studie des Instituts für Solare Energieversorgungstechnik, ISET e.V., April 2009
ISI	Langfristszenarien für die Transformation des Energiesystems in Deutschland, Kurzbericht: 3 Hauptszenarien; Fraunhofer-Institut für System- und Innovationsforschung ISI, Consentec GmbH, Mai 2021
IVL	Lithium-Ion Vehicle Battery Production, Status 2019 on Energy Use, CO_2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling, Studie des Swedish Environmental Research Institute im Auftrag der Swedish Energy Agency, November 2019

IWU	Forschungsdatenbank NichtWohnGebäude, Institut Wohnen und Umwelt GmbH, Schlussbericht, März 2022
KBA	Zahlen im Überblick – Statistik, Kraftfahrt-Bundesamt, Juni 2018
LCA	Müller A, Friedrich L, Reichel C, Herceg S, Mittag M, Neuhaus H. A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory, Solar Energy Materials and Solar Cells, Volume 230, 2021
LFU1	Berechnung von Immissionen beim Brand einer Photovoltaik-Anlage aus Cadmiumtellurid-Modulen, Bayerisches Landesamt für Umwelt, 11-2011
LFU2	Beurteilung von Kunststoffbränden, Az: 1/7-1515-21294, Bayerisches Landesamt für Umwelt, 1995
Li	Li F, Shaw S, Libby C, Bicer B, TamizhMani G, Lead Content Estimation in Silicon PV Modules, 2024 IEEE 52nd Photovoltaic Specialist Conference (PVSC), Seattle, WA, USA, 2024, pp. 0985-0987, doi: 10.1109/PVSC57443.2024.10749202.
Licht1	Analyse des Beitrags von Mini-BHKW zur Senkung von CO_2-Emissionen und zum Ausgleich von Windenergie, Gutachten zum geplanten »ZuhauseKraftwerk« im Auftrag der LichtBlick AG, LBD-Beratungsgesellschaft mbH, 2009
Licht2	Repräsentative Umfrage zu erneuerbaren Energien, Marktforschungsinstitut YouGov im Auftrag der LichtBlick SE, Februar 2020
Lopez	Martinez Lopez VA, Ziar H, Haverkort JW, Zeman M, Isabella O, Dynamic operation of water electrolyzers: A review for applications in photovoltaic systems integration, Renewable and Sustainable Energy Reviews, Vol. 182, 2023
MCC	Wissensstand zu CO_2-Entnahmen, Mercator Research Institute on Global Commons and Climate Change (MCC) gGmbH, 2021
MCK	Flexibilität in der industriellen Stromnachfrage: Ein Schlüssel zur Energiewende in Deutschland?, McKinsey & Company, Inc., Juni 2025
MWV	Jahresbericht 2018, Mineralölwirtschaftsverband e.V., Juli 2018
NETZ1	https://www.netztransparenz.de/EEG/Marktpraemie/Marktwerte
NETZ2	Historische Daten: https://www.netztransparenz.de/EEG/Verguetungs-und-Umlagekategorien
NOW	IndWEDe — Industrialisierung der Wasserelektrolyse in Deutschland, Studie im Auftrag des Bundesministeriums für Verkehr und digitale Infrastruktur (BMVI), 2018
NWS	Fortschreibung der Nationalen Wasserstoffstrategie, Bundesministerium für Wirtschaft und Klimaschutz (BMWK), Juli 2023
ÖKO1	Beschäftigungsentwicklung in der Braunkohleindustrie: Status quo und Projektion, Öko-Institut Berlin, Juli 2018
ÖKO2	Aktueller Stand der KWK-Erzeugung (Dezember 2015), Studie des Ökoinstituts e.V. im Auftrag des Bundesministeriums für Wirtschaft und Energie, Dezember 2015

Prog	Klimaneutrales Deutschland. Prognos, Öko-Institut, Wuppertal-Institut, im Auftrag von Agora Energiewende, Agora Verkehrswende und Stiftung Klimaneutralität, Juni 2021
Quasch	Quaschning V. Solare Unabhängigkeitserklärung, Photovoltaik, Oktober 2012
SCBW	Weiterbetrieb von Ü20-Photovoltaikanlagen — Möglichkeiten nach Ende ner EEG-Förderdauer, Faktenpapier, Solar Cluster Baden-Württemberg, Januar 2021
SMARD	„Redispatch je Energieträger“, https://www.smard.de/page/home/topic-article/211816/213384, Abruf am 5.3.2025
SPE	EU Market Outlook For Solar Power 2023 – 2027, SolarPower Europe, Dezember 2023
Sprin	Motorentechnik — Im Fokus, Onlineartikel, Dezember 2010 https://www.springerprofessional.de/motorentechnik/pkw-antriebe-im-ueberblick-vergangenheit-gegenwart-und-zukunft/6561052
RWE	RWE nimmt Batteriespeicher in Herdecke in Betrieb — Sechs Millionen Euro Investition, sieben MWh Kapazität, Pressemeldung, RWE, Februar 2018
Shell	Shell Scenarios Sky — Meeting the goals of the Paris agreement, Shell International B.V., März 2018
Siem	Weit mehr als nur heiße Luft, Pressemeldung, Siemens AG, März 2017
Test	„Immer sparsamer“, test 1/2012, Stiftung Warentest
UBA1	Erneuerbare Energien in Deutschland, Daten zur Entwicklung im Jahr 2022, Umweltbundesamt, Februar 2023
UBA2	Artikel auf https://www.umweltbundesamt.de/daten/energie/kraft-waerme-kopplung-kwk#textpart-1, Oktober 2018
UBA3	Methodenkonvention 3.1 zur Ermittlung von Umweltkosten – Kostensätze Stand 12/2020, Umweltbundesamt, Dezember 2020
UBA4	Daten und Fakten zu Braun- und Steinkohlen, Umweltbundesamt, Dezember 2017
UBA5	Der Europäische Emissionshandel, https://www.umweltbundesamt.de/daten/klima/der-europaeische-emissionshandel#textpart-1, Download im Juni 2019
UBA6	Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990 – 2022, Umweltbundesamt, Mai 2023
UBA7	Aktualisierung und Bewertung der Ökobilanzen von Windenergie- und Photovoltaikanlagen unter Berücksichtigung aktueller Technologieentwicklungen, Studie im Auftrag des Umweltbundesamtes, Mai 2021
UBA8	Emissionsbilanz erneuerbarer Energieträger, Bestimmung der vermiedenen Emissionen im Jahr 2020, Umweltbundesamt, November 2021
UBA9	Energieziel 2050: 100 % Strom aus erneuerbaren Quellen, Umweltbundesamt, Juli 2010
ÜNB1	Mittelfristprognose zur deutschlandweiten Stromerzeugung aus EEG-geförderten Kraftwerken für die Kalenderjahre 2022 bis 2026, r2b energy consulting GmbH, erstellt im Auftrag der 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, Oktober 2021

ÜNB2	Szenariorahmen zum Netzentwicklungsplan Strom 2037 mit Ausblick 2045, Version 2023; Entwurf der Übertragungsnetzbetreiber, Januar 2022
Vatt	CO_2-freie Energie fürs Quartier: Sektorenkoppelnder Stahlspeicher bringt Energiewende auf Hochtemperatur, Pressemeldung, Vattenfall, Oktober 2018
VDE	Download am 13.11.2021 von https://www.vde.com/de/fnn/dokumente/karte-deutsches-hoechstspannungsnetz
VFL	Berechnung einer risikoadäquaten Versicherungsprämie zur Deckung der Haftpflichtrisiken, die aus dem Betrieb von Kernkraftwerken resultieren, Studie der Versicherungsforen Leipzig im Auftrag des Bundesverbands Erneuerbare Energie e.V. (BEE), April 2011
VGB	Kraftwerke 2020+, Stellungnahme des Wissenschaftlichen Beirats der VGB PowerTech e.V., 2010
ZSW	Untersuchung zur Wirkung veränderter Flächenrestriktionen für PV-Freiflächenanlagen, Studie des ZSW im Auftrag der innogy SE, Januar 2019

32 Appendix: Figures

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). 5
Figure 2: Net PV additions: Actual values until 2024 (yellow) , Expansion path to achieve the legal targets shown in orange [ISE4], [BSW], [EEG2023]. 6
Figure 3: Development of the share of renewable energies in gross electricity consumption in Germany [ISE4], Status 12.03.2025 [AGEE]. 6
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. 8
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, data: BSW [ISE5]..... 9
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], Electricity Price Analysis of the BDEW. 10
Figure 7: Exchange electricity and certificate prices in Germany [ISE4]. 11
Figure 8: PV expansion and differential costs, data from [BMWK1], [BMWK3]. Medium-term prognoses of the ÜNB.....13
Figure 9: Process for removing CO_2 from the atmosphere and storing carbon [MCC]. ..15
Figure 10: Composition of the average household electricity price in 2024 [BDEW1]. ...16
Figure 11: Net Electricity import (purple) and solar electricity production (yellow) in 2024 for Germany [ISE4].....17
Figure 12: Estimation of the LCOE for small PV systems under different irradiation conditions, plus fixed remuneration according to EEG. 18
Figure 13: Value Chain for Photovoltaics. 19
Figure 14: Production capacity according to value chain stage and country, data: Wood Mackenzie, 2023 20
Figure 15: PV production sites in Germany and other European countries [SPE].....21
Figure 16: Funding for PV research categorized by technology in € million [BMWK2]. ..22
Figure 17: Distribution of installed PV power according to plant size by the end of 2023 [ISE5]. 24
Figure 18: Actual and predicted hourly generation of power in 2021 [ISE4]. 25
Figure 19: Average power for the supply of solar and wind power in 2021, 15-minute values [ISE4].....26
Figure 20: Monthly totals of PV and wind power production, data from [ISE4]. 27
Figure 21 Annual maximum of the grid feed-in compared to installed PV capacity at the end of the corresponding month, data from [ISE4]. 28
Figure 22: Example showing the course of electricity trading price, conventional and renewable electricity in the 32th calendar week in 2024 [ISE 4]. 29

Figure 23: System Average Interruption Duration Index (SAIDI) for low and medium voltage grid. Data from [BNA2]. 30
Figure 24: Applications for the integration of photovoltaics. 31
Figure 25: Land use in Germany [FNR]. 32
Figure 26: Building stock in millions, data from [DENA], [IWU]. 33
Figure 27: PV solutions for roofs and façades (top row: roof-mounted systems, bottom row: integrated PV). 34
Figure 28: Survey results on the construction of new power plants, data from [Licht2]. 36
Figure 29: Survey results on the acceptance of different types of power plants [AEE2]. 37
Figure 30: Range of electric and biodiesel vehicles per hectare of land used. 39
Figure 31: Electricity yields of PV power plants and silage maize per hectare of land used. 39
Figure 32: Relative yield potential, no shade, located in Freiburg, calculated online using https://re.jrc.ec.europa.eu/pvg_tools/en/. 40
Figure 33: Forecast full utilization hours for electricity generation from EE, data from [ÜNB1]. 42
Figure 34: Horizontal annual global radiation total in Germany, averaged over the period 2001-2020 [DWD]. 44
Figure 35: Development of atmospheric CO_2 concentration, mean global temperature change and solar activity (http://herdsoft.com/climate/widget/). 45
Figure 36: Estimates of atmospheric CO_2 concentration and temperature difference in Antarctica based on ice cores [EPA]; red: CO_2 measurements from Mauna Loa Observatory [https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html]. 46
Figure 37: Global warming potential of electricity generation with mono c-Si PV for roof-mounted and ground-mounted systems [UBA7]. 47
Figure 38: Global warming potential of different electricity generation technologies [UBA7]. 48
Figure 39: Avoided greenhouse gas emissions through the use of renewable energies in 2024 [AGEE]. 48
Figure 40: Development of annual PV additions [IEA3] and average annual growth rate. 49
Figure 41: Energy flow diagram 2022 for Germany, figures in petajoules [AGEB2]. 55
Figure 42: Value and energy volume of net imports of fossil fuels (left axis: value in EUR billion, nominal; right axis: energy volume in PJ) [KFW]. 55
Figure 43: Structure of final energy consumption by application area for Germany in 2020, figures from [BMWK1]. 55
Figure 44: Schematic representation of the REMod model [ISE3]. 57
Figure 45: Schematic representation of a residual load curve for Germany with electricity supply with 100 percent RE. 58
Figure 46: Development of the global electricity generation by technology and scenario [IEA2]. 60
Figure 47: Electricity yield profiles of PV power plants in different mounting variants, calculated online with https://re.jrc.ec.europa.eu/pvg_tools for a predominantly clear day in May at the Freiburg site, no shading, bifaciality factor 100 %. 61

Figure 48: Electricity yield profiles of PV systems mounted in various ways on a predominantly sunny day in May, no shade, located in Freiburg, calculated online using https://re.jrc.ec.europa.eu/pvg_tools. 62
Figure 49: Electricity yield profiles of PV systems mounted in various ways, no shade, located in Freiburg, calculated online using https://re.jrc.ec.europa.eu/pvg_tools; the percentages provide the relative annual yield in relation to the 45° inclination. 62
Figure 50: 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]. 64
Figure 51: 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].....70
Figure 52: Comparison of conventional and grid-serving operation [ISE7]. 70
Figure 53: Technologies for the storage of electrical energy at efficiencies achievable today.....72
Figure 54: Extra-high voltage grid [VDE] and gas transmission grid [Fern]. 73
Figure 55: Installed capacity of hydropower plants in neighboring countries, figures from [IHA].....74
Figure 56: 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. 75
Figure 57: Important power generators, converters and storage units, additional estimates and assumptions in square brackets ([ISE3], see also Section 22.3.7). 76
Figure 58: PV Module: Share of mass and value of the recovered materials [Peters].....80
Figure 59: Electricity generation and consumption terms. 85