Recent Facts about Photovoltaics in Germany

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1 What purpose does this guide serve?

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

2 Are we reaching our annual capacity target?

The annual target of the German Federal Government for PV expansion was exceeded in 2019, but the goals of the energy revolution are still far away.

In order to cover all of our energy needs from renewable energies (RE), a massive expansion of the installed PV power is necessary, along with a number of other measures. Various model-based scenarios anticipate an expansion corridor of 120-310 GW, depending on assumptions on boundary conditions and accompanying measures ([BCG], [ACA], [ESYS], [ISE5], [IWES], [UBA], [ISE11], [UBA8], [IRENA]). If we assume a PV expansion of 200 GW by 2050, then an average of 5 GW of PV will have to be added annually. Increasingly, old systems also have to be replaced. These replacement installations are currently negligible, but they increase in fully exploited condition with an assumed useful life of 30 years to almost 7 GW per year.

The coalition agreement of March 2018 provides for an interim goal to increase the share of renewable energies (RE) to 65 percent of gross electricity consumption by 2030. For this, an average annual PV addition of at least 5-10 GW is necessary, depending on the development of the electricity demand ([AGORA1], [BEE]).

From 2013-2018, power plants with a nominal output of only 1.8 GW/a were installed on average in Germany, in 2019 it was around 3.6 GW. The federal government's draft climate protection program, adopted on October 9, 2019, provides for a total expansion goal of 98 GW of photovoltaics by 2030. This would require an average of 4.5 GW/a of additional photovoltaics.

3 Does PV contribute significantly to the power supply?

Yes.
In 2019, PV generated 8.2% of gross electricity consumption (definition in Section 8524.8) with an electricity generation of about 46.5 TWh [ISE4] in Germany, all renewable energies (RE) came to 43% (Figure 1). On sunny days, PV electricity can temporarily cover up to 50% of our current electricity consumption. At the end of 2019, PV modules with a nominal output of almost **49 GW** were installed in Germany [ISE4], distributed over **1.7 million systems** [BSW1].

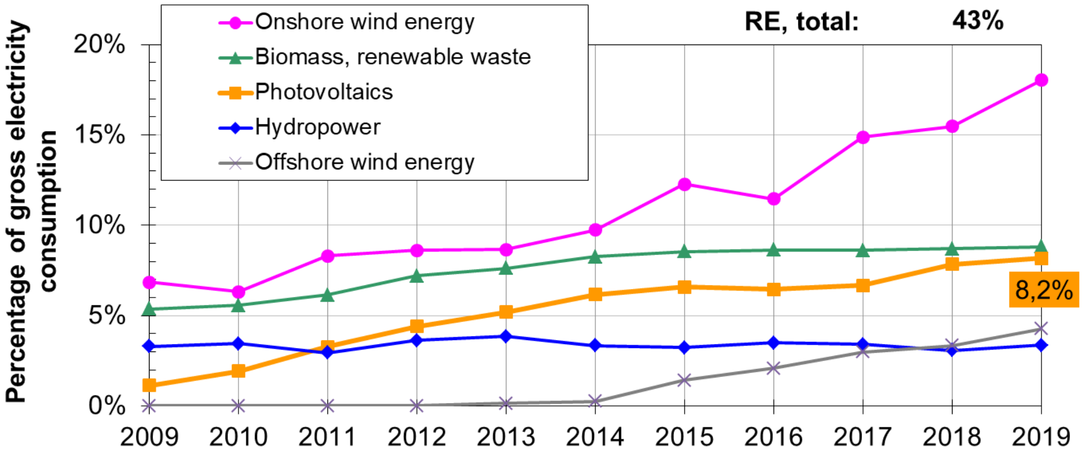

Figure 1: Percentage renewable energy in net electricity consumption for Germany, data from [BMWi1], [BDEW3], [ISE4]

4 Is PV power too expensive?

It depends on the reference point.
It is difficult to compare the costs of PV electricity with fossil and nuclear electricity since external costs incurred by environmental, climate and health damage or risks as a result of pollutant emissions are largely left out ([UBA3], [FÖS1], [FÖS2]).

The marginal costs for nuclear power are in the order of 1 €-ct/kWh, for coal-fired power 3-7 €-cts/kWh, for gas-fired power 6-9 €-cts/kWh. The fixed costs of power generation (e.g. investments, capital) are added on top of this. The marginal costs essentially cover the provision of the fuel, but not the neutralization of the radiating waste or polluting emissions (CO_2, NOx, SOx, Hg). Although an EU-wide emissions trading (European Union Emissions Trading System, EU ETS) was introduced for the energy sector in 2005 to make CO_2 emissions more expensive and to internalize costs to some extent. Due to an overabundance of certificates, however, the price had collapsed by the end of 2017. In addition, certificate trading covers only 45% of greenhouse gas emissions across Europe, because important sectors are excluded [UBA5]. Estimates of the direct and indirect follow-up costs also facing Germany in the coming years due to global climate change are not yet known.

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

In new MW power plants, PV electricity is produced at costs starting at 4-5 €-cts/kWh, under the condition that the produced electricity is directly fed into the grid. The power produced by the older, smaller power plants is much more expensive, due to the previously higher investment costs. In order to bring on the energy revolution and foster investments in PV systems of all sizes, the German Renewable Energy Sources Act RES (Erneuerbare Energien Gesetz EEG) was created in 2000. This instrument guarantees a fixed rate of purchase and enables plant operators to run their installations with an appropriate profit. The aim of the Renewable Energy Source Act is to effect a continual reduction in the cost of electricity generation from renewables by creating a market for RE systems. (See section 4.1).

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

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

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

4.1 Levelized Cost of Energy

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

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

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

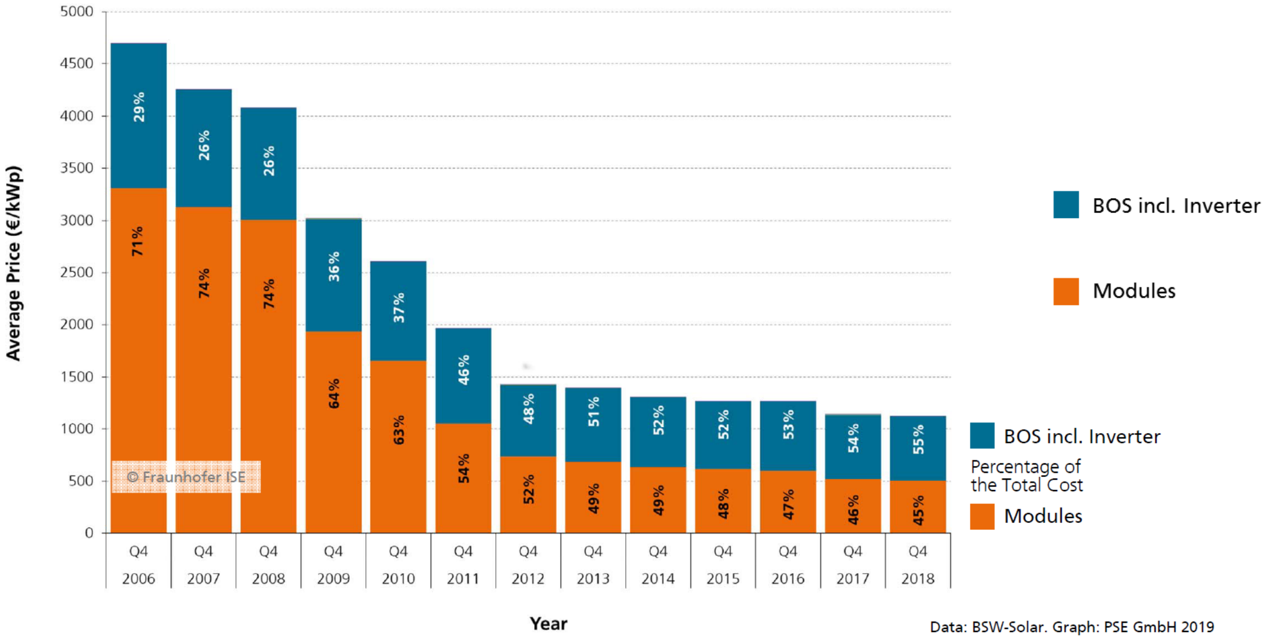

Figure 2: Average end customer price (net system price) for installed rooftop systems with rated nominal power from 10 - 100 kWp [ISE10].

Module costs are responsible for almost half of the total investment costs of a PV power plant of this size. This percentage increases for larger power plants. The price development of PV modules follows a so-called «price learning curve," in which doubling the total capacity installed causes prices to fall by a constant percentage. Figure 3 shows inflation-adjusted world market prices. At the end of 2018, approximately **500 GW of PV power** had been installed worldwide. Provided that significant progress continues to be made in product development and manufacturing processes, prices are expected to keep dropping in accordance with this rule.

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

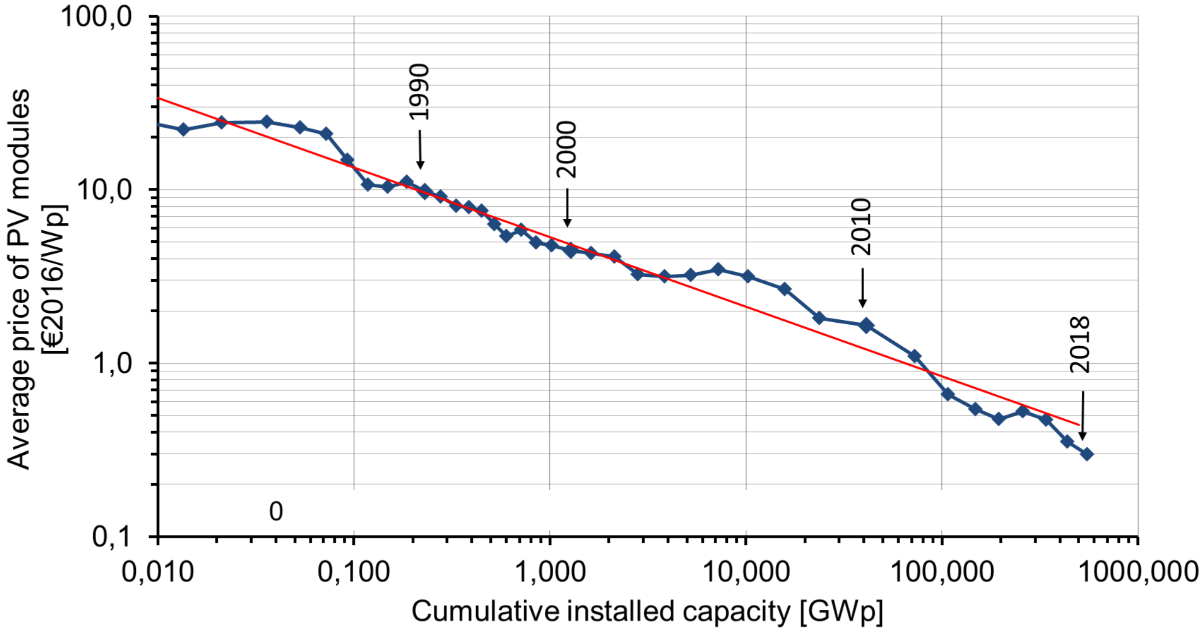

Figure 3: Historical price development of PV modules (PSE AG/Fraunhofer ISE, data from: Strategies Unlimited/Navigant Consulting/EuPD). The straight line shows the price development trend.

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

4.2 Feed-in Tariff

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

To delay PV expansion in hopes of lower costs in the future would not only be a cynical reaction with respect to the progressing climate change but would also slow down the dynamics of cost reductions. The first EEG in 2000 and the subsequent changes have shaped the growth of PV installments in Germany.

According to its 2017 amendment, the EEG defines an expansion corridor for RE as a share of gross electricity, attempting to both support and restrict the growth in PV capacity:

- Since 2010, PV systems may only be constructed on arable land in 110 m corridors along federal motorways and railways
- The size of PV ground-mounted systems has been limited to 10 MW since 2012
- Since 2012, the power of PV systems must either be able to be reduced to 70% of their nominal capacity or be regulated by the grid operator
- Self-consumed PV energy is taxed above a certain nominal power (approx. 10 kW) with 40% of the current EEG surcharge (Section 4.6), which means that the PV electricity generation costs increase by approx. 2.7 € ct / kWh
- Since 2016, plants only receive a fixed feed-in tariff up to a nominal power of 100 kW; For plants with a rated output of 100-750 kW, the PV energy must be marketed directly
- Since 2017, new plants with a rated output of more than 750 kW are required to partake in calls for tender and must not contribute to self-consumption; the annual tender volume is limited

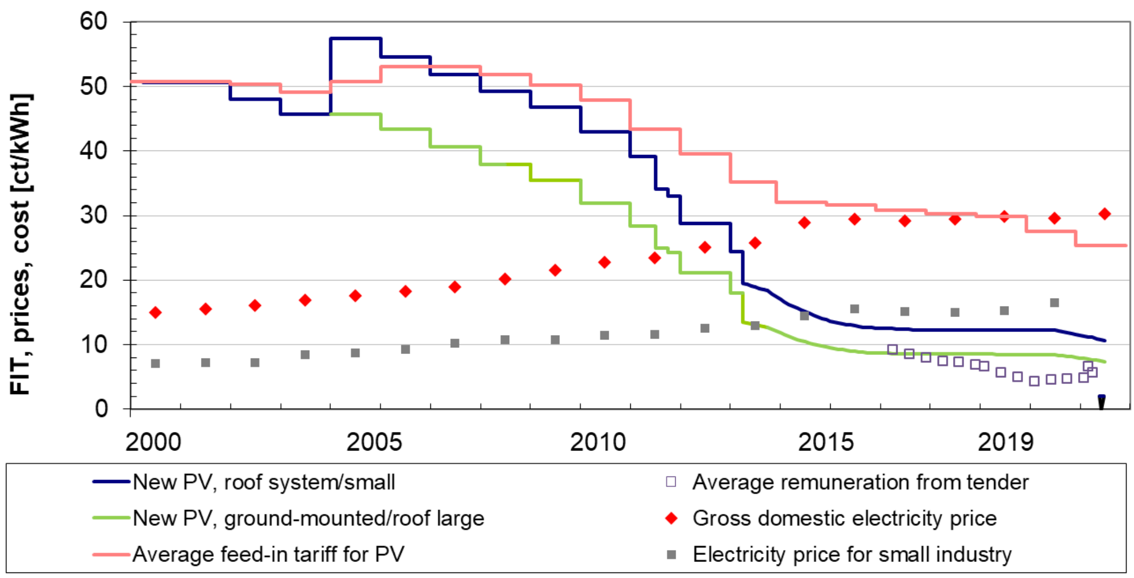

Figure 4: Feed-in tariff for PV power as a function of commissioning date, average remuneration of the bidding rounds of the Federal Network Agency, electricity prices and average compensation for PV power, data from [BMWi1], [BDEW6], [BMWi5].

Depending on the system size, the feed-in tariff for small roof systems put into operation until **January 2020** can be up to **9,87 €-cts/kWh** and is guaranteed to the operator over the next twenty years. For medium-size systems from 750 kW up to 10 MW, the feed-in tariff is set by the licensing agreement. The last licensing round of the Federal Network Agency on the bid date February 1, 2018 set the lowest mean value of **4.33 €-cts/kWh** ever.

To compare: The tender for electricity from onshore wind systems for the same bid date brought an average price **of 4.60 €-cts/kWh**. On the global scale PV electricity prices in locations with high radiation levels has been offered at record low levels from 1.75 (Brasilia) to 2 $cts/kWh (USA). The negotiated strike price for the planned nuclear plant Hinkley Point C in England translates essentially to a feed-in tariff of 12 €-cts/kWh plus inflationary adjustment for a period of 35 years. The plant is planned to start operation in 2025.
The feed-in tariff for PV power drops faster than any other regenerative power source, in the last 15 years approx. 80% for small rooftop installations and 90% for systems of medium size.

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

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

4.3 Pricing on the energy exchange and the merit order effect

To estimate sales revenues from PV electricity, a mean electricity price is calculated based on the prices achieved on the European Energy Exchange. The running EEX price is determined by the merit order principle. Plant operators offer specific quantities of electricity, defined mostly by their marginal costs, and ranked in ascending order of price (Figure 5). The purchase offers of power consumers are arranged in descending order. The point of intersection of the two curves shows the energy exchange price of the entire quantity traded. The most expensive offer influences the profit margins of the cheaper suppliers.

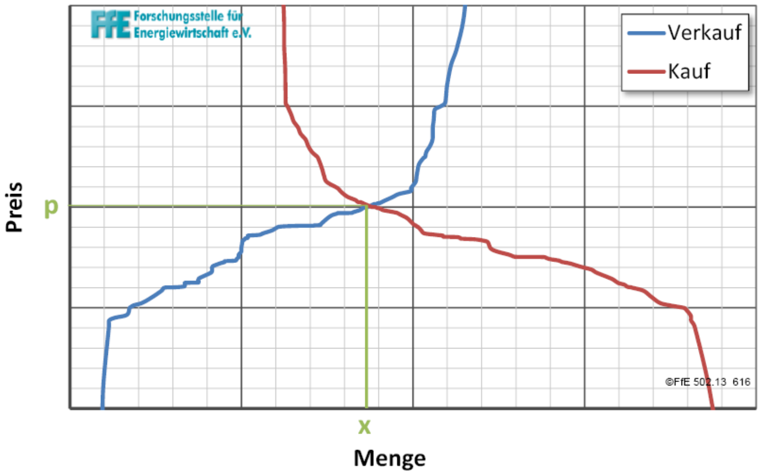

Figure 5: Pricing on the European Energy Exchange EEX [Roon].

PV power feed-in has legal priority, meaning that it is found at the start of the pricing scale due to the merit order effect. With fictitious marginal costs of zero, PV power is always sold when available. PV power is predominantly generated during the middle of the day when power consumption (and previously, but no longer, the electricity price) is at its midday peak. During these periods, PV power mainly displaces electricity from expensive peak-load power plants (especially gas-fired plants and pumped-storage). This displacement lowers the spot price of electricity on the market and leads to the merit order effect of PV feed-in (Figure 6). Together with the prices the revenues of all conventional power producers (nuclear power, coal, gas) sink. However, the revenues for electricity from RES (solar power, wind power, hydropower) are also falling accordingly. Furthermore, solar power reduces the utilization of conventional peak load power plants (gas, water).

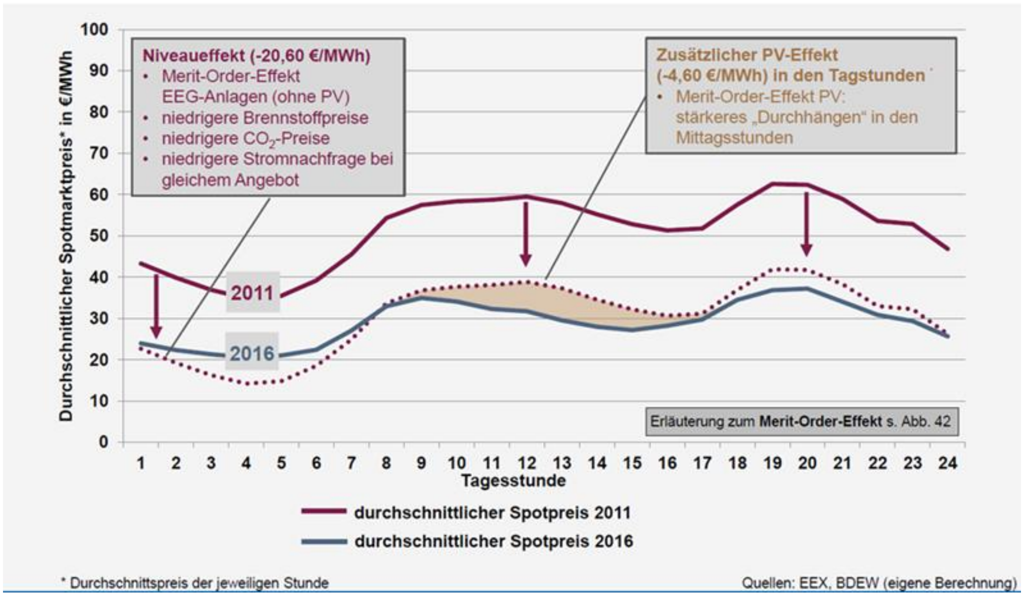

Figure 6: Influence of RE on the average spot price on the energy exchange (EEX) [BDEW2].

The increasing amount of renewable electricity being fed into the grid, lower coal prices and surplus of CO_2 allowances have drastically depressed prices on the EEX (Figure 6).

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

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

4.4 Determining the Differential Costs

The remuneration for PV power feed in accordance with the German EEG is determined annually by the transmission system operators. The differential costs shall cover the gap between the remunerations paid out according to the EEG promotion and the sales revenue collected from PV electricity. Following a peak of almost 7 €-cts/kWh, the spot price of electricity, used to determine the differential costs, has since fallen to below 4 €-cts/kWh in 2015 (Figure 7). The amount of electricity from PV and wind that is fed into the grid is increasing. This reduces the spot market price through the Merit Order Effect and thereby, paradoxically increases the calculated differential costs. According to this method, the more PV installed, the more expensive the support of PV appears to be.

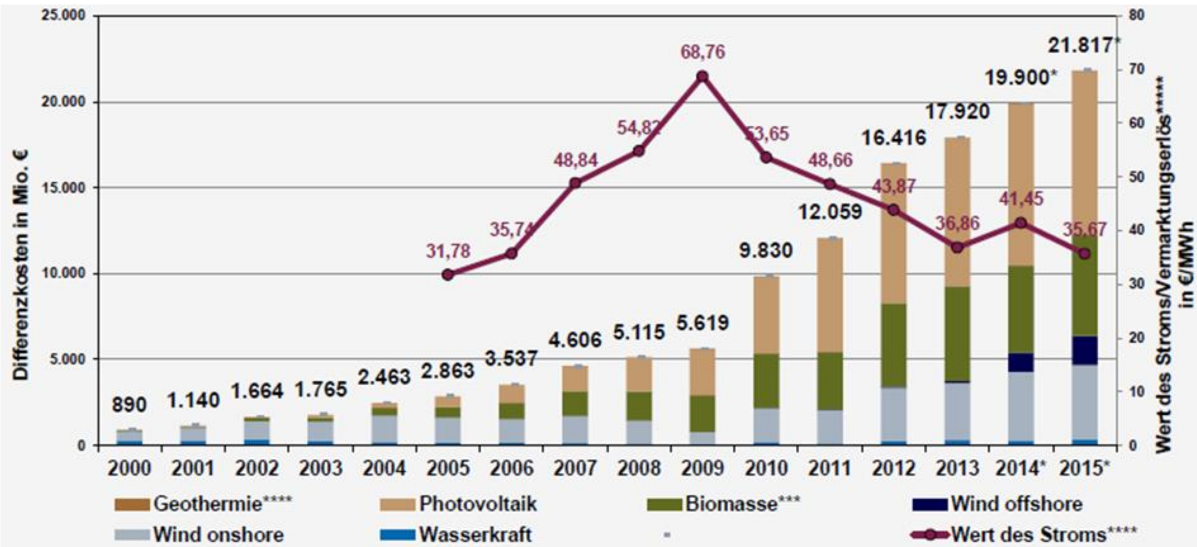

Figure 7: Development of the average spot electricity price and the calculated differential costs [BDEW2].

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

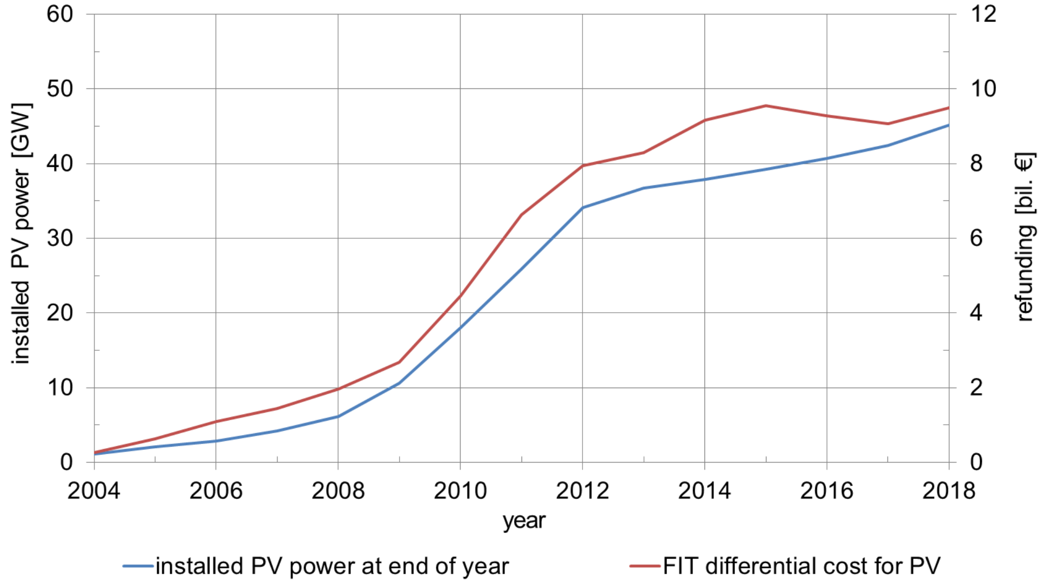

Figure 8: PV expansion and remuneration amount, data from [BMWi1], [BMWi5]

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

4.5 Privileged Electricity Consumers

Policy makers determine who shall finance the transformation to renewable energy [BAFA]. They decided that energy-intensive industries, i.e. those who spend a high proportion of their costs on electricity, are to be exempted from the EEG surcharge to a large extent. In 2018, almost half of industrial consumption was privileged (Figure 9). This wide-scale exemption increases the burden on the other electricity customers, in particular, private households, who account for almost 30 percent of the total power consumed.

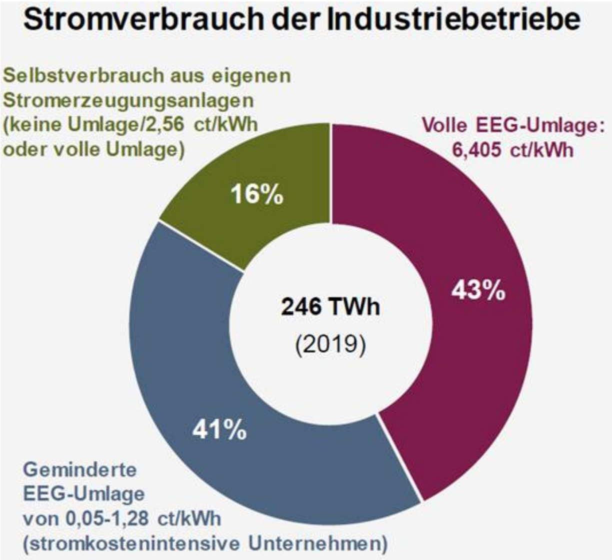

Figure 9: Electricity consumption of industry and EEG surcharge 2019 [BDEW6]

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

4.6 EEG Surcharge

The difference between the remunerations paid out and the sales revenues generated from renewable electricity (supplemented by other items) is compensated by the EEG surcharge (Figure 10). The cost of the surcharge is borne by those power consumers, who do not fall under the exemption scheme. For 2020, the EEG surcharge is set at **6.76 €-cts/kWh**. End users must pay value added tax (19%) on this surcharge so that the costs imposed on private households increases to **8.04 €-cts/kWh**.

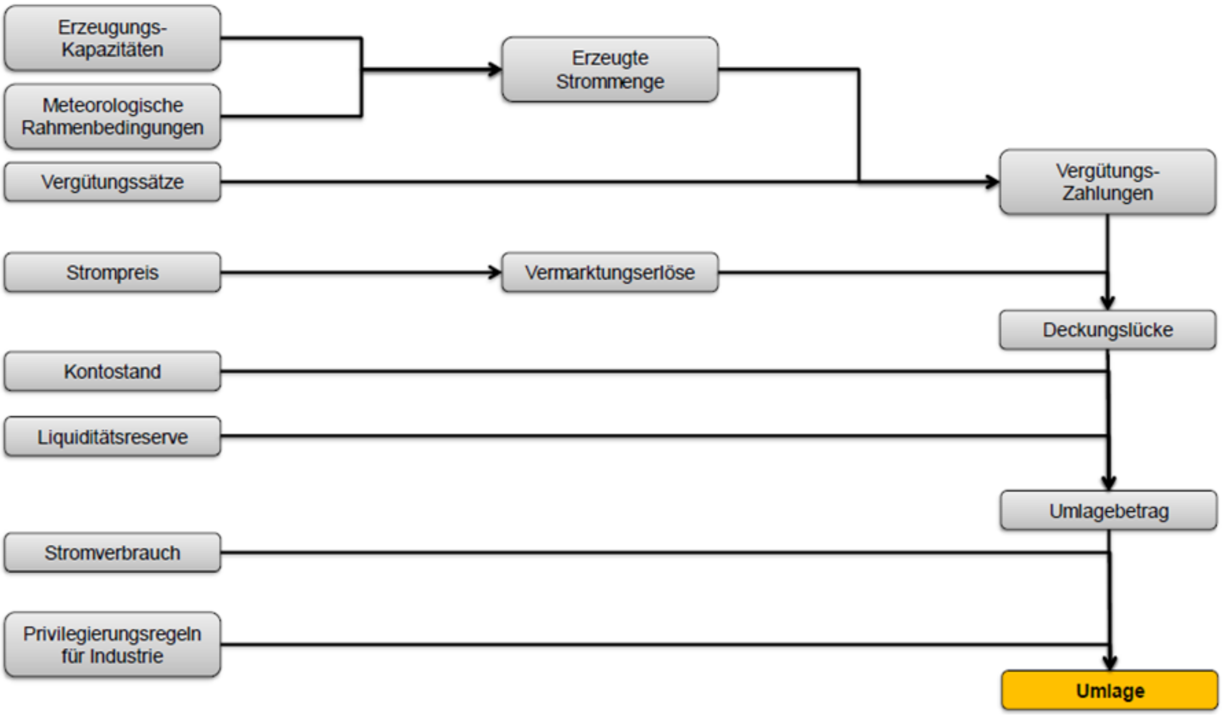

Figure 10: Influential parameters and calculating method for the EEG surcharge [ÖKO]

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

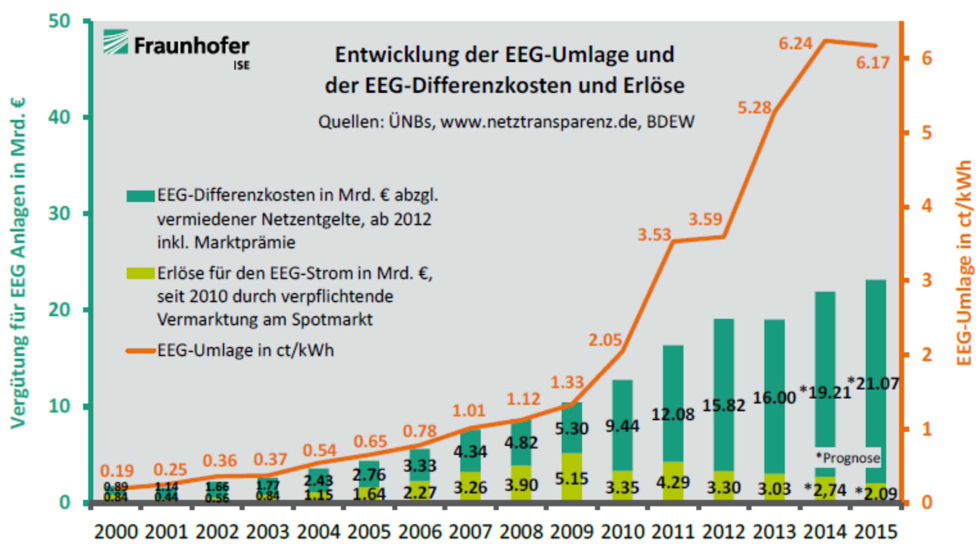

Figure 11: Development of the EEG surcharge and the EEG differential costs [ISE9]

Based on the way it´s defined, the EEG surcharge would increase for the following reasons:

1. Increasing quantities of power used by «privileged" consumers
   Because energy-intensive industries are virtually exempt from contributing to the surcharge, smaller-sized consumers, such as private households, small industry and commercial consumers must bear additional costs amounting to billions of euros.
2. Merit order effect and PV feed-in during daytime.
   PV power feed-in during, for example, midday when the EEX spot price formerly peaked reduced the electricity price very effectively, benefitting electricity customers. (See section 4.3). At the same time, however, the difference between the feed-in tariff and the market price, the basis of calculating the EEG surcharge, increased. This disadvantages smaller customers bound to pay the EEG levy.
3. Merit order effect and electricity surplus
   For many years, increasingly more power has been produced in Germany than effectively consumed, and namely power from fossil and nuclear power plants with low marginal costs being used as expensive peak load power plants. Due to the merit order effect, this surplus reduces the market price, pushing peak power plants out of the energy mix.
4. Declining electricity consumption through efficiency measures
   Initiatives supporting more efficient energy use (e.g. energy saving lamps) reduce the amount of electricity purchased, and thereby increase the surcharge per kWh consumed.
5. Additional expenditure from compulsory direct marketing
   The compulsory direct marketing creates additional administrative expense that power producers must compensate with a higher EEG remuneration.
6. Increasing production from RE power, without self-consumption
   The expansion of RE drives the levy up at least on the short term both directly (because more feed-in remuneration is paid out) as well as indirectly (due to the reduced price of emission certificates leading to a cheaper price for energy from fossil fuel plants.)

5 Subventions and Electricity Prices

5.1 Is PV power subsidized?

No. The support is provided through a selective surcharge, which applies also to self-produced and self-consumed PV electricity.

The investment incentives for PV power are not supported by public funds. While fragmentary reports often quote figures relating to past and future PV power feed-in tariff payments in the hundreds of billions and call these «subsidies", a true subsidy is supported by public funds. The EEG, on the other hand, makes provisions for a surcharge in which energy consumers make a compulsory contribution towards the energy revolution, a necessary and agreed upon resolution. This interpretation is also supported by the European Commission. The EEG surcharge is not the total remuneration, but rather the differential costs, calculated as the difference between costs paid (remuneration) and revenues received (see section 4.4). The cumulative costs paid out for PV power fed into the grid up to and including 2018 amounted to ca. **82 billion euros,** according to the German Federal Ministry of Economics.

To calculate the EEG surcharge, the financial benefits of PV power are determined according to the market clearing price. By this method, the benefits of PV power are underestimated systematically. For one, PV power has long been having the desired effect on this market price, namely that of driving it downwards (see section 4.3). Second, the market price leaves out the heavy external costs of fossil fuel and nuclear power production (section 5.2). Considering total costs of fossil fuel and nuclear power production of ca. 10 €-cts/kWh, the additional costs of the PV feed-in tariff decline so quickly that the first intersection point occurs already in 2013. The differential cost decrease to zero and thereafter are negative.

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

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

5.2 Are fossil fuel and nuclear power production subsidized?

Yes.
Policy makers also influence the price of electricity generated by fossil fuel and nuclear power plants. Political decisions determine the price of CO_2 emission allowances, conditions for filtering smoke and, where necessary, for the permanent storage of CO2 (carbon capture and storage, CCS), the taxation of nuclear power as well as insurance and safety requirements for nuclear power plants. This means that policy makers decide to what extent energy consumers must bear responsibility for the elusive risks and burden of producing electricity from fossil fuel and nuclear sources. As these aspects are more rigorously priced, it is very likely that PV power will make the electricity mix less expensive. Until this happens, fossil fuel and nuclear power will be sold at prices that conceal their external costs and pass the burden on to future generations.

Contrary to initial plans, and with costs of 5-25 euros per metric ton of CO_2, CO_2 emission allowances only have a minor effect on the costs of generating power from fossil fuels (see Figure 12). According to calculations by the Federal Environment Agency, however, the emission of one ton of CO_2 causes damage of around 180 euros. In terms of Germany's greenhouse gas emissions in 2016, this corresponds to costs of around 164 billion euros [UBA3].

Figure 12: Price of CO_2 allowances [BDEW6]

It is currently impossible to pinpoint the actual costs and risks of generating power from fossil fuel and nuclear sources. The majority of these shall only emerge in the future (CO_2-induced climate-related catastrophes, nuclear disasters, the permanent storage of nuclear waste, nuclear terrorism, permanently contaminated sites), making a comparison difficult. According to experts, the risks of nuclear power are so severe that insurance and reinsurance companies the world over are not willing to offer policies for plants generating energy of this kind. A study conducted by the Versicherungsforen Leipzig sets the limit of liability for the risk of the most serious type of nuclear meltdown at 6 trillion euros, which, depending on the time period over which this sum is accrued, would increase the electricity price per kilowatt hour to between 0.14 and 67.30 euros [VFL]. As a result, it is essentially the tax payers who act as the nuclear industry’s insurers. This is essentially forced upon them both against their wishes, since the majority of Germans have been opposed to nuclear energy for many years, and as an unspecified amount, because no fixed price has been established to date for damage settlements. This is a subsidy whose burden on the future cannot be predicted.

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

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

5.3 Do tenants subsidize well-positioned home owners?

No.

This notion, which makes a popular headline and in this instance is taken from the «Die Zeit" newspaper published on December 8, 2011 is a distorted image of reality. Except for the politically willed exception granted to energy-intensive industry, the costs of switching our energy system to RE are being borne by all consumers (including all households and thereby home owners and tenants) according to the cost-by-cause principle. In addition to PV, these costs also contribute funding to wind power and other renewables. All electricity customers can decrease their energy consumption by selecting and using energy efficient appliances. Many municipalities offer free consultations on energy saving advice and also grants to help pay for new, more efficient devices. Electricity tariffs that increase with consumption would be a suitable means to reduce the burden on low-income households and simultaneously to reward energy efficiency.

PV systems installed by home owners are usually under 10 kWp. The systems within this power range make up less than 15% of the total installed PV power in Germany, while large systems above 500 kWp make up about 30 % (Figure 21). The larger systems are often financed with citizen participation or funds, in which tenants can also participate.

5.4 Does PV make electricity more expensive for householders?

Yes.

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

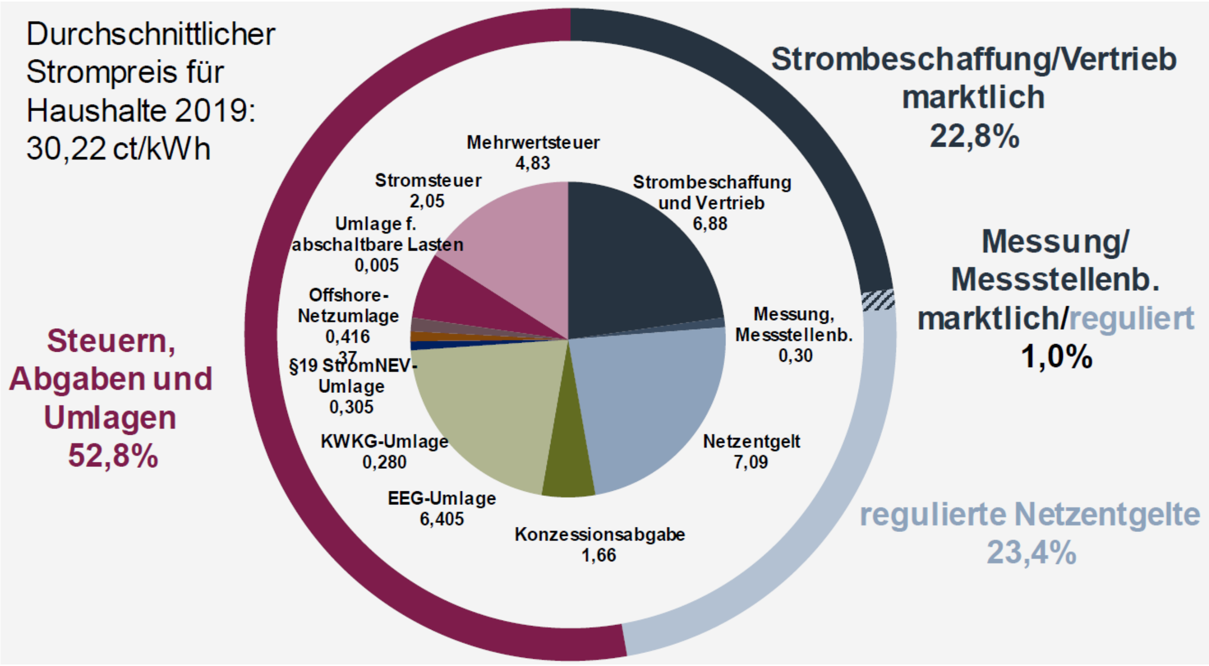

Figure 13: Components of the average domestic electricity price in 2019 (CHP: German Combined Heat and Power Act); German Electricity Grid Access Ordinance (Strom-NEV): easing the burden on energy-intensive industries; concession fee: fee for using public land) [BDEW6].

A typical household with an annual power consumption of 3,900 kWh pays an electricity price of approx. **30,22 €-cts/kWh** in 2019 [BDEW6]. Figure 13 shows a typical breakdown of this electricity price. The electricity levy was introduced in 1999. According to the law, the levy intends to make electricity more expensive; the proceeds go principally into the public pension fund. Private households must pay value added tax on the electricity levy and the EEG surcharge.

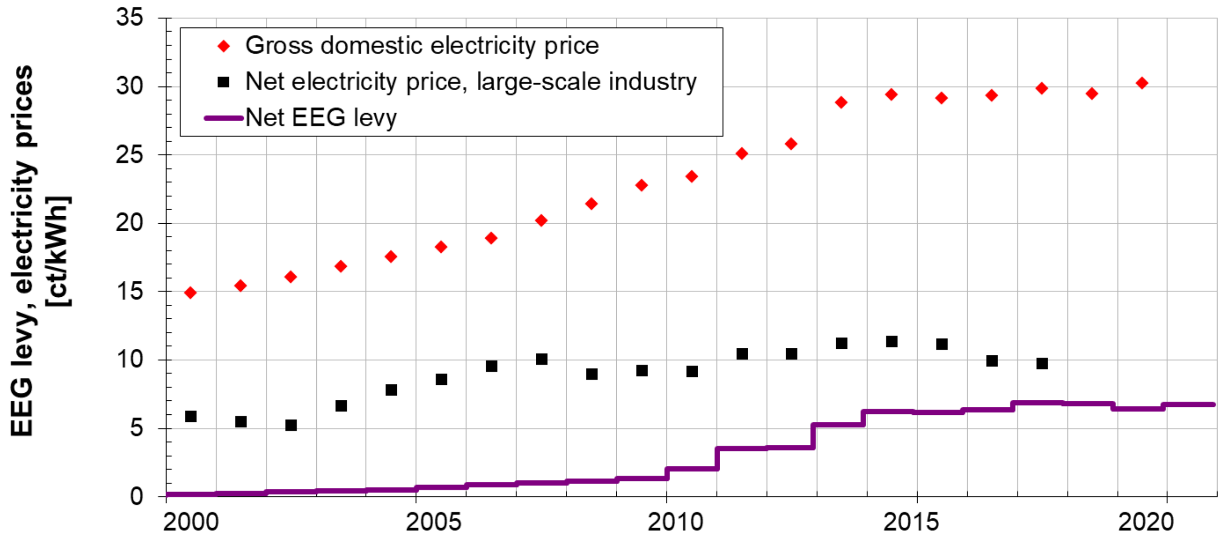

Figure 14: Development of gross domestic electricity prices, net electricity prices for large-scale industrial consumers and the EEG surcharge, Daten aus [BMWi1]

In many European countries, the electricity price for private households is much lower than in Germany. However, taking into account the purchasing power of the countries, Germany is in the European midfield. Germany has a very high level of security of supply: in low-price countries such as Romania or Bulgaria, power cuts are common.

5.5 Does PV increase the electricity price for industry?

Yes and no. There are clear winners but also losers.

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

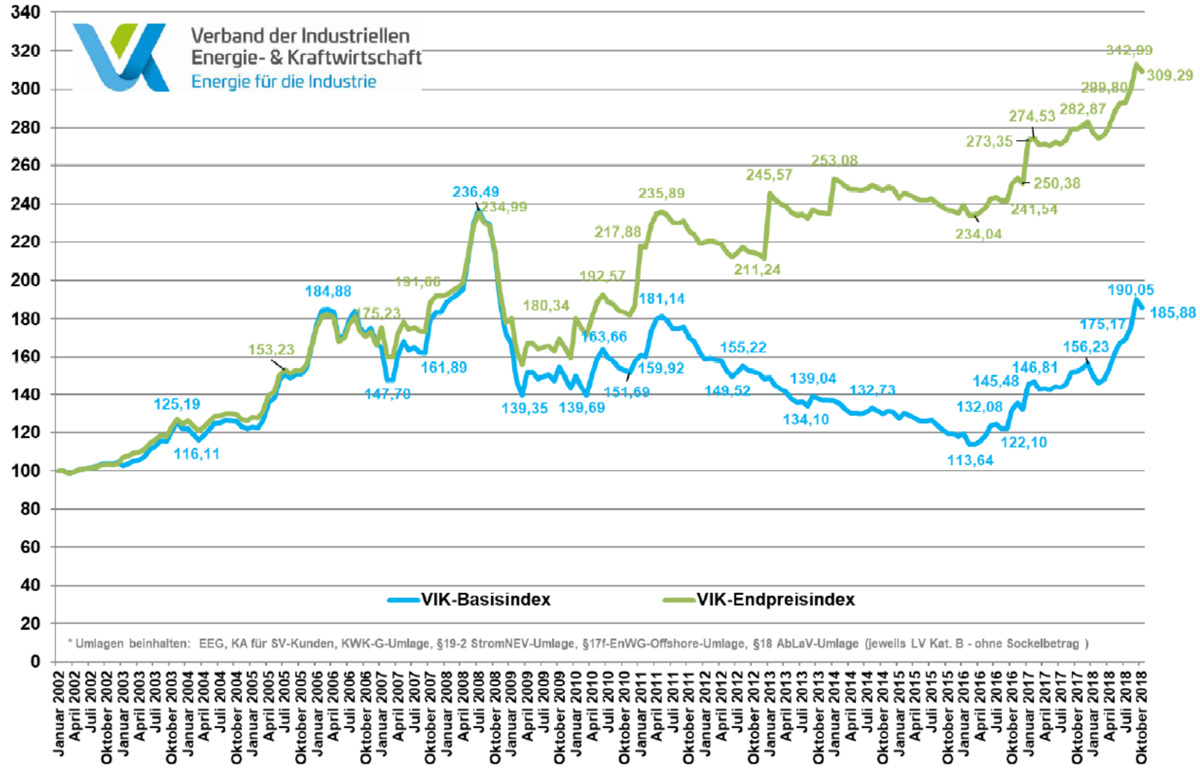

Figure 15: VIK electricity price index for medium-voltage customers [VIK]

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

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

Figure 16 shows the increase in electricity exports since 2011 [ISE4]. The monthly values of the Energy Charts (www.energy-charts.de) show that the export surplus was conspicuously high in winter, i.e. in months with a particularly low PV power production. The average price per kWh achieved in electricity exports has been somewhat below the average import price for some years.

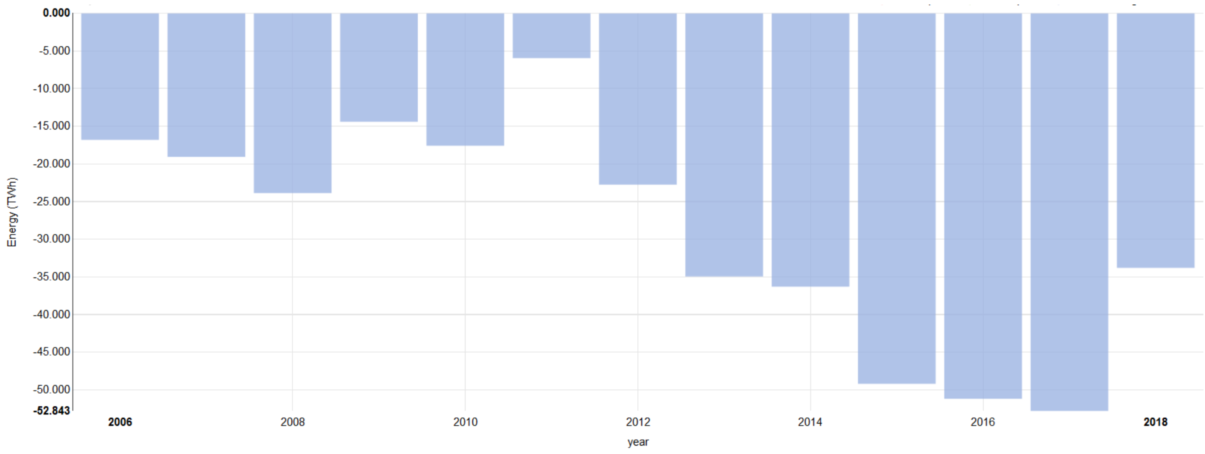

Figure 16: Electricity export (negative values indicate export) for Germany [ISE4]

The fact that the German power plant park is increasingly producing for export should also be related to the low production costs for coal electricity, in particular the low CO_2 certificate prices (Section 5.2) of recent years.

7 Can new PV plants bring reasonable rates of return?

Yes.

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

Self-consumption becomes more worthwhile, the greater the difference is between the cost of delivering PV electricity and the LCOE of the PV system. For systems without energy storage, the self-consumption is dependent on coinciding supply and demand profiles. Independent of the system size, households generally consume 20-40 % of their self-produced electricity [Quasch]. Larger systems increase the percentage of PV coverage for the total power, however, reduce the percentage of self-consumption. Commercial or industry consumers achieve an particularly high rate of self-consumption as long as their consumption profile doesn't collapse on the weekends (e.g. Refrigerated warehouses, hotels and restaurants, hospitals, server centers, retail). Energy storage and technologies for energy transformation offer a large potential for increasing the self-consumption (compare Section 18.3).

The PV system yield is higher in sunnier regions, however, regional irradiation differences do not transfer to specific yield in a one-to-one ratio (kWh/kWp). (See section 24.4.) Other parameters, such as the module operating temperature or the duration of snow cover, also affect the annual yield.

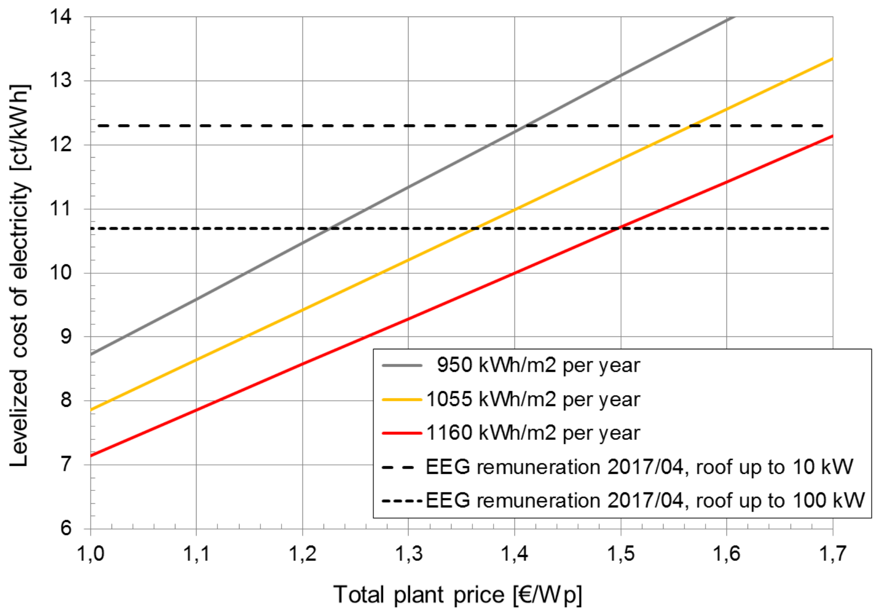

Figure 17: Rough estimate of levelized cost of electricity (LCOE) for PV power plants at different annual irradiances

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

- optimal orientation of module (approximately 30° south)
- average annual total of horizontal global irradiation in Germany 1088 kWh/m²/a
- performance ratio (section 24.6) of 85 percent
- annual yield degradation of 0.5 percent
- lifetime of 20 years
- annual operating costs of 1 percent (of plant price)
- inflation rate of 0 percent
- nominal imputed interest rate of 5 percent (average of own and borrowed capital investments)

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

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

It is currently not possible to calculate the energy yield beyond the twenty-first operating year of a PV system. It is likely, however, that many plants will continue to generate significant quantities of electricity at marginal running costs. However, the guidelines governing self-consumption and the future pricing and remuneration concept of ESCs as well as any interventions from policy makers also affect yield calculations. There is no guarantee on the PV plant's rate of return during the EEG remuneration period. Neither the manufacturer's guarantee nor plant insurance policies are able to remove the risk to the investor entirely.

8 Does installing PV only create jobs in Asia?

No, however over the last few years Germany lost many jobs in the PV industry.

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

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

In 2017, the German inverter manufacturers held notable shares of the global market with approx. 10%, poly-silicon manufacturers (Wacker as number 2 worldwide), silver paste manufacturers (Heraeus as number 1 worldwide) and manufacturers of production systems.

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

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

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

In the long term, the falling costs of PV module manufacturing coupled with increasing freight costs and long delivery times shall improve the competitive position of manufacturing companies in Germany.

9 Are large energy suppliers interested in PV?

In 2016, the majority of Germany's installed PV capacity belonged to private individuals, farmers and commercial businesses. The four big power plant operators EnBW, Eon, RWE and Vattenfall (called «big four" in Figure 18) owned a mere 0.2 percent. Where does their aversion to PV power come from?

1. The electricity consumption in Germany is showing a declining to stable tendency since 2007. The construction of new renewable power plants will force either a reduction in the utilization rate of existing power plant parks or an increase in electricity export.
2. Because PV electricity is generated primarily during periods of peak load, conventional peak load power plants are required less often. This reduces their utilization and profitability in particular. Paradoxically flexible power plants with fast response times are increasingly in demand for the energy revolution.
3. PV power plants deliver power during the day at times when demand is at a peak (Figure 47). This lowers the market price of electricity on the EEX, which carries over to all plants presently producing electricity. (Section 4.3). Previously, the big power plant operators were able to sell inexpensive base load power at a lucrative price during midday. Since 2011, PV led to price reductions on the energy exchange and thus to dramatic slumps in profit.
4. Because PV power production fluctuates, the slow start-up and shut-down properties of nuclear of older coal-fired power plants cause difficulties with increasing PV expansion. One particularly striking example is negative electricity prices on the market. Coal is being burned and the consumers must pay for the electricity. This leads to system wear in places where controls are technically feasible but no provision in the necessary frequency exists.

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

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

As the balance sheets of the «BIG 4" German power producers began to worsen dramatically, they began to react: RWE transferred two-thirds of its staff to its daughter innogy, which handles all business related to the energy revolution, including PV electricity. In its mid-year report for 2017, it states that Innogy operated less than 100 MW PV at the end of 2016. Similarly, E.ON SE has formed Uniper to handle its traditional gas and electricity and is now concentrating on renewable energy, including PV. In 2013, EnBW stated that it is redirecting its activities to focus on the energy transformation. As of September 2016, the company operates 50 PV plants. Vattenfall is selling its lignite sector and plans to concentrate on renewable electricity production, and since 2016 also PV.
According to its own statement, EnBW focused on the energy revolution in 2013 and, as of February 2019, operates PV systems with a total nominal output of 70 MW. At the beginning of 2019, EnBW announced plans to build the first PV power plant in Germany without EEG support. Specifically, this is a 175 MW project in Brandenburg [EnBW]. Vattenfall would also like to install PV systems on land from the lignite opencast mine in the Lausitz PV without EEG support.

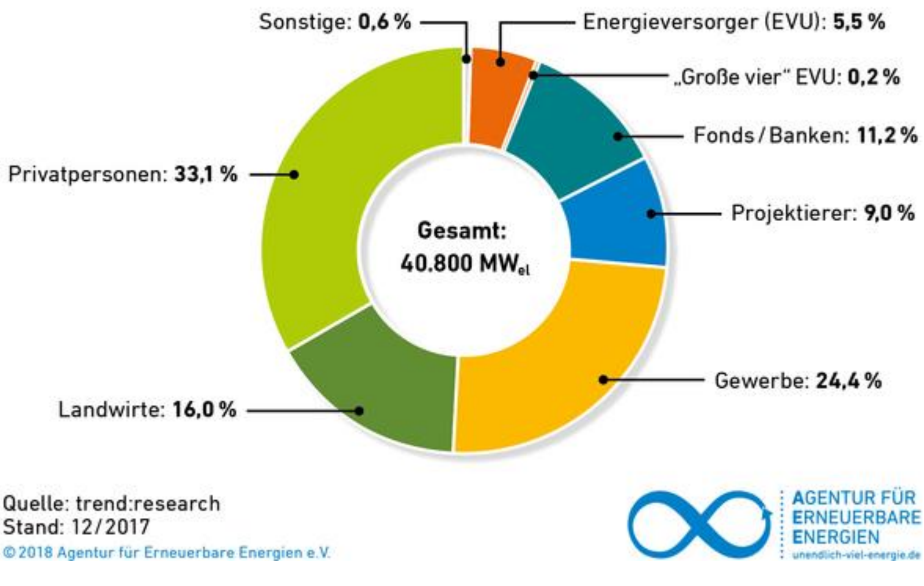

Figure 18: Division of ownership of the total installed capacity of PV plants at the end of 2016 [AEE3].

Many of the approximately 1000 municipal electricity suppliers in Germany recognized the challenges facing the energy revolution early on and have reacted by offering new products and integral concepts, e.g. «virtual power plants" (Figure 19).

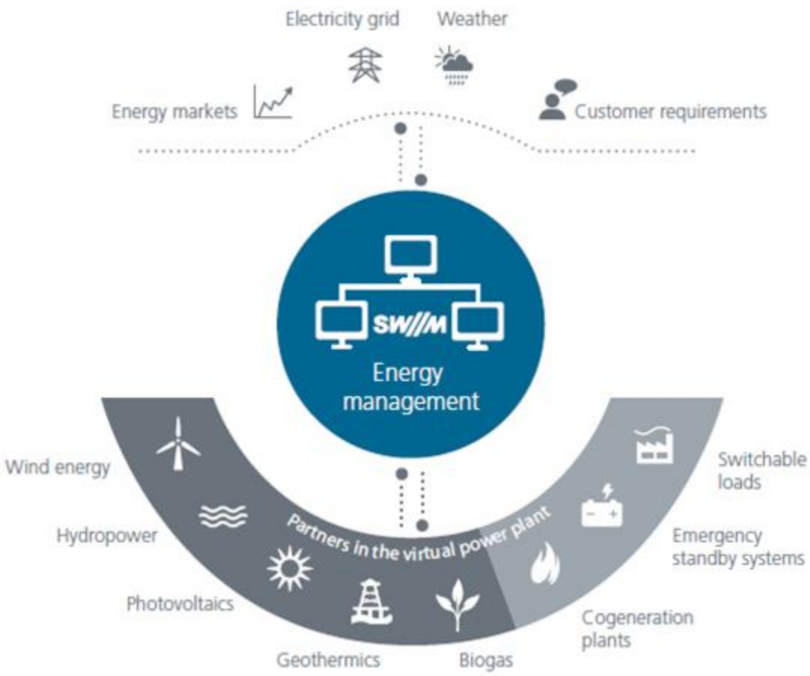

Figure 19: Concept for a virtual power plant of the Stadtwerke München (Munich municipal works) [SWM]

10 Is PV research taking up high levels of funding?

Looking back at previous numbers, Figure 20 shows that it took time for renewable energy and energy efficiency to become a focal point of energy research.
Figure 21 shows the funding granted for PV research by the federal ministries.

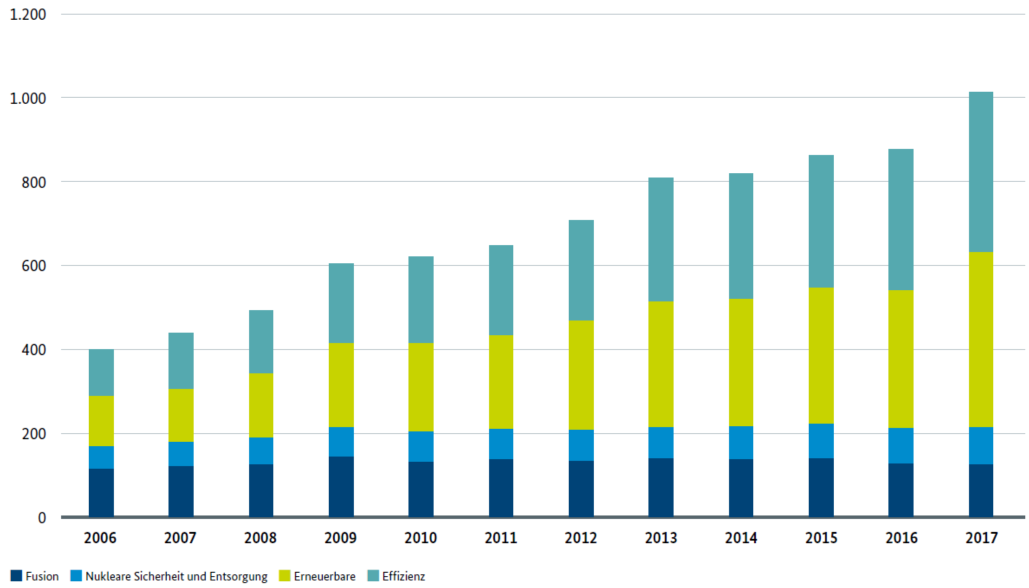

Figure 20: Germany's expenditure in the Energy Research Program of the Federal Government by topic in € million [BMWi6].

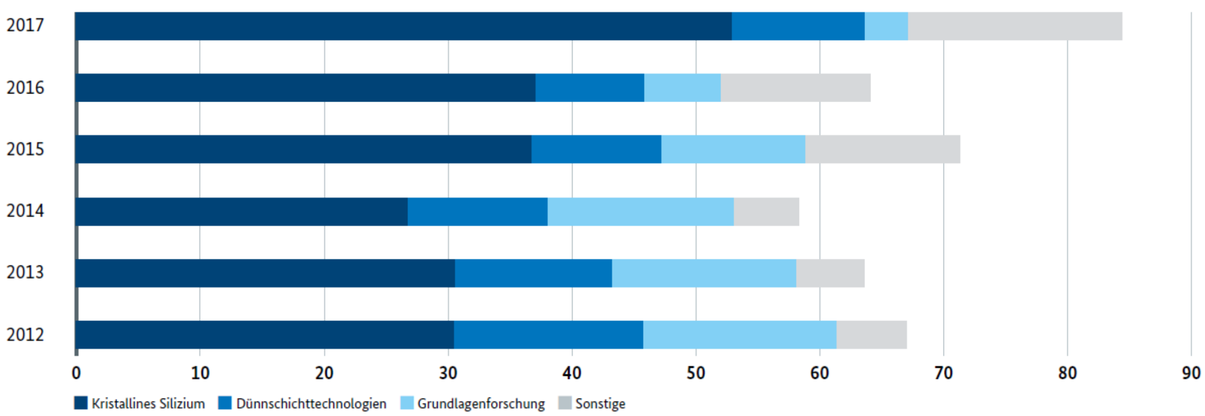

Figure 21: Funding for PV research categorized by technology in € million [BMWi6].

11 Does PV power overload our energy system?

11.1 Transmission and distribution

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

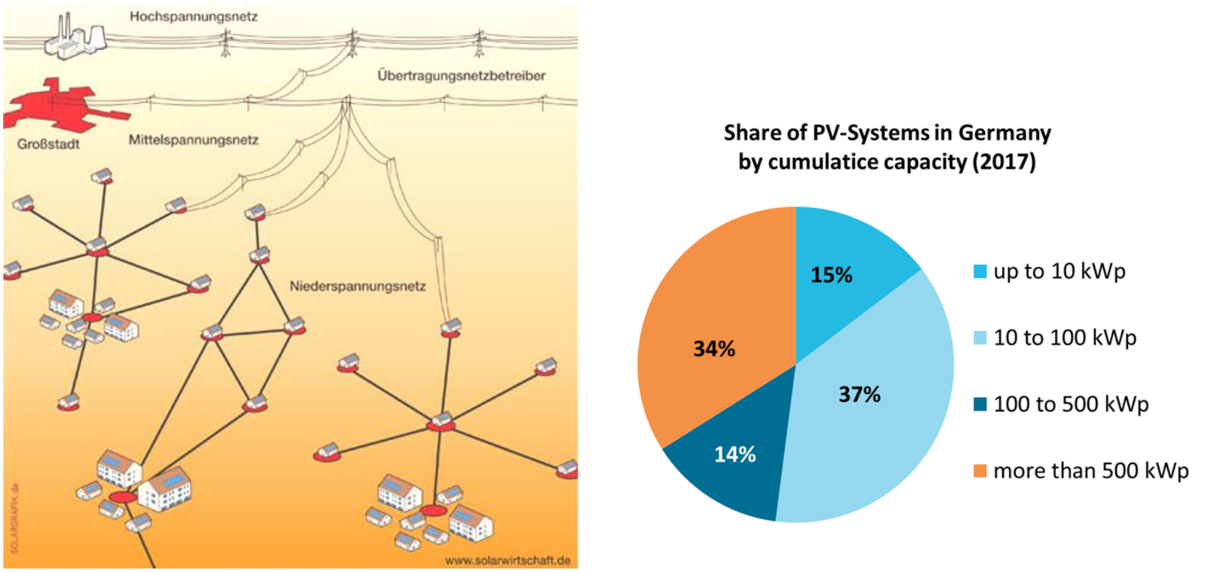

Figure 22: Left: Feed-in of PV power [BSW], Right: Distribution of installed PV power according to plant size [ISE10]

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

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

According to a study by the "Agora Energiewende", the German electricity grid will be able to transport the required amounts of electricity even with an installed PV capacity of just under 100 GW in 2030 [AGORA1]. In particular, measures to modernize and improve the use of existing networks are needed, but no significant development.

When there are currently network bottlenecks, PV power is rarely the reason (Figure 24). Due to surplus wind power in Northern Germany, electricity deficits due to power plant shutdowns (nuclear in Southern Germany) and a sluggish grid expansion, grid bottlenecks often occurred in the German transmission grid. Because the grid expansion – a necessary step to alleviate the bottlenecks – will still take some time, redispatching measures will be increasingly required in the foreseeable future. Redispatching means that the transmission operators (TSO) intervene in the market-based operation schedule of the power plants (dispatch) to redistribute the electricity feed-in, prevent power surges in the grid (preventative redispatch) or to carry out fixes (curative redispatch). Before a bottleneck occurs, the energy feed-in is reduced (negative redispatch) and afterwards increased (positive redispatch) [BDEW4]. In **2017**, the total cost of redispatch measures amounted to **€ 1.4 billion**.

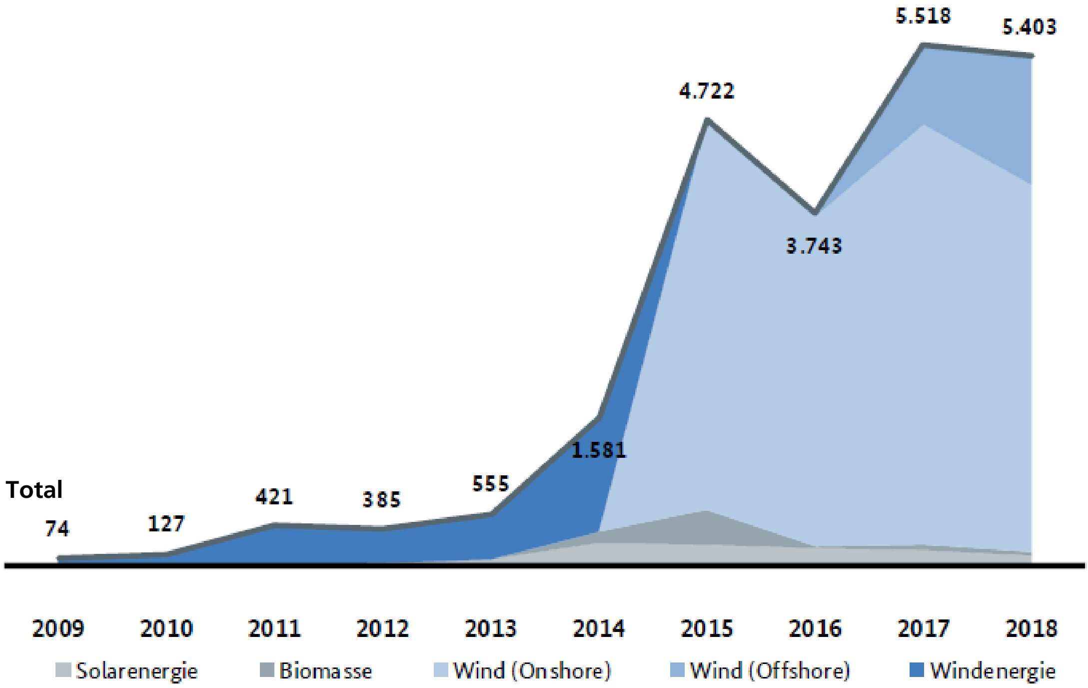

Figure 23: Electronically limited electrical energy in GWh/year [BNA]

11.2 Volatility

11.2.1 Solar power production is predictable

Reliable national weather forecasts mean that the generation of solar power can now accurately be predicted (Figure 24). Because PV power generation is decentralized, regional changes in cloud cover do not lead to serious fluctuations in PV power production throughout Germany as a whole.

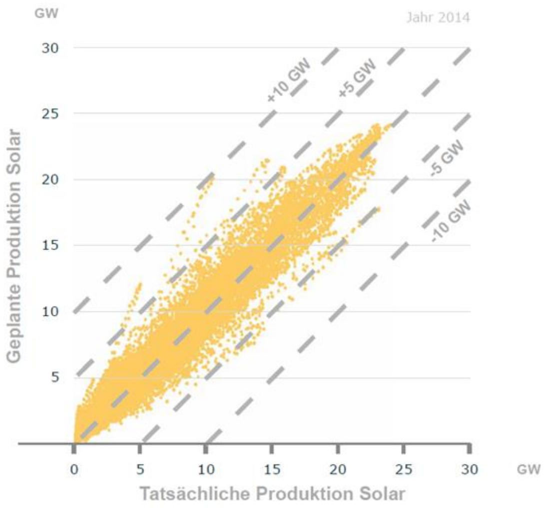

Figure 24: Actual and predicted hourly generation of power in 2014 [ISE4].

11.2.2 Peak production is significantly lower than installed PV capacity

Due to technical losses (performance ratio PR <= 90%, see section 22.6) and inconsistent weather conditions, a real generation of electricity above 70% of the installed rated output (see chapter 3) is very unlikely throughout Germany, cf. also Figure 25.

Limiting («feed-in management”) individual plants to 70 percent of their rated power leads to an estimated loss of revenue of between 2 and 5 percent. A statutory regulation that actually enforces this limit for small plants came into force in 2012.

11.2.3 Solar and wind energy complement each other

Climate-related high solar radiation and high wind forces in Germany correlate negatively on all time scales of hours to months.
On an hourly basis, with an installed capacity of 42 GW of PV and 56 GW of wind power at the end of the year, in total only rarely more than 45 GW of power was connected to the grid in 2017 (Figure 25).

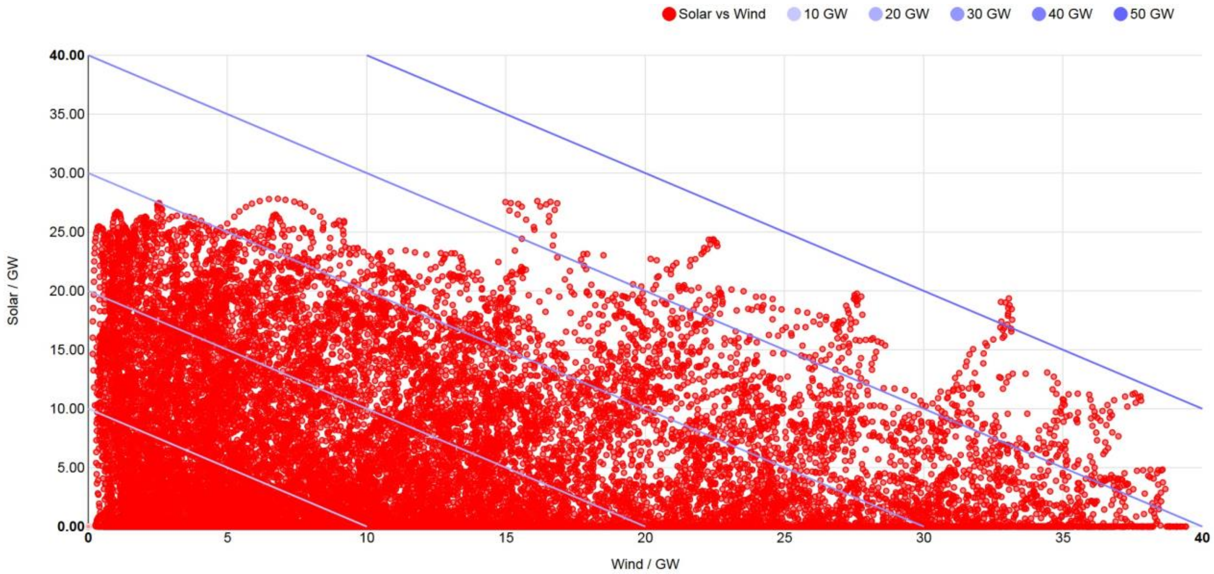

Figure 25: Average power for the supply of solar and wind power in 2017, 15-minute values [ISE4].

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

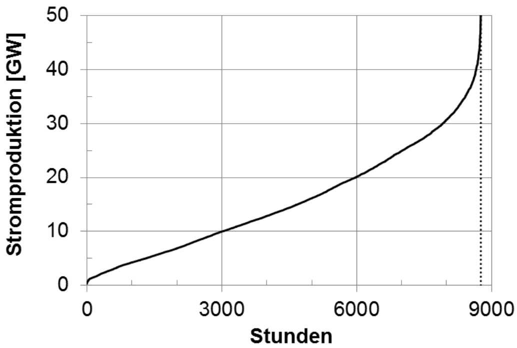

Figure 26: Electricity production of PV and wind in ascending hourly values for the year 2017

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

Figure 27: Monthly production of PV and wind power for 2014 - 2017 [ISE4].Figure 27 shows the monthly values of electricity production from PV, wind power and their total, as well as the respective linear trend lines for the years 2014 - 2017. The relative deviations from the trend line for PV and wind in total are significantly lower than for the individual sectors.

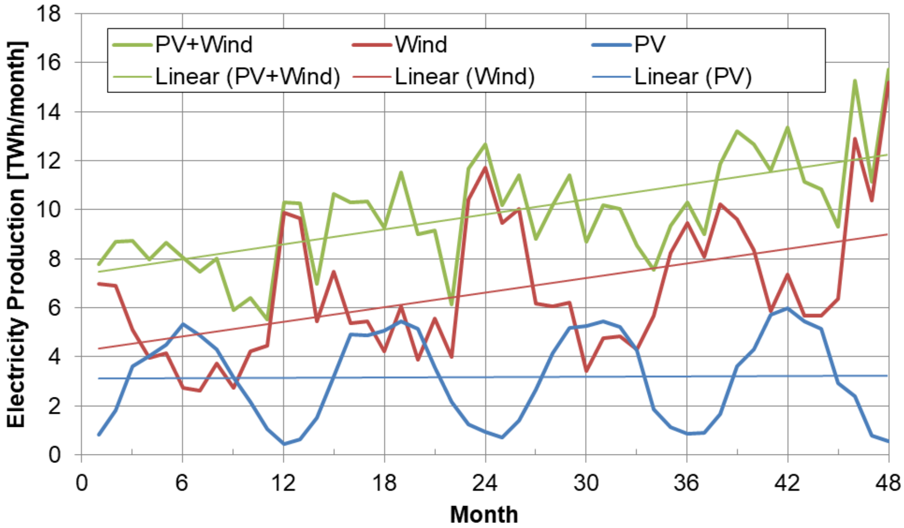

Figure 27: Monthly production of PV and wind power for 2014 - 2017 [ISE4].

11.3 Controllability

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

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

11.4 Conflicts with slow-response fossil and nuclear power plants

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

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

During past heat waves, the rivers used as cooling reservoirs for fossil fuel and nuclear power plants became critically warm. The PV installations in Germany were able to help relax this problem and can also help to reduce this problem in neighboring countries such as France. Especially during summer, the installed PV in Germany categorically reduces the load on the fossil fuel and nuclear power plants.

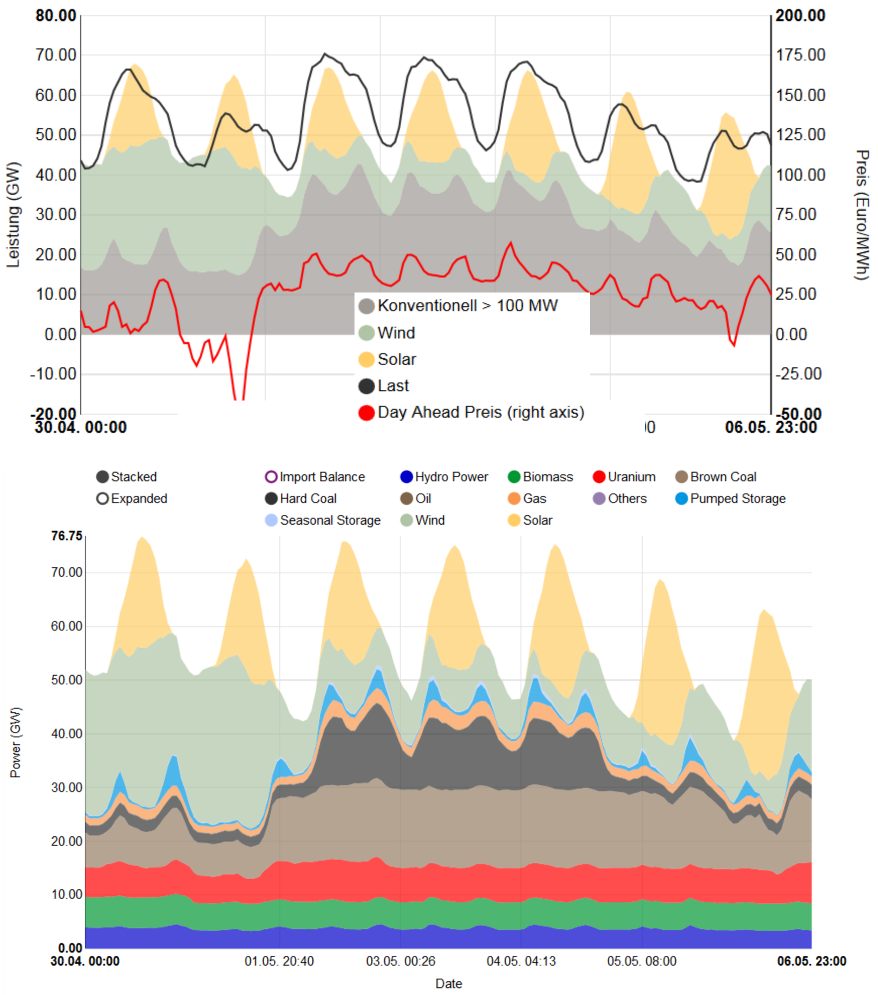

Figure 28: Example showing course of electricity trading price, conventional and renewable electricity in the 18th calendar week in May 2018 [ISE 4]

11.5 Does volatile solar power endanger security of supply?

No.

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

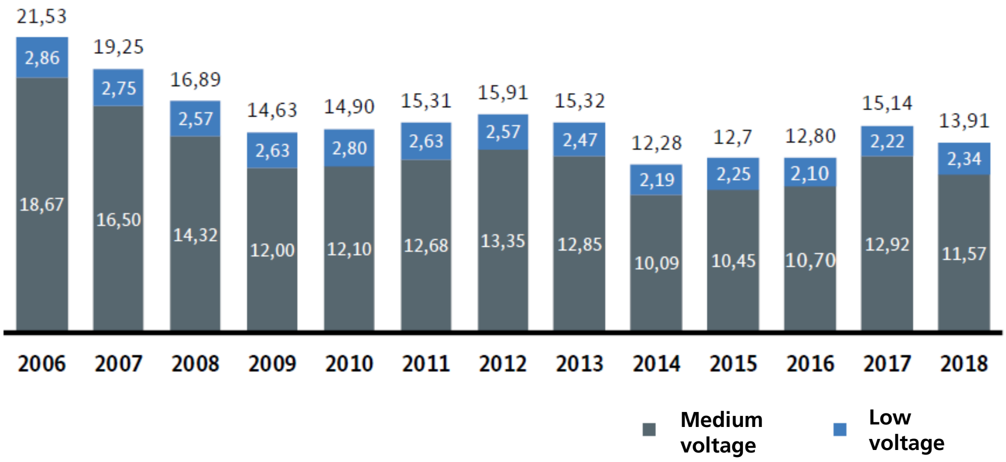

Figure 29: System Average Interruption Duration Index (SAIDI) for different network levels in minutes / year [BNA]

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

No, not in the next few years.

Investing in storage is first profitable when large differences in the electricity price frequently occur, either on the electricity exchange market EEX or at the consumer level. Currently investments in storage, specifically pumped storage, are even being deferred because cost-effective operation is not possible.

A continued expansion of PV and wind will first cause prices on the electricity exchange EEX to sink more often and more drastically. On the other hand, a reduced amount of nuclear electricity caused by the planned phase out and more expensive electricity from coal-fired plants due to the imposed CO_2 allowances or taxes will result in price increases on the EEX. This price spread creates the basis for a profitable storage operation. If the price difference is passed on to the final customer through a tariff structure, then storage also becomes an interesting alternative for them.

A study by "AGORA Energiewende" identifies 12 measures to modernize the grids to include among others, approximately 100 GW of installed PV power by 2030 [AGORA1].

12 Does the manufacture of PV modules consume more energy than they can produce?

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

Harvest factor and energy payback time of PV plants vary with technology and plant location. A recent study from 2017 [RAUG] found a harvest factor of 9-10 for PV power plants with wafer-based modules based on measured PV yields from Switzerland and an assumed lifetime of 25 years, corresponding to an energy payback period of 2, 5 - 2.8 years. Wind power plants have significantly shorter energy payback times, usually less than a year.

13 Is there enough space for PV in Germany?

Yes, without any significant use of arable land.
A study commissioned by the German Federal Ministry of Transport and Digital Infrastructure estimates the potential for expansion of non-restriction open spaces for PV ground-mounted systems to 3164 km^2 in Germany [BMVI]. With an area consumption of 1.4 ha/MW according to the current state of the art [ZSW], these areas offer a technical potential of **226 GW**.

The agricultural area in Germany was around 16.7 million hectares in 2017. Energy crops are grown on 14% of this area (Figure 30), especially for the production of biogas, biodiesel/vegetable oil and bioethanol [FNR]. With agrophotovoltaics (APV), agriculture and electricity production can be combined on the same area (www.agrophotovoltaik.de). A number of crop plants show hardly any loss of yield with reduced radiation, others even benefit. If the current acreage of these two plant classes in Germany is assumed to be a technical potential, this corresponds to a nominal output of **1.7 TW**. APV is already being installed worldwide on a GW scale.

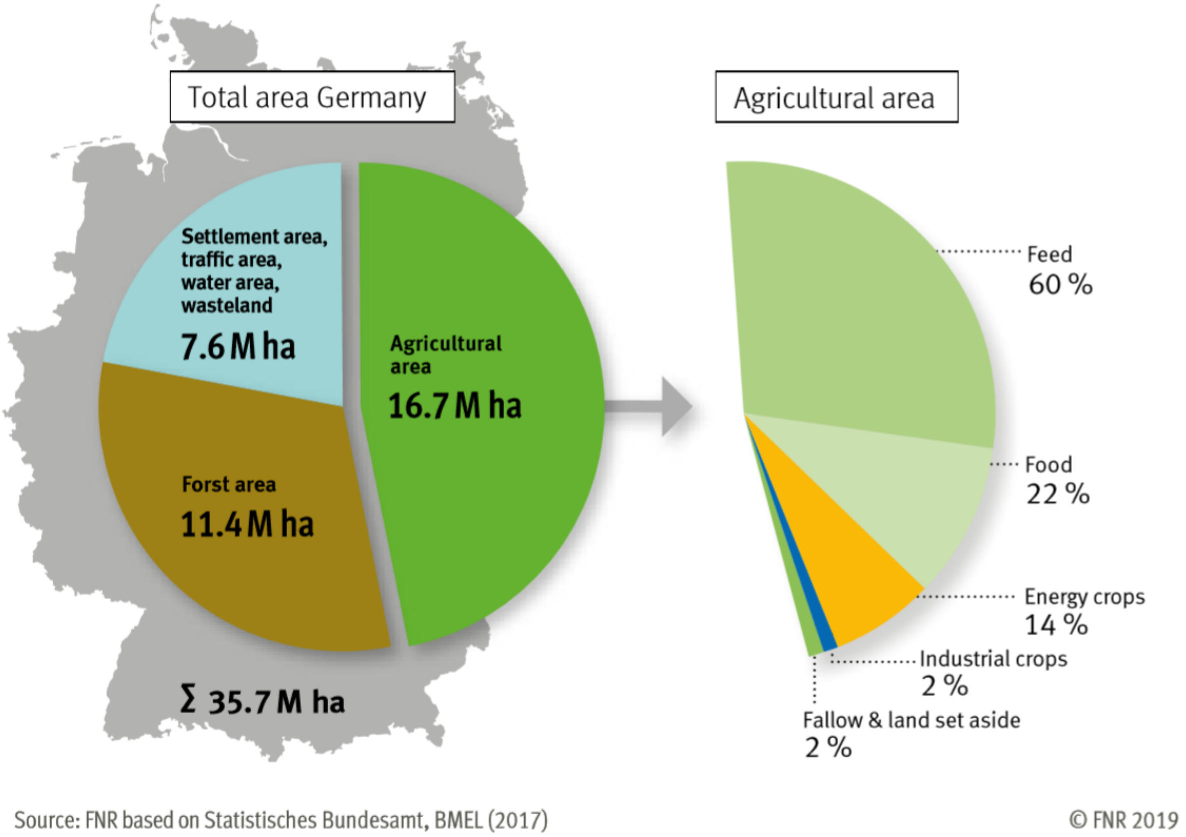

Figure 30: Land use in Germany [FNR]

Building envelopes, i.e. roofs and facades offer a technical potential of at least **1,4 TW** [FATH]. PV modules can not only be mounted on existing flat or pitched roofs, they can also be integrated directly into the building (BIPV). These include PV roof tiles, PV roof sheeting, modules for cooling facades, thermal insulation composite systems (ETICS) with PV, opaque and transparent PV insulating glass.

Brown coal mining has destroyed an area of 1773 km² [UBA4] in Germany, more than three times the area of Lake Constance. If one quarter of this area is flooded and covered with floating PV (FPV) this opens up a technical potential of **55 GW**. Worldwide, more than 1 GW of floating PV systems is already installed.

A study by the German Federal Environmental Agency assumes 670 km² of sealed settlement areas [UBA], corresponding to **134 GW** of technical potential for PV installations. These include structurally characterized settlement areas, but without building and traffic areas such as roads or railways. Part of this area can be covered with PV modules as a shade dispenser or covered with special, drivable modules (UPV, from "Urban PV").

Further potential on the GW scale is provided by noise barriers, selected traffic areas, track bodies (RIPV, from "Road Integrated PV") and in perspective the roofs of electric vehicles (VIPV, from Vehicle Integrated PV").

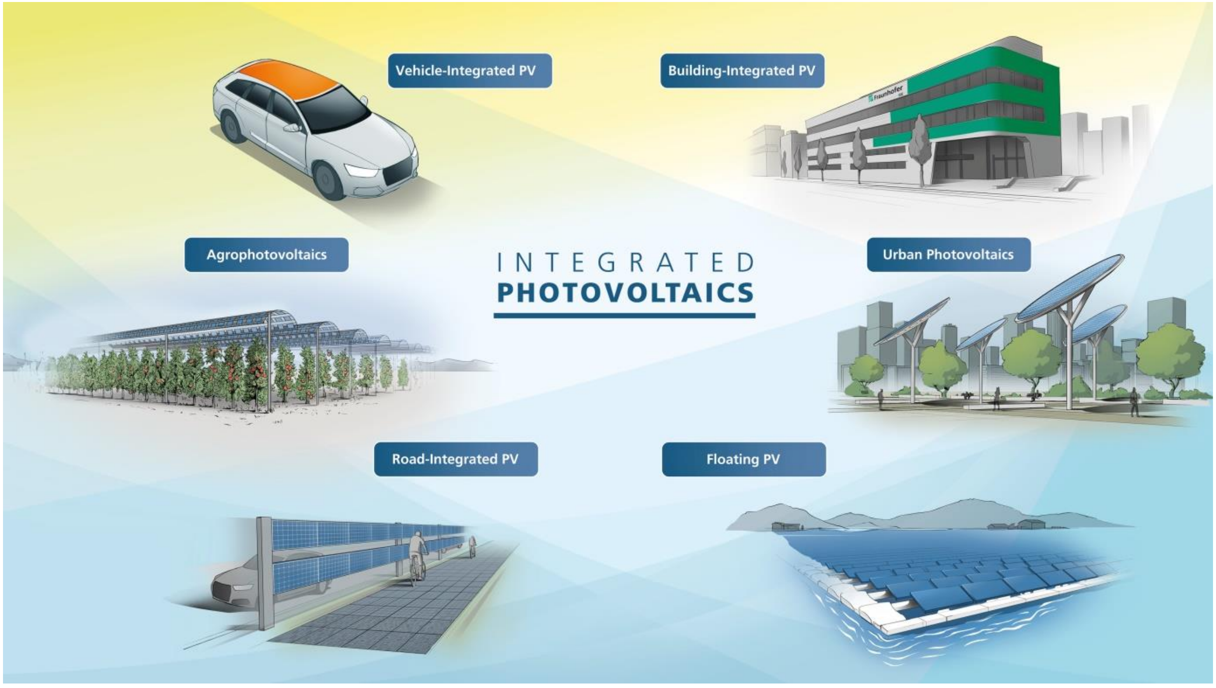

Figure 31: Applications for the integration of photovoltaic

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

14 Do PV power plants find acceptance in the population?

Yes. The free scalability of PV power plants enables decentralized expansion, even down to so-called "balcony modules" ("plug-in PV") with a few hundred watts rated power. The high number of more than 1.6 million PV systems in Germany, of which about 60% are small systems with outputs below 10 kW, shows that extensive use is made of these technical possibilities. From a local perspective, PV power plants are by far the most popular power plants, according to a survey by the Renewable Energy Agency (Figure 32). The popularity increases when such power plants in their own neighborhood are practically experienced.

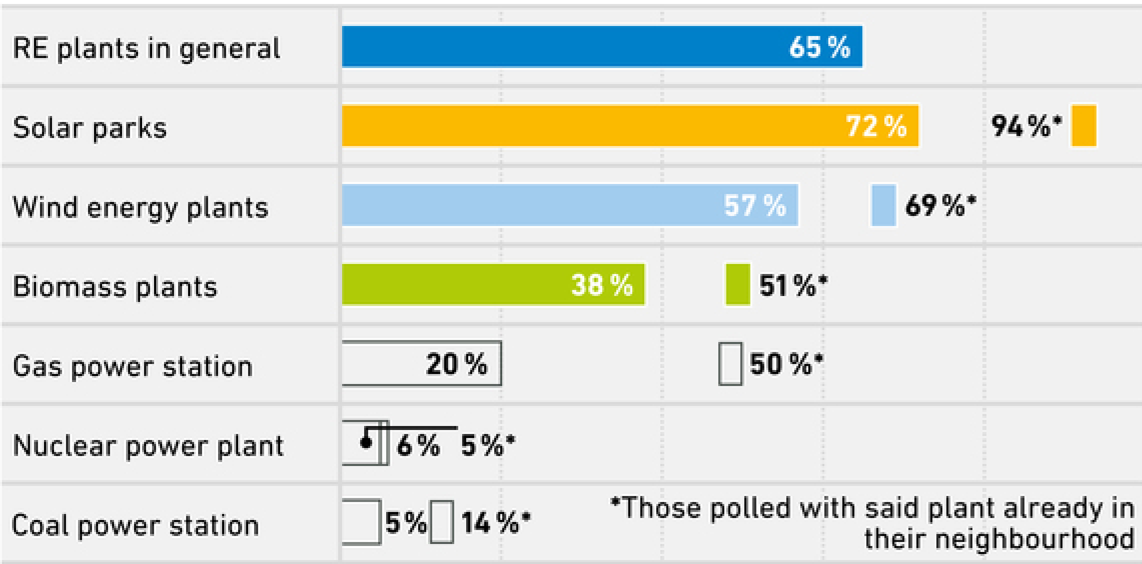

Figure 32: Survey results on the acceptance of different types of power plants [AEE4]

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

15 Are PV plants in Germany efficient?

The nominal efficiency (see section 24.2) of commercial wafer-based PV modules (i.e. modules with silicon solar cells) in new production has increased in the last few years by approx. 0.3 percentage points per year to average values of approx. 17.5% [ISE10] and a peak performance of 22%. They provide a nominal output of 175 W per square meter module, top modules up to 220 W.

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

Depending on irradiance and performance ratio (PR), specific yields of around 900-950 kWh/kWp are typically generated in Germany and in the sunnier regions up to 1000 kWh/kWp. This corresponds to around 150 kWh per square-meter module and for premium modules around 180 kWh. An average 4-person household consumes around 4400 kWh electricity per year, corresponding to the annual yield generated by 30 m² of new modules with today's average market efficiency. Calculations show that a south-facing, tilted roof of a detached family home is typically expansive enough to accommodate about 20 PV modules. This would be sufficient to supply the equivalent of the family's annual electricity needs.

To increase yield, PV modules are optimally tilted on flat roofs and open land to achieve the highest yield. Tilted south-facing modules, positioned at suitable distance from one another to prevent shading, require an area approximately 2 to 2.5 times of their own surface area. For the year 2015, an average area requirement of 1.6 ha per megawatt of installed capacity was determined for open space installations, with a strongly decreasing trend [BNA4]. In comparison, when converting energy crops into electricity, the efficiency value calculated on the basis of irradiance is significantly less than one percent. This amount falls further when organic fossil fuels such as coal, oil or natural gas are converted into electricity. The efficiency of combustion-based power plants is based on the chemical energy which already exists in fossil fuels. Based on this method of calculation, Germany's coal-fired power plants report an average efficiency value of 38 percent, for example.

Burning biofuels in vehicles results in modest efficiencies in relation to the irradiated energy and land use. Figure 33 compares the annual ranges of vehicles with internal combustion engines with the range of a battery-electric vehicle. The drive energy of the internal combustion engine comes from one hectare of cultivated area for biofuels, while the electricity for the electric car comes from a PV power plant covering the same area.

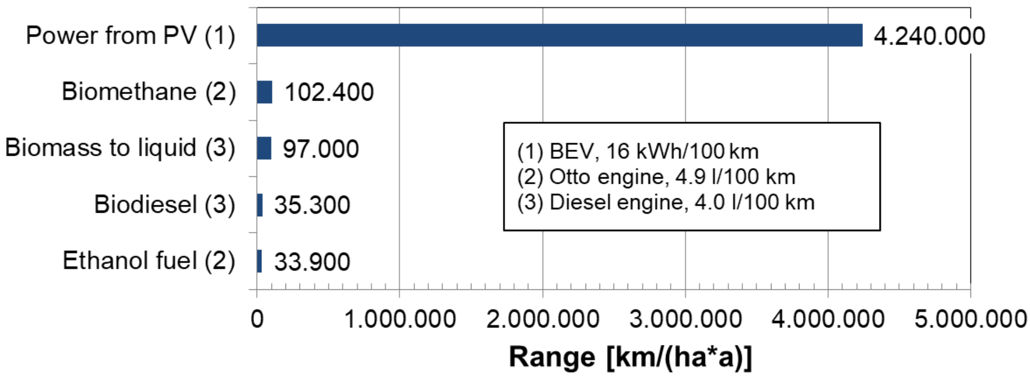

Figure 33: Vehicle range with the annual yield from 1 hectare PV power plant (1) and 1 hectare energy crop cultivation (2.3; figures adjusted from [FNR1])

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

15.1 Do PV plants degrade?

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

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

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

15.2 Can PV modules become soiled?

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

15.3 Do PV plants often operate at full capacity?

No.
The performance indicator «full-load hours" is the quotient of the actual energy generated by a power plant in the space of a year and its rated power (see section 24.3). Due to the fluctuating and cyclical solar irradiation patterns, PV plants actually operate for less than half of the 8760 total hours per year, and even when they are operating, the system generally operates at partial load. Based on a trend scenario, the transmission system operators (TSOs) assume an average of 980 full load hours per annum for PV systems in Germany and 892 hours per annum for roof-mounted systems [ÜNB]. Figure 34 gives the forecasted full load hours per annum for different renewable energy systems in Germany.

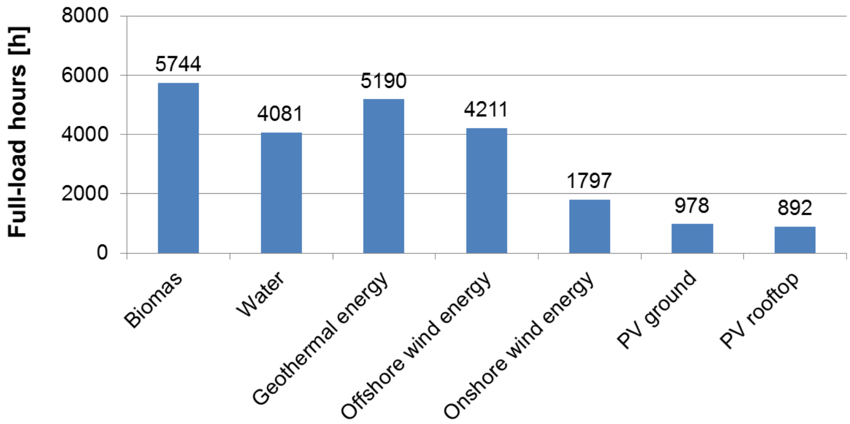

Figure 34: Forecasted hours of full-load operation for renewable energy plants, mean values from 2012-2016 [ÜNB]

The average annual sum of horizontal global irradiance in Germany for the years 1998-2018 is 1088 kWh/m²/a with a linear trend of +0.3% per year according to figures from the German Weather Service. Figure 35 shows the irradiance distribution across Germany for an earlier period, with an average annual sum of 1055 kWh/m² at that time. In order to maximize yields, PV modules are oriented facing south and are installed with a tilt angle 30–40° to the horizontal. This increases the average incident irradiation to roughly 1250 kWh/m² per year throughout Germany.

A performance ratio PR (see section 24.6) of 85 percent and an ideal orientation would result in a geographical average across Germany of more than 1060 full-load hours. Since some roof-mounted systems are not ideally oriented and many still have a PR of less than 85 percent, the actual average number of full-load hours is somewhat lower. Technical improvements in the module and installation can increase the incident irradiation, the performance ratio PR, the yield and thus the number of full-load hours of a PV system. The improvements entail:

- Tracking (see section 18.3.1)
- Bifacial PV technology
- Reducing losses caused by shading
- Reducing the temperature coefficient of the solar cells
- Reducing the operating temperature of the module by backside ventilation
- Increasing the module properties for weak light and askance light conditions
- Reducing module losses caused by snow cover and soiling
- Early detection and repair of reduced output
- Decrease degradation over the module lifetime

In wind power plants, the greater the hub height, the greater the number of full-load hours. When required, nuclear, coal and gas-fired power plants are capable of working almost continuously (one year = 8760 hours) at their rated power. In reality, according to [BDEW1], lignite-fired power plants reached 6640 full-load hours in 2007, while hard coal-fired power plants achieved 3550 hours.

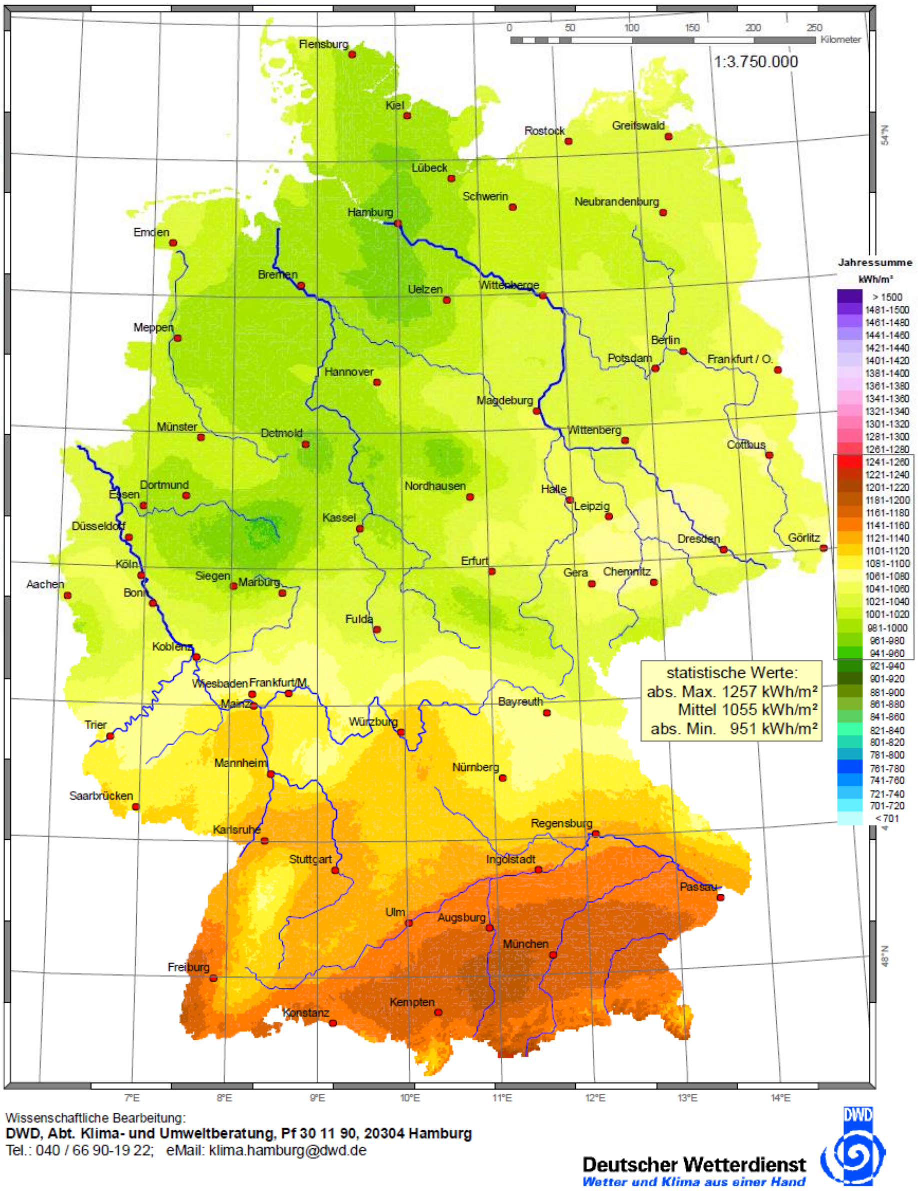

Figure 35: Horizontal annual global irradiation in Germany averaged over 1981-2010

16 Does PV make relevant contributions to climate protection?

16.1 Do anthropogenic CO_2 emissions danger the climate?

Yes. Most experts see a substantial risk.

Increasing global warming has been proven beyond doubt [IPCC]. Compared to the pre-industrial age, the mean global temperature has risen by 0.8° C [IEA2]. The vast majority of the scientific community believe that anthropogenic emissions of CO_2 and other greenhouse gases significantly increase the growth of atmospheric greenhouse gas concentrations and, moreover, cause the increase of the average global temperature to become extremely likely. In May 2013, the atmospheric CO_2 concentration reached 400 ppm for the first time in 800,000 years.

Figure 36 and

Figure 37 show the development through today of the atmospheric CO_2 concentration and the global or Antarctic temperature to date.

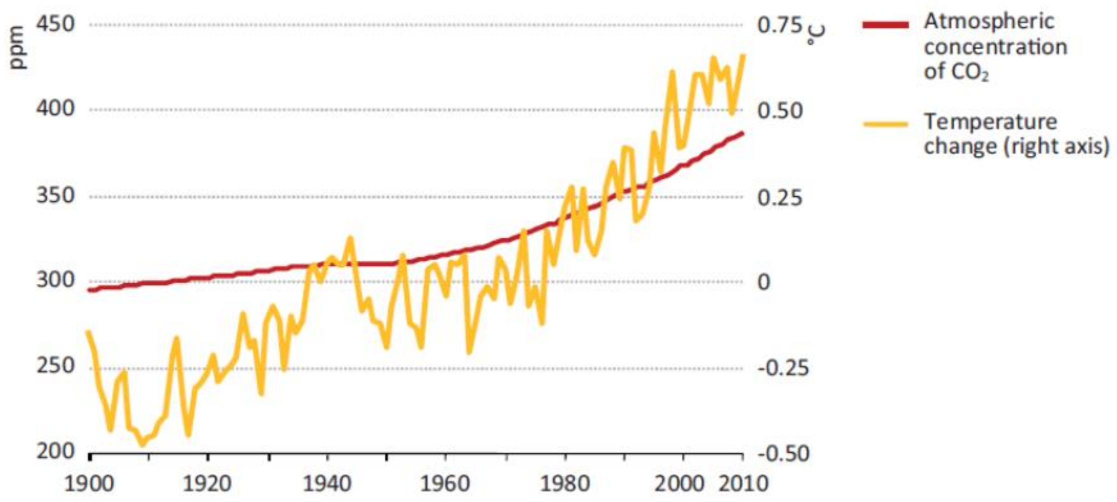

Figure 36: Development of the atmospheric CO_2 concentration and the mean global temperature change based on the NASA Global Land-Ocean Temperature Index [IEA2].

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

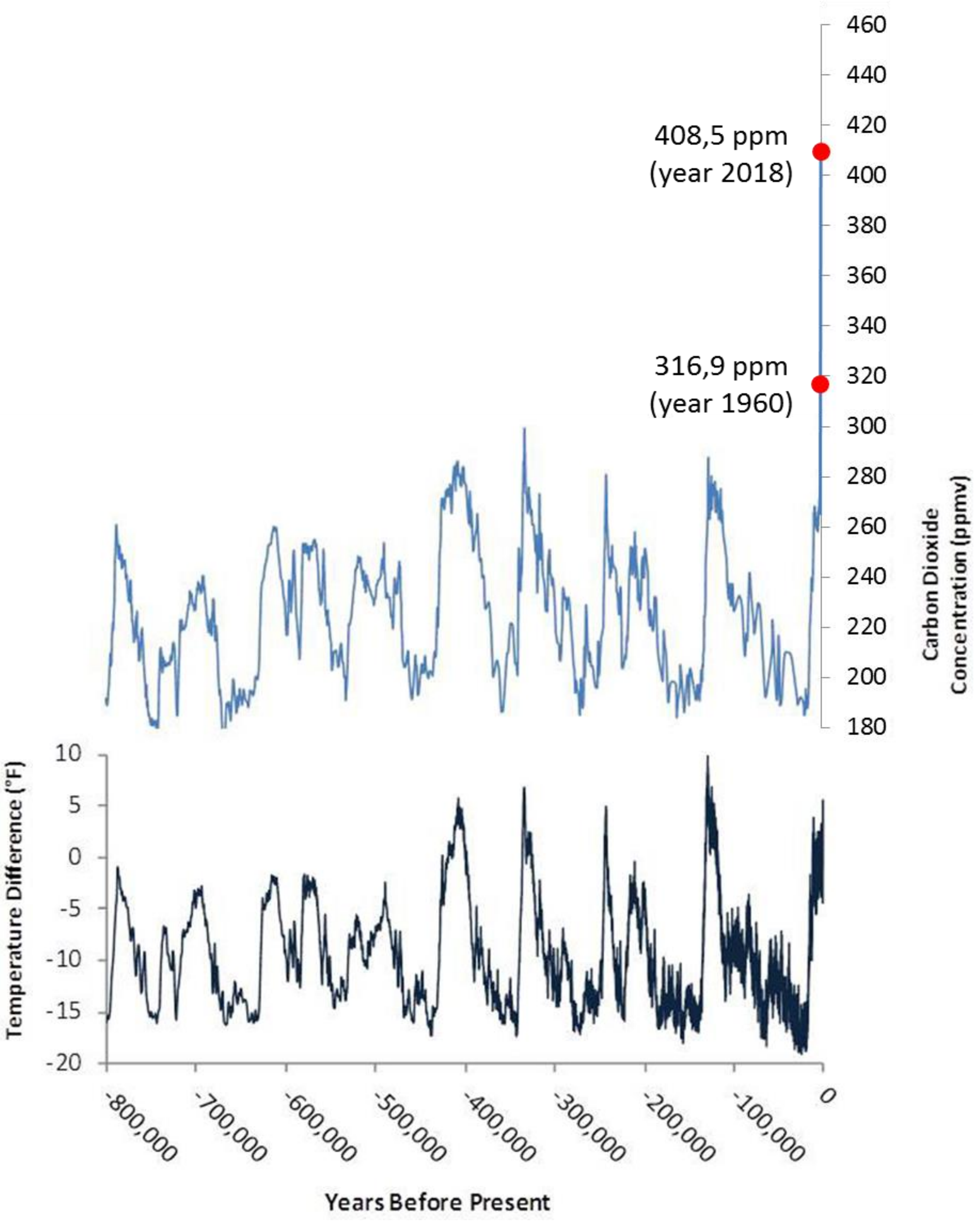

Figure 37: Estimate of the atmospheric CO_2 concentration and the temperature in Antarctica based on ice core data [EPA], added two recent readings from Mauna Loa Observatory for CO_2 concentration [https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html]

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

Yes.

While PV systems do not release CO_2 during operation, a holistic view must also take into account the manufacture of the system and its disposal. If one considers the life cycle of a photovoltaic roof system operated in Germany, plausible estimates lie between approx. 50 (Figure 38, [EnAg]) and 67 g CO_2 eq./KWh solar power [UBA7]. With the spread of new technologies such as diamond wire saws, greenhouse gas emissions from PV production have decreased significantly in the recent past.

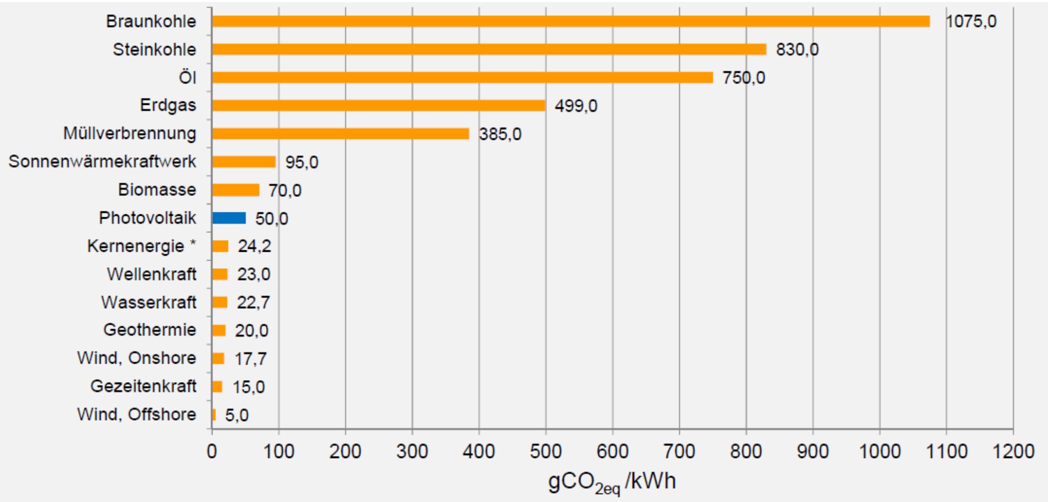

Figure 38: Average CO_2 equivalent emissions of various power generation technologies [EnAg]

By expanding RE, the CO_2 emission factor for electricity generation in Germany could be reduced to 474 g CO_2/kWh by 2018 (Figure 39).

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

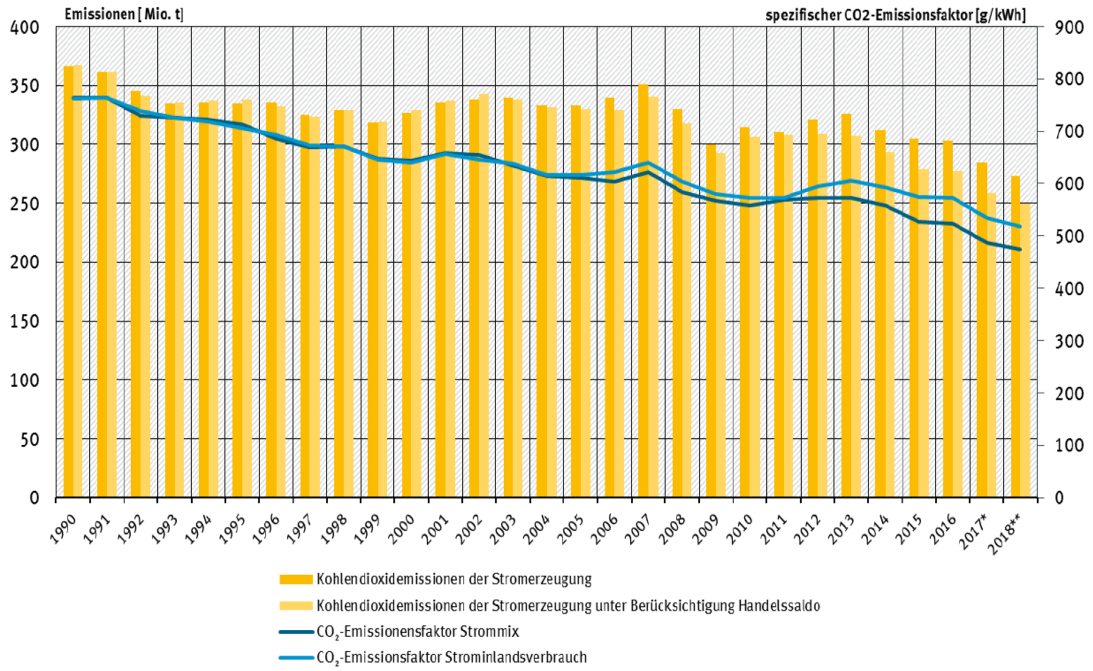

Figure 39: Specific and absolute CO_2 emissions of electricity generation in Germany [UBA6]

In 2018, the use of PV in Germany avoided around 28.4 million tons of greenhouse gas emissions (Figure 40), i.e. 621 g/kWh with an electricity production of 45.75 TWh.

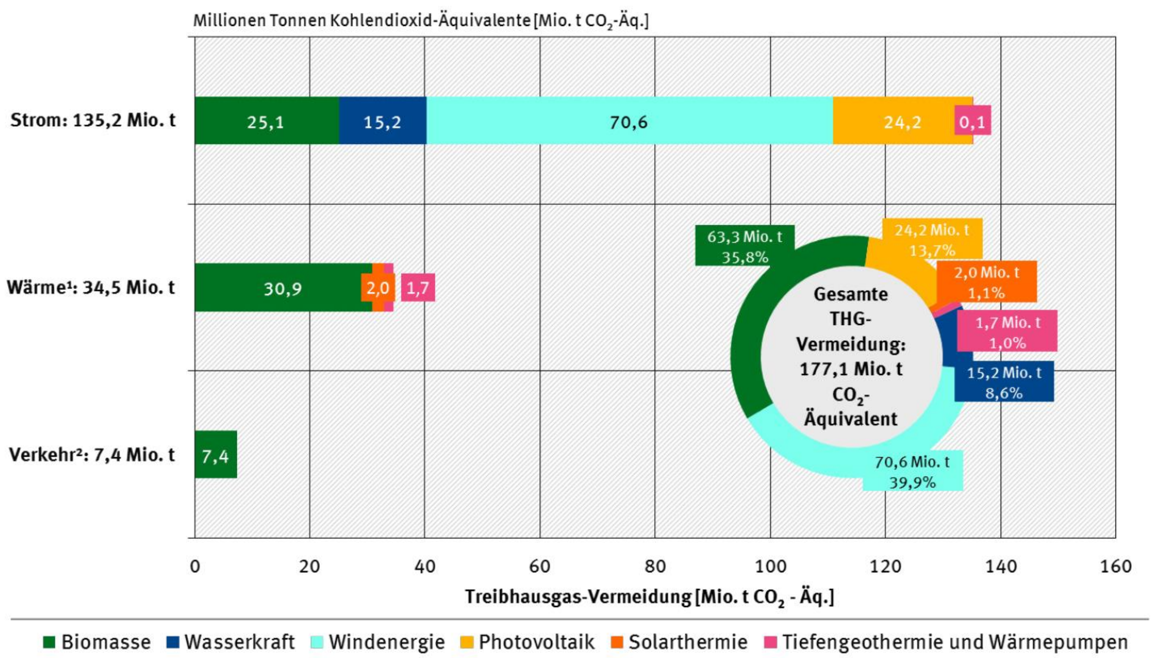

Figure 40: Greenhouse gas emissions avoided by using renewable energy in 2018 [UBA1]

Germany's energy policy has influence on a global scale. With a production volume of 171 million tonnes in 2016, Germany was the number 1 international lignite mining company, ahead of China. Although less than three percent of the global electricity consumption was due to Germany (with consumption showing a downward trend), German policy makers are leading the way in terms of developing incentive programs for RE. The EEG is the best example of this. The EEG and its effect have been closely observed around the world. It has been used by dozens countries as a model for similar regulations. Meanwhile, China is leading in expanding its PV capacity and has surpassed Germany in annual installed power many times over.

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

In terms of avoiding CO_2 emissions, the EEG achieved the highest impact due to a side effect: The creation of the largest and most secure sales market for PV, which lasted many years and decidedly accelerated global expansion, technology development and price reduction (Figure 41). Worldwide PV is reducing the use of fossil fuels for electricity production.

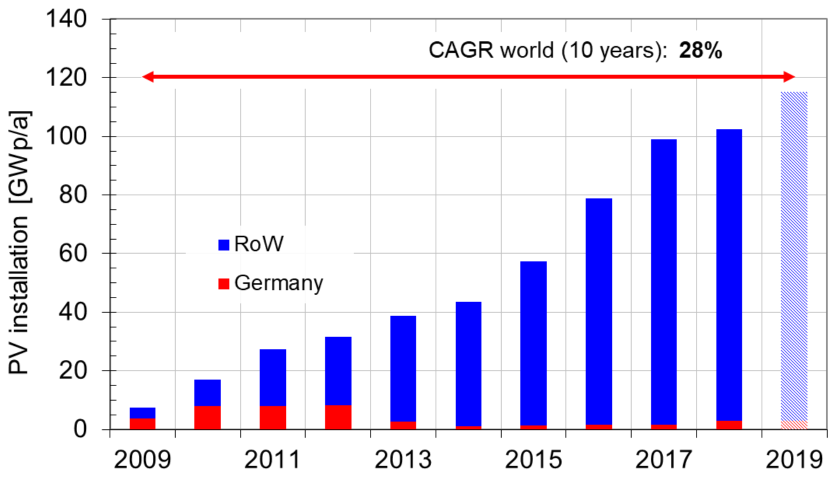

Figure 41: Development of annually installed PV capacity for Germany and globally, or Rest of World, (RoW), numbers from EPIA (up to 2010), IHS (up to 2017), PV Market Alliance (estimate for 2018) and IEA (forecast for 2019)

The German EEG has made PV power affordable faster, also extending out to people in developing countries. In this context, the EEG is «possibly the most successful development program of all time when it comes to energy supply," says Bodo Hombach in the

"Handelsblatt" newspaper on January 11, 2013, and also helps developing countries to save significant amounts of CO_2.

16.3 In addition to CO_2 are there other environmentally harmful gases released during the production of PV?

Yes, in the case of some thin film technologies.
During the production of thin-film PV and flat screens, nitrogen trifluoride (NF_3) is still used, in part, to clean the coating systems. Residues of this gas can thereby escape into the atmosphere. NF_3 is more than 17,000 times as harmful to the environment as carbon dioxide. Current emission quantities are not known. As of 2013, however, NF_3 emissions are to be determined in 37 countries according to the revised Kyoto Protocol.

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

Solar radiation plays an important role in the Earth's energy balance. Light-colored surfaces reflect a larger amount of incident solar radiation into the atmosphere, while dark surfaces absorb more sunlight causing the Earth to heat up.

PV module installation alters the degree of reflection (albedo) of the ground on which the system is mounted. For example, the total thermal output of a PV module with 17 percent efficiency emits as much heat (locally) as an area with an albedo of ca. 20 percent. (To compare, asphalt has an albedo of 15 percent, meadow below 20 percent, and the desert ca. 30 percent (http://wiki.bildungsserver.de/klimawandel/index.php /Albedo). In consideration of the relatively low amount of area required by PV modules (Section 13), the albedo effect is marginal. Furthermore, PV electricity use replaces the power from fossil fuel plants, reduces carbon emissions and thus slows down the greenhouse effect.

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

No, not in the near future.
PV and wind power may currently be capable of reducing the use of fossil fuels, imported energy consumption and CO_2 emissions but until considerable storage capacities for electricity or hydroelectric storage facilities are available in the grid, they are not capable of replacing capacities. Calm, dull winter days, when power consumption is at a maximum and no solar or wind power is available, present the most critical test.

Despite this, PV and wind power are increasingly colliding with conventional power plants with slow start-up and shut-down processes (nuclear, old lignite power plants). These power plants, which are almost only capable of covering the base load, must be replaced by flexible power plants as quick as possible. The preferred power plant choice is multifunctional electrically powered CHP plants fitted with thermal storage systems (Section 18.3.6).

18 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 revolution.

18.1 Energy demand and supply

The traditional energy industry promotes fossil and nuclear energy sources (primary energy), converts them and prepares them for end users (
Figure 42).

The conversion and consumption are subject to dramatic efficiency deficits. For example, the end energy consumed in traffic is predominantly converted into waste heat via internal combustion engines; only a small part is transferred as mechanical energy to the drive train (load-dependent approx. 10-35%). Of the drive energy generated, a considerable part of the braking is still irreversibly burned, especially in city traffic, because internal combustion engines do not recuperate. Thus, motorized road traffic burns fossil fuels with a very low efficiency, based on the transport performance. Households, which use about 75% of the final energy consumed for heating, could halve their consumption through simple heat protection measures.

Germany is highly dependent on energy imports (Figure 43) combined with the risk of political interference by mining and transit countries and the risk of disturbances in raw materials logistics, for example due to low water levels in the rivers.

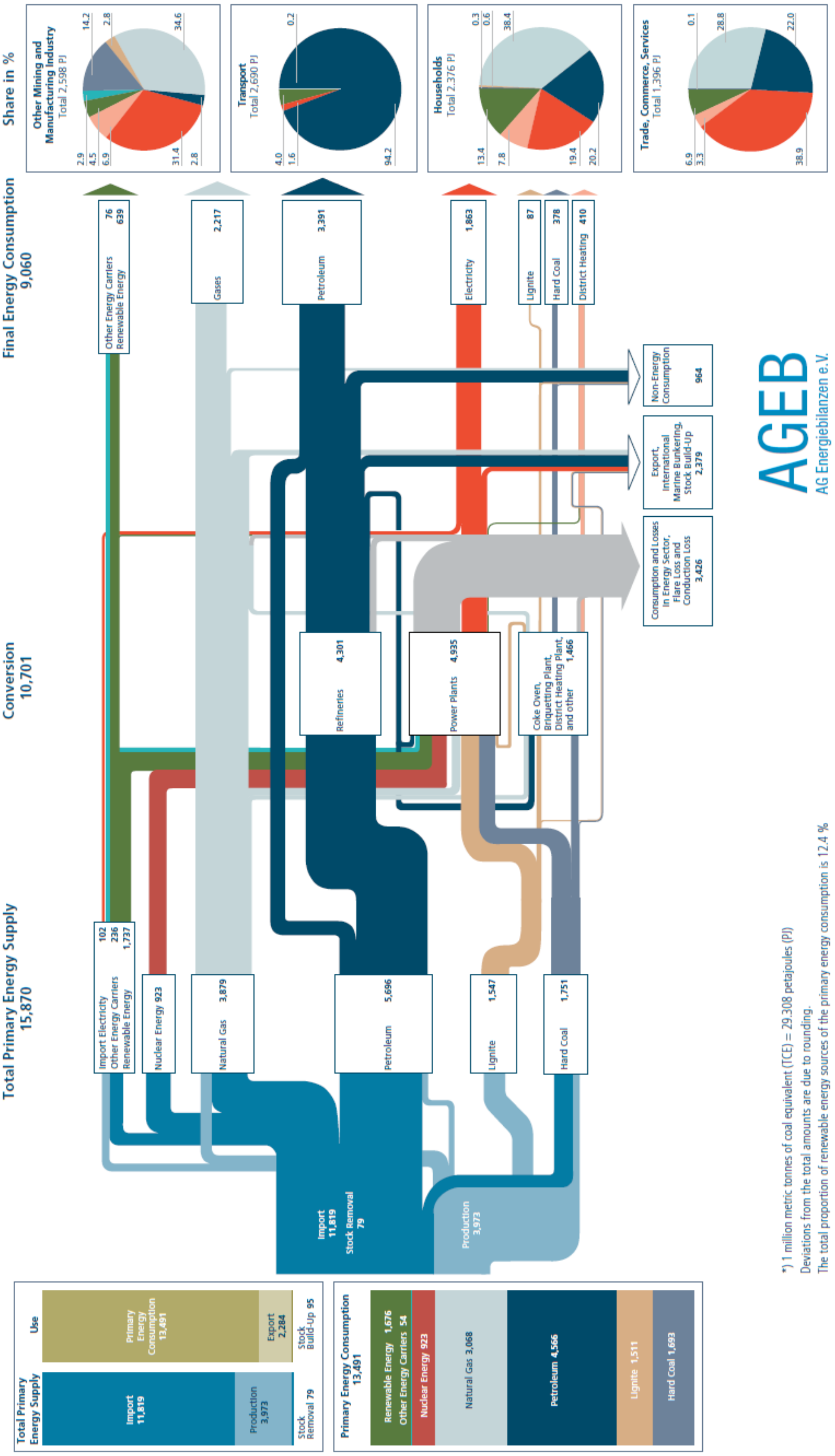

Figure 42: Energy flow diagram 2017 for Germany in petajoules [AGEB2].

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

Figure 43: Germany's import quotas for fossil and nuclear energy sources (www.umweltbundesamt.de)

The costs of energy imports are shown in Figure 44, minus their import revenues, which are around 50-100 billion euros per year. Much of the money goes to autocratic regimes.

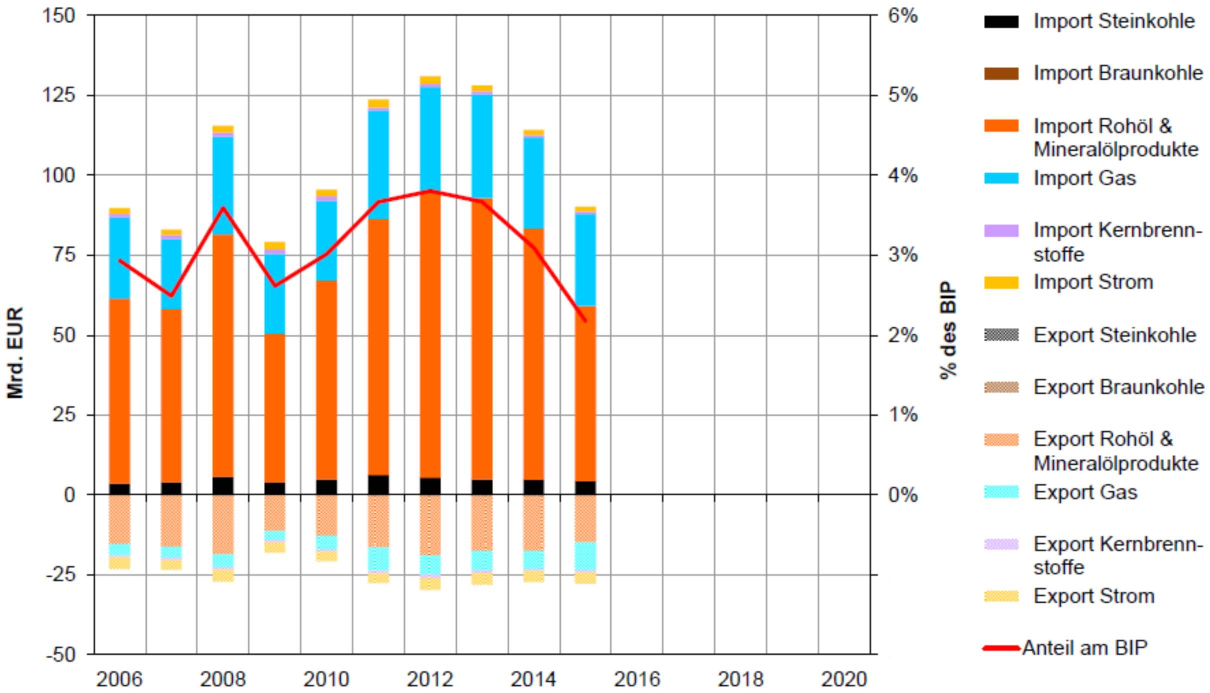

Figure 44: Cost development for the provision of primary energy in Germany [ÖKO3]

The majority of final energy (39 percent) is used to generate mechanical energy (force) for vehicles and stationary engines (
Figure 45). For space heating and hot water, about 800 TWh of final energy is used annually [BMWi1].

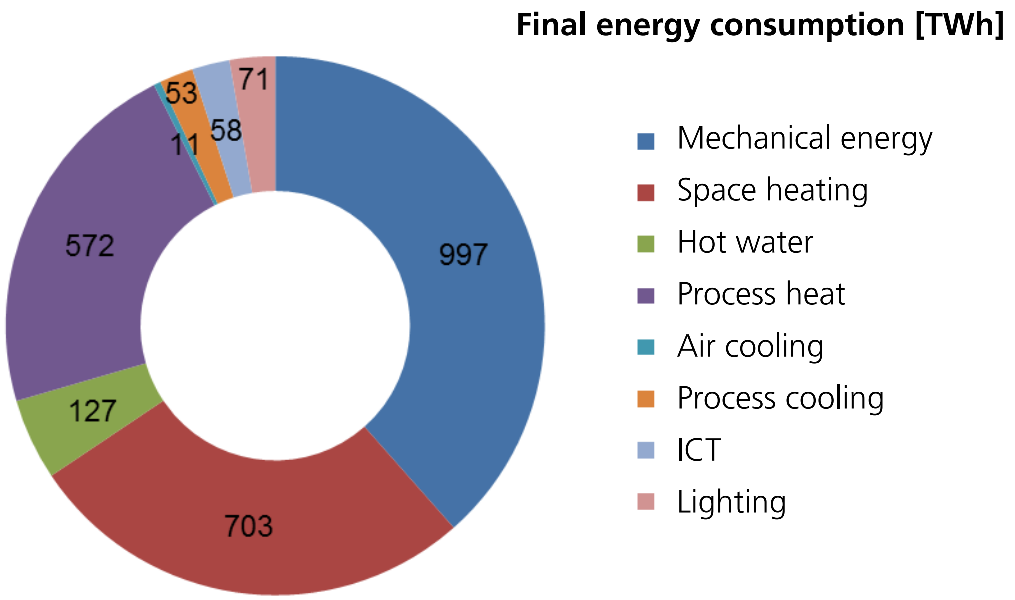

Figure 45: Share of final energy in Germany, categorized by utilization 2017, Figures by [BMWi1]

The electricity load fluctuates periodically: more electricity is needed during the day than at night, and on weekdays more than on weekends and public holidays. Electricity providers differentiate in the load profile between basic, medium and peak load, see Section 24.7. The base load is the load share of 30-40 GW, which barely changes over 24 hours. The intermediate load fluctuates slowly and predominantly periodically, the peak load comprises the rapidly changing load portion above the basic and intermediate load.

Electricity consumption and the energy needed for hot water is slightly lower in summer than in winter. The petroleum sales (petrol and diesel fuel) show very low seasonal fluctuations [MWV]. The heating demand correlates negatively with global irradiance, with the highest point of intersection being found in spring.

18.2 Energy scenarios

Our current energy system in Germany, which is based on generating power from fossil fuel and nuclear sources, cannot survive in the long term. A variety of energy scenarios have been created for the coming decades, and they are increasingly incorporating the use of RE [UBA, ACA, ISE5].

Researchers at the Fraunhofer Institute for Solar Energy Systems ISE have investigated an energy system for Germany in a simulation based on hourly time series (Figure 46). It is entirely based on renewable energies and includes the heating sector with its potential for storage and energetic building renovation. In an economically optimized generation mix PV contributes with an installed capacity of approx. 200 GW [ISE5]. A balanced bottom line was assumed for cross-border electricity trading.

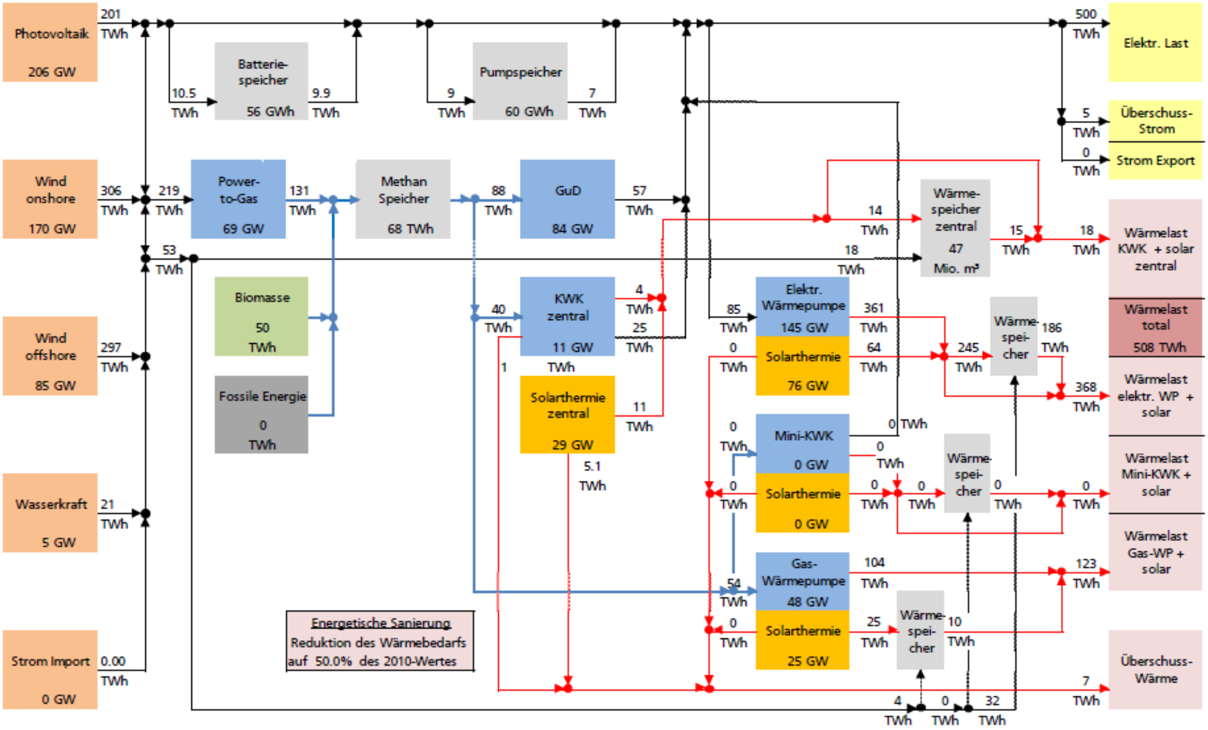

Figure 46: Scenario of a German energy system, schematic representation of the system composition. [ISE5]

Figure 47 shows a schematic residual load curve for Germany with a 100% renewable power supply. Shown are the descending ordered hourly values of the residual load for one year. The residual load is the difference between irreducible electricity load and electricity production from volatile renewable sources (PV, wind, run-of-river). Volatile power production can be limited at any time technically, but at the price of an economic loss of power of the corresponding amount of electricity. An electricity price with a reasonable tax function would fall from left to right along the residual load curve in Figure 47.

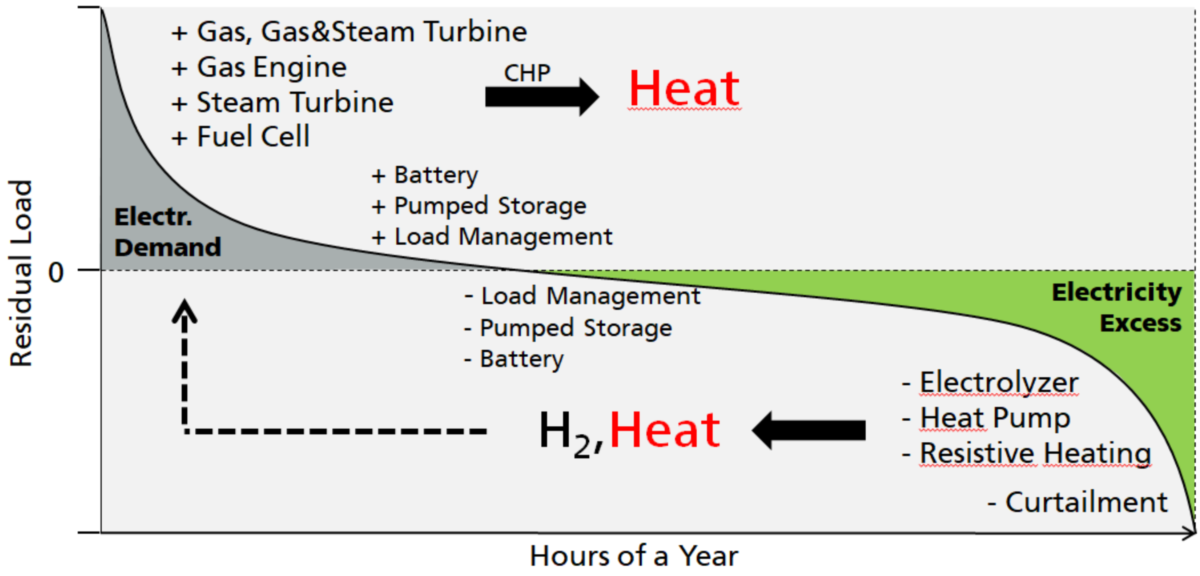

Figure 47: Schematic representation of a residual load curve for Germany with power supply with 100% EE, with generators (+) and loads (-)

On the **demand side**, flexible loads are reduced, batteries and pumped storage are discharged, fuel cells, steam turbines, gas and steam generators (CCGT) and gas turbines are activated in the order of their marginal costs to cover the residual load. For the REMod-D energy system model, the operational management order is laid down in [NOW], Appendix 5. Hydrogen or methane, produced with EE, is used as an energy source. When there is local demand for heat, power generators are designed with combined heat and power (CHP) and produce usable waste heat. CHP gas turbines provide high-temperature heat for industrial processes.

On the **surplus side**, flexible loads are increased, batteries and pumped storage are loaded, electrolysers, heat pumps and resistance heating ("heating elements") are activated when electricity prices are falling in order to decrease the electricity that is not currently required. Electrolysers can also be operated as CHP systems and produce usable waste heat. Resistance heaters and high-temperature heat pumps can supply heat for industrial processes. Ultima ratio is the regulation of electricity production, if the installed purchase capacity or the network capacities are not sufficient for a few hours of the year.

In order to be able to operate heat-generating converters (Figure 47) on both sides of the curve in a current-regulated manner, they require thermal storage and heat consumers close to the location or a connection to heat networks (Section 18.3.6). Generators (eg simple gas turbines) and consumers (eg resistance heating systems) with particularly low performance-related investment and reserve costs (€ / W) are needed for the two-sided extensions of the residual load curve. Being rarely in operation, they do not have to be highly efficient.

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

The **storage capacity** of the system must be designed for the worst case of a multi-week primary energy failure (sun and wind), for example a prolonged winter slack with full snow coverage. For this purpose, appropriate quantities of hydrogen and derived synthetic energy carriers and raw materials must be provided. If there were no support from wind power, then a multiple of the PV storage capacity would be necessary to cover large parts of the winter half-year. Because of their limited capacity, batteries and pumped storage fail relatively fast in continuous operation as generators (minutes to a few hours). Their benefit is the frequent change of operation between loading and unloading, which they implement faster and, above all, more energy-efficiently, compared to the electricity-to-electricity path via hydrogen. Many load management options also have a short impact. Vehicle batteries must primarily meet mobility needs. They can therefore only be charged to a limited extent depending on the offer (load management) or operated bidirectionally as a battery in the network (storage). Many millions of grid-connected electric vehicles can still support the power grid bidirectionally for a few hours.

The **power generation capacity** of the system on the left side of Figure 47 must be sufficient to take over the entire supply in the order of 100-150 GW when the hourly reserves (load management, pumped storage, battery) are exhausted. This situation often occurs, for example, in windless nights, and may in some cases last over several weeks (see above).

The **power consumption** of the system on the right side of Figure 47 in the order of several 100 GW must be sufficient to largely absorb the production of electricity from volatile RE minus the current power consumption. The power consumption starts as soon as the capacity of the hourly reserves (load management, pumped storage, battery) has been exhausted. If the power consumption is insufficient for rare production peaks, power generation must be regulated. This can happen, for example, on stormy nights or on sunny and at the same time very windy weekend days when low demand and very high electricity production come together. For these few operating hours, no further expansion of the acceptance performance is worthwhile.

Converters that allow reversible operation operate on both sides of the curve in Figure 47 and achieve high utilization. In addition to batteries, this also includes reversible fuel cells that can operate electrolysis in the event of excess electricity. The technologies and measures mentioned in Figure 47 **are scalable**, with the exception of turbines and pumped storage. They can not only be operated centrally on a multi-MW scale, but also on a single-digit kW scale. Appropriate devices are commercially available as domestic technology.

A quick glance at global energy scenarios: The study "Shell Scenarios Sky - Meeting the goals of the Paris Agreement" by Shell International B.V. from March 2018 considers PV to be the world's most important source of renewable energy (Figure 48). Global electricity consumption will rise from 22 PWh today to 100 PWh in 2100.

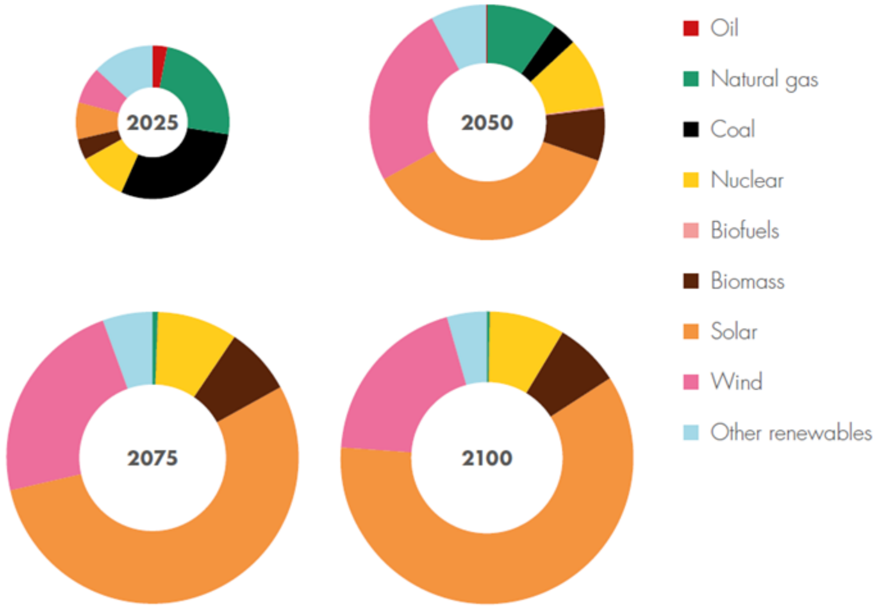

Figure 48: Development of global power generation by technologies in the Sky-Scenario; the diameter of the pie charts corresponds to the global power requirement [Shell]

The International Energy Agency (IEA) has been publishing scenarios for the worldwide expansion of PV (Figure 49) for years and reliably underestimates the actual development (black curve). IEA expects that the worldwide installed PV output will overtake wind power in 2020, hydropower in 2027, coal power in 2032, gas power in 2035 and reach an order of magnitude of over 3 TW by 2040 [IEA5].

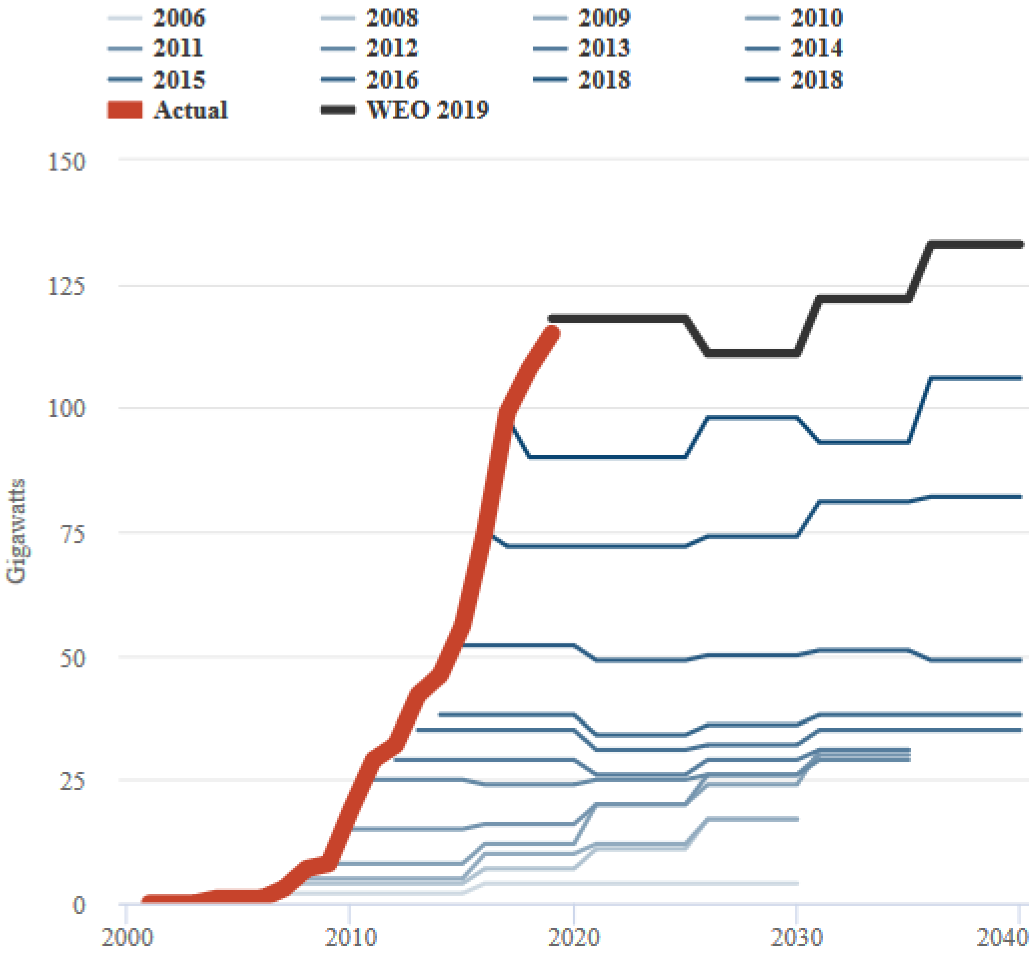

Figure 49: Forecasts of IEA since 2006 and actual development of global annual PV construction [Carb]

18.3 Transformation measures

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

18.3.1 Keeping PV power production constant

How can we keep the PV power supply constant in the grid?
A constant level in the daily run increases the full load hours of a PV power plant and reduces the need for compensation, for example through load management and batteries. One of the simplest approaches is the installation of roof- and ground-mounted PV modules with east/west orientation (Figure 48). This type of installation reduces the area consumption, but the specific annual yield per installed module capacity decreases compared with the south orientation. Single and dual-axis tracking systems not only make

power production more constant throughout the day (Figure 48), they also increase the specific annual yield by approx. 15-30%. Compared to stationary systems, they can also reduce yield losses caused by snow cover or increased operating temperatures. Another option is vertically mounted, bifacial modules with north-south gradient, which provide more electricity in the morning and afternoon than at noon.

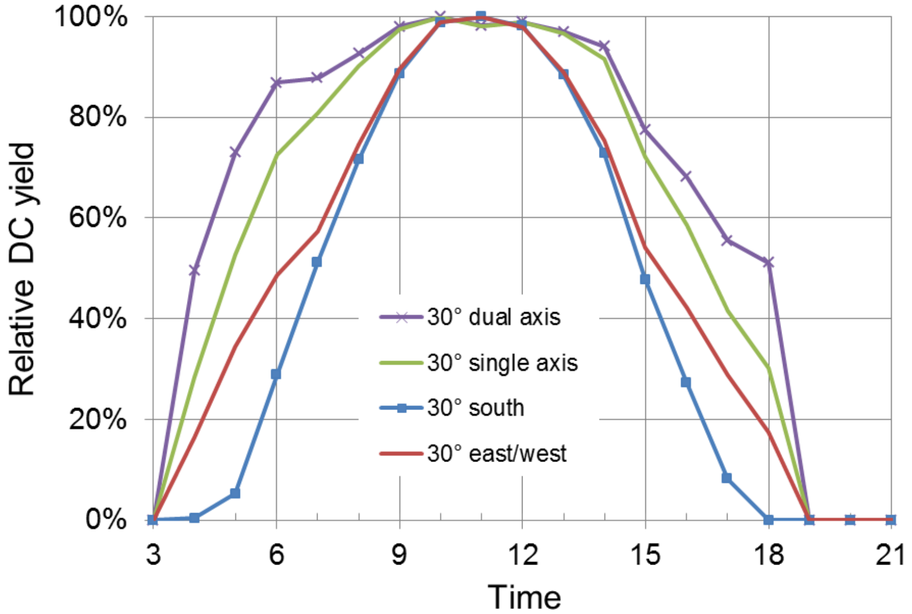

Figure 50: Yield development throughout the course of a day of PV plants installed in a variety of different ways, calculated using the software PVsol on a predominantly clear day in July in Freiburg, Germany.

The very pronounced seasonal fluctuation in PV power generation can be minimized by mounting south-facing modules with higher angles of inclination (Figure 50). As a result, the electricity yield in the winter half-year increased slightly, but at the cost of larger losses in the summer and in the total yield (in the calculation example -6%).

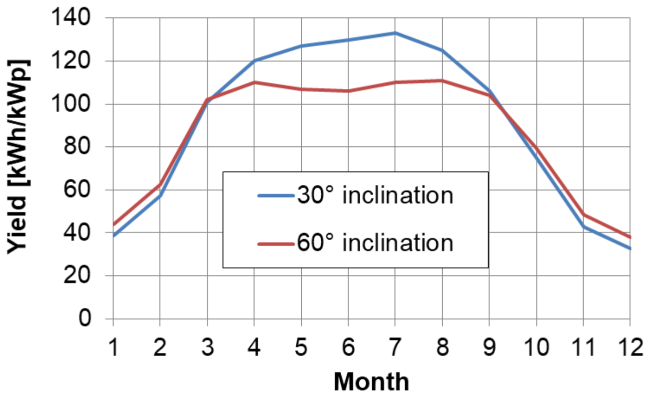

Figure 51: Calculation example for the specific monthly yield of a PV system at Freiburg for south-oriented modules with 30° inclination (maximum annual yield) and 60° inclination.

The slightly higher costs of electricity production for the alternative installation variants mentioned above can already be amortized in the context of increased self-consumption and the associated savings in electricity purchases, especially for commercial customers. Feed-in tariffs, which reward a higher value of electricity in the morning and evening hours, promote the construction of systemically advantageous PV power plants, which are not only optimized for maximum annual electricity yield. The measures to increase the number of full-load hours mentioned in section 15.3 also contribute to the stability of the PV electricity supply.

18.3.2 Complementary operation of power plants

It is technically possible to operate, design or retrofit many fossil fuel power plants in a way that they are able to follow the residual load (Figure 52). Partial load operation, increased wear and any associated retrofitting increases the power production costs.

Gas-fired power plants, in particular, are highly suitable to cover fluctuating loads. In combination with combined heat and power systems (CHP), natural gas power plants have a very high efficiency of 95 % [UBA2]. Simple gas power plants based on gas motors have only a fraction of the investment costs (€/kW) of combined cycle (gas and steam) power plants (CCPP). However, since PV is already noticeably reducing the residual load and the mid-day price peak on the energy exchange, and the favorable CO_2 balance of gas power plants hardly comes to bear because of low emission costs, gas-fired plants are currently not a worthwhile investment.

Today, gas-fired power plants burn natural gas and biogas. Most of the natural gas must be imported (about 95% in 2017 [AGEB6]), in particular, Russia and Norway deliver to Germany. As part of the energy revolution, gas power plants will switch from natural gas to mixed gases with increasing proportions of electrolytically generated hydrogen.

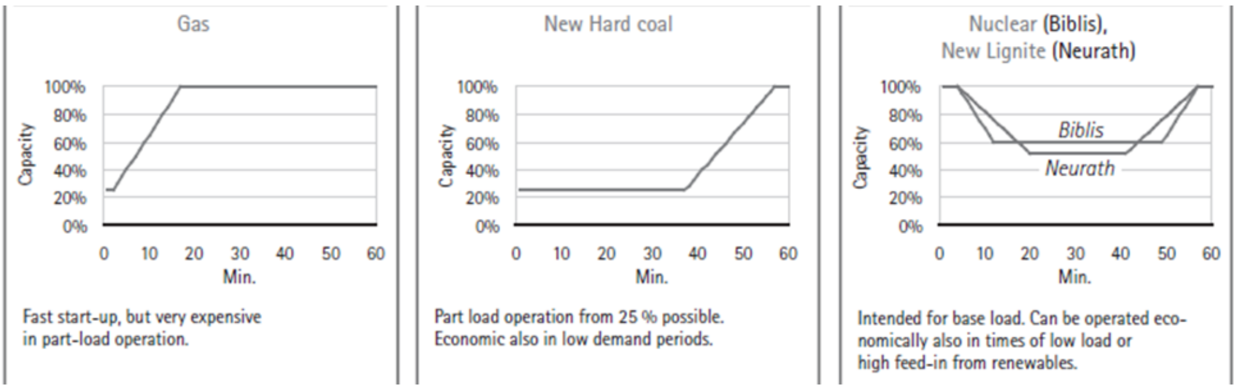

Figure 52: Power plant availability [VGB].

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

18.3.3 Increasing the energy efficiency

Measures for improving the energy efficiency in households and in the industry are among the most cost-effective for reducing the residual load. The Stiftung Warentest found, for example, that a house, which is equipped solely with older appliances, uses twice as much electricity as a comparable house with energy saving devices [Test]. Especially effective are measures that reduce the nighttime electricity consumption, when solar power (and in windless nights even wind power) can be provided only by comparatively complex storage.

18.3.4 Load management

Load management ("Demand Side Management") allows an active, temporary shift of power consumption, without affecting the long-term consumption. Electricity consumption by households (Figure 54), commerce and industry offers flexibility options with regard to supply-side management. Several studies have identified load management potential in the range of 20 GW and more for households and 14 GW for commercial consumers [AEE1]. However, the technical prerequisites and economic incentives for the development of these potentials still have to be created.
Load management ("Demand Side Management") enables an active, temporary shift in electricity consumption without affecting longer-term balance. Depending on the application and possibly the storage capacity, shifts by hours or days are possible. Flexibility options with regard to supply-based management are offered by

- electrical heating and cooling generator, in connection with thermal storage
- electric vehicles, by shifting the charging time
- household appliances, by postponing operations
- industrial processes, by supply-oriented control of electricity-intensive process steps

Several studies have identified load management potentials in the order of 20 GW and more for private households and up to 14 GW for commercial consumers [AEE1]. For the most part, the technical requirements and economic incentives for tapping these potentials still need to be created. Basic requirements are variable electricity tariffs and electricity meters, which enable time-dependent billing. In the best case, variable tariffs reflect the current residual load. For example, a "sunshine tariff" can provide useful incentives, i.e. a fixed reduction in the core daytime, when solar power production usually reaches its maximum. The self-consumption of solar power has an analogous effect, because it significantly reduces the price of electricity, when obtained directly from the own roof.

18.3.4.1 Electrical heating and cooling

Electric heat pumps use electrical energy to generate useful heat or cold. The efficiency of a heat pump (electricity to heat) is given as an annual performance factor and is around 300% depending on the technology and load. Resistance heaters (heating rods) convert electricity into heat with 100% efficiency. In the case of high-temperature heat, the conversion takes place with a high degree of exergetic efficiency. The generation of low-temperature heat by combustion is exergetically inefficient.

Thermal storage capacity, especially for low-temperature heat, can be provided much cheaper than electricity-to-electricity storage capacity via batteries or hydrogen storage. With sufficient dimensioning of the thermal storage capacity and the heat pump output, the heating and cooling generation can make a significant contribution to load management. For this purpose, the heat storage and cold storage for example of air conditioning systems, cold stores and food markets, are preferably charged in the core daytime or according to electricity price signals. If, however, there is a lack of generously dimensioned thermal storage, the thermal sensitivity of the electricity load increases and larger power reserves in power plants have to be taken into account.

18.3.4.2 Electric Mobility

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

If the electric vehicle is not in operation, it can contribute to load management in its role as a consumer, if the charging of its battery is supply-oriented. In order to charge PV electricity, they have to find charging stations at their daytime parking spaces, for example at work, in parking garages or in public parking lots. The decisive factor for mobilizing the potential is the availability of price signals in real time and as a forecast. This means that private individuals will take favorable charging times into account when refueling as well as e-logistics companies when planning their route.

Plug-in hybrid electric vehicles can travel up to approx. 80 km purely electrically with one battery charge. Pure electric vehicles offer standard ranges (NEDC) of up to 380 km with 40 kWh storage and up to 520 km with 60 kWh storage. In mathematical terms, the total mileage of all cars registered in Germany in 2017 of 630 billion km [KBA] with a consumption of 160 W/km [AGORA2] corresponds to an annual electricity consumption by electric vehicles of 100 TWh.

According to earlier plans by the German government, one million electric cars should be registered in 2020. With a charging power of approx. 40 kW per vehicle in quick charging mode, 25,000 vehicles on the power grid can already provide a gigawatt of bidirectionally controllable power for the primary, secondary and minute reserves. However, the energy revolution in private transport begins on two wheels: at the end of 2018, over 4 million e-bikes were sold in Germany compared to only 83,000 pure electric cars (BEV) (de.statista.com).

Figure 53 shows the complete greenhouse gas emissions of a current BEV with 35 kWh battery power over the mileage for mixed use city/country, compared with a gasoline and a diesel car, with 3 variants for the electricity mix. Consistent charging with solar power (or wind power) leads to a particularly flat course of the BEV emission line (yellow). If the BEV is sold together with a small PV system with a nominal output of 3 kW_p, the vehicle runs on balance sheet with 100% solar power, with an average annual mileage of over 15000 km, a specific annual yield of 950 kWh / kW_p and 15% charging losses.

If you consider pure city traffic with typical stop-and-go operation, consumption and GHG emissions per km decrease for BEV thanks to recuperation, while they increase for combustion engines due to braking losses and inefficient part-load operation. Smaller batteries with a capacity of, for example, 15-20 kWh are usually sufficient in the city, which further reduces GHG emissions for production and operation.

Recent studies show an interim reduction in battery-related GHG emissions to values of 61-106 kg CO_2-eq/kWh battery capacity [IVL], compared to the 145 kg CO_2-eq/kWh in 2017 (Figure 53). In the future, increasing proportions of RE with correspondingly decreasing greenhouse gas emissions will be used in the production of BEV.

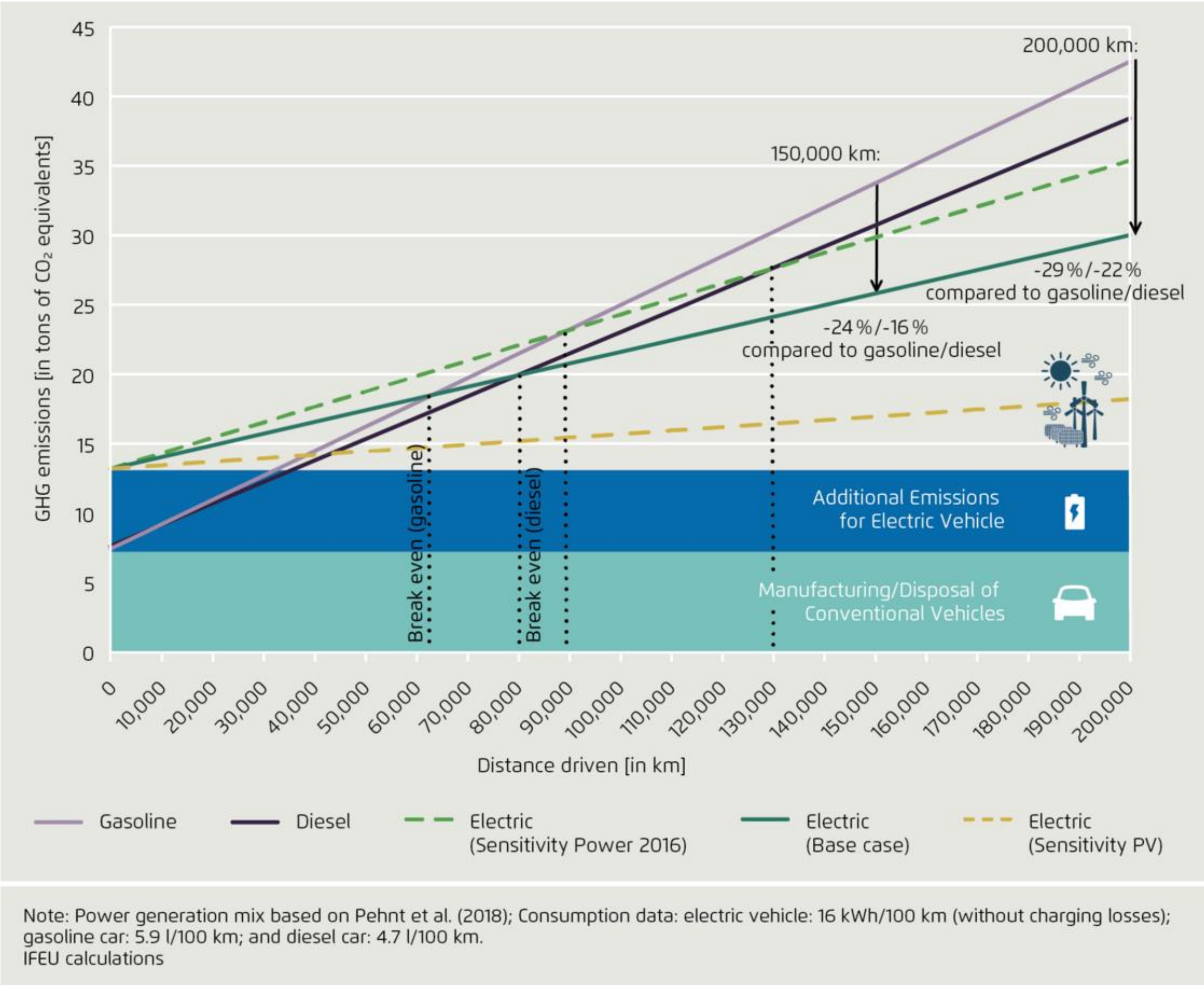

Figure 53: Greenhouse gas emissions from today's compact vehicles as a function of driving performance [AGORA2]

18.3.4.3 Electricity-intensive industry

The electricity-intensive industry has significant potential for adapting consumption profiles. If companies accept short-term, announced reductions in power delivery, they can already receive a contractually agreed compensation payment. As soon as very inexpensive daily electricity is available more often, i.e. the installed PV output continues to increase, then the flexibility on the industrial consumer will also increase. Investments are often necessary to convert processes to EE (e.g. the direct reduction of iron ore through green hydrogen, whereby hydrogen production can take part in load management), or to make electricity-intensive process steps more flexible (e.g. electrolytic aluminum production).

18.3.4.4 Appliances

Household appliances, whose operation may also start delayed, must be technically enabled with approval by the user, to wait for the core day or corresponding price signals.

This includes washing machine, dryer or dishwasher of a household (Figure 54). High flexibility potential can also be realized in connection with thermal storage in electrical heat generation (heating, process water) and cooling (see section 18.3.4.1).

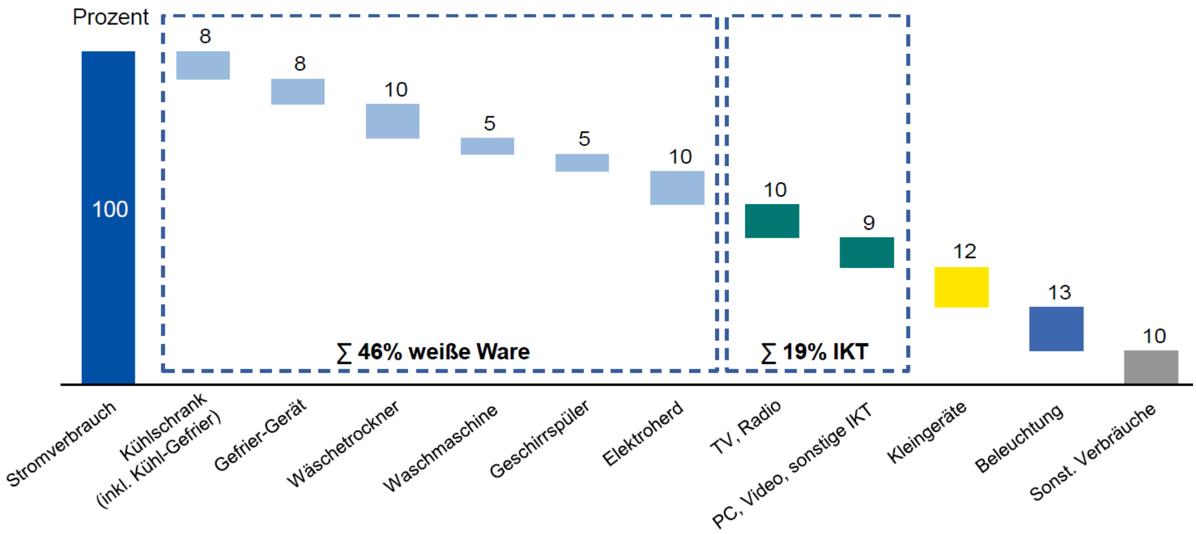

Figure 54: Energy consumption of an average household in Germany, not including hot water production [RWE].

There are also potentials for the adaptation of consumption profiles in the power-intensive industry. However, they are activated only when very cheap daily electricity is available more frequently, ie when the installed PV output continues to increase. Often, investments are required to increase the capacity of energy-intensive process steps, with decreasing capacity utilization, and to increase storage capacities for energy-intensive products. Electric heat generation in conjunction with thermal storage offers considerable potential for load management (Section 18.3.6), as does electromobility (Section 18.3.9).

18.3.5 Balanced expansion of PV and wind power capacities

In Germany, weather patterns show a negative correlation between the PV and onshore wind power generated on both the hourly and monthly scales. If it is possible to keep the installed capacities for PV and wind power on the same scale, their combination reduces the need for equalization.

In terms of hourly fluctuations, the total amount of electricity generated from PV and onshore wind rarely exceeds 50 percent of the total rated power. If you theoretically upscale the PV and wind power installed in 2017 with their hourly power production to 200 GW each, then the production curve from Figure 55 results.

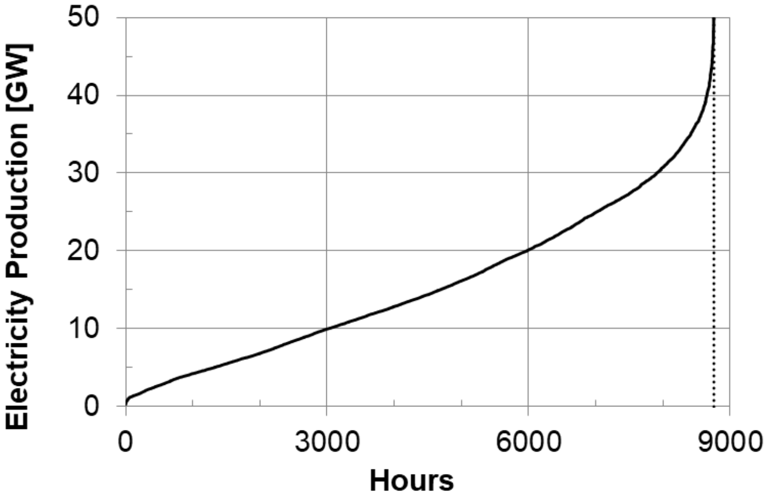

Figure 55: Fictitious annual electricity production (8760 hours) for 200 GW PV and 200 GW wind, extrapolated on the basis of installation and yield data for 2017

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

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

18.3.6 Cogeneration of power and heat

Low-temperature heat for space heating and hot water, as well as industrial process heat at a high temperature level are still largely obtained today through the combustion of fossil resources and in conjunction with small heat storage capacities. In a renewable energy system, large amounts of useful heat are generated during the transformation of electrical energy from the waste heat of converters. Large heat storage capacities for low temperature heat (Section18.3.7.1) enable the current-driven operation of the converter. The expansion of heat distribution networks is limited to a much greater extent by distance-dependent transport losses than in the electricity sector. For this reason, systems with combined heat and power (Figure 45) must be tailored in their performance and placement to local heat consumption and existing heating networks. These can be local heating networks with a heat transfer between neighboring buildings or district heating networks that supply districts or entire cities.

High-temperature heat for industrial processes can be obtained from the waste heat of cogeneration gas turbines (up to approx. 550 ° C).
In Germany, at the end of 2014, about 33 GW of electrical CHP power was connected to the grid [ÖKO2], which mainly uses natural gas, biomass and coal. CHP plants achieve

overall efficiencies of up to 90%, and gas CHPs as much as 95% [UBA2]. Even micro-CHPs for a single-family home can achieve electrical efficiencies of up to 25% and overall efficiencies of up to 90% [LICHT]. They use combustion or Stirling engines to generate mechanical power. As the energy revolution progresses, CHP plants are being converted from fossil fuels to hydrogen and methane, with some still burning biomethane or biomass.

18.3.7 Energy storage

18.3.7.1 Low-temperature heat storage

Once converted into low-temperature heat, energy can be stored efficiently and inexpensively. Low-temperature heat storage, especially hot water storage, enable the current-driven, highly efficient operation of CHP systems on both sides of the residual load curve **Figure 47**(Figure 47), as well as heat pumps and heating rods on the customer side. The same storage can be loaded simultaneously, for example, at high power surplus via heat pump and heating rod, in electricity demand by a CHP. Heat storage systems are scalable from single-family house to multi-family houses and commercial enterprises to neighborhood supply. The proportionate storage losses and the specific costs decrease with the size of the storage. Large storage tanks (from several thousand m³) can be operated as seasonal heat storage (http://www.saisonalspeicher.de). They enable the transfer of useful heat from the summer to the winter half-year with its much higher heat requirement.

Thermal storages increase the self-consumption of PV systems when they are loaded by heat pumps or heating rods, especially in the summer months. Seasonally, the PV system can heat up the domestic hot water, in particular when the PV modules with high inclination are mounted on steep south-facing roofs or on southern facades. As soon as price signals become available, decentralized thermal storage units can also be charged from the power grid and, for example, use excess wind power.

18.3.7.2 High-temperature heat storage

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

18.3.7.3 Batteries

With small, stationary batteries in-house, the self-consumption of PV power can be extended into the evening hours and thus massively increased (typically doubled, see Figure 56). In August 2018, the number of 100,000 PV storage systems in Germany was exceeded.

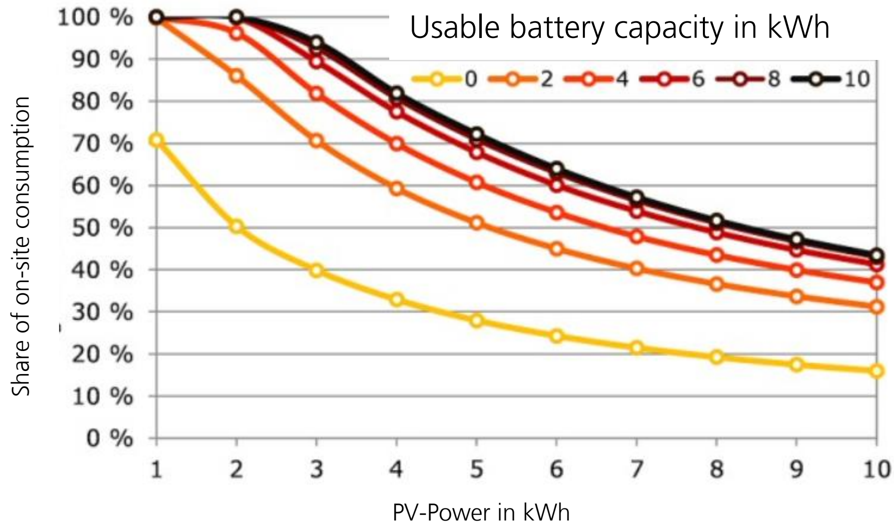

Figure 56: Percent of on-site consumption in dependence of the battery capacity and PV array power for a single-family home with an annual electricity consumption of 4,700 kWh. [Quasch]

Systems with grid-optimized operation can reduce the grid load by decreasing the grid feed-in at peak times as well as the electricity purchased in the evenings (Figure 57). Storage systems thus promote the installation of PV systems. Pilot projects are also currently investigating the storage of electrical energy in large, stationary batteries [RWE1]. The total installed battery capacity in Germany is still under 1 GWh.

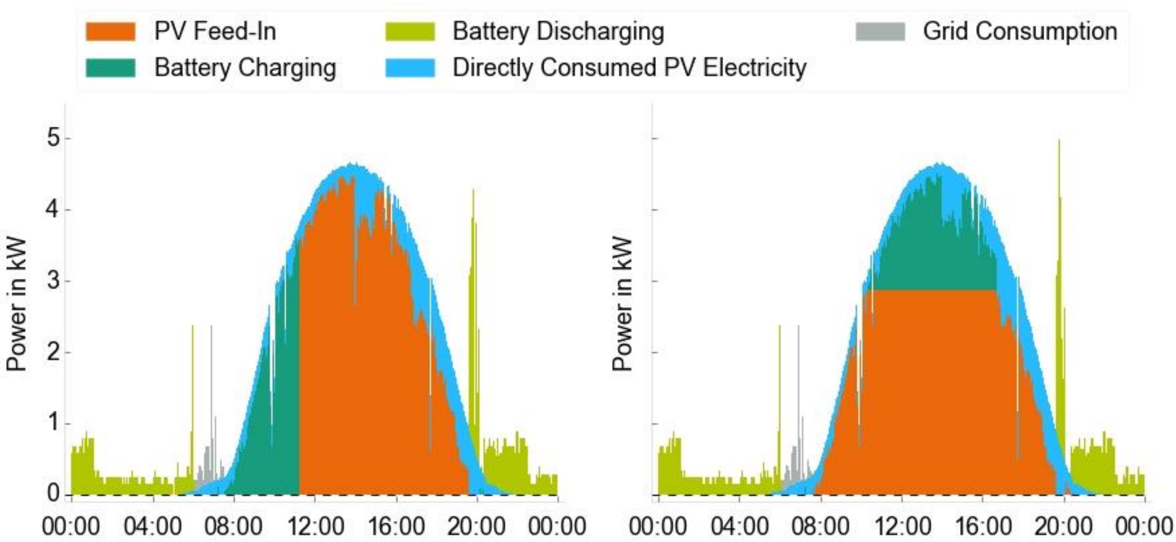

Figure 57: Comparison of the conventional and grid-optimized system operation [ISE7]

As semi-flexible power consumers, electric vehicles are not only predestined for load management (Section 18.3.4.2); they will also act bidirectionally as carriers of battery storage systems [ENER]. E-vehicles, which are currently connected to the network and do not have to keep the full range as a driving readiness, can be operated with the appropriate technical equipment as a power-current storage. With 10 million e-vehicles (each with 20 kWh of disposable capacity, which means 40 - 60 kWh total capacity) on the grid it arithmetically comes to a value of a battery capacity of 200 GWh. In 2019, 46 million cars with combustion engines were registered in Germany [KBA]. Private cars park on average about 23 hours a day, even the limited capacity of traffic routes forces most cars to stop most of the time. Electric vehicles connected to the network can also generate economic benefits from their batteries even when stationary, unlike their predecessors with combustion engines.

18.3.7.4 Mechanical storage

The currently installed pumped storage capacity in the German grid stands at almost 38 GWh, while rated power is approximately 6.4 GW and the average efficiency value is 70 percent (without transmission losses). As a comparison, the aforementioned storage capacity corresponds to the yield of the German PV power plant park from less than one operating hour under full load. If some of the projects that are or were planned are realized, the output of the pumped storage power plants can be increased to approx. 10 GW. However, the current market and price mechanisms do not allow new power plants to operate economically, although they are urgently needed for an efficient energy revolution. Run-of-river power plants can hardly make regular contributions in complementary operation due to the lack of stowage capacity, but can only curtail them. Their contribution of approx. 5.5 GW nominal output and approx. 20 TWh generation in 2017 [ISE4] is not very expandable. The mechanical storage of electrical energy in compressed air accumulators (adesabatic compressed air energy storage, CAES) is also being investigated.

18.3.7.5 Hydrogen and synthesis products

The electrolytic conversion of excess solar and wind energy into hydrogen, with subsequent methanation and further processing into synthetic liquid fuels, is under scaling and testing [AMP]. High-temperature electrolysers achieve efficiency of up to approx. 80%, additional energy may be required for gas compression, liquefaction and the subsequent synthesis steps. In April 2019, electrolyzers with a total capacity of around 30 MW were connected to the grid, and 273 MW [DVGW] were planned. Figure 58 shows current and projected investment costs for various electrolysis technologies.

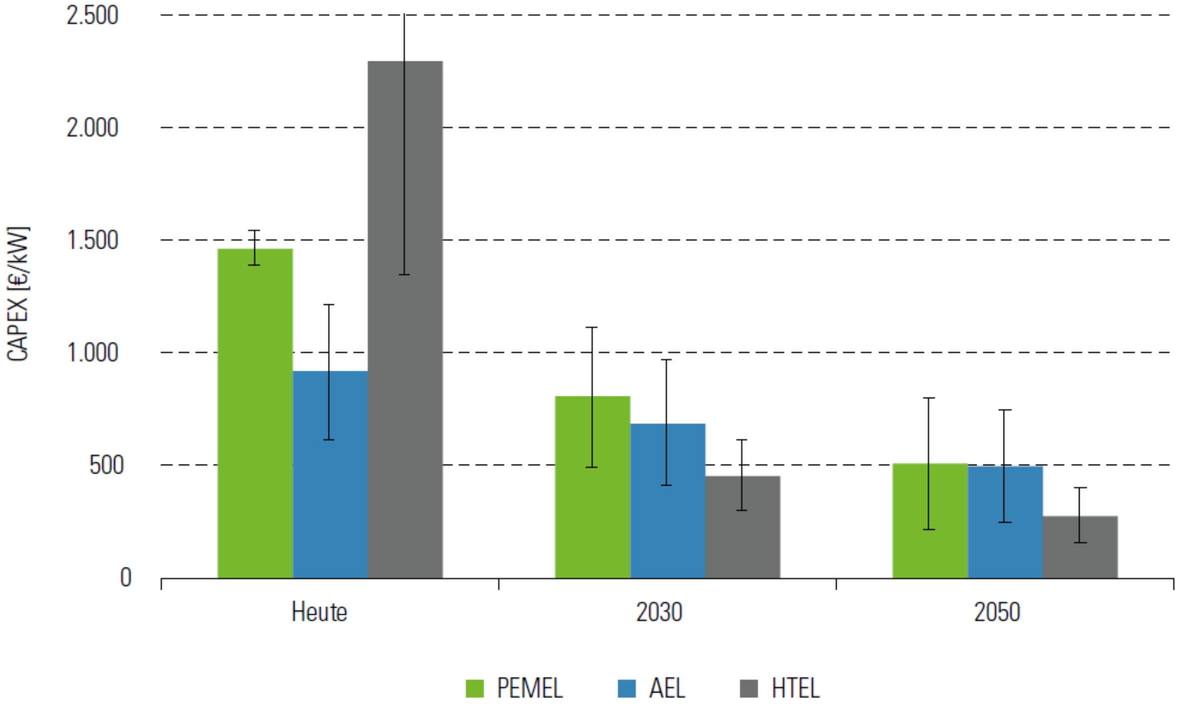

Figure 58: Specific investment costs for different electrolyzer technologies (PEMEL: Membrane electrolysis, AEL: Alkaline electrolysis, HTEL: High-temperature electrolysis, [NOW])

The conversion of renewable energy to storable energy sources gas ("Power-to-X") opens up huge, already existing storage possibilities. It is already technically possible today to increase the hydrogen content in the gas network to up to 20%. In total, more than 200 TWh of energy (equivalent to 720 petajoules) can be accommodated in the existing gas network as well as in underground and above-ground storage facilities.

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

18.3.7.6 Overview

Figure 59 shows paths for storing and converting PV and wind power. In addition to the technical efficiency, the practical relevance of these paths includes to consider the costs of the nominal power of converters to be installed (€/W) and the capacity of storage systems (€/Wh).

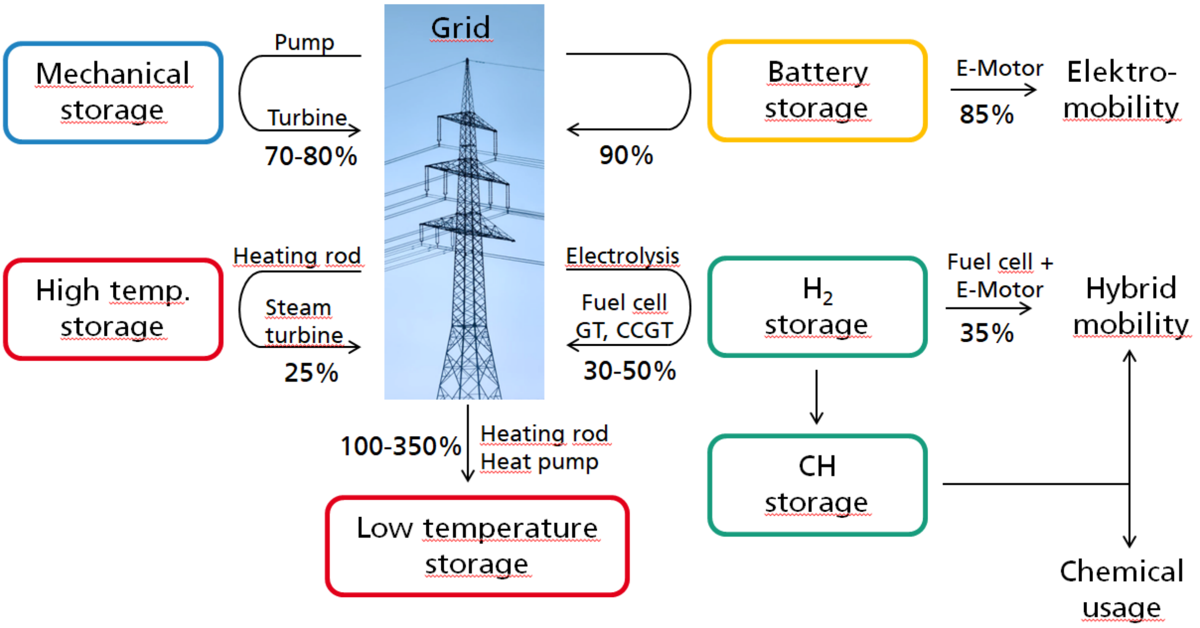

Figure 59: Technologies for energy storage and converters with today's achievable efficiencies at the end of the converter chain, without combined heat and power

18.3.8 Grid expansion

18.3.8.1 National grid expansion

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

In order to avoid local network overloads due to generation or consumption peaks, battery storage is increasingly being implemented as an economically interesting alternative to expanding the network. Comparatively high grid expansion costs arise for the transmission of wind power from northern to southern Germany and for the connection of the off-shore wind power plants.

18.3.8.2 *Strengthening the European grid*

The German power grid is part of the European network. An increase in the cross-border dome capacity of currently around 20 GW enables a better compensation of volatile PV electricity production via European electricity trading. Figure 60 shows the installed capacity of run-of-river and storage hydro power plants as well as of pumped storage power plants. Storage power plants can be operated as a complement to PV generation, pumped storage can act as efficient electricity-to-electricity storage.

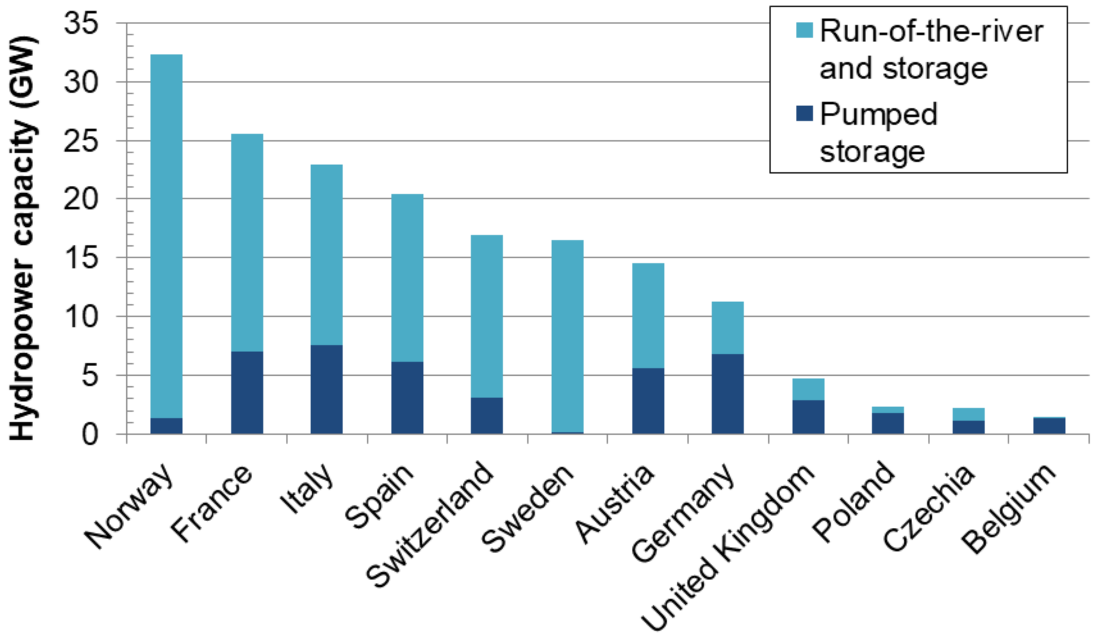

Figure 60: Installed capacity of hydroelectric power plants in neighboring countries, figures from [IHA]

18.3.9 Overview

From today's perspective, an energy system based on almost 100% renewable energy is technically and economically feasible. Figure 61 shows the main elements connected to the grid, from extraction to transformation and storage to consumption. In order to reduce the storage requirements, the power consumption in households and industry is made more flexible sometimes. ICT stands for information and communication technology. The dashed boxes indicate that currently very low power (of converters) or capacities (in storages) are available.

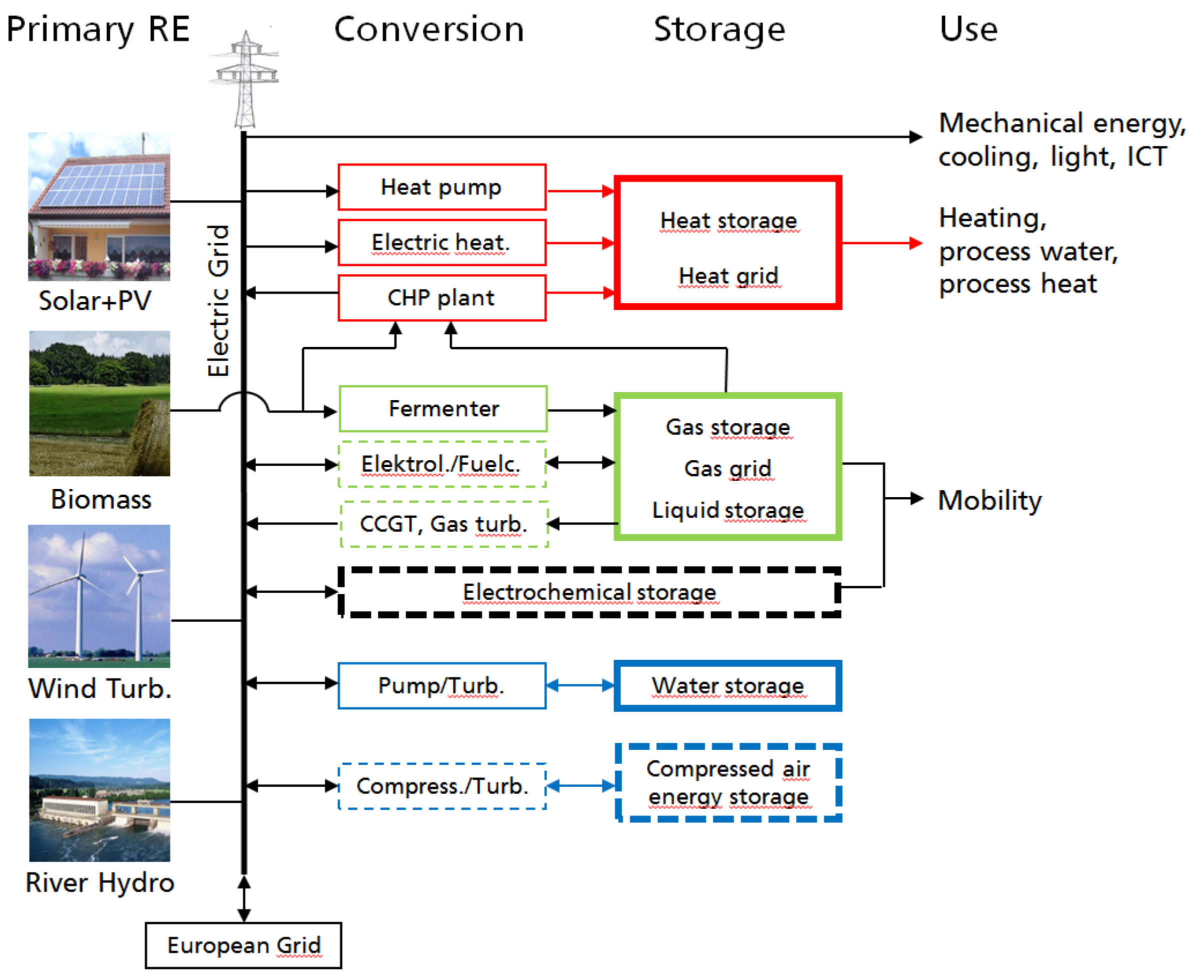

Figure 61: Simplified scheme of a Renewable Energy System with the most important grid-related components of the categories production, conversion, storage and consumption.

In the "**heat**" sector (red), cogeneration units, heat pumps and - in the case of supply peaks on the electricity side - heating elements load the heat storage units. Wherever the collection density permits, for example in neighborhoods, efficient storage takes place centrally in large heat storage facilities.

In the "**gas**" sector (green), biomass fermenters produce methane and electrolyzers hydrogen, which can also be methanized or processed into synthetic fuels. Partly biomass is burned directly in the CHP. When electricity is needed, combined gas and steam turbines, fuel cells and, if demand peaks occur, even pure gas turbines are used. Hydrogen electric vehicles refuel their fuel from stationary gas storage, vehicles for long distances (especially aircraft) refuel liquid synthetic fuels.

In the "**battery**" sector (black), stationary, central or decentralized electrochemical stores are charged or discharged depending on the residual load. Mobile batteries in electric vehicles primarily serve the mobility needs, but can also support the network bidirectionally at standstill. In most electrochemical storage systems, the converter and the storage tank are structurally fused; only so-called redox flow batteries have external, scalable storage tanks.

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

Time horizon until 2025: focus on "**flexibilisation**"
1. The energy efficiency of electricity consumers is increasing in all sectors.
2. The installed PV power is increased to 70-80 GW, close to consumption, for steadying of production in East / West orientation or with tracking, with grid-supporting inverter functions, for a production of approx. 60-70 TWh/a solar power at peak power up to approx. 50-55 GW. Wind power capacities are being expanded in similar dimensions.
3. Load management: Parts of household, industrial and e-mobility power consumption are adjusted to the availability of PV power (and wind power) through demand-side management (supply-based tariffs or signals).
4. Thermal storage, local and district heating networks are being expanded.
5. PV systems and electric vehicles are provided with relevant network storage batteries.
6. Pumped storage performance and capacity are being expanded.
7. For the power utilization of occasional EE current peaks low-cost (€/W) heating rods are built into thermal storage.
8. For the power utilization of frequent excess electricity surges, electric heat pumps with feed-in into thermal storage are constructed.
9. Low-cost (€/W) gas turbines are built to cover occasional residual load peaks (eg from the recycling of aircraft turbines)
10. To cover frequent residual load gaps, efficient CCGT/CHP power plants with feed-in into thermal storage are set up
11. Existing coal-fired power plants will, if possible, be optimized for flexible operation, otherwise shut down.
12. The power grid connections to our neighboring countries will be strengthened.

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

In order to avoid costly undesirable developments and to keep pace with the above steps, incentives are needed: a stable EEG, investment incentives for energy efficiency measures, multifunctional power plants and pumped storage, price and investment incentives for supply-side electricity consumption and incentives for demand-based electricity supply. A further measure could be the reduction of the implicit subsidy for coal-fired power plants through a shortage of CO_2 allowances or, nationally, by a CO_2 tax.

18.4 Does the energy revolution have to wait for federal policy?

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

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

19 Do we need PV production in Germany?

Yes, if we want to avoid new dependencies in energy supply.
As the energy revolution progresses, Germany will leave behind the «fossil fuel" century, in which we spent 90 billion euros for oil and gas imports annually and thus financed authoritarian governments.

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

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

Yes, with focusing on the energy revolution process.

The current market mechanisms would provide too little incentive for long-term investment in the energy revolution without the support of an EEG. The main reasons is the sectoral gaping pricing of CO_2 emissions, which fluctuates with the stock market and is much too low overall. A socially balanced **national carbon tax**, such as that introduced in Sweden in 1991 and in Switzerland in 2008 as a "tax levy", can bridge these shortcomings.

As a rule, PV power plants of all sizes require a **grid connection** in order to deliver electricity that can neither be consumed on site nor saved economically. In order to maintain the diversity of actors involved in PV generators, a legal framework must entice the grid operator to make connections easily.

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

21 Do PV modules contain toxic substances?

That depends on the technology and materials used.

21.1 Wafer-based modules

The silicon wafer-based modules (more than 90 percent of the market share) often contain lead in the cell metallization layer (around 2 grams of lead per 60-cell module) and in the solder used (approximately 10 grams of lead). Lead, a toxic heavy metal, is soluble in certain, strongly acidic or basic environments, and lamination in the module does not permanently prevent mass transfer [IPV]. In wafer-based modules, lead can be completely substituted by harmless materials at low additional costs. Some module manufacturers use backsheets containing fluoropolymers, for example polyvinyl fluoride

21.2 Thin-film modules

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

21.3 Solar glass

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

21.4 Take-back schemes and recycling

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

22 Are there enough raw materials available for PV production?

22.1 Wafer-based modules

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

22.2 Thin-film modules

The availability of raw materials depends on the technology being used.

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

23 Do PV plants increase the risk of fire?

23.1 Can defective PV plants cause a fire?

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

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

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

The most important characteristic of PV systems is that they produce direct current. Since they continue to generate electricity for as long as light falls on their modules, they cannot simply be turned off at will. For example, if a low-quality or poorly installed module connector becomes loose, the current flow is not always interrupted immediately, potentially resulting in an electric arc, which, in the worst case scenario, may cause a fire to break out. Accordingly, investigations are being carried out on how to prohibit the occurrence of electric arcs. In addition, detectors are being developed that sound an alarm as soon as only a small electric arc occurs.

PV plants do not present a greater fire risk than other technical facilities. Sufficient regulations are in place that ensure the electrical safety of PV systems and it is imperative that these are followed. Fires often start when systems are fitted by inexperienced pieceworkers. Weak points are inevitable when solar module connectors are installed using combination pliers instead of tools designed especially for this purpose or when incompatible connectors are used, and system operators should not cut costs in the wrong places.

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

23.2 Do PV plants pose a danger to firefighters?

Yes, as is also the case with many systems fitted with live cables.

Standing at least a few meters away from the fire when extinguishing a fire from outside of the building protects firefighters from electric shocks. This safe distance is normally given for all roof-mounted installations. The greatest risk for firefighters arises when extinguishing a fire from inside the building in areas where live, scorched cables connected to the PV plant come into contact with water or the firefighters themselves. To minimize this risk, the industry is developing emergency switches that use safety relays to separate the modules from their DC connection in close vicinity to the roof.
In Germany, no firefighter has to date been injured by PV power while putting out a fire. An incident widely reported in the press confused solar thermal collectors with PV modules and no PV plant was fitted to the house in question whatsoever.
«Comprehensive training courses for the fire brigade could eliminate any uncertainties firefighters may have. As with every electrical installation, depending on the type of electric arc it is also possible to extinguish a fire using water from a distance of one to five meters. Based on investigations to date, all of the claims stating that the fire brigade could not extinguish a house fire due to the PV system have been found to be false." [ISE6]

23.3 Do PV modules prevent firefighters from extinguishing fires externally from the roof?

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

23.4 Are toxic emissions released when PV modules burn?

The Bavarian Environment Agency (Bayerisches Landesamt für Umwelt) has calculated that the dispersion of fumes following a fire involving CdTe modules does not pose a serious risk for the surrounding area and general public [LFU1].For CIS modules, independent investigations for the different module types are referenced.

For wafer-based modules, the rear side foils can contain fluoropolymers, which themselves are not poisonous. In a fire at high temperatures, however, they can decompose. Upon examination, the Bavarian Environment Agency came to the conclusion that during a fire, conflagration gases other than fluoropolymers play a more critical role in defining the potential danger [LFU2].

24 Appendix: Terminology

24.1 EEG surcharge

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

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

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

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

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

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

24.2 Module efficiency

Unless stated otherwise, module efficiency is given in terms of nominal efficiency. Under standard test conditions (STC), it is calculated in terms of the relationship between the amount of electricity generated and the level of irradiation on the module's total surface area. STC conditions imply a module temperature of 25 °C, vertical irradiance of 1000 W/m^2 and a standard solar irradiance spectrum. During actual operation, conditions are normally so different from these standard conditions that efficiency varies.

24.3 Rated power of a PV power plant

The rated power of a power plant is the ideal DC output of the module array under STC, i.e. the product of the generator surface area, standard irradiance (1000 W/m^2) and nominal efficiency of the modules.

24.4 Specific yield

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

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

24.5 System efficiency

The system efficiency of a PV plant is the relationship between the useful yield (alternating current yield) and the total amount of irradiance on the surface area of the PV modules. The nominal module efficiency affects system efficiency.

24.6 Performance ratio

The performance ratio (PR) is often used to compare the efficiency of grid-connected PV plants at different locations with various module types.

Performance ratio is defined as the relationship between a plant's useful yield (alternating current yield) and ideal yield (the product of the total amount of irradiance on the generator surface area and nominal module efficiency).
New, carefully planned plants achieve annual PR values of between 80 and 90 percent.

24.7 Base load, intermediate load, peak load, grid load and residual load

«Power demands fluctuate throughout the course of the day, generally peaking during the day and falling to a minimum at night between midnight and 6:00am. Power demand development is depicted as a load curve or load profile. In traditional energy technology, the load curve is divided into three sections as follows:

1. base load
2. intermediate load
3. peak load

Base load describes the load line that remains almost constant over a 24-hour period. It is covered by base-load power plants, such as nuclear power plants, lignite coal-fired power plants and, for the time being, run-of-the-river power plants.
Intermediate load describes self-contained peaks in power demand which are easy to forecast and refers to the majority of power needed during the course of a day in addition to base load. Intermediate load is covered by intermediate-load plants, such as hard coal-fired power plants and combined cycle power plants powered by methane with oil-fired power plants being used now and again. Peak load refers to the remaining power demands, generally coming into play when demand is at its very highest. Peak load is handled by peak-load power plants, such as gas turbines and pumped-storage power plants. These can be switched to nominal output within an extremely short space of time, compensating for fluctuations and covering peaks in load."
(…) «Grid load refers to the amount of electricity taken from the grid, while residual load is the grid load less the amount of renewable energy fed in." [ISET1]

24.8 Electricity generation and consumption

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

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

Figure 62 shows the energy path from the primary energy source, e.g. solar irradiation (irradiance [W/m^2]), wind or natural gas (energy density during combustion [J/kg]), down to the net energy that is important to the consumer. Large gas turbines show conversion losses of 60-65%. PV power plants have conversion losses of 80-85%, with practically free and unlimited primary energy. The gross electricity generation, adjusted for the import balance, corresponds to the gross electricity consumption. Storage losses occur during the operation of pumped storage power plants or batteries. Losses from pumped storage power plants amount to approx. 25% of the stored amount of electricity, with Li-ion batteries it is 5-10%, plus the losses in the battery management system. If hydrogen is used as a power store via stationary electrolysers and fuel cells, the losses are around 50%. Storage losses will increasingly play a role for PV electricity as the installed PV capacity is expanded.

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

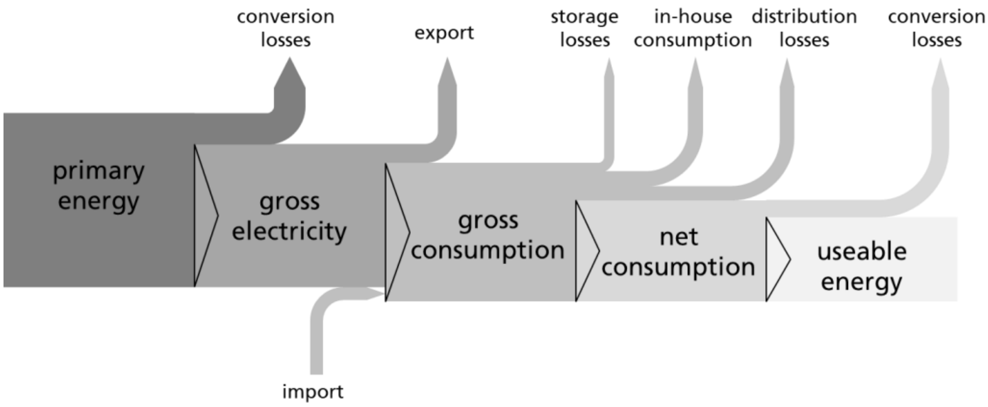

Figure 62: Terms of electricity generation and consumption

25 Appendix: Conversion tables [EEBW]

Vorsätze und Vorzeichen

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

Umrechnungen

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

Typische Eigenschaften von Kraftstoffen

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

Typische Eigenschaften von festen und gasförmigen Energieträgern

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

26 Appendix: Abbreviations

BEV	Battery Electric Vehicle
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BSW	German Solar Industry Association
CCGT	Gas and steam generators
CCS	Carbon dioxide capture and storage – segregation of CO_2 from power plant emissions and storage in geological formations
CHP	Combined heat and power – the principle of simultaneously generating mechanical energy (ultimately converted into electrical energy) and useful heat
CHP plant	Combined heat and power plant – a plant that uses combustion engines or gas turbines to generate electrical energy and heat
EEG	Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act, EEG)
ESC	Energy supply company
GHG	Greenhouse Gas
ICT	Information and communications technology
IEA	International Energy Agency
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaics
RE	Renewable energy
W_p	Watt peak – rated power of a PV module or array

27 Appendix: Sources

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