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Analysis

Flexibility Technologies and Measures in the German Power System

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Executive Summary

Germany's goal of climate neutrality is just around the corner. In order to reach it by 2045, Germany will need to increase its renewable energy production and, along with it, its power system flexibility. For the past decades, solutions have been developed and implemented, such as the establishment of market rules that enable competition between flexibility measures, along with a technology-neutral approach that ensures a broad mix of technologies and participants.

On the way to a power system based entirely on renewable energy, conventional power plants, in particular gas power plants, will continue to play a role. Today, coal- and gas-fired power plants are the most relevant source of flexibility in Germany. However, the phase-out of coal-fired power plants by 2038 at the latest, and of nuclear power by 2022 will lead to an increased use of other flexibility options. Large-scale batteries, which are a fitting solution for providing primary control energy and for industrial applications, and small-scale batteries, which provide user-related flexibility in private homes will play an increasingly important role.

Flexibility will continue to be provided by biomass- and biogas-operated and pumped-storage power plants, currently the second most important source of flexibility. In addition, technological development as well as the phase-out of financial and regulatory barriers, particularly the double burden requiring operators to pay consumer fees twice, may trigger the use of power-to-X technologies, which are not yet widely deployed in Germany.

Price signals on the wholesale market are expected to trigger higher demand-side flexibility in the industry and small and medium-sized enterprises. Residential demand-side flexibility will play a greater role with the gradual introduction of intelligent measuring systems (smart meters) and other digital technologies.

Last but not least, system operation regulations will need adjustments in order to increase grid flexibility.

The report provides a detailed overview of the main flexibility technologies and measures in the German power system. While it reflects the status quo, it also indicates needs for the development of the power system to reach climate neutrality and provides valuable input for ongoing policy debates.

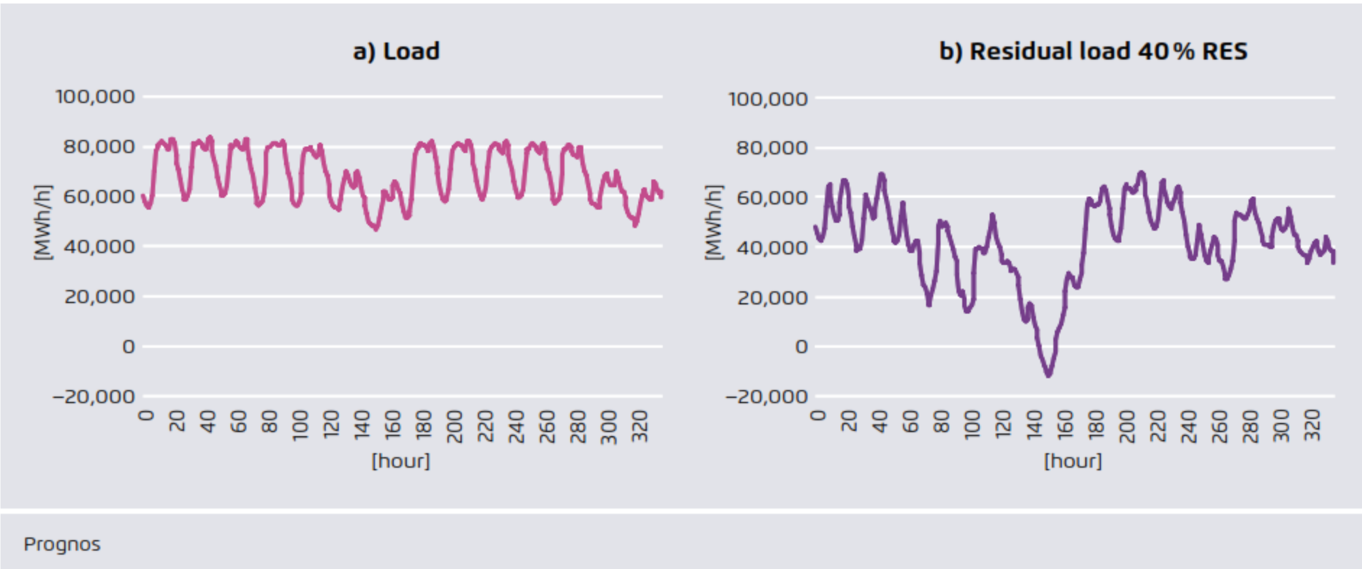
1 Background, Definitions and Historical Overview

1.1 What is flexibility in the power system, and why is it relevant?

Flexibility in the power system – understood to be the ability to easily modify or change by increasing or decreasing generation or load – can apply to different power system elements, the services they provide, or to the system as a whole. Generation units as well as distribution and transmission grids can be operated flexibly, providing the grid and the electricity system with flexibility. Electricity consumers, such as industry, electric vehicles or households, can also adjust their electricity demand, serving the electricity system. The design of regulatory measures and market rules can either enhance or hinder the flexibility of the power system elements or of the system as a whole.

With growing shares of variable renewable energy (RE), such as wind and solar photovoltaic (PV), in the energy mix, flexibility measures will play an increasingly important role in the power system. Germany's target is to achieve climate neutrality by 2045, which will require further renewable energy growth. Reaching this goal will inevitably lead to a greater demand for flexibility, mainly due to the increasing **volatility or variability** of generation and, as a result, of the **residual load**, defined as electricity consumption minus variable RE generation. The residual load in the German power system can frequently decrease to almost zero and then increase significantly within a short period – either days or hours.[1] Therefore, flexibility at the system level can be described as the ability of an aggregated park of generating units and loads to react to the variability of the residual load.[2] To address this development, it is necessary to make changes to the power plant fleet, demand-side response, market rules and system operation.[3]

Figure 1. Flexibility requirements with high shares of RE – example load curves for two weeks during the winter in Germany



Source: Prognos in: Agora Energiewende 2017a, p. 24

The following table summarises flexibility options and their functions in the German context.

In Germany, changes in market rules addressing the need for more flexibility have led to changes in the power plant fleet and electricity consumption patterns as well as, to a lesser extent, in system operation.[4] Therefore, flexibility measures in the German power system largely serve **market-related functions**. Market-related functions are mostly **grid-serving** if they contribute to the operation and stability of the grid. An exception is that grid-serving functions are not market-related if the grid operators apply the measures themselves. Due to **unbundling rules**, grid operators cannot own generation assets and thus be involved in electricity trading. Unbundling is a rule of the EU single electricity market that states that electricity transmission and distribution grids must be operated by a separate entity than electricity generation units. The Federal Network Agency exempted what it referred to as "grid boosters" (German: Netzbooster), such as large-scale batteries, from this rule. According to the Grid Development Plan 2019, grid boosters can be operated by TSOs in pilot projects.

Table 1. Flexibility options and their significance in the German context

Provider of the service	Receiver of the service	Measures & technologies		Functions in the system
Consumers or plant operators	Balancing group managers (BRPs), DSOs or TSOs	Technical flexibility options	Retrofit of conventional power plants, incl. cogeneration (CHP plants) Retrofit of biomass- and biogas-operated power plants Pumped-storage systems Batteries PtX	User-related functions Market-related functions Grid-serving market-related functions Grid-serving functions
		Demand-side flexibility (DSF) options	Industry SMEs Households	
DSOs and TSOs unilaterally or through cooperation		System operation	Grid expansion Redispatch Curtailment Advanced forecasting of RE generation Higher utilisation of the existing grid Cooperation between DSOs and TSOs Cooperation and coordination between TSOs Cross-border power exchange	

Regulatory agencies and the legislator	Consumers, BRPs, DSOs or TSOs	Market design	Increasing granularity in the power market Ancillary services Support schemes	

Source: Own representation.

1.2 Power system development in Germany and the integration of flexibility

In this chapter, we will cover different types of flexibility demand in Germany. The various flexibility options described in sections 1.2 to 1.5 can be deployed to meet these different types of flexibility demand.

Demand for technical flexibility

The demand for technical flexibility is **determined by the residual load gradient or the ramp rate**. The system's residual load ramp rate varies depending on several factors: A higher share of RE, especially PV, provides a faster residual load ramp rate and thus a greater need for flexibility. In contrast, the larger the grid area with high feed-in from wind power and the more interconnectors between grid areas, the lower the residual load gradients, leading to a lower need for flexibility.[5]

A high rate of change in the residual load requires a high ramp rate for the feed-in from dispatchable technologies, such as storage or conventional generation systems, namely coal and gas power plants.[6]

Above an RE share of 30% and with a PV share of 20% to 30%, the residual load gradients exceed the highest demand profile ramps.[7] This is mainly due to an increased number of generation peaks and the fact that PV covers a large share of the electricity demand during certain days or hours.

The table below illustrates how the residual load gradient and share of RE have changed in Germany over the years, showing how the demand for technical flexibility has developed

Table 2. Development of demand for technical flexibility in Germany

Year	RES share in electricity generation	PV share in RE share	Wind share in RE share (on- and offshore)	Average residual load (GW)	Total net installed capacity (GW)	Residual load variation (GW)	Average residual load gradient
2014	21% (a)	22.19% (a)	36% (a)	44.83 (b)	196 (a)	10.25 (b)	1.82 (b)
2015	23.22% (a)	20.51% (a)	42.7% (a)	36.47 (b)	205 (a)	10.98 (b)	2.77 (b)
2016	22.66% (a)	20.09% (a)	42.14% (a)	35.65 (b)	212 (a)	10.99 (b)	2.27 (b)
2017	26.11% (a)	18.21% (a)	48.86% (a)	34.15 (b)	218 (a)	11.73 (b)	2.28 (b)
2018	34.94% (c)	20.37% (c)	48.92% (c)	34.35 (e)	221 (c)	12.5 (f)	... (g)
2019	39.74% (c)	19.13% (c)	51.9% (c)	29 (f)	226 (c)	14 (f)	... (g)
2020	50.5% (d)	20.82% (d)	53.38% (d)	26 (f)	226.8 (d)	14 (f)	... (g)

Sources:

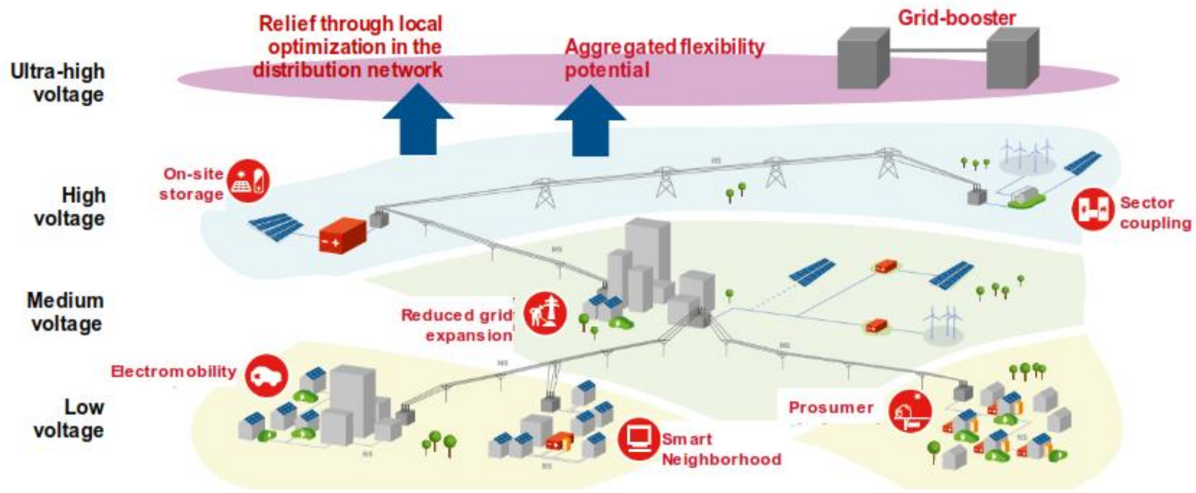
(a) BMWi 2019.
(b) Virtuelles Institut Smart Energy et al. 2018, 28.
(c) BMWi 2021.
(d) Fraunhofer ISE 2021.
(e) Own rough estimate based on: Bundesnetzagentur/SMARD.
(f) Own rough estimate based on: Fraunhofer ISE, Energy-Charts.
(g) Not estimated.

As evident from the development depicted in the table above, the **average residual load** has steadily decreased.

The **average residual load gradient** increased in the period between 2014 and 2017. This development requires all flexibility options to react more frequently to residual load changes.

Other factors may also lead to a higher demand for technical flexibility in the immediate and near future. These factors include load increases leading to higher and more frequent peak loads or load ramps at low and medium voltage levels due to the **simultaneity** of applications, such as the charging of electric vehicles or heat pumps.[8]

Figure 2. Consumers become more flexible – simultaneity of applications



Source: dena 2017a, 4-5

Grid expansion and upgrades are solutions to the growing demand for technical flexibility. They need to be complemented by the use of flexibility options, as they help optimise grid expansion and reduce costs for electricity consumers. A particularly useful solution to avoid increased costs due to grid development is the **multi-use approach** (economic optimisation of the technology application) that implies **both the grid-serving and the market-related** use of flexibility.[9] This dual use leads to the more efficient use of the grid while also fully utilising the flexibility option. This can lead to a significant reduction of the overall system costs. However, grid-serving and market-related use of flexibility require proper incentives and regulatory frameworks.[10]

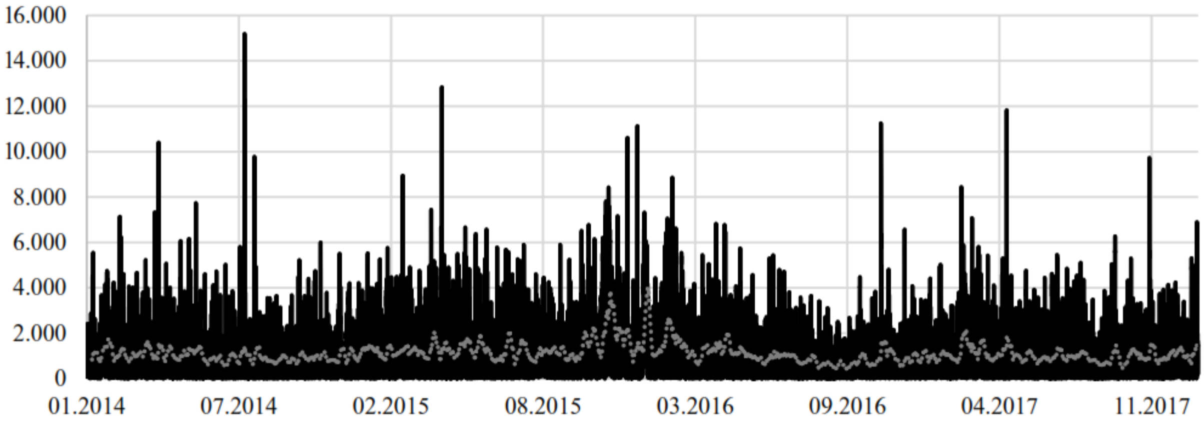
Demand for stochastic flexibility

Stochastic flexibility relates to flexibility demand, which cannot be predicted with great precision due to conditions that may change accidentally or arbitrarily, such as weather, technical failures and changing electricity demand profiles. Therefore, the demand for stochastic flexibility is determined by the **forecast quality** of RE and conventional generation, as well as the electricity demand.[11] In the event of a deviation from the forecast, flexibility must be activated at short notice. The most uncertain variable is the RE feed-in, which is directly influenced by weather variability. Better forecasts may thus reduce the demand for overall flexibility.

When determining the demand for stochastic flexibility, a distinction can be made between the **absolute and relative forecast error**. The absolute forecast error is the difference between the forecast and the actual feed-in. The relative forecast error is the mean of the ratio of the absolute forecast error and the actual feed-in.[12] The relative forecast error shows how the absolute forecast error changes depending on the increasing RE share.

European Energy Exchange (EEX) data concerning forecast and actual feed-in from RE shows that the absolute forecast error remained constant in 2014–2017, notwithstanding an increasing RE share.

Figure 3. Absolute RE forecast error



Source: Virtuelles Institut Smart Energy et al. 2018, 29.

Y-axis – Absolute forecast error (in MW)

------- – Absolute forecast error

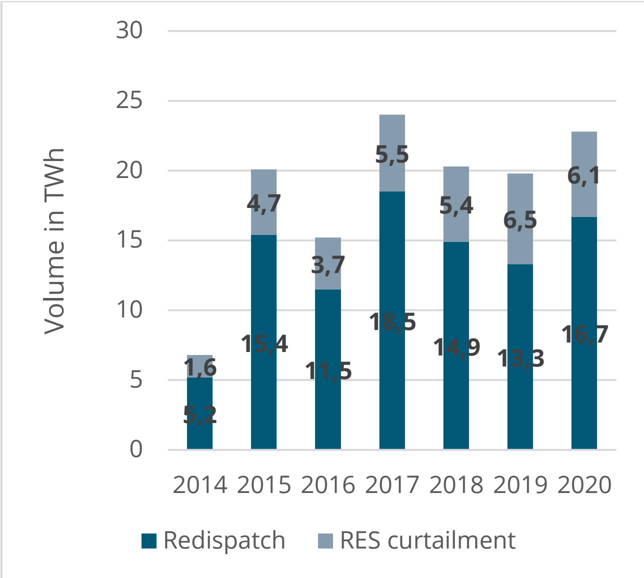
- - - - - - – Weekly average

According to Virtuelles Institut Smart Energy, the absolute forecast error remained fairly constant due to the improvement of the relative forecast error, which indicates the improved forecast quality in relation to the increasing RE share. In other words, the improved forecast quality compensates for the increasing absolute uncertainty of feed-in from RE. Due to improved forecasting methods and technologies, the relative forecast error declined from 10% in 2014 to 7% in 2017. While there has been a continuous improvement in forecast quality in recent years and further improvement appears likely, an error-free forecast is improbable.[13]

Demand for short-term localised flexibility

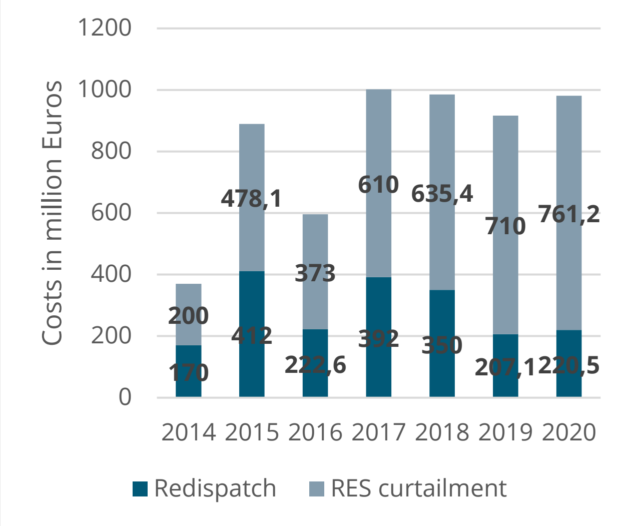
Demand for short-term localised flexibility depends on the percentage of grid bottlenecks (imbalance or overload in the grid). It occurs when grid bottlenecks make it necessary to adapt (increase or decrease) the feed-in or the electricity demand locally. Two measures in the German power system are available to address this issue: **redispatch and curtailment**. The volume and costs of these measures indicate the intensity and frequency of grid bottlenecks in the German power systems.[14]

Figure 4. Development of the redispatch and curtailment volume



Source: Own representation based on the data from: Bundesnetzagentur 2016, 6; Bundesnetzagentur 2019b, 9; Bundesnetzagentur 2020b, 9.

Figure 5. Development of the redispatch and curtailment costs



Source: Own representation based on data from: Bundesnetzagentur 2019b, 9; Bundesnetzagentur 2020b, 9; Virtuelles Institut Smart Energy et al. 2018, 32 (year 2014).

Both the volume and costs of redispatch and curtailment have increased since 2014 by almost two-thirds. Whereas the costs amounted to about 370 million euros in 2014, they rose to almost 1 billion euros in 2020. An outlier was the year 2015: An unusual high wind power supply that year resulted in higher volume and costs than in the following year.[15]

The curtailment and redispatch data indicates that demand for short-term flexibility increased until 2017 and then flattened. This indicates that grid operators have had to curtail more and more RE production to avoid imbalances and overloads in the grid. This produces economic waste and is detrimental to the environment; therefore, the system needs to develop alternatives to meet the demand for short-term localised flexibility.

Grid expansion is one option for decreasing redispatch and curtailment. According to new estimates by TSOs, planned grid expansions will reduce redispatch volume by 11.4 TWh from 16.7 TWh in 2020 to 5.3 TWh in 2025.[16]

Allowing the **participation of RE in redispatch** is also an option to reduce its overall volume and costs. Until recently, conventional power plants above 10 MW, such as coal and gas power plants, have provided redispatch. A new regulation named **Redispatch 2.0** was issued in 2019 to include RE and CHP plants as small as 100 kW in redispatch measures starting from October 2021.

A multi-use approach is an economically more effective alternative to both grid expansion and redispatch.

1.3 Milestones and measures to increase flexibility in the German power system

In recent decades, the German government introduced several laws and regulations to meet the growing flexibility demand. In addition, the rules of the European Power Exchange EPEX SPOT were adapted to stimulate the development of flexibility. The following table summarises the most important milestones for enabling flexibility in the German power system, some of which will be then discussed in more detail.

Table 3. Flexibility milestones in the German power system

2005	Adoption of the Ordinance on Electricity Grid Tariffs
2008	EPEX SPOT established with 1-hour auctions
2009	Renewable Energy Sources Act (EEG): Introduction of direct marketing of RE
2011	Nuclear phase-out by 2022 decision
2012	EEG: Introduction of a premium market model for RE
2012	EEG: Introduction of a flexibility premium for biogas power plants
2012	Adoption of the Ordinance on Interruptible Loads
2013	Establishment of a grid reserve
2014	EEG: Introduction of auctions for RES
2014	EEG: Introduction of a flexibility supplement for biogas power plants
2014	Reduction of EPEX SPOT auctions to 15 min
2014	First LSB participates in the primary control energy market
2015	Adoption of the Law on the Expansion of Power Lines
2015	Reduction of EPEX SPOT lead times to 30 minutes
2015	First small-scale battery aggregator pre-qualified for the primary control energy market

2016	Adoption of the Electricity Market Law: introduction of the electricity market 2.0 and capacity reserve
2016	Adoption of the Law on the Digitalisation of the Energy Transition
2017	Decision of the Federal Network Agency including amendments to the procurement of primary control energy (reduction of auction length from weekly to daily from 2019 to 2020 and from daily to 4-hour auctions since 2020)
2017	Reduction of EPEX SPOT lead times to 5 minutes
2018	Batteries provide the majority of primary control energy
2019	Small-scale battery capacity surpasses 1 GWh
2020	Reduction of primary control energy to 4-hour auctions
2020	Coal phase-out by 2038 decision
2020	Adoption of National Hydrogen Strategy with the aim to develop a competitive hydrogen market and provide additional funds for research and market ramp-up projects
2021	72 power-to-X pilot projects
2021	Participation of RE in redispatch (Redispatch 2.0) (based on the Grid Expansion Acceleration Act (NABEG 2.0) adopted in 2019)

Source: Energynautics 2021and own representation.

In 2016, the German government carried out the largest electricity market reform since it was liberalised in the 1990s, adopting the **Electricity Market Law** (Strommarktgesetz) that included a set of measures to develop the existing electricity market into an **Electricity Market 2.0**. The goal was to establish a market capable of remunerating the necessary capacities via market mechanisms without an additional capacity market. To this end, the law strengthened competition mechanisms between generation, demand and storage while improving the incentives for their flexibilisation. It also introduced a safeguard mechanism, the **capacity reserve** (Kapazitätsreserve), which refers to additional capacity outside the market available when there is insufficient supply on the wholesale or control energy market to meet the entire demand. Such situations are rare emergencies.

In the same year, the German government adopted the **Law on the Digitalisation of the Energy Transition** (Gesetz zur Digitalisierung der Energiewende), which laid the foundation for introducing intelligent measuring systems (smart meters) and other digital technologies. Smart meters can measure electricity consumption at any time and thus highlight potential savings to consumers or other market participants, such as aggregators or DSOs. Using advanced digital technologies can enable dispatchable consumption devices, such as thermal energy storage or electric vehicles, to charge when electricity is available at low prices.[17] The rollout of smart meters is also a precondition for **Demand-Side Flexibility (DSF) measures**, such as variable end user tariffs.

In 2017, large consumers and producers installed the first smart metering systems in Germany. In 2020, the rollout of smart metering targeted private households with high electricity consumption.[18] In the coming years, the rollout will extend to include smaller consumers.

Concerning system operation, an important regulation was adopted **in 2015** with the amendment of the **Law on the Expansion of Power Lines** (Gesetz zum Ausbau von Energieleitungen) to prioritise the use of underground cables over overhead lines. This provision will help increase public acceptance of grid expansion, especially for the planned high-voltage transmission lines from Northern to Southern Germany, namely the SuedLink and SuedOstLink.[19] Grid expansion can help increase the flexibility of system operation.

From October 2021, redispatch will include RE and CHP plants as small as 100 kW **(Redispatch 2.0).** This is also an important step in meeting an increasing demand for flexibility.

2 Technical Flexibility Options

2.1 Conventional power plants

Conventional power plants are facilities that produce electricity from fossil fuels (mostly lignite, hard coal and natural gas) or uranium by means of thermal generators (mostly gas turbines or steam turbines).[20] Coal- and gas-fired power plants are currently the most relevant source of flexibility in Germany. Nevertheless, the phase-out of nuclear power by 2022 and coal-fired power plants by 2038 will lead to the development and more intense utilisation of alternative flexibility options as the system will be lacking an important part of a baseload power fleet. However, conventional power plants, especially gas power plants, will still play a role during the transition period. Thus, even if the electricity output from conventional power plants declines, their capacity will not necessarily decline – at least in the next few years until other flexibility measures such as storage are widely deployed. In the short term, conventional power plants will still provide the required dispatchable capacity—generation capacity that is available on demand, regardless of weather conditions—as well as **ancillary services** that require their operation at a minimum load.[21]

At the same time, due to the growing share of volatile RE in the system and its priority dispatch, the need for the flexible operation of conventional power plants will increase. The flexibilisation of existing conventional power plants is therefore essential to integrating large shares of RE.[22]

Flexibility of conventional power plants

The flexibility of **conventional power plants** refers to any measure that expands the capability of a power plant to adapt power production to the system's requirements, such as to cope with changes that occur more quickly and more frequently, as well as to cope with fewer load hours and longer downtimes.[23] Three key parameters characterise the flexibility of conventional power plants:[24]

- **Minimum load** (PMin) describes the lowest possible net power a power plant can deliver under stable operating conditions and is measured in percentage of nominal load (%P_n).
- **Ramp rate** describes how quickly a power plant can change its net power during operation and is specified in MW per minute (MW/min) or in the percentage of nominal load per minute (%P_n/min).
- **Start-up time** (t) describes the period from starting plant operation until reaching the minimum load.

The lower the minimum load and the start-up time, and the higher the ramp rate, the more flexible the power plant is. This flexibility mainly serves the purpose of fulfilling market-related and grid-serving functions.

Table 4. Flexibility status of German coal power plants and the estimation of the potential for their further flexibilisation

Flexibility parameters	Unit	Lignite coal power plants			Hard coal power plants		
		Existing, current status	New, current status	Flexibility potential	Existing, current status	New, current status	Flexibility potential
Typical size / capacity	MW	150–900	1,100		100–860, many are < 100	1,000	
Minimum load[1]	%P_n	60	35–50	25–40	30–40	25	20[2]
Ramp rate	%P_n/min	1	2.5	4–5	1.5	3–4	6

[1] Monoblock systems. Duoblock systems enable a lower minimum load of the entire system.
[2] < 10% possible in case of indirect firing.

At a load range of 50–90% P_n					At a load range of 40–90% P_n		
Hot start-up[3] time	hr	6	4	2	2–3	1.5–2.5	1–2
Cold start-up time[4]	hr	10	5	4	10	5–8	6

Sources: Markewitz et al. 2017, 20; Ernst et al. 2020, 14.

Table 5. Flexibility status of German gas power plants and the estimation of the potential for their further flexibilisation

Flexibility parameters	**Unit**	**Gas turbines**			**Combined cycle gas turbines (CCGT)**			**Open cycle gas turbines (OCGT)**	
		Existing, current status	**New, current status**	**Flexibility potential**	**Existing, current status**	**New, current status**	**Flexibility potential**	**Existing, current status**	**New, current status**
Typical size / capacity	MW	HD:[5] < 100–340 AD:[6] < 5–50	340 100[7]		< 10–600	500–600			
Minimum load	%P_n	25–30	25[8]	20	50	40–45	35–40	50	40
Ramp rate	%P_n/min	8	12	15	2	4	8	12	8
At a load range of 40–90% P_n									
Hot start-up time	hr		< 0.1		0.5–1.5	0.4–1.3	0.35–0.4		< 0.1
Cold start-up time	hr		< 0.1		2–4	1.5–3.5	1.3–1.4		< 0.1

Sources: Markewitz et al. 2017, 26; Ernst et al. 2020, 14.

[3] Hot start-up refers to a start-up after a standstill of less than 8 hours.
[4] Cold start-up refers to a start-up after a standstill of more than 48 hours.
[5] HD: heavy-duty gas turbines.
[6] AD: aero derivative gas turbines.
[7] LMS100 – (Land Marine Supercharged) is an aero derivative gas turbine produced by Ge Distributed Power. It produces approximately 100 MW.
[8] Up to 20% P_n in case of small(er) turbines.

Generally, power plants fired with solid fuels, even those with flexibility retrofit, are significantly less flexible than plants fired with liquid fuels or gas.[25] The limitations of coal-fired power plant flexibility relate to the design of the combustion chamber: stable operation is not possible below a certain power level. State-of-the-art hard coal power plants typically achieve minimum load levels of 25–40% of nominal load. For lignite power plants, that range is 35–50%.[26] Minimum load is higher in lignite-fired units due to the lower combustibility of the fuel.[27] Some pilot projects have reached minimum load levels as low as 12% after retrofits. [28]

By contrast, the minimum load levels of power plants built 10–20 years ago in industrialised countries ranged from 40% for hard coal plants to 60% for lignite plants.[29]

Gas power plants have much lower minimum loads and start-up times and higher ramp rates than lignite and hard coal-fired power plants, thus offering higher operational flexibility. However, they are often restricted by emission regulations, as low-output operation tends to emit more harmful gases.[30] The role of gas power plants may increase further due to the phase-out of coal and nuclear in Germany combined with the growing demand for system flexibility.

The technical minimum load levels of **CHP plants** are comparable to non-CHP units using the same fuel and/or technology but are often limited by meeting the demand for heat.[31]

Ramp rate and start-up times in steam power plants, such as coal power plants, gas turbines and CCGT units, are limited by thermal stress in the steam cycle. Lignite power plants are further limited by lignite drying processes that use combustion heat: less lignite can be dried at low output levels, so it takes longer for the unit to ramp up from low levels. The flexibility of CCGT units depends largely on the design of the steam cycle. To a great extent, German CCGTs were designed as mid-merit power plants for operational flexibility and can therefore be operated fairly flexibly. This contrasts with some units in Ireland or the U.S. that were initially designed only for baseload operation.[32]

Main technical solutions

To improve system flexibility, the grid requires all the measures and investments that enable power plants to run in a wider load range, operate at a lower minimum load, reach minimum load faster and handle more frequent load changes. Those measures can be implemented as part of **retrofit investments**.

The following table provides a comprehensive list of technical solutions to increase operational flexibility in coal-fired power plants.[33]

Table 6. Coal plant retrofit options, their effect on flexibility parameters and their limitations

Option	Minimum load	Start-up time	Ramp rate	Limitations
Indirect Firing	✓		✓	Fire stability
Switching from two-mill to single-mill operation	✓			Water-steam circuit
Control system and plant engineering upgrade	✓		✓	Fire stability/ thermal stress
Auxiliary firing with dried lignite ignition burner	✓		✓	Fire stability and boiler design
Thermal energy storage for feed water pre-heating	✓			N/A
Repowering		✓	✓	N/A
Optimized control system		✓		Thermal stress
Thin-walled components/special turbine design		✓		Mechanical and thermal stresses
"New" turbine start		✓		Turbine design
Reducing wall thickness of key components			✓	Mechanical and thermal stresses

Source: Agora Energiewende 2017a, 76.

There are also specific retrofit options to optimise the flexibility of **CHP plants**. Their aim is to increase the plant's ability to modulate power production without impairing its ability to provide the required heat.[34] This implies that CHP plants operate in a **power-oriented manner** instead of classical operation whereby operation follows heat demand and power is generated as a by-product to heat[35]. The most important measures to optimise CHP plants include:[36]

- The installation of a (generally smaller) extra unit – a boiler – that produces additional heat
- **Heat storage** that allows the CHP unit to produce excess heat, store it for a certain period and use it when heat production is lower
- A **power-to-heat unit (PtH)** that produces heat from electricity (e.g. an **electric boiler**)

Examples of retrofit investments in CHP plants

Investment	Flexibility impact
Installation of a boiler	Reduce minimum load Optimise start-up Increase ramp rate
Heat storage	
PtH units (electric boiler)	

The less flexible CHP plants with back pressure steam turbines benefit more from flexibilisation through heat storage than the more flexible CHP plants with extraction condensing turbines.[37] Retrofitting options for coal-fired power plants have the following limitations:

- Reducing minimum load is more efficient and flexible than frequent start-ups
- Fire stability in the boiler of hard coal and lignite-fired power plants limits the minimal load reduction
- Allowable thermal and mechanical stress of power plant components limits the reduction of start-up times
- The major limitations for increased ramp rates are thermal and mechanical stress during ramping, which reduce component life. During the design phase, there is a trade-off between thick-walled design for high efficiency and thin-walled design that permits a higher temperature change rate and, therefore, higher ramp rates. Quick temperature changes in thick-walled components induce thermal stress, which is a limiting factor for start-up times and higher ramp rates.[38]

Main market and regulatory measures or restrictions

The most important market and regulatory measures that led to the flexibilisation of conventional power plants in Germany include the following:

Main market and regulatory measures

Measure	Impact
Priority dispatch for RE	Conventional power plants need to react/incentive for operational flexibility
Power exchange price volatility	Incentive for operational flexibility
Shorter spot market timeframes: tradable contracts reduced to 15 min. in 2014, lead times reduced to 5 min. in 2017	Incentive for operational flexibility
Shift away from coal and complete phase-out by 2038 (decided in 2020)	Incentive to take measures increasing flexibility of the power plants even though this reduces their lifetime

Available capacity and potential

In the future, further residual load volatility increases and the development of alternative flexibility measures (many of which are described in this report) may make coal power plants redundant or at least further reduce their competitiveness. This also applies to retrofitted coal power plants, which have been made more flexible. Appropriate market design rules and fossil fuels phase-out policies may reinforce this process.

Currently, the installed capacity of all conventional power plants in Germany (except nuclear power plants, which will be phased out by 2022) amounts to around 75 GW. Almost all (around 91%) coal-fired plants are CHP plants (20.48 GW). Around 62.3% of lignite-fired plants are CHP plants (13.3 GW), and nearly 64.8% of gas-fired plants are CHP plants (20.55 GW).[39]

Table 7. Installed capacity of conventional power plants in Germany

	Installed capacity	Installed capacity of CHP plants	CHP share
Hard coal power plants	22.5 GW	20.48 GW	91%
Lignite power plants	21 GW	13.3 GW	62.3%
Gas power plants	31.7 GW	20.55 GW	64.8%
Total	75.2 GW	54.33 GW	

Source: Bundesnetzagentur/SMARD Strommarktdaten.

Costs

Retrofit measures cause high costs that may even increase the operating and maintenance costs. These measures may also reduce the service life of individual power plant components as well as their efficiency.[40] However, coal power plant operators choose to carry out retrofit measures as these investments pay off in the current market conditions – often with negative electricity prices due to the feed-in priority for RE.

Investment costs vary significantly on a case by case basis. A 2017 study by Agora Energiewende estimated the costs of retrofitting coal power plants at 100–500 euros/kW (price per installed capacity unit).[41, 42]

Gas-fired power plants are generally already much more flexible than coal-fired power plants, and the cost of their flexible operation increases with the steepness and the length of the ramp. Moreover, they are exposed to gas fuel costs, especially in markets that rely on imported liquefied natural gas (LNG).[43] Therefore, a general cost estimate is not possible.

The operators of CHP plants receive a fixed CHP supplement for feeding electricity into the grid. The supplement should incentivise power-oriented operation, offsetting the costs for increasing/enabling flexibility. The payment of this supplement varies according to the size of the plant and amounts to between 3.1 and 8.0 ct/kWh. CHP plants that use RE can also optionally receive this EEG remuneration.[44]

2.2 Biomass and biogas power plants

Biomass- and biogas-operated power plants are another relevant source of flexibility in Germany, with many advantages compared to conventional power plants. Biomass and biogas combustion generates less greenhouse gas than fossil energy. As dispatchable power plants, they complement variable RE (wind and PV) well. Since biomass cultivation can negatively affect the environment, such as cultivating monocultures and using pesticides, and there is limited availability of agricultural land, the European Union (EU) adopted a set of sustainability criteria restricting its use.

Main technical solutions

In Germany, units using solid biomass (mainly wood) as fuel generally operate as CHP and are subject to the same flexibility limits as fossil-fuelled CHP units. All the retrofit options for conventional power plants described above also apply to biomass-operated power plants.

Biogas power plants are generally operated in baseload mode with continuous biogas production and a storage capacity that is typically only sufficient for a few hours of operation (buffer storage). Larger storage capacity and/or additional generators help to achieve greater flexibility with the same fuel input (from the same digester). The current support scheme in Germany favours the option of adding extra generators to enable existing buffer storage to operate more flexibly.[45] Under this scheme, plant operators receive payments only for additionally installed flexible capacity.

Biomass- and biogas-operated power plants fulfil the following functions in the German power system:

Functions of biomass- and biogas-operated power plants in the German power system

<table>
<tr><th colspan="2">Market-related functions</th><th colspan="2">Market-related grid-serving functions</th></tr>
<tr><td>Peak or load shifting
Peak or load shaving</td><td>Spot market trading (arbitrage)</td><td rowspan="2">Ancillary services</td><td rowspan="2">Provision of primary and secondary control energy
Integration into virtual large-scale battery or virtual power plants (VPP)</td></tr>
<tr><td>BRP / compensation energy</td><td>Selling electricity to BRPs to compensate for short-term deviations from schedule</td></tr>
</table>

Main market and regulatory measures or restrictions

There are currently no incentives for the flexible operation of biomass-operated power plants, except for power exchange prices.

The main regulatory measure to incentivise the operational flexibility of biogas-operated power plants is the **flexibility premium** (Flexibilitätsprämie), replaced in 2014 by the **flexibility supplement** (Flexibilitätszuschlag).

Available capacity and potential

In 2018, Germany had an installed capacity of 8 GW of biomass-operated power plants and 5.6 GW of biogas-operated power plants.[46] The retrofit and flexibilisation/expansion potential amounts to +/- 16 GW by 2030.[47] Positive potential means additional capacity, whereas negative potential means that the capacity is switched off.

Costs

Investment costs for flexibility improvements of biogas-operated power plants can be derived from the flexibility premium and the flexibility supplement:

- 130 euros/kW/year for a duration of 10 years for units commissioned before 31 July 2014
- 40 euros/kW/year for a duration of 20 years for units commissioned after 31 July 2014, from 2017 to 2021
- 65 euros/kW/year for a duration of 20-year units commissioned after 31 July 2014, after 2021[48]

2.3 Pumped-storage power plants

Pumped storage is the most common technology used to balance the volatility of electricity generation from RE, both in Germany and worldwide. It is currently also the only technology that can store electricity on a large scale, apart from large scale batteries.[49] Limitations to their operation and further expansion exist due to the restricted availability of suitable water reservoirs and environmental concerns, such as protecting fish stocks.

Main technical solutions

Pumped-storage power plants use hydroelectric power to pump water to a reservoir at a higher altitude to store electricity in periods of low demand. In periods with high demand, the water flows back down through turbines that generate electricity.[50] Therefore, pumped-storage power plants can produce electricity through turbine operations to supply peak loads.

The efficiency of pumped-storage power plants is typically between 70 and 85%.[51] In modern pumped-storage power plants, the entire load range can be continuously adjusted between maximum pumping and maximum turbine operation. Complete hydraulic short-circuit operation makes it possible to switch from pure turbine operation to pump operation and vice versa within approximately 30 seconds.[52] In the case of a grid failure, most pumped-storage facilities can quickly be put into operation.[53] The start-up time to maximum power range from 75 to 110 seconds from standstill and is only a few seconds from partial load operation.[54] The main technical measures to increase flexibility include the enlargement of the upper water reservoir and additional turbines.

Pumped-storage power plants fulfil the following functions in the German power system:

Functions of pumped-storage power plants in the German power system

Market-related functions		**Market-related grid-serving functions**	
Peak or load shifting **Peak or load shaving**	Short-term daily storage Spot market trading (arbitrage)	**Ancillary services**	Black start capability Provision of primary and secondary control energy Integration into virtual large-scale battery or VPP
BRP/ compensation energy	Short-term daily storage Selling electricity to BRPs to compensate for short-term deviations from schedule		

Main market and regulatory measures or restrictions

There are currently no incentives for the flexible operation of pumped-storage power plants except for power exchange spot market prices. An existing unfavourable regulation, also referred to as the **double burden**, currently reduces the profitability of pumped-storage power plants. The operators of power plants are required to pay end consumer fees twice over the entire pumped-storage process: once when drawing electricity for pump operation and again when feeding electricity into the grid. This situation especially hinders the construction of new pumped-storage power plants. The same regulatory obstacle applies to all storage systems drawing electricity from and feeding it back into the grid, above all large-scale batteries (LSBs) and PtX.

Available capacity and potential

In 2020, the total storage capacity of pumped-storage power plants in Germany amounted to 37 GWh,[55] and the total installed capacity amounted to around 6.7 GW.[56] Another 2.9 GW are located in Austria and Luxemburg but are connected to the German power grid.[57] In 2015, 8 TWh of electricity was stored in German pumped-storage power plants[58] compared to 647 TWh or 1.2% of total electricity generation.[59]

Pumped-storage power plants provide the majority of storage capacity in Germany:

Table. 8. Installed capacity of different energy storage technologies in Germany as of 2018

	Total	**Pumped-storage**	**LSBs**	**Small-scale battery storage**	**Compressed air energy storage**	**Power-to-X**
Installation (GW)	8.31	6.7 (a)	0.45 (b)	0.5 (b)	0.32 (c)	0.34 (d)
Proportion	-	80.6%	5.4%	6%	3.8%	4.09%

Sources:

(a) dena a (current).
(b) Figgener et al. 2021, 11 (2019).
(c) Yanan et al. 2020, 21 (2018).
(d) dena 2020, 33 (2017).

It is estimated that pumped-storage systems in Germany could provide around 2 TWh storage capacity in the long term.[60] Based on planned projects, the total installed capacity could reach between 8.6 and 12.7 GW by 2025.[61] Further technical potential exists beyond the currently planned projects; however, the sites with sufficient economic potential are limited, and nearly all of them are already exploited.[62]

Costs

The cost structure for pumped-storage power plants is presented below, based on estimations from 2014:[63]

- Fixed costs: 2.86 euros/kW/year
- Variable costs in relation to the amount of electricity generated: 0.56 euros/MWh (not including costs for purchasing electricity)
- Variable costs per start-up for turbines: 3.34 euros/MW
- Variable costs per start-up for pumps: 8.95 euros/MW

2.4 Batteries

Batteries are electrochemical energy storage devices that store energy in chemical form within the battery and transform it into electricity when needed. They come with different properties, sizes and technologies, mainly Li-ion, lead-acid, sodium-sulphur and redox-flow.[64] Their advantage is the rapid and dynamic adaption to high loads and the provision of short-term power or flexibility that can occur within a few seconds, or even in less than 1 second, and up to at least 30 minutes.[65] Due to increasing competition in the electricity market, underpinned by policy measures, growth in RE generation and significant technological advancements, batteries are the fastest-growing segment among all flexibility options.

In this report, we differentiate between small-scale and large-scale batteries. **Small-scale batteries** are batteries with a charge/discharge capacity less than 50 kW or a storage capacity less than 50 kWh – although a standardised classification does not yet exist.[66] Batteries with a charge/discharge capacity of more than 50 kW or a storage capacity of more than 50 kWh are considered **large-scale batteries (LSBs)**.[67]

Small-scale batteries

Main technical solutions

Small-scale batteries are typically used for short-term storage, in particular for daily use in home storage solutions. If available in households, they are often used in combination with electric vehicles and heat pumps.[68] Their main functions include the following:

Functions of small-scale batteries in the German power system

User and market-related functions		Market-related grid-serving functions	
Increasing the level of self-sufficiency **Reducing electricity prices** **Peak or load shifting** **Peak or load shaving**	Short-term daily storage Spot market trading (arbitrage) (mainly after integration into virtual large-scale battery or VPP)	**Ancillary services** **Participation in the wholesale market**	Integration into virtual large-scale battery or VPP
Uninterruptable power supply (UPS)	Black start capability Islanding		

In 2015, new business models started to appear that aggregate multiple home storages to provide primary control energy in the form of a virtual power plant (VPP). Multiple companies currently offer this service, although it remains a small sector.[69]

Virtual power plants (VPPs)

A VPP is a network of decentralised, medium-scale power generating units, such as wind, PV, CHP, as well as flexible power consumers and storage systems. The units remain independent in their operation and ownership, but they are interconnected through the central control room of the VPP via a remote control unit. The central control room monitors, coordinates and controls the dispatch of all involved assets in order to optimise and distribute their power generation or consumption intelligently. It is also responsible for trading the electricity on the energy exchange.

The overall purpose of a VPP is to reduce peak loads, thereby reducing the need for redispatch and curtailment, power arbitrage, and providing control energy. In general, individual small plants cannot provide control energy or offer their flexibility on the wholesale market, as they are too variable or do not meet the minimum bid size and other criteria to participate in electricity markets.

The bidirectional data exchange between the individual plants and the VPP provides real-time data on the capacity utilisation of the networked units. Moreover, the VPP's central control system also processes data on current prices at the power exchange, the weather and price forecasts, as well as grid information from system operators. Using intelligent algorithms, this information can be used to generate precise and individual forecasts for trading electricity and scheduling the dispatchable power plants and loads.

Source: based on Next Kraftwerke c.

Small-scale batteries used for homes storage are almost exclusively lithium-ion battery technology (> 99%). Their installation costs are high, but their efficiency is also high across the entire power range, with low efficiency only at extremely low outputs (< 5–10%).[70]

Main market and regulatory measures or restrictions

The following framework conditions contribute to the rising use of small-scale batteries in Germany:[71]

- The option for residential owners to choose between receiving feed-in tariffs for electricity sent to the grid (approximately 7.5 ct/kWh as of 2021) and self-consumption to avoid paying electricity prices (approximately 30 ct/kWh as of 2021). Batteries help improve self-consumption from PV and small wind.
- Obligation for small-scale PV systems below 25 kW to have an inverter limiting the active power feed at 70% of PV capacity (if they are not remotely dispatchable), providing an additional incentive to install battery systems that are operated in a grid-serving manner.

Available capacity and potential

Around 66% of the total battery capacity installed in Europe is located in Germany.[72] Here, the number of new installations of small-scale batteries per year increased from 20,000 in 2015 to about 60,000 in 2019.[73] In 2021, Germany may even install 150,000 residential batteries.[74] According to figures from the German energy storage association, there are now more than 300,000 battery storage systems installed in German households, with the average installation size around 8–9 kWh in 2019 and 2020.[75] In 2018, most newly installed batteries (about 55%) operated in combination with PV rooftop systems;[76] this number has now increased to 70%.[77]

The storage capacity of small-scale batteries increased six-fold since 2015, from 210 MWh[78] to roughly 2.3 GWh in 2020.[79] The estimated small-scale battery potential in Germany is practically unlimited.[80]

Costs

In 2019, the retail price for batteries with an installed capacity between 5 to 10 kWh ranged from 900 to 1,100 euros/kWh.[81]

Small-scale batteries are extremely flexible. There are no additional costs for low loads, frequent start-ups and high ramp rates.[82]

Large-scale batteries (LSB)

Main technical solutions

LSBs can potentially fulfil many functions in the German power system:[83]

Functions of batteries in the German power system

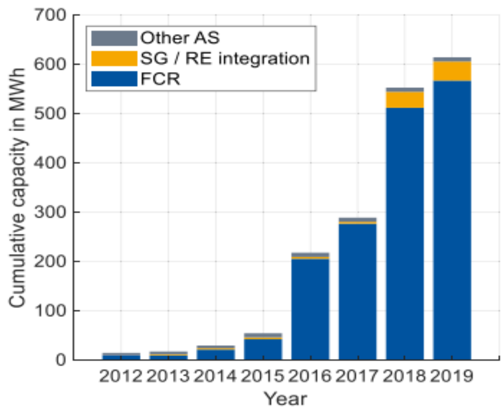
User-related funcitons		**Market-related functions**		**Market-related grid-serving functions**	
Increasing level of self-sufficiency **Reduction of electricity costs**	Area-wide solutions* On-site battery for PV/wind park or conventional power plants (absorbing otherwise curtailed/ redispatched energy) Optimisation of electricity grid charges based on different provisions related to tariff discounts	**Peak or load shifting** **Peak or load shaving**	Spot market trading (arbitrage) Integration into virtual large-scale battery or VPP	**Ancillary services**	Black start capability Provision of primary control energy Integration into virtual large-scale battery or VPP Grid boosters
UPS	Black start capability Islanding	**BRP/ compensation energy**	Selling electricity to BRPs to compensate for short-term deviations from schedule		

* Area-wide solutions: Different kinds of energy-related services to supply a housing complex in a certain area. In German: *Quartierlösungen*.

These functions can be fulfilled either independently or in combination with RE or conventional power plants.

Currently, LSBs are mainly used for short-term storage, primarily to provide primary control energy. Approximately 600 MW of primary control energy is auctioned. In recent years, the primary energy market has been almost exclusively served by LSBs due to their lower costs compared to other control energy sources such as conventional generators, hydropower and pumped-storage hydro. Therefore, the market has already reached saturation, and large-scale battery storage capacity for providing primary control energy is not expected to increase much further.[84]

Figure 6. Development of LSB capacity in Germany according to application areas



Explanation of the abbreviations:

AS: ancillary services
SG: smart grid
RE: renewable energy
FCR: frequency containment reserve (primary control energy)

Source: Figgener et al. 2021, 18.

However, other use cases for LSBs are in development and are expected to flourish. These other use cases include using batteries as grid boosters, industrial applications to increase self-consumption or reduce peak demand, participation in other ancillary service markets and electricity price arbitrage. In most of these application areas, however, only pilot projects exist for the moment, and none have reached the commercial stage.[85]

Approximately 70% of installed LSB capacity are lithium-ion batteries. Their installation costs are high, but they are also highly efficient across the entire power range, with low efficiency only occurring at extremely low outputs (< 5–10%).[86]

Main market and regulatory measures or restrictions

Compared to small-scale batteries, LSBs face several economic obstacles. Not only are there no significant incentives for their use, but the regulatory framework is fragmented and lacks consistency. One barrier is the issue of double burden, also faced by pumped-storage and power-to-x (PtX) facilities. Despite this issue, the installed capacity of LSBs in Germany has increased significantly since 2016 due to increasing competition in the electricity market, substantial growth in RE generation and significant advances in battery technology and cost.[87] One application where LSBs have been particularly successful has been the control energy market. As mentioned, other use cases are expected to develop in the future.

Available capacity and potential

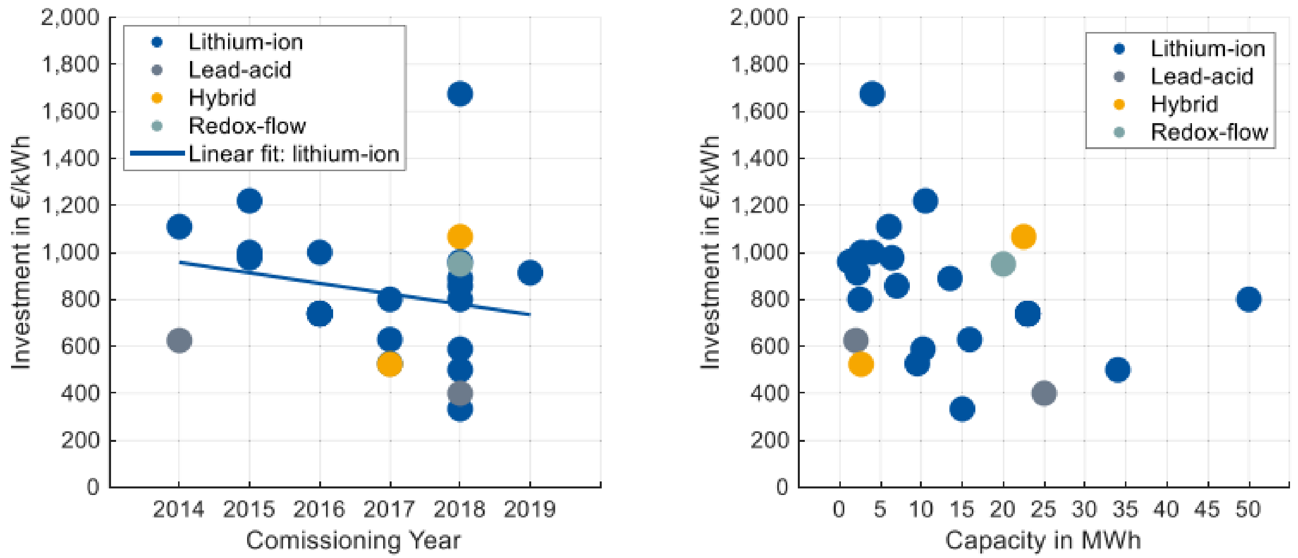
Since 2013, Germany has experienced unprecedented growth in the installation of LSBs, reaching more than **450 MW in total in 2019.**[88] The cumulative power of all LSB projects amounted to 450 MWh in the same year.[89] Particularly high growth has taken place since 2016, as investment costs decreased rapidly and the price of primary control energy changed.[90] The **estimated potential** for LBSs in Germany **is practically unlimited.**[91] Projections by Navigant from 2019 indicate **an 11-fold increase by 2028 up to 5,000 MW** in total.[92]

Costs

Investment costs vary considerably and depend on what is included in the investment costs, such as power electronics, building, land, grid connection and VAT. The trend line indicates LSB investment prices between 700 and 1,000 euros/kWh of installed storage capacity (decreasing) for the time period from 2014 to 2019.[93] In terms of installed capacity, investment costs range up to 1,500 euros/kW.[94]

LSBs are extremely flexible. Low load, frequent start-ups and high ramp rates do not incur any additional costs.[95]

Figure 7. Development of LSB investments by time (left) and storage capacity (right)



Source: Figgener et al. 2021, 11

2.5 Power-to-X

Power-to-X (PtX) refers to a variety of technologies used to transform electricity either into chemical energy in the form of hydrogen or methane (power-to-gas, PtG), into liquid fuels (power-to-liquid, PtL) or into heat (PtH).[96] As a result, this technology can be used to displace conventional, fossil-based fuels and feedstock, for sector coupling purposes and as a flexibility measure if used as large-scale energy storage, especially as PtG. However, PtG and PtL are not yet widely used in Germany due to high costs and complexity concerning required changes in the regulatory framework. Most of the PtG and PtL facilities are pilot projects, and most commercial PtX projects are PtH facilities.

Main technical solutions

PtG is the most widely implemented technology, with 72 plants in operation as of 2021. Most PtG plants serve the industrial sector, especially the chemical industry, refineries and ammonia production. Other applications that are less economically viable so far are for purposes such as heat, re-electrification or mobility.[97] The electrolysis efficiency is approximately 77%, and electrolysis in combination with methanation has reached 62% efficiency.

Concerning **PtL**, only very few pilot projects exist to create synthetic fuels, and none of them have reached commercial viability**.**[98]

PtH is the second most widely implemented PtX technology in Germany. At the beginning of 2019, 36 large PtH modules were installed in Germany – mostly at municipal utilities.[99] The two main technologies used for heat generation are **heat pumps** and **large electric boilers**. Heat can either be produced in a decentral manner at residential and commercial buildings or centrally before it is fed into district heating grids: several such industrial and commercial projects exist in Germany. Thermal storage in aquifers can help address seasonal variability in supply and demand.[100] The efficiency of heat pumps is 4–19 times higher than the efficiency of PtG facilities due to the lack of conversion losses.[101]

The functions of PtX are similar to those of batteries.

Main market and regulatory measures or restrictions

So far, PtX support is mainly in the form of funding for research projects. In 2020, the German government adopted a National Hydrogen Strategy highlighting the planned steps to develop a competitive hydrogen market and provide additional funds for research and the market ramp-up of projects.[102] The European Commission has undertaken similar efforts by adopting a “Hydrogen strategy for a climate-neutral Europe” in 2020.[103] Recently, the regulations have been updated based on new analyses concerning the maximum permissible hydrogen content in the gas grid.[104]

Available capacity and potential

Installed PtG capacities are expected to increase over the next years in Germany, with at least 494 MW of installed electrolyser capacity scheduled for 2021–2025.[105] This is a significant increase, as there were only around 34 MW of installed or planned PtG projects registered in 2017.[106] As of 2021, there were 72 plants in operation in Germany, most of which were only pilot projects with a limited size of a few MW.[107]

The estimated potential for PtG in Germany is very high. It ranges from 3 GW to 10 GW by 2050[108] to practically unlimited[109] if the otherwise curtailed RE potential that PtG facilities can absorb is not considered.

The total output of PtH facilities in Germany amounts to approximately 555 MW. As of 2020, there were 36 plants in operation in Germany, most of which were in commercial use, and their size ranged between 0.5 and 60 MW.[110]

As is the case for PtG, the estimated potential for PtH in Germany is very high and practically unlimited if the otherwise curtailed RE potential that PtH facilities can absorb is not considered.

Costs

PtG: The investment costs for utility-scale solutions range from 400 $/kW_{el}$ to 1,400 $/kW_{el}$ for the entire **electrolyser** system.[111]

Re-electrification using **fuel cells** results in investment costs:

- Ranging from 200 $/kW_{el}$ to 700 $/kW_{el}$ for smaller, mobile applications up to approximately 400 kW,
- And ranging 3000 $/kW_{el}$ to 6000 $/kW_{el}$ for larger, stationary fuel cells from 100 kW to several MW.[112]

PtL: Due to the small number of pilot projects, there is no reliable data on investment costs.[113]

PtH: Investment costs vary greatly with regard to scale and technology. Investment costs for **electric boilers**, which are primarily used in district heating networks, range from 75 euros/kW to 100 euros/kW and 100 euros/kW to 200 euros/kW in high-temperature applications. In general, large plants that use CHP or electric boilers are particularly lucrative, as they can amortise after only a couple of years at current prices in the control energy market.[114] Smaller, decentralised plants prove to be economically less profitable, as they incur higher specific costs for the same specific revenues.

For small applications, residential **heat pumps** are most common. They are priced at about 1,200 euros/kW for air source heat pumps and between 1,750 euros/kW and 2,100 euros/kW for ground source heat pumps.[115]

3 Demand-Side Flexibility Options

The aim of demand-side flexibility (DSF) is to match electricity consumption more closely to electric power generation. Depending on the size of the consumer, there is a distinction between **industrial DSF**, **commercial DSF** in small and medium-sized enterprises and **residential DSF**.

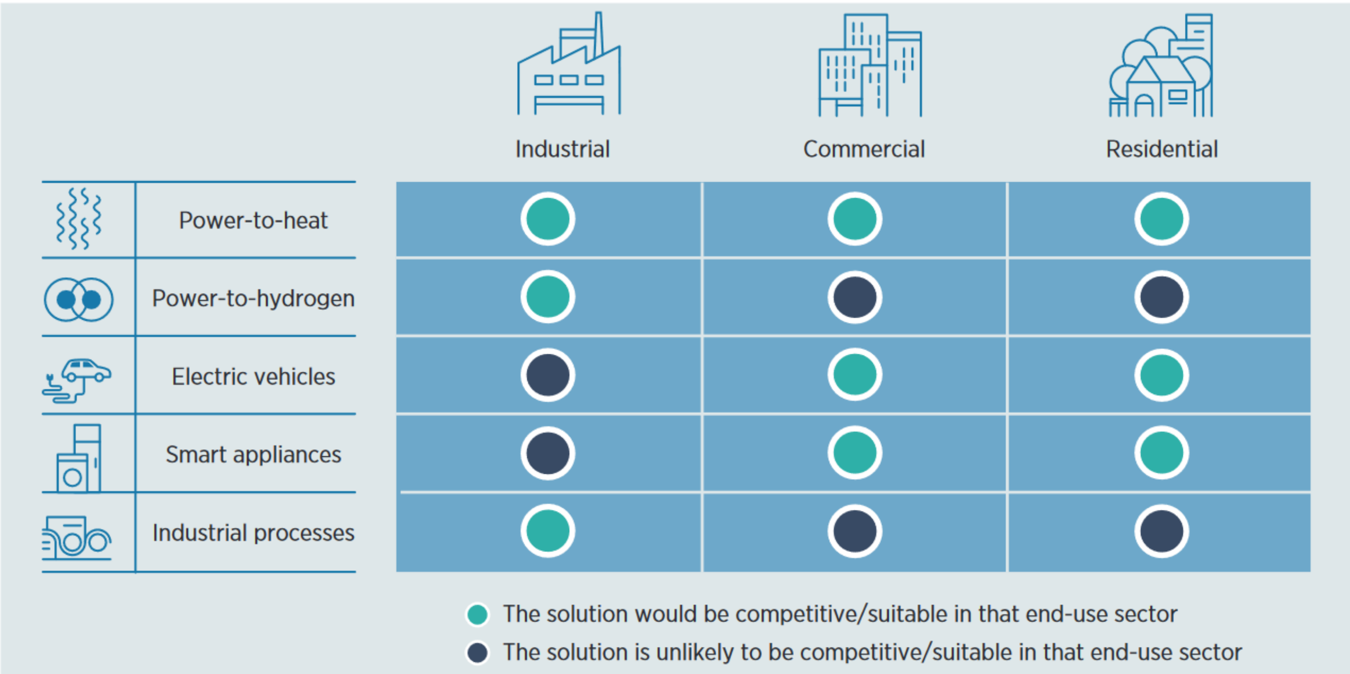
DSF involves the active and, in many cases, automated management of electric loads in response to an external price signal or a contractually agreed switching signal.[116] In this regard, the following types of DSF measures are the most common:[117]

- Temporary adjustment of consumption – shift in consumption to times of high RE generation
- Change in performance – reduction of consumption at peak load times, increase in consumption during periods with lower loads

The feasible DSF potential describes the flexibility that a company or household is able and willing to offer under the given market conditions.[118] Thus, when calculating the feasible potential of DSF, both the technical and economic conditions need to be considered.

Higher degrees of flexibility depend significantly on developing a framework that enables electricity users, especially energy-intensive industry, to maximise their potential and react to system needs. The existence of some form of incentive signal for flexibility, such as a market price, is essential. This signal should reflect the system needs and prescribe neither the technology nor the actor who offers the service. This approach can be described as a **"level playing field"** for flexibility.[119] A **technology-neutral** approach thus enables different DSF technologies to be used in different end-use sectors.

Figure 8. DSF technology mapping by end-use sector



Note: Competitiveness/suitability is based on how inexpensive the solution is in comparison to others for the same sector. For example, the industrial sector has very few renewable options apart from green hydrogen, whereas direct electrification with renewables is a cheaper alternative for the commercial and residential sectors. Therefore, the potential for gaining demand-side flexibility from hydrogen production could be larger in industry.

Source: IRENA 2018a, 13.

3.1 Industrial and commercial DSF

Main technical solutions

Industrial and commercial DSF may fulfil the following functions in the German power system:

Functions of industrial and commercial DSF in the German power system

User-related functions		**Market-related functions**		**Market-related grid-serving functions**	
Reduction of electricity costs **Load shifting** **Load shaving**	Optimisation of electricity grid charges based on different provisions related to tariff discounts	**Load shifting** **Load shaving**	Spot market trading (arbitrage)	**Ancillary services**	Provision of primary control energy Provision of other ancillary services
		Balancing group management/ compensation energy	Marketing power to BRPs to compensate for short-term deviations from schedule		

Main market and regulatory measures or restrictions

In recent years, DSF markets have developed significantly in Germany and Europe. Entry conditions for DSF to provide control energy have improved. Due to higher competition between electricity suppliers, many of them have introduced flexible contracts. Companies have started to take advantage of these developments and have formed **aggregators or VPPs** to participate in the wholesale market, control energy market and other ancillary service markets, such as interruptible loads.

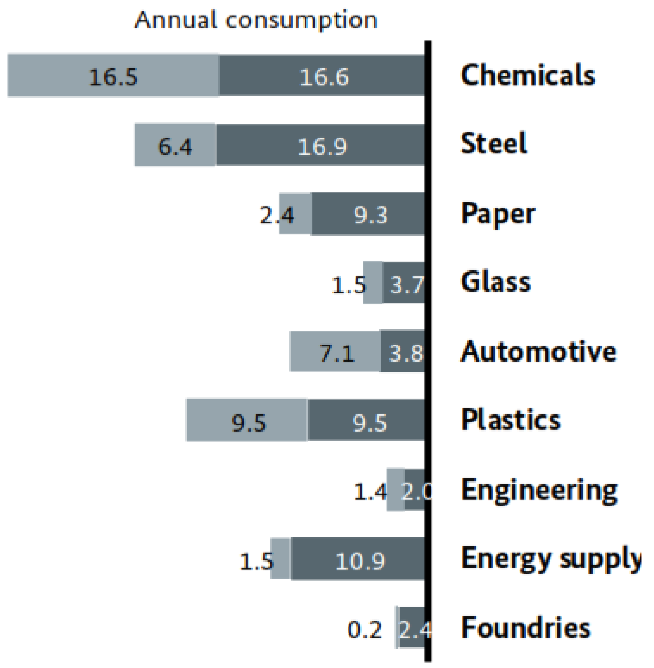
Low wholesale electricity prices have provided little incentive for companies to flexibilise their electricity consumption. This may change in the medium term when further expansion of RE replaces more conventional power capacity, leading to larger market price signals.

Available capacity and potential

The technical potential for industrial DSF lies particularly in energy-intensive industries such as the chemical, steel and glass industries. Additional markets include DSF in the water supply, wood, construction materials and food industries.

Some of this potential has been already exploited. Figure 9 shows the annual consumption of sites with and without DSF in industry branches in Germany in 2019. Load-managed consumption significantly exceeded unmanaged consumption and amounted to 75.1 TWh.[120]

Figure 9. Annual consumption of sites with and without DSF by industry branch in TWh, 2019



Explanation:

Light grey: Annual consumption of sites without DSF.
Dark grey: Annual consumption of sites with DSF.

Source: Bundesnetzagentur/Bundeskartellamt 2019, 220.

The capacity of interruptible loads in Germany amounts to around 2,416 MW.

The estimated technical potential for DSF in Germany in industry ranges from 5 to 15 GW[121] and from 3 to 10 GW in SMEs.[122] The extent to which the technical potential can be developed economically depends on the development costs and the revenue available.

Costs

For most companies, high opportunity costs for the provision of flexibility mean that they only market DSF to a limited extent. Soon, better price signals for DSF and, therefore, higher flexibility demand can be expected, primarily due to the nuclear and coal phase-outs.[123]

Concerning the costs of DSF, a distinction must be made between the investment required to provide the service and the variable utilisation costs (load reduction or increase). The investment costs vary in the different end-use sectors, and the variable load reduction cost ranges from 0 to 500 euros/MWh.[124]

A further distinction must be made between load shifting and load shedding orders. In 2015, the majority of orders were load-shifting orders. Variable costs for this were very low in part, i.e. from 0 to 100 euros/MWh. The cost for load shedding orders was at least 350 euros/MWh with peak values up to 2,000 euros/MWh in the paper industry, for instance.[125]

3.2 Residential DSF

Main technical solutions

Examples of residential DSF include the flexible charging of **electric vehicles** and the flexible use of **heat pumps**, as well as, to a smaller degree, the use of other **electrical household** devices as smart appliances. Residential DSF has the potential of fulfilling functions similar to industrial and commercial DSF. The primary mechanism of residential DSF is consumers' reaction to price signals, such as through variable consumer tariffs.[126]

Main market and regulatory measures or restrictions

There are various possible solutions for developing the potential of residential DSF, ranging from manual to semi-automatic to automatic approaches, depending on how much freedom customers have to react to an (economic) incentive to use electricity at certain times.[127] Different incentives and business models have been discussed or are currently being discussed and tested in pilot projects in Germany to enable more residential DSF, including the:[128]

- Introduction of variable end user tariffs based on the spot market price (for example, time-of-use tariffs or real-time pricing)
- Flexibilisation of the RE levy (*EEG-Umlage*) based on the spot market price
- Flexibilisation of grid charges
- Flexibility bonus
- Flexibility markets
- A smart and coordinated mix of all of these different instruments

An essential prerequisite for residential DSF is the availability of an appropriate measuring system.[129] In Germany, the introduction of such a system has begun with the adoption of a law mandating the introduction of intelligent measuring systems (smart meters) and other digital technologies. The regulatory framework needed to increase the role of residential DSF in the energy transition is currently the subject of heated debates. The central topics debated are whether and how households can provide flexibility, what the proper incentives and measures are and how to prevent the **simultaneity** of applications from increasing the required grid capacity.

Available capacity and potential

Residential DSF has significant untapped potential in Germany. Mainly research and pilot projects exist to test the possibilities of this measure and to determine the technical and economic feasibility.[130] The main application field is currently **electrical heating** (storage heaters, heat pumps and other electrical heating devices). DSOs and small electricity customers can conclude **load control agreements** that give the DSO the right to manage the electricity consumption of one of the customer's electrical devices. In turn, the electricity customer benefits from a discount on the grid tariff charged by the DSO.[131] According to Team Consult estimates for storage heaters in 2019, load control agreements were signed for an electric capacity of approximately 5 GW and a storage volume of approximately 45 GWh.[132]

The technical potential of residential DSF is estimated to be even higher than the potential of DSF in industry and small and medium enterprises. It amounts to between 7 and 21 GW.[133]

Costs

The provision costs for flexibility are significantly higher in the private sector than in industry due to economies of scale.[134] The costs of **heat pumps** amount to about 1,200 euros/kW for air source heat pumps and between 1,750 euros/kW and 2,100 euros/kW for ground source heat pumps.[135]

Until 2025, German buyers receive a purchase premium (9,000 euros) for **electric vehicles** with a net price of over 40,000 euros. Electric vehicles are often cheaper than vehicles with combustion engines when all a car's costs (the purchase price, operating and maintenance costs, loss of value minus purchase premium) are taken into account. The base net purchase price is between approximately 31,000 and 200,000 euros without the purchase premium.[136]

4 System Operation Flexibility

Besides flexibility services used for self-optimisation and/or the provision of flexibility to BRPs or grid operators, there are also flexibility measures applied unilaterally by grid operators to stabilise or optimise the grid to increase its flexibility.[137] We classify all these measures as **system operational flexibility**. They can be either:

- **user-related** – if the grid operators apply the measures themselves or
- **market-related grid-serving** – if the grid operator requires a certain service from a third party for compensation or the third party applies a certain measure to increase its system flexibility (such as RE forecasting).

These measures include:

Functions of system operation flexibility in the German power system

User-related functions	Market-related grid-serving functions
Higher utilisation of the existing grid Cooperation between DSOs and TSOs Cooperation and coordination between TSOs Cross-border power exchange Advanced forecasting of RE generation	Redispatch and curtailment Advanced forecasting of RE generation

Redispatch and curtailment are **ancillary services**. However, in contrast to **voluntary ancillary services**, organised in a market-based way, they are not voluntary services. They are merely obligations set on power plant operators resulting from system operation requirements and are remunerated through compensation.

4.1 Redispatch and curtailment

Redispatch and curtailment are both measures used by grid operators, mainly TSOs, to manage grid imbalances and overloads. Grid bottlenecks in the transmission grid are usually the cause for these measures.

Redispatch affects only conventional power plants above 10 MW, such as coal and gas power plants. TSOs or DSOs can demand that power plant operators increase their electricity generation on one side of a grid bottleneck and decrease electricity production on the other side.[138]

According to the new regulation **Redispatch 2.0**, starting in October 2021, smaller RE and CHP plants as small as 100 kW are included in redispatch measures because of the actual and anticipated increase of grid bottlenecks in distribution grids due to the further RE expansion, sector coupling and the simultaneous use of new consumers, such as electric vehicles and heat pumps. RE plants are often located more closely to the point of overload, making them quite efficient in resolving imbalances.[139] This measure should help to decrease redispatch costs.

Curtailment is a procedure similar to redispatch, but it only affects RES and CHP plants regulated by the EEG. According to the EEG, grid operators can **reduce or curtail** the amount of energy generated by RE or CHP plants above 25 kW connected to their grid. PV systems smaller than 25 kW can be curtailed if their active power feed is higher than 70% of PV capacity (section 14 subsections 1 and 2 of EEG 2021). Until the amendment of the EEG in 2021, only RE above 30 kW and CHP plants above 100 kW could have been curtailed (Next Krafwerke d). As of 2021, smaller power plants can also be affected by curtailment. The prerequisite is the availability of special intelligent measuring systems that enable grid operators (DSOs) to monitor and control the feed-in remote (section 14 subsections 1 and 2 of the EEG 2021). The purpose of curtailment is “to ensure the safety and reliability of the electricity supply grid” (section 14 subsections 1 and 2 of the EEG 2021). At the same time, the power plants on the other side of the grid bottleneck have to increase their feed-in. TSOs may call on a DSO for curtailment in the event of bottlenecks in the transmission grid, which are more frequent than bottlenecks in distribution grids.[140] In these cases, the TSOs initially bear the costs (section 15 of the EEG 2021).

Since the EEG was amended in 2021, grid operators must pay power plant operators a compensation payment for the entire lost revenue. Grid operators pass these costs on to end consumers, including them in the grid charges. However, they are required to prove that the curtailment was necessary and that all other measures, such as grid optimisation, reinforcement and expansion have already been exhausted.

4.2 Advanced forecasting of RE generation

More precise and accurate forecasts for the provision of RE lead to fewer imbalances in the power grid. Therefore, short-term, complex and eventually more expensive flexibility measures are necessary less often. RE producers, BRPs and grid operators also have more time to plan or implement adjustments or interventions, such as buying electricity or selling surplus electricity at short notice on the intraday spot market. In recent years, sophisticated techniques have improved weather forecasts for RE based on artificial intelligence and cloud computing technology. The forecast period can range from 5 minutes up to 48 hours.[141] Deviations range from 3% to 6% for hour-ahead forecasts and 6% to 8% for day-ahead forecasts.[142]

Advanced forecasting of RE generation can be used both by RE producers and by grid operators. Grid operators can use such forecasts to better plan grid utilisation and demand-side measures and implement flexibility measures.

4.3 Higher utilisation of the existing grid

The technical performance of the power grid can be improved through grid reinforcement or expansion or grid optimisation through higher utilisation. Higher utilisation of the existing grid can be achieved by using LSBs as **grid boosters** and **dynamic line rating (DLR).**[143]

Grid boosters are fast power sources, usually LSBs, allowing power lines to be loaded beyond their current stability limits. One LSB absorbs electricity from the grid on one side of the bottleneck. At the same time, another LSB feeds the same amount of electricity into the grid on the other side. Three German TSOs, namely Transnet BW, Amprion and Tennet, are planning to build and operate grid boosters in pilot projects with a total capacity of 450 MW. The Federal Network Agency approved these grid boosters in the 2019 Grid Development Plan.[144] TSOs expect a 9% reduction of curtailment with savings of up to 25 million euros by implementing grid boosters.[145]

Moreover, grid boosters can also be used as **grid operating resources** for voltage maintenance.

Dynamic line rating (DLR) is a dynamic adjustment (mostly increase) of the capacity of transmission lines to the ambient climate. Normally, transmission lines work with a standard (static) capacity rating derived from the most unfavourable conditions: no wind and high ambient temperatures. However, if the weather conditions are more favourable, the capacity can be increased, which means the line can transmit more electrical power. Different methods are used to measure the possible grid capacity adjustment. In Germany, all TSOs currently apply DLR in their grids, although in different proportions.[146]

4.4 Cooperation between DSOs and TSOs

Communication, cooperation and coordination between DSOs and TSOs may lead to the better management of flows and flexibility between different grid voltage levels. The current cooperation between TSOs and DSOs in Germany is based on the MaBiS guidelines of the Federal Network Agency and the EU directive on electricity transmission system operation.[147]

The introduction of the previously mentioned Redispatch 2.0 regulation will reinforce this cooperation, as smaller electricity generation units (as low as 100 kW) connected to the distribution grid will be included in the redispatch regime. DSOs will be required to include the operators of these smaller generation systems in their balancing of the grid, assess the flexibility potential, and communicate this potential to TSOs and BRPs.[148]

In addition to these policy guidelines, there are also pilot projects in which more advanced cooperation methods between DSOs and TSOs have been tested, for example, the enera project.

Project enera

Enera is one of five projects in the research program "Smart Energy Showcase – Digital Agenda for the Energy Transition" (SINTEG). It develops solutions for a climate-friendly, efficient and safe energy supply with a high proportion of RE and demonstrates them on a large scale. Further goals include the interaction of all actors in the intelligent grid, the efficient use of the existing grid structure and a low need for distribution grid expansion.

The enera project encompassed testing and developing solutions for grid operator cooperation, mainly involving the following partners: EWE NETZ GmbH, AVACON Netz GmbH and TenneT TSO GmbH. In this context, a "flex market" for grid congestion management was developed. This market provides a market platform on which grid operators can "exchange" capacities in the event of changes or deviations in the generation or consumption profiles compared to the original plans and prognoses. The experience gathered in this project can be applied in the context of Redispatch 2.0.

4.5 Cooperation and coordination between TSOs

The four control zones of the German TSOs are interconnected via **coupling points.** They enable the transmission from an inland **control energy area/zone** with excess electricity to a control area with electricity shortages. This is more secure, technically stable, efficient and cheaper than independent grid operation. The control zones may also be disconnected, if necessary, to avoid a total collapse/blackout in the event of major shortfalls in one control zone. The control areas can then continue to operate as isolated grids (islands).[149]

Control energy area/zone

Control energy area (or zone) is a geographically defined area in which the responsible TSO manages and controls the stability of the transmission grid. Germany has four control areas managed by TenneT TSO GmbH, 50 Hertz Transmission GmbH, Amprion GmbH and Transnet BW GmbH.

The coupling points allow for the flexible management of possible imbalances across control zones. To coordinate across zones, the TSOs set up a formal cooperation in 2008, which gradually expanded to encompass all four German TSOs. One responsible TSO, Amprion, manages and coordinates the electricity flows across all control areas.[150]

The cooperation between TSOs is based on four principles:[151]

- **Avoidance of counter activation of control energy:** The excess electricity from one control area can pass to another control area.
- **Joint dimensioning of control power:** TSOs jointly determine an optimal amount of control energy across all control areas and provide it to other areas if needed.
- **Joint procurement of secondary control reserve:** Not yet in use. The aim is to enable individual providers to offer control energy in all control areas, even if they are only pre-qualified in one control area.
- **Cost-optimised activation of control energy:** Not yet in use. The aim is to implement a uniform merit order across all control areas instead of one merit order per control area.

Implementing all these principles will bring the highest value in terms of cost- and resource-efficiency and will help to better integrate RES.

4.6 Cross-border power exchange

The transmission and exchange of electricity have always played an important role in European integration. This cooperation has been continuously expanded to encompass more countries and provide more possibilities to transmit and trade electricity among said countries. Currently, the responsible organisation in Europe is the Union for the Coordination of Transmission of Electricity (UCTE).

Two conditions must be fulfilled to enable the cross-border exchange of power:[152]

- **Synchronous operation of the grids** in the countries that exchange electricity and
- **Existence of cross-border interconnectors** across the border of two countries or bidding zones.

Since the necessary infrastructure is very expensive and results in immense administrative efforts, it is crucial to use the existing infrastructure as efficiently as possible. For this purpose, the **Market Coupling Western Europe (CWE Market Coupling)** was established as a cooperation mechanism between the national electricity trading centres (European power exchanges such as EPEX SPOT) and the TSOs in different countries.[153] It includes the countries of France, Belgium, the Netherlands, Luxemburg, Germany and Austria.

The market coupling with Scandinavian countries (Finland, Sweden and Norway) has a separate cooperation structure known as **the Interim Tight Volume Coupling (ITVC)** that was established as a temporary solution due to its inefficiency.[154]

Implementing the **Price Coupling of Regions (PCR)** system in 2010 has strengthened both mechanisms. This system consists of 19 European countries, including CWE und ITVC countries as well as the Baltic States, Great Britain, Poland, Portugal, Spain, Italy and Slovenia. The PCR system established an exchange mode for the **day-ahead and intraday trading** between electricity trading centres in or among the various European countries. The exchange takes place automatically with the goal of calculating the optimal use of transmission capacities based on the mechanism of price convergence. Since 2015, this system has been supported through the **flow-based market coupling (FBMC)** that, in part, allocates transmission capacities parallel to the market clearing on the electricity markets.[155]

To enable the exchange of more cross-border power, European countries and the EU have recently initiated various joint projects to build new interconnectors. In May 2021, the NordLink subsea cable, with a capacity of 1,400 MW of power via HVDC transmission lines, went into operation between Germany and Norway. The European Commission is monitoring and promoting current progress in this area. According to its report, more than 100 projects are in the planning stages.[156]

5 Market Design Flexibility

Market design flexibility refers to policies and incentives that facilitate the use of flexibility. This type of flexibility can be **for the user** (when the seller benefits from participating in the market), **for the grid** (if the measure contributes to grid operations and stability) **or for both** the user and the grid.

Before exploring market design policies and incentives, we would like to introduce the multi-level structure of the electricity market in Germany as well as additional components outside the market. The goal of doing so is to facilitate a better understanding of the electricity market composition in Germany and provide an overview of different markets and their designs. Depending on their design, markets enable or incentivise different degrees of flexibility. The table below presents the structure of the electricity market in Germany, its additional components, the characteristics of the services offered, and the current flexibility resources.

Table 9. Structure of the electricity market in Germany

<table>
<tr><th>Market type</th><th>Market sub-type</th><th colspan="2">Service type/characteristics</th><th>Organiser</th><th>Flexibility measures participating/sellers</th><th>Buyers</th></tr>
<tr><td rowspan="2">Wholesale market</td><td>Spot market</td><td>1) Day-ahead market
2) Intraday market
3) Day-after market</td><td>- Auctions (power exchange) or OTC markets
- Products are delivered the next day, within one day or one day after the trading took place</td><td rowspan="2">- Specialised companies, such as EPEX SPOT
- OTC platforms through brokerage firms
- Bilateral (direct OTC transactions)</td><td rowspan="2">- All conventional power plants (when in operation)
- Gas power plants
- Energy storage
- RE
- VPP operators or other specialised companies serving as direct marketers for RES
- Brokerage firms (electricity traders)</td><td rowspan="2">- BRPs
- Large electricity consumers (industry)
- Energy storage
- VPPs
- Brokerage firms (electricity traders)</td></tr>
<tr><td>Derivative market</td><td colspan="2">1) Future market
- Auctions or OTC markets
- Products are delivered on a specified date up to several years in the future (for example, month- or year-ahead)
2) Forward market
- OTC markets
- Products are delivered on a specified date up to several years in the future (for example, month- or year-ahead)</td></tr>
<tr><td>Retail market</td><td></td><td colspan="2">- Direct selling of electricity by energy utilities to end users</td><td>- Direct contracts between energy utilities and end users</td><td>- Potentially DSF in SME and residential DSF</td><td>- End users (private households, SMEs)</td></tr>
</table>

Control energy market (or reserve market or balancing) market		1) Primary control energy/reserve (or frequency containment reserve) - Activation: automatic - Time until fully available: 30 seconds 2) Secondary control energy/reserve - Activation: automatic - Time until fully available: 5 minutes 3) Tertiary control energy/reserve (or minute reserve) - Activation: manual - Time until fully available: 15 minutes	- TSOs (tender)	- All conventional power plants (when in operation) - Gas power plants - Energy storage - VPPs - Large energy consumers (industrial DSF)	- TSOs (costs passed on to the end users)
Additional components outside the market (chronological presentation)[157]					
Grid reserve or "winter reserve"		- Established in **2013** - Set up in the winter each year for six months to increase redispatch capacity - Demand estimation for winter 2021/22: 5,670 MW - Payment: compensation for operational costs	- TSOs and Federal Network Agency	- System-relevant power plants that are not in operation or are closed, as well as suitable plants in other European countries - Plants are not allowed to sell on the market	- TSOs (costs passed on to the end users)
Capacity reserve		- Established in **2016** - Additional capacity for times when there is not enough supply available on the wholesale or control energy market to meet the entire demand - Amount capped at 2 GW - First delivery period started on 1 October 2020 and will end on 30 September 2022 - Capacity in the first delivery period: only 1.056 GW (= 1,056 MW) - Payment: annual remuneration as compensation for closures	- TSOs and Federal Network Agency - tenders organised by the TSOs	- Retiring coal plants (when closed) - Energy storage facilities (if not selling on the market) - DSF - RES (if not selling on the market)	- TSOs (costs passed on to the end users)
"Security readiness" or safety reserve		- From October **2016 to 2023** - Total capacity: 2.7 GW - Payment: annual compensation based on agreement, no payment for regular shutdown,	- TSOs and Federal Network Agency	- Gradually built up out of eight lignite blocks - Should be closed after 4 years in the reserve - Plants are not allowed to sell on the market	- TSOs (costs passed on to the end users)

		one-time compensation for early shutdown			
Special grid resources or grid stability reserve		- Established in **2019** - Additional capacity for short-term restoration of grid stability after a failure of one or more generation units - Amount capped at 1.2 GW - Plants must provide full load within 30 minutes and be able to hold it for at least 38 hours; total operating time is at least 500 hours per year - Criticism: 500 hours does not indicate an emergency case; therefore, the service should be organised as a market	- TSOs and Federal Network Agency - Tenders organised by the TSOs (min. capacity 100 MW)	- Medium-sized gas power plants	- TSOs (costs passed on to the end users)

Source: Own representation.

Balance responsible parties in the electricity market in Germany

Balance responsible parties (BRPs) (*Bilanzkreisverantwortliche*) can be electricity traders or suppliers (for example, an energy utility) or large industrial companies that procure their electricity independently. BRPs are responsible for a balanced result between electricity feed-in and consumption within a **balancing group**. BRPs also schedule deliveries to and from other balancing groups (section 4 of the Strom NZV).

A **balancing group** is a virtual account for electricity, made up of any number of electricity feed-in and take-in/up-take points that are energy producers and users/consumers within a control energy area. The BRP's main task is to manage the group (section 4 of the Strom NZV). One control energy area may consist of one or more balancing groups (there are usually several balancing groups in one control energy area).

In the event of balancing group balance deviations, the BRP assumes economic responsibility towards its control energy area's TSO, which acts as a **balancing group coordinator**. They both conclude a **balancing group contract** that regulates the balancing group's managing and billing. As a balancing group coordinator, the role of the TSO is to merge the necessary data of the balancing groups within the control area, adjust the remaining unforeseen deviations between the balancing groups and ensure the overall balance within the control area (section 4 of the Strom NZV; TenneT).

If deviations between the feed-in based on the forecast in the balancing group and the actual consumption cannot be sufficiently compensated by TOSs through offsetting with other balancing groups, TSOs compensate for them by means of **control energy** (*Regelenergie*) and charge the BRP for it.

To simplify – a BRP is a connection point between energy producers/users and TSOs and manages the energy flows between all of them within a defined area.

5.1 Increasing granularity in the power market

The functioning and regulation of the power market also affect system operations and the use of flexibility. The higher the **product granularity** in the power market, the better market participants can manage flexibility and balance mismatched demand and supply.[158] Product granularity refers to product differences in the market: the more products differ, the better the use of flexibility, as more economical and efficient product choices are available. For example, better granularity in the intraday spot market enables more short-term flexibility.

The following main indicators serve to assess the granularity of the products in the electricity market:[159]

Indicators of product granularity in the electricity market

Delivery period Defines the time period when the product is delivered	**Day-ahead**: products are delivered the next day **Intraday**: products are delivered within one day to help adjust purchases and sales based on the results of the day-ahead market/trading **Future markets**: products are delivered on a specified future date, up to several years in the future, for example, the next month (**month-ahead**) or the next year (**year-ahead**)
Lead time Time between the end of the trading session and the start of the delivery period, or time up to which the product is open for trading before delivery	Currently **5 minutes** in the German intraday market (introduced in 2017)
Product duration/tradable contracts or auction duration Describes how long products are available/can be auctioned	Currently **15 minutes** (introduced in 2014), **30 minutes**, **1 hour** and **blocks of several hours** in the German intraday market
Minimum and maximum price Defines the minimum and maximum total price	Both are currently **3,000 euros/MWh** in the German intraday market
Minimum price increment Defines the minimum price increment that can be offered in incremental steps	Currently **0.1 euros/MWh** in the German intraday market
Minimum volume increment Defines the minimum volume that can be traded and thus move up or down on the exchange	Currently **0.1 MW** in the German intraday market
Spatial resolution/delivery zones Describes the bidding zones or markets where the products can be traded	Products in Germany can also be traded on the Luxemburg market (**joint bidding zone**)

5.2 Ancillary services

The role of ancillary services is to ensure that **technical values (frequency, voltage)** are maintained in the power grid by managing imbalances if trading results in the electricity markets are not in line with the physical boundaries of the power system.[160] Ancillary services can also serve to restore the grid in case of blackouts. They provide short-term localised flexibility.

In most cases, TSOs employ ancillary services, but electricity producers can also employ these services (user-related functions). Ancillary services can be provided by both TSOs and grid users that fulfil the preconditions specified in the guidelines for ancillary services (mainly conventional power plants, storage systems, DSF).[161] How to further develop these guidelines to allow more RE and other flexible actors and options, such as LSBs and DSF, to provide ancillary services is currently a subject of discussion in Germany.

Ancillary services can be organised in a **market-based** way, whereby participants offer their services voluntarily. They can also be **mandatory** as part of contractual conditions for a grid connection. Another category is **grid-based** ancillary services used by grid operators. Examples include **grid operating resources**, such as overhead power lines, reactive power compensation systems (for example, electromagnetic coils, capacitors, converters) or grid boosters and **operational management**.

The table below summarises selected ancillary services in the German power market, their roles and providers.[162]

Table 10. Summary of selected ancillary services, their roles and providers in Germany

Selected ancillary services				
Role				
	Frequency maintenance: keeping the frequency within the permissible range	**Voltage maintenance:** keeping the voltage in the permissible range limiting voltage drops in the event of a short circuit	**Operational management**: coordination of grid and system operation	**Grid restoration:** restoration of supply after disruptions
Measures				
Market-based measures	Control energy: primary, secondary and tertiary control energy Interruptible loads			
Mandatory measures	Spinning reserve (*Momentanreserve*) Curtailment Rolling blackout (*Lastabwurf*) Reserve power plants (grid reserve) Special grid resources	Redispatch Reactive power (*Blindleistung*) Rolling blackout	Redispatch Curtailment	Black start capability
Grid-based measures		Grid operating resources: - Overhead power lines - Reactive power compensation systems - Grid boosters	Grid analysis/ monitoring Coordination of ancillary services across grid levels	Protective measures to isolate the fault
Providers				
	RE Conventional power plants LSBs DSF	RE Conventional power plants Grid operators: grid operating resources	Grid control systems in interaction with grid operating resources and conventional power plants	Grid control systems Conventional power plants Pumped-storage power plants

Source: dena 2014, 22 with own modifications and additions.

In the following sub-sections, we focus on **market-based** ancillary services that serve the system as an additional source of flexibility.

Control energy

The primary role of control energy *(Regelenergie)* is to ensure a balance between taking electricity from and feeding electricity into the power grid to maintain the **frequency** within acceptable limits and avoid disruptions. The provision and supply of control energy in Germany is organised in a market-based way – there is a **control energy market** where the buyer (TSOs) purchases control energy from providers on demand – in case of frequency deviations.

Control energy providers are various market actors that fulfil pre-qualification criteria concerning minimum technical requirements, such as voltage level, capacity, required availability, power rating, minimum and maximum load, start-up time and ramp rates. These criteria are part of the grid and system rules for German TSOs (the Grid Code or Transmission Code) and are based on a provision in the Energy Industry Act. TSOs must examine the fulfilment of these criteria by grid users.

Control energy can be:

- **positive** – providing power – mainly generation units and energy storage, including batteries and pumped-storage power plants or
- **negative** – taking power from the grid – mainly large power consumers, but also energy storage, including batteries and pumped-storage power plants.

Depending on the different characteristics of the market participants and the different requirements of the TSOs, the German balancing market differentiates between three control energy products. For all three products, TSOs organise joint auctions on the Internet platform to allocate control power. The following table summarises the control energy products, their characteristics and their providers:

Table 11. Table of control energy products in the control energy market in Germany

Control energy product	Activation mode	Time until fully available	Activation period (up to)	Remuneration	Providers/flexibility measures allowed to participate
Primary control energy/reserve (or frequency containment reserve, FCR)	Automatic	30 seconds	15 minutes	• Only capacity (readiness to activate the facility) is auctioned and remunerated • Commodity (actual provision of control energy) is not auctioned and remunerated since it is assumed that positive and negative control energy balance out over time • Auctions are separated into six blocks of **four hours** per day and divided into positive and negative control energy	- All conventional power plants (when in operation) - Energy storage - VPPs - Large electricity consumers (industry) - Min. 1 MW
Secondary control energy/reserve (or automatic frequency restoration reserve, aFRR)	Automatic	5 minutes	15 minutes	• Both capacity and commodity are auctioned and remunerated separately (since November 2020) • Auctions are separated into six blocks of **four hours** per day and divided into positive and negative control energy	- All conventional power plants (when in operation) - Energy storage - VPPs - Large electricity consumers (industry) - Min. 5 MW
Tertiary control energy/reserve (or minute reserve or manual frequency restoration reserve, mFRR)	Manual	15 minutes	1 hour	• Same structure as for secondary control energy	- All conventional power plants (when in operation) - Gas power plants - Energy storage - VPPs - Large electricity consumers (industry) - Min. 5 MW

Source: Consentec 2014, dena 2018, 7 and Team Consult, with own modifications and additions.

Theoretically, wind and PV can participate in balancing markets; however, in practice, the variability of these resources limits their participation to short time intervals. Several companies, such as Next Kraftwerke, Energy2market and Grundgrün, currently operate VPPs, in which they pool RE and/or storage capacity.

Control energy costs are primarily incurred by the BRPs that caused the need for control energy through imbalances. These costs are passed on to consumers via electricity prices and grid charges.

Since 2008, the demand for secondary and tertiary control energy has decreased, and the demand for primary control energy has risen.[163] This seems to be the consequence of an increase in the number of players offering primary control energy, as the sufficient availability of primary control energy reduces the need for other types of control energy. Total control energy costs amounted to 286 million euros in 2019, or about 14% of the total cost of ancillary services.[164]

Interruptible loads

Interruptible loads can be contracted by TSOs from market participants selected on a tender. These are mainly large energy consumers, usually large industrial companies primarily in the aluminium, chemistry and paper sectors. As interruptible loads are more expensive than control energy, they are used as a last resort when grid stability cannot be maintained otherwise.[165] The costs of this measure are also passed on to consumers.

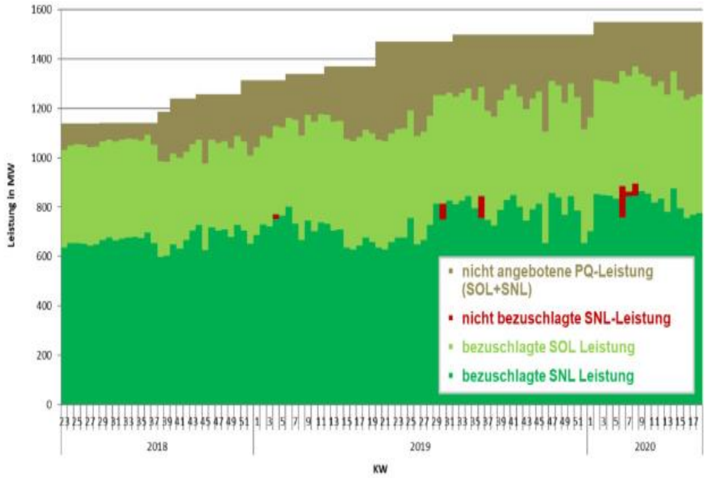
According to the Ordinance on Interruptible Loads (*Verordnung zu abschaltbaren Lasten,* AbLaV), large energy consumers that tender and register their load availability must hold the load capacity available for interruptions in case of electricity shortfalls in the grid according to certain terms and conditions. The contracting procedure consists of several steps:[166]

- **Pre-qualification process** – providers of interruptible loads must fulfil certain technical conditions in order to be allowed to participate in tenders. TSOs are responsible for qualifying potential providers.
- **Tender of interruptible loads** – TSOs conduct tenders with volumes of 750 MW each once a week for both QILs and IILs to select the cheapest providers among those pre-qualified. The lowest-priced bids are accepted first. Bid conditions are as follows:
    - Minimum offer 5 MW, maximum offer 300 MW
    - Minimum interruption period 15 minutes, maximum interruption period 32 quarters of an hour (32 x 15 minutes)

  Price bid design includes the following components:
    - **Capacity charge** and **commodity charge**, the former is paid for holding the capacity available during the contract period and the latter for the amount of electricity that was not delivered due to the interruption
    - **Price limits** for both price components: 500 euros/MW for capacity charge and 400 euros/MW for commodity charge to protect end users
- **Contracting interruptible loads** – all successful companies sign a contract with the TSO, which includes provisions on the availability of the interruptible loads, the time intervals in which interruptions may occur, the maximum number and duration of the interruptions, the notice period and the contractor's remuneration.

Not all pre-qualified interruptible loads take part in the tenders and are contracted. But all immediately interruptible loads (IILs) and almost all quickly interruptible loads (QILs) that take part in the tenders are contracted. This is indicative of a very low competition level in both segments.

Figure 10. Pre-qualified and contracted interruptible loads



Explanation:

Brown: Prequalified load not offered (IIL + QIL)
Red: QIL not contracted
Light-green: IIL contracted
Dark green: QIL contracted
KW: calendar week

Explanation of the abbreviations:

QIL (quickly interruptible load) – ordered remotely by the TSO, must take effect within 15 minutes
IIL (immediately interruptible load) – triggered automatically based on the grid frequency and takes effect within 350 milliseconds or is ordered remotely by the TSO

Source: ÜNB 2020, 6 (figure) and Team Consult, 27 (explanation of the abbreviations).

Interruptible loads can be pre-qualified for both QILs and IILs, but they can participate in only one tender a week. The following table presents the current volumes of pre-qualified interruptible loads:

Table 12. Status of volumes of pre-qualified interruptible loads in Germany

Interruptible load	Capacity
QIL	802 MW
IIL	1,614 MW

Source: Internetplattform zur Vergabe von Regelleistung (*abschaltbare Lasten*).

In 2019, interruptible loads amounted to ca. 31.3 million euros, of which around 3 million euros were paid as a commodity charge and approximately 28 million euros as a capacity charge.[167] The costs are passed on to all end users via a levy calculated once a year based on the cost forecasts. This levy usually ranges from 0.005 ct/kWh to 0.01 ct/kWh, which means that it is very low compared to other electricity price elements. It amounts to only around 1.5% of the total costs incurred by the TSOs for ancillary services and stabilisation measures.[168]

5.3 Support schemes: RE and grid charges

Appropriate policies and incentives facilitate efficient system operation and the use of flexibility.[169] A good example is the **EEG (Renewable Energy Act)**. Introduced in 2000 as a support scheme for RE, the EEG has been amended several times. All of the amendments mainly pursue the goal of better integrating and optimising renewable energy generation by making it more demand-oriented.

EEG 2009 introduced a **direct marketing** scheme that enabled RE operators to choose whether to market electricity under the regular compensation system or on the spot market on a monthly basis.

EEG 2012 introduced the **market premium model**, a method for calculating the payment for RE operators selling electricity on the spot market. The market premium represents the difference between the EEG tariff and the attainable market price on the spot market.

EEG 2014 introduced auctions that limited RE expansion through defined volumes to better match their development to the development of the grid and other infrastructure. It also introduced a regulation prohibiting compensation when spot prices were negative for at least six consecutive hours on EPEX SPOT.

These measures have all led to better adapting RE generation to fulfil market needs and infrastructure capabilities.

In the case of biogas power plants, an additional support scheme was adopted in 2012. The **flexibility premium** (*Flexibilitätsprämie*) supported additional installed capacity that could be used flexibly, providing 130 euros/kW per year for ten years. It was replaced in 2014 with the **flexibility supplement** (*Flexibilitätszuschlag*), which awards 40 euros/kW per year to units commissioned after 31 July 2014 for additional installed capacity that can be used flexibly for twenty years (older units still receive the flexibility premium). In 2021, the flexibility supplement was increased to 65 euros/kW. Its aim is to increase the share of dispatchable power plant capacities that enable demand-oriented electricity production.[170] Power plants must provide evidence of their flexible operation through appraisal by an external evaluator. The requirements for receiving the flexibility supplement are specified by law.[171]

The grid also supports RE by offering discounted grid charges for consumers engaged in **peak shaving** through consumption time shifting

Appendix 1. Available capacity and estimates of potential and implementation of different flexibility options in Germany

Table 13. Available capacity and estimates of potential and implementation of different flexibility options in Germany

Technology	Available capacity	Estimated potential and estimated implementation	Sources and further remarks
Conventional power plants			
Retrofitted lignite power plants	PMin = 50 – 60% P_n Ramp rate = 1 – 3% P_n/min t = 4 – 10 h	= 25 – 40% P_n = 4 – 5% P_n/min = 2 – 4 h	Markewitz et al. 2017, 20
Retrofitted hard coal power plants	PMin = 25 – 40% P_n Ramp rate = 1.5 – 4% P_n/min t = 1.5 – 10 h	= 20% P_n = 6% P_n/min = 1 – 6 h	Markewitz et al. 2017, 20
Retrofitted gas turbines	PMin = 20 – 30% P_n Ramp rate = 8 – 12% P_n/min t = < 0.1	= 20% P_n = 15% P_n/min Potential already exhausted	Markewitz et al. 2017, 26
Retrofitted CCGT	PMin = 40 – 50% P_n Ramp rate = 2 – 4% P_n/min t = 0.4 – 4 h	= 35 – 40% P_n = 8% P_n/min = 0.35 – 1.4 h	Markewitz et al. 2017, 26
CHP	54.33 GW (current) 113 TWh (net electricity generation in 2019)	120 TWh (net electricity generation; German target for 2025)	Bundesnetzagentur/SMARD Strommarktdaten (available capacity); Umweltbundesamt (2021) (potential and implementation)
Redispatch	16.7 TWh (2019)	5.3 TWh by 2025; practically unlimited potential, as RES included from 2022	Bundesnetzagentur 2020b, 9 (available capacity); 50Hertz et al. 2020, 6 (potential and implementation)

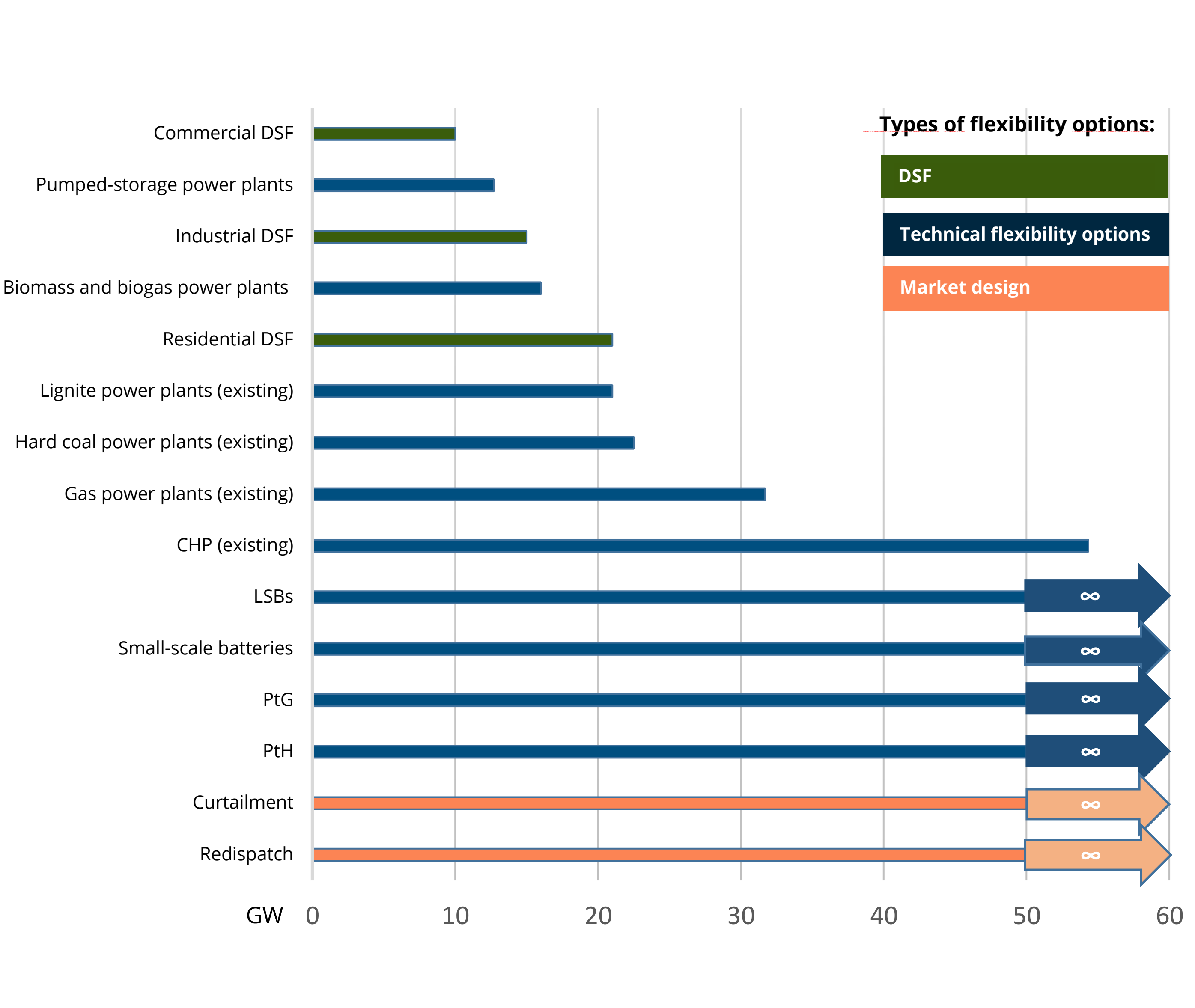
RES			
Curtailment (including CHP plants)	6.1 TWh (2019)	Practically unlimited potential	Bundesnetzagentur 2020b, 9 (available capacity); own estimate (potential and implementation)
Biomass and biogas power plants (electric power)	8 GW (biomass. 2018); 5.6 GW (biogas. 2018)	Up to +/- 16 GW by 2030	Agentur für Erneuerbare Energien (available capacity); Krzikalla et al. 2013, 9 (potential and implementation)
Storage			
Pumped-storage power plants	6.7 GW in Germany + 2.9 GW in Austria and Luxemburg 1,300 MWh 8 TWh – amount of electricity stored in German pumped-storage power plants in 2015	Between 8.6 and 12.7 GW by 2025 Up to 2 TWh in the long term	dena a; Energynautics 2021, 9; Team Consult, 51 (available capacity); Bundesnetzagentur 2014, II; Krzikalla et al. 2012, 9 (potential and implementation)
Small-scale batteries	750 MW (2019); 1,400 MWh (2019)	Practically unlimited potential	Figgener et al. 2021, 5 (available capacity); Krzikalla et al., 2013, 9 (potential and implementation)
LSBs	450 MW (2019) 450 MWh (2019)	Practically unlimited potential; 10-fold increase by 2028 to 5,000 MW	Figgener et al. 2021, 11 (available capacity); Krzikalla et al., 2013, 9; Navigant Research 2019, 2 (potential and implementation)
PtG	34 MW (2017)	3 GW to 10 GW by 2050; practically unlimited potential	dena 2020, 33 (available capacity); FfE, 2017, p. 42 in: dena 2020, 33; Krzikalla et al., 2013, 9 (potential and implementation)
PtH	555 MW (2020)	Practically unlimited potential	BDEW 2020, 4 (available capacity); own estimate (potential and implementation)
Demand side flexibility options			
Industrial DSF	75.1 TWh (load shifting) 2,416 MW (interruptible loads)	5 – 15 GW (technical potential)	Team Consult, 3; Internetplattform zur Vergabe von Regelleistung *(*interruptible loads) (available capacity); dena b (potential/implementation)
Commercial DSF (SME)	In part exploited, but rather to a limited extent	3 – 10 GW (technical potential)	Ladwig 2018, 42

Residential DSF	Untapped potential	7 – 21 GW (technical potential)	Ladwig 2018, 42
Storage heaters (incl. SME)	5 GW and 45 GWh (2019)		Team Consult 29-30
Electric vehicles (incl. SME)	Untapped potential	1 – 6,5 GW by 2030; 3 – 16 GW by 2050	Ladwig 2018, 204
Heat pumps (incl. SME)	Untapped potential	12 – 25,5 TWh/year by 2030; 20 – 42,4 TWh/year by 2050	Ladwig 2018, 203

Sources: As specified in the last colum

Appendix 2. Flexibility potential of selected flexibility options in Germany

Figure 11. Flexibility potential of selected flexibility options in Germany (in GW)



Source: Own representation based on Table 13.

List of Abbreviations

AD – aero derivative gas turbines

aFRR – automatic frequency restoration reserve

BNetzA – *Bundesnetzagentur* (Federal Network Agency)

BRP – balance responsible party

CCGT – combined cycle gas turbine

CWE Market Coupling – Market Coupling Western Europe

CHP – combined heat and power

DLR – dynamic line rating

DSF – demand side flexibility

DSO – distribution system operator

EEG – *Erneuerbare-Energien-Gesetz* (Renewable Energy Act)

EnWG – *Energiewirtschaftsgesetz* (Energy Industry Act)

EEX – European Energy Exchange

EPEX or EPEX SPOT – European Power Exchange SE

EU – European Union

FCR – frequency containment reserve

FBMC – flow-based market coupling

hr – hour

HD – heavy-duty gas turbines

HVAC – high voltage alternating current

HVDC – high voltage direct current

IIL – immediately interruptible load (*sofort abschaltbare Lasten*, SOL)

ITVC – interim tight volume coupling

LMS100 – Land Marine Supercharged (an aero derivative gas turbine that produces approximately 100 MW)

LNG – liquefied natural gas

LSB – large-scale battery

min – minute

mFRR – manual frequency restoration reserve

NABEG 2.0 – *Netzausbaubeschleunigungsgesetz* (Grid Expansion Acceleration Act)

PCR – Price Coupling of Regions

PMin – minimum load

Pn – nominal load

PtG – power-to-gas

PtH – power-to-heat

PtL – power-to-liquid

PtX – power-to-X

PV – photovoltaic

OCTG – open cycle gas turbine

QIL - quickly interruptible load (*schnell abschaltbare Lasten*, SNL)

OTC – over-the-counter

PV – photovoltaic energy

RES – renewable energy sources

SME – small and medium-sized enterprises

TSO – transmission system operator (*Übertragungsnetzbetreiber*, ÜNB)

UCTE – Union for the Co-ordination of Transmission of Electricity

UPS – uninterruptable power supply

VPP – virtual power plant

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