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Incentivizing Flexibility: The Role of the Power Market in Germany

Sino-German Energy Partnership

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c/o
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Torsten Fritsche
Köthener Str. 2
10963 Berlin

Project Management:
Yin Yuxia, Ma Qiongying, Maximilian Ryssel
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Authors:
Dr. Bernhard Ernst, Dr. Shan Weiwei
Fraunhofer Institute for Energy Economics and Energy System Technology IEE

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@Beijing, October 2019

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aFRR	Automatic Frequency Restoration Reserve
IPP	Independent Power Producers
mFRR	Manual Frequency Restoration Reserve
P_N	Rated Power of a Power Plant
PRC	Primary Control Reserve
SCR	Secondary Control Reserve or Secondary Reserve
TCR	Tertiary Control Reserve or Tertiary Reserve
TSO	Transmission System Operator
VG	Variable Generation (wind and solar PV)

Introduction

Within its climate protection plan, Germany aims to reduce its greenhouse gas emissions by 55% by 2030 and to achieve greenhouse gas neutrality by 2050 (in comparison to 1990's levels). Whereas in 1990 only 3% of electricity consumption was covered by renewable energies, this share has risen to 44% in the first half of 2019. Until 2030, renewable energies are planned to cover a 65% share of gross electricity consumption. The ever-increasing share of renewables poses new challenges for Germany's power system. Today, roughly 75% of renewable electricity in Germany is generated by wind and solar PV, i.e., variable and intermittent power sources. Hence, power system flexibility plays an important role in integrating the rising share of such variable generation (VG).

The concept of flexibility often arises when policymakers ask system planners how much wind and solar generation can reliably be added to the power system. This is important as electricity load and generation need to be balanced at all times. As VG can vary a lot due to weather changes, flexible (often conventional) generator units need to compensate for this. In this context, flexibility is often seen as the technical ability of power plants to operate flexibly and described by parameters such as ramp-up and ramp-down time, minimum load or start-up time. While power plant flexibility is important for physically enabling VG integration, the German case shows that system flexibility, i.e., flexible market rules and system boundaries, play at least an equally important rule. In fact, physical flexibility has never been a large challenge in Germany due to a high share of gas turbines in the electricity system.

Furthermore, German system operators took advantage of a simple effect to decrease the need for physical flexibility: While the output of a single wind plant can vary considerably in a short time period, the total output of a cluster of wind farms is much smoother due to weather homogenization in a larger area. German system operators (virtually) increased the system size, hence reducing the variability of VG over the whole system and reducing the need for flexibility.

In addition, setting the right market rules for enabling the flexible operation of load and generation in the power system is of great importance. Taking advantage of flexible power plants means to flexibly schedule and dispatch power plants, including last minute changes in dispatch schedules. Every change in power plant operation needs to be coordinated with the system operator which requires an exchange of data. To ensure all the data-exchange a liberalized power market needs, it is important to establish a fast and reliable process which took a lot of effort for the German system operators. When Germany began liberalizing its power market in the late 1990s, the established market rules did not allow any flexibility in power plant operation. A schedule once handed in on the day-ahead market could not be changed anymore. The market and scheduling rules have been gradually adapted to allow more flexibility. Nowadays, changes are possible until the last minute. These market reforms have proven to be the foundation of Germany's flexible power system. To date, no (direct) incentives have been necessary to 'flexibilize' power stations or build more flexible power stations. The market rules themselves serve as both incentive and enabler of power plant flexibility.

Hence, figure 1 depicts the main enablers of system flexibility: 1) a flexible power plant fleet, 2) flexible market rules and 3) a liquid reserve market. Everything is based on measures for (virtually) increasing the system size by close cooperation of the system operators. This significantly reduced the need for flexibility. The study will follow the structure of the three columns. The first chapter describes the challenges associated with the operation of power systems with high share of renewables and introduces the basic German balancing principles. Furthermore, (indirect) incentives given to build and operate flexible power plants in Germany are described.

As all balancing is based on market mechanisms, it is important to get an idea of how the electricity market works. Therefore, chapter 2 gives an overview of how the market-based planned balancing works. It shows the process of forecasting, planning, energy trading and scheduling of power plants. In the last years these processes got more automated, so more last minute changes, that take full advantage of the technical flexibility of the power plant fleet, are possible. The power exchange takes a major role in the trading process. It simplifies trading as it acts as a central platform open for every market participant.

As described in chapter 3, reserves are used for any unexpected events like power plant outages or forecast errors that cannot be balanced by the electricity market as described above. In these cases, very flexible generation needs to be activated to balance the system.

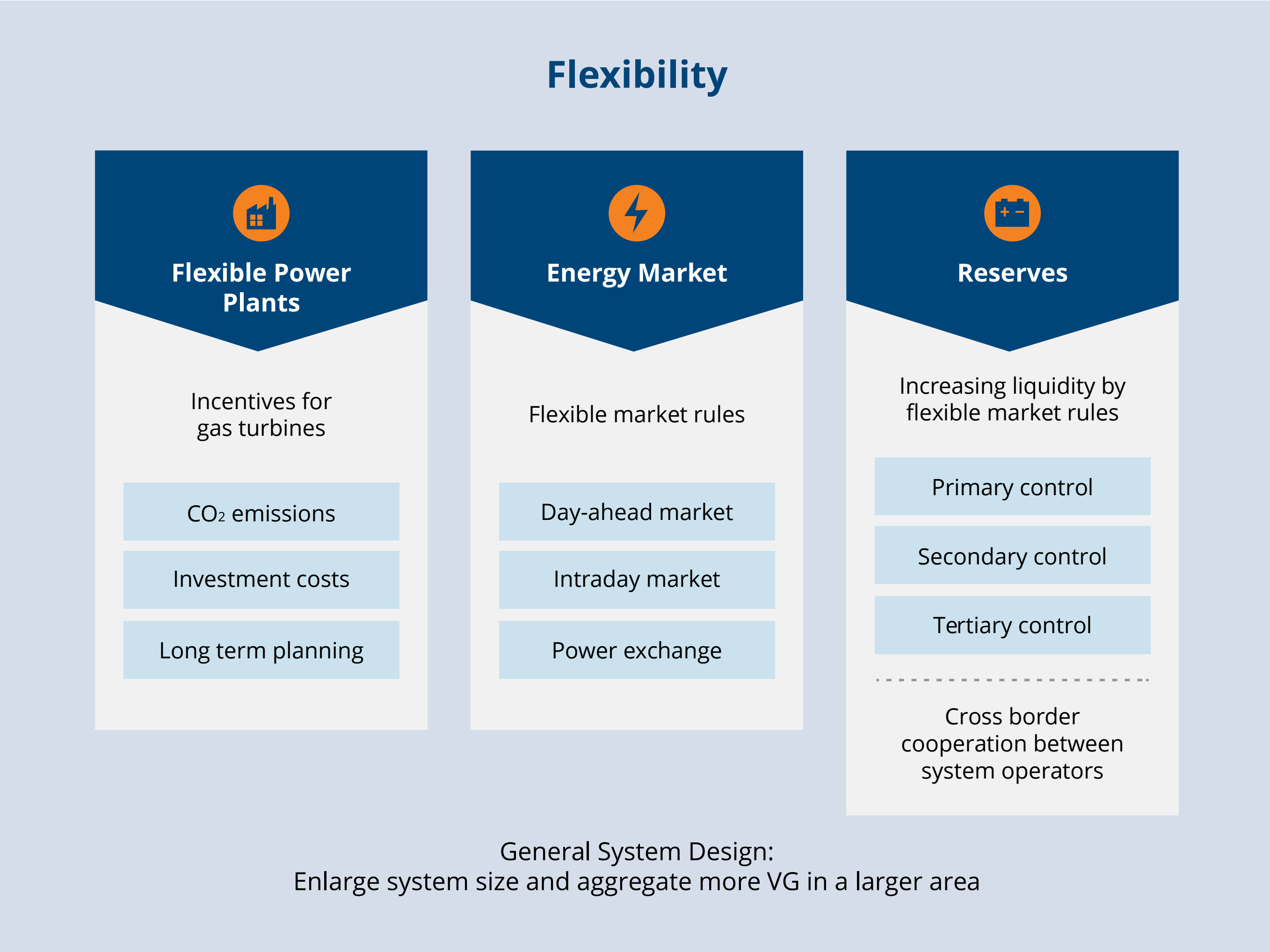


Figure 1: Three main pillars for guaranteeing a flexible power system in Germany.

Therefore, the system operators sub-contract power plants that can react on demand on very short notice. Especially the opening of the market rules towards small generation units increased the liquidity in this sector a lot, so by now many market participants can offer their flexible generation towards the system operators. A close cooperation between neighboring system operators decreased the demand for reserves of each individual system operator and therefore increased free liquidity in the sector even further. Finally, chapter 4 describes exemplary business models of flexible power generators, such as gas turbines, batteries and pumped hydro storage, in the German power system.

1 Role of Flexibility in the German Power System

Germany's climate protection policies aim at Germany's economy reaching carbon neutrality by 2050. The energy sector plays a crucial role in achieving this goal. Within the scope of the German Energiewende, the German government has set the target of covering 80 – 100% of its electricity consumption with renewable sources by mid-century. With roughly three quarters of renewable electricity stemming from VG today – namely wind and solar due to their large potential in Germany – VG will continue to play an increasingly important role in the future. In general, a rising VG share calls for more power sector flexibility to allow the grid integration of VG, namely changes in the power plant fleet, in market rules and system operation. In the German case, however, only the changes in market rules and system design were triggered by a need for more flexibility.

During the last decades, German regulators took several measures to optimize system operation and allow a high share of VG. These measures included:

- Enlarging the system size. German system operators took advantage of a simple effect: the larger the system size, the smoother are any weather dependent fluctuations (or other anomalies). For example, while the output of a single wind turbine can vary considerably in a short period of time, the total output of a large cluster of wind parks will show a much smoother power output due to weather homogenization effects in a larger area. The same applies to solar PV, but also the demand side. Hence, virtually increasing the system size helped German grid companies reduce the need for flexibility. This was done through a cooperation between German transmission system operators (TSOs) (s. chapter 1.1 for more information).

- Adjusting market rules. When liberalization of the power sector started in the 1990s, the energy market, but not the power plants themselves, was very inflexible. Despite a sufficient availability of physical flexibility on the power generation side, power plant scheduling was done on the day ahead and changes in the schedules were not possible (or at least very difficult) due to inflexible market rules. Hence, the German regulators decided to adapt market rules and allow for rescheduling during the day (intraday changes). Adjusting the market rules hence enabled the system to better utilize the available (physical) flexibility without the need for retrofitting or adding power plant capacities.

- Facilitating a flexible market. Further reforms were aimed at increasing liquidity and market acceptance. In terms of power trading, the introduction of the electricity spot exchange market has helped to ease doing business by securing payment, consumption and delivery for all market participants. Further, technical optimizations of the trading mechanisms and scheduling systems have enabled market participants to act closer to real time (including last minute changes in dispatch) and exploiting the full technical potential of existing flexible power plants. In addition to this, power exchange cooperation across Europe and cross-border trade on the intraday market has helped to increase market size and liquidity a lot.

Due to these system reforms, the German power system was never short of flexibility, despite the rapid development of renewable energy and VG over the last decades. Hence, direct incentives for adding or upgrading flexible power plants were neither necessary nor given. Spotlight 1 gives an overview of the deciding factors for enabling flexibility in the power sector.

The following sub-chapters will show the above principles in more detail and show how the market and system design contributed to flexibility. While not many direct incentives for building flexible power plants were given, chapter 1.3 briefly outlines some indirect incentives that helped increase the share of gas turbines in the German electricity system.

Spotlight 1: Decisive factors for enabling flexibility

Flexibility in power systems is inherently tied to the regulatory and market rules that help shape operations. As power systems evolve to incorporate more renewable energy and responsive demand, regulators and system operators are recognizing that flexibility across all elements of power systems must be addressed by ensuring:

Flexible system operations:
practices that help extract flexibility out of the existing physical system, such as

- making decisions closer to real time and more frequently;
- improved use of wind and solar forecasting;
- better collaboration with neighboring systems (and countries).

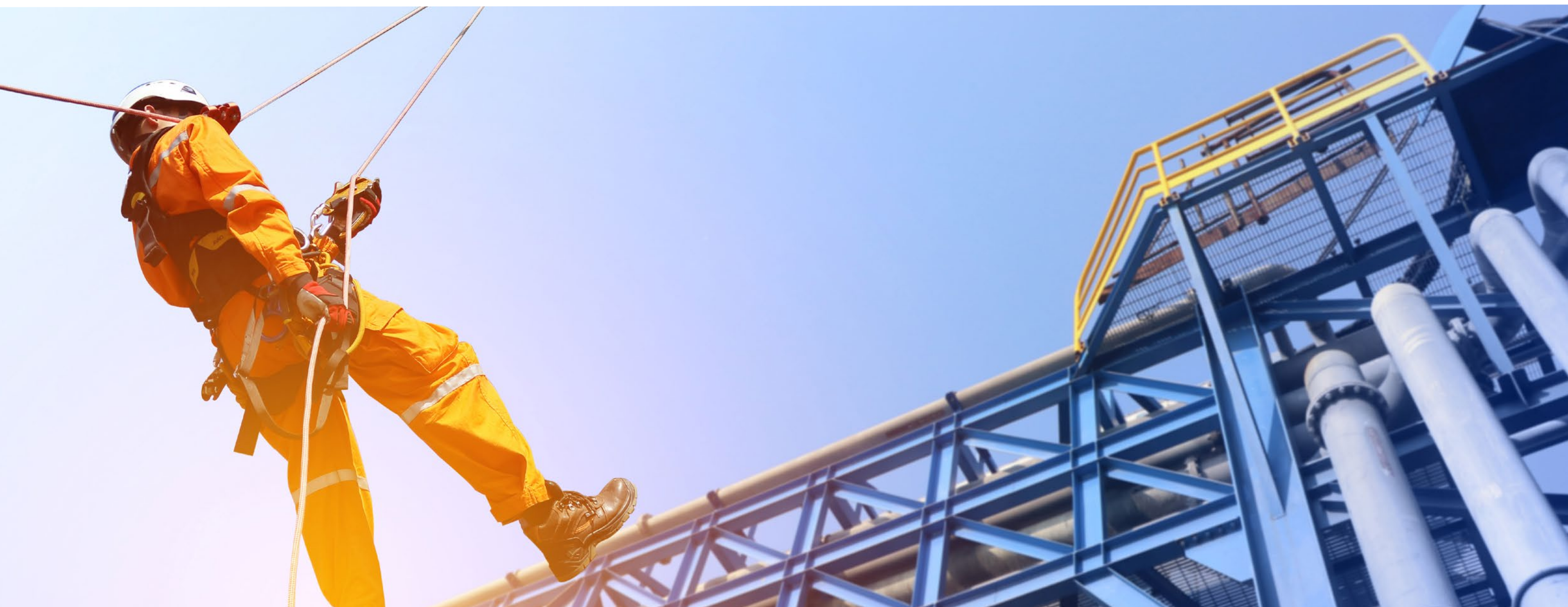
Facilitate flexible markets:

- Encourage market operators (like power exchanges) to allow for trading close to real time.
- System operators need to allow for last minute changes in planning and scheduling of power plants, so market participants can do changes until the last minute.

Flexible generation:
power plants that can ramp up and down quickly and efficiently and run at low output levels (mainly gas turbines have this attributes), including upgrading of conventional power plants and retrofitting to allow for higher ramp rates and lower minimum generation.

Flexible transmission:
transmission networks with limited bottlenecks and sufficient capacity to access a broad range of balancing resources, including sharing between neighboring power systems, and with smart network technologies that better optimize transmission usage.

Flexible demand-side resources:
incorporation of smart grids to enable demand response, storage, responsive distributed generation, and other means for customers to respond to market signals or direct load control.



1.1 System Size and Flexibility

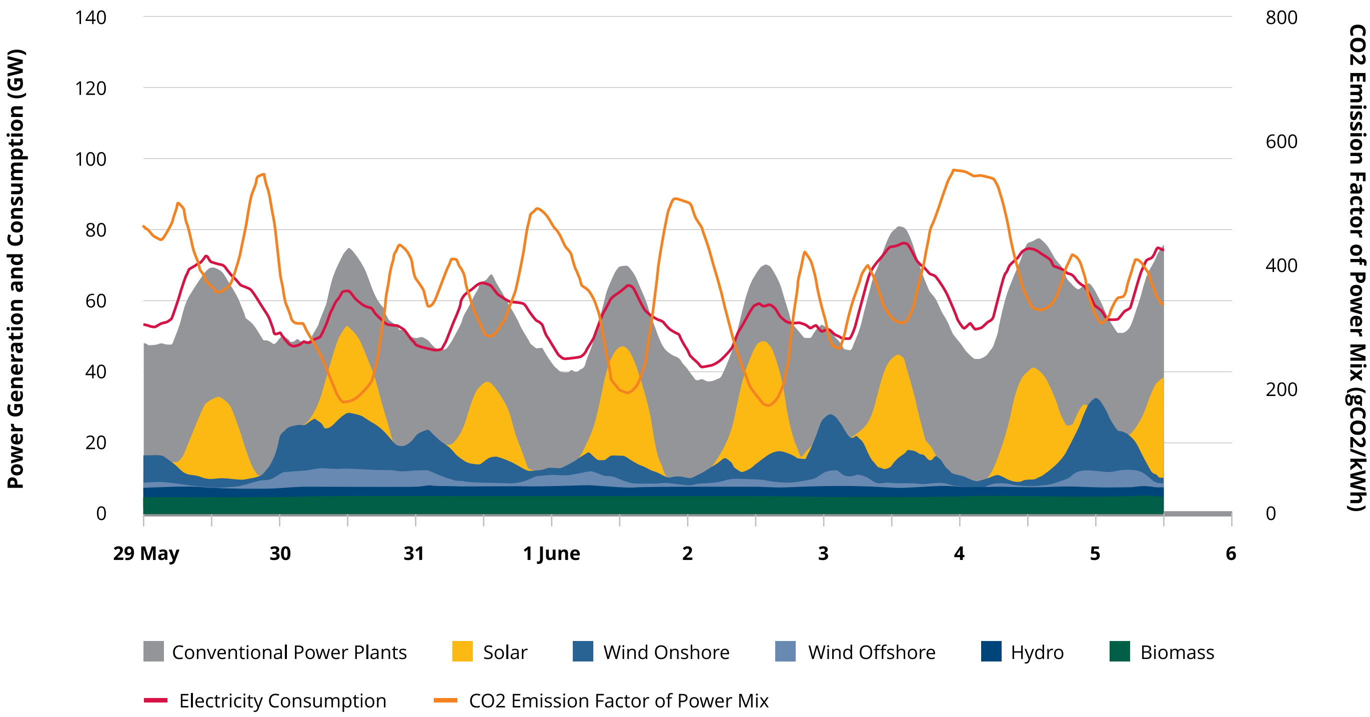
Increasing the size of the balancing area[1] usually reduces the need for flexibility. For example, switching on and off a large load (like a steel mill) in a small system can affect the balancing process quite severely. In a large power system like Germany (or Europe) the effects of even large loads are negligible. However, this requires a sufficient transmission grid.

The same principle applies for VG. E.g. the output of a single wind plant can vary a lot even in a short time. The total output of a cluster of wind plants is much smoother due to the homogenization of the weather in a larger area. Given there is enough transmission capacity available, it is very useful not to balance single VG plants but large clusters of plants together. The simultaneity factor or correlation of changes in output decreases with the distance of VG plants as the weather at distant places doesn't change at the same time in the same direction.

In addition to the inherent need for flexibility of VG described above, even more flexibility is needed due to forecast errors. Since a perfect forecast is impossible, the possibility remains that conventional generation needs to be adapted quickly as VG does not follow the forecasted schedule. Forecasting local weather is much more difficult than forecasting weather for a large area. Therefore, the relative forecast error decreases significantly with increasing size of the balancing area. Again, forecasting a large area reduces the needs for flexibility. Both the known forecasted variations as well as the unpredictable forecast errors drop with an increasing size of the balancing area.

About 15 years ago, the four German TSOs agreed to balance VG together in one large area which significantly reduced the need for flexibility. In addition, the German TSOs, together with the neighboring countries, cooperate in usage of reserves

Figure 2: Load and Generation for one week in Germany (example). The difference between total generation and load is covered by electricity import or export.



Source: Agora Energiewende, https://www.agora-energiewende.de/en/

[1] A balancing area is a geographic boundary within which electricity supply and demand is balanced by the TSO. Therefore, the TSO measures all in- and outgoing power flows and compares them with the scheduled flows. In case of mismatch, the TSO activates positive or negative reserves power to reduce mismatches to zero.

which virtually increased the balancing area. Chapter 2 will give more information on this.

As an example, figure 2 shows generation, load and exchange to neighboring countries for a week with high VG share in Germany. One can see that the renewable generation varies quite a lot during one day, so the conventional generation needs to be flexible to compensate this. However, the graph also shows that there is no step or very steep ramp in VG. This is because it shows the total output of Germany as a whole, an area of about 700 km x 1000 km. This result is quite logical as VG is weather-dependent and the weather does not change rapidly in a large area.

Spotlight 2: Variable Generation for Enabling Flexibility

It is possible to provide flexibility by VG. Technically, VG can ramp very quickly (within a few seconds) between zero and the power of the primary source (wind or solar irradiation). Therefore VG could provide flexibility but only when it is somehow curtailed and running below the possible output. For economic reasons, curtailment of renewables should be avoided wherever possible, as this is a waste of energy. However, to ensure reliable grid operation, it may sometimes be necessary. It is conceivable that in extreme situations the ramp rate of VG needs to be limited if the flexibility of the grid is insufficient. The following example illustrates this. A wind plant is predicted to reduce power output quickly at a given point in time. The conventional fleet is not able to compensate for this fast enough. In this case the wind plant can be slowly curtailed ahead of time to give the conventional fleet enough time to ramp up. However, up to now there are no signs for such demand in Germany in the foreseeable future.

Spotlight 3: Grid control cooperation

In 2012, German TSOs started a close cooperation in the operation of reserves (s. chapter 3). Prior to this, every TSO had balanced its own balancing area using reserves. Quite often it happened that balancing was needed in opposite directions at the same time. E.g. one TSO's balancing area was short causing the TSO to activate positive reserves while the neighboring TSO needed to activate negative reserves because of a surplus of power at the same time. Since the start of the cooperation, TSOs have been checking with their neighbors before activating reserves and, if possible, exchanging energy before activating reserves. This operation reduced the average number of reserve calls. As the need for reserve capacity is derived from the average and maximum use of reserves, the needed (and purchased) reserve capacity also decreased. In the last years, the cooperation was expanded to the neighboring countries, which amplified the effect even more.

1.2 Basic Principles of the German Electricity Market

In an electric power supply system, load and generation must be in balance at every second. So, any load change must be compensated by the generation. As load is changing all the time, generation also needs to be constantly adapted. In addition to the load, VG is changing with variations in wind speed and solar irradiation challenging the balancing process even more. Only gas turbines and hydro storage plants can be operated in a very flexible way with short planning time. Large conventional power plants have a limited flexibility. Therefore, it is important to plan their operation ahead of time (at least several hours up to a day). An optimal system operation therefore requires accurate forecasting of both load and VG. Further flexibility reserves are necessary to account for forecasting errors or unpredictable events (such as power plant outages).

Balancing load and generation is one of the essential tasks of transmission system operators (TSOs). In Germany, parts of this task are transferred towards the market participants (see Spotlight 3 "self-balancing and self-scheduling" below). This chapter will introduce the basic principles of the electricity market. More details will be given in chapter 2. Any real time balancing of unforeseeable events (e.g. power plant outages) is done via reserves. Therefore, an additional reserve market is established which is described in chapter 3.

- Principle of balancing: Balancing, which refers to the process through which TSOs or load dispatch centers manage the physical equilibrium between injections (generation) and withdrawals (consumption) on the grid, lies at the core of system operation. This principle serves as a basis for all mechanisms described below. In a first step load, VG and other non-dispatchable renewables are forecasted. The remaining energy needs to be covered by conventional generation. The dispatchable generation (mainly conventional generation) is scheduled to follow the given load and generation. To give enough time for good planning, most balancing is done by day-ahead scheduling of power plants on the day-ahead market. As forecasting gets better with shorter forecast horizon[2], updated forecasts are used for fine-tuning the balancing on the intraday market when getting closer to the time of delivery. In this case, the planning is revised, and new schedules are generated and processed. Due to the highly automated scheduling system in Germany this is possible up to a few minutes before delivery time now. However, even with the best forecasting, unexpected imbalances can occur in the system and need to be balanced in real time. For that purpose, the TSOs, who are responsible for resolving remaining imbalances, use reserve power which is the most flexible but also most expensive generation in the system.
- Energy only market and capacity market: To understand the study, it is useful to know the principles of the reimbursement scheme in the Germany electricity market. The day-ahead and intraday markets are energy only markets, which means that power plant operators get reimbursed for the delivered energy only. Cost of ramping or starting and stopping, as well as the investment need to be included in the energy price. The reserve market has two components, a capacity price and an energy price. The capacity price is paid for being available, the energy price is paid when the reserve is called, and energy is delivered. This will be further explained in chapter 3.

In the late 1990s, when liberalization of the energy sector started and the energy market was established, the market rules didn't allow for flexibility in power plant operation. A schedule once given on the day ahead could not be changed anymore. Step by step, the market and scheduling rules were adapted to allow for more flexibility. Nowadays, changes are possible until the last minute.

This and the principle of self-balancing and self-scheduling are main enablers why all the flexibility the German power system provides can actually be used. More details are given in chapter 2.

[2] Forecast horizon is the time the forecast looks into the future.

Spotlight 4: Self-balancing and self-scheduling

The principle of balancing applies to every electric power system. In liberalized market, like in Germany, the process of balancing is split into many subtasks carried out by different players. The German power system follows the principle of self-balancing and self-dispatch. Each consumer does its own load forecasting and finds a generator on the market that provides the energy. Small consumers like residential or small commercial customers are pooled by aggregators like municipalities or local utilities. All generators and consumers provide all energy transactions between themselves via so called nominations to the TSO. This includes all energy delivery relations between the market participants but no information about the price. The TSO checks if all nominated positions between the partners match and if they are balanced in itself. If not, the TSO requests a corrected schedule. Once a correct version of schedules is submitted, the schedule can then be adapted. Of course, any changes need to be agreed by both market participants, load and generation.

Market participants that deviate from their nominal position cause an imbalance to the market. This happens for example in case of wrong load forecast, power plant outages or wrong VG forecasts. In this case the TSO uses reserve energy to balance the system. The cost for this is reimbursed via imbalance charges/penalties which are levied on market parties who deviate from their nominated position.

Self-dispatch is a scheduling and dispatch arrangement where independent power producers (IPP) determine a desired dispatch position for themselves based on their own economic criteria to provide commercial independence within a market. E.g. an IPP that operates several units can choose which units to use at which point in time. This ensures that the optimal economic and most flexible operation of the power plant park is guaranteed. In other markets around the globe, the TSOs decide which actual units are used. This gives the TSO more control over the system but reduces the level of flexibility. The TSO does not know all the parameters of a power plant and might, for example, dispatch a flexible plant for base generation or vice versa. The power plant operator knows about the internals of his generation fleet and can choose the optimal usage. However, in the case of emergency the German TSOs have access to all power plant units directly. Hence, under normal operation the economic optimum is chosen by the plant operator but TSOs can take over when system security is endangered.

Dispatching of VG works a little different. Although VG is acting at the market like every other generator due to the low marginal price (close to zero) the VG operators are always able to sell all of the generated power. Therefore, VG is always “dispatched” as forecasted based on the primary source wind or sun. If new forecast requires and updated schedule VG operators can trade with other IPPs to fulfil their position and not causing imbalances.

1.3 Indirect and Direct Incentives for Flexible Power Plants

Despite a lack of direct incentives for increasing power plant flexibility (direct incentives have only been in place for biogas plants), the German electricity system is quite flexible. This is because of the installed power plant fleet in combination with the market rules and design. Regarding the power plant fleet, a mixture of many different primary sources including a large portion of gas turbines are installed in Germany. Gas turbines in particular provide a high degree of flexibility by nature.

The following incentives have been in place which have triggered investment and utilization of flexible plants and therefore increased overall flexibility of the power plant fleet.

- Incentives to reduce CO_2 emissions not only drive the installation of renewable but also gas turbines as they cause relatively low CO_2 emissions. As a side effect this increases the flexibility as gas turbines can operate in a flexible way.
- The German energy system is in the phase of a transition to a carbon-free system, as demanded by politics and society. As the path to get there is not yet clear, many uncertainties remain. This is why power plant operators prefer to invest in small to medium-sized plants, and not in large, long-term investments such as coal-fired power plants. Gas turbine plants are more in line with this preference as investment costs are lower, permits are easier to obtain, they are easier and quicker to build and promise an earlier return on investment.
- Because of balancing of VG, the German power market often asks for energy on a short notice or for a short period of time. So, starting and stopping or ramping of power plants is needed relatively often. As mentioned above the German energy market is an energy only market which means that power plant operators don't get reimbursed for ramping or starting and stopping. Only the delivered energy is paid. To operate under these market conditions, a flexible power plant is needed. This is an indirect incentive for flexible power plants. However, there is no direct payment for flexibility. In this way, a lot of flexible gas turbines have been installed as they fulfill the requirements the best. In addition, all kind of storage plants such as batteries and pumped hydro storage can profit from this as they can ramp up very quickly and be recharged at times of low energy prices.
- The decommissioning of inflexible plants creates space for other, more flexible generation. Nuclear and coal-fired power plants have been and will be decommissioned as a consequence of decisions by the Federal Government. The reasons for this are nuclear safety and CO_2 emissions in the case of coal. It can be expected that the plants will mainly be replaced by renewables and flexible generators, such as gas turbines.
- Since 2017, direct incentives are given to upgrading existing biogas plants in terms of flexibility by installing a gas storage and a larger generator. The idea is to further develop the technology and, in the long run, to create a renewable flexible fleet. So far, the flexibility provided by upgraded biogas plant does not play a significant role in the electricity system as their total power is just too small.

For the reasons given above, Germany has sufficient flexible production even without many direct incentives to build flexibility. Although coal power plants provide flexibility up to their abilities, most of the flexibility is provided by existing or new gas turbines. So far, no upgrade of existing power plants (e.g. coal power plants) was needed from a system perspective. It is very unlikely that this will change in the future even with an increasing share of VG. Nevertheless, some coal power plants have been upgraded towards lower minimum load, higher ramp rates and higher efficiency. Whether and to what extent these upgrading measures are profitable, varies on a case-by-case basis in relation to plant characteristics such as age of the plant or repairs and replacement of components that are due anyway.

The challenge, however, was to exploit full flexibility in a liberalized market. Market rules and operations were therefore adapted to enable last minute changes in plant operation. This is described in detail in chapter 2.

Spotlight 5: Germany's Power System

The share of renewables within the German generation mix is constantly increasing. The following table lists the main sources for electricity in 2018. In the first half of 2019 the share of renewables was even higher and reached 44 % due to further installations of VG and very windy weather in spring.

Plant type	Share of generation in 2019
Coal (hard coal + lignite)	35 %
Renewables	35 %
Gas turbines (open + combined cycle)	13 %
Nuclear	12 %
Others	5 %

In terms of flexibility, power plants have quite different characteristics. Gas plants are the most flexible ones while lignite is most difficult to cycle. The following table gives an overview of the technologies used the most in Germany. Nuclear is not listed here as nuclear power plants are operated on full power only in Germany.

Parameter description		Power plant type			
		Hard Coral	Lignite	Combined cycle gas turbine	Open cycle gas turbine
gradient	$\%P_N$[1]/min	1,5 / 4	1 - 2,5	2 - 4	8 - 12
at load range of	$\%P_N$	40 - 90	50 - 90	40 - 90	40 - 90
minimum load	$\%P_N$	25 - 40	50 - 60	40 - 50	40 - 50
start-up time					
hot-start	h	3	4 - 6	1 - 1.5[2]	< 0.1
cold-start	h	5 - 10	8 - 10	3 - 4[2]	< 0.1
minimum stand still time	h	2 - 4	6	1 - 2[2]	0
minimum operation time	h	3 - 16	3 - 24	1 - 8[2]	0

[1] P_N = rated power of a power plant
[2] Gas turbines, as part of a combined cycle plant, can be operated as quickly as single cycle turbines. Parameters listed here describe the steam cycle.

2 Planned balancing

Based on the principles described above, this chapter discusses planned balancing in more detail and how the day-ahead and – especially – the intraday market contribute to enabling flexibility. The second part of the chapter describes the role of a power exchange in the balancing process and how the exchange can simplify trading and increase liquidity.

2.1 Day-ahead and intraday market

As described above, Germany's electricity market follows the principle of self-balancing, i.e., every load is responsible for forecasting and finding one or several trading partners that can meet its needs. Therefore, different strategies, from long term procurement until last minute balancing, are used.

A large portion of the energy is traded a long time ahead (months or even longer) based on long term (statistical) forecasts or rough estimations. This ensures price certainty for both generators and consumers. The exact load and VG forecasting, however, is done day ahead. These forecasts are used to trade at the day ahead market and balance as accurately as possible.

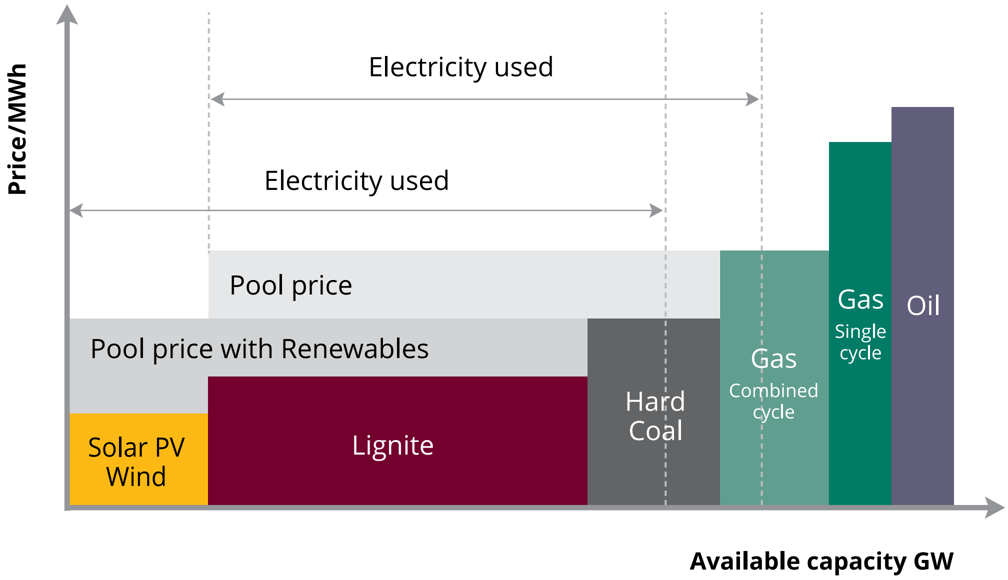


Figure 3: Merit order

While conventional generation is generally dispatched according to demand, VG usually sells all available energy. Due to its low marginal costs[3], VG offers energy for a price close to zero and is therefore the cheapest energy source on the merit order[4]. Hence, VG is always sold. Figure 3 shows the merit order list for different power plant types starting on the left side with the lowest marginal price. When more VG is generated (in green color), this shifts all other generators to the right resulting in a lower pool price. Therefore, even the dispatch of conventional generators is highly influenced by VG, and the VG needs to be forecasted as accurately

[3] "Marginal cost" or "marginal price" describes the additional cost of a power plant for generating electricity without depreciation or fixed costs. So, it is mainly fuel and maintenance cost. As VG has no fuel cost and very little maintenance, the marginal price is close to zero.
[4] Merit order list shows the marginal cost of all power plants on the market in order from low to high. The market always chooses the power plants with the lowest costs first. The highest accepted bid sets the price for the whole pool. The merit order is the underlying principle of the German energy market.

as possible to ensure balancing at all times.

While long term contracts (months or years) are used for price risk mitigation, short-term markets have a direct impact on the physical balancing of demand and supply as power producers decide whether production takes place or not depending on their price signals. If prices are below their own production costs, power plants shut down or decrease their power output and buy energy on the market to fulfil the obligations towards their customers. This ensures an optimal economical operation. These low prices occur usually when the demand is low, e.g. during the night or on weekends. As VG has a very low generation cost, it is always on the market when available. Therefore, the prices are low during times of high wind and/or solar PV generation as well.

All energy exchanges between market participants need to be nominated towards the TSO in a schedule by each market participant. The TSO compares all schedules and accepts only matching schedules. In case of a mismatch the parties involved are obliged to send a correction. If they fail to do so, the complete schedules of both participants are rejected.

When forecasts are updated during the day, intraday trading is used to adjust the generation to the new values. In this case, the parties involved need to send updated schedules to the TSO. As load forecasts don't vary much between day-ahead and intraday it is mainly the forecast of VG that needs to be updated due to changes in the primary sources wind and sun. The following example is for clarification:

Spotlight 6: Day ahead and intraday trading explained

On the day ahead, a wind plant is forecasted to generate 80 MW between 2:00 and 3:00 pm. The plant operator (here named A) sells 80 MW in the day-ahead market to a load (named B) and both send corresponding schedules to the TSO. In the morning at 8 a.m. of the next day (day of delivery) a new forecast predicts 95 MW for the time between 2:00 and 3:00 pm, so the wind plant operator (A) sells another 15 MW in the intraday market to a gas turbine operator (C). Afterwards A and C send an updated schedule to the TSO. At 1 p.m., a new forecast expects only 90 MW so A buys 5 MW from another power plant (D) and again A and D send schedules to the TSO. The tables on the following page show fictive schedules of all four market participants. Market participant X stands for any other trades. Also, generation and consumption are listed in a schedule as a schedule needs to be balanced in itself.

With the day-ahead and the intraday market the market participants are able to almost completely balance their portfolio. Only unforeseen load deviations, VG forecast errors or generation losses (e.g. power plant outages) cannot be balanced with these tools. These are then balanced by the TSOs using reserves as described in chapter 3. The prices the TSO charges to the participant for this service is much higher than the price on the day-ahead or intraday market. That gives a strong incentive for accurate self-balancing. However, always finding a trading partner might be difficult. This is in particular the case for last minute trades. Hence, the power exchange can solve this problem as described in the next chapter.

Spotlight 6 (continued): Day ahead and intraday trading explained

Schedules of wind plant A

	Time	Genaration	Delivery to B	Delivery to C	Receiving from D
Day ahead schedule	2 pm - 3pm	80 MW	80 MW		
8 a.m. update	2 pm - 3pm	95 MW	80 MW	15 MW	
1 p.m. update	2 pm - 3pm	90 MW	80 MW	15 MW	5 MW

Schedules of load B

	Time	Consumption	Receiving from A	Receiving from X
Day ahead schedule	2 pm - 3pm	220 MW	80 MW	140 MW

No updated schedules

Schedules of C

	Time	Genaration	Delivery to X	Receiving from A
Day ahead (no trading with A)	2 pm - 3pm	200 MW	200 MW	
8 a.m. update (include trade with A)	2 pm - 3pm	185 MW	200 MW	15 MW

No further updates

Schedules of D

	Time	Genaration	Delivery to X	Delivery to A
Day ahead (no trading with A)	2 pm - 3pm	290 MW	290 MW	
1 p.m. update (include trade with A)	2 pm - 3pm	295 MW	290 MW	5 MW

2.2 Simplifying the Trading Process with a Power Exchange

Nevertheless, bilateral trading between generators and load (as described above) requires several prerequisites such as knowledge of and trust in your customers or suppliers, time and ability to negotiate prices, and access to several customers for selling your whole generation portfolio or supplying all your consumption, amongst others. This poses a challenge to many participants on the electricity market, especially for new and small participants. However, to ensure a large number of market participants, which guarantees competition, liquidity and hence flexibility on the market, a power exchange was established.

A well-working power exchange acts as a central agency that simplifies all the points above. It takes care of the price finding, the security of payments and provides enough liquidity to fulfil all needs. All participants simply need to send in their bids and offers before gate closure. The matching is done by the power exchange, which then acts as trading partner to all participants. Offers and bids sent to the exchange are mandatory once they get accepted by the matching algorithm.

The trading volume shows that the power exchange fulfills the expectations just described and is well accepted by the market. The net electricity consumption in Germany in 2018 reached 512 TWh. In total, around half of the physically delivered energy was traded via the power exchange. The exchange is also very important for trading of VG. About 150 TWh of trading volume came from trading renewable generation on the exchange which is about 2/3 of the renewable generation.

On the spot market of the power exchange, trades are done on the day-ahead and on the intraday market similar to the bilateral trade (s. chapter 2.1). The day-ahead auction ends at 12:00 p.m. (noon) and power for the following day (hours 0-24) can be traded in form of single hour or block bids.

In addition to this, it is possible to continuously trade in a separate market platform, the so-called intra-day market platform. This platform opens some hours after clearing of the day-ahead market in the late afternoon and stays open until the end of the following day. Especially for small market participants this platform opens the possibility to trade until the last minute without the time consuming prerequisites listed above. Single hours and 15-min blocks can be traded continuously during the day, depending on the area affected:

- Within the area of one TSO in Germany: up to 5 min before delivery.
- Between German TSO areas: up to 30 min before delivery.
- Between European countries: up to 60 min before delivery.

Of course, trading up to 5 min before delivery is the best in terms of flexibility. However, as trading between balancing areas requires the coordination of the both TSOs involved, which takes more time, trading on the platform is only possible until 30 min before delivery. Even more coordination is necessary to deliver energy between countries, so cross border trading is only possible up to 60 min before delivery.

When the intraday trading platform first opened 9 years ago, the daily traded volume reached less than a thousandth of the energy consumption. By now the volume on the intraday market reaches about 15% of the day ahead trading volume and is still rising. Not all of this is traded “last minute”, but it gives in indication that there is a growing need for flexible generation.

3 Real time balancing

In Germany, balancing is mainly done on the energy only market by the market participants (generation, load, traders). However, unexpected or unpredictable load and generation are physically balanced by the control reserve of the TSO. These are for example remaining forecasting errors for VG production and load, which could not be balanced on the intraday market, power plant outages or unexpected unavailability. Accountability for not complying with production and consumption schedules is enforced by the imbalance pricing mechanism.

In some systems the reserve is made up of spinning as well as non-spinning reserves. Spinning reserves are generators that are synchronous to the grid, non-spinning reserves are not currently connected to the grid but can be synchronized quickly if needed. In Germany (and Europe) reserves are qualified based on their capability to ramp up and down but not on the technology or by spinning/non-spinning. The classification (described as qualities in the following) is primary, secondary and tertiary reserves. Reserves are the most flexible generation as some of them can change output power within seconds. Chapter 3.4 gives an overview of the sources of reserves such as power plants or flexible loads. Finally, chapter 3.5 describes how the reserve market works and how reserves are purchased by the TSO. It also describes the incentives for a flexible generator to participate in the reserve market and not in the energy market.

In the following, three different types of reserves as used in Germany are described in detail. Their main difference lies in the ramp up or activation time. Figure 4 shows how reserves are used in the event of a power plant failure. The red line shows the frequency drop at the beginning, which is stabilized by the automatic activation of a primary control reserve (the fastest reserve type). Shortly after, a secondary control reserve sets in (also automatically activated) and brings the frequency back to normal. A tertiary control reserve is then activated to free up part of the secondary control reserve to be prepared for a possible next event. Tertiary reserve is the slowest of the three reserve types and is activated manually by the control room staff. Please note that the graph just shows the principles. A graph for a real event would look different in detail.

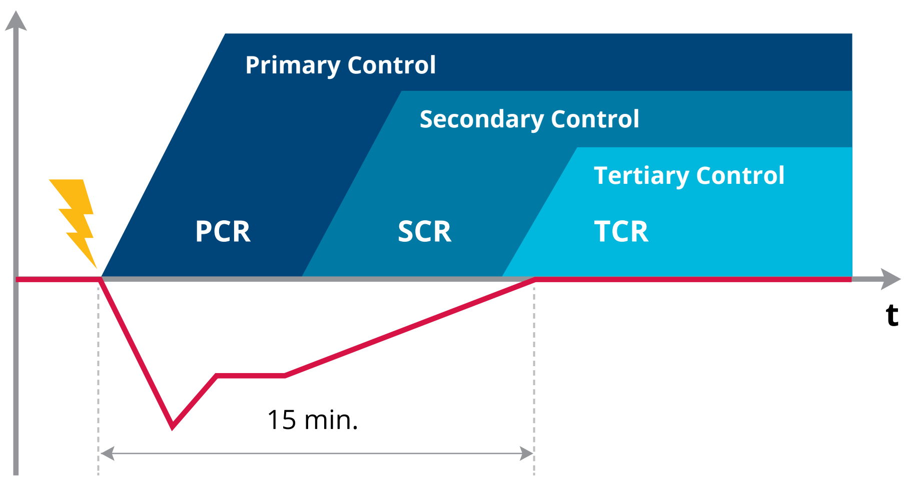


Figure 4: Use of reserves in Europe (Source: Andreas Walczuch, Amprion GmbH)

Table 1 gives an overview of the different reserves in Germany, their parameters, purpose and price components. As imbalances can occur in both directions, surplus and lack of energy, reserves are available in both directions, positive and negative. In the following sections mainly positive reserves are described as this is sufficient for understanding.

Table 1: Requirements of the different types of control reserves in Germany

	Primary control reserve	Secondary control reserve	Tertiary control reserve
Purpose	Stabilize grid frequency after a disturbance	Balance balancing areas, bring grid frequency back to nominal value, replace primary control	Complement and replace secondary control
Time until complete activation	30 sec.	5 min.	15 min.
Reaction time	5 sec.	30 sec until first change of power for pooled reserve providers[5]	15 min.
Activation	Local, triggered by the frequency	Immediately by the TSO via set points	Manually
Price components (see chapter 3.5)	Capacity	Capacity and energy	Capacity and energy

3.1 Primary Control Reserve

In Europe, the grid frequency is 50 Hz in all synchronous zones[6]. Germany is part of the central European synchronous zone which is the largest in Europe. The primary control reserves react on frequency deviations in both positive and negative directions to keep the frequency deviation in a limited range. Generators (or loads) deviate from their normal operation point in case of frequency deviation within a short time. This is used for example to compensate for a sudden loss in power generation in case of a power plant outage. The total primary control reserve in central Europe is 3000 MW as this is the necessary amount to cover the failure of the two biggest generation units in central Europe.

The reserve is distributed as evenly as possible over the participating countries. The respective shares are defined for one calendar year based on the share of the energy generated within one year in relation to the entire synchronous zone. The sum of all shares must amount to the total primary control reserves. Germany needs to provide about 700 MW.

The primary control power must be delivered until the power deviation is completely offset by the secondary control reserve of the balancing area in which the power deviation has occurred (the minimum duration for the capability of delivery for primary control is 15 minutes). The time for starting the action of primary control is a few seconds starting from the incident. To qualify as a primary reserve, the generating unit must be able to, amongst other things, deploy its reserve power within 30 seconds.

The primary reserves are activated automatically by the facilities of the grid users which provide this service. The primary reserve's function is to avoid inadmissible frequency deviations. For this purpose, disturbances of the load balancing especially due to breakdowns of big power units must be compensated within several seconds.

[5] Pools providing secondary control reserve have to show a first reaction to the secondary control activation signal of the TSO within 30 seconds, at the latest.
[6] A synchronous zone describes an interconnected electricity system where all generators are synchronized.

3.2 Secondary Control Reserve

In case of frequency deviations, all balancing areas contribute to the control process in the synchronous zone. For example, a power plant failure in one balancing area will cause an un-scheduled power flow from other balancing areas into the affected one.

Secondary control[7] has two functions:

1. Keep or restore the system frequency to its set-point value of 50 Hz and, consequently, ensure that primary reserves are not needed for that event anymore and are available for a possible next event.
2. Restore the power balance in each balancing area and bring the power interchanges with adjacent balancing areas back to their programmed scheduled values.

All balancing areas provide mutual support by the supply of primary control power during the primary control process, but only the balancing area affected by a power imbalance is required to undertake secondary control action for the correction. Consequently, only the controller of the balancing area, in which the imbalance between generation and consumption has occurred, will activate the corresponding secondary control power within its balancing area.

Thanks to the primary frequency action, the frequency stabilizes at a value different from its target value. Therefore, the secondary control must not only restore frequency but also bring interchanges back to their target value.

Secondary control must begin within 30 seconds of the disturbance concerned. When the scheduled exchange between balancing areas and adjoining areas is modified, the set point value of the interchange will be adjusted. If the loss of the largest generating unit supplying the area concerned is not covered by the secondary reserves of that area, provision must be made for an additional reserve which will offset the loss of capacity within the requisite time. Each TSO is responsible for the maintenance of secondary control in its own balancing area.

3.3 Tertiary Reserves

As imbalances occur, system operators need to decide what is responsible and for how long it is expected to last. The assessment of the situation is mainly based on the experience of the control room staff. In the case of power plant failures, it is very clear that the deviation will last for a longer time, so the activation of tertiary reserves[8] is mandatory. In other cases, for example the change of schedules at the full hour, the imbalances will only last for several minutes. In these cases, the control room staff will decide not to activate tertiary reserves.

The call for tertiary reserves frees up secondary reserves for the next event. The procurement process for tertiary reserves is quite similar to the one for secondary reserves. The tertiary reserves have lower requirements than the secondary reserves. The main difference is the time to be fully activated, which is 15 minutes.

3.4 Sources of reserves

Reserve capacity is mostly provided by the supply-side of a power system. Recently, however, the demand-side has succeeded in providing reserves as well using controllable loads. On the supply-side, thermal and hydro power plants have been dominant. When they are online, gas, coal, lignite and nuclear plants can provide all three reserve types described in this section.

The following example illustrates this. A coal plant with a rated power of 600 MW and a minimum power

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[7] The secondary reserve is also known as automatic Frequency Restoration Reserve (aFRR) as it brings the frequency back to 50 Hz.
[8] The tertiary reserve is also known as manual Frequency Restoration Reserve (mFRR).

of 300 MW runs on 550 MW and provides ±50 MW of reserve power. When the TSO calls for 50 MW of positive reserve it increases its output to 600 MW. When the TSO calls for negative reserve it reduces to 500 MW. As the example shows, a power plant can participate in the energy market and provide additional reserves. However, the power plant could not provide negative reserves for an operation with 300 MW, as this is already the minimum capacity of the plant. Participation in the energy market and the provision of reserves therefore requires good planning and scheduling of the plant.

An important factor influencing the type and amount of reserve a plant can offer is the so-called ramp rate, i.e. percentage of capacity that a generator can ramp up and/or down per minute. The only type of thermal power plants that can provide tertiary power reserves in offline operation are gas turbines due to their short start-up times. Other thermal power plants require more than 15 minutes to start. In the case of hydropower plants, their ability to provide reserves also depends on the type of plant. Due to their limited ability to hold back water, run-of-river plants can only serve as primary reserves. As they can start up very quickly and have high ramp rates, storage and pumped-storage hydro power plants can provide any type of reserve capacity. However, most pumps can only be operated at full speed, which makes pumped-storage plants inflexible in pumping mode. However, this can be overcome by using part of the pumped water at the turbine.

In the medium term, renewable energy resources are also expected to contribute to providing reserves, as the nature of wind turbines, PV inverters and biomass allow very high ramp rates. In contrast to conventional sources, the most important renewable energy sources, sun and wind, are not constantly available, but depend on the weather. There are also controllable renewable energy sources such as bioenergy. According to the rules, renewables could already offer all three types of reserves. However, as prices at the reserve market are quite low at the moment, it does not make economic sense to do so.

Spotlight 7: Controllable loads

In Germany, immediately and quickly interruptible loads like aluminum smelters or electrolyzers participate in the reserves market. In this context, interruptible loads are large consumption units which consume a large volume of electricity more or less continuously and can reduce or interrupt their consumption on short notice for a certain period of time. By reducing their load, they can provide positive reserves. Like other reserves, they receive a capacity price for staying available and an energy price if they are called. The market mechanism is described below.

So far only large (industrial) loads are used as source of flexibility. One of the reasons for this is the lack of smart meters in Germany which makes it hard to pool and control a large number of distributed devices. Another reason is that more flexibility provided by loads is just not needed yet.

3.5 Reserve market

At the reserve market, the TSOs are the only buyers who also set the rules and facilitate the market. To guarantee a non-discriminatory and transparent process, the rules are supervised by the German regulator Bundesnetzagentur (Federal Network Agency). The TSOs in Germany run a common internet platform for the tendering of reserves on a daily basis. The tendering procedure for reserves is pay-as-bid, i.e., each supplier receives the price he offers.

Potential providers of reserves must first pre-qualify at one of the four TSOs to demonstrate that they can meet the technical requirements for providing one or more types of reserves. Once prequalified, the market participants can send in their bits into the TSO's tendering procedure. When selected in the tender, the providers must stay available with their capacity but must not generate electricity until the TSO calls for it.

The following sections describe the market for the different types of reserves followed by the development of the market rules and its influence on the market participation. As described in chapters 1 and 2, the increasing system size leads to a smaller need for flexibility and the efficient self-balancing leads to lower usage of reserves. For these reasons, the TSO tender for less reserves as described in spotlight 8.

Purchase of primary reserves

Primary reserves are tendered on a weekly basis. It only has a capacity price component but no energy price. The energy delivery (in case of under-frequency) or energy absorption (in case of over-frequency) is based on frequency deviations. As the frequency deviation is zero in average, the energy delivery (or absorption) is also zero in average. Therefore, no energy component is needed.

When participating with a certain amount of capacity in the reserve market, the generator cannot use this capacity to generate energy for the energy market. This amount of capacity must not be used until the TSO calls for the reserve (see also example in chapter 3.3). The idea of the capacity price is to pay for these losses and give an incentive to participate in the reserves market. The same applies for secondary and tertiary reserves.

Purchase of secondary and tertiary reserves

Unlike the pure energy-based day-ahead and intraday markets, the reserve market for secondary and tertiary reserves has two price components, a capacity price and an energy price. The capacity price is paid to keep the reserves available while the energy price is paid in case the reserve is actually called by the TSO. Capacity that successfully takes part in the reserve market is not allowed to take part in the energy market. For example, a 300 MW power plant offered 100 MW in the reserve market and got awarded. This plant can sell only 200 MW on the energy market and needs to keep 100 MW available in case the TSO calls for the reserve.

Price finding for secondary and tertiary reserves is based on a combination of capacity and energy price so each market participant's bid contains two prices, a capacity price (€/MW) and an energy price (€/MWh). When the bid is accepted, the capacity price is paid as remuneration for being available. The energy price is paid when the reserve is actually called by the TSO. The cheapest capacity bids are selected first. However, the energy prices are also considered with a lower weight. This is done to avoid gambling as bids with extraordinary energy prices get refused not matter how low the capacity component is.

First the TSOs pay all dues to the reserve provider. The capacity price is remunerated by the network tariffs that all loads (from households to industry) connected to the grid need to pay. The energy price is charged to those market participants that cause the imbalances. That is also called the imbalance pricing mechanism.

The energy prices for reserves are usually much higher than the prices on the day-ahead or intraday market which gives the market participant a strong incentive to be balanced at all times using the energy market (especially the intraday market). That drives the demand for flexibility on the market.

Spotlight 8: History and Development of Reserve Markets in Germany

Regulation: When the reserve market started in Germany almost 20 years ago, rules and regulations where quite strict and designed for large power plants to participate as reserves were provided by these power plants before the liberalization. Also, a lot of processes in the tendering but also in operation were executed manually. Therefore, the tender period for primary and secondary reserves was set to six months. Only tertiary reserves were tendered daily. In addition, a minimum size of 30 MW of capacity per generation unit applied.

Over the years, processes got more and more automated. Today, the tendering period for a primary reserve is one week while secondary and tertiary reserves are tendered daily. This attracted more power plant operators to take part in the reserve market as they don't need to block their capacity for a longer time. Furthermore, the minimum size was reduced to 1 MW and pooling of smaller units is allowed in addition. Therefore, e.g. Diesel gensets used as backup in hospitals can be pooled together by an aggregator and offered as reserve to the TSO.

Since a few years VG can prequalify to offer reserves. However, because of the low prices at the reserve market VG, operators don't offer this service on the market right now.

All these measures increased the liquidity of the reserve market significantly. So, the amount of flexibility has grown even without incentives for upgrading of power plants in terms of flexibility.

Market Participants: In addition to conventional power plants, alternative suppliers like flexible loads have increasingly been marketing their services on the reserve market in recent years. In the past, the basis for this was created by adjustments to the reserve market products and in particular the approval of pooling as described above.

In total, the number of prequalified providers increased from 5 to 2119 for primary regulation, from 5 to 28 for secondary regulation and from 20 to 4220 for the tertiary reserve market between 2007 and 2014. Prequalified providers are all power plant operators, pool providers or operators of large loads who have concluded a valid framework agreement for the provision of balancing power with at least one transmission system operator and at the same time have prequalified power amounting to at least the minimum offer size. As reserve power is the most flexible form of generation, the increase in the number of suppliers shows that the amount of flexibility has also grown in this sector, even without direct incentives [1], [2].

Spotlight 9: Development of Reserve Capacities and Activation

Despite the increasing share of VG, the amount of reserve capacity purchased by the TSOs was reduced during the last years. There are mainly three reasons for this:

1. As shown in chapter 2, the intraday market got more flexible, especially close to real time. Therefore, load and VG could self-balance more precisely, so the TSO needed less reserves.

2. More VG doesn't necessarily need more reserves. VG distributed over a large area doesn't change very quickly, so balancing of VG can be done mostly on the energy market instead of by reserves.

3. German TSOs started a close cooperation in the operation of reserves in 2012 (s. spotlight 3).

Spotlight 9 (continued): Development of Reserve Capacities and Activation

As mentioned before, a primary reserve capacity of ±3000 MW is required in the central European synchronous area and did not change over the years. In contrast, the amount of secondary and tertiary reserves changed as it is determined on the actual calls of reserve by the TSOs. When less reserves are needed because market participants are able to balance their position more precisely (e.g. via the intraday market) the TSOs purchase less reserves in the following year. As an example, Figure 5 shows the usage of secondary reserves. Figure 6 shows the purchase of secondary and tertiary reserves in the same time. Both are declining over the years. This trend continued, so recently, in October 2019, German TSO purchase about ±2800 MW of secondary (SCR) and tertiary reserves (TCR) in total.

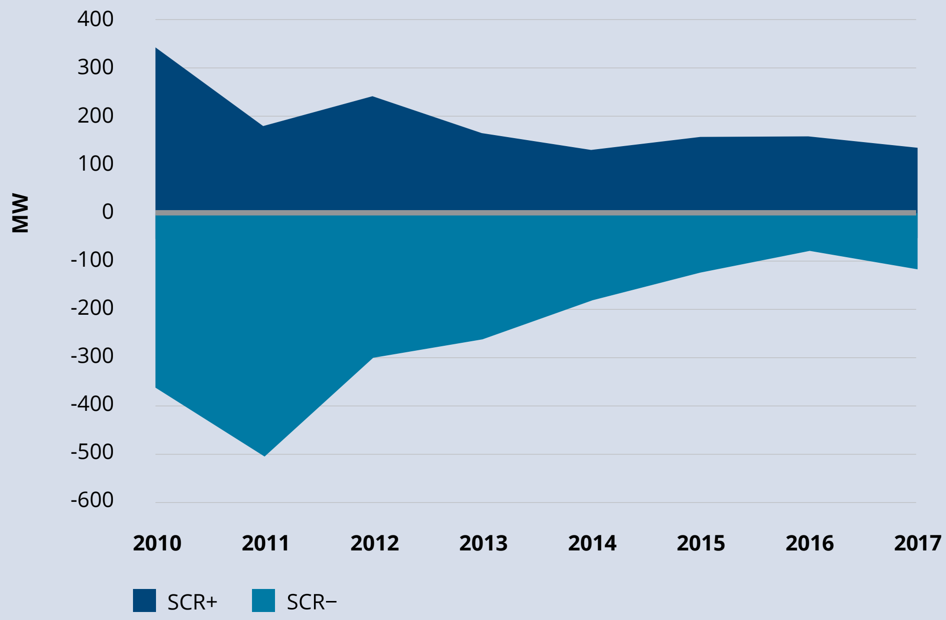

Figure 5: Decline in calls for positive and negative secondary control reserve (SCR+, SCR-)

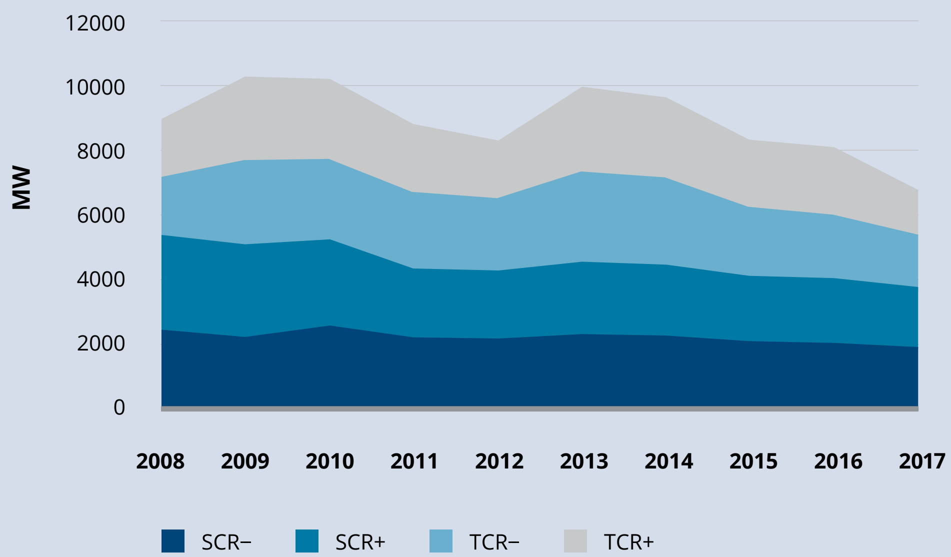

Figure 6: Tenders for secondary (SCR+, SCR-) and tertiary reserves (TCR+, TCR-) in the years 2008-2016

4 Business Models for Flexibility and Storage in Germany

Electricity generators in Germany must market their produced energy on the energy market. Therefore, two basic options exist: a) long-term and short-term bilateral trading with their customers or trading via the power exchange (s. chapter 2) and b) providing ancillary services on the reserve market to the TSOs (s. chapter 3). Generally, utilities will choose a combination of long-term and short-term transactions (including offering reserve markets) to reduce overall operational risks. In the following, three case studies present and discuss examples for marketing electricity along these two basic options.

Short-Term Market Operation for Gas and Lignite Power Plants

Due to their high activation speed, gas turbines offer very high flexibility for short-term and reserve markets and may benefit from (potentially more) advantageous prices in short-term trading. As an example, figure 7 shows the short-term prices on the power exchange for two days in October 2019. As shown, prices are strongly influenced by electricity consumption and generation from VG. The price peaks in the mornings and afternoons can be seen very clearly in the graph, which are caused in particular by the high demand for energy of the household sector. Although the demand around noon is even higher than in the morning and in the evening the generation by solar PV reduces the need for conventional generation and therefore the price (see merit order model, figure 3).

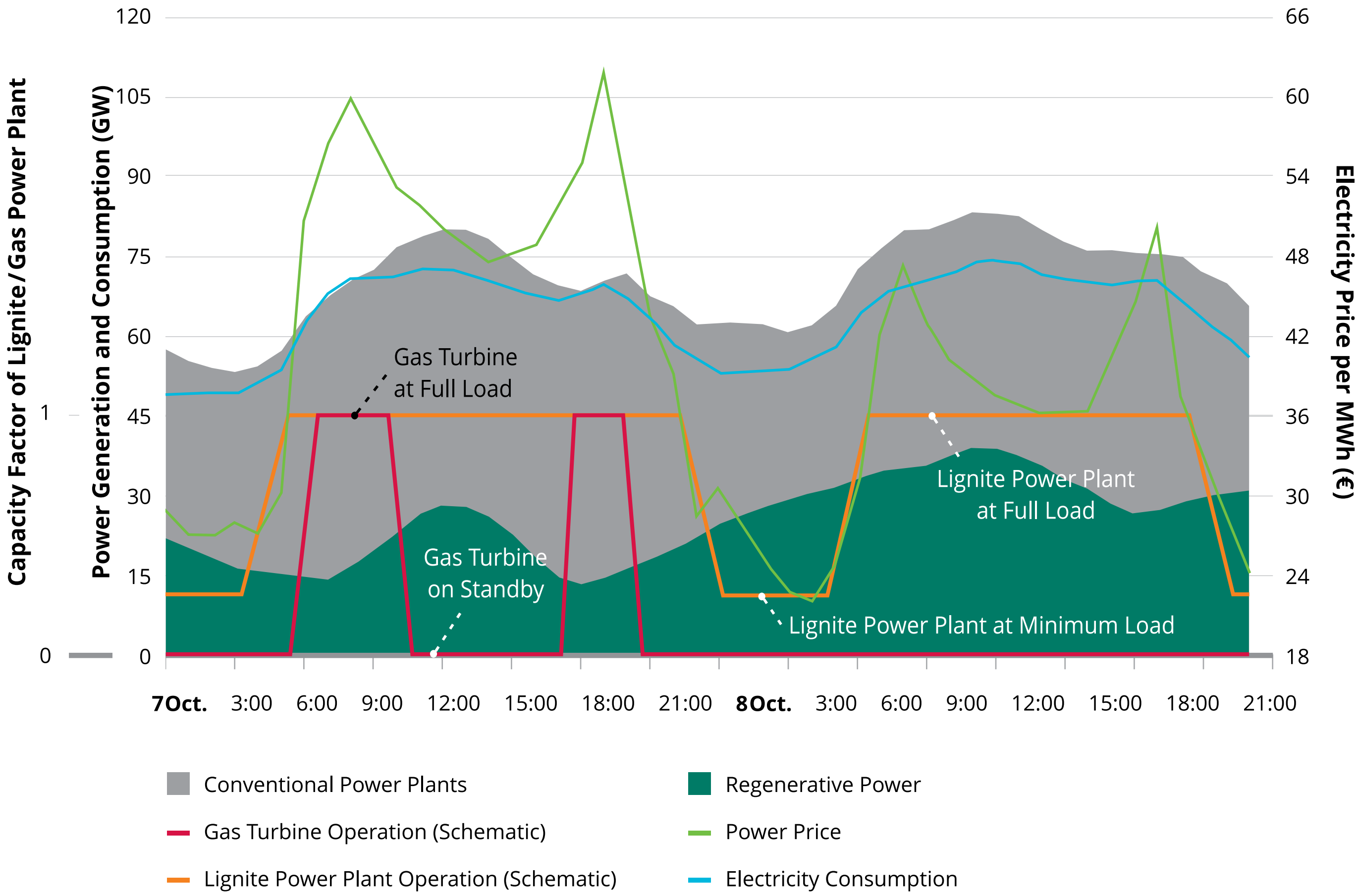

Figure 7: Gas turbine and lignite power plant spot trading (schematic) for spot market prices on October 7 and 8 (data from Agora Energiewende, https://www.agora-energiewende.de/en/)

A gas turbine operator (or any other electricity generator) looking at maximizing his revenue on short-term markets will, generally, always generate as long as the prices are above the plants marginal costs (i.e., the fuel and variable operating costs). As flexible power plants can always react on these price signals, even within a short time period, an incentive to invest in a flexible plant is given. In case of a (fictitious) example of a gas turbine with marginal costs of 54 EUR/MWh, and assuming that the plant would trade only short-term products (either bilaterally or on the power exchange), the gas turbine would only run between approx. 5am to 10.30am and again from around 5pm to 8.30pm on October 7 (figure 7). Between 10am and 6pm the gas turbine would simply be switched off.

Of course, the same applies to a less flexible generator, such as a lignite power plant. Also, a lignite power plant operating on a short-term market will try to operate as flexibly as possible. Nevertheless, this is much more difficult due to its technical restraints, especially due to the long start-up and stand-still time. In the above example, a lignite plant with marginal costs of 36 EUR/MWh would have to decide to switch-off or go into minimum load for 7 hours between 11pm on October 7 and 6am on October 8. However, assuming a minimum stand-still time of 6 hours and hot start time of 4 hours (s. spotlight 5; not taking into account the time for going into standby), the plant operator does not have enough time to go into standby during the low prices in the night, but will have to operate in minimum-load and sell generated electricity at less than the marginal costs. Nevertheless, this is still cheaper than switching off, which means not operating on the next day during high prices. Here, the market too provides an incentive for conventional producers to operate more flexibly – the shorter the start-up times, stand-still times, and the lower the minimum load, the more money an operator can make on short-term markets.

Reserve Market Operation for Gas Turbines

In addition to energy trading, the flexibility potential can also be used to offer reserves as described in chapter 3. The following example illustrates this. The owner of a gas turbine offers a tertiary reserve in one of the four German balancing areas. The gas turbine is pretty old, has high maintenances costs when it is running and has a low efficiency. That means that the marginal price is pretty high compared to other generation, e.g. 70 EUR/MWh. Assuming that figure 7 represented a standard price distribution throughout the year, such a gas turbine could not compete in the energy market and would be taken out of service although its flexibility could be used from time to time. Only in a situation with very high demand can the prices raise high enough to cover the marginal costs of such a turbine. This does not happen often enough to make a business case for such a plant.

However, in the reserve market this turbine could be profitable because of the two price components and the "pay-as-bid" principle. As described in chapter 3, the price components for secondary and tertiary reserves are a combination of a capacity price, covering fixed costs (e.g. regular maintenance, staff etc.) and an energy price (e.g. fuel and operation). Assuming that the gas turbine bids successfully on the secondary reserve market, its fixed costs could be covered by the capacity price component. If the gas turbine is requested to operate by the TSO, the energy price would cover its marginal costs and could guarantee economic operation.

With this scheme, even power plants that are not competitive on the energy market anymore can stay in operation and provide flexibility on the reserve market when needed. This increases the overall available flexibility. By providing reserve, the supplier reduces the risk of blackouts or increases grid stability and in return receives payments in the amount of the price the provided energy was offered.

Short-term Market Operation for Pumped Storage Power Plant

Here, a highly flexible pumped storage power plant with natural water inflow at the upper reservoir is considered, which is predestined for the provision of flexibility to both energy and reserve markets. For the long-term planning and trading the expected water inflow of the upper reservoir will be taken into account. However, it is important to take uncertainties such as in seasonal weather conditions into account, so the plant operator will not sell all expected energy via long term contracts. Furthermore, the pumped-storage plant would market its flexibility on the day-ahead, intraday or reserve markets (secondary or tertiary).

Taking the example from figure 7, the storage plant would stop generation or even pump (i.e. buy electricity from the grid) at night hours – or during low price hours due to a high supply of renewables – when prices are low and generate at the price peaks. The spread between high and low prices gives the incentive for operating (and building) storage plants.

Example on Flexibility Provision by a Battery Energy Storage System

The battery storage business model includes several sources of revenues from different market segments, such as participation on the energy market (similar to the example of pumped-hydro storage above), to providing reserves and so-called peak shaving. In peak shaving, the battery is used to cut the peak load of a large costumer to reduce grid fees. For large customers, the grid fees are based on two components, the energy consumption and the highest power demand within a year. The highest demand usually occurs only during a few hours of the year and is very well predicted. Hence, only during these few hours, the battery will act as provider of the additional peak demand.

The rest of the time, the battery storage can act on the day-ahead, the intraday or the reserve markets as described for other plant types above. In the case described here, the main incentive to install a (flexible) battery is the peak shaving because the savings potential on grid fees in Germany are significant. However, most of the time the battery is available as a flexible resource on the energy and reserve market which helps the system by increasing overall flexibility and generates revenue for the plant operator.

The economic viability of the business model is strongly influenced by the regulatory framework which determines, for example, the price for the highest power demand and therefore is important for the profitability of this business model. So far not many of these systems have been installed, as the market for battery systems is still in the stage of developing in Germany.

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