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Security of Supply in the German Electricity Sector

A short review of challenges and measures

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Imprint

The report "*Security of supply in the German electricity sector - A short review of challenges and measures*" introduces German experiences in securing its energy security when transitioning its energy system towards more renewables, aims at sharing valuable measures and experiences with Chinese audiences. It is published in the framework of the Sino-German Energy Partnership between the German Federal Ministry for Economic Affairs and Climate Action (BMWK), the National Development and Reform Commission (NDRC) and the National Energy Administration of the People's Republic of China (NEA). As the central dialogue platform on energy between two countries, the main objective of the partnership is to foster and advance the far-reaching and profound energy transitions ongoing in both countries by exchanging views, best practices and knowledge on the development of a sustainable energy system, primarily centered on improving energy efficiency and expanding the use of renewable energy. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH implements the project under commission of BMWK. As a German federal enterprise, GIZ supports the German government in the achievement of its goals in international cooperation for sustainable development.

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Content

1 Executive Summary

The German energy transition ('Energiewende') sets out to shift the entire energy system away from fossil and nuclear fuels to climate-neutral energy carriers within one generation. These include electricity based on renewable energy (RE) as well as green hydrogen and hydrogen derivatives. The transition also entails several challenges for security of supply and energy affordability. This report summarizes recent and current measures policy makers have undertaken to ensure security and improve affordability.

Until the recent war in Ukraine, the energy supply system proved to be reliable despite the profound changes it underwent. Germany has pursued an active climate policy for two decades with the promotion of renewable energy at its core. The Energy Concept of 2010 provided a comprehensive approach with a broad set of targets, including a 35% share of renewable energy in electricity generation by 2020. Although Germany narrowly missed its 2020 emission abatement target, the expansion of renewable energy is generally considered a success, with renewables reaching a share of 45% in electricity generation in 2021. The German Parliament had also enacted a nuclear and a coal phase-out, with nuclear to retire by the end of 2022 and coal by 2038. Since this decision, 13 of 16 nuclear plants have retired and many coal-fired plants have been either decommissioned or mothballed.

The German energy transition has so far proceeded without any impact on Germany's electricity supply security, despite some earlier concerns. Policy makers adopted adjusted policies and market rules to prepare the system to become reliable with more variable renewable energy expansion. The German power system has few outages relative to other advanced economies and has steadily improved its reliability performance as measured by security of supply indicators.

Germany has adopted several measures to ensure electricity supply security:

- Electricity markets in Germany feature high-volumes of day-ahead and intraday power trading over short time intervals, and wide price fluctuations have incentivised flexible operation of conventional thermal plants without subsidies or capacity payments.
- Market players trade electricity across the control zones of the four German TSOs. Trading takes place primarily over the country's well-functioning and liquid electricity markets.
- Furthermore, the integration of the EU's internal market for electricity provides additional security by cross-border electricity trade and flows.
- In recent years, reforms promote new asset categories like storage and DSM to provide balancing and other ancillary services.
- The government and the regulators promote the expansion of transmission and distribution grids, contributing to the integration of new renewable energy capacity, though the transmission expansion faces delays. Additionally, the TSOs have increased the use of redispatch measures to manage network congestion on the system level.
- To uphold generation adequacy, the government has established a reserve system encompassing a capacity, a network, and a security reserve. The reserves consist of decommissioned coal and oil-fired power plants.

As a response to physical gas shortages, and the necessity to prioritize gas storage for winter heating, policy makers have allowed the reactivation of coal-fired power generators to replace gas turbines to provide flexibility service. As of 2021, gas-based generation provides around 12% of German electricity consumption. However, gas turbines and combined cycle plants contribute significantly to generation adequacy and ancillary services due to their high flexibility. Therefore, the current gas supply crisis has implications for the future of the electricity system. As of today, Germany has activated its mostly coal-based security reserve to ensure generation adequacy in the following months. They will show which energy carrier is best suited to bring the energy transition forward under the new geopolitical circumstances.

Hydrogen should facilitate Germany and the EU to achieve their 2045 and 2050 climate neutrality targets. New policies are under discussion to tackle further challenges arising from the phase-out of conventional power generation, aiming at an enhanced use of flexibility provided by electricity storage and demand side management on the distribution level. Most policy scenarios attribute an important role to hydrogen-based power generation beginning in the early 2030s.

Germany has managed to achieve energy security in transiting away from fossil-based energy. Although the wholesale electricity price in Germany increased considerably, especially during current war in Ukraine, the public support and faith for German energy transition has never changed. And to accelerated energy transition and renewable energy development has even become the solution for Germany to achieve supply security.

2 German energy transition—policies, legislation, cost development and environmental impact

The German energy transition sets out to shift the entire energy system away from fossil and nuclear fuels to climate neutral energy carriers within one generation. In the electricity sector, Germany met and surpassed its 2020 targets for renewable energy, and in 2021 renewables provided 45% of the country's electricity. High electricity prices for industries and households remain a concern, despite renewables contributing to reduced wholesale prices in power markets. Recent price spikes are due to the high price for gas due to shortages related to the ongoing war in Ukraine.

2.1 German climate policy—the foundation for energy security

German energy and climate policy

The **German Federal Government's energy concept** of 2010 laid the foundations of current German energy policy. It was built upon three key objectives: **security of supply**, **economic efficiency,** and **environmental protection**. In 2011, in the aftermath of the Fukushima nuclear disaster and based on the **German Federal Government's energy concept**, the Federal Government proclaimed the energy transition (Energiewende), It targets at the phase-out of nuclear energy, coal, and eventually all fossil fuels through improving energy efficiency, developing renewable energy, and sector coupling, supported by digitisation andinnovation.

A set of policies and regulations were released to support German energy transition. In 2016 the German government adopted the **Climate Plan 2050**. This long-term strategy integrates all existing targets and principles of the national climate policy and describes the pathway to a largely greenhouse gas-neutral Germany by the year 2050. It created separate targets for the different economic sectors and introduces intermediate reduction targets (55% greenhouse gas (GHG) emissions reduction until 2030). In 2019, the German government adopted the **Climate Change Act**, which set a clear and binding path toward **climate neutrality by 2050**.[1] Over the following years, the German government and the responsible authority revised the climate change act in light of more ambitious European climate targets and following a decision by Germany's highest court deeming previous climate action insufficient. Since its revision in 2021, the law has the objective of **climate neutrality by 2045**, making Germany one of few countries in the world to have climate neutrality by mid-century enshrined in national law.

The first monitoring report on the progress of the energy transition developed a **target architecture** structuring and prioritising these different goals.[2] The core objectives describe the overarching policy goals such as the climate targets of reducing GHG emissions, the coal phase-out as well as strategic targets like increasing the share of renewable energy in energy consumption. Then steering targets elaborate the core objectives by specifying targets in different sectors. Different measures, based on criteria like cost-efficiency and system integration, contribute to those targets. These measures should be aligned so that the core objectives (climate targets) can be achieved in the most reliable and cost-effective way.

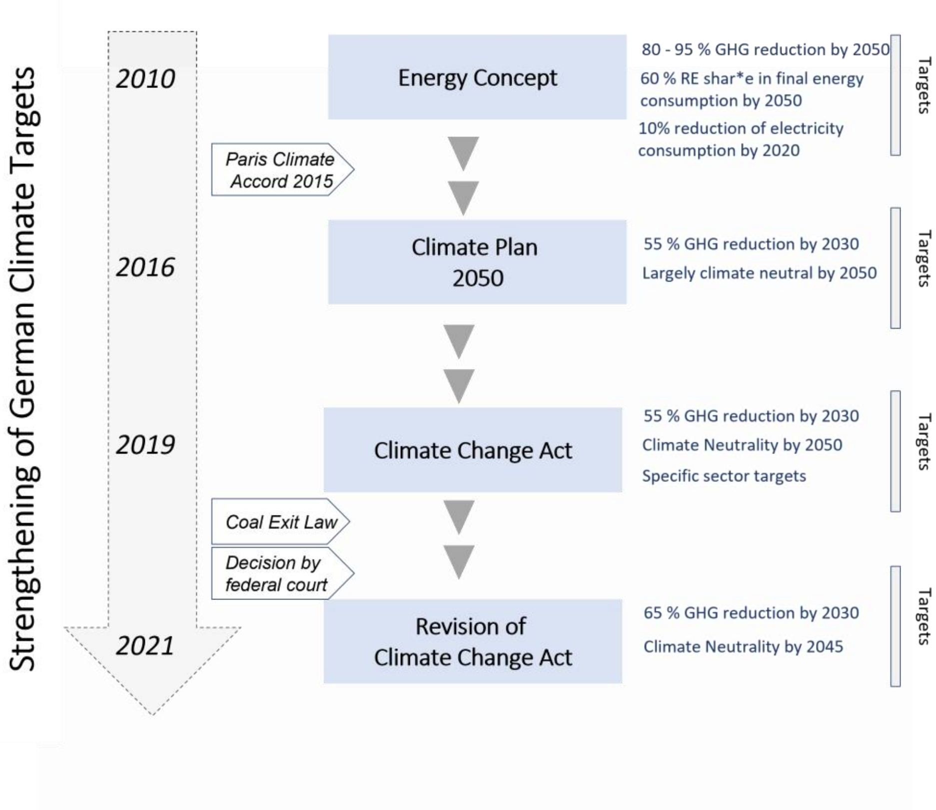

Figure 1: Development of German Climate Targets

Climate targets in the EU and Germany today

The amended Climate Change Act sets emissions reductions in line with ambitious European climate policies. With the European Green Deal, the EU created a legislative framework that supports the goals of the Paris Agreement. The EU decided to raise its **2030 emission reduction target to -55%** and aim for **climate neutrality by 2050**. This requires a set of measures the EU decided to include in the Fit for 55 package.[3]

In Germany, the adopted Climate Change Act of 2021 calls for emissions reduction of 65% by 2030 compared to 1990 and climate neutrality in 2045. It sets ambitious targets for the electricity sector, the buildings, transport, industry sector as well as for agriculture and the LULUCF sector (land-use, land-use change and forestry). The new German governing coalition strengthened some of these targets once more. Achieving these goals requires a set of measures and policies.

Overview of German energy legislation

The government and relevant ministries implement the German energy transition through different laws and instruments. As an EU member state, the framework of EU climate policies significantly shapes Germany's climate policy**.**

- The power and some industry sectors are part of the **EU Emissions Trading System (ETS)**
- Non-ETS emissions in transport and heating are subject to the **Effort Sharing Regulation (ESR)**
- The implementation of the **European Green Deal** with the comprehensive Fit for 55 package will likely address the design of the ETS and ESR, with the ESR transitioning into a trading system.[4]

Other important EU policy instruments influencing the national policy are:

- **Renewable Energy Directive (RED II)** as the legal framework for the development of renewable energy across all sectors of the EU economy, currently in revision
- **Energy Efficiency Directive** promotes energy efficiency as an overall principle of EU energy policy and sets rules and obligations for achieving the EU's 2020 and 2030 energy efficiency targets.

- **Internal Electricity Market Directive** strengthens the rights of consumers and their participation in the electricity market in Europe.
- **Electricity Market Regulation** stipulates the opening of 70% interconnectors for cross-border trade.

On the national level, different laws and directives complement the energy concept as the basis for national energy policy.

The Energy Industry Act (*Energiewirtschaftsgesetz—EnWG*)—for the first time enacted in 1935—defines the framework necessary for a secure, affordable, consumer-friendly, and environmentally friendly supply of electricity and natural gas. It regulates the electricity and gas supply networks to ensure effective and undistorted competition and aims to intensify cooperation, particularly with Germany's neighbouring states. At the same time, it implements European Union law in the field of network-based energy supply.[5] In particular, in a series of fundamental changes from 1998 onward it implemented the liberalisation of the electricity and gas market. To achieve its objectives, the Energy Industry Act uses various measures, particularly restrictions on the exchange of cost information between generators to avoid collusion, licensing and notification requirements, ownership unbundling, and the intervention rights of the Federal Network Agency.

For hydrogen networks, policy makers are still developing the regulation, since Germany currently has no dedicated hydrogen networks. The government will also have to harmonise the national hydrogen regulation with European regulation.

The **Renewable Energy Sources Act** (*Erneuerbare Energien Gesetz—EEG*), introduced in 2001, promotes the use of renewable energy in the electricity sector. It includes provisions for the financial support of these sources, their preferential feed-in into the power grid, and sets clear targets for the development and expansion. The EEG is the successor of the Electricity Feed-In Act of 1991 and is subject to regular revision. Following the current coalition agreement, the new German government has introduced new policies to address challenges and speed-up the development of renewable energy. The Easter Package is a Spring 2022 set of amendments to the Renewable Energy Sources Act (EEG) and other policies. The package represents a major effort to achieve an **80% target of renewable power generation** by 2030.

The **Offshore Wind Energy Act**—enacted to expand offshore wind energy—governs the legal framework for German offshore wind parks, particularly as they relate to nature conservation, shipping, and offshore connection lines. The German legislative passed an amendment to the act in July 2022. It aims to increase offshore wind turbines' installed capacity from 8 GW in the year 2021 to a total of 30 GW by the year 2030 and 70 GW by the year 2040. It almost doubled the previous ambition for offshore capacity by 2045.[6] The act aligns the expansion of offshore wind turbines and the expansion of offshore grid connectors required to transmit the generated electricity.

2.2 Prominent role of renewable energy in Germany's energy mix

The German energy system is undergoing a massive change, and by 2045, Germany will achieve climate neutrality for the entire energy system. Primary energy consumption in Germany has increased by 2.6% and has reached 12,265 PJ, or 3407 TWh, in 2021 but has remained below pre-pandemic levels. Fossil fuels made up approximately 80% of primary energy consumption in 2021: oil accounted for 32%, natural gas for 27%, coal for 18%, nuclear energy for 6%, and renewable energy for 16% (see Figure 2).[7]

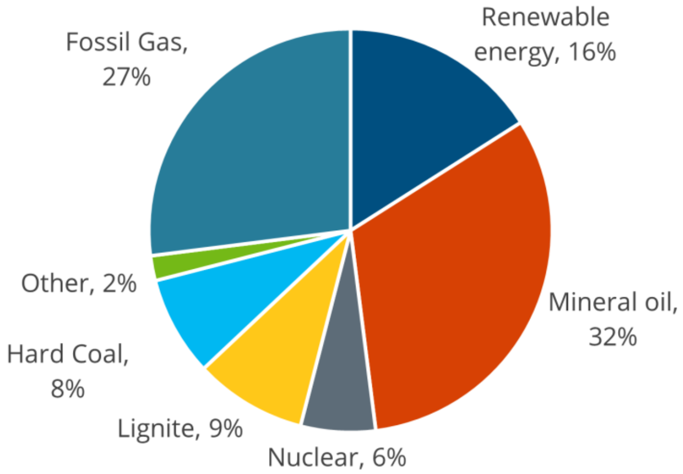

Figure 2: Primary Energy Consumption in Germany 2021

The **electricity sector has undergone the largest change**, and the share of renewables reached 45% of electricity consumed in 2021. Variable wind and solar met roughly one-third of electricity consumption in 2021. In the first half of 2022, renewables surpassed a 50% share.

Wind and solar energy were the main drivers of this shift. In 2021, wind provided 24% of electricity consumption and solar 9%.[8] Scaling up these energy sources initially depended on the price guarantees provided by the Renewable Energy Sources Act (EEG). The EEG and other policies helped bring down costs and make these technologies competitive around the world. Germany's decision to step up its climate ambition will rely on accelerating the growth of renewable energy capacity and output.

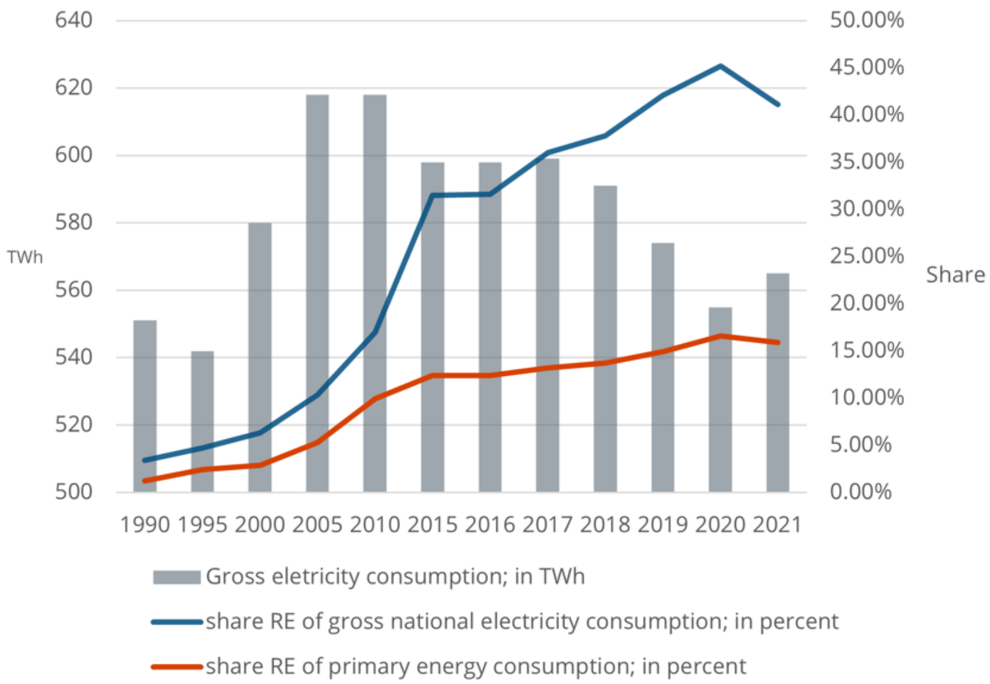

Figure 3: Share of Renewable Energy in Total Energy Consumption until 2021

Renewable energy in other sectors cannot yet contribute significantly to climate protection and emission reduction (see section 2.4 below). The RE share in primary energy consumption is lower than in the electricity sector. Going forward, electricity and renewable energy will take a more prominent role in the primary energy consumption due to a significant uptake of electric vehicles, heat pumps, and the electrification of industrial processes.

2.3 Affordability of energy

German electricity prices for consumers and industries have increased since 2008, mainly due to various fees, surcharges, and taxes. In addition to provoking criticism of renewable energy adoption among some users, these fees have slowed the electrification of end-use sectors, and therefore prolonged Germany's reliance on gas—with implications for energy security.

Renewable energy lowers wholesale electricity prices

When discussing high **electricity prices** in Germany, one has to differentiate between wholesale prices, energy prices for households, and industrial consumers. Integrating renewables into the energy system has generally led to a steady **fall in wholesale prices for electricity** due to the lower variable costs of renewables. Marginal prices of wind and solar are close to or zero. The wholesale market prices do not reflect the market integration costs of RE, such as balancing costs or redispatch costs. Figure 4 depicts the decrease in wholesale prices until recently when developments took a turn and prices started to rise. Prior to 2021, higher carbon prices of EU ETS explain the slight increase in electricity prices.

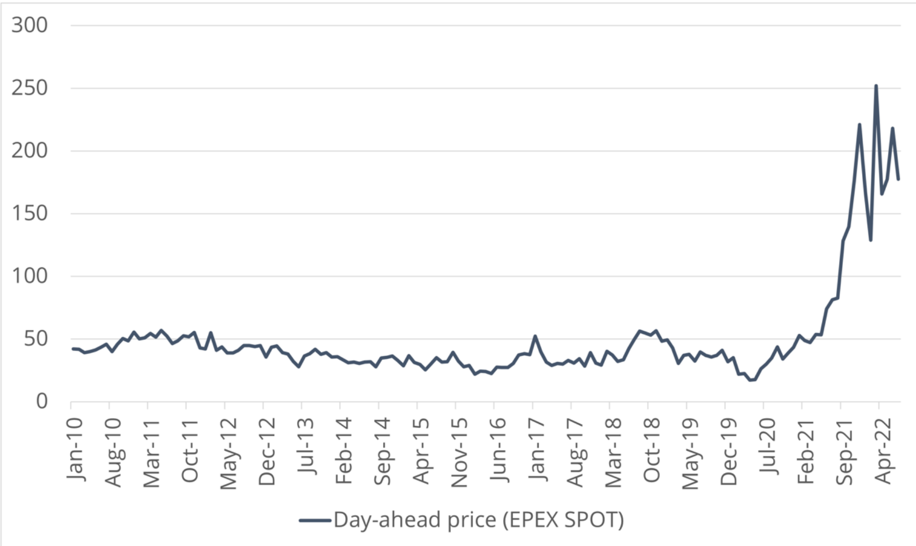

Figure 4: Monthly average day-ahead wholesale electricity price, €/MWh, 2010-2022[9]

Germany at times had the lowest day ahead prices in Europe, with less than €40/MWh. In addition to the trend of lower wholesale prices, the integration of high shares or variable RE did also lead to increasing number of negative prices on the German day-ahead market. Negative prices usually appear at times of high production from renewables in combination with low demand. Negative prices will likely become more frequent as more wind and solar enter the system.

While negative prices threaten the profitability or financial viability of renewable sources and could theoretically reduce investment in these urgently need resources, negative prices also incentivize investment in and operation of demand-response and efficient energy storage, ultimately helping alleviate or eliminate negative price periods.

It is important to note that the trend towards lower prices reflects the situation before 2022. The current energy crisis and high electricity prices break with the trend, for reasons described below. 2021 and 2022 have seen fewer instances of negative prices.

Wholesale gas prices remained at a steady and low level in recent years, with low average spot prices of €13.79/MWh in 2020, before taking up in 2021 and 2022.[10] Recently, gas prices have spiked due to the gas supply crisis following Russia's war against Ukraine.

Rising household electricity prices due to fees and surcharges

Even as wholesale prices declined, other price components have increased significantly, especially fees and taxes. These include fees for using the electricity grid as well as state-imposed price components, such as taxes and the EEG surcharge.[11] The Federal Network Agency regulates the electricity grid fees. Grid fees vary across regions but make up a share of around 25% of the electricity price for private households. In total, around 50% of the electricity price results from taxes, levies, and surcharges.[12] Since the beginning of the liberalisation of the European power market in 1998, the share of taxes, levies and surcharges had increased by 250%,[13] reflecting the cost of renewable energy support, other climate policy measures and an increase in grid fees. In July 2022, the government abolished the EEG surcharge to reduce household and commercial electricity prices and promote electrification of appliances and transport.

Electricity prices for private households in Germany have increased mainly due to policy related price components, which more than compensated for the drop in wholesale prices. Figure 5 depicts the development of electricity prices for private households. With an average of €0.32/kWh in 2021, they are the highest within the EU.[14] Sales taxes, electricity taxes, surcharges for the CHP and renewables, and other fees make up almost half of the electricity price.

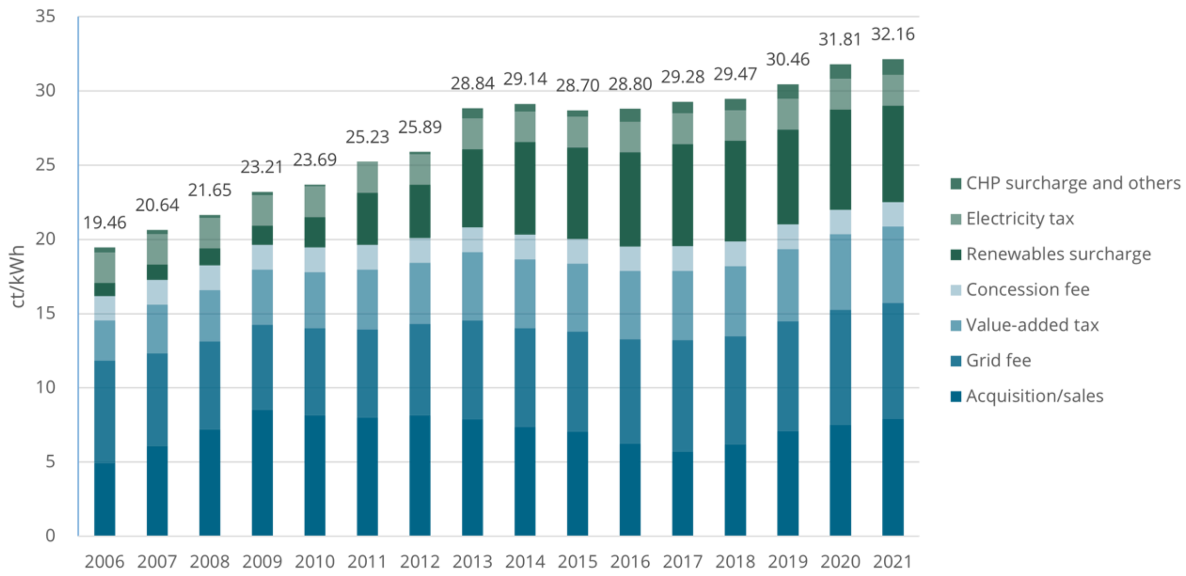

Figure 5 : Average German household electricity price

Total household energy costs include both electricity and heating, which is supplied mainly by gas, but also by oil and district heating. The share of energy expenditures for German households is in the lower third compared with other EU countries.

Gas prices include the price for gas acquisition and marketing, grid fees, and taxes. Since 2021, a national carbon price applies to the provisioning of gas and other fossil fuels for heating purposes and transport.[15] Gas prices stayed steady in recent years, with a slow decline through 2020. The development took a sharp turn in 2021 and 2022 when prices spiked.

Lower energy costs for industry versus households

For industrial energy consumers, some of the government induced price components and grid fees vary significantly in relationship to the amount of electricity consumed.

Industrial consumers have significantly lower tax expenditures than private households, as different exemptions alleviate the economic pressure to ensure international competitiveness. The largest industrial consumers are exempted from most taxes, levies, and fees. Their electricity prices are below €0.10/kWh. Other industrial consumers pay roughly €0.20/kWh.[16] Two prominent examples are the following:

- Energy-intensive businesses are eligible for a 90% deduction of the electricity tax.
- Only 15-20% of the EEG surcharge is applicable for the power consumed above a threshold of 1 GWh

Hence, different industrial consumers face widely different electricity prices due to the design of exemptions and various support policies for different price components.

When comparing prices for industrial consumer across the EU, German wholesale electricity prices tend to be lower than the EU average. In contrast, the final electricity prices in Germany are among the highest within the EU. For industrial consumers with an annual consumption of up to 2000 MWh, electricity prices are 64% higher than the EU average (Figure 6).[17]

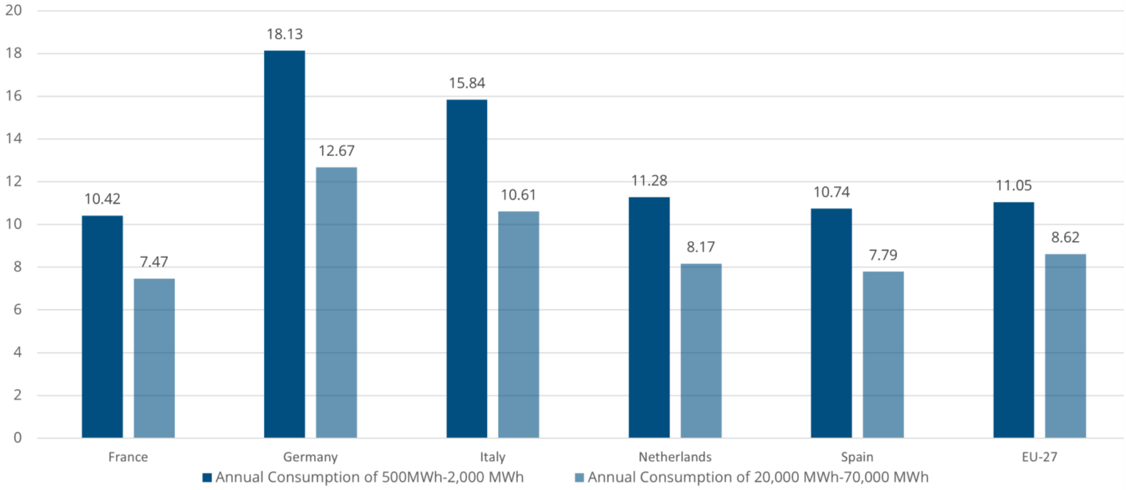

Figure 6: Industry electricity prices in selected EU member states (2021)

Industrial consumers have also paid lower **gas prices** than private households. Gas prices dropped from below €0.04/kWh in 2018 to €0.0253/kWh in 2020, which is more than half the price of private consumers.[18] For reasons of international competitiveness, large and energy-intensive industries also benefit from government incentives. The energy tax can be reduced for manufacturing industries and for some industries above a threshold of energy consumption, peak compensation applies. In addition, the Carbon Leakage Regulation stipulates that industries can apply for free allocation of emissions allowances to counter the risk of carbon leakage.[19]

2021-2022 gas price crisis

There was an unprecedented spike in energy prices across Europe since the second half of 2021. On the German wholesale market, electricity was traded for €5/kWh during some hours and €0.097/kWh on average in 2021, which was three times as in the previous year.[20]

The high electricity prices were mainly driven by record prices for gas with the following reasons:

- Overall strong recovery after the pandemic leading to high energy demand,
- Cold winter in 2020-2021 leading to relatively low gas storage in Europe,
- Asian industrial recovery in 2020-2021 leading to high demand for limited LNG imports,
- Pipeline outages unrelated to the Ukraine war, and
- Lower gas deliveries from Russia.

The increase in gas and electricity prices until 2021 was followed by a major jump in 2022, which is currently aggravated by Russia's invasion of Ukraine. This spike in wholesale prices is also reflected in prices for private consumers and industries. High energy prices are threatening the low-income households dwelling in poorly insulated buildings. The 10% least-income households spend around 6% of their income for energy in recent years.[21] This number could double in 2022 with an estimation based on the prices of the first half of 2022 showing an increase of energy bills from €2,500 in 2021 to €4,000 in 2022 for households with an average energy consumption, prior to the recent additional spike in prices.[22]

More recently, the reduction of gas supply to Germany by the Russian state-owned Gazprom has led to further warnings of gas price increases as well as physical gas shortages. The German government has activated an emergency policy on gas supplies: At the first stage, already invoked, the government asks consumers to save on gas. At a higher level of alert, industry faces gas rationing rules to ensure supplies to private households.

The current high gas prices are also a particular issue for industries like the chemicals industry that relies on gas and oil as feedstock for their products. Some industries have begun to switch production from gas-based to oil or coal-based production to reduce the gas demand while at the same time increasing emissions.[23]

These developments and the corresponding social issues fuelled political discussions about compensation for private households.

2.4 Sustainability and environmental impact of the energy system

Though Germany reached its intermediate greenhouse gas reduction targets, much work remains. In 2020, Germany reached its 40% emissions reduction target, partly because the pandemic halted much of public life and mobility. Combined with shrinking coal consumption, the pandemic led to an emissions reduction of 8.7% compared to 2019. The effects were, however, not enduring, as emissions bounced back by 4.5% in 2021 due to the economic recovery. The main driver for increased GHG emissions was a rise in coal power generation driven by historically high gas and oil prices. Additionally, poor wind conditions and higher power consumption contributed to the reverse of the emissions reduction trend. These factors led to overall emissions of 763 million tonnes of CO_2 equivalent in 2021, a 38.7% decrease compared to 1990.[24]

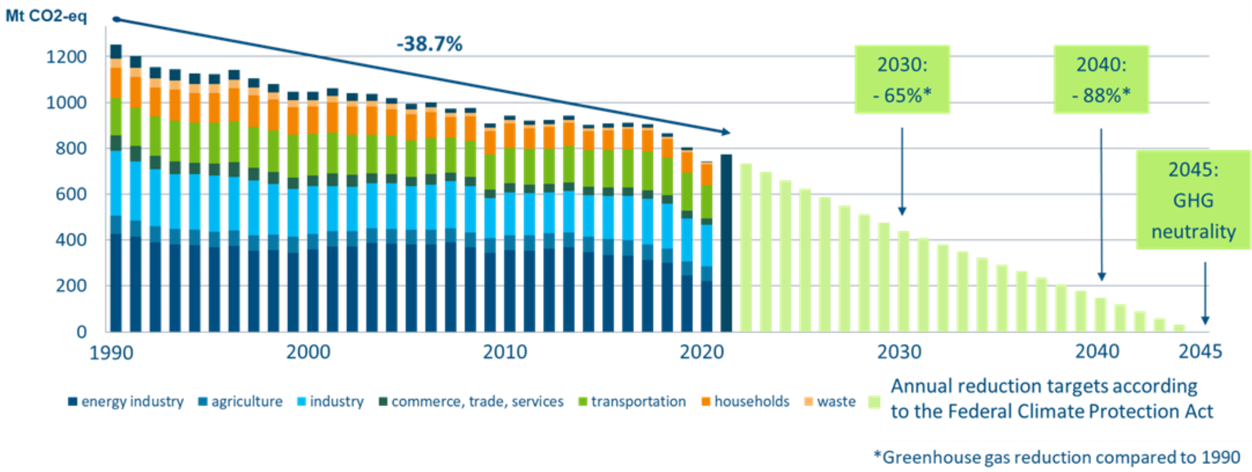

Figure 7: GHG emissions in Germany and projected development

The **electricity sector** is the only sector consistently reducing its emissions in Germany. The **industry sector** has experienced significant emissions reduction during the 1990s, becoming stagnant for much of the time since 2000. The main factors are that improved efficiency cannot balance the emission from rising production levels . The **transport sector** shows similar trends: an increase in car traffic by 20% from 1995 to 2019 and a trend toward more powerful engines have made up efficiency gains and improved emissions standards. Total emissions in the transportation sector have thus risen by 5.1% in the specified period.[25] This makes the transport sector the only sector that has been unable to reduce emissions in the last decade. The **buildings sector**, which makes up around 30% of CO_2 emissions in Germany, has reduced emissions by 43%

since 1990. During the last decade, the buildings sector has made little progress, leaving a gap to the targets of the climate protection law.[26]

The contribution of renewable energy expansion on GHG reduction

Better energy efficiency, fuel switching from coal to gas, and the share or RE are major drivers for emissions reductions in Germany. The most significant driver of energy related CO_2 emissions is economic growth.[27] The expansion of renewable energy is the central pillar of the German energy transition and is necessary for achieving the national climate targets. Over the past two decades, the development of renewable energy contributed to the achievements of emission reduction, as did energy efficiency improvements and the increased use of gas instead of coal in the wider economy. Thus, analysing the effect of renewable energy on the emissions reduction and thus on climate integrity requires analysing different drivers for emissions and thoroughly accounting their respective part in the development.[28]

An analysis by the German Federal Ministry of the Environment estimates that renewable energy has contributed to emissions reductions of 221 Mt CO_2 equivalent in 2021.[29]

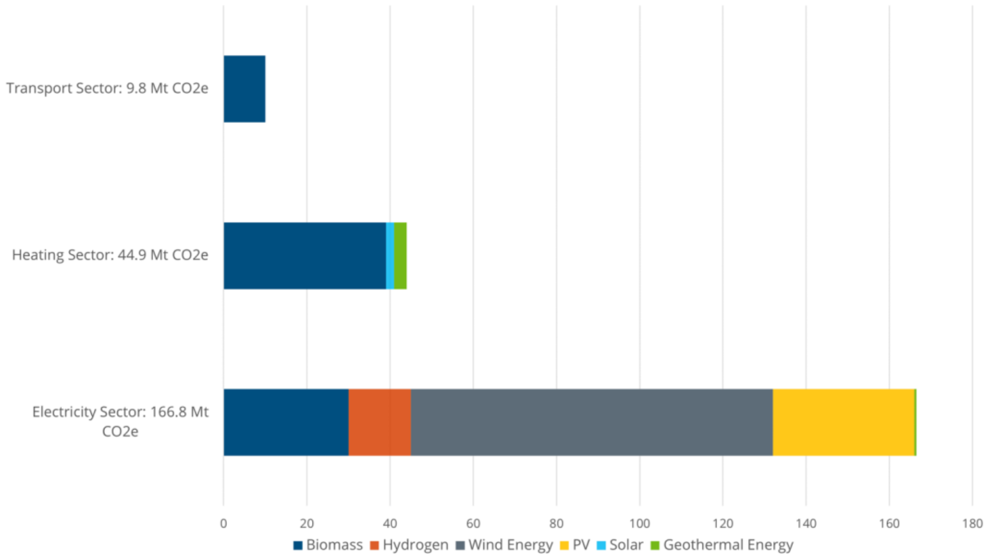

Figure 8: Net balance of GHG emission reduction due to RE expansion

3 Security of supply in Germany: past and present

In the early years of the energy transition, policy makers worried that a rising share of variable renewable energy would cause security of supply problems. However, electricity supply has remained reliable over the past two decades despite the strong rise of the wind and solar PV share in the German energy mix, and is predicted to remain adequate through the 2030s (barring temporary problems following from the war in Ukraine). Several policies have contributed to ensuring system stability and generation adequacy, most notably market reforms aimed at improving flexibility and the introduction of reserve mechanisms. Other challenges remain, notably the need to expand the transmission grid and incentivise flexibility in the distribution grid. Most recently, the shortage of gas supply due to the war in Ukraine has led to security of supply concerns in Germany. In the electricity sector, the government activated the coal-based security reserve to ensure reliable supply over the next months.

The German power system has remained reliable and stable in the past two decades as the share of variable wind and solar energy has risen steadily, and now reached 32%, with enewables supply around half of Germany's electricity. Germany's main security of supply concerns relate to the price and physical supply of gas and whether to temporarily slow the retirement of coal and nuclear to prioritise gas for heating and industry.

Notwithstanding the reliability of electricity supplies in Germany and Europe, the expansion of variable renewable energy leads to challenges in all three categories of power system reliability: generation adequacy, system stability and grid adequacy.[30] Generation adequacy refers to the mid-term and sometimes long-term availability of sufficient electricity supply to match demand. Shortages in this sense occur in times with medium to high load and low generation of wind and solar PV assets, for example periods in winter, when electricity demand is up due to electric heating devices, and when wind speeds and solar radiation are both low.

System stability, in contrast, refers to the short-term match of demand and supply, which in AC based electricity systems refers to the stability of frequency in the range of milliseconds. Here, the issue is the limited predictability of variable renewable electricity generation, which depends essentially on the weather, in comparison to conventional power generation. Regulators and system operators have developed rules and technical measures to cope with these challenges over the past two decades. Also, the integration of EU electricity wholesale markets has alleviated regional electricity shortages. Further challenges arise from the disparate geographical distribution of large-scale renewable generation and industrial load across Germany that leads to transmission grid requirements addressed by recent legislation, but not met by expansion so far. Also, Germany has only recently introduced measures to cope with challenges arising from distributed generation.

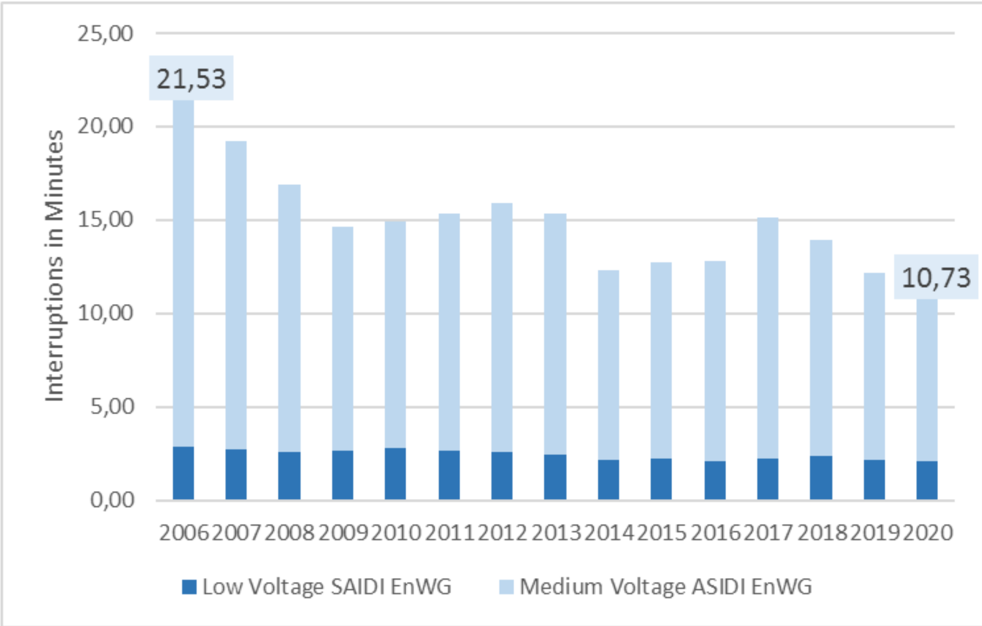

Figure 9: Development of electricity supply indices ASIDI and SAIDI for Germany 2006-2020[31]

Nonetheless, Germany's electricity supply has remained reliable over the past years, and experts are confident that this trend will continue during the next phase of the energy transition. In Germany, security of supply is monitored by the grid regulator BNetzA, which publishes annual reports assessing the state of the system, using several quantitative indicators.[32] One of these is the System Average Interruption Duration Index (SAIDI) that highlights a weighted average of the duration of interruptions. The German SAIDI of 2020 stands at a value of 10.73 minutes, which is a reduction of roughly 50% compared with the year 2006. An international comparison shows Germany consistently being among the countries with the best SAIDI score reflecting very high security of supply.[33]

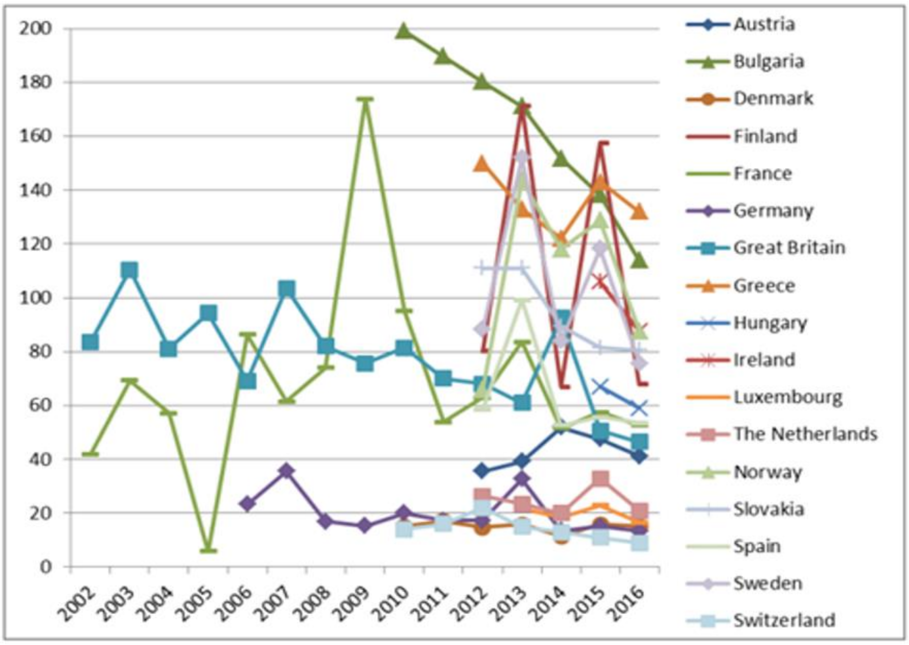

Figure 10: International comparison of unplanned SAIDI index 2002-2016

3.1 Overview electricity system

Germany's wholesale electricity markets have played a vital role in both maintaining reliable electricity supplies as well as accommodating the integration of new wind and solar capacity. This subsection explains the elements of the German electricity market model, which is based on a decentralized bilateral wholesale market with a high volume of trading in short-term electricity spot markets.

Bilateral power trading

The Single European Act of 1987 as the first major revision of the treaty of Rome of 1957 set the objective of establishing a single market within the EU. The concept of establishing an internal market for energy one year later aimed at creating a single European energy market with cross border transmission, the removing distortions of competition, and liberalizing energy markets overall. Several other Directives and Regulations by the EU furthered these goals. They include:

- EC (European Community) White Paper on Internal market (1988)
- First Energy package (1997-1998)
- Second Energy Package (2003)
- EU Climate and Energy package / 2020 strategy (2007-2009)
- Third Energy package (2009)
- 2030 Energy Strategy (2014-today)
- European Green Deal (2019-today)

Instigated by the EU legislation, the liberalisation of the German power market started in the 1990s requiring the unbundling of formerly vertically integrated energy monopolies. The term unbundling refers to the separation of those activities that can be subject to competition (such as production and supply of energy) from those activities where competition is not possible or allowed (such as the transmission and distribution). In the EU transmission and distribution of electricity and gas are regulated monopolies. The introduction of unbundling implies that generators engaged in market competition cannot also perform transmission services regulated as a monopoly.[34]

The most common EU market design then became the decentralized bilateral market where production and supply of energy is legally separated from the transmission and distribution of electricity. Decentralized markets are also called bilateral contract markets, as they allow generators and suppliers to engage into any type of contractual obligations for the delivery of energy. Generators and suppliers act as traders and can engage in either short-term or long-term contracts. Long-term contracts have durations lasting one month to as long as several years.[35] Bilateral trading is usually complemented by anonymous trading at an electricity exchange. The market operator of an organized market receives bids and offers from market participants. The market-clearing price is set by matching the bids and offers.

In Germany, as in most decentralized markets, the role of the system and market operator are formally divided. Four regional Transmission System Operators (TSO) — Amprion, TenneT, 50Hz, TransnetBW—are responsible for ensuring system balance including the management of operational constraints and of the balancing market

Structure of wholesale market in Germany

A decentralized market is typically based both on centralized and decentralized trading. Trading on the wholesale market in Germany is characterized by different time horizons being **futures**, **day-ahead** and **intraday markets**. Prices of these trading products may vary considerably.[36] The **spot market** consists of the day-ahead and intraday market. Electricity is traded either for the next day (day-ahead) or the same day (intraday), allowing traders to plan their obligations over a longer period. Before the spot market, trade occurs via bilateral long-term contracts, Over the Counter Trading (OTC) or anonymously on futures market at an exchange.

On the futures market, participants trade electricity days, weeks, months, or years before delivery. These products are called futures on the exchange, while in over-the-counter trading, they are known as "forwards". The forward and futures markets are important for many large producers, large consumers or traders to hedge electricity prices for a certain period. Hedging of prices comes along with financial certainty of the purchase or selling of a certain volume for a pre-agreed price.[37] The volume of future trading in 2020 was 1416 TWh, in comparison to 231.2 TWh day-ahead-market trading.[38]

In electricity markets, the initial generation schedule is typically determined one day ahead of delivery. In a decentralised market this is based on internal production planning of market participants. Generators must usually provide indicative generation schedules to the system operator. The outcome is a day-ahead schedule of all generation sources that are supposed to match the expected demand.[39]

On the **day-ahead market**, participants can sell and buy electricity in an auction for the 24 hours of the next day in (hourly) blocks. The bulk of physicial electricity is traded in the day-ahead market, closing at noon on the day before delivery. The market operator (that is the power exchange operator) receives bids and offers from market participants and clears the market based on the aggregate supply and demand curves.[40] The intersection of demand and quantity offered determines the electricity price and volume for each hour. As the day-ahead market has a single clearing price (per hour), it best reflects the value of electricity during different hours, so that the clearing price on the day–ahead market is often referred to as "the electricity price". Importantly, however, only part of the electricity is traded via the power exchange, whilst some volumes are also traded under bilateral contracts.[41]

As the time of the agreed electricity supply draws closer, it gets easier for market participants to estimate the actual generation and real consumption. Following the submission of generation and exchange schedules to the system operator, market participants have the option to adjust their positions in the **intraday market**, to minimise discrepancies or surpluses and employ the available generating installations cost-effectively.[42] Buyers and sellers can adjust their order volumes in line with better load and renewable feed-in forecasts or unexpected power plant outages. It is possible to trade power continuously in time periods of a quarter hour, one hour or even longer intervals.[43] Over the years, lead times for intraday trading[44] (the time between gate closure and the start of the supply) have been shortened to better reflect the variability of RE and to reduce the need for balancing. For trading within Germany, the lead time for each quarter-hour interval was reduced from 45 minutes before 2015 to just 5 minutes currently.[45]

After gate closure, the system operator (in Germany: the TSO) obtains the schedules for feed-in and feed-out plans based on the market outcome. These are updated throughout the day prior to delivery. The TSO plans and updates technical delivery accordingly. All market participants are mandated to follow the schedules they agreed upon to avoid compromising system stability (so-called balancing responsibility). However, some deviations from planned feed-in or feed-out may occur. These can have technical reasons, for example the unplanned outage of a generation asset or a large machine (load). Moreover, the generation forecast for variable renewable energy depends on the quality of the weather forecast; sometimes unforeseen weather events can thus lead to deviations. For this purpose, the TSO uses balancing services to ensure frequency (and overall system stability), that is to balance the system by ramping up or down additional feed-in. Balancing services are offered by generators, storage, flexible demand etc., based on the advance contracting of ancillary services (see below).[46] This balancing market is a tendering regime separated from the day-ahead and intraday markets and set up by the TSO.

Ancillary services

To guarantee quality, reliability, and security in power transport and distribution, system operators must ensure that thermal limits of network assets are not exceeded, and frequency and voltage are always upheld. Fluctuations between generation and the actual energy consumption must balance at all times to ensure that the grid remains stable. TSOs continuously monitor and regulate electricity supply and demand with **ancillary services**.[47]

In general, there are **four distinct types** of ancillary services:

1. **Frequency Regulation:** TSOs need to balance generation and consumption to maintain a stable frequency of 50 Hz. Instruments for frequency control are balancing energy and interruptible loads.
2. **Operation Management:** Grid operators must organise a safe operation of the power grid including the monitoring and regulation of generation and load. Main instruments are redispatch and other grid congestion management measures.
3. **Voltage Stability:** TSO and distribution system operators(DSO) are legally obligated to keep the voltage within their respective grid area within certain thresholds, such as by providing reactive power
4. **Re-establishment of power connection:** In case of a blackout, TSO must be capable to re-establish the power connection within a short time.

The most important ancillary services are balancing services, procured by the TSO in structured markets. In the unbundled national electricity markets in Europe, balancing markets deal with the balancing of electricity demand and supply. From a technical point of view, keeping the system in balance corresponds to keeping the system frequency in a very narrow range around the target value of 50 Hz. At each point in time, total production must be equal to total consumption. TSOs use balancing power to balance unplanned fluctuations in the production of electricity and to maintain a stable frequency. Frequency control is one of the four main types of ancillary services introduced above. The presence of variable RE complicates the precise matching of demand and supply, as their generation is variable (depending on the wind and solar radiation at any given moment) and only partially predictable.

In Germany, every producer and every consumer must be part of a balancing group. The Balance Responsible Party (BRP) is required to ensure that there is no gap between production and consumption in its balancing group. According to the Electricity Grid Access Ordinance and the balancing group contract between BRP and TSO, BRPs are required to ensure that their balancing groups are balanced every 15 minutes. Otherwise, frequency deviations will emerge and may decrease system stability. Imbalances between production and consumption are first offset between different German TSO and European TSO (balancing groups provide imbalance energy to one another), the remaining imbalances are balanced by the TSO via the use of balancing energy procured on the balancing market. The Balancing Responsible Party can be an individual generator or consumer, a retailer or a portfolio of generators and consumers (balancing group).

The BRP is financially responsible for its imbalance—defined as the deviation from its commercial trade schedule. The BRP pays or receives the imbalance price depending on its schedule and total system imbalance. The costs for the provision of balancing capacity are passed through to the end consumer via grid fees. In contrast, the BRPs directly bear the costs for activating balancing energy. The imbalance prices reflect the cost of activating balancing energy to address system imbalances. The TSO calculates the imbalance price. Imbalance prices are paid for both positive and negative deviations of the trade schedule.

There are three types of balancing or control energy that is primary control energy (also known as the frequency control reserve or FCR), secondary control energy (automatic frequency restoration reserve, or aFRR), as well as tertiary control energy (manual frequency restoration reserve, or mFRR).[48] The Energy Industry Law requires that tendering must be open, transparent and free from discrimination according to guidelines of the Federal Cartel Office (Bundeskartellamt—BKartA), the national regulatory authority (Bundesnetzagentur, or BNetzA) and EU Guidelines. In practice, balancing energy is tendered via a procurement platform and can be activated in various timeframes. Since 2007, the four German TSO have used a common procurement platform. Bidders must prove that they can deliver balancing power according to technical requirements to pre-qualify their resources.

The auctions are pay-as-bid auctions. Bids are accepted based on their capacity price, while the resources are dispatched according to the energy price. Hence, there are two independent prices for balancing capacity and balancing energy. The TSO operates the balancing capacity and balancing energy markets and acts as the single buyer in these markets. On the supply side, Balancing Service Providers (BSPs) offer balancing services to TSO. The amount of balancing capacity procured is determined during the balancing reserve sizing process. The balancing market is a defining instrument and addition to the energy-only market (an electricity market design that does not remunerated or pay for available capacity as such). Further system services contribute to the stability of the system and highest possible security of supply.

Redispatch refers to the intervention ordered by the TSO in the market-based, originally planned schedule of conventional power generation plants to shift feed-in to prevent or eliminate power overloads in the power grid. In this process, the power feed-in is reduced upstream of a bottleneck and increased downstream of a bottleneck. To counteract short-term bottlenecks in the power grid, not the amount of electricity fed into the grid is changed, but its local distribution and potential type of power generation plants.

TSO determines the need for redispatch measures based on the probable energy production reported on the day ahead. A complex modelling by the TSO generates an overview if grid stability is endangered. TSO then require grid congestion measures in areas with bottlenecks that could risk grid stability.

Initially only large conventional power plants larger than 10 MW participated in the redispatch process, which means that generation from renewable energy did not participate. Policy makers felt that the feed-in of renewable energy should have priority and only be curtailed as a last resort. The redispatch mechnisms has been updated recently to include RE sources as well (see redispatch is called feed-in management.

3.2 Electricity system reliability—challenges and solutions

The energy transition as described in the previous chapter entails increasing shares of both centralized and distributed variable RE generation, leading to challenges to the electricity system reliability. There is widespread agreement, however, that security of supply as one of the pivotal requirements of the power system must remain of highest concern while allowing the integration of new RE sources as well as the integration into the European power market.[49] This section explains the challenges and the policy solutions taken by the government in response.

As for **generation adequacy**, Germany faces challenges arising from policy-based phase out decisions: First, the ongoing phase-out of nuclear power, instigated by the Fukushima disaster of 2011, has led to the decommissioning of large generation capacities, which are mainly located in Southern Germany. The last three nuclear power plants are scheduled for decommission by the end of 2022. Second, the coal exit law adopted in 2020 requires that coal-fired power generation must close by 2038 the latest. In their coalition agreement of 2021, the current government announced it planned to accelerate the phase-out, aiming for the year 2030. The ongoing gas supply crisis clearly render this target more difficult.

Beyond the phase-out decisions, there is another, fundamental challenge to generation adequacy: variable renewable energy feed-in leads to a problem called the merit-order-effect[50]. In a liberalised electricity market, generators offer their units into the wholesale market; under perfect competition, they offer them at their variable cost. This means that, the installations generating electricity with the lowest variable costs are dispatched first on the electricity market, and then in increasing order of their variable cost (the merit-order**Error! Reference source not found.**). Consequently, the price of electricity on the power exchange generally corresponds to the variable costs of the most expensive generating installation in use. This installation is known as the marginal installation. The merit order minimises the cost of supplying electricity.

The Renewable Energy Sources Act mandated a priority feed-in of renewable energy sources. Most renewable energy generation has zero variable costs: wind and solar PV have almost no operating costs, because they do not need fuel. There are thus two consequences of high shares of renewable energy: On one hand, renewables lower the average wholesale electricity price as the expensive marginal installations are needed less often. On the other hand, with fewer hours of production, higher marginal cost installations have difficulties earning back their capital cost. Utilities argue that they cannot invest into new marginal capacity under these circumstances and might have to decommission existing marginal capacity.

However, in times of low wind and PV generation, the thermal marginal generators are needed to serve the load, in the absence of adequate electricity storage and DSM. By reducing economic margins and profits for conventional generation in the electricity market, the merit order effect could lead to a lower firm capacity and thus reduce generation adequacy.

Both the phase-out of nuclear and coal plants and the merit-order effect also have implications for **system stability**: traditionally conventional power plants connected to the transmission grid provided ancillary services, many of them are marginal plants in the merit order. Their eventual closure thus might have consequences for the ancillary service market as well. At the same time, the increase in less predictable central and distributed renewable energy generation tends to lead to higher balancing needs.

Finally, renewable energy expansion poses a challenge to **grid adequacy** as well. On the transmission system level, there is a pronounced geographical imbalance between the industrial load centres in the South of Germany and large-scale renewable generation, which is concentrated in the North—here weather conditions for both on—and offshore wind power are most suitable. On the distribution grid level, high-level of solar PV feed-in could lead to issues such as the potential violation of thermal limits of network assets, voltage and backfeed problems.[51] Until recently, grid adequacy problems were often solved by curtailment of renewable feed-in on both the system and the distribution level, but this resulting loss of energy is unsustainable in a carbon-free electricity system. In 2020, Germany had 2.8% curtailment of renewable energy, according to the monitoring report by the BNetzA.[52] This affected predominantly onshore wind and to a lesser degree offshore wind.

Electricity demand will rise substantially with electrification of end-use sectors, including heat pumps and electric vehicles. Current annual electricity consumption in Germany is about 500 TWh. The government expects a rise to 750 TWh in 2030.[53] Given the target share of 80% renewable energy in the energy mix of 2030, experts see considerable urgency in addressing the security of supply challenge.

The following section explains the solutions German policy makers have devised to tackle the challenges explained above. The German government has already implemented some of the solutions, while others remain under discussion.

Grid expansion

Grid expansion plays an important role for the integration of new renewable energy capacities, both on the distribution and transmission levels. As explained above the geographical focus of renewable energy expansion is in the North of Germany, while industrial load centres are in the South. In the first half of 2022, renewables generated more than half of the German gross electricity consumption. The lack of transmission and rise of geographically-concentrated renewable output increasingly cause grid congestion, leading to redispatch, curtailment, and other short-term measures. At the same time, the phase-out of coal and nuclear energy and the integration of European power markets pose additional challenges for congestion management.

Having recognized the significance of the problem, policy makers have worked to accelerate grid expansion, and the German Parliament has passed two laws,[54] but progress has been slow. In 2015, Germany amended the Law on the Expansion of Power Lines setting a regulatory framework for planned high-voltage transmission lines from Northern to Southern Germany, namely the SuedLink and SuedOstLink. However, the TSO responsible for the implementation face ongoing resistance by local communities that resist network expansion in their neighbourhoods. Germany's permitting and licensing procedures allow for objections and lengthy settlement negotiations. The new German government has stated its aim to reduce the complexity of licensing procedures to allow for faster network expansion. For the time being, redispatch remains the main tool for TSO to guarantee grid adequacy.

Distribution grid expansion faces similar obstacles with regards to permits and licenses. The underlying technical problems are somewhat complicated by the fact that DSO do not dispose of the sophisticated set of ancillary services available on the transmission level. This made the Reform of Redispatch (Redispatch 2.0) necessary.

Improving flexibility in the distribution grid

Over the past two decades, electricity grid operators have been learning how to cope with the intermittent renewable feed-in. In the beginning, the regulatory framework and the technical monitoring capability proved sufficient. More recently, however, it has become evident that both technical upgrades and regulatory amendments are required to tackle the challenges of electricity systems with high shares of renewable energy. Using available flexibility provided by batteries and DSM for congestion management is key. The need for reform is particularly significant on the distribution level, as the TSO have fully used all flexibility on the system level in the form of ancillary services.

On the distribution grid level, both batteries and DSM offer potential for flexibility. Batteries are owned by prosumers or suppliers, and DSM provided through load control of commercial appliances such as storage for cold or heat also offer technical flexibility.

Smart grid technologies are a prerequisite for harnessing DSM and batteries for congestion management. Smart grid technologies include monitoring and control capabilities for the DSO. Regulators will also have to allow DSO to use new ancillary services on the distribution grid level or flexibility markets. These will enable the DSO to contract the flexibility needed from operators of flexibility assets. The 2021 energy industry law change will allow some forms of flexibility contracting.[55]

Reform of Redispatch (Redispatch 2.0)

Because of the slow transmission grid expansion, Germany has faced rising demand for redispatch. The demand for redispatch has slowed in recent years, however, the need for measures by network operators in Germany to relieve grid congestion has risen sharply up to 2015, and has fluctuated at a high level ever since. In 2018, around 4% of electricity generation in Germany was affected by redispatch measures.[56]

The costs for redispatch result, on one hand, from the reimbursement of the fuel costs and the ramp-up costs of the respective power plant and, on the other hand, from the balancing of the balancing groups of the system operator affected by the redispatch measure by the TSO, as is the case in the complete shutdown of a power plant. Costs of national and cross-border redispatch amounted to €220.5 million in 2020.

When curtailed through feed-in management, operators or RE plants are subsequently compensated for costs incurred and lost profits.

To keep the curtailment of renewable energy to a minimum and address the mentioned challenges, the government adopted various reforms to redispatch measures since 2019.[57]

The 2019 Act to Accelerate the Expansion of Energy Lines combined the former redispatch and feed-in management into Redispatch 2.0. The target of Redispatch 2.0 is to optimise redispatch, minimise costs and thereby also reduce grid fees. Since October 2021, all conventional and renewable energy installations with installed capacities over 100kW are now participating in the process. Redispatch can also aggregate medium-sized plants as well as small and micro plants to participate in redispatch.[58]

Redispatch 2.0 entails significant challenges for the distribution grid. DSO are now obligated to participate in congestion management and contribute to security of supply.

Development in balancing markets

The progress of the energy transition comes with two challenges concerning the provision of balancing energy:

- In principle, variable renewable energy feed-in increases the need for balancing energy due to the discrepancy between generation forecast and actual generation.
- The number of balancing providers will decrease since most balancing providers are thermal power plants.

The integration of variable RE in theorgy tends to increase balancing requirements due to wind and solar forecasting error. In practice however, improved weather forecasts and expanded intraday electricity trading markets have alleviated balancing energy demand despite increasing share or variable generation from wind and solar. Nonetheless, balancing energy remains an essential requirement of any electricity system. Moreover, since 2014 the EEG introduced a mandate for large renewable plants to market their own generation and thus become fully balancing-responsible. Balancing needs have not increased since this measure came into effect indicating that adequate policies can help integrate high shares of variable renewables without increasing balancing needs.

Due to the declining number of thermos power plants in the balancing markets, in the future other assets will have to step in to provide this service. Variable renewable energy assets are generally better suited for negative balancing power, gas and biogas fired CHP, battery systems (industrial batteries and batteries from electric cars), hydropower and demand side management can also provide necessary balancing energy. Today, pumped storge facilities and large-scale batteries provide balancing power on the system level. In principle, DSM has high potential to offer ancillary services on the system level. Similarly, aggregation of distributed flexibility can make additional flexibility available for balancing and other ancillary services. As of today, both options are underdeveloped.[59]

Still, small-scale installations are harder to be steered by DSO and require intelligent data and control systems. Currently, the participation of variable RE in electricity balancing markets, whether individually or aggregated is still limited.[60]

Wind and solar power are technically capable of rapid upward or downward ramping, without significantly increasing maintenance costs or affecting the service life of the plant. In contrast to the ramping of thermal plants, which causes temperature changes for boilers, tubes and turbines inducing fatigue. Wind and solar can ramp up only if they are operated below their potential output, so that providing positive balancing energy requires a higher and more constant level of generation curtailment, whereas curtailment of wind and solar for downward balancing services requires lower curtailment and therefore entails lower costs.[61]

Overview of Germany's reserves system

Germany developed a system of reserves starting in 2016 to alleviate the risk of a shortfall of capacity during the winter months as well as to reduce excessive redispatch in the absence of enough transmission capacity. Because Germany and Europe overall are well-supplied with capacity, even with the retirement of coal and nuclear plants, the creation of this reserve proved controversial, and the amount of reserve authorities deemed necessary remained smaller than anticipated. Even in late 2021, the government did not anticipate activating the reserve capacity. Only after the gas supply crisis in 2022 did the government change course and temporarily activate the reserve.

Generation adequacy requires that supply and demand remain in balance at all times, including periods of peak demand. In systems with a high proportion of wind and solar, system adequacy assessments focus on times of low renewable energy output. To determine the generation capacity necessary to uphold generation adequacy, TSO use a methodology that adds the net generation capacity and then subtracts all non-usable capacity and outages. The reliable or firm available capacity combined with system service reserves make up the available capacity. This available capacity must equal the peak load. Flexibility such as demand side management in industry can reduce the need for capacity.

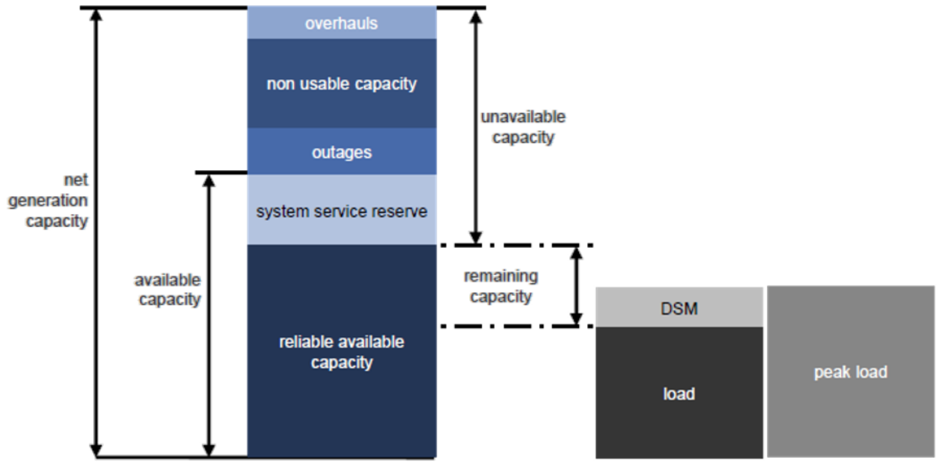

Figure 11: Methodology used by the German TSO assuring generation adequacy

The amended Electricity Market Act, which came into force in 2016, provides for the establishment of various mechanisms to ensure the security of power supply, including the systems of reserves. BNetzA established an additional safety net of non-market-related safety reserves. This system of reserves complements the German energy-only market and together form the Energy-Only Market 2.0

The reserve system consists of conventional electricity generation assets, which would otherwise have been decommissioned due to insufficient revenue in the market or as part of the government-led phase-out plan for coal and lignite. Different reserve mechanisms are utilised in a sequential manner and entail the **network reserve**, **capacity reserve** and the **security reserve**.

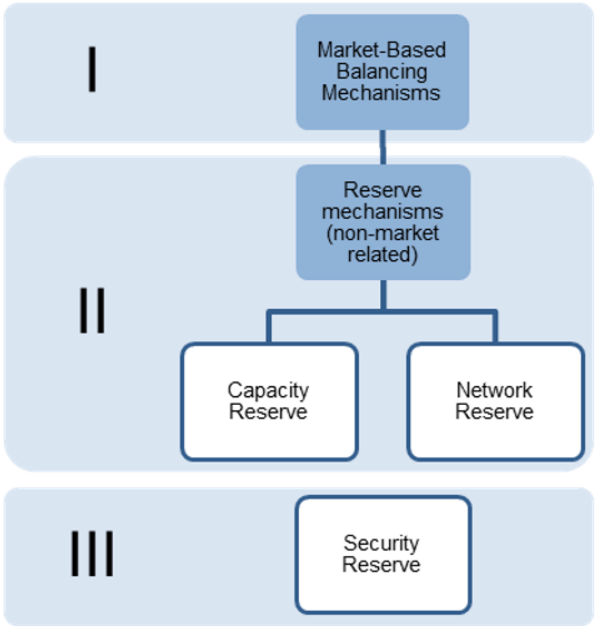

Figure 12: System of reserves, order of appearance

The network reserve ensures that sufficient capacity is availability for redispatch measures. The demand for electrical energy is usually particularly high in winter. In North Germany, more energy is produced while the industrial south is in higher demand of energy. Occasionally, the existing transmission grid is insufficient to transport the full amount of energy. These grid bottlenecks require a redispatch of power plants: in the north power plants are redcuing their output or are being shut down and in the south plants with the same capacity are started or ramped-up by the respective TSO to relieve the electricity grid and fully meet demand. Because of the withdrawal of thermal and nuclear plants at the end of 2022—especially in southern Germany—this north-south divide is expected to intensify.[62]

Every year, the BNetzA determines the required size of the network reserve, also known as the *winter reserve* or *cold reserve*, based on analyses by the TSO. For the winter of 2020-2021, the network reserve stood at 6.6 GW, and consisted of non-operational plants or those awaiting decommissioning. This distinguishes the network reserve from standard redispatch services: the power plants are not allowed to participate on the electricity market during their time in the network reserve. Currently, both coal-fired and gas-fired power plants are part of the network reserve, with a few oil-fired plants as well. [63] The network reserve is regulated by the Grid Reserve Ordinance (NetzResV) and the use of the power plants in §13d (1) of the Energy Industry Act.

It is the respective TSO's responsibility to determine and make available the capacities needed for the network reserve. The stand-by costs, that is the one-off and ongoing costs of establishing and maintaining operational availability, are then reimbursed to the TSO.[64] The costs are allocated to the grid fees. The cost of the network reserve for 2020 amounted to €282 million.

The capacity reserve on the other hand is necessary to support the system balance in exceptional and unpredictable situations and in this way maintain the balance between electricity generation and consumption. To ensure security of supply, the capacity reserve is to be used if, despite free pricing on the electricity exchange, there is insufficient supply to meet the demand for electrical energy. It is therefore independent of the electricity market and thus creates additional security for consumers. For this purpose, existing generation plants, storage facilities or loads are kept outside the electricity market.[65] The Capacity Reserve is pursuant to §13e of the Energy Industry Act (EnWG).

Power plants can participate in both the capacity reserve and the network reserve. An important prerequisite for inclusion in the capacity reserve is a ramp-up time of less than 12 hours, which is why most coal-fired power plants are not suitable for the capacity reserve. In the period of 2020-22 all power plants reserved for the capacity reserve are gas-fired plants.[66] The capacity reserve does not serve to balance peak loads, but only to balance supply fluctuations.

The TSO must procure the capacity reserve in a competitive, transparent, and non-discriminatory tendering procedure. In the period of 2020-2022, eight power plants with a total installed capacity of 1.056 MW are part of the capacity reserve. Plant operators receive a fixed sum of € 68,000 per MW of provided capacity. This amounts to € 72.42 million per year.[67] The TSO are remunerated through grid fees levied on end customers.

In addition to the network reserve and the capacity reserve, the security reserve is a third safety net in the German power system.

The security reserve (based on lignite) was introduced in 2015 and formalized by the 2016 Electricity Market Act. The measure provides for eight lignite-fired power plant units with a total capacity of 2.7 GW to be transferred into the security reserve and finally shut down after a period of four years. The security reserve is designed in case of insufficient electricity production, including all regular security measures (such as redispatch, control energy, flexible loads, network reserve and capacity reserve). Coal plants subject to decommissioning initially transfer into a so-called safety standby. During this period, the power plants shut down and can only be reactivated in extreme situations. After four years, the safety standby period ends, and the power plant is shut down permanently.

Given that the last plant was added to the security reserve in 2019, the security reserve will completely end in 2023.

As for power plants in the grid and capacity reserve, power plants in the security reserve may no longer be active on the power market. In the event of a request by the TSO, the plants must be ready for operation within 240 hours (10 days); once they have been made ready for operation, they must be able to be started up to minimum partial output within 11 hours and to net nominal output within a further 13 hours. In return, the plant operators (MIBRAG, RWE and Vattenfall) have received compensation totalling €1.61 billion since 2016 (€230 million per year, as of 2021), which will also be passed to consumers through grid fees.[68]

Table 1: Generation assets in the reserve system[69]

Type of Reserve	Type of plants listed
Network Reserve	The Network reserve lists three types of plants: Gas-fired plants, oil-fired plants, and coal-fired plants.[70] • Gas: 1.4 GW (19% of network reserve) • Oil: 1.6 GW (22%) • Coal: 4.3 GW (59%)
Capacity Reserve	The capacity reserve lists only gas-fired plants of 1.3 GW.
Security Reserve	The Security reserve lists only lignite power plants of 1.9 GW.

TSO have several options at their disposal to manage and guarantee grid and system stability (as seen above). These include different ancillary services (predominantly balancing energy), redispatch and feed-in management (now Redispatch 2.0) and the reserve system. Most of the costs are passed on to the end consumers via the grid fees.[71] The total costs for system service—including procurement of electricity lost in transmission and distribution and payment to curtailed renewable electricity generators—were €2.0 billion in 2020, which is a slight increase since 2019.

Costs for balancing capacity decreased due to several reasons in recent years. Especially relevant is the higher European competition in the balancing market. This indicates that enough balancing capacity is available in the market.

3.3 Fuel security

Apart from the electricity system design aspects discussed in the previous section, the secure supply of electricity also depends on the reliable procurement of conventional energy carriers. Germany uses lignite and hard coal mainly for electricity generation purposes. In 2021, lignite and hard coal accounted for 28.1% of German electricity generation.[72] In 2021, primary energy consumption of hard coal and lignite were almost at the same level. The former amounted to 292.2 TWh and the latter to 313.9 TWh. Gas-fired power plants have an important share in electricity generation, contributing 12.6% in 2021. Moreover, both gas-turbines and combined-cycle gas-fired power plants offer considerable flexibility in power generation: they can ramp up and down generation within a short timeframe. Thus, they often provide ancillary services such as balancing energy. Gas-fired power plants typically cover peak load generation. However, coal-fired power plants can deliver these services as well, though typically at higher cost (due to must-run conditions).

Supply of hard coal and lignite

Germany meets most of its lignite demand with domestic production. Since phasing-out domestic hard-coal production in 2018, Germany imports its entire coal demand. In 2021, it imported around 32 million tonnes of hard coal, over half of it from Russia. Germany's next biggest import sources were Australia and the U.S., each accounting for around 15% of total imports. The German government has taken measures to reduce and effectively end Russian coal imports by the end of 2022. Since coal infrastructure requirements are less rigid than gas, coal sources are easier to diversify. Germany plans to increase coal imports, among others, from South Africa, Australia, the U.S., Colombia, and Indonesia.[73]

Gas supply security policies

Gas supply matters for Germany: As of 2019, 48.2% of German households used gas-fired central heating for their homes. Moreover, German industry with its focus on manufacturing used a total of 366 TWh (or 36% of total consumption) in 2021. Consequently, the security of gas supply is highly relevant for German consumers and industry alike, including the security of supply of electricity. Though Germany has large amounts of gas storage capacity, it has hardly any conventional gas reserves, and import capacity is constrainted by the gas import pipeline. The recent gas supply crisis shows the vulnerability of the energy system with respect to gas shortages.

As a response to an earlier gas supply crisis in 2009, the European Commission adopted the regulation (EU) 994/2010. The regulatory framework includes a security and supply concept for natural gas applicable to all Member States in order to be prepared for a possible disruption of supplies from the East, especially during fall and winter. In case of crisis, the European Commission regulates that neighbouring countries should provide a minimum of gas for 7 or 30 days to protected customers depending on the defined scenario. A uniform EU-wide definition of protected customers is therefore mandatory to help the affected EU countries to determine which customers are protected. In principle, households as well as small and medium-sized enterprises are considered protected customers, although it is still up to the Member States themselves to determine the level of protection. The neighbouring countries for Germany defined by the EU Commission are limited to the Czech Republic, Poland, and Slovakia. The solidarity mechanism regulates that in case of a supply risk for private households, health services, emergency and security services, neighbouring states may interrupt the gas supply to their non-protected customers out of solidarity.

To ensure that the necessary amounts of gas are available on the EU internal market without any physical constraints, the security of supply law includes regulations to improve cross-border pipeline capacity. For member States depending on a single import pipeline, the n-1 rule applies. According to this rule, countries are obligated to ensure natural gas supply even if the main infrastructure fails. To increase the entry capacity and have access to new sources, the regulation requires TSO to enable permanent bi-directional capacity on all relevant cross-border points, and regulatory authorities must check the need for reverse flows when they update their risk assessments.

To estimate the proximity and probability of an immediate crisis, an adequate and comprehensive monitoring is crucial. Competent authorities of all Member States must assure the maintenance of warning tools such as real-time alerts to enable the commission and authorities on a regional level to mobilise and incentivise market players to reduce gas consumption.

The strategic reserve for gas and oil in Germany

Gas storage capacity in Germany was around 274 TWh in 2020, corresponding to about a quarter of German annual gas demand. This capacity has remained relatively stable since 2015. Prior to 2015, Germany had gradually increased storage capacity from the mid-1970s through 2014, when storage capacity peaked. Twenty-three companies operate underground natural gas storage facilities as of 2020. The three companies with the largest storage capacities had a market share of around 67% at the end of 2020.

Domestically, natural gas has been stored in underground storage facilities since the mid-1950s. It was not until the mid-1970s that storage of significant quantities began. Germany uses two main types of gas reservoirs for storage. The first is pore storage, a naturally occuring type of reservoir, mainly in former gas and oil fields, or saltwater aquifers. In 2020, about 36% of Germany's gas storage capacity is in pore storage facilities. Cavern storage facilities (artificially created cavities in salt caverns, rock caverns, or abandoned mines) provide additional storage space. Around 64% of Germany's gas storage capacity is located in cavern storage facilities.

Due to relatively low storage levels in German gas storage facilities in the summer of 2021, the German government decided to pass a bill to amend the Energy Industry Act (EnWG) to introduce fill level requirements for gas storage facilities. This bill makes amendments to the Energy Industry Act and sets corresponding minimum fill levels for gas storage facilities. As of mid-August 2022, Germany gas storage are filled to 75% of their capacity. However, market players are criticising that they are under constraint to buy gas at high prices to reach the minimum filling level and would suffer financial losses when selling at low prices. For this reason, the gas industry is currently calling for the federal government to provide financial safeguards. One of the leading gas suppliers, Uniper, receives government support as of 22nd July.

The German Ministry for Economic Affairs and Climate Action (BMWK) addressed this problem and will launch auctions for so-called long-term options, whereby the state rewards gas retailers when withholding gas reserves instead of marketing them. Furthermore, the government also plans to expand its solidarity contracts to countries like Poland, Italy, or France. The governing administration plans to conclude nine additional solidarity contracts in line with EU regulation on gas supply security. The defined protected customers in Germany include households, hospitals and district heating systems.

The target fill level for the 1st of November is 90%. The Federal Network Agency does not expect this target to be reached after Russia reduced its gas exports drastically and is only exporting gas via the Nord Stream1 pipeline at a capacity of 20%. In reaction to a potential gas shortage during winter 2022/2023, the European Union reached an agreement to reduce natural gas demand in the EU by 15% this winter.

Germany holds 132,480,000 barrels of proven oil reserves as of 2016, which would cover the daily oil consumption of 2,383,393 barrels for a period of 56 days only. This leaves Germany highly dependent on oil imports to meet oil demand. Consequently, the government reacted with precautions any measures against short-term disruptions of supply and embedded an emergency oil supply and oil crisis management within national operations.

Since 1998, the Petroleum Stockpiling Association (in charge of Germany's strategic petroleum reserves and under public law with legal capacity) set a strategic petroleum reserves equivalent to 90 days' worth of domestic consumption to offset three months of total disruption of all oil imports. The Association stores reserves of some 15 million tonnes of crude oil and 9.5 million tonnes of finished petroleum products to fulfil its legal requirements to respond quickly in case of emergency Germany holds reserves of petroleum products in all parts of the country. Most of them are located in caverns in the north of Germany.

Being able to respond fast in case of an emergency requires a sound crisis management in place. For Germany that means that the Federal Ministry for Economic Affairs and Climate Action would issue an ordinance pursuant to the Oil Stockpiling Act, reducing the storage requirements for a limited period and subsequently make reserves available at market prices. This enables market players to access additional amounts of gasoline fuel within a few days. The legal framework under which the government can free up reserves exists in Section 12(1) of the Oil Stockpiling Act.

3.4 Political debate on generation adequacy 2012-2022

The simultaneous phase-out or displacement of conventional generation assets and expansion of variable renewable energy potentially leads to a generation adequacy problem. There is no consensus among energy economists that conventional (or at least flexible) generation assets are needed to guarantee security of supply in the markets.[74] Some economists argue that peaks in residual load (which refers to total load minus solar and wind generation) could be met by flexibility measures alone, including the use of electricity storage, DSM and cross-border trade. These issues have been subject of an intense debate in Germany as well as other European countries. In order to provide generation adequacy, Germany has adopted the system of reserve mechanisms described in section 3.2, consisting of conventional electricity generation assets (based on lignite, coal and gas)

In the late 2000s concerns were raised that Germany is facing a power shortage and a lack of controllable power generation. Since 2012, several market participants had published proposals for different capacity mechanism designs. A capacity mechanism can take different forms, with one fundamental difference between different models: It either consists of a mechanism remunerating the availability of generation capacity in addition to the sales revenue in the wholesale market (capacity payments or market), or it is a set of generation assets operated by the TSO outside the market and activated in times of need (reserve mechanism). In a series of publications, experts proposed different models of capacity mechanisms for Germany.

In August 2014, the German Federal Ministry of the Economy and Energy (BMWi) published three independent studies with an assessment of options to improve the Energy-Only-Market to cope with current problems and different capacity market options. All three studies concluded that a capacity market was not required to guarantee long-term security of supply for Germany. They argued that in the future the wholesale market prices were going to increase following the decommissioning of conventional generation assets and that price spikes would suffice to incentivise the investment into flexible assets, including both gas-fired power plants and DSM. Additionally, two of them recommended the introduction of a strategic reserve.

BMWi's 2015 publication *A power market for the Energiewende* recommended a number of actions to improve the German wholesale market. Among other measures, it proposed a system of reserve mechanisms that the German government finally adopted in 2016. The stepwise introduction of the reserve mechanism, begun in 2015, was a political compromise with the utilities: Several lignite and gas-fired generation assets that were threatened by decommissioning due to insufficient market revenues were transferred into the reserve, providing them with new economic revenues outsde of the market and without generating electricity.[75]

Description of different capacity mechanisms

All capacity mechanisms generally aim at remunerating the provision of capacity, as distinct from the remuneration of electricity generation. Generally, this remuneration is financed by a fee paid by all electricity users.

There are several design options for capacity mechanisms. A fundamental consideration relates to the setting of the capacity payment. The payment can either be fixed administratively or by a market mechanism.

Under **price-based capacity mechanisms**, plant owners receive a defined payment for providing capacity chosen by policy makers. This can be fixed over a longer period (fixed payment), or vary, dependent on the development of power market indicators (dynamic payment).

Under **quantity-based capacity mechanisms**, policy makers do not fix capacity payments, but set quantity targets for future capacity; the remuneration is then set under a procurement scheme.

In a **centralized capacity market** the operator being an independent entity (for example the regulator) sets a capacity target that is then procured in an auction for remuneration. All secure capacity that is procured receives the same remuneration per unit of capacity (priced in €/kW). In a **decentralized capacity market**, electricity suppliers have to purchase capacity certificates from generators that ensure secure generation.

A second important design option is between a **comprehensive** or **selective capacity mechanism**. A comprehensive capacity market sets a target for total capacity. All plants that provide secure capacity can participate. Selective capacity markets aim at incentivising investments into or avoiding decommissioning of power plants. Only prequalified operators can participate in selective capacity markets. Prequalification criteria could be that the power plant is about to be decommissioned or that a highly flexible and low-carbon new plant is built.

A **strategic reserve** is a selective capacity mechanism that is operated outside the market by the TSO. The TSO contracts a certain quantity of capacity which often consists of plants that would otherwise have been decommissioned. The strategic reserve is activated under pre-specified conditions, usually if prices at the wholesale exceed a strike price or if total demand exceeds total supply. Proponents of a strategic reserve argue that it requires only little intervention in the market design and is in principle well reversible.[76]

Within Europe, there are several different capacity payment or market designs. The European Commission has set some rules that aim at ensuring capacity markets do not comprise the functioning of the internal market for electricity. In 2016, the European Commission found 28 different capacity mechanisms across its member states.[77] While the mechanisms differ in detail, the fundamental difference is the use of a capacity market, such as in France, versus a strategic reserve, such as the one adopted by Germany.

France passed a law to enable the introduction of a capacity market in 2010, after a long elaboration period and discussions with the European Commission, France began operating its capacity market in 2017. In the years preceding the legislation, the French TSO RTE had warned repeatedly of risks of major outages in winter, caused by peak loads due to electric heating. The French capacity market is comprehensive: all generation capacities above the threshold of 1 MW must participate. Apart from conventional generation assets renewable energy and demand side management facilities also participate in it. Flexible consumers have the right to sell capacity certificates the same way as generators. In the market, generators and DSM operators sell capacity certificates corresponding to the available power capacity they can provide to the system during peak periods defined by the TSO.[78] If they fail to make their capacity available in these periods, they are subject to severe fines. On the demand side of the capacity market, suppliers and large consumers of electricity are mandated to purchase the capacity certificates, based on an estimate of their peak demand. In critical times of the electricity system, they must not exceed the load set by the certificates they purchase.

Importantly, the capacity market is separated from the wholesale market: a capacity certificate mandates the issuer to make its capacity available to the wholesale market, but not to any specific client.

A decentralized capacity market was proposed for Germany by the association of municipal utilities (VKU); a proposal Agora Energiewende criticised.[79]

Debate on generation adequacy prior to the gas supply crisis of 2021/2022

Discussions about the future security of supply often revolve around the question whether the current market design with a capacity reserve is suitable for a carbon-neutral future. The obvious challenges: Today's capacity reserves consist mainly of fossil-fuel based generation assets (German TSO contract some DSM as well). Some experts suggest that the expansion of DSM and batteries, enable by higher electricity prices and price spreads in the spot market will suffice to guarantee generation adequacy. Most studies, however, suggest that a significant capacity of highly flexible and controllable gas-fired power plants are needed in addition to that. Those power plants must be hydrogen-ready, to facilitate a climate neutral power system as soon as sufficient green hydrogen is available. Clearly, current events challenge this view, as they highlight that the security of supply of gas is a fundamental problem in its own right.

The gas supply crisis and Germany's reserves

The gas supply crisis after the 2022 war in Ukraine illustrates the high European and German dependency on imports of Russian gas and sparked immediate efforts to diversify the European energy supply and reduce gas demand. Germany has accelerated legislative efforts to safeguard security of supply and expand the deployment of renewable energy. Electricity supply is adequate and secure, but gas supplies used mainly for heating and industry are not.

In the beginning of 2022, the German Government passed the largest energy policy amendment in decades, modifying and expanding, among others, the Renewable Energy Act, Offshore Wind Act, and Energy Industry Act. Additionally, the Government enacted measures to react to a deterioration of the supply situation on the energy markets.

The war in Ukraine has led to a spike in energy prices, and especially to concerns about the future security of gas supply. Therefore, the German government implemented the Substitute Power Plant Standby Act and the Energy Security Act designed to withdraw gas-fired power plants from the power market to save gas in electricity production and to expand the responsibilities of the Federal Network Agency. The law also temporarily allows the participation of oil- and coal-fired power plants of the reserve system (total capacity of 8 GW) in wholesale electricity market.

The Substitute Power Plant Standby Act governing the coal plant activation limits the coal power plant reactivation until 31 March 2024. Germany has thus delayed the retirement of coal-fired plants next year to deal with physical gas shortages and thereby prioritise limited gas supplies for heating in households, public buildings, and industry, where short-term replacement is more difficult than in power generation. The law represents a temporary insurance in case of a severe gas shortage for heating and industry this winter.

The immediate consequences of the energy crisis are two-fold: First, the crisis has pushed policy makers to further accelerate the expansion of renewable energy. The reforms listed above intend to accelerate the expansion of renewables further. The Renewable Energy Act defines renewable energy as an overriding public interest of national security. This will accelerate permitting and planning procedures and creates incentives for a faster expansion of PV and the production of green hydrogen.

Second, the crisis has slowed the phase-out of coal. While more renewables will have mid- to long-term benefits for both supply security and climate, the coal plant extension and reactivation has more of an immediate, short-term effects on the security of supply in Germany.

The new policy on coal retirements puts Germany's climate goals under pressure. The reactivation of coal plants leads to unplanned additional carbon emissions. As these emissions are subject to allowances of the EU ETS, total emissions in the EU will not increase. However, the measure has a negative impact on German emission targets, and German policy makers are considering ways to compensate these emissions with purchases of carbon credits and reduce emission further in other sectors such through a ban of new gas heating systems from 2024. A new plan also envisages a large uptake of heat pumps.

3.5 Summary

This chapter summarizes Germany's overall present security of supply situation, focusing on the electric power sector, but incorporating observations about the present gas supply crisis brought about by the war in Ukraine.

In general, a well-functioning spot market, flexible dispatch, reformed policies for redispatch, mandates for uptake of renewable energy, and connections to Germany's neighbors have provided sufficient incentives to generators and grid companies to maintain adequate capacity, with sufficient flexibility to absorb a steadily increasing share of renewable energy.

Starting in 2016, Germany also adopted a system of reserves, consisting of capacity reserves, network reserve, and security reserve. All consist of fossil-fuel pwoer plants undergoing the process of decommissioning. While the introduction of the reserve systems was controversial and the government until recently did not expect to ever activate the reserves. The ongoing gas supply crisis allows power plants operators temporarily reactivate some of their oil-and coal plants to delay the decommissioning of others. While policy makers hadn't designed the reserve system to respond to a gas supply crisis, arguably the present situation suggests the ongoing value of such emergency capacity to deal with unexpected contingencies.

The gas supply crisis also highlights the inherent vulnerability of energy systems that rely on fuel imports from one large supplier, and the benefits of Germany's energy transition in replacing fossil fuels with renewable energy. While Germany and the EU have designed various measures to improve the security of the gas supply system, such as the 1 + n capacity policy, these are clearly inadequate to handle a major shortfall in physical gas imports. The German government has acted to accelerate renewable expansion and the electrification of gas-dependent heating and industrial processes. These policies will still take years to fully implemented and show their effects, to avert current gas shortage those policies should have been adopted by the government years earlier.

China is at the early stage of integrating variable renewable energy into its power system, and most provinces by 2030 will still have a lower share of wind and solar than Germany does today. China's energy system is also far less reliant on imported gas than Germany, and its power system is almost entirely reliant on domestic fuels. Therefore, the most relevant German security of supply measures relate to the adoption of liquid spot markets and flexible dispatch to integrate high proportions of renewables.

The next chapter turns to the future, looking at the measures Germany will need to reach full decarbonisation of its power sector over the next decade.

4 Ensuring adequacy in the future

Achieving the goals of the German energy transition—in particular, the goal of climate neutrality by 2045 on the basis of reliable energy supply —requires bold policies. Most experts agree on the vital role of renewable energy in a future energy system and on the need for comprehensive electrification of sectors reliant on fossil fuels today, including passenger transport and heating. Moreover, there is consensus that hydrogen and its derivates will be part of the future energy mix. DSM, smart charging of EVs, and vehicle-to-grid technologies could also play a role in providing flexibility and ensuring security of supply.

4.1 Future German energy supply

The new government published its targets for the energy transition as part of its coalition agreement in December 2021. They include a target share of 80% renewable energy in the electricity sector for 2030 and the goal of a climate neutral system in 2045. For 2030, the government expects an increase of use of electricity to 680-750 TWh per year. The massive expansion of variable RE in the electricity sector will require further enhancing system flexibility on both the supply and demand sides.

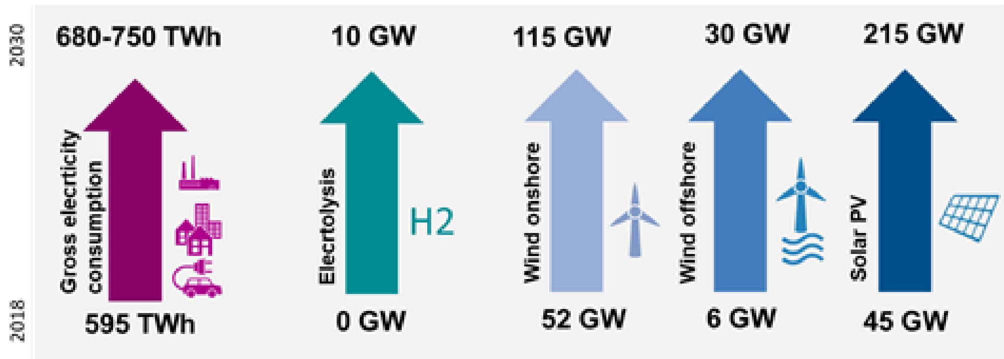

Figure 13: German energy transition targets for 2030

Prior to the government's formation, several institutions published scenario-based studies on the future of energy supply in Germany, in line with the climate neutrality target for 2045 that had been passed into law by the previous government. Among the institutions, the dena lead-study Towards Climate Neutrality analysed likely developments with a consortium of 70 companies and associations, representing various sectors of the German energy supply system and the economy as a whole.[80] The study suggests that even a climate neutral electricity system can provide the highest standards of security of supply. Final energy consumption is projected to fall over time because of lower fossil fuel use and increase electrification with renewables. Electricity and hydrogen consumption rise, while biomass stagnates. Both coal and natural gas phase-out over time.

The 2021 dena study results are in line with other transition scenario research: All studies predict a fall in final energy consumption and an increase in the use of electricity. The main difference between the scenarios is with regards to the role of gas: the share of methane in energy consumption in 2030 varies between 16% and 27%, being replaced by other energy carriers thereafter. The contribution of PtX, including hydrogen, to energy consumption varies between 4% and 25% in 2045.

4.2 Future electricity sector

As outlined in the previous section the decrease of power generation by coal and nuclear power in line with the German law is accompanied by a strong uptake of RE. This is government policy, and this is also reflected in most future scenarios. These vary, however, with regards to total installed capacity and generation in 2045.

Building on a broad consensus with regards to RE expansion, the government now focusses on removing obstacles in permitting and licensing processes. So far, onshore wind farms have faced opposition in some regions, resulting in long procedures due to objections by local citizens. At the same time, the general support for renewable energy expansion is high, given significant cost reductions over the past decade.

Satisfying peak demand

As the future energy system will have a higher share of electricity in final energy consumption, peak electricity demand will be also higher. On the demand side, peak demands increase mainly due to the simultaneous expansion of heat pumps and electric vehicles, but also due to the electrification in the industry sector. On the supply side, periods of low wind and solar PV generation add to the challenge of satisfying peak demand. Securing the continuous supply of electricity or generation adequacy requires that the maximum inflexible load (the peak demand in the end-use sector accounting for flexibilities) can be met by remaining generation capacity in the system accounting for low RE generation. With coal and nuclear energy to be phased out over the next years, the remaining flexible generation technologies are power plants based on biomass/-gas and hydrogen. The differences in scenario outcomes reflect the importance the studies give to load flexibility and storage which reduce the maximum inflexible load and thus the underlying generation adequacy problem.

According to the dena study the peak demand can be reduced by 4 GW through demand flexibility in the industrial sector while other loads are considered inflexible. The maximum inflexible load increases from 77 GW in 2019 to 94 GW by 2030, and then up to 107 GW in 2045. Prior to the Ukraine war, planners assumed gas-fired plants would cover inflexible loads for the remainder of the decade, while batteries and other flexible technologies would play a bigger role in the time after 2030.

Market design challenges

A power system with high shares of variable RE represents challenges with regards to the security of supply, which may make adaptations in the market design necessary. As for generation adequacy, the previous subsections outlined the projections made by several studies with regards to the future German energy mix. Given the merit order problem, the built-up of flexible generation assets may require changes in present market design. The dena lead study recommends to introduce a capacity market, to provide additional incentives for the development of new gas-fired power plants, as it identifies an additional capacity of 15 GW until 2030. These should be hydrogen-ready, that is a fuel switch in the investments 2030s should be easy to implement. Clearly, however, given the current gas supply crisis, the implementation of that recommendation has been put into doubt. Currently, gas generation is reduced, resulting in additional coal power generation. It is conceivable that coal will have a greater role in bridging the time from today into the future where both DSM and hydrogen will be more readily available than today.

Independent of the fuel used by backup capacity, RE development with its impact on marginal costs is a challenge for capital-intensive investments in power generation as their cost recovery will be increasingly difficult. Decentralised generation also raises the coordination effort across different grid levels.[81] It remains to be seen whether incentives for investment into controllable power generation, storage and DSM suffice under the present system. The alternative to the introduction of a capacity remuneration (most likely a capacity market) would be a reformed reserve system. The present system has contributed to secure supply over the past decade; however, in the long run coal-fired capacity would have to be substituted with carbon-neutral alternatives. Further issues are intertwined with generation adequacy: most notably the future of ancillary services depends on the available generation assets (as well as DSM and storage).

Currently, the debate on this matter is open. Therefore, the German government has announced it will introduce a platform for debate that develops a set of final, binding recommendations on market design issues, solving the questions on generation adequacy and others. Apart from generation adequacy, important topics of discussion also include measures to increase flexibility in the distribution grid, participation of battery energy storage in energy markets, and a greater role for DSM.

4.3 Future gas sector

As explained above, scenarios of the future energy system foresee a stepwise reduction of the use of methane and a parallel increase of hydrogen use, with large variations in the relative importance of each energy carrier during the transition and in the future energy system. Most observers agree on the role of hydrogen in future industrial processes, and a majority assumes that secure operation of the electricity system will require some hydrogen-based generation capacity (with different views on the scope). In contrast, the role of hydrogen for heating in residential and commercial buildings is highly controversial among expers and policy makers. The underlying reason is uncertainty with regards to the future cost and the security of supply of hydrogen. Germany will be able to produce only a relatively small imported from countries outside of the EU. Clearly, both the EU and Germany need to undertake comprehensive efforts to achieve their goals. To that end, several support programs for hydrogen generation have been developed, both on the national and EU level. They include schemes that provide hydrogen importers from outside the EU long-term purchase contracts with take-or-pay clauses, providing investment security for investors in green electrolysis.

Both the EU and the German government have published hydrogen strategies outlining the way forward.[82] While these include important commitments for hydrogen as part of the future energy system, several questions remain unanswered today. These concern, among others, the regulation of future infrastructure and comprehensive support schemes enabling users to undertake the fuel switch from methane to hydrogen. Gas system/network operators have clarified their proposal to engage in a stepwise technical upgrade of their assets, repurposing existing structures for the future use of hydrogen transport. Clearly, however, they favour a governance structure that leaves the refurbished assets

share of the hydrogen needed for its future energy needs. A large part of the hydrogen will instead be imported. The dena study projects that for hydrogen imports from other European countries will likely provide most of the demand while additional hydrogen will be

in their possession (their regulatory asset base), regulated under similar conditions as the gas infrastructure today. In contrast, the European Commission favours strict unbundling of the methane and hydrogen infrastructures.[83] Its proposal is currently under consultation, with an open outcome.

As for support schemes, the current gas supply crisis has sparked a debate about an acceleration of the fuel switch to hydrogen. This is reflected in the German government's plan to introduce so-called Carbon-Contracts-for-Difference (CCfD) which will support German industry on the path of transformation towards climate neutrality. This includes the investment into new, hydrogen-based production capacity, set to engender demand.

As of today, there is a vision for the future German energy system and there are plans for the transition. The current gas supply crisis, however, requires short-term answers that may alter the path; in which way remains to be seen.

5 Conclusions and highlights

The topic of security of supply in Germany presents a paradox. On one hand, Germany faces a severe energy crisis brought about by the war in Ukraine, which may lead to physical shortages of gas. On the other hand, Germany's electric power system remains highly reliable, and Europe has adequate capacity to maintain reliability even in the face of a major short-term crisis. The measures Germany and Europe have adopted to achieve adequacy and flexibility were necessary to achieve a high proportion of clean, low-carbon, renewable energy—which in turn directly alleviates the impact of short-term crises like the current one.

Lessons from the present crisis

Physical gas shortages could severely affect winter heating and industrial production in Germany and Europe. The gas crisis shows that Germany's reliance on imported gas during the transition to a low-carbon economy reduced the country's energy security, including in the electric power sector, which faces sharp price increases due to the role gas has in setting marginal prices on the European spot markets. The outages of French nuclear plants have exacerbated the price spikes, both in gas and power prices.

While Europe has adopted several policies to expand its gas grids and improve resilience, these measures are insufficient to cope with a severe interruption of gas imports. The most effective long-term measures to deal with the loss of imported gas involve accelerating renewables adoption, electrification of heating and industry, and boosting energy efficiency of homes and businesses. However, in the short-term, Germany had to reactivate its coal plant reserve capacity to reduce gas consumption in the electricity sector and make it available to heating and industrial uses that will take years to replace gas.

Lessons from Germany's energy transition

Renewable energy is helping reduce the cost of the gas crisis. Every kWh produced by renewables replaces the need for a kWh from coal or gas. Germany could not have achieved a 50% share of renewables without ensuring reliable electricity supplies, and hence it is valuable to consider the measures Germany and Europe have taken to scale up renewables while maintaining reliability.

- Well-functioning electric power markets, especially high-volume day-ahead and intraday spot markets and sophisticated redispatch policies, have played a central role in integrating renewable energy and incentivizing flexible operation of conventional power plants.
- While Germany's transmission grid build-out has lagged, flexible and bidirectional operation of interconnections with neighbouring countries has helped to maintain reliability and system adequacy, particularly within Germany, but also in the wider European electricity market. The transmission system will play a larger role in maintaining future system security.
- Germany's various coal plant reserves were initially designed as an emergency measure for a shortfall in generation or outages in the grid, but have proven useful in dealing with the present gas crisis—albeit with a climate cost. Had Germany acted earlier to decarbonise heating and industry, it could have avoided calling on these reserves.
- Germany has not needed a capacity market or capacity payments for operational plants, and this issue is still debated. It is possible that batteries, DSM, hydrogen, and other measures and technologies will provide flexible and firm capacity in the future.

Suggestions for China

Germany's current situation is clearly unique, especially given that China does not face any comparable risks in terms of gas supplies. However, considering the longer-term measures Germany has taken, and those policy makers now realize they could have taken earlier, the following suggestions appear relevant.

- The sooner China can adopt short-term spot electricity markets across large geographical areas, the easier it will be to absorb high proportions of renewable energy without building large amounts of coal or other thermal capacity as backup.
- Fees and taxes for electricity can disincentivise electrification that would ultimately reduce fossil fuel and improve efficiency. Incentives for increasing energy efficiency should incorporate incentives for electrification of heating, which has hindered the transition away from fossil fuels in both Germany and China.

- Gas imports through LNG involve high capital costs, supply security risks, and stranded asset risks. Given the technology alternatives, policy makers should prioritize direct electrification over LNG.

The low-carbon energy transition is one of the largest shared projects ever undertaken by humanity, lasting decades and requiring a complex mix of technology, policy, and social changes. Energy is essential to life and to economic development, yet energy security requires evaluating future risks subject to high uncertainty. Through discussion and sharing of experiences, we can reduce that uncertainty and uncover policies that benefit security no matter which contingency may arise.

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