Quo vadis, grid stability? Challenges increase as generation portfolio changes

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Kurzfassung

Quo vadis, Netzstabilität?

Herausforderungen wachsen mit der Veränderung des Erzeugungsportfolios

Das Stromerzeugungsportfolio im deutschen Hochspannungs-Übertragungs- und Verteilnetz verändert sich seit 2011 ständig. Nach mehreren Jahrzehnten mit einer relativ konstanten Segmentierung in Grund-, Mittel- und Spitzenlast und einem entsprechend darauf ausgelegten Kraftwerkspark haben sich in den letzten 10 Jahren deutliche Veränderungen ergeben. Als wichtiges Ergebnis der sogenannten Energiewende, die 2011 mit der Abschaltung der ersten deutschen Kernkraftwerke (KKW) nach dem Reaktorunfall in Fukushima begann, werden die letzten KKWs bis Ende 2022 endgültig vom Netz gehen.

Das Kohleausstiegsgesetz vom 8. August 2020, eine weitreichende Änderung mit Bedeutung für die Energiewirtschaft in Deutschland, verlangt die Abschaltung aller Kohlekraftwerke bis spätestens 2038.

Spätestens ab diesem Zeitpunkt wird es im deutschen Kraftwerkspark keine großen, induktiven Kraftwerke zur Erzeugung von Grundlast mehr geben.

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Introduction

The power generation portfolio in the German high voltage transmission and distribution system has been constantly changing since 2011. After several decades with relatively constant segmentation into base-, medium- and peak-load and a power plant park designed accordingly for these purposes, significant changes have occurred in the last 10 years. As an important result of the so-called Energiewende[1], starting in 2011 with the shutdown of the first German nuclear power plants (NPP) after the reactor accident in Fukushima, the last NPPs will go eventually offline by the end of 2022.

The Coal Phase-Out Act of August 8th, 2020, a far-reaching edit with significance for the energy industry in Germany, requires the shutdown of all coal-fired power plants by 2038 at the latest.

From this point in time at the latest, there will be no large, inductive power plants for generating base load in the German power plant park.

Basic mechanism for a stable electrical power grid

The electrical power grid is stable when generation and consumption are balanced within the overall system. Excess electrical energy cannot be stored directly, and the grid itself cannot store any energy. Generated electricity needs to be consumed instantaneously. Indirect storage in pumped hydroelectric energy storage, battery storage systems, or by other storage technology are possible in principle, but are only implemented to a limited extent in today's electricity supply system [1].

The biggest Battery Energy Storage System (BESS) in central Europe is in Jardelund/Germany close to the German offshore wind farms in the North Sea. The BESS Jardelund has a power of 48 MW, fully charged, and provides 50 MWh of energy before needing to be recharged [2]. In comparison to the power class of a conventional 1,100 MW coal-fired power plant or even a 1,300 MW NPP, the capacity of BESS Jardelund would be exhausted after 2 min 44 sec of the coal-fired power plant respectively after 2 min 18 sec of the NPP full load operating time.

In principle, BESS could make a contribution to storing energy resulting from excess generation by renewables. A review of energy storage technologies in cooperation with wind farms is given by Rabiej [3]. Many publications are produced around the globe which investigate the potential contribution of BESS. Those BESS should be used to enhance the stability of the power grid, ensuring system reliability, increased grid flexibility, and to make further expansion of renewable energy possible – all in regard to the changing electricity market's growing influence of renewables [2, 4, 5, 6]. The application of BESS is promising, but still at a deployment level in terms of maturity, power spectrum and recharge/discharge capacity [7, 8].

A brief assessment of the power spectrum illustrates the current situation of BESS: the annual total net generation in Germany in 2018 was 592.3 TWh [9], which means an average net generation of about 1.6 TWh on a daily basis is required, orders of magnitudes greater than the storage capacity of the largest European BESS Jardelund. The prognoses of storage requirements in Germany vary widely from only[2] 8 TWh up to 61 TWh in [10], 16 TWh in [11][3], and 22 TWh in [12] or even 80 TWh in [13] depending on the deployment level of renewables. It is questionable if studies offering lower capacity prognoses have considered that weather phenomena like the *Dunkel-*

[1] German energy transition.

[2] Even the smallest prognose 8 TWh storage capacity means unbelievable 160,000 times the BESS Jardelund.

[3] Authors of [11] are assigned to the affirmatives of the energy transition. It is noteworthy that they deny explicitly the statements made in [12]. The smaller numbers were obtained since curtailment of renewables has also been considered but not in [12]. In that case, the comparison is hampered.

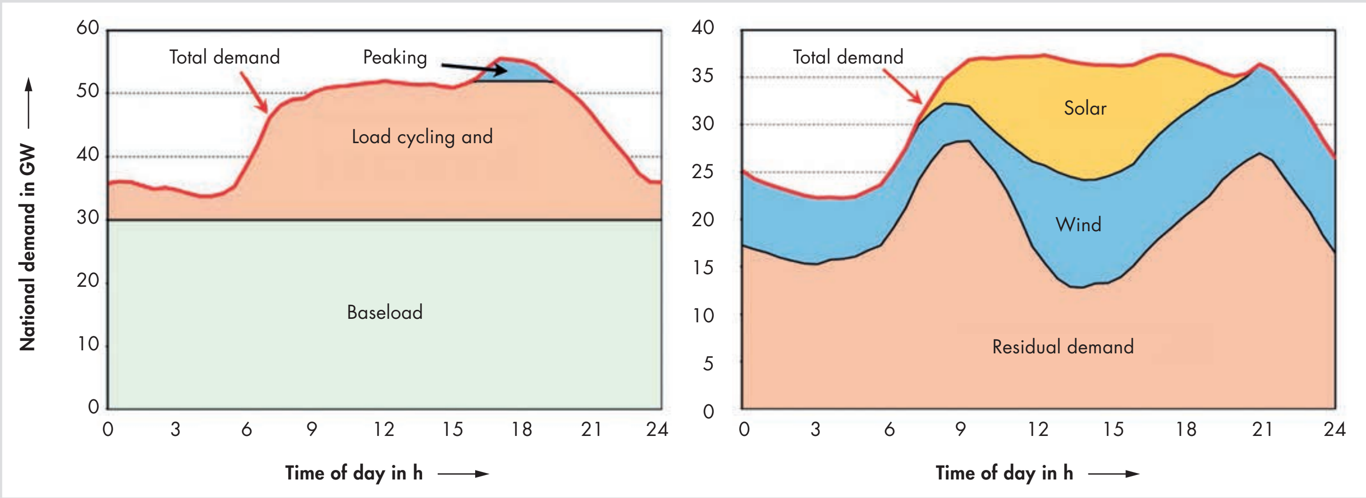

Fig. 1. Covering daily demand before appearance of renewables (left), coping with renewables with leftover demand [19].

flaute[4] will never occur with fully charged batteries, which would additionally increase required demand.

Cost estimates are given in [17] referenced in [16] and can be projected to 750 Euro per kWh capacity in 2020, to 300 Euro per kWh in 2030 and to 150 Euro per kWh in 2050 due to economies of scale. With today's prices, the commission of the smallest storage capacity (8 TWh) would cost 6 trillion (10^{12}) Euro, operational costs excluded. These enormous costs must be additionally associated with the comparably short lifetime of BESS, approximately 10 years (see i.e. [18]).

Currently, the only mature, fully commercialized energy storage technology within a seriously considered power is pumped hydroelectric energy storage. Disadvantages in comparison to other generating units is, that they turn to consumers when it is necessary to recharge their upper located water reservoirs; in contrast, they have no fuel costs except the power needed for pumping mode. Thus, economical aspects come into play regarding variable costs.

Particularly in Germany with its north-south divide of coast and mountains, pumped hydroelectric energy storages appear in the south by reason of necessary geodetical height, whereas wind farms are in the flat northern countryside, or offshore, along the coast, with enhanced upstream flow conditions due to the lack of mountainous "obstacles."

In addition, there is another relevant north-south divide in Germany[5] in terms of high industrialization in the south (and west) and the northern regions, generally characterized as more rural and agricultural. Thus, in the south, pumped hydroelectric energy storage predominates near huge industrial consumers. In the north, wind farms (particularly those located offshore) tend to be further from load centers.

In today's overall climate of expansion of energy storage systems, the introductory statement remains valid: generated electricity needs to be consumed instantaneously.

From a technical point of view, the power balance is maintained when the grid frequency is kept within a very narrow range around the setpoint of 50 Hz. If consumption exceeds generation, energy is withdrawn from the rotating generators of the power plants, and consequently grid frequency drops, with the obverse true if generation exceeds consumption. Control systems must have access to controllable power generating units or controllable consumption devices in order to be able to return the current imbalance in a targeted manner [1].

The scale-pan of consumption is characterized by the day-to-day constant consumer load profile for ordinary working or weekend days with seasonal and predictable long-term fluctuations over decades. At times, special events take place and characterize the consumer load profile differently to the ordinary day (viz., the "roast goose-peak" or the "church attendance-sink" at Christmas or the finale of a soccer game with German participation). These events are singular, predictable, and therefore easy to handle for the control systems in charge of the operational readiness of additional generating units, if available in the system.

The scale-pan of power generation tends to follow suit regarding the consumer energy demand profile illustrated in Figure 1. In previous decades, prior to the growth of renewable energy, (left-hand side of Figure 1), the power supply was divided into the three categories: 24 h night and day base load, load following during daytime, and peak load for a short daily period[6].

The electrical power generation system consists of a range of units utilizing varying fuel sources for electrical generation, up to and including auxiliary power for pumped hydroelectric energy storage used for recharging. In balancing generation and demand, it is customary to operate the generating units in that sequence to minimize overall operating costs. Therefore, the generating units with the lowest marginal production costs are operated at full load as long as possible to cover the baseload. Generating units with higher marginal production costs are operated with changing electrical output to match generation with residual demand beyond baseload. The generating units with the highest marginal production costs are only operated during day peaks, with pumped hydroelectric energy storage having recharged upper water reservoirs during low price base load periods. This cost-optimal employment sequence of the generating units is known as merit order.

All available generating units are sorted in ascending order according to calculated marginal costs, and plotted against the cumulative installed electrical power, see Figure 2. Current demand indicates the generating unit which must be employed. It then becomes the marginal power plant with the highest current costs. The left panel in Figure 2 shows sorted generating units covering demand with the market-clearing price of the marginal power plant. The units indicated to the right of the current demand are not requested, since demand is already covered, and they cannot provide power for price. Generating units with marginal production costs that are lower than the market-clearing price benefit from earning incremental reve-

[4] Dunkelflaute is a compound German word combining "Dunkelheit" (darkness) and "Windflaute" (little wind). It is used in the context of energy sector and describes periods when solar and wind power generation is very low. In Germany a Dunkelflaute may last about 2 weeks, particularly in winter season. Reference is given i.e. to [14] and [15].

[5] There are a lot of north-south divides in Germany but that is beside the topic.

[6] For example, at the early evening homecoming from work but with still running and power consuming industry.

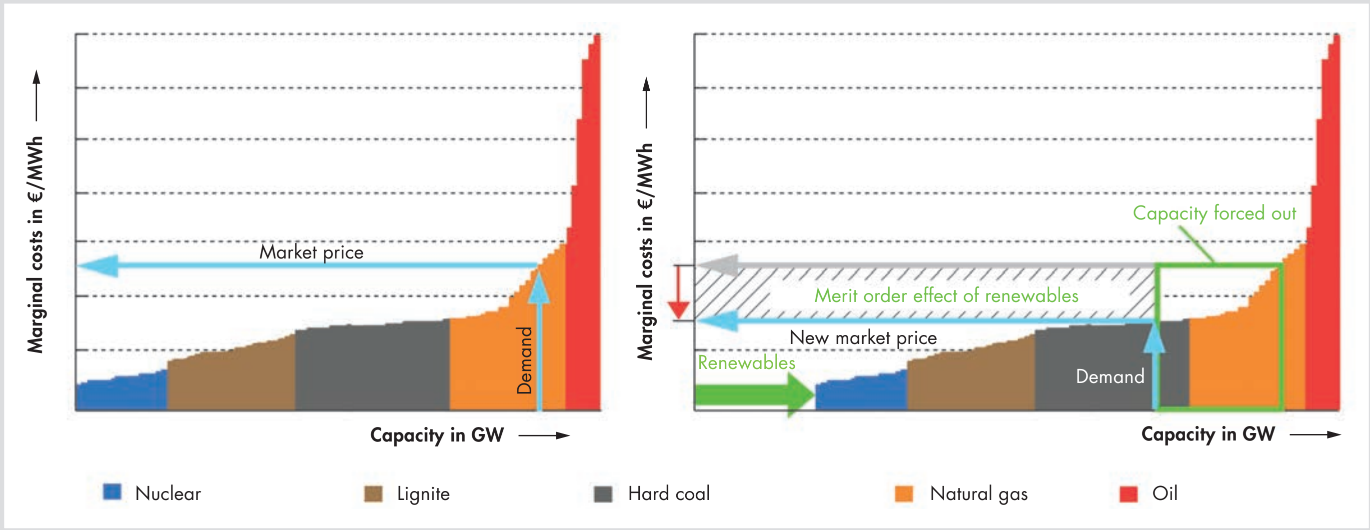

Fig. 2. Principle of merit order in former times without renewables (left) and with must-run renewables (adapted from [21]).

nues, which contribute to their fixed costs. The marginal power plant is only able to cover its variable operating and maintenance costs [20].

With the deployment of renewable technologies, the merit order of generating units is no longer driven by economic aspects. The legal framework for the expansion of renewable energies in Germany is found in the Renewable Energy Sources Act [22]. On one hand, it regulates the priority supply of electricity from renewable sources into the power grid. On the other, the law determines a guaranteed feed-in remuneration for renewables which elevates them to a special status. Whenever wind is blowing or the sun is shining, the operators can feed into the power grid, without caring whether it is needed. The status of renewables can be described as "must-run"[7] in the merit order.

The "must-run" renewables with marginal costs near zero are sorted at the beginning of the ascending order and shift the whole conventional fleet of generating units to the right side of the diagram (right panel in Figure 2). Due to the reduced residual demand covered by the conventional fleet (Figure 1, right-hand side), the threshold for the last generating unit to be requested will be a cheaper one than in the previous example. The previous marginal power plant, suffering from low capacity, is forced out of the market, with the units represented on the right coming into play with increasing rarity. With fewer operational hours of the units forced out, fuel costs per MWh rise, which make requests for reemergence into the market even more difficult.

Ultimately, it is always a matter of costs, and, finally, if one may ruminate with a soupçon of bemusement, a matter of soothing the green conscience. At first glance, nature seems to provide that much-vaunted win-win situation: the sun is shining, the wind whips round the blades of windmills, and costs are nil. Current demand should thus dictate that expensive gas-fired power generation be forced out by renewables, which then engenders a reduction of wholesale power prices, which in turn has a negative impact on the profitability of conventional power plants [23]. Thus, the cheaper generating units on the left-hand side must content themselves with lower incremental revenues. This is known as the merit order effect of renewables. The matter of minimizing costs would seemingly appear to be settled. Furthermore, as fossil-fired generating units are forced out of the market, societal awareness of the environment, specifically of sustainable concepts fomented to combat climate change, and governmental strategies designed to reduce carbon emissions, are on the ascent. The matter of the soothing of the green conscience might also seem to be covered, but in truth this mollification is easier pontificated than achieved.

The main issue that counteracts the win-win-consideration is that renewables have largely intermittent output with limited predictability, a result not correlated with variations in electricity demand [19], if so, it is pure coincidence. To posit these realities within the cant of pragmatic resignation, consider this idiom: "When wind is there, it's there:" [24]. Rather than steadying supply, renewables disturb efforts to maintain grid frequency stability due to their unreliability – forecast deviations preclude the energy from being dispatched. The supply curve increases and decreases depending upon climatological conditions. The greater the penetration of renewables, the larger the shift in the supply curve, coupled with a rise in price volatility [20].

One of the core tasks of Transmission System Operators (TSO) is to ensure system stability. TSOs fulfill this task through ancillary services, including, amongst others, the maintenance of power balance and frequency through the provision and application of three different kinds of balancing reserve in the continental European transmission network [9].

The primary control reserve[8] immediately stabilizes the frequency after a disturbance within 30 seconds at a steady-state value by joint action within the entire continental European synchronous area. It is completely automated and delegated to the large-scale power plants [25]. The subsequent secondary control reserve[9] is triggered by the disturbed load frequency area and returns the frequency towards its set point within 5 minutes. The primary control reserve remains activated until it is fully replaced by the secondary reserve in a ramp-wise characteristic so that the work capability of the primary reserve control is restored again for the next possible disturbance. Additionally, the secondary reserve is replaced and/or supported by the tertiary control reserve (or minute reserve)[10] within fifteen minutes in a ramp form [26].

The dynamic hierarchy of the balancing reserve is illustrated in Figure 3. In recent years, with growing deployment and penetration of must-run renewables linked with reduced inertia, grid maintenance complexity has increased enormously.

Role of the nuclear power in grid stability

NPPs belong to generating units with the lowest marginal production costs. Thus, following the rules of merit order, they are

[7] The term "must-run" is not yet correct. The privilege has been abridged by an amendment of the Renewable Energy Sources Act. More information will be provided in a further chapter about misalignments.

[8] Also called Frequency Containment Process (FCR).

[9] Also called Frequency Restoration Process (FRR).

[10] Also called Reserve Replacement Process (RR).

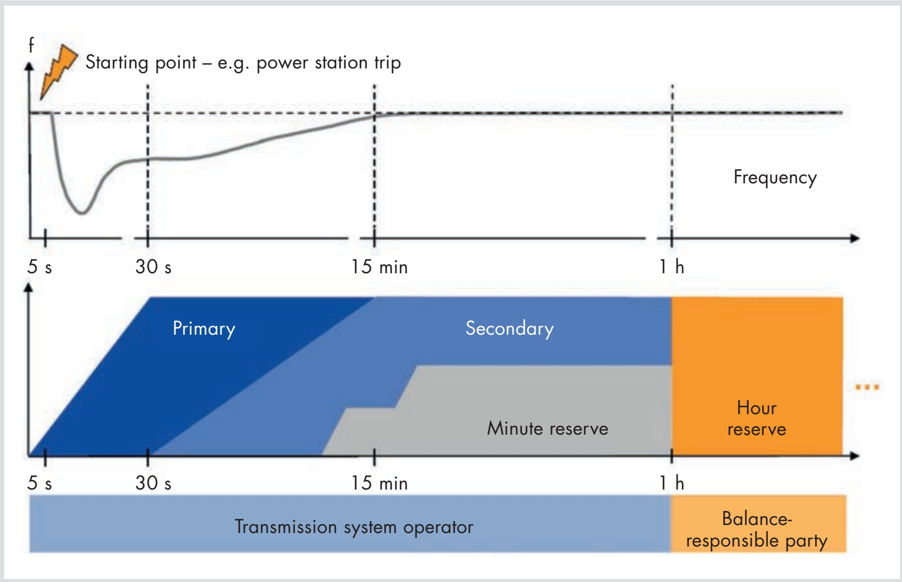

Fig. 3. Dynamic hierarchy of load-frequency control processes [26, 27].

operated at full load when possible. The public perception of NPPs suggests that they are only made for baseload operations and are too inflexible for any kind of load change. Such pronouncements were aired not just by anti-nuclear organizations but also by the German Federal Environment Ministry, which ascertained that NPPs are the most inflexible facilities within the traditional power plant fleet due to their inflexibility and frequent starts and shutdowns, and, if possible, should be avoided for safety reasons [28] (in [29]). During discussions in the late 2000s regarding lifetime extensions of NPPs, sloganeers suggested that the plants might clog the power grid and jeopardize the development of renewable energies.

Among the curious myths surrounding nuclear energy that have been met with dismay and incomprehension by experts, allegations of inflexibility earn a special, Stygian ranking, due to the simple fact that the exact opposite is true [30].

Of course, due to low marginal production costs, NPPs have reliably contributed to base load demand over the decades since their introduction. Due to market mechanisms, there was never an economic need to throttle the power of the NPPs if more expensive generating units remained in operation. A persistent canard suggests that due to their supposed inability to manage load changes – not because of their low-cost operational status – NPPs ran only in base load. This supposition proved apparently sturdy, however, and the perception that NPPs always operated at full power – or were only able to do so – became entrenched. Even published power chart illustrations mirrored the conjecture, that NPP "always" or rather "only can" operate at full power.

In fact, German NPPs are the most flexible generating units in the portfolio, and were particularly able to demonstrate that capability in practice. In the case of renewables' high feed-in, it more frequently occurs that a huge part of current demand is covered by renewable sources, with one of the NPPs then becoming the marginal power plant, and all fossil-fired plants located on the right-hand side of the NPPs in the merit order diagram (Figure 1 right-hand side) not being employed at that moment – always a snapshot – and are thus forced out of the market. In that case, even the NPPs must throttle power generation. Due to the geographical imbalance, NPPs in the north are particularly affected to conduct load following operations.

Their high flexibility remains an open question. Due to the oil crisis and its tremendous dependency on foreign energy resources, Chancellor Willy Brandt's government launched the first German energy program in 1973. Among other issues, the intention of the initiative was to increase the capacity of NPPs up to at least 40 GW, and preferably up to 50 GW, through 1985 [31]. Regarding the ascending order of generating units in the merit order diagram, it would have led to a very broad interpretation of the NPP category. In the forward-looking 1985 scenario, NPPs would have undertaken duties beyond baseload operation, including load following operations. The design of NPPs already had to be adapted for that purpose in their planning phases to have the flexibility to meet the requirements of the designated scenarios with large shares of nuclear power. In the end, the commission of 50 GW installed capacity was not realized, but constructed NPPs have been given the capability of flexible operation by design (and not by retrofit).

The load change rate over time is shown in Figure 4 for various thermal generating units. The NPPs have the largest load change rate, paired with the biggest power generation per single unit. Load following down to 50 % can be conducted in NPPs with a gradient of 5 % of nominal power per minute, down to 80 % (but not below) even with a gradient of 10 % per minute; thus, with an enormous 140 MW/min. The operating manuals[11] of the KWU-type PWR, which contain all operational and safety-related instructions, indicate even higher performance ranges. Load changes of up to 80 % of nominal power – thus, down to 20 % – are permitted (published e.g. in [32]). This strong load reduction comes at the expense of the load change rate. It decreases to a gradient of 3 % of nominal power per minute (42 MW/min), which is, however, still competitive with the fossil-fired power plants.

The fastest non-nuclear units are a small number of new fossil-fired power plants, which were designed in consideration of

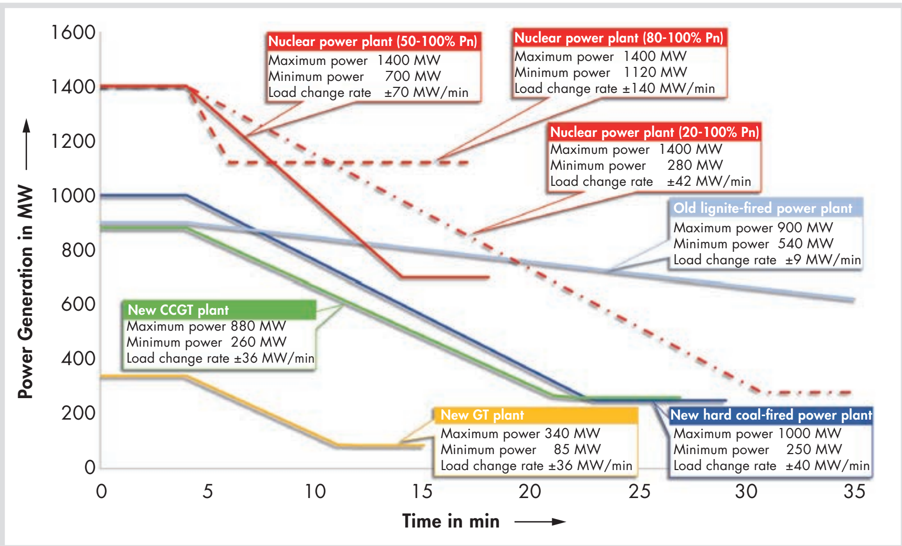

Fig. 4. Comparison of load change rates of conventional generating units (adapted from [33] with data from [32] and [34]).

[11] Not publicly accessible.

the increased demands of flexibility. With changing markets and the prioritized, fluctuating feed-in of renewables, efforts were made to enhance the design of coal-fired plants to more suitably meet load following requirements. Enhancements were implemented to further lower minimum permissible power, but not expressly to increase the load change rate [35]. Factors limiting an increase of load change rate in coal-fired power plants include combustion performance, the mass flow of fossil fuel through the coal mill, and particularly the thermal stress of thick-walled components. Fluctuations of pressure and vapor temperature due to declining control accuracy also play roles as limiting factors [36]. The best performing units reach a gradient of around 40 MW/min[12].

The load change in NPPs is not limited to a mass flow of fuel. Due to the high energy density of a nuclear core, a smooth insertion or withdrawal of control rods leads to a strong load change. The thermal stress of components as limiting factors for the load change rate is not that significant in NPPs as well. Regarding secondary circuit, water-moderated NPPs do not superheat steam to obtain high efficiency, as do fossil-fired plants[13]. The steam generation in water-moderated NPPs is limited to the saturated vapor line. Temperature differences are not as high as in power plants with superheating capabilities.

One of the hallmarks of KWU-type pressurized water reactors (PWR) is the constant average coolant temperature over a wide range of their partial load reactor power levels, resulting in minimal changes of pressurizer level. Figure 5 schematically depicts the partial load diagram of a KWU-type PWR. It shows the temperature of the primary coolant at inlet/outlet of the reactor pressure vessel, as well as the average cooling temperature, depending on the reactor's power [37, 38]. Particularly in the upper power range, under special focus for load following operation, the average coolant temperature remains constant more than half of the entire power range.

This enables quick, subtle load changes with precise control behavior and minimal thermal stress and fatigue on the primary circuit components [29, 30]. In regard to safety, all physical reactor parameters such as neutron flux, power density and power distribution are kept under constant double surveillance by the reactor limitation systems and the reactor protection system.

With the capability of fast and nimble load changes, NPPs fulfill the technical requirements to provide varying levels of balancing energy as requested by the TSO [29, 39] illustrated in Figure 3. The NPP can be operated automatically by controlling the power set point of the generator. The primary side follows suit with the demand of the secondary side and regulates the average coolant temperature. Figure 6 shows the power control in practice due to fluctuations of solar and wind power.

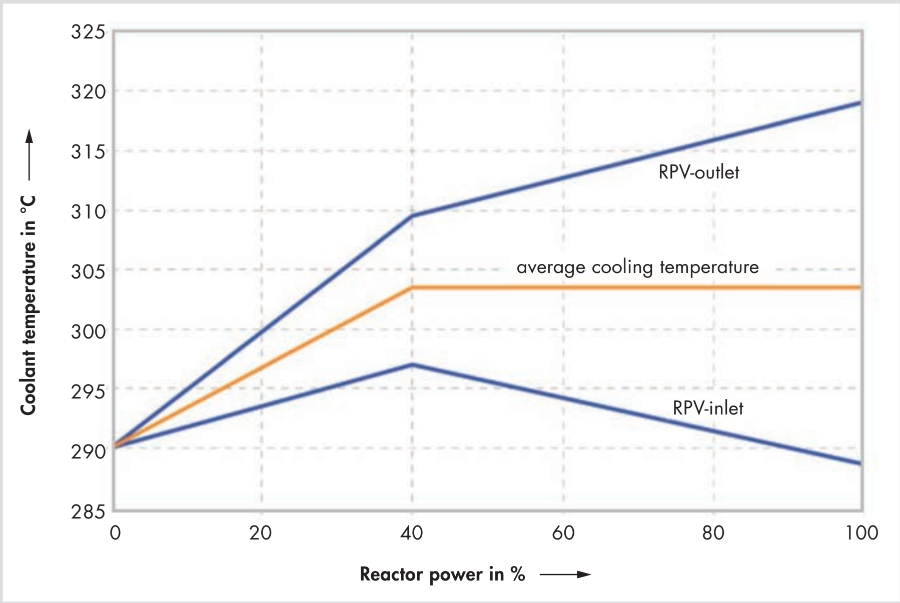

Fig. 5. Partial load diagram of a German PWR (simplified) [38].

PWRs have the ability to automatically counteract changes in coolant temperature resulting, for example, from a requested power ramp on the generator side, by changing the reactor power accordingly, see Figure 7. This feedback behavior is adjusted by means of coolant temperature control, based on the neutron-kinetic effect of the negative coolant temperature coefficient of reactivity GK.

A requested reduction of generator power leads to a throttling of turbine admission valves and an increase of upstream main steam pressure. Due to thermal coupling of the steam generators, particularly with the primary's cold legs, an increase of coolant temperature results. In short, as the turbine demands less power than is generated by the reactor, the primary circuit becomes temporarily warmer. With the rising temperature of the coolant, density decreases, and reactivity is consumed. Via neutron-kinetics, the neutron flux j decreases and hence reactor power as well. A decrease of reactor power releases positive reactivity via Doppler effect by a reduction of the average fuel temperature, and by an increase of fuel density owing to reduced average fuel temperature. Both effects are subsumed in the power coefficient of reactivity GP, which always automatically counteracts any change of reactor power ΔP. It is part of the inherent safety concept of nuclear reactor design. In this case, the gain in reactivity related to a decreased demand in power balances the reactivity consumed by the rising average coolant temperature.

Decreasing reactor power has a feedback on heat transfer, which counteracts the indirect increase of coolant temperature (returning orange arrow) caused by the throttling of turbine valves.

For a requested increase of generator power, the antipodal result occurs. An excess of power prevails on the turbine side; more

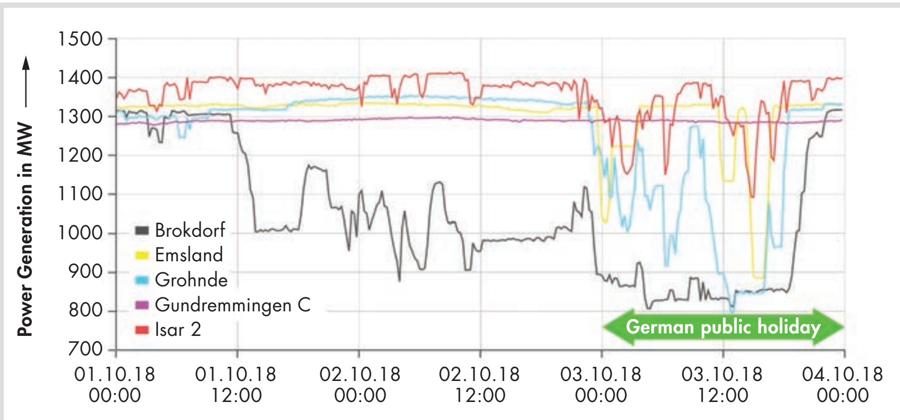

Fig. 6. Real example of power control in practice on first week of October 2018 (adapted from [27]).

[12] One must keep in mind that the coal-fired plants are often build as multi units at one site.

[13] Some of the coal-fired plants even operate with supercritical water.

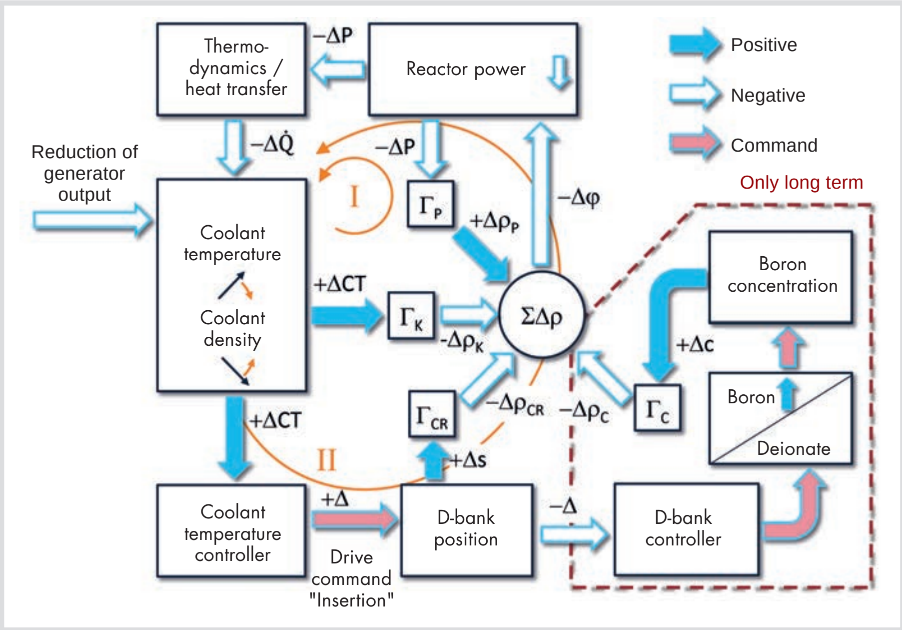

Fig. 7. Feedback of reactor power on requested load reduction (for a requested increase invert all signs).

power is extracted from the steam generator towards the secondary side, and the primary circuit becomes temporarily sub-cooled. With lower coolant temperature, reactivity is gained, and reactor power increases again. The heat transfer increases and balances the drop of coolant temperature. Part of the gained reactivity is compensated in this case by the negative contribution of power reactivity feedback. An increase of power consumes reactivity (Doppler effect and fuel density).

The requested change of the generator power set point is initially buffered by the reactivity feedback of changing coolant temperature. If the coolant temperature deviates from its dead band (in both directions), it is then transferred to the control rod position controller.

KWU-type PWRs have control rods that are functionally divided into two control rod banks – the L and D banks. The majority of control rods are assigned to the L bank, which remains at a high position during power operation and preserves the shutdown margin, an important parameter for safety [38]. The four D banks, each comprising four control rods, are used for regulating integral reactor power. They are weaker in comparison to those comprising the L bank and do not markedly disturb power distribution [40]. Depending on the control rod maneuvering concept, one or more of the D banks are partially inserted or withdrawn, which accordingly elicit prompt feedback on reactor power so that coolant temperature returns smoothly to its set point. Thus, during partial load operation, the automatic movements of control rod banks provide the method of choice to ensure a balance of reactivity despite load ramps.

For a considerably lengthier partial load operation – and only in that case – the control rod banks tend to be withdrawn again to avoid both a stronger peaking of the axial power distribution and a burn-up imbalance between bottom and top core regions. For that purpose, the control rod bank controller regulates the reactivity balance by feeding boron into the coolant while the bank is slowly withdrawn. The gained reactivity from the removal of control rods[14] is compensated by an increase of the concentration of the neutron absorber. The reactor core will be operated in partial load with fully withdrawn control rods, but with increased boron concentration[15]. In case of a positive load change, deionized water will be fed into the coolant to decrease the boron concentration, while control rod banks are partially inserted. The increase or dilution of boron concentration is quite slow, and this operation mode significantly slows the possible load change rate of the NPPs. Aspects of Xenon build-up also come into play. Changes of boron concentration are not usually carried out if the NPP is requested by the TSO for short-term load following operation.

Development and progression of the energy transition and its misalignments

The German Energy Transition with public incentives for more investments is leading to a steadily growing share of renewable energy in the German electricity mix. But, particularly regarding the installed capacity from wind turbines on land and sea, it can be observed that there is still a clear geographical imbalance between the locations of the prevalent, lower power plants in northern Germany and the consumption centers in the south. In addition to the expansion of renewable energies, the nuclear phase-out in Germany is also progressing, thus, huge conventional generating units with high capabilities of load following operation will exit the market by end of 2022.

In the case of other conventional generation technologies, a steady decline in the capacities connected to the grid can also be observed, due to market forces under the rules of merit order making operation too expensive. Should this occur, the costs of power generation might not be able to be covered, leading to a vicious economic circle prior to a new request. Since the marginal costs of production per MWh will rise

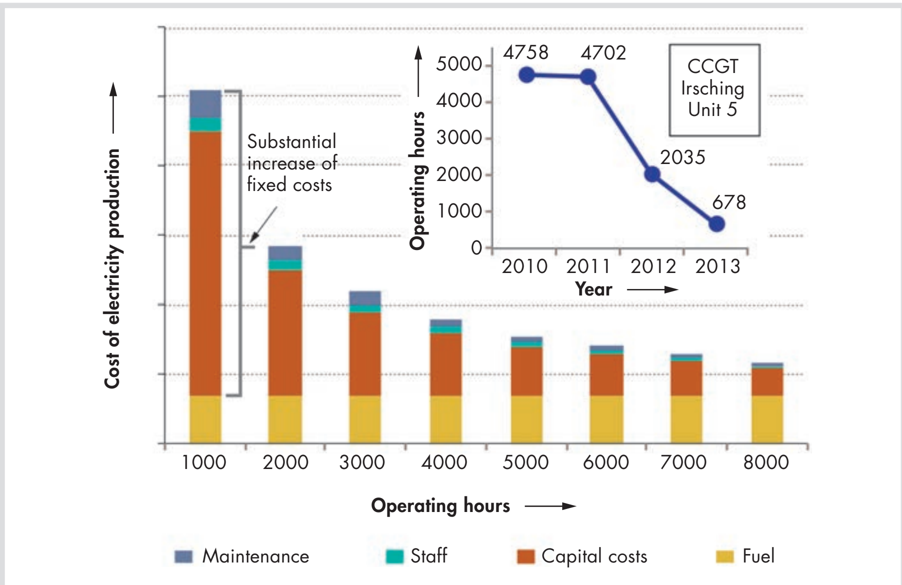

Fig. 8. Marginal costs of specific power generation versus operating hours [21]. Operating hours CCGT Irsching Unit 5 (commissioned 2010) [42]

[14] In difference to the illustration in figure 7, the reactivity contribution based on control rod movement is $+\Delta_{\rho CR}$ because of their removal $-\Delta s$.

[15] The reactivity contribution of the control rods $\Delta_{\rho CR}$ is replaced by the reactivity contribution based on boron concentration $\Delta_{\rho C}$.

with reduced time of operation, see Figure 8, the affected power plant will be ranked farther on right side in the ascending merit order, see Figure 2. In the case of the highly efficient but expensive combined cycle gas turbine (CCGT) Irsching Unit 5, which was commissioned in 2010, its operating hours have fallen tremendously to a level of economic inefficiency which prompted the utility to apply for shutdown. Conversely, decline in capacity can be observed due to stipulations in the recently enacted German regulations for the phase-out from the coal-fired power generation by the end of 2038 [41].

The import of electrical energy from neighboring countries in the north and Scandinavia with the simultaneous export of electrical energy to neighboring countries in the south creates a burden for the transmission network. This north-south divide of international electricity transport is superimposed on the requirement to transmit nationally generated electricity from wind farms in northern Germany to the load centers in southern Germany [43].

To avoid an overload of the transmission grid, two main measures are adopted by the TSOs: redispatch and feed-in management measures. Both belong to the ancillary services as well and have received increasing importance in recent years.

Redispatch means the local reduction or increase in the feed-in capacity of power plants due to bottlenecks in the transmission network in order to relieve and stabilize the grid. Negative redispatch is applied to reduce feed-in capacity of conventional power plants in northern Germany in cases of excess power generation of must-run renewables in geographic proximity. In strong wind phases, however, even wind farms are assigned by the TSOs to reduce power input and become part of the negative redispatch measure. With the employment of ever-greater numbers of wind farms, renewable energies are often obligated to throttle their power feed-in as well. As regulated in the Renewable Energy Sources Act [22], the operator of curtailed renewable generating units is entitled to compensation for the lost power feed-in with guaranteed remuneration.

Positive redispatch is performed on the other side of the transmission grid – the power sink – by running-up capacities in the case of excessive transmission rates to southern neighbors or in the case of the unforeseen trip of a power plant[16].

Energy provided or lost via redispatch is counted in GWh. Figure 9 illustrates the cumulative generated redispatch energy in 2018 and the most affected generating units. The top ranking of power plants clearly shows that the "award-winning" units for negative redispatch (Table 1) are located in northern Germany, and the "award-winning" units for positive redispatch (Table 2) in southern Germany. For example, the hard coal-fired power plant Wilhelmshaven (operated by Engie) was not allowed to feed-in 866 GWh (data taken from [44]) of energy in 2018 due to redispatch measures. In relation to power capacity, the unit has lost 1,185 h (nearly 50 days) of power generation (full load hour equivalent in Table 1). Considering its hours of operation and sensitivity to the costs distribution in Figure 8, it seems to be only a matter of time before the unit is shut down for operational reasons. The affected power plant receives renumeration for energy not generated and for its participation in the redispatch service regulated in [45].

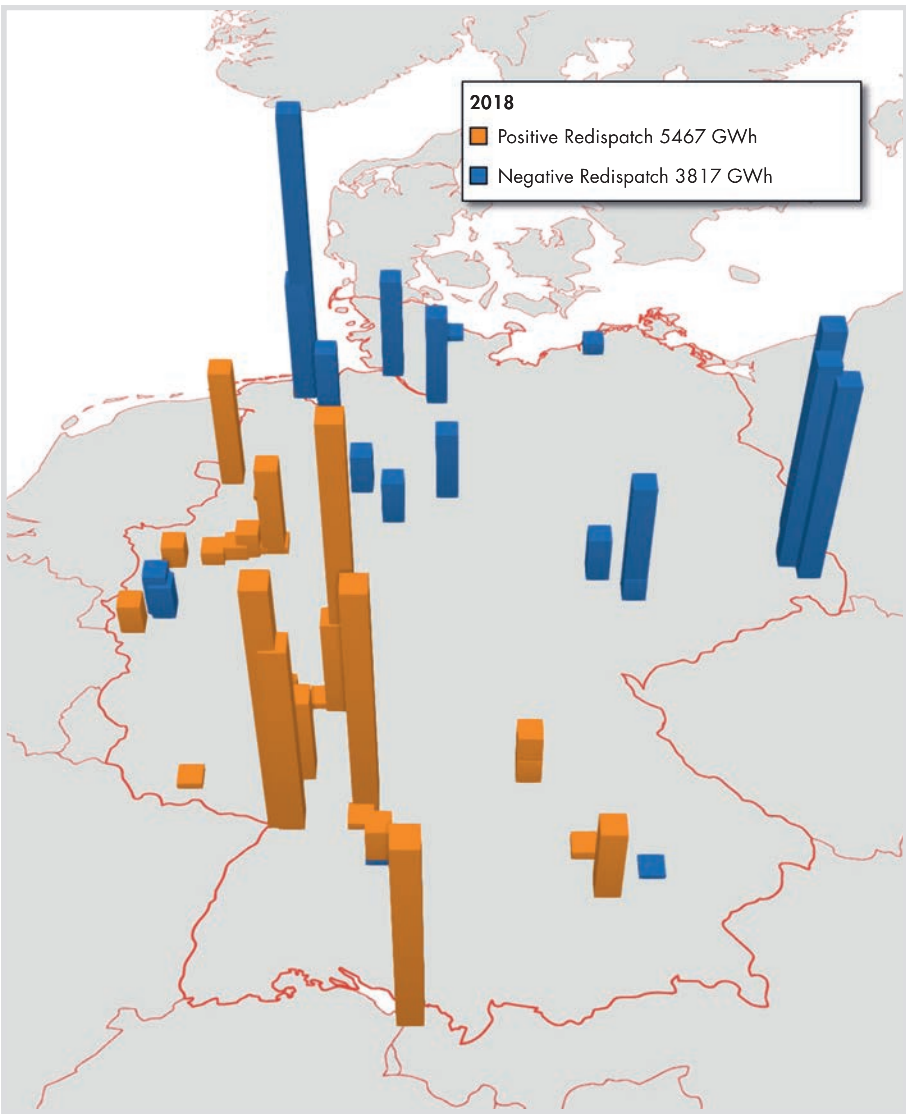

Fig. 9. Redispatch measures in 2018. Negative redispatch via reduction of power generation (blue), positive redispatch via raise of power generation (both cumulated) (own illustration with data from [44]).

Table 2 for positive redispatch is headed by the south German hard coal-fired power plant Staudinger Unit 5, which usually can be found more on the right-hand side of the ascending merit order diagram. It was requested for 517 GWh of additional energy. However, in the course of the German act on the phase-out from the coal-fired power generation, the utility has already announced it will close Unit 5 in 2025 [46] because of suffering from low capacity in the regular market.

The top ten contains also Staudinger Unit 4, a gas-fired plant, which has already been taken from market and contracted by the German Bundesnetzagentur[17] (BNA) as a network reserve power plant. Other affected sites in the top 5 list contain units which were designated by the utility to close, but are obligated to remain in operation by the BNA, which classified the majority of units south of NPP Grafenrheinfeld[18] as sys-

[16] A pumped hydroelectric energy storage in a currently restoring operation modus can also be assigned to stop electricity consumption to not wring out the power sink furthermore.

[17] German Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway.

[18] The so called Mainlinie from the river Main originates from historical and political boundary of the two major powers Austria and Prussia in the 19th century. Today it is used amongst others by the BNA to divide the affiliation of power generating units to northern or southern part of Germany.

Tab. 1. Top ranking units 2018 for negative redispatch measures.

Reduction of power generation Top ranking in 2018		Negative redispatch energy	Full load hour/ day equivalent
1.	Wilhelmshaven (Engie)	866 GWh	1185 h / 49.4 d
2.	Jänschwalde	658 GWh	219 h / 9.1 d
3.	Schwarze Pumpe	635 GWh	397 h / 16.5 d
4.	Boxberg	606 GWh	236 h / 9.8 d
5.	Wilhelmshaven (Uniper)	377 GWh	498 h / 20.8 d
..	..	..	..
8	Moorburg	166 GWh	166 h / 6.9 d

Tab. 2. Top ranking units 2018 for positive redispatch measures.

Raise of power generation Top ranking in 2018		Positive redispatch energy	Classified as systemically relevant
1.	Staudinger Unit 5	517 GWh	Not, shutdown in 2025 [46]
2.	Karlsruhe (RDK Unit 8)	448 GWh	Not, but Unit 4S [47, 48]
3.	Heilbronn (Unit 7)	413 GWh	Unit 5, 6 (2018,2020) [49, 50]
4.	Vorarlberger Illwerke (Austria) (Hydro power)	365 GWh	-
5.	Karlsruhe (RDK Unit 7)	347 GWh	No, but Unit 4S [47, 48]
..	..	..	..
7	Staudinger Unit 4	173 GWh	2018 [51]
..	..	..	..
9	Mannheim (GKM)	157 GWh	Unit 7 (2020)[52]

temically relevant for grid stability. For further information, references are made in Table 2.

Recently, power plants Moorburg (ranked as #8 in Table 1) and Mannheim (ranked as #9 in Table 2) were highlighted in the national media and entered public discourse [N1, N2, N3, N4]. Power plant Moorburg is in Hamburg and belongs to the youngest and therefore most efficient hard coal-fired units. Unfortunately, it was constructed on the "wrong side" of Germany. Although it was foreseen in [41] to run until the end of 2038 – the legally stipulated last year of coal-fired power plants – Moorburg came to the decision [N1] to apply for the first tender of the BNA in 2020 to quit coal-fired power generation against financial compensation. Just recently, both units of Moorburg had been awarded the contract to quit electricity generation from hard coal as early as 2021 [53, 54]. Conversely, power plant Mannheim is in the south and Unit 7 has applied to the operator to be closed. It will not be allowed to do, however, since it has recently been classified by the BNA as systemically relevant [52] until at least 2025. The information was made available to a broader audience by [N3] and [N4].

If hedged and market-based power plant capacities are not available in sufficient quantities to carry out redispatch measures, the TSO will procure the required capacities from existing, inactive power plants to ensure the safety and reliability of the electricity supply system (e.g., Staudinger Unit 4).

Network reserve power plants are not required because of insufficient generation capacities, but because of excessive electricity transmission and the resultant overload of the transmission network. Generally, these network reserve power plants are only used outside of the energy market to ensure grid stability, and thus are used exclusively for redispatch [43].

The BNA regularly releases reports for future reserve power plant requirements for the upcoming winter, in additional to those for the next few years (e.g. [43]). The numbers of recent reports up to winter 2024/25 have been picked up and graphically illustrated by [55] as can be seen in Figure 10. Certain discrete dates are introduced within, including disturbance values for the capacity planner. Based on these reports, new build projects can also be invited to tender. In the case of Irsching [N5], the energy transition reaches absurd extremes. It was even described as "insane" by [N6]. Following a tender from the German TSOs for a new network stability reserve, a new gas-fired power plant has been awarded at the Irsching site – it will be known as Unit 6 [56]. Curiously, the utility applied for the shutdown of Unit 4 and the highly efficient Unit 5 on several occasions,

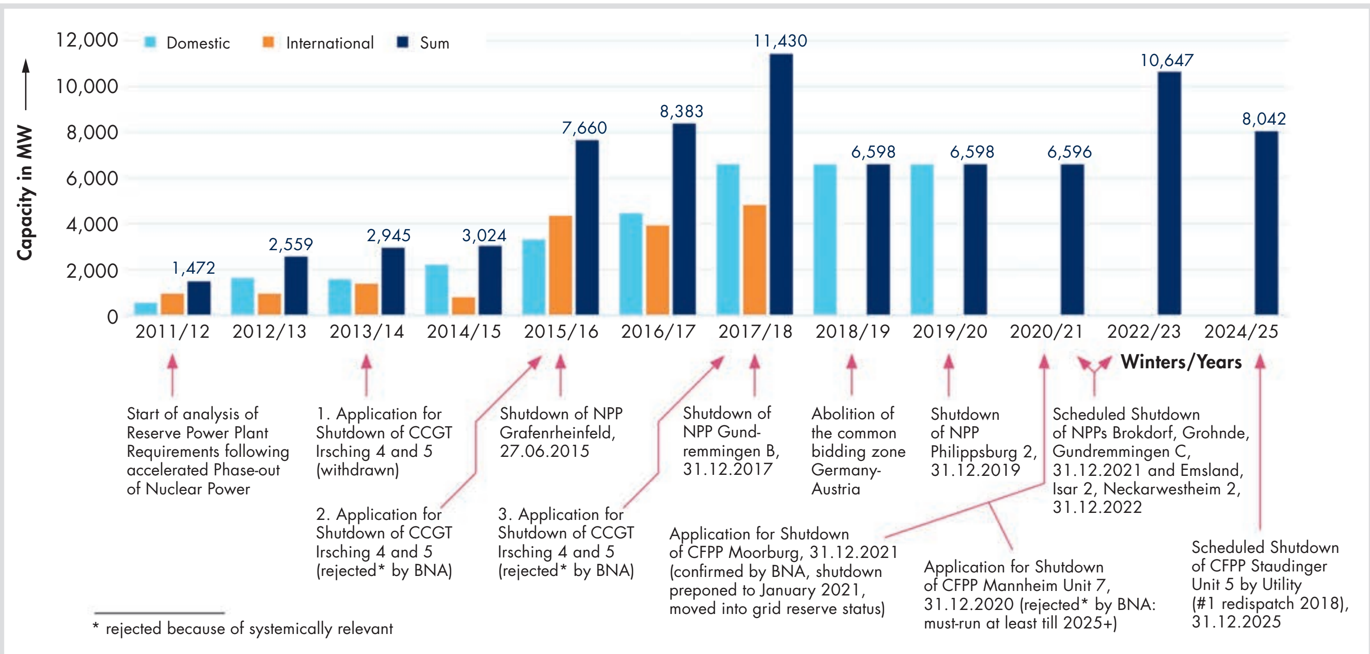

Fig. 10. Totalized capacity of domestic and international grid reserve power plants and identified requirements for the winters/years (in MW) (adapted from [55]).

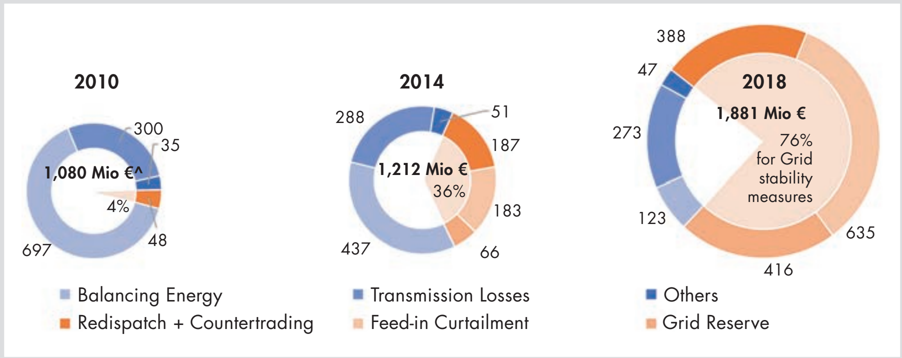

Fig. 11. Cost allocation of ancillary services in Million Euro with increasing share of grid stabilizing measures in % (sum of orange colored segments) (data taken from [9], [58], [62]).

see Figure 10. Even during the regulatory approval of emissions for Unit 6, the application for mothballing Units 4 and 5 was incidentally alluded to [57]. Irsching Unit 4 and 5 are also taken from market and contracted by the BNA as network reserve power plants.

Eventually, the provision and application of network reserve power plant capacities as well as the shedding of loads is assigned to the range of tasks of the TSOs [9]. For further information, refer to the annual reports of the BNA [58, 59, 60, 61]. The redispatch of power plants and network reserve power plants, as well as the feed-in management measures regarding curtailment of renewables, not only play roles of increasing importance for grid stability, but have also claimed an increasing share in the price of electricity over the last few years, see Figure 11. This increasing service is paid for by a levy on electrical consumption by the end user – the Renewable Energies Act levy.

Due to the merit order effect of renewables, wholesale electricity prices have fallen below the marginal costs of even highly efficient (but expensive) CCGT. Although a cheaper portfolio of generating units covers the market as originally intended by the Renewable Energy Sources Act, renewable technologies are often not the cheapest in terms of total cost (but not of marginal cost). In markets with high penetration of renewable energy, this leads to a divergence between the true cost of the system and the evolution of the price of electricity in wholesale markets. In the longer term, investors will be hesitant to reinvest or recapitalize electricity markets without sufficient guarantees on returns [20]. In Germany, incentives for investors are provided by a public feed-in tariff subsidy program with a guaranteed remuneration to boost the deployment of renewables. These costs are also borne as a further part of the Renewable Energies Act levy. Despite low wholesale prices, the cost of the renewables levy causes the end consumer to pay the most expensive retail prices across Europe. Due to the skyrocketing expense of the levy in recent years, the German government decided to limit the levy for consumers in 2021 and 2022 by subsidizing its residual costs with state aid from tax revenues [63]. Without this subsidy, the levy would increase by approximately 40 % in 2021 [N7].

The deployment of renewables will be borne by consumers and taxpayers. But to what extent? A 100 % penetration of renewables cannot be achieved on stand-alone basis without any subsidy program, because investors of renewable generation would be unable to earn a return on risk. Electricity prices would be at the renewables' marginal costs, equal to zero, and renewables could fall victim to their own success, as stated by [20].

Conventional power generating units are still required to provide security of power supply, but suffer from low capacity or have applied for shutdown. Investors would be discouraged from continuing operation of these units or even entering the market following tenders for new reserve power plant capacity. Thus, investments in conventional generation capacities deemed to be necessary in the long run have been cancelled. In the end, potential investors might even call for public support to build conventional generation capacities. But subsidizing renewables and conventional capacities would contradict the idea of a liberal market according to [23].

Another phenomenon has appeared in the public arena in regard to the energy transition: negative electricity pricing [N8, N9]. Colloquially known in Germany as "Ökostromschwemme" (green power glut) or "Ökostromparadox" (green power paradox), the term implies that renewables are responsible. In Figure 4 it can be seen that conventional generating units have a minimum permitted limit of partial load operation. In those situations where the limit is greater than the residual demand – this can be for a few hours – exceptions to the marked rules may be needed to avoid shutdowns of generating units that may not be available when demand increases shortly thereafter [19]. The power oversupply, with its simultaneous necessary consumption, leads to negative prices in the wholesale market. The concept of guaranteed feed-in remuneration for renewable sources seems to be out of place during this undesired situation of oversupply and negative electricity pricing. In an amendment of the Renewable Energy Sources Act, the 6-hours-rule has been complemented in 2017. It notes the guaranteed feed-in remuneration for renewables (with certain power class determined in the law) will be suspended, if the exchange electricity price in day-ahead trading is negative for six hours or more. If this happens, the renewable generating units do not receive any remuneration retroactively from the first hour with negative electricity prices. Incentives to continue operation of renewable generating units are not only removed, but operators, to ease the situation at the electricity exchange, also throttle feed-in of renewables. In this manner, the legislator adjusts one of the misalignments of the energy transition.

Conclusion

Differing from the usual introductory survey, the paper opens with the question of what will become of grid stability. For a better understanding of why the question arises, the scope of the inquiry has been extended by explaining basic mechanisms regarding a stable electrical power grid. Differences have been elucidated for an electricity sector operating within the "undisturbed" conditions of a competitive market economy. The entrance and massive deployment of electricity generation from renewable sources, whose success is primarily based on a public subsidy program, undermines market economy principles. Guaranteed feed-in remuneration elevates renewables to a specific prioritized position, forcing conventional generating units out of the market.

Further deployment of highly volatile renewable sources, along with more conventional generating units being forced out of the market, makes the power grid increasingly sensitive to weather-related fluctuations. Unusual weather phenomena like the Dunkelflaute constitute major challenges facing the power grid's supply security and stability. The largely intermittent output of solar and wind farms is not correlated with variations in electricity demand. The oversupply of renewables may be buffered at low-power demand periods, and the stored capacity may be fed-in again to the grid at high-power demand periods when fewer renewable sources are available. However, large scale battery energy storage systems, already promisingly announced, are still not in sight, due to their low levels of capacity and maturity, and because of their exorbitantly high costs for deployment.

As long as economical energy storage systems are not established, even proponents of the current alignment of the German energy transition must admit that reliable conventional power plants will still be needed for a long time.

However, new boundary conditions in the electricity market are challenging for the entire fleet in the conventional generation portfolio. The merit order effect of renewables allows them to suffer from low capacities, and incentives for a continuation of operation, or even for investments in new generating units, are lagging. All this at a time when new capacity is particularly required for grid stability.

The importance of nuclear power plants for supply security in base load operations, as well as their capability for highly flexible concurrent grid operation with renewables, has been demonstrated. The NPPs seem to be made for the energy transition towards carbon free power generation. However, the Atomic Energy Act provides an imminent end of nuclear power generation by end of 2022.

The carbon emission intensive coal-fired power plants, which are ranked between the NPPs and the expensive gas-fired power plants in the merit order chart, are also doomed by the end of 2038 at the latest. As envisaged by legislators, at least, if not by being abandoned much earlier by utilities due to operational or economic issues.

In a nutshell, unresolved questions remain after the phase-out of the last NPP and the imagined phase-out of coal-fired power generation. Which units will be redispatched to release the grid if there are no units left? Which unit is capable of conducting large load following operations? What kind of incentives can be made to continue the operation (or even for the new builds) of unpopular but still required conventional power plants? Who will pay for it?

In the perception of the public, the German energy transition is also quite unpopular, since the savings from the merit order effect of renewables (in which most expensive units are forced out of the market, leading to lower wholesale prices) do not benefit end consumers. It is overcompensated by the expenditures for ancillary services of transmission system operators, essentially the grid-stabilizing measures.

The misalignment of the energy transition raises these questions, ones demanding adequate and urgent address. Otherwise, the initial question remains alarmingly open: Quo vadis, grid stability?

Abbreviations

BESS	Battery Energy Storage System
BNA	Bundesnetzagentur, German Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway
CCGT	Combined cycle gas turbine power plant
CFPP	Coal-fired power plant
GKM	Power plant Großkraftwerk Mannheim
GT	Gas turbine power plant
KWU	Kraftwerk Union AG (company)
NPP	Nuclear Power Plant
PWR	Pressurized water reactor
RDK	Power plant Rheinhafen Dampfkraftwerk Karlsruhe
TSO	Transmission system operator

Nomenclature

c	Boron concentration
CT	Coolant temperature
Δ	Delta, difference
j	Neutron flux
GC	Boron coefficient of reactivity
GCR	Control rod coefficient of reactivity
GK	Coolant temperature coefficient of reactivity
GP	Power coefficient of reactivity
P	Power
Q	Heat flow
rC	Reactivity contribution based on boron concentration
rCR	Reactivity contribution based on control rod position
rK	Reactivity contribution based on coolant temperature
rP	Reactivity contribution due to load change
s	Displacement (of control rods)

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