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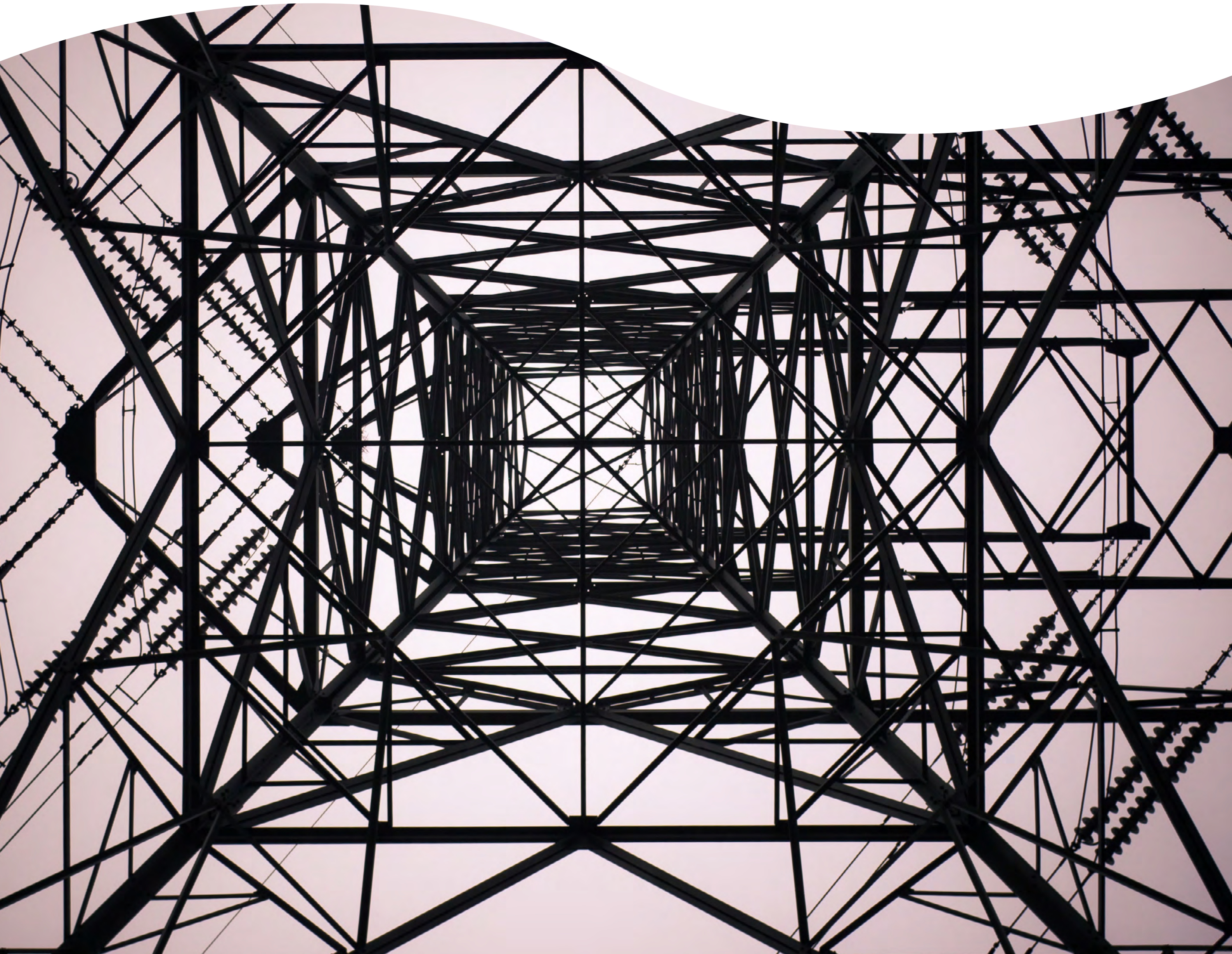
A WORD ON GRIDS

How Electricity Grids Can Help Integrate Variable Renewable Energy



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How Electricity Grids Can Help Integrate Variable Renewable Energy

COMMISSIONED BY:

Agora Energiewende
Anna-Louisa-Karsch-Straße 2 | 10178 Berlin
P +49. (0) 30. 700 14 35-000
F +49. (0) 30. 700 14 35-129
www.agora-energiewende.de
info@agora-energiewende.de

AUTHORS:

Stephanie Ropenus, with
Philipp Godron
Markus Steigenberger

stephanie.ropenus@agora-energiewende.de

Proofreading: WordSolid, Berlin
Layout: Marica Gehlfuß

Cover image: unsplash.com/ Shane Rounce

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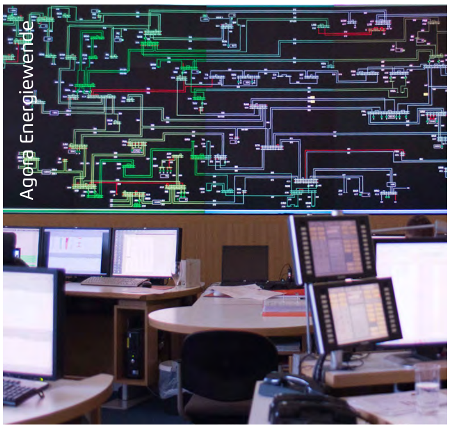
WHAT YOU WILL LEARN

Why wind and solar power pose new challenges to grid operation and planning

more on page 13

Electricity generation from wind power and solar photovoltaic depends on the weather. In order to keep the system stable despite real-time variability, power demand must always match power supply. The operation of power systems with a growing share of variable renewable energy sources (vRES) and steeper ramp rates is a complex undertaking. Renewable energy often comes from small, modular power generation units that are frequently connected to the distribution grid, close to electricity consumers. This is a departure from the conventional power system, in which a few large thermal generators feed power directly into the transmission grid. A high share of vRES makes the coordination of power generation and demand an increasingly complicated task for planners and operators.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How the existing grid infrastructure can be optimally utilised for integrating variable renewables (vRES)

more on page 17

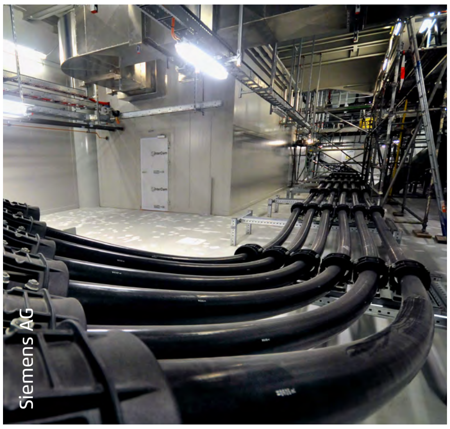
Changes in the generation landscape often necessitate grid expansion. The good news is that the existing grid infrastructure can be adapted to integrate a growing share of vRES. Temperature monitoring of existing transmission lines allows better utilisation of their capacity. The implementation of phase-shifting transformers enables grid operators to control and optimise electrical power flows – and to relieve grid constraints. Through grid reinforcement, existing power lines can be upgraded without the need for building new ones. There is no one-size-fits-all solution, but the optimal choice of measures needs to account for conditions in each grid region and country. The application of the “GORE principle” – “grid optimisation before grid reinforcement before grid expansion” – reduces costs and increases public acceptance should new transmission lines have to be built if grid optimisation and reinforcement measures fall short.


Bystrup.dk

How grid planning can account for high vRES shares early on

more on page 20

There are different ways to approach grid planning. With the conventional approach, grid expansion follows new generation and demand. But the long lead times for building transmission lines means that grid expansion cannot keep up with new vRES stations like wind turbines and solar panels, which can be installed rather quickly. Instruments for aligning grid planning and vRES deployment are better suited for a holistic planning approach.


Siemens AG

What to do in case of grid bottlenecks

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If delays in grid expansion occur as the share of vRES increases, grid congestion and bottlenecks may follow. A well-developed grid can prevent such congestion. For instance, in Germany, renewables cover around one-third of annual electricity demand, and only around 2 to 4 percent of renewable generation is curtailed. Nevertheless, even countries with a strong grid infrastructure can experience grid congestion. When they do, their grid operators need to take specific actions based on a variety of instruments and follow clearly prescribed rules. Otherwise vRES generation may be curtailed when considerable levels of conventional power generation are still being produced. The curtailment of renewables should be a measure of last resort in order to maximise the amount of green electricity in the grid. Remote-controlled access to vRES plants and their real-time generation data can help grid operators manage the system.


Siemens AG

How to procure ancillary services in times of lower conventional generation

more on page 33

Traditionally, conventional thermal generators have delivered ancillary services, such as frequency and voltage control, which are necessary for reliable system operation. But today conventional power generation is down, so new sources of ancillary services have become crucial. Renewable power plants can provide certain ancillary services if appropriate provisions are defined, say, as part of their connection requirements. In addition, components for the provision of ancillary services (without the co-generation of electricity) can also be built directly into the grid (such as STATCOM equipment). Even generators at decommissioned nuclear power plants can be turned into rotating synchronous condensers and contribute to voltage support. In distribution grids, voltage fluctuations – or voltage rises induced by solar photovoltaic feed-in – can be offset by installing variable-voltage transformers.


fotolia.de/Kara

Why it is important to anticipate the system impact of vRES early on

more on page 34

It is easy to overlook vRES when their share in the power system is small. But it is important to anticipate the impact of a growing share of vRES early on, because retrofitting existing plants for improved reliability is costly and cumbersome. A master registry that records all renewable generation plants (including their relevant technical requirements) is crucial for keeping track of the impact of vRES on the system – and for determining whether additional measures may be necessary.


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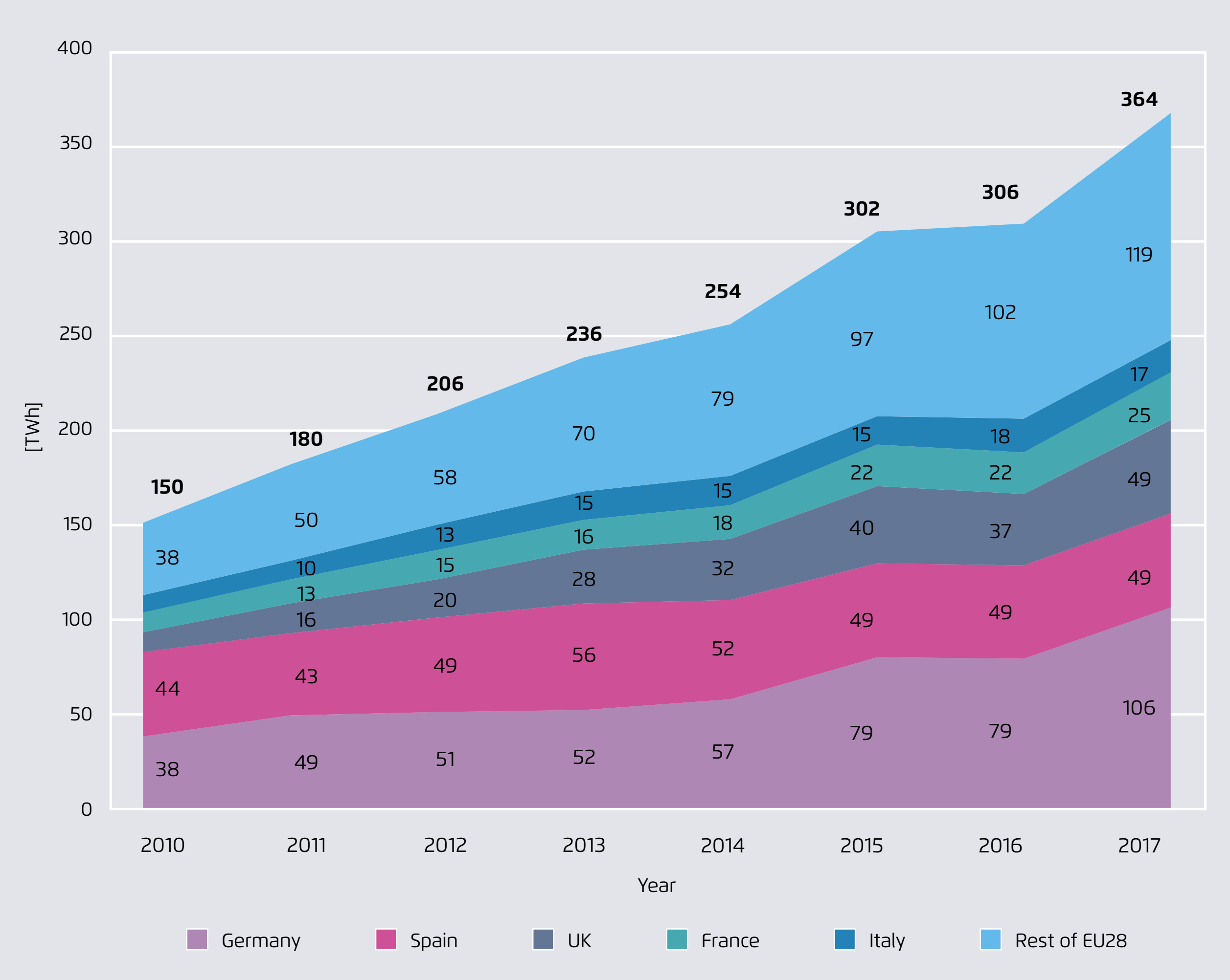
CONTENT

Introduction

Grid integration of renewable energy

Generation costs for solar photovoltaics and wind energy have decreased at an impressive pace in recent years. In Chile and Morocco investors have won auctions with remuneration rates for electricity from solar photovoltaics and wind generation below 3 eurocents per kilowatt-hour. In Germany the price for onshore wind power plummeted to 3.82 eurocents per kilowatt-hour in the third auction round in November 2017.[1] Many places around the world reported bids for onshore wind and solar power at around 5 eurocents per kilowatt-hour in 2016.[2]

Wind electricity generation in the EU-28 (including TWh output for each country in the top 5) Figure 1



Agora Energiewende and Sandbag (2018), p. 16, based on EUROSTAT data from 2010 to 2015; our own calculations were used for 2016 and 2017

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[1] In 2018, auction results were 4.59 eurocents per kilowatt-hour for ground-mounted solar photovoltaic (in June) and 5.73 eurocents per kilowatt-hour for onshore wind energy (in May) in Germany.

[2] See BNetzA (2017 a), BNetzA (2017 b), ENEL Green Power (2016), Bloomberg Markets (2016) and Reneweconomy (2016).

Due to falling costs, wind power and solar photovoltaics are the fastest-growing sources of electricity globally, and they are expected to make up a considerable share of the electricity mix in the near future.

Wind energy and solar energy are weather dependent. As the share of variable renewable energy sources (vRES) increases, fundamental changes to grid operation become necessary. Many researchers and policymakers are therefore looking at countries in which variable renewables already make up a considerable share of the electricity supply, such as Denmark (with more than 40 percent vRES), Ireland, Spain and Germany (with around 20 percent vRES each).[3]

Integrating high shares of vRES can be a challenge for system operators. Yet countries with high shares of vRES appear to fare quite well, and the reliability of electricity supply continues to be very high. For example, key indicators such as the System Average Interruption Duration Index (SAIDI) and the loss of load expectation (LOLE) show that the power system in Germany is among the most stable in the world (Figure 2), despite its rising share of vRES and decreasing level of baseload production.[4] This data suggests that high grid reliability and the integration of increasing shares of renewables need not be incompatible.[5]

In this paper we provide an overview of some of the lessons learned from integrating vRES into the grid of countries that, like Germany and Denmark, have high shares of variable power. We will present current practices in the context of their regulatory framework, as well as changes that have been adopted in order to cope with challenges that grid operators have faced along the way. *Section 1* describes future trends and challenges for grids in power systems with rising levels of vRES generation. *Section 2* focuses on the building of new power lines and transformer stations. *Section 3* focuses on system operation and ancillary services.

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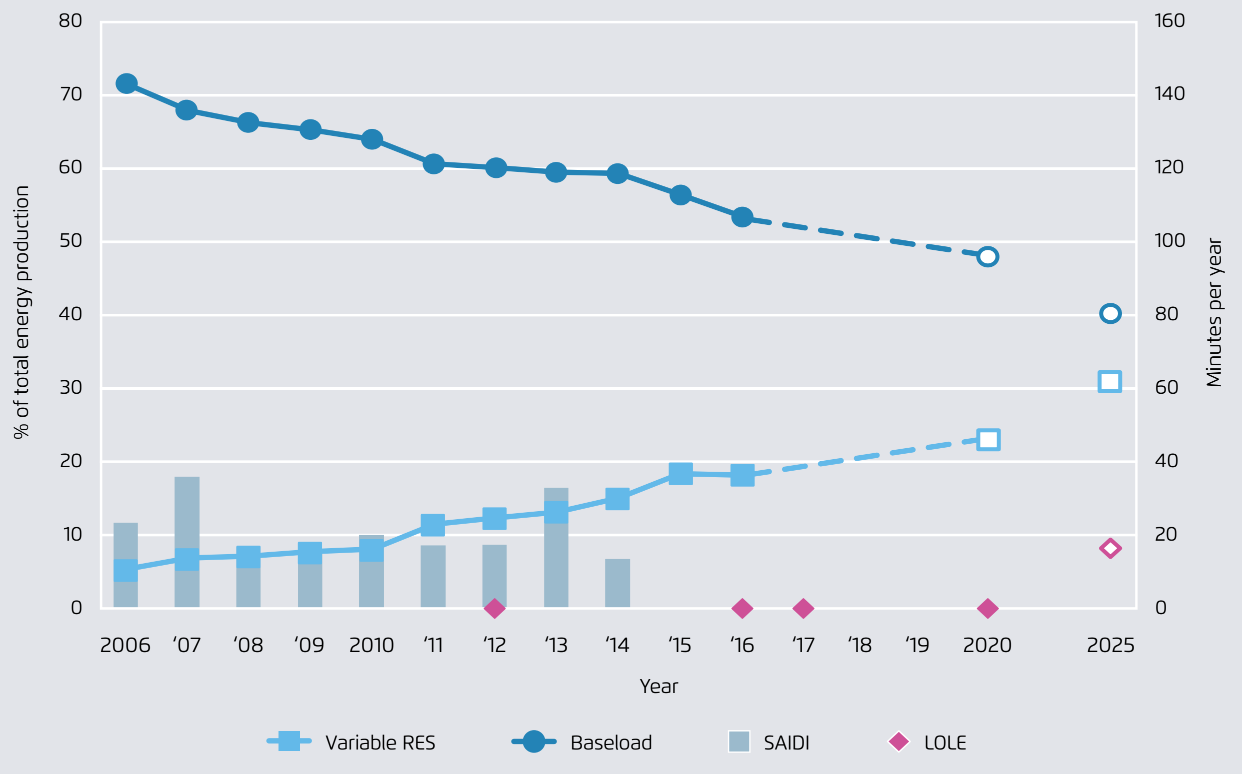
[3] See IEA (2017).

[4] See Hogan et al. (2018).

[5] No single indicator exists for measuring system reliability (and power quality). Though the SAIDI indicator reflects only electricity interruption, we believe that it gives a good impression of overall quality. LOLE indicates how many minutes per year generation in a control area is likely to fall short of demand.

Germany: resource mix vs. grid reliability **Figure 2**



Hogan et al. (2018)

1. Wind, solar and the grid: future trends and challenges

Like the road infrastructure, electricity networks can be divided into long-distance, high-capacity transmission lines ("highways") and regional and local distribution lines ("main roads and residential streets"). The primary purpose of the **transmission grid** is to move power over long distances from areas where power generation is high to cities and industrial centres, where most of the electricity is needed. Electricity exchange also takes place across national borders by means of interconnectors. The **distribution grid** transports power to individual power consumers who are connected at lower voltage levels. Traditionally, electricity has been produced by conventional thermal power plants based on lignite, hard coal, gas, nuclear energy and hydropower plants. Typically, these large-scale generation units are located near large load centres and are connected to the transmission grid. Electricity is transported "top down" from the transmission network to lower voltage levels in the distribution grid and then, ultimately, to private consumers. By contrast, much of vRES production feeds into the network of distribution grids. For the most part, onshore wind turbines are connected to the medium- or high-voltage level.[6] Many solar photovoltaic installations, notably rooftop solar photovoltaic systems, feed their power production into the low-voltage grid, in close geographical proximity to consumers. However, there are also types of vRES, such as offshore wind farms, that – due to their large capacity sizes – need to connect to the extra high-voltage transmission grid. Some large-scale onshore wind farms and ground-mounted solar photovoltaic installations also connect directly to the transmission grid. Figure 3 illustrates the changes in electricity production in Denmark from a centralised system based on conventional thermal generation towards a distributed system made up of decentralised combined heat and power plants and wind energy.

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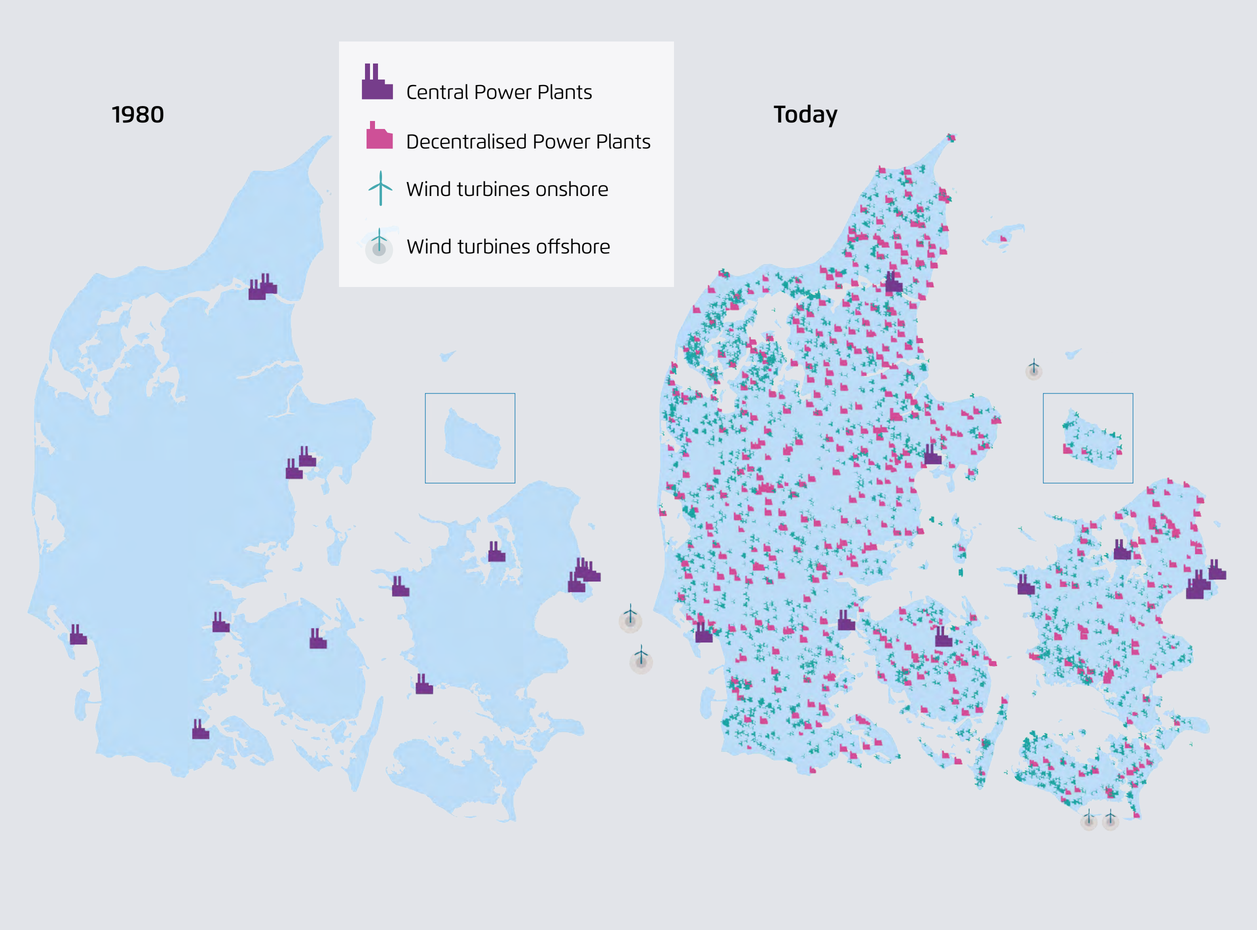
[6] In some countries, such as Germany, high-voltage lines (110 kV) are part of the distribution system; in other countries, the 110-kV level belongs to the transmission system.

Key insights:

- → As vRES increases, more electricity enters the distribution grid. This is especially true when vRES comes from rooftop solar photovoltaic and onshore wind energy.
- → The future of the electricity grid depends on the spatial distribution of new generation and demand.
- → The variability of renewable power supply makes system operation more complex and requires more flexibility.
- → The future energy system must allow more coordination of supply and demand amid a proliferating number of power sources, aggregators and demand applications.
- → More ancillary services are needed in view of the declining number of providers of traditional ancillary services.

Electricity production in Denmark in 1980 and today: from centralised to distributed generation Figure 3



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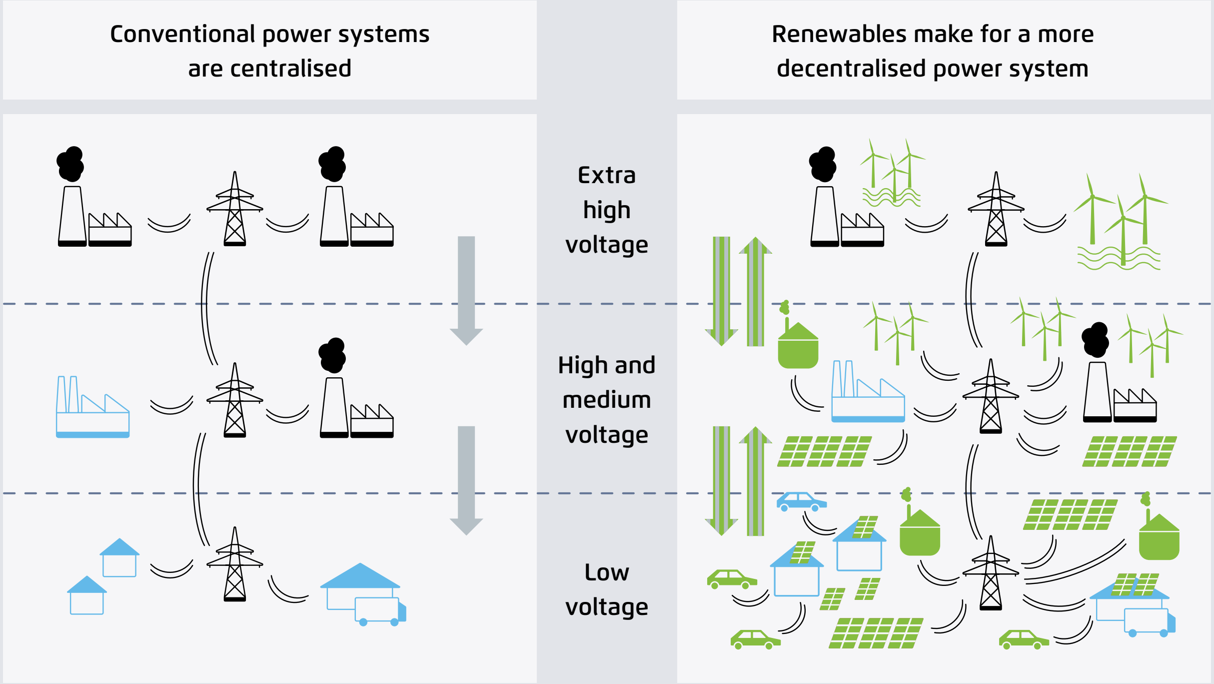
When more power generation enters the distribution grid, the **role of the distribution system** changes. It is no longer used solely for the top-down transmission of electricity from large generation plants to consumers. Rather, if electricity from distributed generation is not consumed locally, it is sent "bottom up" to higher voltage levels where it is dispatched to other regions. This results in **bidirectional power flows** – from the transmission grid to the distribution grid and vice versa – and represents a major departure from the unidirectional, top-down flow of conventional power systems. In other words, changes in generation structure can strongly impact grid planning and operation (Figure 4).

Consider another example. For decades, demand curves followed the same predictable pattern throughout the week and across seasons. This is no longer the case. Now, **new and unpredictable demand patterns** are creating new challenges for grid operators and planners. Another factor that heavily influences the layout and operation of the electricity system is the increasing use of heat pumps, electric vehicles and new business models for demand-side management.

All in all, we have identified four major energy system trends and their accompanying challenges:

From a traditional unidirectional system towards a more decentralised bidirectional system

Figure 4



Agora Energiewende (2017), p. 16

Trend 1: The grid of the future must adapt to the spatial distribution of new generation and demand.

For the most part, wind turbines and solar photovoltaic plants are located in areas with good site conditions in terms of wind yield and solar irradiation. If new vRES generation is concentrated in areas with low local electricity demand, the grid will need to be expanded so that power can be distributed to other regions. This is especially true if new vRES plants are located in areas where the network is weak and the grid is already congested. At the same time, changes on the demand side may significantly affect the planning and operation of the system. These changes can include the implementation of efficiency measures to reduce and/or enable more flexible power consumption, such as low-power appliances, machines, lighting and cooling systems. But they may also include new types of electricity demand, e.g., electric vehicles, heat pumps, electric boilers and fuel factories (for the production of methane or hydrogen). The spatial distribution of generation and demand is an important driver in determining the need for power line expansions and the layout of the future power grid. The lead time for implementing grid expansions may be fairly lengthy, taking up to several years longer than the realization of wind or solar projects.

Trend 2: Rapid changes in supply and demand produce steeper ramp rates.

Variations in wind speed and solar irradiance can cause rapid fluctuations in electricity generation. Electricity is a real-time good and necessitates an instantaneous balancing of supply and demand. There are two types of situations during which

imbalances may occur: times when power generation exceeds demand (caused, say, by high wind speeds and/or bright sunshine)[7] and times with very little or no vRES generation. Although forecasting has improved over time, the level of vRES generation can change quite rapidly, forcing grid operators to take short-term balancing measures when necessary.
A similar effect occurs when variability increases on the demand side. For example, electric vehicles and heat pumps may contribute to system balancing if they draw electricity during hours of excess generation. However, they may also lead to high ramp rates and create new demand peaks if activated all at once (e. g. the mass charging of many electric vehicles versus a "smart" charging approach that alleviates system constraints). The challenge lies in coping with higher ramp rates in both power supply and demand while maintaining system balance.

Trend 3: The number of power sources on the supply side and the number of electric-powered devices on the demand side are increasing.

High penetration levels of renewable energy typically increase the number of power sources on the supply side. This is because renewable power installations mostly consist of small-scale and modular energy conversion units – in contrast to systems that use just a few large-scale thermal power producers. On the demand side, more and more electric devices such as battery-powered cars and heat pumps are entering the market. In some countries, such as Norway, this is occurring quite rapidly. At the beginning of 2018 there were 142,490 electric vehicles registered in Norway. This was an increase of 42.5 percent relative to early 2017.[8] In addition, one can observe a growing number of "prosumers" who both produce and consume power. These prosumers typically combine solar photovoltaic panels with battery storage – a particularly attractive option because prices for these technologies have fallen considerably. The proliferation of power sources on the supply side and electric devices on the demand side influence the grid in real time. Their impact depends both on *where* they produce or consume electricity and *when* they do it. The challenge lies in coordinating all these power sources and demand applications and in managing the resulting grid complexity. Digitalisation and the diffusion of information and communications technology (ICT) are becoming increasingly important for obtaining real-time grid data and for enabling communication between power sources and electric-powered devices.

Trend 4: More ancillary services are needed in view of the declining number of providers of traditional ancillary services.

Grid operators are responsible for the provision of ancillary services. These services comprise frequency control, spinning reserve, voltage support, grid loss compensation, as well as black start and island operation capability. In a nutshell, ancillary services are necessary to maintain stable, reliable operation of the grid at all times. Traditionally, thermal power plants deliver ancillary services along with electricity generation. The challenge lies in striking a balance between ensuring the availability of ancillary services for safeguarding reliable system operation and finding new ways of procuring them.

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[7] Note that it does not only depend on the amount of wind power production, but also on the flexibility of the energy system (e. g., flexibility of conventional power plants, flexible demand, and storage) to accommodate a sudden increase in power production.

[8] See SBB (2018).

2. The grid as a flexibility option: a toolkit for grid planning and expansion

The transmission grid constitutes an important flexibility option for enabling system balancing across regions and for smoothing fluctuating wind energy and solar photovoltaic feed-in. One major challenge lies in anticipating the length and location of future power lines – and predicting which technological innovations will provide alternatives to classical grid expansion.

2.1 The GORE principle – grid optimisation prior to grid reinforcement prior to grid expansion

The GORE principle is an approach to grid planning that prioritises the improvement of already existing grid infrastructure over building new transmission lines. Standing for *G*rid *O*ptimisation before *R*einforcement before *E*xpansion, GORE always begins with measures for optimising the capacity of existing transmission lines (see below). Its next step is to reinforce existing transmission lines by, say, upgrading them with special line conductors that can transmit a higher current. Only when all of these options have been exhausted does it focus on the construction of new power lines. This approach minimises costs and reduces the negative impact on citizens and the environment. Germany is one country already practicing the GORE principle.[9]

2.1.1 Optimisation means safely utilising the existing power grid to its full capacity at all times

For the operation of power grids, it is critical that transmission lines, transformers and other electrical equipment remain within their thermal limits. The more electrical energy is transported through

Key insights:

- → The transmission grid is essential for balancing supply and demand across regions.
- → One approach to grid planning that increases public acceptance and minimises cost is the GORE principle: grid optimisation prior to grid reinforcement prior to grid expansion.
- → Among the "low hanging fruits" are the systematic implementation of dynamic line rating and the replacement of existing transmission lines with special lines that can carry a higher current.
- → Instruments for aligning grid planning and vRES planning can improve the coordination of grid expansion and vRES deployment.
- → Partial undergrounding of transmission lines in sensitive regions and consultations with local stakeholders can help increase public acceptance.
- → A master registry for all new power plants, including new vRES installations, should be created early on.

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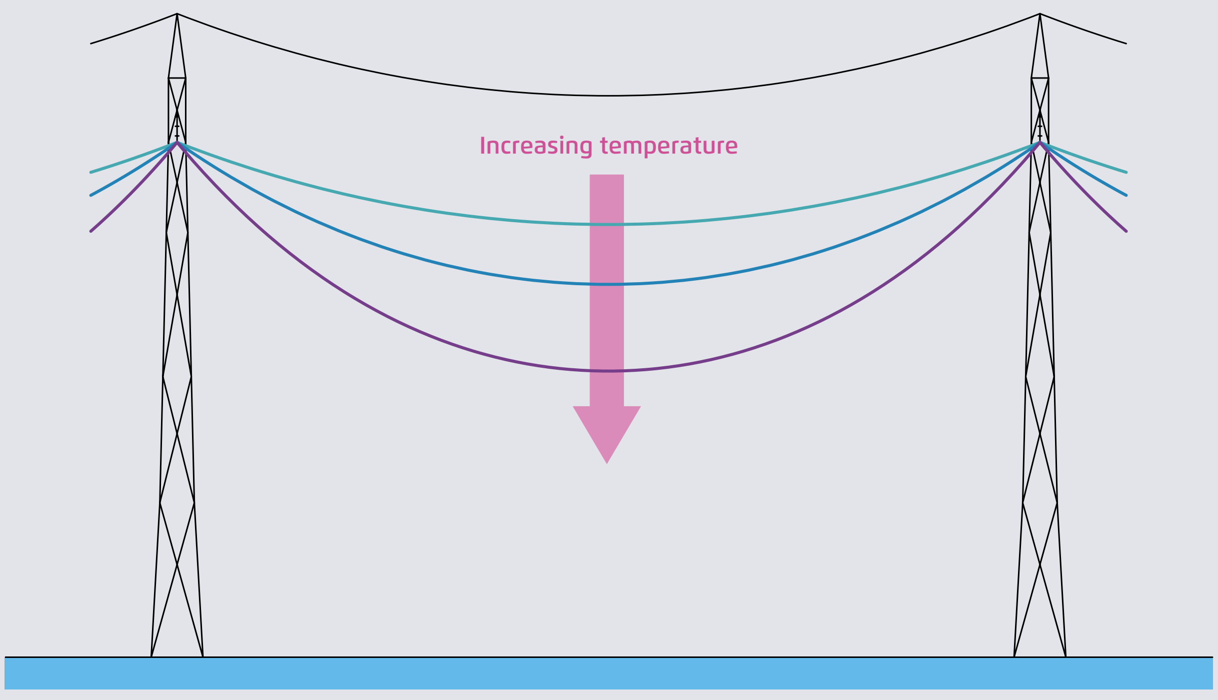
[9] In German the system is called "NOVA" ("Netz Optimierung vor Verstärkung vor Ausbau").

a transmission line or a transformer, the higher the operating temperature of the conductor becomes. If the operating temperature of an overhead transmission line exceeds its thermal limit, the material expands and the line sags below acceptable levels (Figure 5). This can place excessive mechanical stress on the transmission towers und expose the environment to strong electric and magnetic fields.[10]

The operating temperature of transmission lines is influenced by various factors, such as line losses, wind speed and direction, solar irradiation and conductor material properties. Traditionally, line rating is determined statically assuming "worst case" conditions, but these often underestimate the actual carrying capacity of transmission lines. *Dynamic line rating* safely utilises the transport capacity of existing transmission lines based on the real conditions in which power lines operate. In contrast to static line rating, which uses deterministic or probabilistic methods for calculation, dynamic line rating takes actual atmospheric conditions into account. Because dynamic line rating considers cooling conditions as well, it allows a higher "dynamic" current to be transmitted than would a static rating. In this respect, wind energy and the ambient temperature of power lines are "ideal partners": the more the wind blows, the lower the ambient temperature of power lines becomes, and the more electrical energy can be transmitted during periods of high wind energy feed-in. Dynamic line rating requires the continuous temper-

Illustration of transmission line sag as operating temperature increases

Figure 5



Energynautics (Agora Energiewende and Energynautics (2018), p. 35)

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[10] The sag of a transmission line is the distance between the two points of support (at the transmission tower) and the lowest point of the transmission line connected between the two towers. If the transmission line sags, its distance to the ground decreases. Other limiting factors such as line tension may also play a role, in addition to power line sag.

With special transformers, so-called phase shifters, power flows can be diverted from heavily loaded lines to less loaded lines.

ature measurement of overhead transmission lines. This can be done by installing technical devices such as sensors and infrared thermal cameras. The collected data must then be transmitted to the grid operators.

Phase-shifting transformers and other power-flow-controlling devices can also help optimise grid utilisation. Since power flow control is part of grid operation, these technologies are covered in section 3.1.3.

2.1.2 Grid reinforcement means upgrading existing power lines without building new ones

Grid reinforcement refers to the retrofitting of existing power lines in the transmission and distribution grids. One grid reinforcement measure is the replacement of "conventional" overhead transmission lines with high-temperature low-sag (HTLS) power line conductors. Compared with the aluminium-core steel-reinforced (ACSR) cable typically used in overhead transmission lines, HTLS conductors are capable of higher operating temperatures though they are the same diameter as conventional ACSR cables. This means that HTLS conductors allow a larger current in the same power line. Other grid reinforcement measures include upgrading the grid to higher voltage levels and adding a second circuit to already existing transmission lines. Under ideal conditions, grid reinforcement with HTLS can increase transmission capacity by 50 to 100 percent relative to conventional overhead transmission lines. The actual increase in transmission capacity from HTLS depends on the materials that are used.[11]

2.1.3 There is no one-size-fits-all solution, but the optimal choice must account for the heterogeneity of the grid

Grid optimisation and reinforcement measures may enhance transport capacity significantly. In light of the inherent uncertainty of future developments, system operators have an interest in identifying robust grid development measures that do not lead to stranded investments. In this respect, grid optimisation and reinforcement may be regarded as "no regret" measures provided they are feasible. Optimisation and reinforcement measures do not render grid expansion superfluous, but they can spare many

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[11] Kenge et al. (2016) provide an overview of different HTLS conductors in comparison.

INFO BOX – Grid requirements mandated by German law: priority access, shallow connection charges and grid capacity expansion

In Germany, renewable power generators receive immediate priority grid access, and they only incur costs from their generation plant to the point of connection after leaving the power plant (known as shallow connection charges). This has contributed significantly to the continuous penetration of renewable energy in Germany's power system.

Key insight: priority grid access for renewables is key; this includes grid reinforcement and optimisation at higher voltage levels.

→ *Priority grid connection.* Also known as priority access, priority grid connection requires grid operators to connect new renewable installations to the grid system at the appropriate voltage level and at the shortest linear distance (unless there is a technically and economically more suitable connection point). Notably, renewable power producers may select a different grid connection point provided that it does not bring significant additional costs for the grid operator.

→ *Mandatory grid optimisation, reinforcement and expansion for renewable installations.* Most grid operators that connect renewable installations to the grid are also distribution system operators. They are obliged to optimise, reinforce and expand their network from the low-voltage to the high-voltage (110 kV) levels whenever needed to transport renewable power to areas of demand.

→ *Cost allocation scheme: shallow connection charging.* The grid operator bears the costs for the optimisation, reinforcement and expansion of the grid. The renewable power producer bears only the costs for the direct line from the plant to the grid connection point and for the metering devices installed along this route. In this sense, the grid connection point can be considered the "dividing line" in terms of cost allocation (Figure 6). The inclusion of grid reinforcements up to the 110 kV-level is also relevant for renewable power plants connected at the medium voltage level. Experience has shown that the early anticipation of the impact on voltage levels above the connection level for renewable power plants leads to more consistent grid planning.

→ *Priority dispatch.* Grid operators are obligated to prioritise the purchase and transport of renewable electricity. Curtailment of renewable power production is a measure of last resort. (See section 3 for more details.)

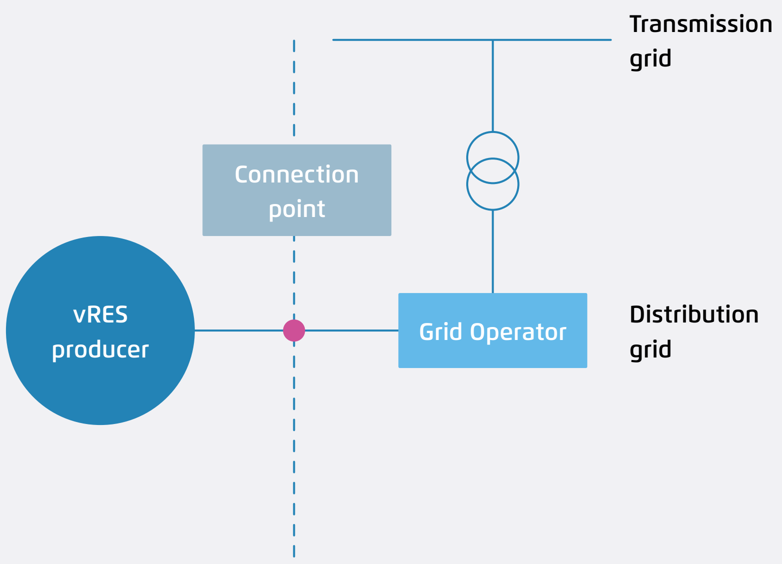
kilometres of new lines. The challenge lies in finding the optimal combination of grid optimisation, reinforcement and expansion. The optimal combination will depend on the case, as the structure of the grid can be very heterogeneous. The GORE principle prioritises "low-hanging fruits" in grid optimisation and reinforcement before constructing new transmission lines.

2.2 Grid planning process

Grid planning requires foresight. The realisation of new transmission line projects often takes a significant amount of time. Not only does it involve the construction of new transmission lines and towers; it also involves long lead times for permitting processes and environmental impact assessments. The major question faced by grid planners is how many

Grid connection point as a "dividing line" for the cost allocation of grid connection

Figure 6



- → Grid operator bears costs for optimising, reinforcing and expanding the grid.
- → Claim for grid capacity expansion also on upstream grid operators up to 110 kV.
- → "Dividing line" for cost allocation: grid connection point

- → *Exceptions can be made when it is economically unreasonable.*

Own illustration

kilometres of new transmission lines will be needed – and where. This question is particularly important in light of the astounding pace at which the share of renewables is increasing. One challenge in grid planning lies in striking the balance between anticipating developments in advance while maintaining a certain degree of flexibility. This section introduces different grid planning approaches and instruments.

2.2.1 The "grid expansion follows generation and demand" approach

A conventional approach to grid planning consists of two consecutive steps. First, planners develop *scenarios* that describe where and how much load and new generation will be located in a certain target year (e.g., 2030). These assumptions serve as input parameters. Second, planners carry out a *grid simulation* based on the input parameters from the scenarios. In many cases, planners also run a power-market dispatch model in order to simulate the dispatch of conventional power generation and vRES. The results of the power-market dispatch model are then fed as input parameters into the grid simulation. Any congestions arising in the grid simulation point to the need for new transmission lines.

The underlying assumption of this approach is that *grid expansion follows generation and demand*. One country that uses this approach is Germany. There, the four transmission system operators[12] apply a three-stage process:

Stage 1 – Scenario framework. Some questions need answering before planners can estimate the need for future grid expansion: How much generation capacity and which type will exist at a given point in time (e.g., 2030)? Where will it be deployed? How high will power demand be? Where will consumption

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[12] The German transmission grid is operated by four transmission grid operators: 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH and TransnetBW GmbH.

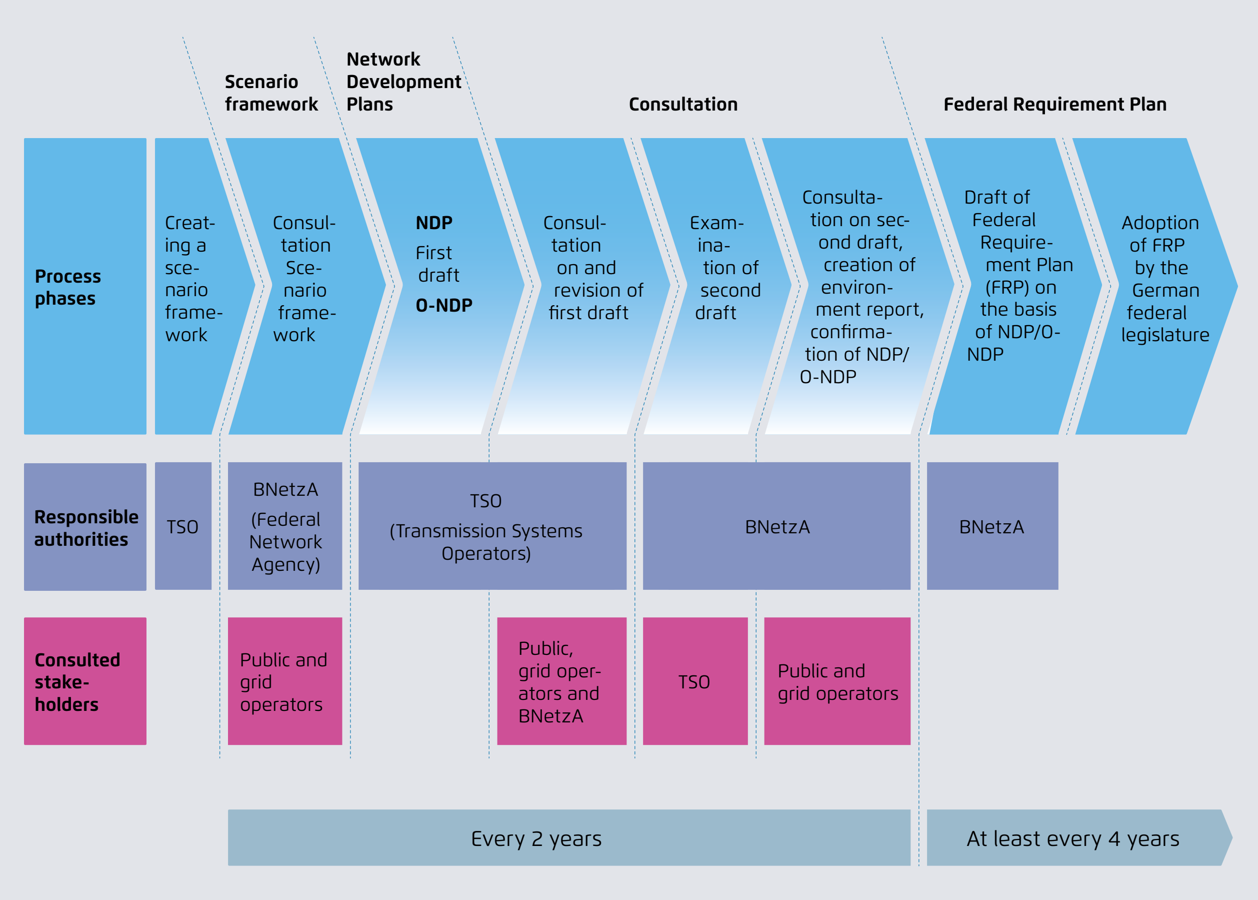
centres be located? What are other major drivers that will influence grid layout? To assess these questions, German transmission system operators draft what is known as *scenario framework* every two years. It consists of at least four scenarios; three of which cover the next 10 or 15 years, and the remaining one must cover the next 15 or 20 years. The scenario framework is approved by the German regulatory authority, the Federal Network Agency *(Bundesnetzagentur)*.

Stage 2 – Network Development Plan. Using the input parameters from the scenario framework, planners perform a market simulation based on a power-market dispatch model. A subsequent grid simulation then calibrates grid optimisation, reinforcement and expansion measures required for the next decade. The estimated transmission line expansions go into the Network Development Plan in accordance with the GORE principle (see above). The Network Development Plan includes all necessary measures and a time schedule for implementation. Before the Network Development Plan receives approval from the regulatory authority it must pass an environmental impact assessment.

Stage 3 – Federal Requirement Plan. Every four years, the Federal Network Agency submits the Network Development Plan to the federal government.

A multi-stage process: from scenario framework to Network Development Plan and Federal Requirement Plan.

Figure 7



50Hertz et al. (2017), p.3

The Network Development Plan serves as the basis for the Federal Requirement Plan, which comprises high-priority grid expansion projects and defines their start and end points. Once the German Parliament adopts the Federal Requirement Plan, it becomes legally binding (Figure 7).

The implementation of network expansion plans has proven difficult in many countries, where significant delays have occurred due to local opposition to high voltage lines or to lengthy planning and permitting procedures. Delays in grid expansion can make grid operation difficult in times of high congestion. This is why Germany has devoted considerable attention to the development of solutions for aligning grid planning and renewable energy deployment in regions whose transmission grids see high levels of congestion. This has resulted in the implementation of a number of innovative solutions:

The three-percent-approach: peak shaving in grid planning

Initially, the German Network Development Plan required that grid operators integrate all renewable power production. The layout of the grid was dimensioned to accommodate vRES generation at all times, even during hours with exceptionally high wind energy and solar photovoltaic feed-in and very low load. But this general requirement is not economically efficient because the extreme conditions it covers occur only for a few hours each year. The idea behind the *three-percent-approach* is to strike a balance between grid expansion and cost efficiency. In this approach, transmission grid operators factor in a vRES peak shaving of up to three percent of annually forecasted generation. This eliminates the need to build new lines to cover a very limited number of hours during the year, and leads to a significant reduction in grid expansion costs.

Transporting machinery and equipment requires a certain infrastructure, like ports and roads. Due to the size of some components as rotor blades and tower segments, wind projects have higher requirements than solar pv projects.

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“Grid-friendly” placement of new vRES

Regions with very high shares of vRES can place significant strain on the transmission grid if new lines are not built quickly enough. The resulting congestion requires an increasing volume of re-dispatch (ramping conventional power plants up and down to alleviate grid bottlenecks) and curtailment (reducing output of renewable generation). During recent years, situations like these have occurred in Northern Germany, where more than 70 percent of electricity is based on wind energy. As a result, the government decided to restrict the installation of new onshore wind turbines in areas where the transmission network is already overloaded (known as grid expansion regions) until additional grid capacity becomes available.

2.2.2 The “renewable energy zone transmission planning process” approach

As noted above, the discrepancy between the relatively short time frames for building wind and solar power plants and the relatively long time frames for building transmission lines represents a challenge for traditional transmission grid planning. Accordingly, the "grid expansion follows generation and demand" approach may not be able to meet the growing transmission needs of vRES deployment fast enough. Wind and solar power are located in windy and sunny areas that are sometimes far away from high-load centres. Even large vRES projects can be constructed within one to three years. This is considerably faster than the construction of conventional power plants. It is also faster than planning and building new transmission lines to connect remote areas with high levels of wind or solar energy to high-load centres, a process that typically requires five to ten years, sometimes longer. Ideally, transmission planning decisions should be made well in advance of renewable generation development decisions. In practice, however, this is rarely feasible because of the difficulty of anticipating where new vRES generation will be deployed. Often, the result is a time lag between new vRES deployment and grid expansion.

One effective response to this problem is the renewable energy zone (REZ) transmission planning process, which was developed in the US state of Texas.[13] It aims to encourage vRES investment in so-called best resource areas, that is, areas ideally suited for renewable energy production, while ensuring the timely construction of transmission infrastructure.

In this approach, transmission planning carries out an in-depth solar and wind resource assessment of the country or region in order to identify renewable energy zones, or REZs. These zones are "geographic areas that enable the development of profitable and cost-effective grid-connected renewable energy. A REZ has high-quality renewable energy resources, suitable topography and land-use designations, and demonstrated interest from developers, all of which support cost-effective renewable energy development. [Based on the designation of these REZ], the REZ transmission planning process is an approach to plan, approve and build transmission infrastructure that connects REZs to the power system."[14]

The steps for developing the transmission plan are shown in Figure 8.

As in traditional transmission planning, the process is organised and led by a designated ministry, regulatory authority, or transmission company. Even more than in traditional planning, however, its success depends on the active participation of developers, investors, environmental authorities, utilities and non-governmental organizations. If carried out successfully, it can help provide adequate transmission resources for accelerated wind and solar development at the most favourable locations.

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[13] For more information, see N. Lee. et al. (2017).

[14] See N. Lee et al. (2017), p. iii.

The REZ process: an overview

Figure 8

STEP 1. PROCESS DESIGN & VISION STATEMENT		
STEP 2. RENEWABLE ENERGY RESOURCE ASSESSMENT	**Summary:** Select areas with highest potential **Output:** Study areas map and supply curves	→ Assess resource → Screen exclusion areas → Identify the areas with the highest quality, developable resource
STEP 3. CANDIDATE ZONES SELECTION	**Summary:** Identify zones with highest probability of development **Output:** Candidate zone map and supply curves (one per area)	→ Gauge commercial interest → Identify areas where high quality resources intersect with commercial interest
STEP 4. TRANSMISSION OPTIONS DEVELOPMENT	**Summary:** Bundle candidate zones and conduct analyses of the options **Output:** Cost, benefit, and reliability impacts for each transmission alternative	→ Select scenario creation (bundling) methodology → Conduct cost-benefit analysis of options → Steady-state, dynamic stability, production cost, and reliability analysis
STEP 5. FINAL TRANSMISSION PLAN DESIGNATION	**Summary:** Select transmission option according to pre-set criteria **Output:** Final transmission order	→ Select transmission option that best complies with predetermined criteria, including reliability standards, economic benefits, and environmental goals
STEP 6. TRANSMISSION SYSTEM UPGRADE		

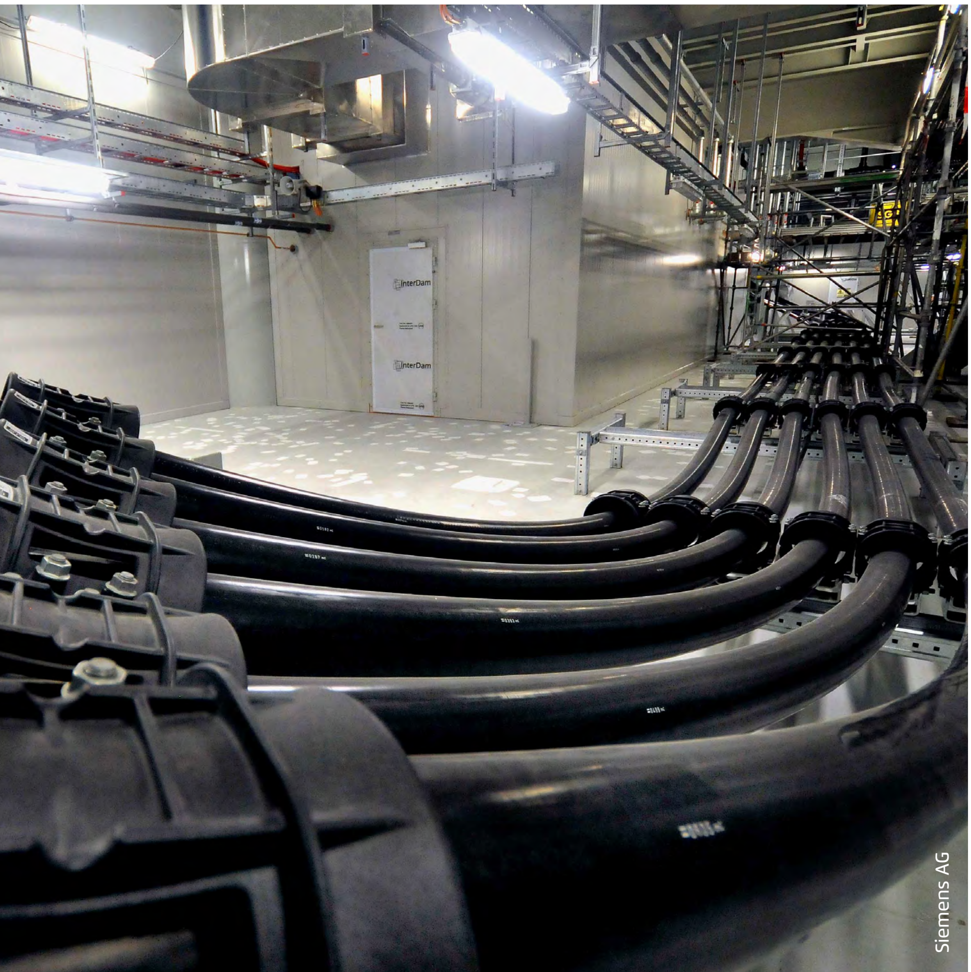
Lee, N. et al. (2017), p.3

2.3 Increasing public acceptance for new transmission lines

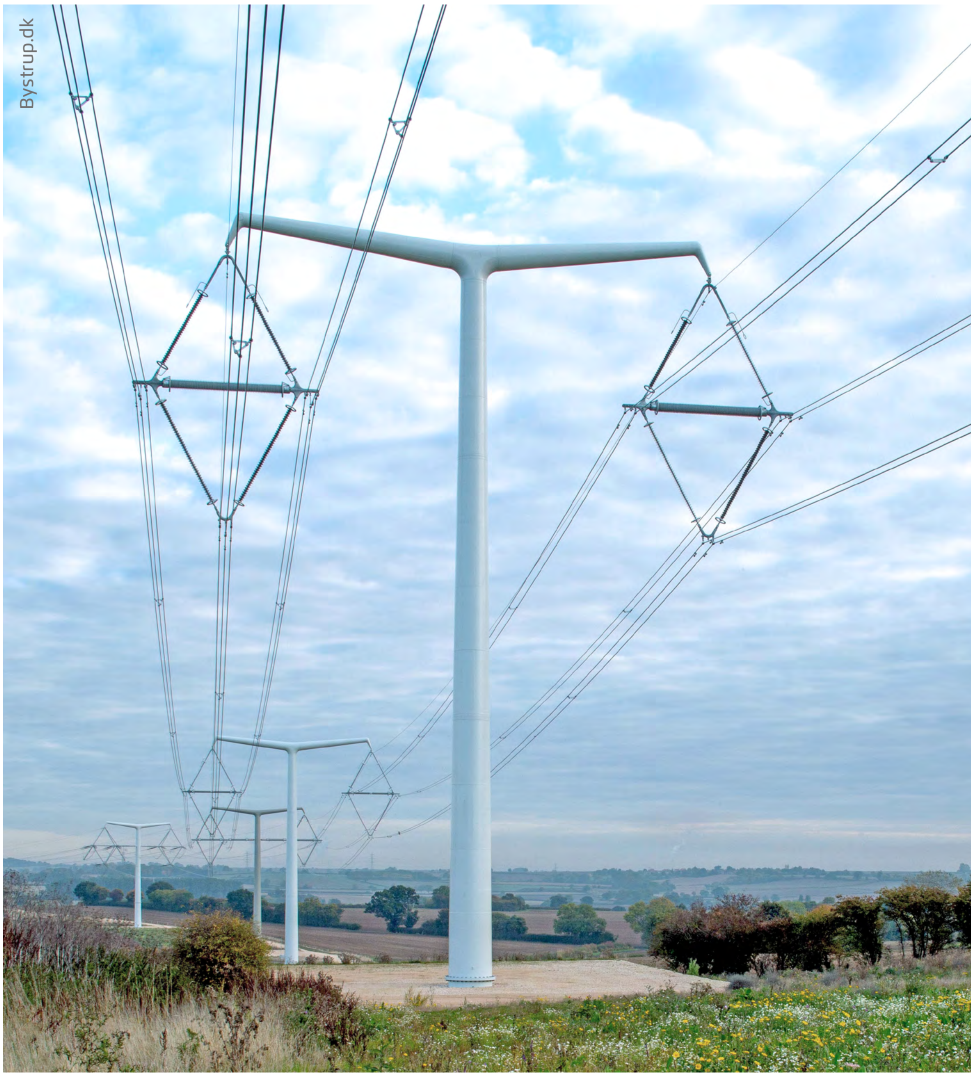
Transparency and the early involvement of citizens living near the newly planned transmission lines are crucial for winning public support. Local residents can be affected by the transmission lines in several ways: they may perceive the lines as marring the landscape, their property values may decline or they have concerns that exposure to electric and magnetic fields will adversely affect human health or local plants and animals. It is important to take all these issues seriously and address them properly.

There are various ways to increase public acceptance. The use of underground cables instead of overhead transmission lines in selected areas (partial undergrounding) is one option. In Denmark, transmission lines are usually built as overhead lines, but some sections, especially those passing near nature reserves areas or municipalities, are underground. In Germany, policy makers have decided on an underground design for the new large high-voltage direct current (HVDC) lines connecting the North and the South of the country. The advantages are obvious: underground lines are less visible than classical overhead lines, emit smaller electric and magnetic fields, and have fewer negative effects on birdlife and bats. On the other hand, underground cables are significantly more expensive than overhead transmission lines – their exact cost depends on various factors such as cable length, soil consistency, and transmission technology – and are thus usually reserved for particularly sensitive areas.

In order to minimise the impact of transmission lines, Denmark initiated a "beautification" plan of already existing 400-kV overhead transmission lines. Measures include the replacement of overhead lines by partial undergrounding over shorter distances or the


Siemens AG

Underground high-voltage lines enjoy great acceptance among the public. However, their construction takes longer than conventional lines and is more expensive.


Bystrup.dk

Elegant high-voltage pylons that fit better into the landscape can be an alternative to underground high-voltage lines.

building of transmission towers with less impact on the landscape along with other short-distance route adjustments.[15] The Danish TSO (transmission system operator) solicited input for the project plan from citizens and interest organisations, who expressed route preferences and suggested sections for undergrounding.

Another way to increase public acceptance for new lines is to include citizens early on in the planning process. In Germany, for instance, public consultation and impact assessments have played an important role. The regulatory authority, along with the TSOs, has provided information, solicited written feedback from citizens and other affected stakeholders and held various events where the public has been able to voice their opinions and concerns. Discussion topics have included the scenario framework, the Network Development Plan and the identification of routes within the corridors set by the planners. In addition, a website describes the planned transmission projects, and citizen bureaus in affected municipalities provide information on local projects.

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[15] See Energinet.dk (2018).

3. System operation: a toolkit for integrating rising shares of renewable energy sources

The natural variability of wind and solar energy poses new challenges to power grid operators. Electricity is a real-time good. In order to keep frequency close to the set value (usually 50 or 60 hertz), supply and demand require instantaneous balancing. An increasing share of vRES in power generation requires operators and planners to think differently. The conventional emphasis on baseload capacity with large generation units operating 24/7 does not provide enough flexibility for renewable power systems. To offset fluctuations in renewable power production, flexible resources are needed. Options include dispatchable power plants with fast ramp rates (e.g., gas turbines), demand-side management, storage technologies and – in the longer run – the integration of the power, heating and transport sectors. The Agora Energiewende publication *A Word on Flexibility* provides more detailed information on strategies and technologies for meeting the flexibility challenge.[16]

Transmission grids can provide flexibility by balancing variable power output across regions. The balancing of system supply and demand is a "global" task, but grid congestion occurs at the local level. In theory, situations can arise in which the power supply suffices to meet demand in a given region or even an entire country but the grid lacks sufficient capacity to transport electricity from generation plants to load centres. The following section addresses measures for tackling grid congestion. Later sections will address another prerequisite for reliable grid operation: the procurement of ancillary services such as frequency

Key insights:

- → Delays in grid expansion may lead to grid congestion and bottlenecks.
- → The re-dispatching of conventional power, the curtailing of renewable generation and other such measures are necessary to ensure stable grid operation. Moreover, transparent criteria are needed for vRES curtailment.
- → Real-time vRES plant data and remote output control help grid operators safely operate the grid.
- → As conventional power generation declines, the provisioning of ancillary services from vRES plants and new technologies becomes more important.
- → Voltage rises can occur in low-voltage grids when solar photovoltaic feed-in is high.
- → Innovative technologies such as regulated distribution transformers enable a higher uptake of renewable power and mitigate voltage problems.
- → Already in the planning stages, developers must factor in the system impact of increasing shares of vRES. Otherwise, costly retrofits of existing vRES installations may be needed.

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[16] See Agora Energiewende (2018).

and voltage control. Traditionally, conventional generators provide ancillary services along with power generation. With less conventional thermal power generation in the system, new ways are needed for supplying these services.

3.1 System operation when flexibility is key

Grid congestion occurs when there is insufficient transmission capacity available to transport power from generation plants to demand sites. This happens when too much electric power enters the grid, e. g., during hours of high wind power production, as is often the case in northern Germany. However, congestion can also arise due to delays in grid expansion, inflexible thermal generation or cross-border electricity flows.

The problem with congestion is that it jeopardises system security. This is because each line or transformer in a system has a maximum reliable current-carrying capacity depending on its thermal limit. If the operating temperature of an overhead transmission line exceeds its limit, the line can sag (section 2). If the active and reactive power that passes through a transmission line or transformer exceeds their respective limit for too long, permanent damage will occur. Alongside thermal limits grid operators must also adhere to voltage and stability limits for additional system security.[17] If a single transmission line, generator or transformer fails, built-in redundancy – known as "N-1" criterion – makes sure that the power system can continue stable operation.

3.1.1 Tackling congestion: re-dispatch and curtailment

In preventing congestion, grid operators can take different types of real-time measures. These include grid-related measures (switching operations), re-dispatch (ramping up and down conventional power plants on both sides of a grid bottleneck), curtailment (reducing renewable production) and, in some cases, load shedding. It is important that there are clear and transparent rules for the application and order of these measures. Otherwise vRES generation may be curtailed while conventional power gener-

INFO BOX – Re-dispatch measures and curtailment in Germany

The increased reliance on re-dispatch and curtailment measures over the past few years has been receiving growing amounts of attention in German policy discussions and in the media. The costs of these measures currently total around one billion euros. Because consumers must shoulder these costs via grid fees, public acceptance of such measures may wane. At this point, the curtailment of renewable power generation is still a mostly local phenomenon. Around two-thirds of curtailment take place in the northern state of Schleswig-Holstein, where most wind turbines are deployed. The combined volume of re-dispatch and curtailment currently amounts to approximately 3 percent of gross electricity production, which is a relatively small amount compared with that of other countries. The actual amount of re-dispatch and curtailment during a given year depends on various factors. For example, 2016 saw less re-dispatch and curtailment than 2015 because wind yield was down, and a new transmission line – the "Thuringian Electricity Bridge" – alleviated grid constraints in the eastern part of Germany. In 2017, re-dispatch and curtailment increased again, reaching levels similar to those of 2015. To keep curtailment from growing, policy makers must incentivise flexibility options such as power-to-heat and flexible loads.

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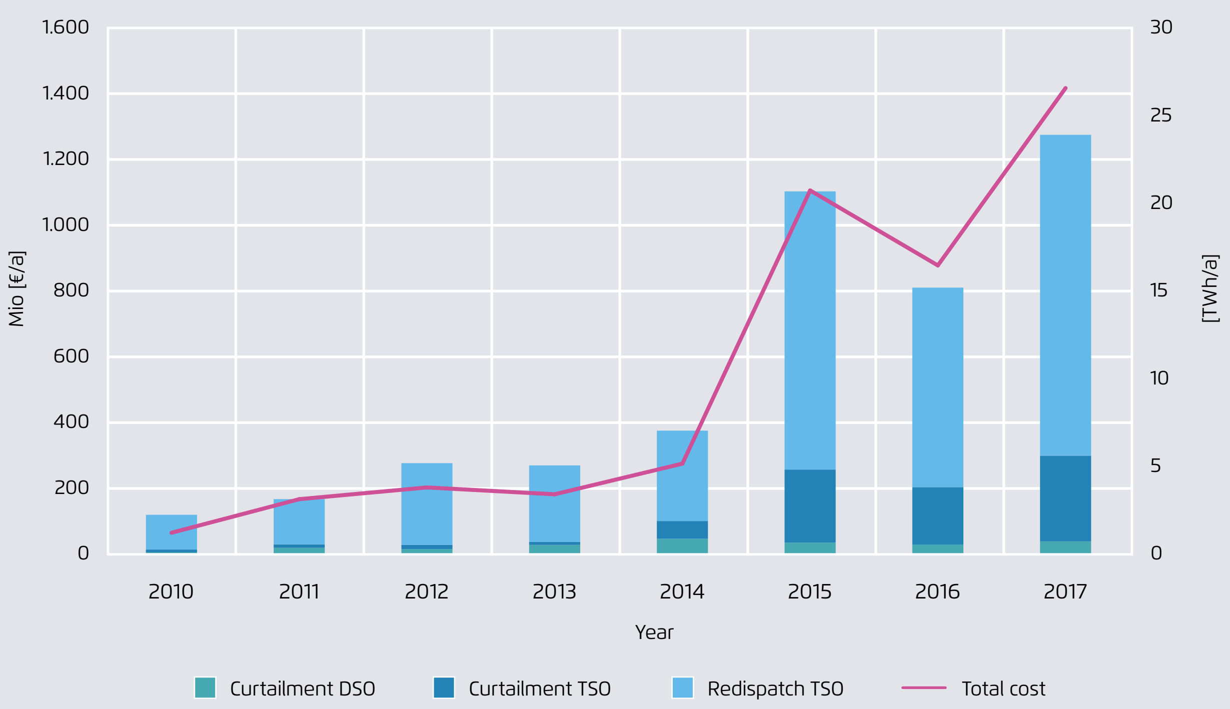
[17] These limits are mentioned here for the sake of thoroughness, though a more detailed discussion goes beyond the scope of this report. At present, stability limits are not a major issue in Germany, but they may become more important in the future. As real-time stability limits are far more complex and less linear in relation to the amount of current transmitted, they require a real-time assessment of the grid's stability (online dynamic stability assessment – Online-DSA).

Re-dispatch and curtailment measures in Germany

Figure 9



Ecofys (2017), updated in 2018 based on data by Bundesnetzagentur and MELUR (Ecofys and Fraunhofer IWES (2017); data reflects updated version)

ation keeps running – and emitting carbon dioxide. Many countries in Europe have established a priority dispatch policy for renewable energy sources. That is, they curtail vRES only after other measures have been exhausted. The priority dispatch of renewables is particularly helpful for integrating and promoting vRES generation in countries with low (but increasing) shares of renewables.

The four major instruments that grid operators in Germany use for the management of grids are as follows (based on order of importance):

- → system-related measures such as *switching operations in the grid;*
- → market-related measures such as re-dispatch (the ramping up and down of conventional power plants with capacities greater than 10 megawatts) based either on contractual agreements between a power producer (or storage operator) and the grid operator or on statutory obligations of the grid operator (to reimburse costs and financial losses incurred by the power producer);
- → the contractual activation of reserve power plants for compensating a deficit of redispatch capacity, with the reimbursement of costs for power producers; and
- → the *curtailment* of electricity based on renewable energy sources and combined heat and power (the gradual reduction or elimination of output at renewable plants or combined heat and power plants), with financial compensation for 95 % of lost revenues for affected producers based on a so-called "hardship clause."[18]

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[18] If the loss is more than one percent of annual revenue, power producers

Other potential last-resort measures include power feed-in adjustment and the offtake of consumers at the grid operator's request (without financial compensation).

3.1.2 Remote monitoring and controlling of vRES generation

Curtailment is more efficient when grid operators have *remote access* to vRES generation data in real-time and the *remote-controlled ability* to reduce output at vRES installations. The integration of vRES becomes much easier if remote online monitoring and control for renewable power plants is installed from the outset so that operators can dispense with the "phone-call option," i.e. calling vRES plant operators and asking them to reduce output. As the share of renewables grows, the controlling and monitoring of vRES generation becomes more time critical. Retrofitting already existing vRES plants can be a fairly cumbersome process, especially when many small-scale solar photovoltaic plants and wind turbines are involved. This is why it is advisable that vRES plants of a certain capacity have remote monitoring and controlling devices in place prior to grid connection. In general, real-time monitoring and controlling has gained in importance as the number of power sources and demand applications and the complexity of grid operation have grown.

3.1.3 Power flow control: the optimisation of power flows and short-term measures for managing grid congestion

The implementation of *phase-shifting transformers and other power-flow-controlling devices* allows grid operators to optimise electrical power flows and to increase the utilisation of already existing transmission capacity. Phase-shifting transformers are a special type of transformer that controls and directs the flow of real power in alternating current (AC) transmission grids. For example, phase-shifting trans-

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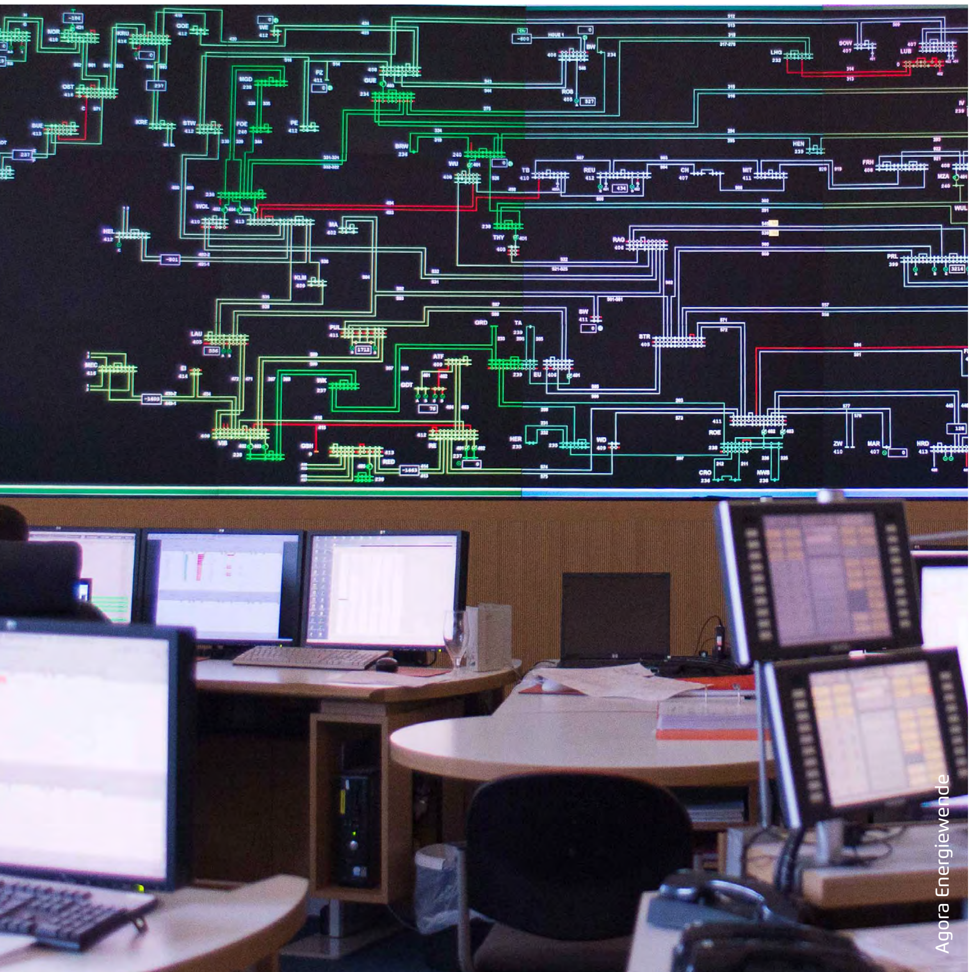
receive total financial compensation instead of 95 percent.


Agora Energiewende

Precise monitoring of power flows and line loads is a prerequisite for grid operation with a high proportion of renewable energies.

INFO BOX – Phase-shifting transformers for relieving grid congestion in Germany

In the next few years, transmission system operators in Germany will install phase-shifting transformers in selected areas with high levels of grid congestion to reduce the re-dispatch and curtailment of renewable power. Prior to their installation, an economic cost-benefit analysis will be carried out to make sure that the implementation of a phase-shifting transformer (or other device for controlling power flows) is more cost-efficient than the costs of re-dispatch and curtailment due to congestion. In 2017, the implementation of phase-shifting transformers became a new short-term measure in the grid planning process for the alleviation of grid bottlenecks in Germany. It is important to stress that the situation in a congested section of a network can improve and that grid bottlenecks may be temporary. For example, grid bottlenecks may disappear after the construction of a new transmission line. If the phase-shifting transformer is no longer needed in this specific network section, it can be used somewhere else. The implementation of phase-shifting transformers usually has a negligible impact on the environment as they can frequently be installed in already existing substations. If several phase-shifting transformers are used in adjacent areas, grid operators must take power-flow-control interdependencies into account. Power-flow control is an important instrument for controlling active power flows, regulating voltage and stabilising the grid.

formers regulate cross-border electricity flows at the interconnectors between Poland and Germany.[19] By the same token, phase-shifting transformers can be used to **control or re-route power flows** in the transmission grid *within one country* so as to alleviate certain transmission lines from grid congestion. Overload on certain transmission lines can be avoided by re-routing power flows to other transmission lines or network areas, provided that there is sufficient transmission capacity available. Phase-shifting transformers can be used as power flow controlling devices in the short term for relieving grid constraints on heavily laden circuits.

3.2 Procurement of ancillary services

If a system is to operate reliably, it requires a broad array of ancillary services. Generally, ancillary services "are all services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality."[20] They comprise frequency control, voltage support, grid loss compensation, as well as black start and island operation capability. As noted above, some of these services can be considered *"global"* or *"system wide"* (e. g., frequency control), whereas other services are *"local"* (e. g., voltage support). In order to provide ancillary services (e. g., frequency control, voltage control) the grid operator organises and procures the necessary system services (e. g., reserves are required for frequency control, reactive power is needed for voltage control) from generators, electricity storage operators and other sources. Traditionally, ancillary services are provided by conventional spinning generators. With the transition of power systems towards increasing shares of vRES, new sources for the provision of ancillary services are needed. Without new sources, a certain share of thermal power plants would need to remain online at all times to provide voltage or security support, limiting the feed-in of vRES. Hence, renewable power generation (along with other alternative options) must contribute to system services.

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[19] 50Hertz and PSE (2016).

[20] See Eurelectric (2004).

INFO BOX – Getting it right from the start: the 50.2 Hertz problem in Germany.

The maintenance of system stability requires a frequency of either 50 or 60 hertz (depending on the country). When power production exceeds power consumption, frequency increases beyond the acceptable level (overfrequency); when there is not enough power production to meet consumption frequency falls below it (underfrequency). Both situations can endanger system stability. In Germany, the grid connection rules initially required that solar photovoltaic plants (typically connected to low-voltage grids) disconnect from the grid at an overfrequency of 50.2 hertz. As long as there were low levels of solar power in the system, this requirement posed no problem. But between 2009 and 2012, Germany installed seven to eight gigawatts of PV per year. Total capacity increased from 11 gigawatts in 2009 to 33 gigawatts in 2012. All the while, onshore wind turbines remained configured to disconnect from the grid at an underfrequency of 49.5 hertz. The resulting situation was precarious: if a large share of solar photovoltaic modules disconnected all at once at 50.2 hertz, the primary reserve would be unable to compensate for the sudden drop in grid frequency. Moreover, the generation loss would have induced underfrequency, which would have forced onshore wind turbines to disconnect at 49.5 hertz. The ultimate outcome of this "domino effect" could have been a blackout. The German Federal Ministry for Economic Affairs and Energy (BMWi) thus required vRES producers to perform the time-consuming task of retrofitting several hundred thousand solar photovoltaic modules and onshore wind turbines and reconfiguring their disconnection levels, which in many cases had to be performed on site. The episode taught German policy makers an important lesson: it was better to assess the system impact of grid connection rules in the planning stages than to change them after they were in place.

3.2.1 Ancillary services provided by renewable electricity generators

The provision of ancillary services has always been a condition that conventional power plants have to satisfy in order to receive a grid connection. These technical minimum requirements are defined by the network codes for respective voltage levels. Renewable generation has no system impact as long as the share of vRES power production is only incremental. As installation rates in Germany have grown, similar requirements have been instituted for wind turbines. The *Ancillary Services Ordinance* was adopted in 2009, a year that saw the installation of around 25 gigawatts of wind onshore. The ordinance introduced requirements for frequency and voltage support for onshore wind turbines and defined technical regulations for onshore wind turbines to supplement existing network codes. The requirements became compulsory for new onshore wind turbines that went into operation in or after April of 2011. Turbines already operating before that date could obtain a premium if their operators adhered voluntarily to the ordinance rules. Today, renewable generation requirements are part of the existing framework of network codes for different voltage levels.

3.2.2 New ways for the provision of ancillary services

As vRES increases, more electricity flows into the distribution grid. Electricity that is not consumed locally is fed upstream into higher-voltage levels of the distribution grid or into the transmission grid. Ever since Germany began the phase-out of its nuclear power plants, many of which are located in southern Germany, voltage stabilisation has become an increasing challenge, as there are fewer central conventional power plants available to provide reactive power. Ancillary services can come from power generators or from grid components for system stability. For example, Static Var Compensators (SVC), static synchronous compensators (STATCOM) and synchronous condensers can provide ancillary ser-

Generators of decommissioned power plants can be converted into rotating synchronous condensers for provisioning voltage support.

vices for voltage support without the co-generation of electricity. In one case, engineers converted the A generator of the decommissioned Biblis nuclear power plant into a rotating synchronous condenser. The Biblis A generator has a capacity of 1.2 gigawatts and is located in southern Hesse. It was the first time that a generator of this size had been made available for reactive power regulation in situations of low or high grid voltage.[21] In Denmark, the transmission system operator Energinet.dk has held a number of tenders for the provision of ancillary services. In some of the tenders, the installation of a new synchronous compensator turned out to be cheaper than obtaining ancillary services from an existing power plant.[22]

3.2.3 The provision of ancillary services in the distribution grid

A voltage increase in distribution grids may be the result of electricity from small-scale solar photovoltaic plants connected at lower voltage levels. This problem is particularly relevant for regions that have a high density of decentralised vRES generation but limited local demand and long distribution distances.[23] One solution for offsetting voltage fluctuations in the low-voltage network is the installation of variable-voltage transformers. Typically, voltage variation in low- and medium-voltage grids has to stay within the range of +/-10 percent. The implementation of regulated distribution transformers enables the utilisation of the entire voltage range of +/-10 percent for each voltage level. Uncoupling the two voltage levels thus allows a higher uptake of power produced from renewable energy sources.[24] Figure 10 depicts the different types of measures applied by the 880 distribution system operators in Germany. While some of these measures are part of conventional grid expansion, the implementation of "smart" technologies for metering and control will become more important in the future. As of April 2017, there were 57 distribution system operators in Germany using variable-voltage transformers and 61 distribution system operators using voltage regulators.[25]

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[21] See Siemens (2017) and Amprion (2012).

[22] For more information, see Ea Energy Analysis (2015), p. 51 ff.

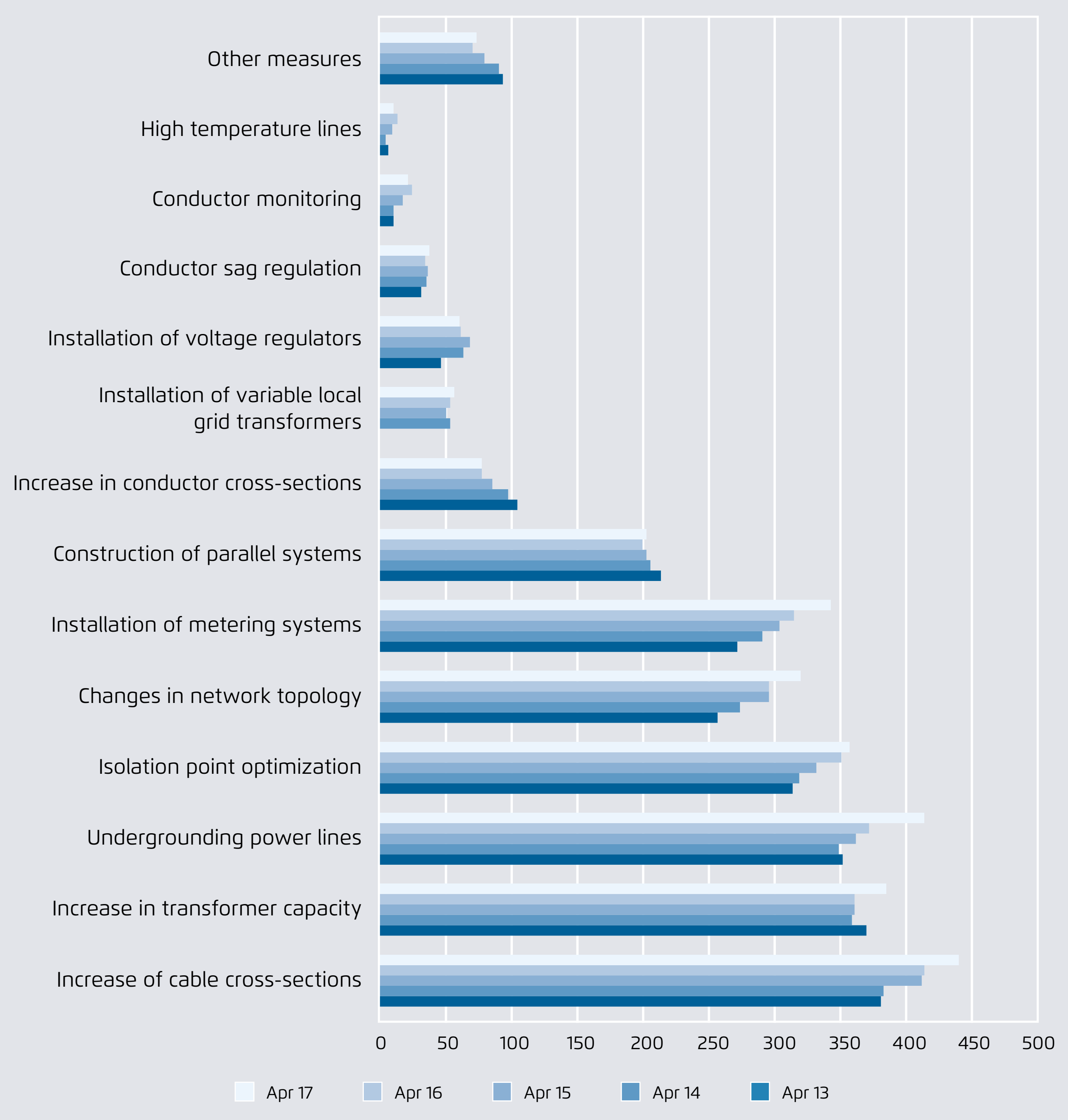
[23] See Ostbayerische Technische Hochschule Regensburg (2017).

[24] This is explained in greater detail in E-Bridge, IAEW and OFFIS (2014).

[25] See Bundesnetzagentur und Bundeskartellamt (2016).

Overview of grid optimisation and reinforcement measures applied under section 12 of the EEG and their frequency of use among grid operators (distribution system operators)

Figure 10



BNetzA and Bundeskartellamt (2017)

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About Agora Energiewende

Agora Energiewende develops evidence-based and politically viable strategies for ensuring the success of the clean energy transition in Germany, Europe and the rest of the world. As a think tank and policy laboratory we aim to share knowledge with stakeholders in the worlds of politics, business and academia while enabling a productive exchange of ideas. Our scientifically rigorous research highlights practical policy solutions while eschewing an ideological agenda. As a non-profit foundation primarily financed through philanthropic donations, we are not beholden to narrow corporate or political interests, but rather to our commitment to confronting climate change.

Agora Energiewende
Anna-Louisa-Karsch-Straße 2 | 10178 Berlin
P +49 (0)30 700 14 35-000
F +49 (0)30 700 14 35-129
www.agora-energiewende.de
info@agora-energiewende.de

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