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Smart grids in Germany: Current situation

Sino-German Energy Partnership

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dena
German Energy Agency

Imprint

The report "*Smart grids in Germany: Current situation*" aims at providing an overview of the currently applicable framework conditions for smart grids in Germany and to explore successful ideas and projects that can inspire further countries. It is published in the framework of the Sino-German Energy Partnership between the German Federal Ministry for Economic Affairs and Climate Action (BMWK), the National Development and Reform Commission (NDRC) and the National Energy Administration of the People's Republic of China (NEA). As the central dialogue platform on energy between two countries, the main objective of the partnership is to foster and advance the far-reaching and profound energy transitions ongoing in both countries by exchanging views, best practices and knowledge on the development of a sustainable energy system, primarily centered on improving energy efficiency and expanding the use of renewable energy. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH implements the project under commission of BMWK. As a German federal enterprise, GIZ supports the German government in the achievement of its goals in international cooperation for sustainable development.

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Content

List of Abbreviations

AI	Artificial intelligence
BEV	Battery electric vehicle
BNetzA	Federal Network Agency (Bundesnetzagentur)
BSI	Federal Office for Information Security (Bundesamt für Sicherheit in der Informationstechnik)
BVES	German energy storage system association
CBA	Cost-benefit analysis
CHP	Combined heat and power
Dena	German Energy Agency GmbH (Deutsche Energie-Agentur GmbH)
DSM	Demand-Side Management
DSO	Distribution system operator
ENTSO-E	European Network of Transmission System Operators for Electricity
EnWG	Energy Industry Act (Energiewirtschaftsgesetz)
EU	European Union
GIZ	German Corporation for International Cooperation GmbH (Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GW	Gigawatt
ICT	Information and communication technologies
iMSy	Smart metering system
IT	Information technology
KRITIS	Critical infrastructures (Kritische Infrastrukturen)
kW	Kilowatt
kWh	Kilowatt-hour
LoRaWAN	Long range wide area networks
mMe	Modern metering device
MsbG	Metering Point Operation Act (Messstellenbetriebsgesetz)
MW	Megawatt
NABEG	Grid Expansion Acceleration Act
NIS-Directive	Network and Information Security Directive
PV	Photovoltaic
RE	Renewable energy sources
SINTEG	Smart Energy Showcases project
SMGW	Smart meter gateway
TSO	Transmission system operators
TWh/a	Terawatt-hour
VPP	Virtual power plant
vRES	Variable renewable energy sources

Editorial

Dear Reader,

Germany’s expansion of electricity generation from renewable energies poses new challenges in the interaction between electricity generation and electricity demand to system operations. Load-following operation of generation from conventional power plant capacities guaranteed in the past the equilibrium of power generation and power demand as well as grid stability. However, as the operating times of conventional power plants are slowly decreasing and electricity is generated to a large extent by intermittent renewable energies, the need to increase the entire energy system’s flexibility and to adapt electricity demand to generation is more pressing than ever. But even when the answers to acute and complex issues, as the ones we are currently faced with, cannot be found immediately, it is worth to focus on concepts and solutions which can indeed deliver benefits and make a difference. As it is the case with smart grids.

While the term may seem vague at first, it ultimately encompasses multiple aspects that need to be part of our future power systems. These aspects include flexibility, reliability, safety and inclusivity. Furthermore, two of the main trends driving forward the energy transition in Germany are the decentralisation of the energy supply and digital transformation of energy systems. These transformation drivers form the main core of smart grids. Lastly, within this concept a bidirectional flow of data and electricity is made possible.

In the last ten years there has been some movement in the development of smart grids. New digital solutions as well as several pilot projects are among main factors helping smart grids to make a decisive breakthrough and fuel their further development.

With the ever more ambitious targets of Germany’s new government, a strong commitment in ensuring the democratisation, digitalisation and sustainability of the energy transition is apparent. Smart grids are a vehicle to ensure the successful implementation of such concepts.

Since a longer time, smart grids seem to be on everyone’s lips in Germany and for a good reason, as they can create new opportunities for active consumer participation in the energy transition, for efficient grid operation and enhanced renewable energy integration. It is ultimately the potential of such concepts that can give Germany and other countries the courage to actively pursue its ambitious energy transition. In spite of challenging times, the current situation can be used to advance climate protection and give new momentum and energy to the global energy transition.

This analysis by the Deutsche Energie-Agentur (dena) – the German Energy Agency - is developed within the framework of the Sino-Germany Energy Partnership, which is implemented by the GIZ and which has been successfully fostering the energy transitions in both countries since 2006. Our aim is to provide an overview of the currently applicable framework conditions for smart grids in Germany and to explore successful ideas and projects that can inspire further countries.

Sincerely,

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Executive Summary

Against the backdrop of an increased renewable energy expansion with a corresponding need for grid expansion and system flexibility, as well as the fact that electricity no longer flows in one direction, fundamental change is taking place in the German electricity system. These changes lead to, among other things, a reorganisation of grid operation, especially with regard to the coordination of decentralised assets and integration of many new flexible electricity consumers (electric cars, heat pumps, prosumers, decentralised battery systems). Generators, grids, suppliers and consumers are called upon to act flexibly, ideally within a smart grid construct. Advanced information and communication technologies play a vital role in this process and can ensure an intelligent network management.

Based on these requirements, this report puts forward the following definition of smart grids: a smart grid implies the existence of a digitalised and decentralised energy system with a bidirectional flow of data and electricity whose different components can be dynamically controlled with the use of information and communication technologies.

Upon closer inspection, however, smart grids bring along additional drivers as well as requirements that have an impact on different sets of actors. Distribution system operators (DSOs) in particular, are in the midst of this transformation process and are faced with increasingly complex challenges as well as new roles. In order to cover these new tasks, DSOs need to increase their communication and coordination with transmission system operators (TSOs) as well as consumers and energy producers are required in the future.

An improved demand side management (DSM) at all grid levels can be achieved in many ways, but must go hand in hand with the development of a robust smart metering and data infrastructure. Germany has been successfully performing DSM for many years already, but improvements are still required, especially during impending ramp-up of e-mobility.

Great importance is therefore attached in particular to the use of smart meters in order to achieve the overall digitalisation of the energy transition. Digitalisation, especially through smart meters, can support system operators in the steering and monitoring processes of their grids by providing access to valuable data on the load as well as generation side.

In this respect, insights into the current status of Germany's smart meter rollout as well as valuable lessons learned on what did not go as planned in this process are outlined.

Among the main constraints, which hamper the further development of smart grids and which have to be overcome in the near future are the available grid capacity for connection of all those new system assets, phase differences between the voltage and current as well as simultaneity factors which come up with the rise of e-mobility. As soon as these challenges are overcome, smart grids can realise their full potential, and contribute to integrating increasing renewables shares and decentralised loads, as well as contribute to make only necessary grid expansions. As costly grid expansions are the subject of many public discussions in Germany, smart grids can provide a feasible alternative by enabling an intelligent steering of new controllable loads, enhancing the utilisation of the existing power infrastructure and lowering the need for grid expansions.

As smart grids are called to improve the integration and coordination of decentralised energy generation and consumption, a multitude of technical, regulatory and operational preconditions still need to be met. Some of these are still in the process of implementation in Germany (digitalisation of operational workflows, price signals); some must be reevaluated fundamentally (reform of network charges) and some are not yet sufficiently mature (application of artificial intelligence in the grid operations). Relevant pilot projects have been particularly booming in the last years, with an active promotion by distribution system operators as well as the relevant ministries. In this report the focus lies on the relevant results from the well-known SINTEG project as well as the NETZlabor Sonderbuch and flexQgrid projects. Such projects make a case for the application of smart grids on a wider scale and test out new concepts.

Through this wide-angled perspective of the latest smart grids developments in Germany, the feasibility of applying such a concept nation-wide is highlighted, ultimately giving a further incentive to push forward relevant research efforts as well as technological, regulatory and operational improvements.

1 The next big thing will be a lot of small things - The rise of smart grids in Germany

Over the last years, Germany's energy supply has been steadily transitioning to renewable energy sources (RE). Parallel to this process a new set of challenges arises. RE production is weather dependent and increasing numbers of decentralised units play an important role in electricity generation. Many new loads are connected to the grid, particularly at the low voltage level. All these different components of the energy system need to be connected and coordinated intelligently. The development of a smart grid becomes inevitable.

1.1 Decentralisation – a driver for smart grids

Driven by the need to decarbonise its energy system, Germany has initiated a fundamental transformation of its energy supply in the last decades, introducing a large amount of variable renewable energy (RE), mostly wind and solar photovoltaic. Years after its initiation, Germany's energy transition, continues to be a focal point of public discussion and political debate. Even at this advanced stage, many steps still need to be taken to ensure the success of this project. This success cannot be achieved by one measure alone. The latest government put forward ambitious targets for the German energy transition, encompassing several aspects. Two main areas are at the center of attention: The energy supply should increasingly shift to renewable energies and electricity should be used more efficiently in order to drive down primary energy consumption. In the electricity sector in particular, a sharp increase in demand for electricity can be expected in a short time, partly due to the extensive electrification of other sectors as well (industry, heating and transport). In order to meet this increased demand and replace fossil-fuel based power generation an extensive expansion of renewables will be required.[1] Relevant targets for the coming years of the energy transition include:

- 80% RE share in electricity demand by 2030
    - Expansion of offshore wind to 30 GW by 2030 (total installed capacity as of 2021: 8 GW) and onshore wind to 115 GW (total installed capacity as of 2021: 56 GW)
    - 215 GWp photovoltaic (PV) installed capacity by 2030 (total installed capacity photovoltaics as of 2021: 59 GWp)
    - 10 GW electrolyser capacity in Germany by 2030
- Reduction of primary energy consumption by 50 % by 2050 compared to 2008

This shift to an increasingly RE based generation has posed new challenges to a fundamental law of today's power systems, which is that consumption and production of electricity must always be balanced. Furthermore, this shift has changed the interaction between electricity generation and demand. Historically, the electricity supply system in Germany was based on the principle that electricity generation followed the fluctuations in demand. Different conventional power plants effectively met baseload as well as any peaks in demand and guaranteed the equilibrium of electricity generation and demand,

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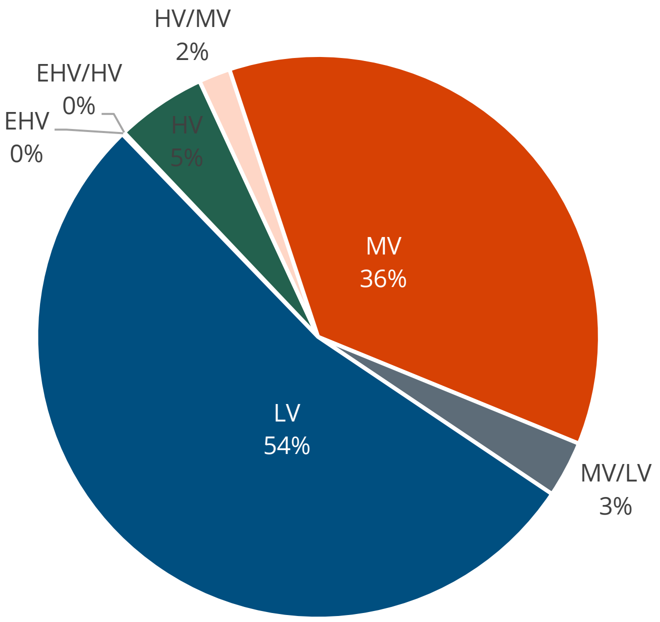
[1] BMWK (Ziele der Energiewende)

ultimately ensuring the stability of the power grid. The electricity generation from RE is subject to significant variation and uncertainty. This has increased the complexity of power system operations and requires a corresponding increase of the system's flexibility as well as a certain extent of adaptation of electricity demand to to generation.

On top of that comes the fact that electricity no longer flows in just one direction: Private households have installed PV systems on their roofs and some companies even have Combined heat and power (CHP) units or fuel cells.[2] As of 2020 there were already more than 1.7 million decentralised generation plants in Germany, feeding green electricity from wind, solar or biomass into the grid. As can also be seen in Figure 1, more than 90 % of these plants are connected to the distribution grids, posing new and complex challenges to network operators.[3] These small decentralised producers actively participate in the market and engage in demand side response. An over 1.7 million kilometers long distribution network connects power plants with households and businesses in Germany.[4]



*Abbreviation

- Low Voltage (LV);
- Medium Voltage (MV);
- High Voltage (HV);
- Extra High Voltage (EHV).

Figure 1: Installed capacity for solar energy by voltage level (2019). Source: Bundesnetzagentur[1]

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[2] E.ON (2022)

[3] Maaßen (2019)

[4] BMWK (Das deutsche Strom-Verteilernetz)

All of the above shows that the energy transition is now more than ever taking place in the distribution grids. And this does not yet take into account foreseeable

developments in areas such as electromobility, sector coupling, storage, etc., which will also be directly affecting distribution grids and thus have a significant effect.[5]

Apart from the diversification on the generation side, today's decentralised energy system is also characterised by the rise of new consumers (e.g. electric mobility, heat pumps, prosumers, decentralised battery systems). This in turn requires an enhanced sector coupling - mainly transport and heat with electricity. These factors influence many German distribution system operators (DSO) in their current activities and may eventually also lead to corresponding grid expansions.

While network operators know that these new loads in the low voltage level will only increase in the future, what still remains unknown is how the behavior of consumers will evolve. In the future it may be that, through new business models, consumers will use electricity when it is particularly cheap, i.e. when there is a lot of electricity from PV or wind in the grid.[6] In this particular case, it may even be possible that customers would charge/use their devices at the same time, which can lead to a simultaneous increase in the load. The current grids are not designed for these additional synchronisation effects that will play a role in the future. The goal, of course, is to integrate these new flexible consumers into the grid safely, quickly and, above all, efficiently.

To ensure that the grid does not become a bottleneck in the ongoing transformation process of Germany's energy system towards a climate neutral energy system, there are various approaches that can be developed and which all fit into the smart grid concept. With the increasing complexity on both demand and supply side, smart grids are key to addressing these challenges.

1.2 Addressing challenges through smart grid development

A smart grid serves several purposes and the shift from traditional electricity grids to smart grids is driven by the factors mentioned above. But why are smart grids necessary and what are the enablers leading to their emergence? The drivers for the development of smart grids in Germany can be summarized as follows:

1. Increasing penetration of RE
2. Integration of new (flexible) loads
3. Encouraging prosumers to act flexibly
4. Need for flexibility to ensure security of supply and grid stability
5. Minimising grid expansion needs

Smart grids are an essential instrument for the successful and efficient integration of a rising number of decentral units into the grid, ensuring a secure electricity supply and reducing grid expansion. The last point is present in many discussions in Germany: that with intelligent solutions, some expensive grid expansions can be avoided at best. To this end, innovative business and technological solutions, streamlined system operations and a fitting market design are important enablers. The combination of drivers and enablers can also be mirrored to some extent in the development of smart grids in Germany.

Grid operations become increasingly sophisticated and new actors and processes constantly appear. In order to take the energy transition to the next level, the deployment of information and communication technologies (ICT) is more imperative than ever. Ultimately, a streamlined smart grid development can increase:

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[5] Verband komunnaler Unernehmen e.V. (2022)

[6] The roles of producer and consumer are increasingly going towards the directions of prosumers and flexumers (flexible consumers) in Germany. Consumers are able to use energy when it is available from RE and also have the option of purchasing or providing energy.

- the share of RE which are integrated in the system,
- the security of supply and system efficiency,
- the acceptance and participation in the energy transition by smaller actors and thereby also enhance development in consumer technology, e.g., electrification of various consumer goods.

1.3 What are smart grids?

In this subchapter, various definitions of smart grids in German literature will be unpacked. The first smart grids activities were bundled under the umbrella of the German government's "E-Energy - ICT-based energy system of the future" funding initiative back in 2013. It was this funding programme, that first connected the smart grid concept with that of a digitalised energy system.[7] While it is relatively easy to pin down a definition of smart grids, it is difficult to summarize everything that makes up a smart grid in a few sentences. An initial definition was put forward by the Federal Network Agency (BNetzA) during the nascent stages of the development of this concept:

"*The conventional electricity grid will become a smart grid by being updated with communication, metering, control, regulation and automation technology and IT components.*"[8]

From this definition it becomes evident, that in order to deal with the significant changes to power grids due to the energy transition, ICT are key. However, things have evolved since then and more coherent definitions of smart grids emerged in the German discussions:

"*A grid becomes intelligent when there is an exchange of information within the grid that can be used to dynamically control power generation, consumption and storage.*"[9]

Furthermore, a smart grid is an *electricity network enabling a two-way flow of electricity and data* [...] *has self-healing capabilities and enables electricity customers to become active participants.*[10]

What can be derived from the aforementioned definitions is that a smart grid implies the existence of a digitalised and decentralised energy system with a bidirectional flow of data and electricity whose different components can be dynamically controlled with the use of ICT. This definition will be used as a basis for the analysis elaborated on in this report.

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[7] Schütz and Uslar (2022)

[8] Bundesnetzagentur ("Smart Grid" und "Smart Market")

[9] Ibid.

[10] i-SCOOP (2022)

1.4 The impact of ICT

The new decentralised reality puts an additional burden on grid operation. Accurate measurements, control and automation of the power flow are key to solving these issues.[11] In short, the application of innovative ICT in the distribution grids is more pressing than ever. This is what ultimately transforms today's distribution grid to a smart grid. Digitalisation is an important component of the decentralised energy transition.

According to a study by Bitkom (Germany's digital association), through an accelerated digitalisation, the energy sector can reduce its CO_2e (carbon dioxide equivalents) emmissions by 23 megatones in 2030.[12] The essential core of digitalisation is the collection and processing of data in digital form. New solutions are continuously developed and existing ones improved on the basis of digital data processing and exchange. Such digital solutions link producers, consumers, storage facilities, prosumers, and flexsumers and enable the secure real-time control and coordination of countless players through partially or fully automated processes.

Smart and remote maintenance

Digitalisation enables the monitoring and control of market participants at the local level, for example in municipalities and neighborhoods. Through efficient and comprehensive digitalisation, the energy system can continue to be designed and controlled in a stable and robust manner despite the greater complexity due to new players and roles. Smart and remote maintenance softwares are also increasingly offered and in combination with AI allow for an easier and faster real-time data analysis for plants´ and devices' maintenance.[13]

Due to the increasing coordination and control effort for market and grid integration in the course of the energy transition, the importance of data for ensuring security of supply will continue to grow. In order to take advantage of the opportunities and possibilities offered by digitalisation, a basis must be created for the reliable handling of high-quality data. At the same time, the increasing level of digitalisation makes the energy system which is a "critical infrastructure", more vulnerable and an increasingly attractive target for cyber attacks. Like the question of secure generation and transmission of energy, the secure digitalisation of the energy transition is particularly an infrastructure issue. Digital infrastructures are therefore also the special responsibility of the state and require comprehensive regulation.

Cyber attacks

In Germany, the critical infrastructures (KRITIS) regulation regulates all critical infrastructures which are of vital importance to the state, the failure or impairment of which would result in lasting supply bottlenecks, significant disruptions to public safety or other dramatic consequences.[14] Sectors and industries where critical infrastructures may be found are the energy as well as information technology and telecommunications sector. As more and more critical infrastructures are becoming more dependent on IT and communications systems, they are increasingly exposed to external threats.

In this respect, it is information security in particular that is given high priority in critical infrastructure legislation.[15] There are several laws and specifications with special relevance for the IT security in the context of KRITIS in the energy sector. Especially the Network and Information Security (NIS) Directive is an important legal text promoting more cyber security in Europe. Since July 2015, Germany has worked on its implementation, by introducing the IT Security Act. This act requires critical infrastructure operators to implement IT security in accordance with the "state of the art" and to report significant IT security incidents to the Federal Office for Information Security (BSI).

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[11] Flore and Gómez (2020)

[12] Bitkom (n.d.)

[13] Franceschelli (2022)

[14] Next Kraftwerke GmbH (2022)

[15] Ibid.

Smart contracts

In an energy system with a large number of decentralised and variable suppliers and consumers, automatic processes for efficient control are becoming increasingly important. The system must be capable of integrating a large number of decentralised generation and consumption plants and coordinating them in such a way that supply covers demand at all times. Smart contracts are a particularly promising technology to meet this daunting challenge. The use of smart contracts, which are "contracts translated into programme code”, is particularly suitable for processes that occur repeatedly in large numbers and run in a standardised manner.

Smart contracts are not contracts in the legal sense, but rather transaction protocols that can execute the terms of a contract automatically. With the ongoing switch to RE as well as increasingly complex grid operation processes, smart contracts together with blockchain technology can simplify such processes. Smart contracts can increase the speed and quality of the processes required by the decentralised energy transition, reduce transaction costs and enable new business models. In principle, their use is conceivable in the entire value chain of the energy industry, for example for guarantees of origin and certificates, smart charging of electric vehicles, trading of flexibilities or local peer-to-peer energy trading.

The German government announced the creation of a smart contract registry back in 2019.[16] Among the main goals of the smart contract registry are the following:

- Enabling an exchange and networking on the topic
- Creating openness and transparency on use cases
- Providing and discussing smart contract descriptions
- Providing smart contracts as code
- Exploring auditing and certification options
- Checking integration into existing software solutions

Artificial intelligence

The use of algorithms as well as artificial intelligence holds great potential. The most important use cases in the energy industry are the recognition of patterns in data, the coordination and optimisation of energy systems with a growing share of renewable energies, and the management of complex, decentralised energy systems. Generally, AI can optimize and efficiently integrate RE into the power grid, can support a proactive and autonomous electricity distribution system as well as open up new revenue streams for demand-side flexibility. There is also potential for it to function as an accelerator in the search for performance materials that support the next generation of clean energy and storage technologies. However, the use of AI in the energy sector is currently still very limited, with a primarily deployment in pilot projects for predictive asset maintenance.[17] More details on this topic may be found subchapter 3.1 of this report.

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[16] Dena has also developed a concept for a smart contract registry. More information may be found here: https://future-energy-lab.de/projects/smart-contract-register/

[17] World Economic Forum (2021)

2 Main focus areas of smart grid development in Germany

The way forward for smart grids is to increase their operational intelligence and flexibility. There are a few prerequisites for smart grids to work and new market roles, processes, challenges and innovative ideas form their evolution path. These requirements have evolved significantly in the last couple of years and will continue to do so in order to guarantee the success of Germany's increasingly decentralised energy transition.

2.1 Shift in mindsets – actors in a smart grid system

Network operators

As a result of the shift to a more decentralised system, DSOs are called to take on new roles and responsibilities. Due to the variability of RE generation, load flow directions may even change several times a day within the distribution grid. In order to ensure a secure grid operation and to comply with the operating parameters of current and voltage, DSOs must increasingly apply reactive power and grid congestion management.

According to Figure 2, a new DSO responsibility which only became relevant in recent years is that of the system management in the distribution network. The previous role of "supporting upstream network operators through measures" implies that only large power plants are directly connected in the transmission grid and that DSOs are required to transport electricity "top-down" to the customer.[18] However, the gradual decommissioning of

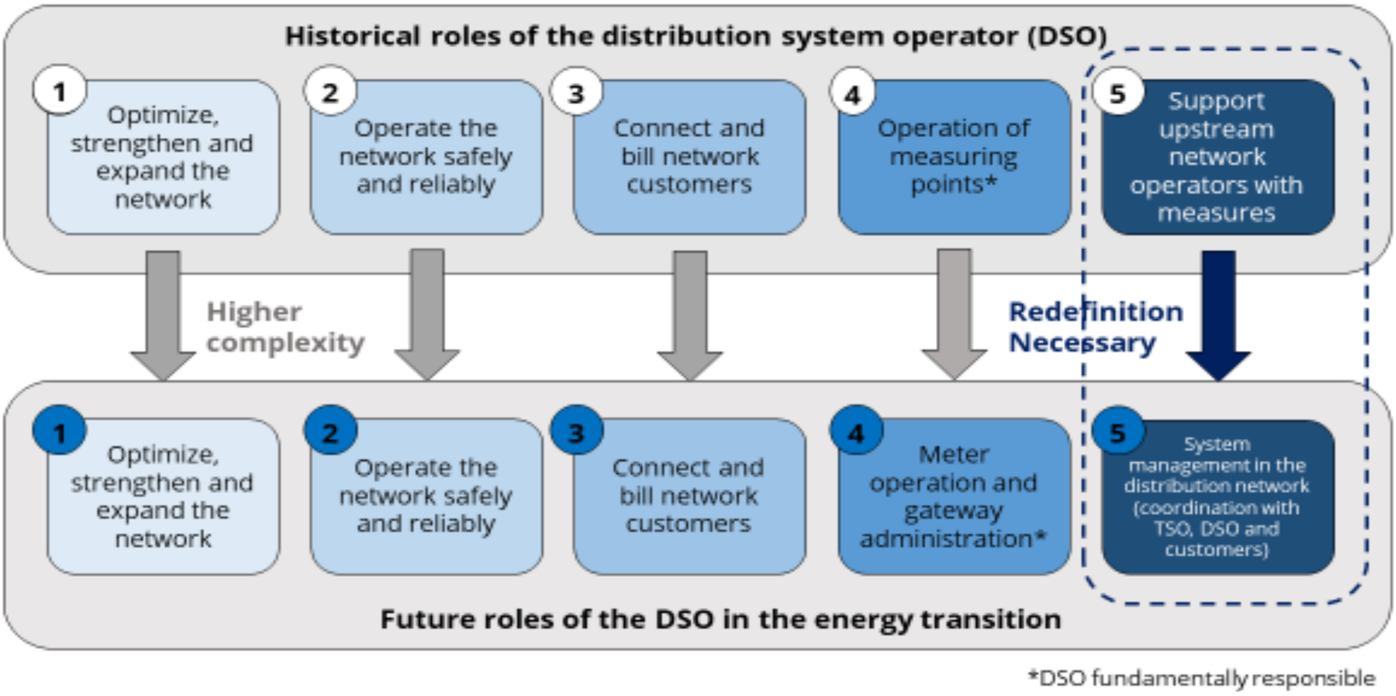

Figure 2: Evolution of the DSO role. Source: BDEW

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[18] AHK Stockholm (2022)

conventional power plants and the rise of smaller and distributed generation make this historical role definition outdated.

Another important DSO role, namely the role of “metering point operator[19] and gateway administrator”, is also shown in Figure 2. Within a smart grid, the transfer of load and feed-in data in short, metering data, between the various actors is essential for accurate forecasts that can be used for billing and balancing purposes. The development of smart meters (see also Chapter 4.) is a necessary condition for this and the DSOs are called to install and operate this equipment. In their roles as metering point operators and smart meter gateway administrators, DSOs are the backbone for providing the necessary metering data for a large number of market and operating processes.[20] Their role is of course constantly evolving with the increasing numbers of prosumers, which pose new demands on metering point operation. This indicates that DSOs will not only be operators of their power networks in the future but also of ICT infrastructure. For many DSOs the actual grid characteristics at a given point in time are still unknown.

Coordination between transmission and distribution system operators

The cooperation between distribution system operators (DSOs) and transmission system operators (TSOs) will become more important with the introduction of the changes in the electricity system discussed above. The role of a DSO does not only consist of distributing the electricity provided by the TSO anymore, but DSOs increasingly act as intermediaries, managing flows and flexibility in cooperation with TSOs.

While balancing is the clear task of TSOs, both TSOs and DSOs are responsible for avoiding network congestion within their own grids and for guaranteeing the overall system stability. In order for each network operator to be able to guarantee stability in its own network, there must be no uncoordinated interventions from neighboring, upstream or downstream networks (cascade principle).[21] Each DSO has a duty to actively participate in overall system stability, regardless of their networks’ size or topology. Similarly to TSOs, DSOs will evolve to "system managers" who, by using the available intelligence and flexibility in their grids, ensure their secure operation; especially in regions with high RE feed-in, more and more DSOs are successfully fulfilling this role.[22]

As decentralised trends are expected to continue, this will eventually necessitate a revision of the way TSOs and DSOs interact. The European Network of Transmission System Operators for Electricity (ENTSO-E) developed a concrete concept on how to facilitate this interaction. These ideas have, in the meanwhile, also found their way into the German public debate.

In order to enable a closer integration of the operation of the transmission and distribution networks, various organisational structures are in place. At the European level, these include the ENTSO-E Network Codes, which specify which information is to be exchanged between TSOs and DSOs and define requirements for the observability and controllability of lower-level networks and decentralised energy plants. In smart grids a large amount of data flows is required for exchanging information between system components. The Network Codes establish the basic framework of the required data for operating the system. Both TSOs and DSOs jointly determine which information they each require, the quality and ownership of the information, as well as how to ultimately ensure confidentiality and transparency.[23]

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[19] A metering point operator is responsible for the installation and operation of smart meters, the metering point being the point in the grid at which a supply to or from the distribution system is measured.

[20] Ibid.

[21] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. (2016)

[22] Verband kommunaler Unternehmen e.V. (2018)

[23] ENTSO-E (2015)

Furthermore, Germany is implementing the EU Directive "System Operation Guideline" 2017/1485 in a step-by-step process. This directive sets up a harmonised framework for exchanging information and data between TSOs, DSOs and other significant grid users.

Overall, the relationship between DSOs with the upstream TSOs is changing, as DSOs take on more responsibilities and increase their contributions to system stability. DSOs are to increasingly support the TSOs in ensuring the stability of the overall system, namely in congestion management as well as voltage and frequency control.

Prosumers

Prosumers are a new actor in the grid world. With the EU's interest in strengthening the prosumer profile, especially at household level, this new actor will play a vital role in smart grids: vital but also very dependent as individual prosumer need smart solutions to actually be part of the system.

When it comes to storage as an important component of a flexible, decarbonised smart grid, prosumers can make considerable contributions to the security of supply. Domestic storage units or electric cars can also help buffer high demand in hours of low electricity feed-in.[24]

Germany represents the largest market for residential small-scale batteries in Europe. According to the German energy storage system association (BVES), in April 2022, the number of installed household battery systems reached 500,000, with an installed capacity of over 2.5 GW, equivalent to the capacity of nearly two nuclear power plants.[25] Since 2020 new tender segments were introduced, that are increasingly promoting innovations and encouraging, among others, the installation of solar PV projects in combination with battery storage devices, which can help stabilise the power system. These innovation tenders have already borne fruit and individual subsidised PV-storage combinations are already in operation.[26]

Also batteries are often used in combination with PV rooftop systems. In this constellation, the generated electricity can be stored for the short-term, in case it is not consumed immediately by the household itself. This increases the level of self-sufficiency and can contribute to decreasing the electricity withdrawn from the power grid. The motivation for this application are high electricity prices for consumers, while at the same time, the costs for battery and PV systems and the remuneration for feed-in of PV electricity into the public grid are declining. The battery can therefore shift the consumption of the generated PV electricity to later times during the day or the early morning when not enough or no PV electricity is generated. However, there have to be enough single, small-scale PV system operators participating in the feed-in to make a tangible difference to system balancing.

While this application is financially attractive to the owner of the battery, it does not per se provide any benefit from a system perspective. Current incentives mainly aim to maximise self-consumption, while the provision of services to the public grid is not really targeted or incentivised. Self-consumption of electricity does not always support the power grid, and can also adversely affect the predictability of electricity fed into the grid.

According to the BNetzA, an obligation for full feed-in of self-generated electricity into the grid, can help to better forecast the amount of electricity injected into the grid. If prosumers use the self-produced electricity for their own consumption then their behavior becomes unpredictable. Not being able to predict the behavior of prosumers, will only increase the balancing energy needs. Incentivising self-consumption alone is therefore not particularly helpful from a systemic point of view. A full feed-in of electricity into the grid must also be promoted. Ultimately, within a smart grid construct, prosumers

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[24] Ibid.

[25] Bundesverband Energiespeicher Systeme e. V. (2022)

[26] ZfK (2022)

should be able react to price signals and in order to reap most benefits an aggregated demand is needed.

Aggregators

As said above, a shared self-supply and demand aggregation will be the main mechanisms available to consumers for contributing towards increased flexibility in the electricity system and participating in the markets for it. However, both the aggregation as well as the market participation are only possible with advanced technical communication and the digitalisation of load metering. Closely linked to the prosumer, but also relevant on the supply side, aggregators are becoming more and more important.

Such aggregators are often refered to as virtual power plants (VPP). These VPP are in short a decentralised energy resource system with a large number of small-scale energy units such as solar and wind energy, CHPs and even fuel cells or heat-pumps and electric vehicles. For all those different generation and consumption units the VPP creates a single energy monitoring profile.[27]

To be part of the energy markets so called commercial virtual power plants (CVPP) are formed. Households and businesses with their own energy generation units could actively participate in electricity trading for the first time. Linking hundreds of small electricity prosumers in a CVPP could dynamically balance out fluctuations in production, and is a business model which has grown a lot in recent years in Germany.

2.2 Smart grid operations

In Germany, an energy information network and the network traffic light concept have also been introduced. The first serves to organize the exchange of data between grid and plant operators. Smart technologies are also used to monitor and control all plants and the situation in the power grid. This is done on the basis of the so-called "network traffic light":

- The “green phase” signals that no bottlenecks are expected based on the forecast values - there are no restrictive measures and the systems can operate without any problems.
- The "yellow phase" occurs when a forecast indicates an imminent bottleneck if no preventive measures are taken. The electricity flows at the grid connection points are adjusted in a way that direct intervention by the grid operator is avoided – direct intervention would mean traffic light color "red".
- In the “red phase”, the system reacts automatically in real time and intervenes to quickly and safely resolve any bottleneck that has occurred. This reaction is based on real-time measurements. [28]

In the yellow phase, free grid capacity can also be traded automatically via a blockchain-based secondary marketplace.[29] Currently, the traffic light concept is further developed in the project *flexQgrid* which is coordinated by Netze BW, a DSO in the South of Germany.[30]

To meet the increasing need for information, it became important to initiate a regulatory reform of redispatch rules. As per BNetzA’s definition, redispatch refers to interventions in the generation output of power plants in order to protect specific power line sections from overload.[31] The “Redispatch 2.0” reform addresses all electricity generation units (down to 100 kW) and includes them in the redispatch regime. These smaller units are connected to distribution grids, requiring the DSOs to monitor and eventually control their electricity output. Until recently, redispatch measures only applied to conventional power plants (with a minimum installed power of 10 MW) that implemented these measures based on the requirements set by the TSO. Now, RE and CHP power plants (with a minimum installed power of 100 kW) also participate in redispatch

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[27] Cambridge (2018)

[28] Netze BW GmbH (2022)

[29] Greenhouse Media GmbH (2021)

[30] AHK Stockholm (2022)

[31] Bundesnetzagentur (Redispatch)

measures, and distribution system operators are given a role in redispatching as well.

Smart metering

In smart grids accurate predictions of electricity demand based on data about weather, energy markets and human behaviour can prove particularly helpful for network operators, because if they know peak demand, they can take action to ensure a stable energy supply.

Smart meters were adopted in Germany back in 2015 as part of the "Digitalisation of the energy transition" law (Gesetz zur Digitalisierung der Energiewende, GDEW). They have been mandatory since 2017, and by 2032 every electricity meter must be digital. The smart meters record consumption in real time and communicate it to the responsible market participants. [32]

According to latest pilot study by dena, there are three components that can be distinguished and which contribute to a solid data infrastructure: infrastructures for data collection, for data transmission, and for data storage.[33] Each component must be able to guarantee a high level of data protection as well as data and IT security - both individually and in interaction with the other components.

In Germany the focus is on smart metering systems (iMSys) as a central component of a secure data infrastructure for smart grids. According to the “Act on the Digitalisation of the Energy Transition”, an iMSys consists of a "modern metering device" (mMe) and its connection to a communication network via a "smart meter gateway" (SMGW). A SMGW essentially connects the electricity meter and flexible consumption and generation devices to the smart grid.[34]

The mMe collects data relevant to the energy industry, while the SMGW controls secure data transmission and data storage. In addition, generation plants and loads are to be controlled via the SMGW in the future. As a central communication unit, the SMGW will enable active and self-determined participation of consumers and prosumers in market communication. The players can thus exert more influence on the consumption or feed-in of renewable energy and at the same time gain more control over the data generated in the process.

Smart meters are continuously increasing the amount of data available and provide a reliable basis for feed-in and consumption forecasts. In the future, this data can provide the basis for automated grid control in combination with feed-in forecasts from decentralised generators.

From a data-driven perspective, the SMGW development takes into account the decentralised character of the energy transition: data should be processed locally and only sent directly to the respective market participants as required by the application.

In addition to the SMGW, the digitalisation of the energy transition requires a fast, secure and cost-effective transmission path. But when looking at the digitalisation of critical infrastructures in specific, neither wired communication networks nor the commercial mobile network are suitable for connecting SMGWs in rural areas, as safety concerns are raised. As an alternative to that, the 450 MHz frequency band is best suited for digitalising critical infrastructures in a blackout-proof manner and can accommodate the demands of smart metering applications for the energy grid. It is worth mentioning that securing the 450mHz frequency for use by the power industry, has been an important step.[35] To ensure control and monitoring functionality as well as communication even in the event of large-

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[32] Ibid.

[33] dena (dena-Leitstudie Aufbruch Klimaneutralität)

[34] BMWK (Was genau ist eigentlich ein Smart-Meter-Gateway?)

[35] An example that addresses the problem of communication network is 450connect (https://www.450connect.de/)

scale power failures (blackout[36]), a self-sufficient radio network for the energy industry is being set up. The expansion of this radio network will start in the first regions of Germany in 2023 and nationwide radio coverage will be available in 2025.

In addition to SMGWs and the networks required for them, low-power long range wide area networks (LoRaWAN) will be increasingly used in the future for the transmission of data. LoRaWAN has proven itself especially helpful in the context of municipal smart city projects and cost-effective sensor technology for environmental data.

Demand side management

Fluctuating load flows in the grids in high quantities are a new reality (Figure 3). Moreover, this trend – increase of fluctuating loads – will stay. The operation of the grids requires significantly higher flexibility and the use of corresponding potentials. While DSM has been widely utilised for a long time in Germany, DSOs need increasingly sophisticated control and metering technologies to cope with an expansion of decentralised RE and e-mobility, heat pumps and new local consumption patterns. To this end, intelligent load management will become increasingly important for achieving a stable grid.

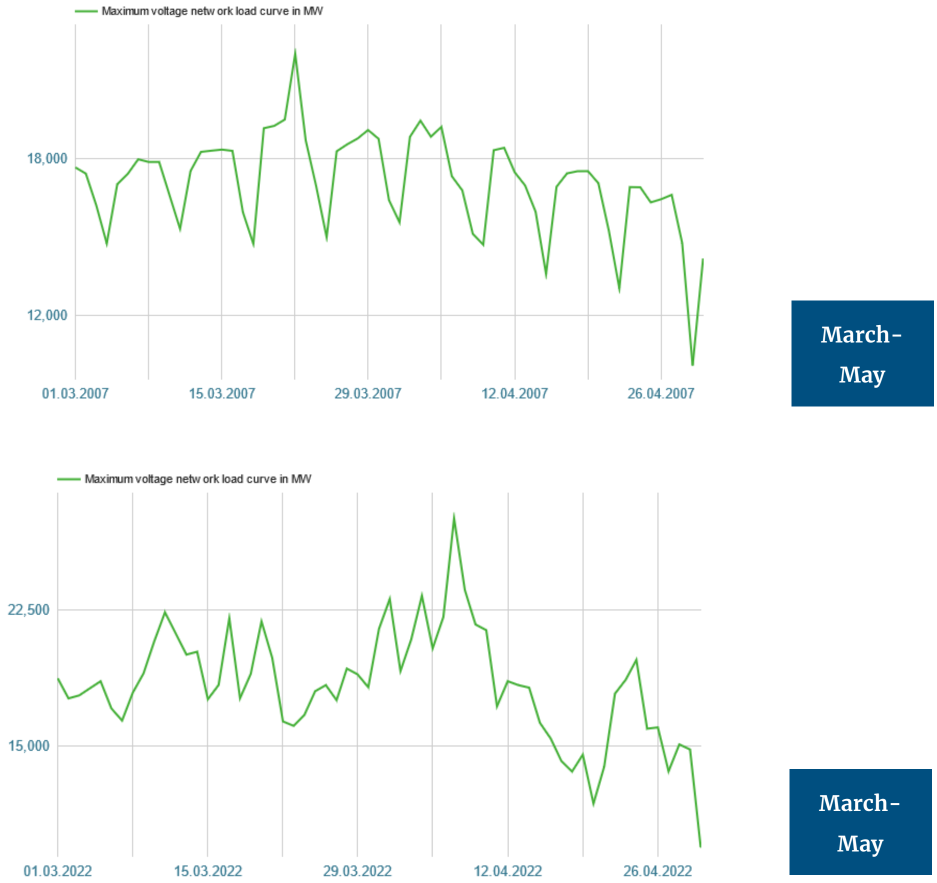

Figure 3: Transitioning to increasingly fluctuating loads in a span of 15 years. Source: TenneT Holding B.V. 2022[37]

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[36] In the event of a blackout, communication can continue via independent radio networks.

[37] TenneT Holding B.V. (2022)

An instrument DSOs have at their disposal are load control agreements. Under this instrument, a DSO and a small electricity customer agree that the DSO has the right to manage the electricity consumption of one of the customer's electrical devices. In turn, the electricity customer benefits from a discount on the network tariff charged by the DSO. Load control agreements are primarily directed at electric heating devices with a storage unit, i.e., mostly heat pumps and storage heaters.

The purpose of load control agreements is to enable a DSO to prevent local grid congestions from occurring. Such congestions may happen when too many heating devices withdraw electricity from the distribution grid at the same time. In such a case, the DSO uses its rights under load control agreements and directs some of the devices to stop withdrawing electricity for a limited period of time. The effect is that the peak in aggregate demand load is capped and electricity withdrawals are distributed across a longer time interval. In other words, the DSO practices load shifting.

Another DSM instrument is the provision of control energy (otherwise also known as balancing energy), which serves to balance out any unforeseeable fluctuations in production and consumption. Providing control energy is often thought of as a task undertaken by electricity producers. However, electricity consumers can also participate in the markets for control energy. If they meet the pre-qualification criteria (the minimum bid size is currently 1 MW)[38], they can take part in tenders and contribute positive or negative balancing power at the different levels of that market (primary, secondary, tertiary) by reducing or increasing their load on the electricity grid.[39]

Another idea is to enable and encourage small facilities to be supplied with dynamic prices that reflect the actual wholesale price. In that way, they are incentivised to shift their consumption to times with low prices and avoid times with higher prices. However, this could eventually leave small actors like private householdes unprotected against the risk of competitive markets.

Up until now DSM has not picked up as much as expected, and mainly large industry players are actively practicing DSM. This is mainly due to missing incentives – please see Chapter 3.2. The highest potential for DSM in the industry is widely considered to be in the most energy-intensive sectors and processes, where the DSM potential was found to amount to 3 - 5 GW. What is also interesting is that several studies point out that industrial DSM potential was found to be lower than in the residential household segment, where the potential is seen in all but one of six studies to be 10 GW or more.[40] With regard to the future growth of DSM potential in the industry, a 2018 study evaluated the DSM potential in Germany at 6.6 GW in 2050, of which 76% (5 GW) are expected to be utilised.[41]

Regarding DSM regulation, an amendment of §14a of the Energy Industry Act (Energiewirtschaftsgesetz – EnWG), had the intention to introduce an instrument for peak load smoothing. Subject of the bill were changes that were to make grid connection for electric cars or heat pumps more flexible for grid operators and enable them to deactivate these assets by remote control, ultimately reducing the need for grid expansion at the lower levels. After several

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[38] Regelleistung.net (n.d.)

[39] Positive control power refers to an increase in electricity generation or reduction of consumption in the case when consumption exceeds generation. And vice versa: negative control power is provided by reducing electricity generation or increasing consumption when electricity generation exceeds consumption.

[40] Görner and Lindenberger (2015)

[41] Ibid.

studies, workshops and public consultations the draft bill was withdrawn on the 17.01.2021. According to the latest developments in this area, the BNetzA will be able to adopt nationwide regulations, amending the EnWG and based on which DSOs and their customers are obliged to conclude agreements on the network-oriented management of controllable consumer units; to this end, the BNetzA will also have to develop corresponding criteria, based on which these agreements will be concluded.[42]

2.3 Distribution grid expansion and smart grid planning

As already mentioned, the actual energy transition currently takes place in the distribution grids as most RE plants are connected there. The same holds for smart grids, where distribution grids are called to connect and integrate different actors and maintain a stable operation. To ensure a stable grid operation, DSOs today regularly expand their networks and increasingly invest in new grid technologies.

According to BNetzA's report on the status of distribution grids in 2021, most DSOs expect an increasing load within the next five years driven by the rise of e-mobility and heat pumps, as well as partly due to new storage facilities.[43] As a result, DSOs also expect an increasing number of congestions, especially in the medium to low voltage grid levels, as grid expansion does not always keep pace with RE expansion. In the medium-voltage level, this development is to be countered mainly with grid expansion, in the low-voltage level with optimisation and reinforcement of existing infrastructure, e.g., with grid boosters, the report mentions.[44]

It is therefore not only the German TSOs that are called to optimise, strengthen and expand their networks, but also DSOs are assigned this role in the meantime. The challenge here is to successfully integrate all those decentralised providers of electricity; a further expansion of the distribution grids cannot therefore be completely avoided. The 2012 dena "Distribution grid" study identified a need for reconstruction and expansion of over 150,000 kilometers of the high, medium and low-voltage networks throughout Germany.[45] This is a distance that extends approximately four times around the world.

The available distribution capacity of existing grids has become an important parameter as well as a limiting factor for the rise of smart grids. The extent of utilisation of a DSO's available capacity, signals whether and how many consumers or generators can still be connected to the network before it has to be optimised, reinforced or expanded.

For optimisation and reinforcement, two variables are decisive: current and voltage. A too high current on the cables/conductors (capacity bottleneck) would heat them up too much and thus cause damage to equipment. Similarly, a too high or too low voltage level in the network can also cause malfunctions or even damage to consumers and generators.[46]

Moreoever, the above has to be put in the context of that in today's electricity grids the flow of electricity is bi-directional. This means that the power flow is no longer excusively distributed from the extra-high voltage level via the high and medium voltage level to the low voltage level, but also the other way around. This is also one of the main causes of bottlenecks and voltage quality problems in the low-voltage and medium-voltage level. To that end new types of transformers like adjustable local area network transformers or power electronics (STATCOMs) allow the handling of these bi-directional power flows. These and other components of smart grids can compensate for phase differences and power flow changes closer to or at the end customer side by means of intelligent control mechanisms (voltage and reactive power control).[47] However, there is still room

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[42] Schaal (2022)

[43] Bundesnetzagentur (Bericht zum Zustand und Ausbau der Verteilernetze)

[44] Ibid.

[45] dena (Dena distribution grid study)

[46] Ibid.

[47] Trattnig and Sovec (2016)

for technological improvements to achieve the envisioned target picture.

With regard to grid expansion, one needs to also consider the significant delays in the expansion of the German power grid, usually caused by public acceptance issues. As of June 2022, grid expansion in Germany is still progressing slower than originally planned, mainly due to the complexity of grid expansion processes, the different interests of politicians, industry and citizens as well as numerous objections (e.g., noise pollution or landscape impairment) delaying the progress of the grid expansion measures.[48] In addition, even though grid expansion might be the simplest and most obvious way to integrate new grid assets, it usually comes at a high cost: according to BNetzA's estimations, around 70 billion euros need to be spend on expanding Germany's transmission grid by 2035 and another 50 billion by 2040. Up to another 45 billion euros will be required by 2030 to equip the distribution network for the energy transition.[49] As it is the consumers that bear the costs of the grid – in the form of grid fees that are included in consumer electricity prices – grid expansion is often the subject of heated debates.

In order to counteract this, a possible solution could be found in the local and regional balancing between load and generation. This is where smart grids enter the picture, as they can offer exactly that: By intelligently steering new controllable loads (e.g. electromobility or storage systems) connected to the grid, DSOs have more flexibility to fulfil their statutory tasks and up to a certain extent the system's balancing can be met without additional grid expansion. In short, according to BNetzA's paper on smart grids, a smart grid leads to better utilisation of conventional power infrastructure, curbing the need to expand it and even improving grid stability while maintaining the same level of capacity utilisation.[50] Especially in the example of e-mobility, managed charging provides a great first alternative to conventional network expansion. An expansion might still become necessary once the managed charging solution affects the electric vehicle user more than necessary, but it should remain the last resort in the process.

Ultimately, a double-pronged strategy is recommended. This will require the systematic utilisation of alternative, operational options and secondly, the expansion of the electricity grid wherever necessary. In other words, improving the utilisation of the existing grid through smart control and flexibilisation wherever possible should precede any grid expansion.

2.4 Integration of e-mobility

With the rise of e-mobility, simultaneity factors are another aspect that must be taken into consideration in future distribution grid planning. The impact of individual battery electric vehicles (BEV) on the network depends on the charging power, the charging duration and the time of day. Typically, charging electric vehicles during existing peak load hours is most critical. The impact of the BEV fleet depends on the number of BEVs being charged simultaneously within a given network area, otherwise known as the simultaneity factor. DSOs use simultaneity factors to plan for sufficient capacity for BEV charging in newly built networks.

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[48] Schopen (2022)

[49] Krapp (2022)

[50] Bundesnetzagentur ("Smart Grid" und "Smart Market")

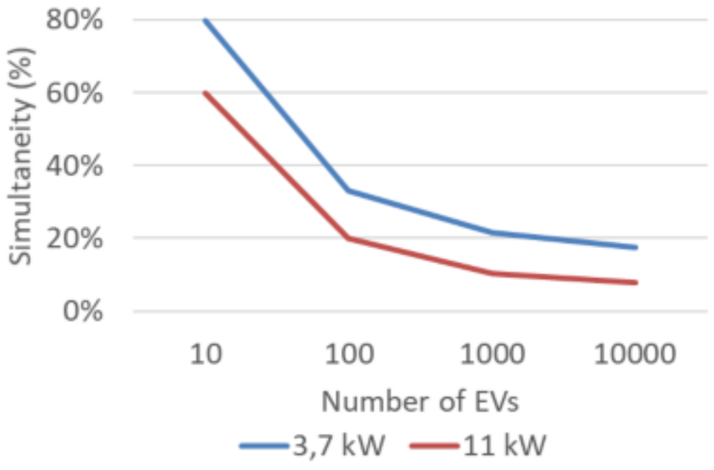

Figure 4: Simultaneity of low power EV charging in Germany. Source: Energynautics and RE-xpertise[51]

As can be seen in Figure 4, there is a high percentage of simultaneity in the depicted charging levels may occur especially in smaller grids where BEV users might have very similar charge profiles.

In any case, the simultaneity of charging actions can be effectively decreased through:

- More (public) chargers,
- Higher charging capacity, i.e., shorter duration of the charging action;
- Diverse use case patterns in a network section (for example a combination of slow and fast charging use cases).

As of 2021, there are around 47 million passenger cars registered in Germany, only a small fraction of which are battery electric vehicles (BEVs). Estimations of the future market share of BEVs vary, but according to the new government's targets, a total number of 15 million BEVs has to be achieved by 2030. In one scenario analysed in the professional literature, 22 million BEVs are assumed to exist in Germany by 2050.

These would create a combined peak load of 16 GW if charged simultaneously and an electricity consumption of 59 TWh/a in 2030. If only a fraction of that electricity can be shifted time-wise to accommodate the needs of DSOs with regard to grid stabilisation, DSM potential from BEVs in the long-term will be significantly higher than the flexibility derived from any other electricity storage technology existing today. In any case, it will be crucial to manage the load from BEV charging such that BEVs in a given grid are not all being charged at the same time. This will be required to avoid overloads of distribution grids in the future.

A look at the simultaneities assumed in the planning of an e-mobility infrastructure, shows that the average assumed connected load for single-family homes with a charging device and/or heat pump differs very significantly from the assumptions for a single-family home without a charging device and without a heat pump. In view of the expected strong growth of e-mobility, this underlines the need to establish efficient control mechanisms for the grid that allow a reliable basis for planning. Only in this way can the necessary grid expansion be limited to an efficient level in the short term and the timely connection of charging facilities be guaranteed.

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[51] dena (Handbook on Planning and Operating an E-Mobility Infrastructure)

Managed charging is the most cost-effective solution for integrating BEV charging into distribution networks. In the case of Germany, compared to unmanaged charging, managed charging makes it possible to reduce peak capacity without loss of comfort for the end consumer, reducing investments by 30 % to 50 %.[52] Apart from that, BEV sales will reach high levels soon, requiring the immediate application of managed charging. The batteries of electric cars could be given an elementary function as energy storage or even serve bi-directional charging within a smart grid and stabilise the power grid. This can be done by temporarily interrupting the charging process or allowing the car to charge precisely when there is an electricity surplus in the grid. That way, the excess supply can be balanced out. The application of managed charging in Germany is still at an early stage, but will pick up speed in the next years.

2.5 The use of data

A DSO survey conducted by BNetzA in 2021, shows that the ability of DSOs to control equipment remotely has increased over time. In 2017, 86% of the network operators surveyed stated that they could at least partially control equipment up to the medium-voltage level centrally; in the latest survey for 2021, 95% of network operators can do so.[53] Digitalisation indeed unlocks the access to various data that make the task of network monitoring significantly easier, both for DSOs and TSOs. Especially in lower network levels, the development of smart metering systems is a necessary condition for a successful monitoring and steering.

Data analysis plays a central role as the final stage of digitalisation. There has been a discussion for several years in Germany about open or closed digital information systems or mandatory disclosure of energy data (open data). On the one hand, the discussion is driven by the overriding interest in using freely available energy data to facilitate the exploitation of economic potential through new services and business models based on innovative data analysis. On the other hand, there is the realisation that it must remain advantageous for the players to be able to profit economically from the values created by their own data collection.

To resolve this tension and as a first step, approaches would be necessary to determine the value of data sets. Another important aspect, which at the same time offers a way to make the value of data sets more tangible, is related todata quality and quantity. Depending on the specific requirements, data as well as technologies and applications can be evaluated on the basis of the properties of integrity, authenticity, availability, confidentiality and anonymity. A systematic assessment of these properties should contribute to a high level of data protection, data security and data sovereignty and ensure the basic prerequisite for digitalisation in the critical infrastructures of the energy industry. At the same time, not only quality but also quantity counts in data analysis. High-quality data, if not available in the necessary quantity, can also be a barrier. For example, an AI software for detecting damage to wind turbine components requires sufficient data on damaged parts to ensure reliable data quality.

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[52] dena (Handbook on Planning and Operating an E-Mobility Infrastructure)

[53] Bundesnetzagentur (Bericht zum Zustand und Ausbau der Verteilernetze)

3 Where action is still needed for smart grids – Relevant research and pilot projects

At this point of the energy transition, almost all involved actors, especially system operators, are in the process of a digitalisation transition as well.This will minimise human interference and every process that is digitalised is a step towards the smart grid. In this chapter we selected a few indicative examples of the main technological, regulatory and operational challenges which must be addressed in the short run to further advance a smart grid evolution. Ongoing research efforts are also highlighted, giving a glimpse of what will be possible in the future once the current hurdles and halts are resolved.

3.1 Main technological challenges

The deployment of artificial intelligence (AI), cloud and digital technologies is essential to realise the transition from traditional power grids to smart grids. Especially the self-learning, adaptability, and calculation capabilities of AI have significant potential to address challenges arising within a smart grid including improved security and utilisation of DSM, more precise forecasting, as well as grid agility and resilience.[54] While there are of course numerous other technologies that still need to be deployed to improve smart grid operations, the focus is placed on AI, exactly because of the various application fields it entails.

As part of a survey, conducted annually by BNetzA on the status of distribution grids, several DSOs were asked whether they use AI in their day-to-day processes such as predictive maintenance, network load forecasts, network planning, and cybersecurity measures.[55] According to the latest survey in 2021, the majority of DSO stated that they do not use or plan to use AI and the DSOs currently employing it or preparing for its use are rather few.[56]

Out of the 59 interviewed DSOs, only four reported relevant AI projects such as satellite-based overhead line monitoring, intelligent (self-learning) video monitoring in substations, inspection of high-voltage pylons by means of drone flyovers, predictive maintenance, forecasting of loads by means of artificial neural networks, and projects on optimisation algorithms in network planning.[57]

This shows of course a rather slow progress in the application of AI in the distribution grid; One of the most important barriers identified by the surveyed DSOs was the lack of machine-readable data. Another problem of a more general nature is the fact that in Germany the public opinion on AI is often linked with negative associations. Even in an international comparison, such concerns dominate especially in Germany.[58]

One way to counteract this, is by showcasing concrete and successful applications of AI in the energy transition. As also mentioned in the introduction, increasingly intelligent algorithms can be used in various applications within a smart grid, for example, in load forecasting. AI can also support the operational optimisation of PV systems with storage and increase the security of supply through targeted peak load capping.

It remains to be seen to what extent these approaches will find their way into the low-voltage grid. DSOs should further promte research and pilot projects to utilise decentralised, automated solutions for controlling the network components.

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[54] SAP (2022)

[55] Bundesnetzagentur (Bericht zum Zustand und Ausbau der Verteilernetze)

[56] Ibid.

[57] Ibid.

[58] E.ON SE (2019)

3.2 Main regulatory challenges

The change in the regulatory framework is the foundation for a power system under transition. An actual challenge of electricity grid regulation in Germany lies in the development of coherent rules on how charges for the use of the electricity grid are levied, administered and distributed to grid operators.

Currently, grid costs in Germany vary greatly from region to region; how much consumers pay through grid charges largely depends on their customer category, their geographic location and the grid expansion required depending on the area, with private end customers generally paying the largest share of grid charges.[59] Such a distribution of grid fees still seemed reasonable back in the times of centralised power generation; the ever advancing RE expansion coupled with an increasing decentralisation and digitalisation, however, make a reform of grid charges necessary. This is mainly due to the fact that a strong expansion of decentralised generation plants causes considerable grid connection and grid expansion costs, mainly in rural areas.

A recent paper by Germanwatch[60] highlights the necessary building blocks for a reform of network charges. These consist of:

- Uniform nationwide grid fees at distribution grid level
- Network charges for electricity producers
- Bi-directional cost shifting
- Reforming non-system-based network charges for industry
- Time-variable network charges for all consumers

The key takeaway of this paper is, that a reassessment of cost allocation and distribution is needed more than ever. While it is difficult to set up a grid charging system that is fair at the same time for all affected actors, the paper ultimately states that in order to develop as sustainable a design as possible, the first step would be an open dialogue among the different stakeholders (TSOs, DSOs, industry, consumer protection groups, NGOs, research institutes, generators and regulators). The goal of the dialogue would be to learn from each other and jointly explore compromises to resolve any conflicting goals that arise. Ideally, in the end of the dialogue, design decisions would be identified with supports from the diverse parties.[61]

In view of this discussion, it is also worth to take a look at the ongoing debate on price signals. Price signals can be incentives for consumers to play an active role in the energy market and enable stakeholders to dynamically adjust their power feed-in or consumption to accommodate the grid's needs. As mentioned in chapter 2.1, by responding to price signals, household and industrial consumers can perform load shifting, and shift their electricity consumption from one time period to another, typically from peak to off-peak hours. A smart metering device should allow consumers to receive (price) signals for grid-serving measures. In the wake of the ongoing energy transition and expansion of RE, greater flexibility and the ability to react to price signals are of particular importance. Time-variable network charges can stimulate a flexible, grid-supporting consumption by means of price signals. The network charge varies depending on the respective grid load and should incentivise a shift of energy demand to periods of high feed-in or otherwise low consumption. This constitutes a significant flexibility potential and can also enable to limit grid expansion in the future.[62] Nevertheless, such a concept also comes at a cost as it can lead to increased regulatory and operational complexity in the system. Strategic behaviour by market participants that leads to price distortions, should also be considered in this regard.[63] For customers to be able to react to prices, their loads have to either react automatically (requiring smart metering and control devices) or to be controlled by aggregators.

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[59] Germanwatch e.V. (2022)

[60] Ibid.

[61] Ibid.

[62] 50Hertz Transmission GmbH (2021)

[63] Germanwatch effective Stromnetzentgelte

There is also another approach put forward by the SINTEG WindNODE project, which favours making the electricity tax and the EEG levy more flexible (the EEG levy on end customers electricity bill has been completely abolished since July 2022). Final consumers would thus receive a tax benefit if they purchase electricity at grid-serving times. This makes it easier and more effective to pass on the electricity price signal to the consumers as an incentive to activate flexibility.[64] Ultimatively, the idea is to have a full fledged flexibility market.

3.3 Main operational challenges

A reportedly limiting factor which significantly delays the implementation of digitalisation is the lack of human resources to accompany and implement innovative processes. The imperative need to digitalise most of their operations and workflows is now much clearer than ever to German DSOs and TSOs. Some operators already show they are up to the task, either by improving existing processes or by trying out and implementing new approaches. These efforts all take place parallel to the day-to-day operations, which are on their own fairly challenging due to regulatory requirements, capital constraints and complex processes. Thus, digitalisation is facing the challenge of lack of operational capacity.

Taking for example today’s control centre systems: Manual data synchronisation is still the routine of some operators, with costly maintenances as well as vendor lock-ins adding up to the unwanted effects. Such processes do not support the implementation of all current business requirements, let alone of future business needs. A digital transformation in combination with extensive testing of new concepts is the vehicle by which the transition to tomorrow’s power system can ensue.

Intelligent system operations are the main component of what ultimately transforms today’s grid to a “smart” one. Improving processes such as data acquisition and data processing, prequalification, the accuracy of RE forecasting, the data exchange with other market parties, as well as developing corresponding tools for system monitoring and congestion management are among the main priorities. German TSOs, such as 50 Hertz, have already developed in-house dedicated solutions to improve the aforementioned processes. Some German DSOs also proceed with the implementation of pilot projects (chapter 3.4), where different smart grid concepts are tested in local communities.

As the energy transition further evolves – perhaps even with greater urgency than ever before in Germany – the grid operators’ mindset and workflows also have to keep pace. The implementation of digital solutions that streamline existing operations and also make them “future-proof”, has already begun. Importantly, this digital transformation should not lose momentum, and German grid operators should be supported by policy and science in their efforts to make their grids smarter and more reliable.

3.4 Relevant research and pilot projects

SINTEG project results

Within the framework of the SINTEG project („Smart Energy Showcases – Digital Agenda for the Energy Transition“) five model regions received funding under the Federal Ministry for Economic Affairs and Climate Action between 2016 and 2020. The project were tasked to find solutions in a renewable energy dominated system in Germany to balance environmental integrity, energy security and economical efficiency. More than 300 partners from science and academia, industry and civil society with expertise in a wide range of different secotrs have been participating in the projects. The focus was placed on utilising innovative grid technology and operating strategies to build smart networks linking up the electricity supply with the demand side and tackle technical, business-related and legal challenges involved.

One of the key features of the project was embedding the showcases in an ordinance that provides a

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[64] Ecologic Institut (2021)

temporary framework for experimenting. This concept of a "Living Lab" creates an environment where new technologies, procedures and business models can be tested and can help speed up the process of moving innovations from the lab to the stage of practical testing and onto the market. SINTEG acts as an regulatory testbed and blueprints can be developed for the implementation of future projects.

The findings of all showcases were compiled by Guidehouse and evaluated, resulting in five comprehensive and topic-specific reports:

- Sector coupling
- Flexibility mechanisms
- Regulatory sandboxes[65]
- Digitalisation
- Participation

Sector coupling can increase grid flexibility significantly by operating related devises based on the electricity prices or the grid's situation. Digital market platforms were developed for exchanging energy pooled from residential units to stabilise the grid. The pooled energy could then be sold on the spot market or could be offered as reserve power. The provision of reactive power, even across grid levels, is possible as well.

Another important part of the SINTEG project is to raise consumer acceptance for the German energy transition in a broader perspective. The public's acceptance of projects relevant to the energy transition, has long been a pressing issue in Germany. Especially a lot of wind power as well as extra-high-voltage grid projects have often faced resistance from the public and have been the subject of long debates.The aim was to create low-threshold offerings to provide information about the energy transition and to offer opportunities for participation for interested citizens. In this way, the general public can also be involved in the necessary transformation processes, especially with regard to wind power and grid expansion. After finishing the project, some follow up projects have already been started to take the project results further.[66]

Energy communities are strengthened in Germany as they can be used for testing regulatory initiatives. As a concept for neighbourhood solutions, energy communities are an interesting test case for smart grids on a small scale, where already a variety of challenges arise and tests can be undertaken in a well defined environment.

In terms of digitalisation and IT security, a decentralised and smart power system can be more resilient because there are smaller units that can also function independently from each other.

NETZlabor Sonderbuch & flexQgrid pilot projects

The largest distribution network operator in Baden-Württemberg, Netze BW, is working on the automatic control of network areas with a high share of volatile RE feed-in and variable loads. Intelligent planning and operating concepts for distribution grids are being researched and tested in practice in the course of a field test since 2011.

The first pilot project was called **NETZlabor Sonderbuch**, which was created in cooperation between the distribution grid operator Netze BW and the Institute for Energy Transmission and High Voltage Technology (IEH) of the University of Stuttgart. The project deals with system solutions for the integration of photovoltaics into the low-voltage network. The aim of the project is to use intelligent solutions to further improve the integration of decentralised energy generation systems into the grid and thus increase the proportion of renewable energies.[67]

With only 190 households and 60 installed PV systems, the town of Zwiefalten-Sonderbuch in the federal state of Baden-Württemberg was selected for

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[65] Exact definition may be found here: https://www.cgap.org/topics/collections/regulatory-sandboxes-financial-innovation

[66] https://www.sinteg.de/en/

[67] Baden-Württemberg e. V. (2020)

implementing the project. During peak times, six to seven times more electricity is fed in than consumed, exceeding the transmission capacity of power lines and pushing the distribution network to its limits. The pilot project used intelligent systems and modern measuring control technologies to make the connection of further photovoltaic systems possible.

The project lasted for nine years, from January 2011 to January 2020, and consisted of four phases [68]:

In the first phase, transformer stations were given modern measuring technology and households were given intelligent meters that provided extensive data on current flows and the voltage in the grid. Based on the measurement data, it was possible to identify significant fluctuations that push the grid to its load limit and prevent the further integration of renewable energies.

Based on the data from the first phase, a controllable local network transformer was set up in the second project phase in order to optimise feed-in management and compensate for fluctuations. Additionally, battery storage was installed to smooth out voltage peaks.

The third phase was about using the existing network more efficiently through intelligent network control. Therefore, the automated network control system "iNES" was installed, which automatically registers the current status and pending strong fluctuations in the local network. The system can use the data to identify undesirable developments and counteract them largely automatically. This takes place independently of a control center, since the intelligence requiredis installed on site in the local network station.

In the last phase of the project, the “Smart Grid Demonstrator” was launched in June 2017. The main focus of the project is now on refining the use of the available components and further developing the automatic control. In addition, the participating households of Sonderbuch, but also those interested in the project in general, should be given the opportunity to follow what is happening “live” via the internet platform. This includes the summarized generation data of the connected systems as well as forecasts for the following day.

At the end of the project, the higher possible feed-in through the controllable local grid transformers ensures compliance with voltage limits, while the combined control of photovoltaic systems and highly flexible battery storage relieves the load on the lines. The tried and tested solutions are based on the reliable communication and data exchange of all components involved via mobile communications and power line. The findings from this NETZlabor will be used in another project.

In the **flexQgrid** project, different types of systems (more storage and consumers such as heat pumps and electric cars) are to be connected in addition to photovoltaic systems. Overall, more flexible system performance is to be integrated.[69]

As part of this project, a research team of nine business and scientific partners in Freiamt in Schwarzwald studied how electricity generated by rooftop photovoltaic systems can be optimally integrated into power systems, built-in test batteries, as well as heat pumps and electric vehicles.

In three different field test areas each with a different generation and consumption structure, the entire grid traffic light is tested with intelligent household devices and loads.[70] The field test begun at the end of August 2021 and should demonstrate concrete applications and further developments of the network light concept by August 2022.

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[68] Klima und Energiewirtschaft Baden-Württemberg (2022)

[69] Netze BW GmbH (2022)

[70] Ibid.

4 Lessons learned in Germany – Smart meter rollout

As evidenced in the previous chapters, smart metering is one, if not the main, prerequisite for the further development of smart grids. For a succesful smart meter rollout, a reliable legal and administrative basis is necessary. In this chapter, the spotlight is on important lessons Germany learned during its smart meter rollout. This section introduces the success and failure of smart meter implementation experiences in Germany. Compared with other EU countries with an extensive smart meter rollout, Germany has lagged behind. As digitalisation will continue to be a pressing issue in the coming years, this section introduces the pitfalls Germany encountered during its smart meters rollout as a reference for other countries.

The smart meter rollout in Germany is based on the EU-Directive 2009/72/EC on common rules for an internal European electricity market, which set a smart meter rollout target of 80% by 2020 in markets with a positive cost-benefit analysis (CBA).

77% of all Europeans are expected to be equipped with an intelligent metering system by 2024. The German smart meter rollout plan stipulates that every meter must be intelligent or at least equipped with a digital interface by 2032. The valuable lessons learned during the smart meter rollout in Germany, can facilitate the future speed-up of such a process and can also be a reference for other countries. The main lessons learned in this respect are summarized as follows and are elaborated on in greater detail further below:

- Set realistic requirements regarding the safety and security of the smart metering system that include existing metering systems available in the market but also to foster new and innovative smart meter technology.
- Set target dates and a cost framework for the smart meter certification process to avoid an unnecessarily costly and lengthy rollout.

In order to assess what went wrong during the introduction of smart meters in Germany, the history of the smart meter is relevant. With the Act on the Digitalisation of the Energy Transition (Gesetz zur Digitalisierung der Energiewende, GDEW) in 2016, the German government laid the foundation for smart meters. At its core is the Metering Point Operation Act (Messstellenbetriebsgesetz, MsbG), which regulates how and when the previous analog electricity meters are to be replaced by smart metering systems (smart meter rollout). The rollout plan includes different rollout periods for different types of end consumers and plant operators categorised either by the energy consumption, or the size of generation assets owned and operated.[71] It requires that consumers with an annual consumption of more than 6,000 kWh and plant operators with an installed capacity of more than 7 kW must be equipped with smart meters. Below these thresholds, smart meters are not mandated. The MsbG also includes specific requirements about collecting, transmitting, and using the metering data. Furthermore, it stipulates that smart meter gateways (SMGW) from at least three manufacturers need to be certified by the Federal Office for Information Security (Bundesamt für Sicherheit in der

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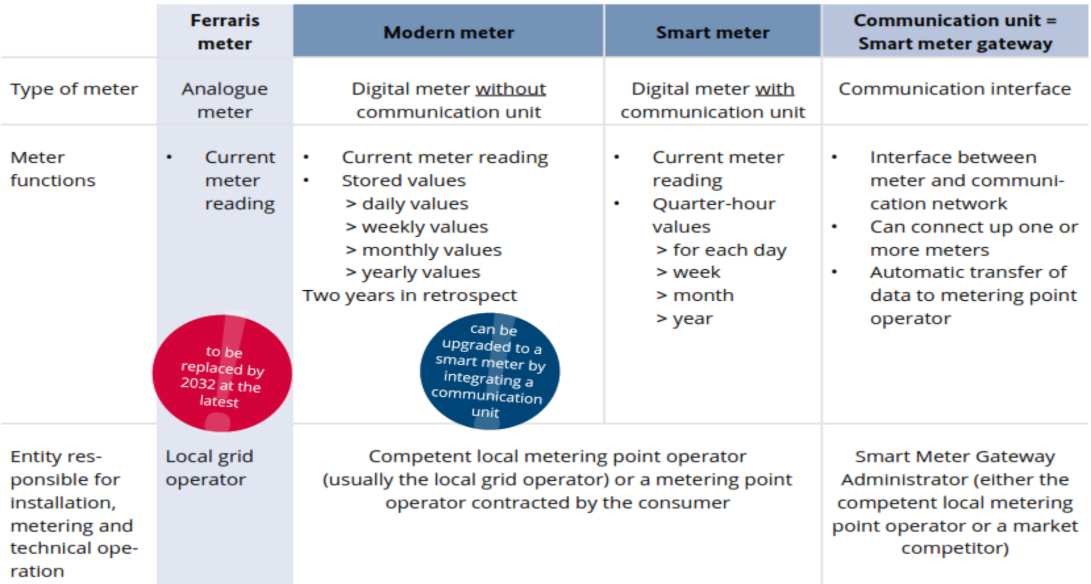
[71] Bundesverband Neue Energiewirtschaft e.V. (2020)

Informationstechnik, BSI) so that users and customers have a choice.[72][73]

The smart meter rollout was initially set to begin in 2017, but it started in January 2020 due to significant delays in the certification of intelligent metering systems. This delay can be attributed to the very high requirements regarding the safety and security of the smart metering system (iMSys) as well as the fact that the legislator did not set target dates or a cost framework for the BSI's certification process.[74]

As a result, the final certified smart meters approved in this stage were only able to provide the same application as previous meters (special time of use-dependent tariffs and information provided directly to the consumer, via display or apps), with the exception of the transmission of measured data. The ability to offer dynamic electricity price contracts, to perform generation and load management, as well as grid-supporting operational applications, which are essential for the smooth operation of smart grids, as mentioned in the chapters above, were either limited or non-existent.[75] For these and other reasons, this first iMSys generation did not really provide the customers with any significant added value. An overview of the currently available modern metering devices, their functions, as well as responsible operators and market roles, may be found in Figure 6 below.

Before the first generation of iMSys, there were already metering systems available on the market that met comparable security and data protection requirements and were compliant with international or industry standards. The introduction of the BSI-approved iMSys, however, meant that these already available smart meters were deemed not legally compliant and should therefore no longer be installed.



	Ferraris meter	**Modern meter**	**Smart meter**	**Communication unit = Smart meter gateway**
Type of meter	Analogue meter	Digital meter without communication unit	Digital meter with communication unit	Communication interface
Meter functions	• Current meter reading to be replaced by 2032 at the latest	• Current meter reading • Stored values > daily values > weekly values > monthly values > yearly values Two years in retrospect can be upgraded to a smart meter by integrating a communication unit	• Current meter reading • Quarter-hour values > for each day > week > month > year	• Interface between meter and communication network • Can connect up one or more meters • Automatic transfer of data to metering point operator
Entity responsible for installation, metering and technical operation	Local grid operator	Competent local metering point operator (usually the local grid operator) or a metering point operator contracted by the consumer		Smart Meter Gateway Administrator (either the competent local metering point operator or a market competitor)

Figure 5: Overview of current metering devices in Germany. Source: BMWK (2021)

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[72] Ibid.

[73] A smart metering system (iMSys) consists of a "modern metering device" (mMe) and its connection to a communication network via a "smart meter gateway" (SMGW). A SMGW essentially connects the electricity meter and flexible consumption and generation devices to the smart grid. The mMe collects data relevant to the energy industry, while the SMGW controls secure data transmission and data storage.

[74] Bundesverband Neue Energiewirtschaft e.V. (2020)

[75] Ibid.

This was followed by a lawsuit from different companies, to which the Higher Administrative Court reacted with an emergency order in March 2021, halting the obligation of high-consumption households and companies to install smart meters.[76] The legislator responded quickly to the court decision and passed amendments to the MsbG, so the smart meter rollout has been resumed despite certain gaps in the framework.

So far, the smart meter rollout in Germany has mainly encompassed modern metering devices (without SMGW), but not smart meters with SMGW. According to the BNetzA, the quantative target for modern metering development for July 2020 was already met in December 2019, which corresponds to 5.8 million compulsorily installed modern metering devices. However, only a few are equipped with SMGW to make them fully functional smart meters for smart grid operations.

In conclusion, the slow rollout of smart meters hinders the digitalisation of the energy sector, which is crucial to realise the next phase of the energy transition. On the other hand Germany has great potential in developing smart meters as enabling tools for consumers to play a more active role in a smart decentralised grid system.

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[76] GreenPocket (2021)

5 Conclusions

Germany's energy system enters a dynamic transitional phase, on course for achieving its ambitious climate targets. It becomes evident that many upcoming challenges in the transformation of the energy, heating and transportation sectors, which can not be satisfied through existing grid capacity as well as the capacity that will be built in the coming years, can be met with increasing electrification and interconnection of decentralised assets in a smart grid.

Smart grids play a pivotal role in transitioning the energy system towards a more sustainable, cost efficient and reliable direction as well as for integrating RE and new flexible assets from the consumer side. Smart grid concepts have evolved rapidly during the last decade, supported by relevant regulatory, technical and research initiatives.

The German power grids will have to face several challenges, especially on distribution level. The expansion of sufficient grid infrastructure must be coordinated with efficiently controlled smart grids by creating the necessary IT infrastructure and by using smart meters as central control point.

The cost-efficient and reliable implementation of smart grids requires the fundamental transformation of the energy sector, including the technical, regulatory and operational framework. Challenges still exist and hamper the advancement of smart grid. Challenges that need to be addressed within the next years are related to:

- the application of AI in system operation
- overall improvements and digitalisation of system operators' workflows
- clarification of appropriate grid charges to incentivise flexibility

To solve the above challenges, the following actions are necessary:

- The optimisation of grid operators' IT infrastructures in the coming years for a future-proof design for (variable) grid fees
- Provision of the legal prerequisites for unlocking most benefits a smart grid has to offer, such as demand side flexibility and grid integration of decentralised assets
- Grid data collection by grid operators needs to lay the foundation for a functional integration of AI into smart grid operation

In transforming the energy system to climate neutrality, decentrally optimised solutions at the regional and local level play an essential role. Increasing flexibility potentials, improved sector coupling, and associated digitalisation through the roll-out of smart metering technology are the cornerstones of a smart grid.

Decentralisation exposes many uncertainties in system operations, so that both TSOs and DSOs will need to jointly re-organise their system planning and operation processes in the short term. However, in the long term a cooperation with all stakeholders within a smart grid is recommended, as grid operators will not be implementing these changes alone. This will in turn require joint IT systems that will also provide all involved actors with access to a common database in the future.

There are many pilot projects as well as other research efforts promoting the development of smart grids. Such efforts should be continuously disseminated by publicising lighthouse projects and best practices. Pilot projects such as the ones presented in this report help develop blueprints for the development of smart grids, which can then be applied many times over in Germany.

The key take-away of this report is: Smart grids developed rapidly in Germany during the past years, and their growth rate will be increasing in the future along with higher shares of distributed RE in the energy system.

List of figures

Bibliography

1) Agnetha Flore and Jorge Marx Gómez,"Development and comparison of migration paths for smart grids using two case studies, Heliyon",Volume 6, Issue 9,2020,ISSN 2405-8440, at https://www.sciencedirect.com/science/article/pii/S2405844020317564.
2) Baden-Württemberg e. V.,"Smart Grids-Plattform Menschen engagiert zusammenbringen", 2020, at https://smartgrids-bw.net/public/uploads/2020/07/Projektbrosch%C3%BCre_komplett_V2.pdf.
3) BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., "Der aktive Verteilnetzbetreiber in einer dezentralen Energiewelt", 30 November 2016.
4) Bitkom, „Klimaschutz", n.d., at https://www.bitkom.org/Klimaschutz
5) Bundesnetzagentur, "Bericht zum Zustand und Ausbau der Verteilernetze 2021", 2021, at https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/NetzentwicklungUndSmartGrid/ZustandAusbauVerteilernetze2021.pdf?__blob=publicationFile&v=3#:~:text=Mit%20dem%20Bericht%20zum%20Zustand,Zeitpunkt%20g%C3%BCltigen%20%C2%A7%2014%20Abs.
6) Bundesnetzagentur, "EEG in Zahlen", 2019, at https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/ErneuerbareEnergien/ZahlenDatenInformationen/start.html.
7) Bundesnetzagentur, "Redispatch", 18 November 2021, at https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Versorgungssicherheit/Netzengpassmanagement/Engpassmanagement/Redispatch/start.html.
8) Bundesnetzagentur, "Smart Grid" und "Smart Market", 2011, at https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2012/120102_EckpunkteSmartGrid.html.
9) Bundesverband Energiespeicher Systeme e. V., "BVES Branchenzahlen 2021/2022: Energiespeicher trenden! 500.000 Heimspeichersysteme installiert.", 6 April 2022, at https://www.bves.de/bves-branchenzahlen-2021-2022-energiespeicher/.
10) Bundesverband Neue Energiewirtschaft e.V., "Smart Meter Roll-out: The German Case", 28 Januar 2020, at https://www.bne-online.de/en/news/article/smart-meter-roll-out-the-german-case/.
11) Cambridge University Press (Publisher), "Smart Grid Technology - A Cloud Computing and Data Management Approach", 2018, pp. 106 – 117 at https://www.cambridge.org/core/books/abs/smart-grid-technology/virtual-power-plant/A8125B8F40D38DDA64B73F23FA80A350.
12) Catiana Krapp, "Deutschland baut sein Stromnetz radikal um – Das sind die drei größten Baustellen", Handelsblatt, 29 Januar 2022, at https://www.handelsblatt.com/technik/forschung-innovation/insight-innovation-deutschland-baut-sein-stromnetz-radikal-um-das-sind-die-drei-groessten-baustellen/28007768.html.
13) David Frank and Kirsten Kleis et al., "Effektive Stromnetzentgelte für die Transformation", Germanwatch e.V., 10 March 2022, at http://www.germanwatch.org/de/85071.
14) Denise Schopen, "Der Netzausbau in Deutschland: Gründe, Pläne & Kosten", 10 June 2022, at https://energiemarie.de/energietipps/wissenswert/stromnetz/ausbau.
15) Deutsche Energie-Agentur (Publisher), "Data centre flexibility in Germany and China – Status quo and best practices", 2022, at https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/EnTrans/Data_centre_flexibility_in_Germany_and_China.pdf.
16) Deutsche Energie-Agentur (Publisher), "Dena distribution grid study", 2012, at https://www.dena.de/themen-projekte/projekte/energiesysteme/dena-verteilnetzstudie/.
17) Deutsche Energie-Agentur (Publisher), "Handbook on Planning and Operating an E-Mobility Infrastructure", at https://www.energypartnership-turkey.org/media-elements/.
18) Deutsche Energie-Agentur GmbH (Publisher), "dena-Leitstudie Aufbruch Klimaneutralität", 2021 at https://www.dena.de/newsroom/publikationsdetailansicht/pub/abschlussbericht-dena-leitstudie-aufbruch-klimaneutralitaet/.

19) E.ON, “Smart Grid: Aufbau, Definition und Funktionen“, at https://www.eon.de/de/eonerleben/smart-grid-so-funktioniert-das-intelligente-stromnetz.html#uebersicht.
20) Ecologic Institut (Publisher), “Handlungsempfehlungen der SINTEG- Schaufenster zur Anpassung des Rechtsrahmens“, 5 October 2021, at https://www.ecologic.eu/de/18446.
21) ENTSO-E, “Towards Smarter Grids: ENTSO-E Position Paper on Developing TSO and DSO Roles for the Benefit of Consumers“, 4 March 2015, at https://www.entsoe.eu/2015/03/04/towards_smarter_grids_entso-e_position_paper_on_developing_tso_and_dso_roles_for_the_benefit_of_consumers/.
22) European Commission, “Smart Metering deployment in the European Union“, n.d., at https://ses.jrc.ec.europa.eu//smart-metering-deployment-european-union.
23) Federal Ministry for Economic Affairs and Climate Action (BMWK), “Modern grids and meters”, January 2021.
24) Federal Ministry for Economic Affairs and Climate Action (BMWK), “Das deutsche Strom-Verteilernetz“, n.d., at https://www.bmwk.de/Redaktion/DE/Infografiken/Energie/verteilernetz.html.
25) Federal Ministry for Economic Affairs and Climate Action (BMWK), “Ziele der Energiewende“, n.d., at https://www.bmwk.de/Redaktion/DE/Infografiken/Energie/ziele-der-energiewende.html.
26) Federal Ministry for Economic Affairs and Climate Action (BMWK), “Was genau ist eigentlich ein Smart-Meter-Gateway?” 26 February 2020, at https://www.bmwi-energiewende.de/EWD/Redaktion/Newsletter/2020/03/Meldung/direkt-erklaert.html.
27) Giuseppe Franceschelli, “Predictive Maintenance and Electrical Grids”, Maps Spa Numero REA, at https://solutions.mapsgroup.it/predictive-maintenance-electrical-grids/.
28) Greenhouse Media GmbH, “Freiamt: Solaranlagen und Speicher versorgen E-Autos und Wärmepumpen”, n.d., at https://www.energie-experten.org/projekte/freiamt-solaranlagen-und-speicher-versorgen-e-autos-und-waermepumpen.
29) GreenPocket, “Stop of the smart meter rolloutdevelopment in Germany?”, 24 March 2021, at https://www.greenpocket.com/blog/stop-of-the-smart-meter-development-in-germany.
30) i-SCOOP, “Smart grids: electricity networks and the grid in evolution“, n.d., at https://www.i-scoop.eu/industry-4-0/smart-grids-electrical-grid/.
31) Johann Schütz and Mathias Uslar et al., “Digitalisierung. Synthesebericht 3 des SINTEG Förderprogramms“, Studie im Auftrag des BMWK, 2022, at https://www.sinteg.de/fileadmin/media/Ergebnisberichte/SF3_Digitalisierung/20220502-SINTEG-SyF3_bf.pdf.
32) E.ON SE in collaboration with BDEW (Publisher) B., “How Artificial Intelligence is accelerating the Energy Transition”, May 2019, at https://www.eon.com/content/dam/eon/eon-com/Documents/en/new-energy/20191202-1022-in150-25039-yearbook-artinelli-170x240-online-5.pdf.
33) E.ON SE (Publisher), “Von Einzellösungen zum Energiesystem der Zukunft”, Designetz, 2019.
34) Klaus Görner and Dietmar Lindenberger et al., “Virtuelles Institut Strom zu Gas und Wärme – Flexibilisierungsoptionen im Strom- Gas-Wärme-System“, p. 35f., 26 Februar 2015, at https://epub.wupperinst.org/frontdoor/deliver/index/docId/5845/file/5845_Virtuelles_Institut.pdf.
35) Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg, “Stromnetz der Zukunft – mitten auf der Alb“, Projektgruppe „Energiewende im Dialog“, n.d., at https://energiewende.baden-wuerttemberg.de/projekte/bildung-wissenschaft/stromnetz-der-zukunft-mitten-auf-der-alb.
36) Mirko Pracht and Ralf Heisig, “Modular Control Centre System”, “The next generation”, 50Hertz Transmission GmbH, 24 March 2021, at https://f.hubspotusercontent30.net/hubfs/8156085/Mirko%20Pracht%20and%20Ralf%20Heisig%20-%2050Hertz.pdf.
37) Netze BW GmbH, “Projekt flexQgrid“, 2022, at https://flexqgrid.de/.
38) Next Kraftwerke GmbH, “Was sind Kritische Infrastrukturen (KRITIS) in der Energiewirtschaft?“, 2022, at https://www.next-kraftwerke.de/wissen/kritis.
39) Nora Fischer and Dr. Verena Adamheit et al., “Smart grids in Germany“, AHK Stockholm, n.d., at https://www.handelskammer.se/sites/default/files/smart_grids_in_germany_-_web.pdf.
40) Regelleistung.net, “Minutenreserve”, n.d., at https://www.regelleistung.net/ext/static/mrl.

41) SAP, "The smart grid: How AI is powering today's energy technologies", 2022, at https://www.sap.com/insights/smart-grid-ai-in-energy-technologies.html.
42) Sebastian Schaal, "Paragraf 14a: Bundestagsausschuss schiebt Spitzenglättung zu BNetzA", electrive.net, 06 June 2022, at https://www.electrive.net/2022/07/06/paragraf-14a-bundestagsausschuss-schiebt-spitzenglaettung-zu-bnetza/.
43) TenneT Holding B.V., "Annual peak load and load curve ", 2022, at https://www.tennet.eu/electricity-market/transparency-pages/transparency-germany/network-figures/annual-peak-load-and-load-curve/.
44) Uwe Trattnig and Tina Sovec et al., "Intelligente Netze und Endkundenanwendungen", Symposium Energieinnovation, University of Applied Sciences, 2016, https://www.tugraz.at/fileadmin/user_upload/Events/Eninnov2016/files/lf/Session_E6/LF_Trattnig.pdf.
45) Verband kommunaler Unternehmen e.V., "Neue Qualität der Zusammenarbeit von Verteilnetzbetreibern in der intelligenten Verteilnetzkaskade", 13 April 18, at https://www.vku.de/vku-positionen/kommunale-energieversorgung/mehr-systemverantwortung-fuer-vnb/.
46) Verband komunnaler Unernehmen e.V.,"Neue Qualität der Zusammenarbeit von Verteilnetzbetreibern in der intelligenten Verteilnetzkaskade", n.d., at https://www.vku.de/fileadmin/user_upload/Verbandsseite/Landingpages/VNB_Portal/171123_polPap_NQDZ_final.pdf.
47) World Economic Forum in collaboration with Bloomberg NEF and dena, "Harnessing Artificial Intelliegence to accelerate the energy transition", White Paper, September 2021, at https://www.weforum.org/whitepapers/harnessing-artificial-intelligence-to-accelerate-the-energy-transition.
48) ZfK, "Innovationsausschreibung: Erstes Projekt vollständig in Betrieb", 9 Februar 2022, at https://www.zfk.de/energie/strom/innovationsausschreibung-erstes-projekt-vollstaendig-in-betrieb.

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