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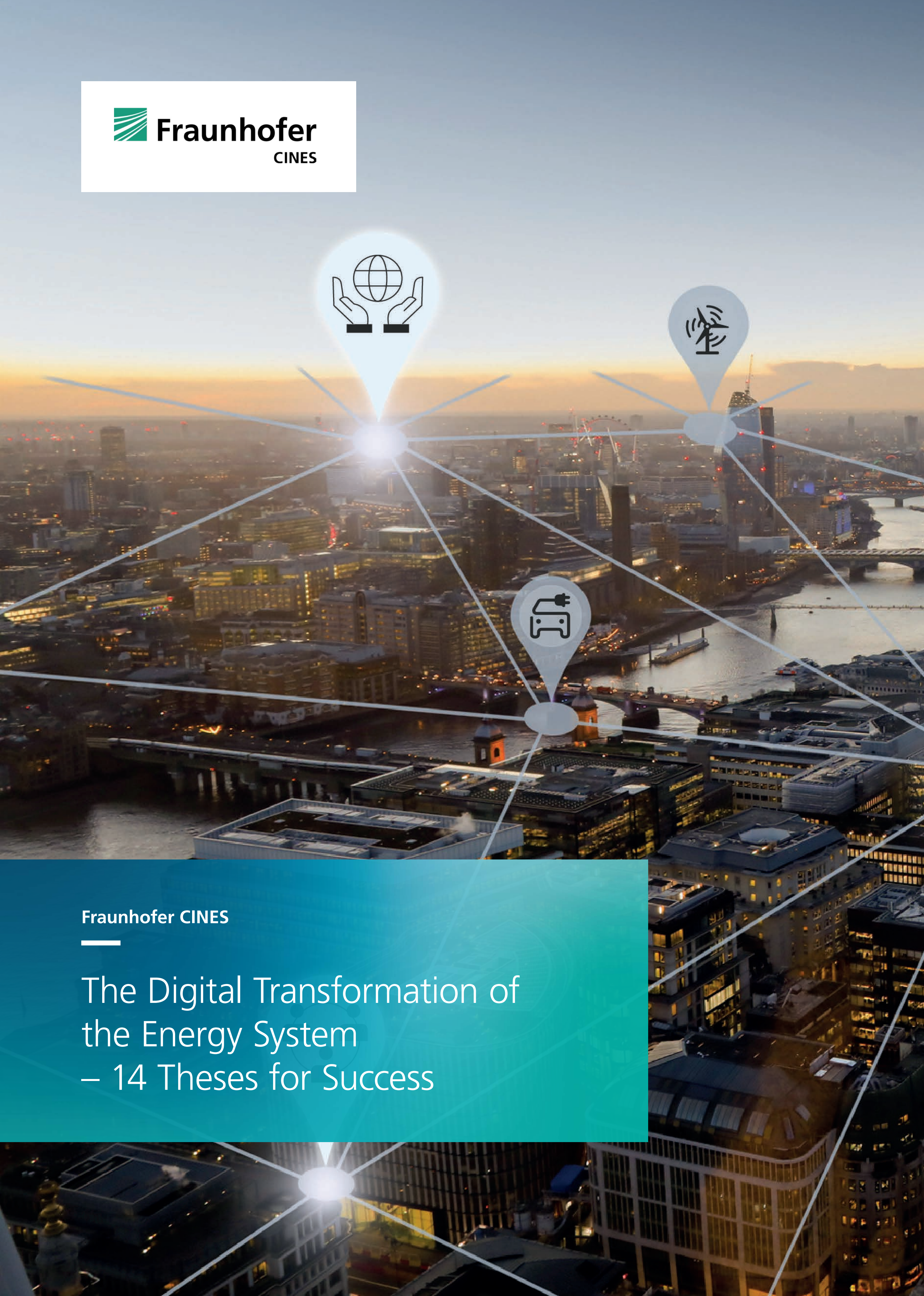

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The Digital Transformation of the Energy System – 14 Theses for Success

Publishing notes

Theses on the digital transformation of the energy system

Project management

Fraunhofer Cluster of Excellence Integrated Energy Systems

EUREF Campus 23 – 24, 10829 Berlin
Wickert, Manuel, manuel.wickert@iee.fraunhofer.de

Responsible for text content

Bergsträßer, Jonathan, jonathan.bergstraesser@iee.fraunhofer.de
Gkoktsis, George, george.gkoktsis@sit.fraunhofer.de
Hirsch, Tilo, tilo.hirsch@iosb-ast.fraunhofer.de
Klaiber, Stefan, stefan.klaiber@iosb-ast.fraunhofer.de
Klobasa, Marian, marian.klobasa@isi.fraunhofer.de
Kohrs, Robert, robert.kohrs@ise.fraunhofer.de
Lauer, Hagen, hagen.lauer@sit.fraunhofer.de
Nicolai, Steffen, steffen.nicolai@iosb-ast.fraunhofer.de
Offergeld, Thomas, thomas.offergeld@fit.fraunhofer.de
Rülicke, Linda, linda.ruelicke@iee.fraunhofer.de
Schmidt, Dietrich, dietrich.schmidt@iee.fraunhofer.de
Warweg, Oliver, oliver.warweg@iosb-ast.fraunhofer.de
Welisch, Marijke, marijke.welisch@zv.fraunhofer.de
Wende-von Berg, Sebastian, sebastian.wende-von.berg@iee.fraunhofer.de
Werner, Daniel, daniel.werner@ise.fraunhofer.de
Wickert, Manuel, manuel.wickert@iee.fraunhofer.de

Moderation und facilitation

Stefan Rötzel, roetzel@sciencepark-kassel.de, Science Park Kassel GmbH

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Management summary

Digital transformation is affecting all areas of our lives, economy and society — not least our energy system, which has seen digital technologies playing a key role for a number of years now. This is particularly evident in the field of renewable energies, which require a higher degree of coordination due to their decentralized and diverse nature. This study aims to contribute to the next stages of the digital transformation of the energy system. For this purpose, the study puts forward 14 theses and highlights their implications for energy system stakeholders. In doing so, the theses contribute to discussions around energy policy, prompt calls to policy makers and devise concrete recommendations for action.

The theses are divided into five focal points which result from an analysis of the most relevant trends in energy system transformation and digital transformation. Based on the identified focal points, the study specifically describes the state of the digital transformation of the energy system. This is by no means an exhaustive list but is based on the objective of focusing on short- to medium-term measures (up to 2030). The following focal points were selected due to the fact that they offer the greatest leverage for supporting the climate-neutral energy sector with digital tools.

Given that data volumes are increasing rapidly, the economic potential of data is becoming more and more relevant — in the context of the so-called **data economy**. Progressive technical options for measuring, storing and analyzing data are fueling business models based on such data. What's more, the use of data spaces ensures that data can be handled autonomously and stored in a decentralized manner. This enables innovative artificial intelligence methods to be integrated into critical infrastructures and considerably increases the efficiency of all energy sector processes.

Digital **sector coupling** is another relevant area in which digital transformation will gain importance in the near future. Power-to-mobility, power-to-heat and power-to-gas/H2 are particularly noteworthy examples. When it comes to sector coupling, digital transformation must take on an (even) stronger role, and digitalized control is a crucial factor.

Plant communication remains essential for the digital transformation of the energy sector. There are two primary areas of interest here. The first is at the technical level and covers device data communication with and via the smart meter gateway. The second focuses on the regulatory level and involves data communication between individual market players in the liberalized energy market.

This form of communication is closely interlinked with increasingly **digitalized grid operation** — which, due to growing complexity, also increasingly requires digital grid planning. The digital transformation has gained a considerable amount of momentum at the different grid levels and has been implemented in the maximum-voltage and high-voltage grids in particular. This trend needs to progress into the lower voltage levels to support the grid with system services.

Cybersecurity is the last area addressed in the study and is currently at the forefront of the digitalized energy system. Considering that supply security is one of the most pertinent energy policy targets, cybersecurity must be regarded as an essential aspect of the digitalized energy system. In this context, it is not enough to focus solely on defending systems against attacks. Instead, the possibility of faults and vulnerabilities needs to be taken into account when designing systems.

For all these key topics, the study authors have formulated theses which are designed to provide a stimulus for a European strategy for the digital transformation of energy supplies, rather than merely offering a national perspective. However, the authors did prioritize the German regulatory and legal situation for their analysis and concrete recommendations for action.

The following 14 theses — derived from the current state of the digital transformation of the energy system — emphasize the potential and reveal obstacles for the digital transformation of the various sectors on a larger scale. The study specifically contains comprehensive information about the significance for stakeholders in the energy sector, messages to policy makers, and concrete recommendations for action. The theses are summarized as follows:

Thesis 1: In the future, the value of energy will depend on linked data

The market value of energy normally depends heavily on uncertainties caused by weather-related supply, among other factors. The more data and information available, the easier it is to decrease the number of uncertainties. In addition to uncertainties, the origin of energy is growing steadily in importance (green properties). In both cases, energy can gain value with additional data and proper management in the face of uncertainties, or through its green properties.

Thesis 2: Digitally driven value creation networks are the future of the energy system

Effective and targeted digital transformation should not be used to automate existing processes, but should create a new process landscape, transforming value chains into value creation networks. New business models in the energy sector must be consistently thought of in digital terms and, in particular, actively involve users.

Thesis 3: A sovereign and resilient European energy system requires an EU-based ICT system

Resilient energy supply in a digitalized energy supply system must also fully take into account the dependencies created by ICT components. As a first step, these must become transparent to the stakeholders — especially in critical processes. The singular dependencies which are identified must then either be resolved or, alternatively, ended by means of global diversification. EU dependence on basic ICT components (hardware and software) from non-EU countries must therefore be reduced.

Thesis 4: Without digitalized sector coupling, the costs of transforming energy systems will rise significantly

Integrating energy systems creates a high level of complexity. Without extensive digital transformation, especially at the interfaces between individual systems, sector coupling is not economically viable and cannot be implemented in practice.

Thesis 5: Viable energy business models for digitalized sector coupling at the district level are currently failing due to regulatory hurdles

Particularly at the district level, where heat, gas and electricity must be progressively integrated, the macroeconomic benefits (e.g., reduction of peak loads at the integration points) of digital business models cannot be monetized. In this scenario, regulations need to be adapted to enable worthwhile, digitalized sector coupling at the district level.

Thesis 6: Efficient decarbonization of the heating sector can only be achieved through digital transformation

Just like the technological transformation of the heating sector, the digital transformation of the heating sector is still in its infancy. The two must go hand in hand to enable rapid and efficient implementation. In this context, there is great potential, especially when it comes to flexibilizing the consumer side.

Thesis 7: The smart metering system are being overtaken by other solutions in plant communication

The smart meter rollout is subject to continued delays and is becoming less and less valuable for the individual stakeholders due to information channels to the plants that have been established in the meantime. Nowadays, manufacturer clouds are able to reach a large number of plants using communication technology. Data exchange partnerships (such as between grid operators and manufacturers) can already leverage great potential, e.g., in developing flexible properties on a broad scale.

Thesis 8: The energy transition requires plant communication based on the latest IT technologies and open documentation

The numerous elements of plant communication rely on communication standards that were developed in the early days of telecontrol technology and for which no further development is planned. New energy plants in particular should use modern IoT protocols that are openly documented.

Thesis 9: Modern plant communication enables plug-and-play and cross-stakeholder process automation

Due to the enormous amount of small and micro-plants that will be actively involved in energy system management in the future, it is no longer possible to manually connect plants. The following measures are required: automating connections, automating the change of an aggregator, for example, and automating all processes to ensure operational readiness.

Thesis 10: Digital transformation is a core area of expertise in future power grid operations

Digital transformation is becoming an ever more integral part of power grid operations. Grid operators will therefore have to build up their digital transformation expertise within their own company. Cooperation networks offer support for this purpose, especially for smaller grid operators. Viewing digital transformation merely as a purchasable service fails to recognize the impact of technology.

Thesis 11: Decentralized energy transition equals complete digital transformation right down to the lower grid levels

The substantial expansion of plants (decentralized generation and new consumers) in the lower grid levels requires active digitalized management of all of the distribution grids. This makes it possible to ensure the supply quality and availability when it comes to switching from pure consumers to prosumers. At the same time, the necessary grid expansion can be supported in a targeted manner and to the necessary extent.

Thesis 12: Timely implementation of the energy transition can only succeed by ensuring the complete digital transformation of planning and approval processes

Transforming the energy system requires enormous infrastructure investments, which are operationalized in various planning and approval processes. The underlying processes and interfaces must be digitalized to make the ambitious schedule possible with regard to approval law.

Thesis 13: Cyber resilience will replace cybersecurity

Viewing the digitalized energy system as an infrastructure that only requires adequate protection falls short of the mark. On the contrary, all stakeholders must understand that — given the complex nature of the system — complete protection is no longer feasible. The digital energy system of the future must therefore be able to deal with errors and faults.

Thesis 14: Reliable energy networks require reliable communication networks

Digital transformation means that energy networks and communication networks are increasingly interconnected. As a result, they depend directly on one another to ensure reliability. The requirements for a reliable energy supply must therefore also be derived from the communication infrastructures used for operation.

Summary

In summary, the authors believe that digital transformation is key to implementing the energy transition. Without far-reaching and consistent digital transformation ranging from plant control, through the entire grid cascade to the individual sectors, a timely and cost-effective energy transition is not feasible. A data economy may enable the required cross-stakeholder process automation. To further increase the security of the energy supply, cyber resilience must also play a major role in a European digital transformation strategy for the energy system.

1 Introduction

Digital technologies are already shaping the energy system — and their role will become increasingly relevant in the future. There is huge potential for digital transformation in the renewable, decentralized energy system of the future. To enable this potential to be developed in an optimum and swift manner, all stakeholders from business, politics, research and civil society must now set the right course. And to do this, relevant research findings must be combined and put into practice. Within this remit, Fraunhofer Energy Research wants to take a joint position on the digital transformation of the energy sector to be able to provide guidelines for successful, sustainable, cost-efficient and rapid implementation. To this end, the following study presents a coordinated outlook with concrete recommendations for action.

The most relevant innovation drivers for the digital transformation of the energy sector have been determined for this purpose in order to establish the areas of the energy sector and the digital transformation tools where there is a great need for action as well as great potential for optimization through the digital transformation. The ongoing energy crisis now, once again, highlights the urgent need for action when it comes to the transformation of the energy system. As a result of this, particular focus will be placed on targets to be achieved in the short and medium term (up to 2030).

The most relevant innovation drivers result from trends that are currently shaping energy system transformation and the corresponding trends in the area of digital transformation. In addition to the overriding issues of energy security and high energy prices, the study highlights other, longer-term **trends in the energy sector** that are particularly significant for the next steps in the transformation.

After assessing the **general trends in the digital transformation**, the study specifically describes the state of the digital transformation of the energy system. The focus here is on areas where short-term to medium-term measures (up to 2030) can help accelerate the energy transition and implement it more efficiently. The following areas offer the greatest leverage for supporting the climate-neutral energy sector with digital tools:

- Data economy
- Sector coupling
- Plant communication
- Grid operation and planning
- Cybersecurity in the energy system

The thesis study has been fundamentally built on the cooperation of the Fraunhofer institutes of the Cluster of Excellence CINES. As part of this cooperation, an interdisciplinary team of scientists compiled an overarching statement by Fraunhofer Energy Research on the state of the digital transformation of the energy system.

The process for this was as follows: A systemic scenario analysis of the digital transformation of the energy system was carried out as part of a moderated process. Relevant key factors and stakeholders were then characterized and prioritized, and relevant fields of application for the digital transformation of the energy supply up to 2030 were identified. In doing so, technological and social trends and the resulting uncertainties and open questions for the future were discussed.

By formulating three alternative visions of the future, various characteristics, interactions and system dynamics of these key factors and stakeholders have been brought to the fore. The best-case scenario addressed an ideal transformation of the energy system, hand in hand with a successful digital transformation. The business-as-usual scenario addressed a low level of digital transformation together with a somewhat hesitant energy transition. The worst-case scenario, however, provided an antithesis for these two scenarios with a long drawn-out energy transition and undervalued digital transformation.

Following the discussion surrounding these future projections, five relevant fields of action were structured and draft theses were created. These draft theses were scrutinized and optimized in several discussion sessions involving external experts from energy supply companies, grid operators, industry associations, manufacturers and service providers who were able to provide constructive criticism and boost momentum, both through online questionnaires and in structured discussion sessions. On the basis of this interaction between science and practice, the project group then honed the theses for the "Digitalized Transformation of the Energy System up to 2030". Particular importance was placed on addressing target groups in an accessible way and formulating concrete recommendations for action, broken down by target group.

The study is structured as follows: Chapter 1 describes the transformation and associated trends of the energy system, which can be understood as requirements for the deployment of technological innovations. Chapter 2 sets out technological trends in the digital transformation, with the focus on tools that have current or potential future application in the energy sector. Chapters 3 and 4 are divided into key topics; chapter 3 begins by describing the state of the digital transformation and chapter 4 builds on this by presenting theses and recommendations for action intended to stimulate discussion on the future design of the digital transformation of the energy system. A conclusion and summary are provided at the end of the study.

2 Energy supply transformation and trends

The energy sector is facing the major challenge of ensuring sustainability and energy supply security in the long term and dealing with an increasingly diversified market environment. The very high energy prices that are currently being seen compared with previous years, as well as possible supply bottlenecks for fossil fuels, are also key developments in the energy sector that are leading to the sector's comprehensive transformation. In the following, we present relevant trends, new and changed tasks, and business models in the energy sector that can support and accelerate a transformation and are already emerging today. Sustainability and energy security are influencing the development of energy infrastructures and leading to greater integration of the entire energy system [1]. The decarbonization of all fields is causing the industrial, heating and transportation sectors to forge strong links with the electricity sector and increases the complexity and interconnectedness of all of these sectors. The digital transformation plays an important role here as an enabler and facilitator, so that the necessary changes to energy sector processes can be implemented more quickly and efficiently.

Significant expansion of renewable energies

The climate policy goals from the Paris Agreement require significant expansion of renewable energies worldwide, including in Europe and Germany, and at the same time demand a further increase in energy efficiency across all fields [2]. The German federal government's Easter Package aims to achieve greenhouse gas neutrality as early as 2045 and therefore to expand the annual expansion of renewable energies to around 23 gigawatts for photovoltaic systems and around 10 gigawatts for onshore wind turbines [3]. With an average photovoltaic system capacity of 20 kilowatts, this corresponds to more than 1 million photovoltaic systems per year (nearly 200,000 in 2021). In the onshore wind sector, with an average turbine capacity of 4,000 kilowatts, the targeted expansion corresponds to 2,500 turbines annually (484 in 2021). This means that significantly more connection inquiries and planning processes can be expected in the future.

At the European level, the EU Commission's RePowerEU plan aims to reduce dependence on Russian gas, oil and coal and accelerate the expansion of renewable energies [4]. To this end, solar capacity is to be doubled in the EU by 2030, approval procedures are to be simplified, and 10 million tons of renewable hydrogen are to be produced in the EU by 2030.

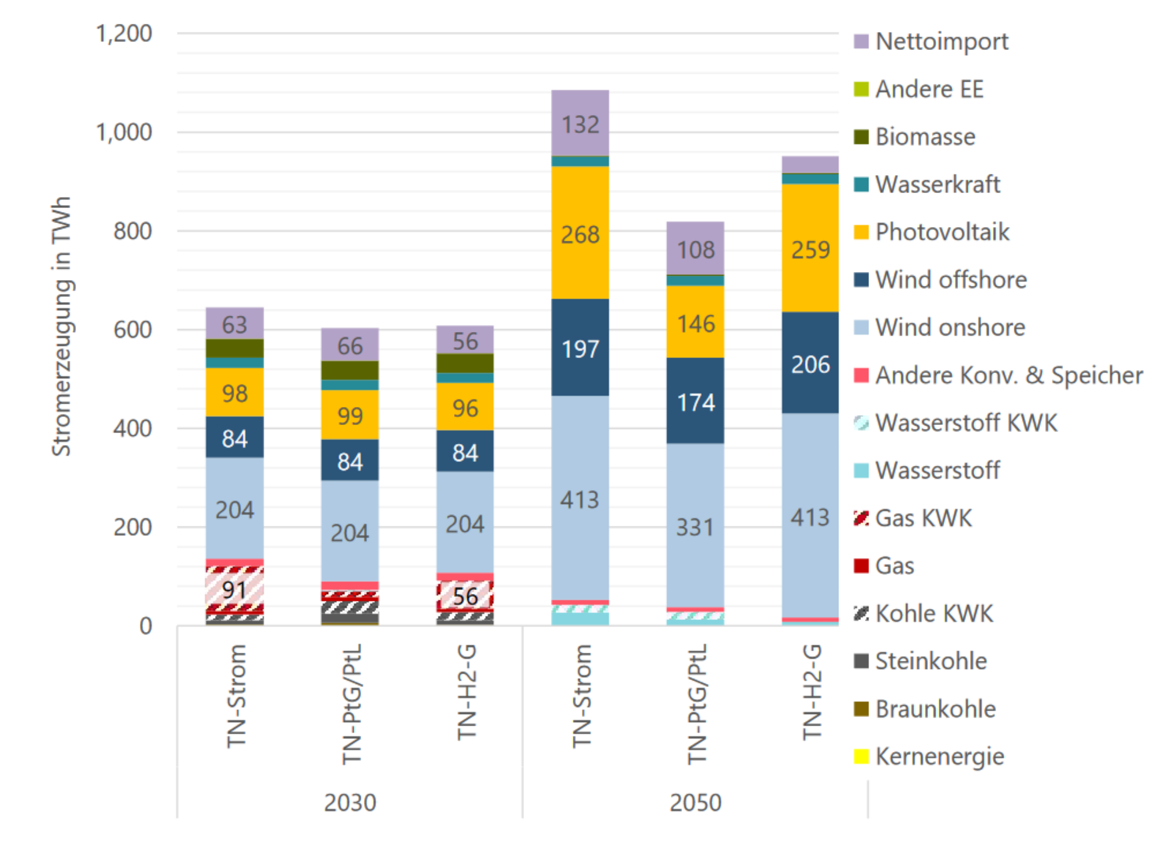
> "The rate of expansion for renewable energies will increase significantly."

How is this trend reflected in long-term transformation scenarios?

Analyses of long-term transformation pathways indicate that the electricity sector could produce significantly more electricity, primarily provided by onshore wind, as well as photovoltaic systems and offshore wind. According to scenario analyses, net electricity imports could also increase.

Figure 1: Electricity generation in Germany in 2030 and 2050 by energy source

GN-Electricity scenario, GN-PtG/PtL scenario, GN-H_2-G scenario



Source: Long-term scenarios from the German Federal Ministry for Economic Affairs and Climate Action (BMWK) 2021

2.1 Energy security and high energy prices

In the wake of the crisis in Ukraine, the availability of natural gas from Russia is very limited and new suppliers play an important role in German energy supply. At the same time, limited availability has a significant impact on the prices of various energy sources, including electricity in particular. As a result of this, information on availability and electricity prices is becoming more and more relevant. Industrial companies are faced with the challenge of maintaining their previous value creation even in a decarbonized energy system and producing at sometimes significantly higher energy prices in the future.

"Predictable energy prices and security of supply are the basis for industrial value creation."

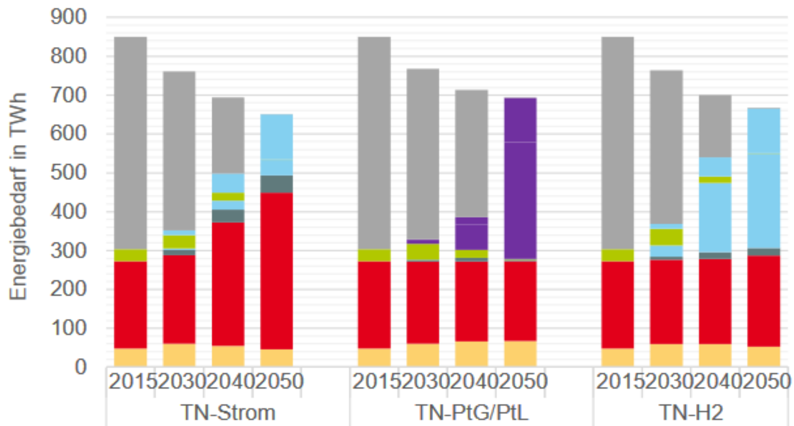
In addition to national generation based on renewable energies, importing energy sources via existing infrastructures, from Europe and beyond, to Germany is of great importance for future energy security and energy price levels. The use of hydrogen as an energy source and as a raw material, especially in industry, will gain in importance. This will also result in the need for new infrastructure, especially for the transport of hydrogen.

How is this trend reflected in long-term transformation scenarios?

In the industrial sector, long-term decarbonization scenarios show that electricity and hydrogen are gaining much more importance as energy sources. This will require additional infrastructure for transporting the energy sources. In addition, there will be greater flexibility in the industrial sector when production processes are more closely aligned with fluctuating renewable energies, plus the expansion of storage options. At the same time, an increase in energy efficiency as a decarbonization strategy is also an effective way of reducing overall energy demand. Scenario calculations indicate a 23 percent reduction in final energy demand in industry compared to 2015.

Figure 2: Transformation in the industrial sector by energy source and final energy demand in Germany up to 2050

GN-Electricity scenario, GN-PtG/PtL scenario, GN-H_2-G scenario



	TN-Strom 2015	TN-Strom 2030	TN-Strom 2040	TN-Strom 2050	TN-PtG/PtL 2015	TN-PtG/PtL 2030	TN-PtG/PtL 2040	TN-PtG/PtL 2050	TN-H2 2015	TN-H2 2030	TN-H2 2040	TN-H2 2050
Fossil	546	408	195	1	546	439	328	0	546	395	160	1
Synthetisches Methan (stofflich)	0	0	0	0	0	2	18	115	0	0	0	0
Wasserstoff (stofflich)	0	13	50	116	0	0	0	0	0	13	50	116
Synthetisches Methan	0	0	0	0	0	10	66	300	0	0	0	0
Biomasse	30	33	20	1	30	41	21	1	30	42	16	1
Wasserstoff	0	5	23	40	0	0	0	0	0	29	178	243
Umgebungswärme	0	13	34	43	0	5	9	4	0	7	17	19
Strom	225	228	318	404	225	211	206	205	225	217	219	235
Fernwärme	48	61	54	46	48	61	66	68	48	60	60	53

Source: Long-term scenarios from the German Federal Ministry for Economic Affairs and Climate Action (BMWK) 2021

2.2 Sector coupling in the transportation sector

Decarbonization strategies play a significant role for the energy system as a whole, as well as for individual stakeholders. This means that information on the current status of energy consumption and the associated emissions is becoming increasingly relevant. On this basis, a large number of stakeholders are developing measures to reduce their emissions. Two fields of application where this is particularly relevant are electromobility and the heating sector, with power-to-heat applications. In the current coalition agreement, the market ramp-up of electromobility with 15 million electric vehicles by 2030 has been defined as a target and represents a central strategy for the decarbonization of the transportation sector. The increasing number of vehicles results in additional electricity demand for vehicle charging and, according to the current scenario framework of the network development plan, this may rise to over 100 terawatt-hours by 2037. At the same time, vehicle batteries also represent a decentralized storage system, which results in new tasks for the energy sector, such as smart, bidirectional charging, as well as improved self-sufficiency in supply.

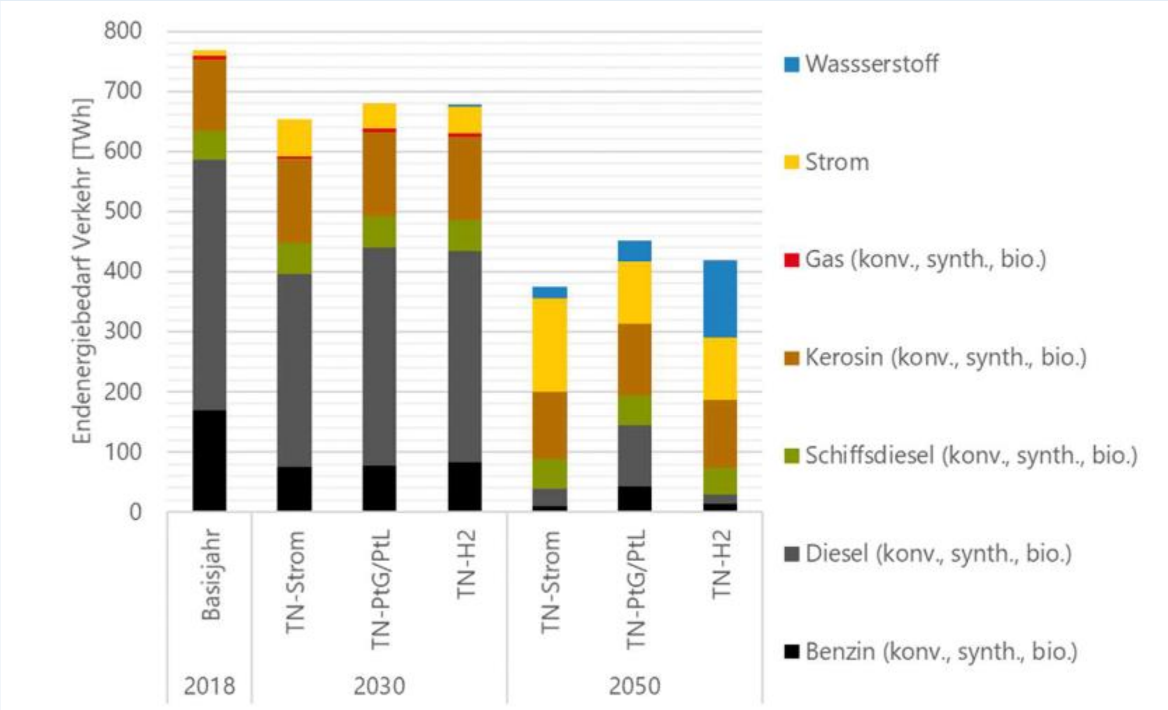
> “New digital business models are emerging for electromobility.”

How is this trend reflected in long-term transformation scenarios?

In addition to a significant increase in energy efficiency, electricity and synthetic fuels used as energy sources will make the biggest contribution to possible decarbonization in the transportation sector in the future. Based on scenario calculations, final energy demand should decrease by 50 percent in the transportation sector, much of which could be achieved by cars and trucks. The expansion of electromobility could enable significant efficiency improvements and would also lead to a sharp increase in the use of electricity as an energy source in the transportation sector. In addition to electricity, the use of hydrogen and synthetic fuels (especially in shipping and aviation) is a decarbonization option to be taken seriously.

Figure 3: Scenarios for the transformation of the energy demand in transportation up to 2050

GN-Electricity scenario, GN-PtG/PtL scenario, GN-H_2-G scenario



Source: Long-term scenarios from the German Federal Ministry for Economic Affairs and Climate Action (BMWK) 2021

The development of electromobility has seen a sharp rise in recent months — so much so that around 14 percent of new vehicle registrations are now battery electric vehicles. Due to the vehicles' increasingly large batteries, business models for smart charging and for supporting the power grid are now the subject of intense discussion [5]. Cheaper electricity with supply-oriented charging or high availability of renewable electricity will benefit individual users. Other energy effects in the overall system are higher grid utilization if battery charging does not take place at peak load times, but also higher grid loads at peak times if charging processes increasingly take place at the same time. For effective grid integration, customers and power grids must be connected by fast and automated data exchange to enable the use of flexibility potentials that benefit customers and improve grid efficiency. This also avoids high grid load and does not overly affect customer acceptance.

Service-oriented offers that couple electric vehicles with a self-sufficient supply and thereby enable optimized operation in combination with an own generation plant are becoming more relevant for the users of these e-vehicles. To provide flexibility using vehicle batteries at public or workplace charging points, small-scale marketing of energy quantities is of increasing importance. A number of different business models have now been developed by energy sector stakeholders, as well as by vehicle manufacturers themselves [6]. The most important applications are as follows:

- Optimized charging strategies (depending on the generation situation and generation costs)
- Providing system services
- Relieving grid congestion and avoiding peak loads
- Assisting with voltage maintenance
- Avoiding feed-in management
- Optimizing self-sufficient supply
- Optimized use of high-power chargers

> "The development and integration of charging infrastructure is a challenge for distribution grids."

The expected increase in electric vehicles will require a comprehensive development of charging infrastructure that must be integrated into existing power grids. It is expected that a large part of the charging infrastructure will be installed in the private sector (especially in single-family and two-family homes) and in workplaces. In addition, the expansion of a public charging infrastructure with medium and high charging capacities is planned in order to make electromobility attractive for longer distances and for users without their own charging facilities [7]. Extensive expansion of the charging infrastructure means that battery storage units in electric vehicles can be used to store energy. In the future, it will be possible to implement vehicle-to-grid (V2G) concepts [6, 8] with suitable communication and control technologies (OCPP/ISO standards) and complement or even replace existing applications for efficient grid operation.

2.3 Transformation of the heat supply

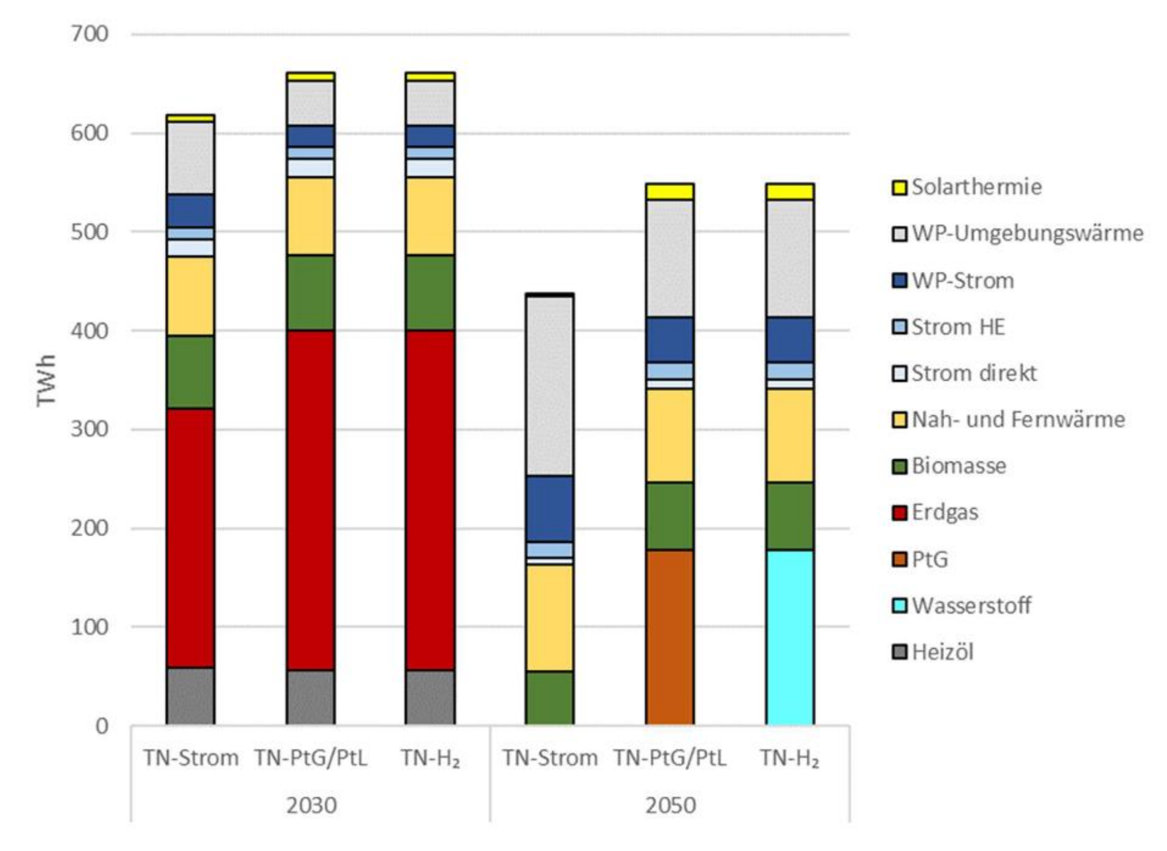
In contrast to the electricity sector, the transformation of the heat supply is progressing rather more slowly. While the share of renewable energies making up final energy consumption rose from around 2 percent in 1990 to 14 percent in 2012, decarbonization of the heat supply has since stagnated at this level. Heat generated from renewable sources is currently obtained mainly from the combustion of solid biomass in private households, while other renewable sources, such as environmental heat, solar thermal energy and geothermal systems, so far generate only 2 percent of the heat required. Fossil fuels, such as natural gas (46 percent) and oil (15 percent), continue to be the dominant energy sources. Although the share of energy taken up with space heating, hot water and process heat is declining due to efficiency improvements, it still accounts for just under half of final energy consumption today, making it the largest consumption sector ahead of electricity and transportation.

How is this trend reflected in long-term transformation scenarios?

The transformation in the heating sector, which includes not only space heating for buildings but also hot water, is characterized in long-term scenarios by a significant increase in energy efficiency and a shift in energy sources away from gas toward electricity. Possible future scenarios for the building sector show a reduction in final energy demand of 41 percent by 2050 compared to 2020. Heat pumps will make a significant contribution to the heat supply in 2050 and, according to scenario calculations, could increase their share from 5 percent in 2020 to almost 60 percent in 2050. At the same time, the share of final energy demand provided by heating networks will increase from less than 10 percent in 2020 to 25 percent in 2050.

Figure 4: Scenarios for the transformation of the energy demand in heating for buildings up to 2050

GN-Electricity scenario, GN-PtG/PtL scenario, GN-H_2-G scenario



Source: Long-term scenarios from the German Federal Ministry for Economic Affairs and Climate Action (BMWK) 2021

Due to the current geopolitical situation, but also due to the increasingly visible effects of climate change, the transformation of the heat supply through decarbonization and sector coupling is becoming more significant and more urgent in Germany and Europe. Thus, the heat supply in particular will experience long-lasting and far-reaching development.

> "The electrification and transformation of heating networks are key technologies in the heating sector."

In addition to increasing energy efficiency and the associated savings in heat consumption, other fields of action for transforming heat supply are currently coming to the fore. This includes the widespread decarbonization of heat generation across the sector. Efficiency improvements and the comprehensive integration of heat pumps into the heat supply as well as the necessary expansion of the grid-based heat supply are also important key technologies in this transformation. In addition to the provision of space heating and heat for domestic hot water, process heat is an important area of transformation, in particular as it cannot simply be electrified or otherwise substituted, especially at higher temperature levels in many fields of industry with intensive energy use. By using gases from power-to-gas plants, the heating sector can play an important role as both a consumer and a storage facility for energy from wind and solar power. In order to efficiently integrate additional renewable generators and waste heat from industrial and other processes into the heating system, existing district heating networks need to be transformed to low system temperatures and new, low-temperature local heating networks need to be implemented. The storage of renewably generated heat in large-scale, long-term storage facilities is also an important building block for local transformation. Long timeframes of decades are anticipated for the corresponding plant technology and infrastructure, so the heat supply transformation is taking a correspondingly long time.

2.4 Power grid transformation

Grid operations have become both much more agile and more volatile over the past 20 years. The state of play has progressed from purely consumption-driven grid operation — with centralized feed-in primarily in the extra-high voltage range — through large fossil-fuel power plants, to a decentralized system, in which feed-in from all grid levels plays a significant role in addition to consumption. This situation offers completely new challenges for all parties involved, as well as new and innovative opportunities to make grid operation more safe and secure, more stable and more efficient. Digital transformation and automation are already playing an important role here, and this will continue to increase in the future.

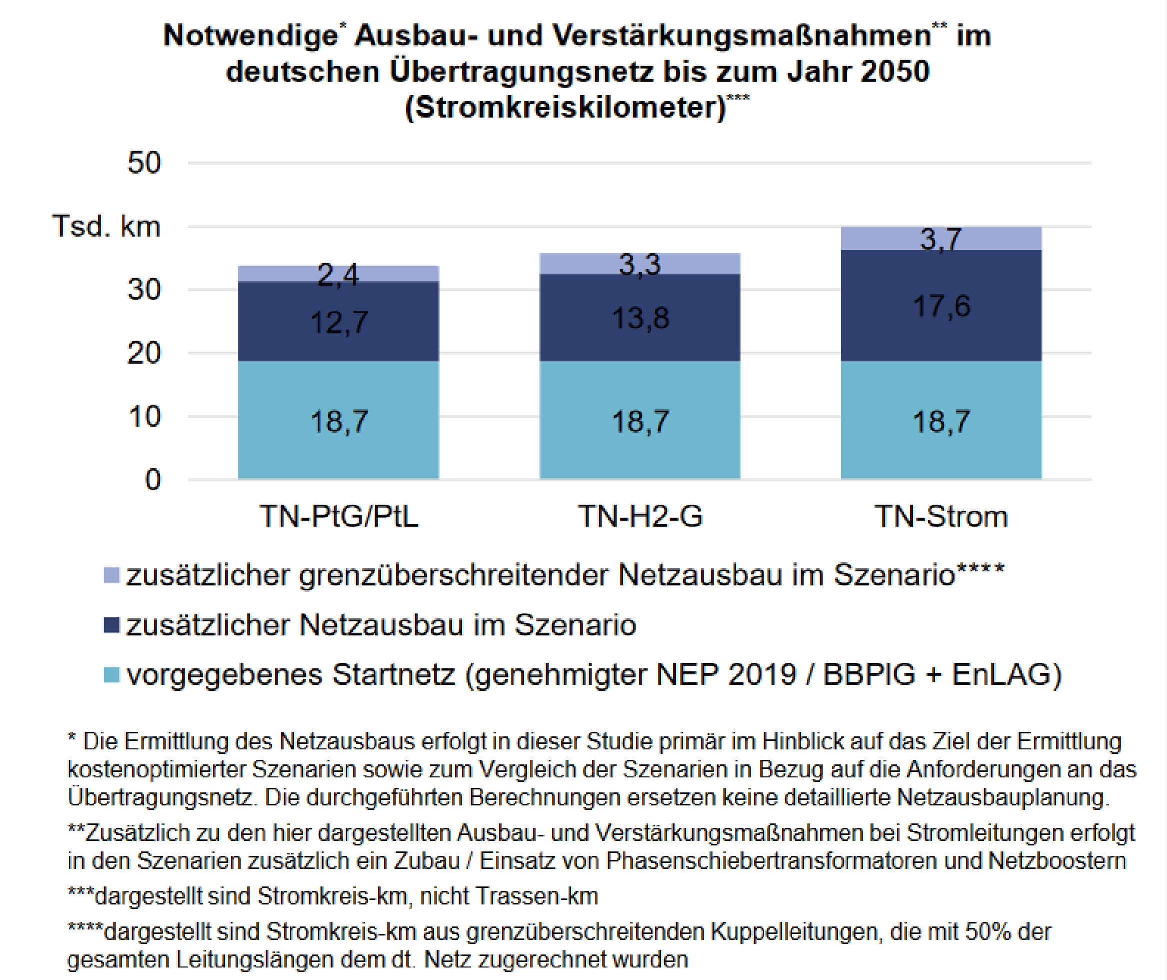
In an energy system that is based only on renewable energies, the coordination between generators, consumers and grid operators becomes more complex; in some cases, very small-scale coordination between a large number of stakeholders in various energy sector processes (including marketing and Redispatch) is necessary. The digital transformation of the data landscape in the field of power grids allows processes to be automated and therefore made significantly more cost-efficient. The time that has been required so far is particularly worth mentioning here, as it has resulted in high personnel costs and skilled workers being tied up with repetitive tasks.

How is this trend reflected in long-term transformation scenarios?

The transformation of the energy system with a significant expansion of electricity demand as well as the development of low-cost locations for renewable energies both in Germany and abroad requires additional infrastructure in the transmission grid. As a result, national and international electricity transmission in the transmission grid will increase significantly. In the BMWK's long-term scenarios, a required expansion of up to 40,000 km of circuit length is calculated if decarbonization of the application sectors relies very heavily on electrification of the most important processes and applications. This would roughly double the circuit length in the transmission grid if the current grid structure data from 2020 (with a circuit length of 37,500 km) is used as a basis. Trading with neighboring countries also increases in these scenarios, so cross-border infrastructure will also need to be expanded. Overall, a significant expansion of planning processes is expected, which will include heat, hydrogen and gas infrastructure, in addition to electricity infrastructure (German Energy Agency — proposed system development plan).

Figure 5: Expansion of the transmission grid and cross-border interconnectors by 2050

GN-Electricity scenario, GN-PtG/PtL scenario, GN-H_2-G scenario



Source: Long-term scenarios from the German Federal Ministry for Economic Affairs and Climate Action (BMWK) 2021

The transformation of the generation structure also leads to a change in the system operation of the grid, as frequency maintenance here can be ensured by rotating masses less and less frequently. New concepts such as grid-supporting transformers and modified Redispatch measures are becoming increasingly important in an energy system dominated by renewable energies [9].

Coordination processes between grid operators are becoming more frequent and can be significantly accelerated if the information to be exchanged is available in a uniform digital and standardized format. The number of Redispatch measures and the number of stakeholders and plants involved in these measures has previously increased significantly in order to resolve bottlenecks in the grid. Faster and more precise actions make power grid operations more cost-efficient compared to the current Redispatch 2.0 process, which still involves manual and, at some points, inefficient Redispatch processes. Both more precise and more efficient coordination between grid operators and communication between these grid operators, smaller plants and equipment will be necessary in future to ensure safe operation and control of grids.

> "The multitude of new generators, consumers and storage facilities at the low-voltage level mean transformation of the distribution grids is essential."

The trend is toward integrating smaller and smaller systems down to household level (rooftop photovoltaic systems, home storage, charging points, etc.). These can be used for system services and to compensate or cushion feed-in and consumption peaks. To make use of this potential, which has so far only been exploited to a limited extent, efforts are currently being made to continue and optimize the Redispatch 2.0 process "downward" (to the lower grid levels) (resulting in Redispatch 3.0). Photovoltaic storage systems, electromobility (with bi-directional charging) and heat pumps are significant factors here, and while these assets offer excellent control opportunities, because of their small-scale nature, they require good coordination to be able to achieve global impact from a local position. A digital information basis for the low-voltage and medium-voltage grids will be fundamental in achieving this and implementing digital automation and coordination processes that build on this.

2.5 Providing flexibility

The transformation from a centralized energy supply based on fossil fuels and nuclear energy sources to a decentralized, renewable energy supply has far-reaching consequences for the energy system. Expanding renewable energies will significantly increase fluctuation in terms of energy supply, resulting in an increasing need for reserve capacity and flexibility, especially in the electric power system. Flexibilization of energy consumption is an important building block for the success of the energy transition. Flexible consumers and plants can help to shift energy demand to times when renewable energy supply is available and to enable direct and efficient use of carbon-neutral renewable energy. This can reduce the need for efficiency-related intermediate storage. In addition, with local balancing of energy consumption and renewable energy supply, pressure can be relieved from the upstream energy system and the integration capability of renewable energy plants can be increased through a targeted use of flexibility options.

Many plants and processes have the potential to separate energy consumption from energy supply in terms of time, and to enable energy demand to be adjusted to volatile energy supply from renewable energy sources. The time, performance and energy potentials of the different flexibility options when it comes to load shifting are manifold. Both large-scale plants and aggregated small-scale plants, especially from the area of sector coupling (P2X technologies), have particular relevance for balancing and making direct use of the volatile energy supply from renewable energy plants (especially wind turbines and photovoltaic systems) [10].

The use of the different flexibility options is possible for several use cases and a distinction can be made between market-driven and grid-driven use cases here. For example, the use of flexibility options to maximize local own consumption of renewable energy and other business models/use cases focused on user-centricity and active participation of users are part of market-driven use of flexibility options. Examples include micro grids, virtual power plants, building energy management, load management for industry, demand side management, controlled charging of electric vehicles and, in the future, energy communities (citizen energy communities or energy sharing) (see also the section on "User-centricity and active participation of users") [11].

> "Energy systems integration and flexibilization of consumption are important building blocks for the success of the energy transition."

Furthermore, use cases for the utilization of flexibility options can result from grid operation (e.g., vehicle-to-grid concepts), which is responsible for and contributes to ensuring security of supply. For this purpose, flexibility options can be integrated into the grid operators' action cascade on congestion management for the initiation and implementation of grid security measures. These flexibility options can also contribute to securing grid operation and can be used in grid operations to improve grid utilization and minimize grid losses [12].

2.6 Transformation of the stakeholder landscape

The energy system has historically been characterized by a high degree of specialization and focus on individual stages of the value chain, which have been dominated by professional stakeholders. Above all, the extraction and production of primary fossil fuels was geographically focused and strongly characterized by internationality [13]. With decentralized, renewable generation plants, the conventional value chain and therefore the stakeholder landscape is changing considerably. Today, in principle, it is possible for anyone to operate their own generation plant. This begins in the smallest plant segment, with the mini photovoltaic systems known as "balcony units" that can provide up to 600 watts of inverter power, and extends right up to wind farms in the megawatt range in the hands of energy cooperatives comprising thousands of people [14, 15].

Due to the geographic distribution of the facilities, stakeholders from outside the field, such as municipal authorities, local residents, landowners and interest groups, must increasingly be involved in the planning, construction, operation and dismantling of the plants and the associated infrastructure. New approaches are needed to ensure participation in the necessary decision-making processes that is active, fair and as rapid as possible.

It will also not be possible to address grid and metering operations with the tools of the past if a large number of non-specialist operators of decentralized energy systems are to be integrated as prosumers. Here, with the smart metering system, for example, new issues such as data protection arise when generation and consumption data is used with a high degree of precision in active distribution grid operation [16, 17]. At the same time, the data from decentralized energy systems could be of potential interest to other stakeholders, such as the plant manufacturers, who would like to offer further use cases on this basis, including health checks or predictive maintenance. This is not dependent on the size of the plant and concerns both end users and professional stakeholders in the energy supply sector [18].

> "The diversity of stakeholders is increasing significantly due to energy systems integration and greater networking."

All in all, these case studies show that conventional value chains are changing and that alternative value creation networks are increasingly emerging, which can be made up of local, regional and (inter)national stakeholders. As a result, new service-oriented business models and changed stakeholder landscapes are forming, which, with the high geographical spread of decentralized energy systems and the necessary infrastructure (expansions), include a large number of new stakeholders to ultimately successfully implement the (digitally driven) transformation of the energy supply.

2.7 User-centricity and active participation of users

For energy consumers, sector coupling is developing new opportunities and options to become actively involved in the energy system and thereby reduce their own carbon footprint. In order to decide on investments in electric vehicles, heat pumps and battery storage, as well as in energy-efficient appliances, users, households and businesses need individual information adapted to their situation. At the same time, feedback from users is crucial to the rapid and efficient diffusion of climate-friendly and energy-efficient technologies if these are to be adopted. Digital transformation can provide an important basis for this.

As already introduced with the example of electromobility, business models are increasingly developing around a rapidly growing segment of flexsumers and prosumers — these can be end users with flexible decentralized energy systems such as heat pumps on the consumption side, or end users who also have on-site generation. Photovoltaic systems in the household sector are the dominant example of this on-site generation, with excess energy fed into the grid once the home's own consumption has been covered [19, 20]. Highly user-centric approaches are used to address these market segments. Above all, maximizing financially attractive own consumption is the primary driver for investment in plant technology and its flexible regulation in the case of smaller generation plants. Other applications for small-scale flexibility may also be a possibility. More specifically, these are usually options that follow the usual distinctions of behind-the-meter (BTM) applications — such as own consumption optimization, section 14a of the German Energy Industry Act (EnWG), variable electricity prices or emergency power capability — and front-of-the-meter (FTM) applications — such as arbitrage transactions, control reserve capacity provision, micro grids or energy sharing within districts/energy communities [21–24].

> "Greater user-centricity due to decentralized, own generation and flexible end users."

Essentially, there are various technical (data) requirements for both BTM and FTM applications. These requirements are fast response capabilities, high-resolution measured values and fast control algorithms; for example, for own consumption optimization, peak load management or the provision of primary control power (frequency containment reserve — FCR). For the billing of variable tariffs or energy flows within energy communities, for example, the quarter-hourly grid of the balancing group billing is usually sufficient. In this context, the main interest is in correctly calibrated readings as opposed to the fastest possible transmission to the relevant market stakeholders. From the perspective of user-centric business models, the focus is primarily on BTM or FTM applications that deliver economic, ecological and possibly social added value. Overall, there are significant overlaps with the field of e-mobility, as shown by typical applications of own consumption optimization within buildings or districts, as well as in energy communities in energy sharing systems [14]. This also applies to the use of variable electricity tariffs, the use of options under section 14a EnWG, and the provision of system services such as control reserve or non-frequency-related system services [11, 14, 18–20].

2.8 Energy system resilience

The number of generation plants, storage facilities and controllable energy and power consumers increases significantly in a sustainable energy system. At the same time, various communication systems are being used for monitoring and control that have not been used on a large scale in the energy system. Greater networking of plants and active integration of decentralized generation plants and controllable loads increases opportunities for targeted disruption of the energy system.

Energy supply security is a constant focus in Germany, the EU and in industrialized countries worldwide. In recent years, the effects of natural events on energy system resilience have been particularly observed here; for example, in the form of extreme cold, which in combination with disturbances led to overloading of the power grid (e.g., the 2021 Texas power grid crisis), or in the form of extreme heat, fires and drought, which lead to disturbances and overloads in the grid [25]. In addition to force majeure, the resilience of the energy supply is also threatened by technical disruptions to computer and control systems (e.g., the 2003 Northeast US blackout) or market manipulation (California electricity crisis) and is regulated and monitored accordingly.

However, the power grid has also become the target of targeted cyberattacks, once again highlighting the challenges of ensuring security of supply in the form of high availability and resilience. Malware such as Stuxnet and Industroyer are examples of software specifically designed to attack and possibly even damage or destroy industrial control systems (ICS). This is where the biggest developments and also gaps, in terms of protecting the power grid, can be seen. Special attention should therefore be paid here to the implementation of concepts for establishing cyber resilience, which must complement conventional IT security systems so that the focus can be on high availability and recoverability despite cyberattacks.

> "Networking and active integration of a large number of decentralized plants increases the risk of targeted disruptions."

3 Digital transformation trends

Digital transformation has fostered huge momentum in recent years and is relentlessly permeating all areas of life. Processes are becoming more efficient and traceable, customer needs are being better recorded and analyzed with each application, new products are being placed on the market more quickly and in a more targeted manner, and there is completely new value creation. Other industries are showcasing the opportunities the consistent digital transformation opens up and a number of trends can be observed that may have a particular influence on further developments of the energy transition. The following pages will describe the most significant trends.

Green IT

The electricity requirements for the information and communication technology sector are simply extraordinary: In 2017, the sector's consumption in Germany was already 58 terawatt-hours, which corresponded to 2 percent of total electricity demand [26]. This huge demand has created an awareness that it is also necessary to think about IT and software in a more sustainable way. Green IT describes the optimization of IT in terms of its environmental friendliness. All aspects of IT are considered, such as the location and layout of data centers, the virtualization of server hardware and its power management, and the use of office monitors and printers that can be recycled. Green IT also plays a role in the design of software, where the positive impact on the environment is weighed against the negative. Therefore, an algorithm that optimizes the load flows in a balancing group must save at least as much energy as would be consumed during the time it takes to run the algorithm [27].

3.1 Data spaces

A key prerequisite for many new technologies, such as machine learning, is the availability of large datasets. Cloud storage is a typical storage location for large shared datasets and cloud infrastructure had revenues of $142 billion in 2020, with growth of 33 percent. The majority of this market is split between just a few companies: AWS has a market share of 31 percent, Azure has 20 percent and Google has 7 percent [28].

In most cases, data is stored centrally, which results in risks when it comes to data ownership, as the data owners have no control over the whereabouts of their data. The EU is taking ambitious steps to solve this problem with its own data spaces, which aim to give data owners full ownership of their data.

Two reference architectures here are international data spaces (IDS) and the closely related Gaia-X project. Both systems make it possible to access data that is hosted at the data owner's premises, i.e., in a decentralized manner. Access control goes down to a granular level for each data user and access can be changed or revoked by the data owner at any time. The data is described in a standardized way to make it machine-readable and searchable [29].

The International Data Spaces Association provides open source code that simplifies IDS use and access, and makes it available to the public [30]. Within the framework of a GXFS-DE initiative funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), GAIA-X federation services are implemented as open source applications and made available to the public [31].

3.2 Internet of Things

Industry 4.0 has driven the digital transformation of production, logistics and products, and the Internet of Things (IoT) is expanding this digital transformation to other areas. IoT is used to generally describe the networking of smart machines online. Household appliances, such as refrigerators and robot vacuum cleaners, are equipped with smart functions, and industrial fittings, such as electronic meters, can be equipped with these functions, too. A large number of distributed, communicating sensors (or IoT devices or edge devices) can create positive added value as swarm intelligence. In the area of location services, for example, anonymized movement patterns of individual devices are used to detect congestion or track objects. The German Corona-Warn-App developed in 2020 is also based on IoT principles, in that sensor data is recorded in a decentralized manner and shared with other app users in an anonymized form when required (e.g., as a warning notification) [32]. With ever increasing digital transformation, people are also talking about the internet of everything (IoE) and the sensor data made available by these devices can be used profitably for new technologies, e.g., artificial intelligence [33, 468ff].

3.3 Cloud computing

Cloud computing describes the provision of computing resources from a pool of shared resources. These are offered "as a service", which means they can be arranged and used flexibly as needed. There are different levels of abstraction and virtualization of computing resources [34, S. 27].

With "infrastructure as a service" (IaaS), the user gets access to the resources of a virtual resource center, such as a server, router or firewall. IaaS users benefit from the fact that they don't have to operate their own data center, but can rent computer resources at any time. This also eliminates the need for hardware maintenance [34, S. 80].

With "platform as a service" (PaaS) — in addition to the virtualization of computing resources — development and runtime environments are also virtualized, in Java or Docker containers, for example. The platforms made available as a service therefore facilitate the development of new applications [33, S. 457, 34, S. 81].

"Software as a service" (SaaS) refers to the operation of standardized applications for end users that can be used without installing additional software. SaaS licensing is based on time or usage limits [33, S. 457, 34, S. 81].

3.4 Edge computing

Edge computing refers to individual nodes that are decentralized, unlike the centralized cloud, and describes the shift of data processing from the cloud to end devices in the field. For example, only the results of preprocessed data are sent to the cloud, that is only the objects detected by video analytics systems are transferred to the cloud instead of the complete image data. This example shows the huge savings potential that edge computing promises in terms of the data to be transferred. This results in advantages such as significantly faster data transmission and reduction of the network bandwidth used [34, S. 53].

3.5 Distributed ledger technologies

Over the past decade, the general public has become familiar with distributed ledger technologies (DLT) due to their use in cryptocurrencies. In this context, DLTs offer decentralized data storage for, in principle, any data. Within this decentralized data storage, integrity is ensured by consensus mechanisms, which ensure that entries are verified and generally become irreversibly part of the ledger. The most well-known cryptocurrency, Bitcoin, uses a blockchain as its public ledger and, within the blockchain, transactions are archived in pseudonymized form. Transactions are then authorized using cryptographic keys [35].

The propagated advantage of decentralized currency systems like Bitcoin is the independence from a centralized banking system and the irreversibility of transactions. DLT is also used in the context of the digital transformation of production (Industry 4.0 and IoT) to ensure the security and traceability of production chains.

Energy-intensive consensus mechanisms (proof of work) and scaling challenges are critical to DLTs. For Bitcoin alone, global energy demand is observed to be on the scale of large German federal states (anti-pattern to green IT) [36]. The switch to other consensus mechanisms (e.g., proof of stake) in cryptocurrencies is being pursued in several places but has not yet been realized.

3.6 Quantum computing

Quantum computers are anticipated to be the next stage in the development of computing machines after digital computers. Similarly to the binary bit for conventional computers, the quantum bit (qubit) forms the elementary information carrier for quantum computers. While a bit is only in one state, either 0 or 1, a qubit can be in superposition of both states. As a result, the number of states and therefore the information contained increases exponentially for several qubits, whereas it only grows linearly for conventional computers. This being the case, the information stored in 500 qubits would require more conventional bits than the estimated number of atoms in the entire universe [37].

Probably the best-known application of quantum computing is prime number factorization, which allows asymmetric encryption schemes to be solved. Using these, the enormous potential of quantum computing was theoretically demonstrated as early as 1994 through the development of Shor’s algorithm [2]. However, no physical quantum computers were in existence to demonstrate practical implementation. Today, their development is progressing rapidly, so it has been possible to increase the quantum volume (the metric for power and performance) from 16 in 2019 to 2,048 in 2021 [38, 39]. However, practical applications still pose a challenge for these systems that are part of the noisy intermediate-scale quantum (NISQ) era. To overcome the hardware limitations, modern hybrid algorithms such as QAOA or VQE are used [40], which utilize both quantum and conventional hardware. These allow the spectrum of solvable problems, such as optimization problems, to be extended and thus open up a wide range of application areas in industry. For example, promising results have already been achieved in [41] for smart charging methods for electric vehicles, and great potential is also seen for the automotive industry and for forecasts and analyses in the fight against climate change [42, 43].

3.7 Artificial intelligence

The field of artificial intelligence (AI) deals with the theory and development of computer systems that are capable of performing tasks that normally require human intelligence, such as visual perception, speech recognition, decision-making and translation [44]. A distinction is made between weak AI, which is limited to clearly defined use cases and therefore cannot be transferred to other problems and areas, or only be transferred with difficulty, and strong AI, which recognizes connections across different areas and deals with problems independently. While the development of strong AI is an active research field, weak AI is actually used in practical applications. The approaches to AI development can be categorized into traditional approaches (expert systems and logical systems) and machine learning. In particular, significant progress has been made in the area of machine learning in recent years due to increased availability of data, algorithmic advancements and increased computing power. AI is used for various problems, such as image processing (e.g., image recognition, self-driving vehicles, security measures), audio processing and computational linguistics (e.g., speech recognition, information extraction, translation), plant control and robotics (e.g., self-driving vehicles, grasping objects), prediction, discovery, planning (e.g., forming groups of data, object classification, predicting values, detecting anomalies for monitoring the operation of machines or cybersecurity), or creating new content [45, 46].

Artificial intelligence helps to extract knowledge from data to use it for predictions, optimizations or action strategies in the local or global energy system. Machine learning methods are frequently used here, and these are divided into three main strands. While unsupervised learning involves learning to detect patterns and relationships in data, supervised learning generates a classification or regression model to make decisions and predictions for a specific task. In the final strand, reinforcement learning, an agent interacts with its environment via a feedback loop to self-learn how to adapt its behavior to new situations. In addition, various AI approaches such as federated learning for learning on distributed systems, transfer learning or domain adaptation for the transferability of models, or multi-agent reinforcement learning for linking models are being discussed in scientific circles and are increasingly being applied [47].

3.8 Digital twins

A digital twin refers to when the behavior of a real, physical object or system is digitally replicated. This kind of model is used for simulation, prediction, optimization and verification of the real object and can be used throughout its life cycle. For example, in the development phase, at which point the real object often does not yet exist, a digital twin can be used to make statements about the later behavior of the product and thus assess and improve the quality of the product.

Digital twins are also particularly suitable for testing outlying cases or extreme situations that cannot be implemented in reality. Digital twins of power grids can be used to predict how the grid would behave in the event of a failure of large generation plants [34, S. 37].

3.9 Mobile networks

Among communication technologies, mobile networks enjoy a prominent role due to high network coverage and broad application. Currently, the 5G roll-out is progressing well, with 53 percent of areas in Germany covered since the end of October 2021 [48]. In many respects, 5G is superior to its predecessor 4G; for example, it has lower latencies and higher data rates, and enables a higher number of connected devices. The disadvantages are the shorter range, the associated need for more transmission towers and the need for internet backbone expansion [34, S. 12-19]. Research is already underway on 6G, the successor to 4G and 5G, with the aim of creating a robust network of land-, sea- and air-based communication that boasts 10 times more devices and 40 times higher data transfer rates than 5G. A major challenge is still the high energy demands from 6G, which also need to be reduced in the context of green IT [49, S. 22].

Outside of metropolitan areas and cellular network coverage, low Earth orbit (LEO) networks are alternatives that have been pursued by commercial companies for several years [50]. LEO networks offer satellite-based internet available even in the remotest corners of the world. Compared to the LEO networks of the 1990s, the technology used has improved significantly and manufacturing costs have fallen. Mega-constellations with up to thousands of satellites are used to span a network of satellites, providing seamless network coverage. This type of network offers low latency and global broadband internet coverage [51].

For battery-powered IoT applications, the energy requirements of the aforementioned technologies are often too high. Low-power wide-area networks such as long-range wide-area networks (LoRaWAN) are intended specifically for such applications. Other characteristics besides the aforementioned low energy requirements are a long range, a low price and the scalability of the systems. The data transfer rate for such systems is low, usually in the range of several tens to several hundreds of kilobits per second [52].

To operate critical infrastructure, the 450 megahertz network [53] establishes a protected, non-public infrastructure for presumably fail-safe power supply communication. Messages can be handled with different priorities, but the bandwidth is not sufficient for wide-area real-time applications down to the prosumer level.

3.10 Data protection and privacy

With increasing digital transformation, regulations and ordinances for the implementation of data protection have become indispensable. The examples provided below are the most important laws and regulations.

The General Data Protection Regulation (GDPR) primarily regulates the securing of data traffic in Europe and the protection of personal data. “Personal” data is very broadly defined [54].

The Digital Markets Act (DMA) is intended to create more competition and prevent particularly large digital companies, known as gatekeepers, from exploiting their dominant position in the market. For example, widely used messaging services such as WhatsApp would have to provide interoperable interfaces for less widely used messaging services. Any violations of this could result in drastic penalties of 10 percent of sales [55].

The Digital Services Act (DSA) also focuses on particularly large digital companies, including search engines, online marketplaces and social networks. For example, these must combat illegal content or deal with user complaints more effectively. Although small companies are exempt from these regulations, the larger the company the more regulations it has to implement [56].

The foundation for a European data exchange model is to be laid with the aid of the Data Governance Act (DGA). In addition, the DGA aims to support the development of common European data spaces. These areas are to include energy, mobility and public administration data. In general, the exchange of data between different sectors and EU member states is to be facilitated [57].

In a related way, the Data Act (DA) aims to regulate the sharing and use of industry data collected from connected devices. Data markets are to be created in order to make user data accessible to companies and industry stakeholders, as well as the data of external companies accessible to public authorities [58].

The Artificial Intelligence Act (AIA) is intended to establish a regulatory and legal framework for artificial intelligence. AI applications are divided into four risk groups. Applications with low risk can be used without restrictions, while applications with risk are prohibited [59]. Applications that affect critical infrastructure, such as energy grids, are rated as a high-risk group and must comply with tight controls during development and operation [60].

The European dimension — regulation surrounding the digital transformation

This section presents the main European policies, legal acts and strategies related to the digital transformation. A brief description of these policies is provided below and mainly covers core aspects of ongoing data and digital transformation policies and how they are linked to the energy sector. Legislative documents and proposals are referenced to provide context.

Digital Markets Act (DMA)

Online platforms often act as an interface between businesses and end users. The DMA regulates competition between relevant platform services and also commits to fair competition for gatekeepers and transparency in horizontal and vertical markets. These core platform services include intermediary services (e.g., marketplaces and app stores) [61]. A variety of digital services and platforms are also emerging in the energy sector, which will also be regulated by the DMA in order to maintain competitiveness for new market participants.

Digital Services Act (DSA)

The DSA protects and regulates the basic rights of consumers in an online marketplace. It also protects the digital space from unethical content, illegal goods and services, and targeted advertising. To achieve this, certain obligations must be met by intermediary stakeholders, including, for example, transparency reporting, cooperation with national authorities as instructed and requirements for terms of use that must take fundamental rights into account [61]. In the context of the energy sector, the DSA is able to regulate end-to-end digital services offered via the internet or online platforms. It also supports corporations and small and medium-sized enterprises in setting up and scaling EU-wide digital energy platforms.

Data Governance Act (DGA)

The DGA is an important strategic pillar of the EU Data Strategy and is intended to increase confidence in the shared use and availability of data. It also creates the foundation for data exchange services and data altruism. The DGA promises to create governance and a set of rules to overcome the challenges of technical barriers and data re-use. It is also oriented toward the creation and development of common European data spaces in key strategic areas involving both private and public stakeholders in areas such as health, environment, energy, agriculture, mobility, finance, manufacturing, public administration and qualifications [62].

Data Act (DA)

The Data Act complements the Data Governance Act proposed in November 2020. It promotes a fair and innovative data-driven economy and provides a legal framework for companies and businesses to share data. In addition, the law stimulates a competitive data market and innovative services and seeks a free data market for non-personal data. It also facilitates data sharing in business relationships between companies and public authorities, which is often inefficient through existing channels. Data has significant value in the energy sector and the Data Act would establish ground rules for data sharing and portability in the energy sector. Third-party providers could privilege access to data from various sources to provide digital services and solutions to end users [63].

Artificial Intelligence Act (AIA)

This legal act regulates the framework and development of artificial intelligence in EU member states. The fundamental objective of this act is to ensure the safe, trustworthy and lawful implementation of AI-related services in the EU. It also facilitates the single market for AI services, investment and innovation in AI systems [64].

AI models and systems play an important role in the energy supply chain; in fact, a number of AI-enabled services and products are already well-placed at various stages of the energy supply chain (e.g., end use, generation and transmission). This specific piece of legislation provides guidance to energy companies, utility companies and small and medium-sized enterprises on how to introduce and integrate a legally valid AI system into their business process.

Open data and the re-use of public sector information (recast)

This promotes the exchange of public data (e.g., from energy suppliers) via a digital data platform that can be used free of charge. It also enables the re-use of data to develop new energy services, products and applications, and encourages energy companies, utility companies and power producers to establish an open data platform [65].

EU Cybersecurity Strategy

This strategy ensures the resilience of critical infrastructures that provide services essential for the smooth functioning of the internal market and for the lives and livelihoods of European citizens. In the context of the energy sector, the Cybersecurity Strategy implements a common network and information security framework (NIS 2.0) for power producers, market operators, aggregators, demand response and energy services. This also includes heating and cooling networks [66].

Regulation on establishing the European High Performance Computing Joint Undertaking (Draft proposal)

European regulation of high-performance computing (HPC) aims to modernize existing infrastructure. HPC systems enable data-driven innovation (e.g., big data analytics, hyperautomation) [67]. In the energy sector, HPC systems would help interconnect various infrastructures and plants by providing advanced digital connectivity. They would also allow energy companies to develop data-intensive AI and machine learning models.

Smart Readiness Indicator (SRI) for Buildings

This is a methodology for assessing the digital readiness of buildings in the EU that provides a common definition and certification system for the smart readiness of buildings [68]. The SRI promotes the digital transformation of energy services in buildings and is closely related to digital aggregation and flexibility services in the energy value chain.

Common European Data Spaces (working proposal)

This proposal accelerates the establishment of common (open) data spaces to ensure data portability and interoperability and covers a number of strategic sectors and areas. These kinds of data spaces will provide easy and secure access to data in order to test innovations and new business models. In the context of the energy sector, a common European energy data space is proposed to strengthen digital data exchange between companies and utilities and to develop new use cases for the benefit of the green transition and digital transformation [69].

Renewable Energy Directive (RED III)

The newly introduced RED III Directive is an important policy initiative to enable the transition to a 100 percent renewable energy grid. It promotes the system integration of renewable energies in a digital way and makes the issuance of guarantees of origin mandatory, as well as ensuring transparency among stakeholders. In addition, RED III emphasizes the electronic exchange of data, such as electric vehicle charging points, heating and cooling system locations, building energy management and aggregator data [70].

European Interoperability Framework (EIF)

The EIF guidelines are a set of recommendations for achieving interoperability at the different levels of business processes. The EIF introduces different levels of interoperability (e.g., organizational, technical, informational) to streamline the free flow of data in end-to-end digital services. It supports rapid customization of open source software technologies, databases and products to avoid a lock-in effect [71]. The energy sector is of great importance when it comes to interoperability of technologies and information. In this sense, the EIF would help implement interoperability at every stage of the energy services value chain.

4 State of the digital transformation of the energy system

Based on the initially separate considerations of the developments and trends in the energy transition and general digital transformation, various workshops were held from which it was then possible to identify five fields of action that represent particularly promising opportunities for greater digital transformation, and which require special attention. These are data economy, sector coupling, networked plant operation, grid operation and planning, and cybersecurity. The basic assessment benchmark is the achievement of the decarbonization target by 2045, i.e., minimum requirements for digital transformation, without which the achievement of the energy transition target seems unlikely.

Two challenges will be discussed here by way of introduction that do not fit into these categories but have a major impact on past and future developments. One is the digital transformation of processes involving public authorities and the other is qualification and the labor market.

The digital transformation of businesses, public authorities and processes

Companies are gearing up for the digital transformation. According to [72], more than half of energy suppliers and grid operators had a digital transformation strategy in 2021. The COVID-19 pandemic also acted as a catalyst for digital transformation in the energy sector, as companies had to realign their processes and digital transformation initiatives were implemented in a very short amount of time. This raised awareness of the need for digital transformation and boosted the visibility of its huge potential [73]. Today, companies expect a change in value creation as well as increasing revenue expectations for digital products, e.g., for offers of decentralized generation plants (e.g., automation or alternative solutions for administrative processes for market participation of plants), automated electricity trading, switching between marketing options, smart city IT, e-mobility and energy management solutions for municipalities and industrial companies. In addition, the field of smart city IT and e-mobility offers numerous options for digital products and services (e.g., infrastructure for integrated communication platforms and decentralized generation plants, one-ticket approaches for mobility options, roaming platforms, sharing services, wallboxes, mobile apps and charging station bookings), which together are already an integral part of many companies' practical operations. A large proportion of companies in the energy sector have also already been able to reduce costs through digital transformation; for example, with the help of digital optimization [72]. Energy supply companies also passively achieve major efficiency gains in core processes within the energy sector, such as through meter data processing, billing and self-service portals [73]. There is also potential for improvement in the application of AI for digital assistance systems, data-driven churn forecasting and prevention, as well as basic data maintenance, digital sales support or the digital transformation of regulated processes [72].

The digital transformation of processes has become increasingly relevant in this context. Automated processes improve the efficiency and therefore the competitiveness of companies. In this regard, large companies often have a head start on small and medium-sized enterprises when it comes to the digital transformation of processes. However, small and medium-sized enterprises are often more agile and have leaner and less complex processes. In the area of grid infrastructure, this is relevant for grid automation, analytically supported construction planning, automation in workforce management, credit note processes for subcontractors, the use of drones for recordings and analyses, as well as self-service business intelligence for regular independent preparation of business reports and analyses, for example [72].

The opportunities offered by digital transformation for public authorities and administration are not being exploited and the COVID-19 pandemic has exposed the need to catch up. Without modernization and digital transformation, which offer enormous potential for faster and simpler processes, public authorities lack the capacity they need to accelerate the energy transition and implement the necessary processes (e.g., for the digital transformation of planning and approval processes for grid expansion) [74]. All in all, the digital transformation of energy sector companies, public authorities, processes, stages of the value chain and stakeholders needs to be consistent and not just selective.

Digital transformation expertise

Digital and data expertise is becoming increasingly important in all sectors. According to [74], there is room for improvement when it comes to digital expertise in the energy sector. The existing staff of (especially small and municipal) public authorities and energy supply companies cannot be further developed and expanded at a sufficient rate to ensure that there is fully adequate knowledge of how to progress with digital transformation. For this reason, expertise must be combined, e.g., by working with central contacts who have at least the sufficient basic knowledge (digital transformation in general, cybersecurity, possibilities provided by modern methods such as AI).

Only half of companies offered their employees digital support for onboarding, training, self-service or further development through e-learning in 2021. In addition, there was a lack of expertise and employee qualifications in the area of data analysis and AI, so much so that companies are not sufficiently tapping into the potential offered by predictive or prescriptive analyses, analytical optimization, optimization based on historical data or predictive maintenance. Furthermore, the roles within companies are changing significantly as the digital transformation progresses, which leads to new expertise requirements for both employees and management [73]. It should also be noted that communication and cooperation with stakeholders who have in-depth expertise in digital transformation is a relevant point here (e.g., research institutions, technology and digital transformation start-ups, and manufacturers of controllable energy systems such as e-vehicles, heat pumps and smart home applications). These developments are already underway but are not yet sufficiently advanced in all areas. Digital expertise also needs to be promoted to a greater degree in vocational and further training for the energy sector, as a shortage of skilled workers in digitalized systems (for digital grids, cross-sector digitalized planning and operation, etc.) is becoming apparent.

4.1 Data economy

Given that data volumes are increasing rapidly, the economic potential of data is also becoming more and more relevant. Progressive technical options for measuring, storing and analyzing data are fueling new digital business models. Expertise in the use of data and algorithms is becoming a factor in the competitiveness of companies, thus increasing its overall economic importance. The availability of data is therefore an essential prerequisite for the digital transformation of energy supply. The exchange of data between market stakeholders is often inadequate and mostly limited to regulatory requirements, meaning the potential for innovative solutions is not exploited. To present the current state of the data economy in the energy sector, the following sections take a closer look at the regulatory and legal environment, the current exchange of data in the German energy sector, and data spaces as a connection point for new value creation networks. In addition to the data exchange considered here, there are a large number of bilateral data exchanges within the energy sector; however, these are not considered in detail here.

The regulatory and legal environment for market communication

Data exchange in the energy sector has been significantly influenced by regulations and specifications up until this point. In the context of market communication between market participants, the following regulatory process documents are applied in Germany: Switching Processes in Metering (WiM); Business Processes for Supplying Customers with Electricity (GPKE); Market Processes for Generating Market locations — Electricity (MPES) and Market Rules for the Performance of Balancing Group Accounting in Electricity (MaBiS). In this context, data and information is exchanged via standardized EDIFACT messages by means of suitable backend systems (e.g., the market communication tools and underlying upstream processes as well as associated tools for balancing and supplier switching).

As first-generation smart metering systems cannot yet technically map multi-point processing and distribution of metered values from the smart meter gateway (SMGW), suitable backend systems are needed here for receiving, plausibility checking, enriching and sending metering data. The legal situation regarding the collection of this data is regulated in the German Metering Point Operation Act (MsbG). In this context, the German Federal Network Agency (BNetzA) and the German Federal Office for Information Security (BSI) are the authoritative regulatory authorities when it comes to the implementation of the statutory requirements. In this regard, the BSI has developed and published minimum requirements for protection profiles and technical guidelines, which describe and define the basic requirement details [75, 76].

Current data exchange in the German energy sector

In the context of the digital transformation and due to the regulatory transparency requirements of the energy transition, digitalized data and information is exchanged at different levels. There are two primary areas of interest here. The first is at the technical level, so covers device data communication with and via the SMGW, for example. The second focuses on the regulatory level and involves data communication between individual market stakeholders in the liberalized energy market.

Seim et al. [77] used a survey to identify limiting factors in the platforms currently available. For example, information is usually not available in the required resolution or is very heterogeneous and not machine-readable.

Data is mostly recorded, processed and made available in the familiar sectors of electricity, gas or heating. Consequently, in combination with a very clearly defined project focus, data silos are created that do not allow for easy exchange of data and lead to the combining and exponentiation of values. A relevant example is the Connect+ platform, which German grid operators use to work together to exchange the necessary information for congestion management (Redispatch 2.0) [78]. As the German Energy Agency's study on the subject also states, it remains to be seen whether open and innovative data exchange is actually possible with Connect+ or whether it will remain a silo solution [79].

> "The importance of data and its economic potential is increasing, but many possibilities and opportunities currently remain untapped."

Data spaces as a connection point for new value creation networks

Implementing a thriving digital data economy requires a simple and secure way to share data. One basis for this is provided by basic technological building blocks for establishing a data space. Here, concepts and initial building blocks have been developed by various organizations, which serve as the basis for all implementations to date.

The International Data Spaces initiative was initiated by the Fraunhofer-Gesellschaft at the end of 2014 with the aim of enabling secure and sovereign data exchange. Through organizational and technical measures, the IDS reference architecture enables data providers to share their data along the entire value chain while maintaining data ownership. For the dissemination and further development of IDS, the International Data Spaces Association (IDSA) was founded. More than 110 organizations already belong to this association in order to use the developed technologies for their use cases and business processes. The IDS architecture [80] as an industry-neutral IT solution is currently being verticalized into specific solutions in various industries. This is driven by the respective stakeholders and use cases.

Alternatively, the Gaia-X reference architecture provides another way to share data stored in a decentralized way within a comprehensive ecosystem [81]. Together with Fiware and the Big Data Value Association, IDSA and Gaia-X are currently developing the most important revival in the field of digital ecosystems. All four of these organizations have joined together to form the Data Space Business Alliance (DSBA) to prevent the creation of data silos and enable sharing between their respective technologies [82].

Based on the recommendations of the DSBA, the European project Omega-X is developing an energy data space for the exchange of data based on data spaces. The focus is on data processing according to European values with the help of decentralized data storage and data ownership. At the same time, the aim is to demonstrate that the value-added potential of the data can still be exploited [83].

Another project is the EU Horizon 2020 project PLATOON [84]. This was launched last year, uses IDS technology and demonstrates efficient data exchange for productive use cases with the help of seven pilot applications. Fraunhofer also conducted an initial feasibility study of the data space concept with the EnDaSpace project. Here, the functionality of the technology was evaluated with the aid of a prototype and practically demonstrated based on a hydrogen use case [85].

The three projects mentioned are a list of examples that can be continued by other projects. This is indicative of the high level of interest in data spaces that can currently be observed in the energy sector and in other industries, such as manufacturing. Data spaces offer great potential to meet the digital challenges of the coming years and to process data in line with European values without sacrificing value creation.

4.2 Sector coupling

Sector coupling involves the conversion and storage of energy and materials between the electricity, heating, gas, transportation and industrial sectors. The use of technologies for sector coupling enables synergies to be exploited between renewable energy sources and energy consumption, allowing the energy system to become more flexible. From a digital transformation perspective, the most relevant integration points between the sectors are currently power-to-mobility, power-to-heat and power-to-gas. Some sector coupling technologies are already technologically mature and widespread, such as heat pumps for power-to-heat and basic electric vehicle charging for power-to-mobility. When it comes to these technologies, current research is primarily related to system integration, for which digitalized control plays an important role. Other technologies, such as bidirectional charging (especially vehicle-to-grid) for power-to-mobility, already have a high level of technical maturity, but can hardly be called widespread because of various regulatory hurdles and ambiguities. These need to be removed in some cases and this is already happening to a certain extent; for example, through the elimination of the German Federal Renewable Energy Sources Act (EEG) surcharge, which previously represented a double burden for decentralized storage. On the other hand, digital transformation also makes it possible to comply with some regulatory requirements in the first place, enabling the integration of technologies into the energy system. Technologies such as electrolysis and hydrogen reconversion for power-to-gas are available in principle but require further development in terms of the technology. Nevertheless, work already needs to be done regarding how such technologies can be integrated digitally into the energy system [86]. The state of the digital transformation at the most relevant integration points is discussed in more detail in the following sections.

> "The digital transformation of the energy systems integration needs to be advanced significantly and hurdles need to be overcome to fully realize the potential of these key technologies for the energy transition."

Electromobility

According to the BMWK, there were more than 70 electric vehicle models from German manufacturers on the market in 2021, and around 46,200 publicly accessible charging points were available for charging with electricity. In 2020, 389,000 new electric vehicles were registered, compared to 681,000 new registrations in 2021 [87]. This ramp-up in electromobility is incredibly dynamic in terms of new registrations and technological developments. When it comes to digital transformation, the areas of particular interest at this point in time are communication with the charging infrastructure, control and communication functionality, customer orientation and grid integration for electromobility. Digital solutions tailored to customers' requirements in terms of charging time, convenience, safety, range, price and additional offers are relevant for the future of electromobility but have not yet been sufficiently implemented. These are essential when it comes to achieving acceptance, dissemination and efficient and targeted grid integration of electromobility [88].

However, to successfully be able to integrate them into the energy system, the greatest possible interoperability and extensive communication with charging management systems is required. Interoperability is limited in part by the fact that some manufacturers operate proprietary systems. For example, only a few electric vehicle models and charging stations support standardized complex communication according to ISO 15118, which is intended to enable user-friendly and secure interfaces between electric vehicles and charging stations. If the vehicles use other communication options, communication with management systems is limited. There is currently a lack of standardization regarding an interface for the connection of charging stations as a connected consumer and generation facility to a local smart power and energy management system. (3) Timely completion of technical work on ISO 15118-20 and smart meter gateway certification is therefore to be sought and a focus placed on controllability functionality including clarification of technology availability. Its implementation has not yet been achieved but is underway. However, timely clarification that is open to new technologies regarding how to ensure technical controllability or flexibilization has yet to be provided [89].

Heat supply

The digital transformation of the energy sector and heat supply can improve the overall efficiency of the system and facilitate the integration of renewable sources. Looking at different energy sectors, digital transformation processes are currently more advanced with respect to electricity than for heat supply.

In heat supply for end users, new-generation appliances, e.g., heat generators (such as boilers or heat pumps) are delivered with a corresponding communication unit to establish a connection to the cloud data system of the respective manufacturer. These interfaces are used to analyze the plant, for example, but as a rule, there is no overarching data evaluation. For larger units in properties, for example, a comprehensive data connection is usually implemented. Heat meters with the appropriate smart capabilities are available on the market and are used for billing purposes and to optimize operation. Even here, though, comprehensive use of the data is not usually carried out.

The introduction and use of modern communication structures in energy technology is an important and urgent task in the district heating sector. Generally, district heating systems have been rather underexposed to digital transformation. The expansion or conversion of existing structures is necessary, as supply systems for heat and electricity will be much more decentralized in the future. The main impetus for this trend is the ongoing transformation of the energy system, in which smaller, distributed generation systems and the use of flexibility on the part of consumers will play a central role. However, systemic regulation and control of energy supply structures requires appropriate communication and signal processing. In the process of decarbonizing district heating systems, the structures, which have been mostly centralized to date, are being transformed into decentralized systems, with the need for digital networking of the plants. District heating systems are expanded to include large heat pumps, solar thermal generators and smaller combined heat and power (CHP) plants.

Furthermore, low system temperatures as well as diversified and generation units integrated into energy systems (e.g., CHP, power2heat, heat pumps) are targeted. In this context, digital transformation in combination with suitable sensor technology leads to better knowledge of heat demand, status recognition in the heating network, and smart and predictive heat storage and generator management. This is necessary to further develop the existing district heating systems and to enable their future-proof operation as well as new business models.

Digital, user-centric business models

In view of decentralized and volatile generation, business models that aim to make electricity consumption more flexible are particularly relevant for the energy transition. This makes the areas of sector coupling (incl. electromobility), flexible electricity tariffs, smart energy management and energy communities particularly interesting. For large-scale consumers, the implementation of corresponding models is easier and also already widespread — yet for household customers in particular, this has been difficult so far. Here, digital transformation offers opportunities for digital, user-centric business models that make households' purchases and feed-ins more flexible. In addition to prosumers, who already use flexibility to adapt their consumption to their generation plants, incentives for flexibility can also be created for pure consumers — for example, through flexible prices or involvement in load management.

As previous use cases regarding the flexibilization of integrated, decentralized energy systems can usually be combined, participants from the energy sector are increasingly offering so-called combination products. Usually, these start with the main use case of own consumption from users' own photovoltaic systems, which is then additionally extended by FCR provision with a battery storage system (BSS), or orientation to the variable electricity prices for cost-reduced coverage of the remaining residual electricity quantities. Furthermore, there are increasing tendencies to combine the residual power supply of flexsumers or the management of excess renewable energy generation of prosumers directly with the provision of one or more decentralized energy system products. Examples of this are "community" products as an on-balance-sheet combination of several prosumers or flexsumers or even "electricity flat rates" for fixed electricity quotas in combination with (flexible) decentralized energy systems.

From a digital transformation perspective, several systems are usually used at this point. On site, a home energy management system (HEMS) is typically used in the residential sector to locally read or control the integrated decentralized energy systems, such as heat pumps or energy storage systems (ESS) as well as (sub)meters. In order to additionally offer FCR or market-side integration in intraday trading, for example, aggregation takes place at a higher level in the form of virtual power plants. For this purpose, cloud-based control systems can be used, which in turn can be IT-linked to downstream trading and/or energy data management systems [21, 24, 90].

At the same time, both on the basis of the measurement data from the (flexible) decentralized energy systems and the pure consumption points, customers can be offered greater transparency about their individual energy flows. For example, this enables members of energy communities to be informed in a targeted manner the extent to which surpluses are currently available or expected in the community in order to increase or incentivize own consumption. In line with this, information about the residual power supply from the superordinate grid can be provided (such as origin or energy quantities). Insofar as the associated CO_2 emissions are tracked at the same time, it is possible — in the same process — to offset the emissions via another add-on product in order to address the increasing demand trend of climate-neutral living or a low-carbon lifestyle that can be implemented in the short term.

For these uses, backend systems are generally used that offer key functionalities such as measurement time series evaluation. For interaction with users, apps on customers' personal devices or a web interface are typical ways to provide information or to handle additional services [21].

In the potentially relevant area of energy communities, it is essential to note that an implementation of renewable energy communities for the more widespread, joint use of (renewable) electricity as well as renewable heat, if applicable, has already been on the cards since the end of June 2021. This is referred to as energy sharing. In detail, however, the corresponding implementation in the German regulatory system of the underlying EU framework directive — Renewable Energy Directive II — is not yet available. Accordingly, it is very complicated, at the district level, for example, to develop economically viable community consumption models for the residents of a district if, for instance, not all energy flows can be realized downstream of a grid connection point [21].

In all the applications mentioned, two points take center stage: Firstly, the majority of customers expect a high level of data protection when using their data for participation, and secondly, in the case flexibilization of decentralized energy systems, it must be ensured that the convenience level is maintained, otherwise the customers involved are likely to reject it [4, 16, 17].

User-centric energy offerings have so far often been driven by new entrants to the energy market who can use expertise in digital transformation to gain an advantage. Existing energy supply companies also need to move toward greater user-centricity if they are to remain competitive. According to [72], not all technical possibilities are being exploited in the area of digital customer-centricity, although companies are aware of the requirement, and initiatives and projects are in the planning stage or have been partially implemented (e.g., personalized targeting and retargeting, near-real time responsive points of sale, online access to consumption and billing data, automated interaction with customers via chatbots, choice of online payment options for customers, switching to other rate packages entirely online by customers, combining other products into an existing contract via online form).

4.3 Plant communication

An energy system in which energy conversion plants are increasingly installed and operated in a decentralized manner depends on powerful plant communication for monitoring and control. In the past, the electricity sector was dominated by a few large power plants, most of which were monitored and controlled locally. In the course of the energy transition, a large number of smaller power generation plants will be installed, most of which are already being marketed dynamically via intermediaries such as aggregators. The same will increasingly apply to controllable consumption devices in the future, which will have greater sensitivity to the availability of low-cost or low-CO_2 electricity.

> “Plant communication to cope with the increasing decentralization of the energy system has already been implemented in some areas, but it needs to be consistently expanded and further developed.”

Smart metering systems

The entry into force of the German Federal Act on the Digitalisation of the Energy Transition [91] laid the foundation for the introduction and roll-out of smart metering systems (smart meters for producers and consumers at the metering location level — all measuring points at metering points). This is seen as an essential building block for the digital transformation of energy supply and is intended to replace the installed and most widespread analog Ferraris electricity meters.

Metering systems are referred to as smart meters if they can digitally record, store, send and receive data. In this context, the term smart refers to the communication capability of the system to send and receive data. Digital measuring devices, compared to Ferraris meters, are referred to as modern metering devices (mME). A smart metering system is essentially made up of two components: a digital electricity meter, which is the modern metering device (mME), and the communication unit, which is the smart meter gateway (SMGW). In preparation for the roll-out of smart metering systems, particular focus has been placed on the SMGW as the security and trust anchor of the smart metering system [92].

As of August 2022, SMGWs from four manufacturers have been certified for use by the BSI [93]. According to the BSI, 46 companies are currently certified as SMGW administrators, although a certain degree of variation is to be expected here, as a certification with a validity is limited [94]. For the certification of SMGW, minimum requirements for the operation of an SMGW have been created according to BSI specifications. These define the system architecture, safety-related requirements, technical guideline TR-03109-1 to 6, assurance regarding the interoperability of the smart metering system and the application of smart metering PKI (SM-PKI) [95].

The regulatory market requirements regarding business and market processes have so far resulted in the following fundamental innovations due to the roll-out of smart meters, which are described in detail in the individual process documents of the German Federal Network Agency [96] and [97].

The Act on the Digitalisation of the Energy Transition also establishes the framework for the mandatory and/or optional roll-out of smart metering systems. In this context, the metering point operator is responsible for implementing any legal requirements. According to the law, an obligation or option to have the metering point operator install smart metering systems applies to the following groups of consumers and installations, subject to their requirements:

1) Mandatory for consumers of more than 6,000 kilowatt-hours per year; optional for consumers of < 6,000 kilowatt-hours, or at least equipped with a modern metering device by 2032.
2) Mandatory for all generation plants with a rated output of more than 7 kilowatts; optional for generation plants between 1 kilowatt and 7 kilowatts.
3) Mandatory for systems with a controllable consumption device, e.g., a heat pump or night storage heater.

Apart from the envisaged functionalities in the field of metering, the smart metering system provides the possibility to implement value-added services, which can be offered by market stakeholders to end customers. The services use the CLS channel of the smart meter gateway, for example, to monitor and control the systems connected via a control box, e.g., charging points, heat pumps or other power-intensive consumers [98].

The smart meter roll-out has often been the subject of controversy in the past [99]. On September 14, 2022, BMWK State Secretary Dr. Patrick Graichen stated during the 20th anniversary of the German Association of Energy Market Innovators (bne) that “practically nothing has been achieved” with smart meters in the past ten years [100]. He therefore announced a relaunch.

Plant communication in direct marketing

The mandatory remote controllability and remote readout of plants has long been regulated by law for direct marketing in the electricity sector in the EEG (currently EEG 2021 section 10b). The requirement has led to new plants in Germany that are intended for direct marketing being equipped with a communication interface. If marketing takes place via the standard reserve markets, further requirements for communication speed, latencies and transmission paths must be taken into account[1].

In practice, existing industrial or energy communication protocols such as Modbus TCP, IEC 60870-5-104 or OPC XML DA are used, some of which have been in use for a relatively long time and have not been further developed. Some equipment manufacturers also use proprietary solutions based on web services or other technology stacks. Protocols that have been described as smart grid protocols for years, such as IEC 61850 or Industry 4.0 protocols such as OPC UA, are currently rarely found in practical implementation, if at all. Here, there is a large divergence between the research landscape and current publications on communication protocols and their practical use.

[1] Minimum requirements for the information technology of the reserve provider for the provision of control reserve capacity; as at March 01, 2022

Plant communication in grid operation

In addition to plant marketing, operators of decentralized generation plants are also obliged to maintain communication channels to the connection grid operator, depending on the plant capacity.

After the plant has been registered with its corresponding master data (such as plant output, plant type and location), transaction data is transmitted to the connection grid operator at regular intervals via this interface for grid monitoring. This can take the form of performance data, for example. Similarly, grid operators can use these data channels to exert a controlling influence on plants. One example of this is the curtailment of power generation plants as part of feed-in management.

In the past, ripple control technology was often used for this purpose (especially for controlling night storage heaters), but it does not allow granular control of individual plants. However, this variant of unidirectional plant communication is increasingly being replaced [101]. The technical design of this plant communication in the process network of the connection grid operator is described in detail in the respective technical connection conditions (TAB) and is often based on industrial communication protocols such as IEC 60870-5-104 or IEC 61850. In principle, the use of the smart meter gateway infrastructure is also conceivable for these use cases, as they are also envisaged in the step-by-step model for the further development of the smart metering system [98].

The Redispatch 2.0 industry solution has been implemented since 2022 for power generation plants with an installed capacity of 100 kilowatts or more and storage facilities. In this context, an additional infrastructure was established for the exchange of master and transaction data between plant operators and different grid operators at all grid levels. The data exchange takes place via the existing central data platform Connect+, to which all affected plant operators and grid operators are directly or indirectly connected [102]. With the help of the exchanged planning and forecast data, grid operation is optimized with the inclusion of the participating plants. The connection to the data platform is made via SFTP or web service [103].

4.4 Grid operation and planning

The digital transformation of grids, plants and devices

Since the start of the energy transition, the digital transformation of power grids in Germany has gained a considerable amount of momentum at the different grid levels and has been implemented in the extra-high voltage and high-voltage grids in particular. There have been particular results at these levels thanks to the integration of decentralized, renewable power plants, and in achieving this there has been a significant need to exchange information between grid operators to ensure stable grid operation. The systemic relevance of the lower voltage levels was much lower, and the costs for a secured and stable digital transformation of these operating resources were not justified. This is changing with increasing decentralized generation in the distribution grid levels and the additional electrical loads from the transportation and heating sectors. Generation and load data provision methodology (GLDPM) and Redispatch 2.0 are excellent examples of new processes that cannot be implemented without a seamless digital transformation. In the Redispatch 2.0 process, for example, it is necessary to determine generation and load flexibility on the basis of digital grid models and to communicate them to the extra-high voltage grid for a forecast period of at least 36 hours, along with the corresponding effectiveness on grid interconnection points. This process currently includes generation plants with an installed capacity of at least 100 kilowatts (as well as smaller plants with actuation capabilities). These plants are predominantly part of medium-voltage grids. In a future Redispatch 3.0 process, micro-flexibility from low-voltage grids and smaller generation plants will also be included in the process [104].

> "The digital transformation is already at an advanced stage in transmission grids and must now be extended to distribution grids."

The need and urgency for grid expansion can be reduced if grids are operated closer to their design limits. Monitoring and smaller-scale control options are then necessary to actively avoid particularly high grid loads, meaning that energy flows need to be controlled. At present, distribution grids are generally not yet at their load limits, and comprehensive status monitoring is not yet mandatory; therefore, for economic reasons, this has only been implemented in very select grids so far. In addition, the current incentive regulation puts grid reinforcement in a better position than operational optimization.

In the field of grid control technology, many communication protocol standards are in use. Many components of the power grid have been in operation for many decades and, in principle, continue to perform their tasks reliably; however, the communication technology is just as old as these components. The system technology has grown over the years and has been adapted to new requirements only when necessary. When it comes to the transformation to end-to-end, interoperable grid control technology, this must therefore function equally well with new and old technologies, even if there are huge deficits in functionality and cybersecurity in some cases. In the case of switchable loads in low voltage, simple unidirectional communication technology such as ripple control technology is still used frequently, as are fixed timers to control or predefine system behavior (e.g., within the framework of section 14a EnWG) [105].

Projections and forecasts of electricity feed-in from wind turbines and photovoltaic systems are important for the cost-efficient integration of volatile generation into the power grid and for ensuring grid stability. Transmission and distribution system operators need these for operational grid management. They are also necessary for the cost-efficient intraday marketing of EEG-subsidized feed-in, which is currently possible up to five minutes before delivery. The projections provide the basis for determining the current grid load, which in turn is a key parameter in monitoring grid stability. As measured values of the actual power fed into the grid are only available for a small proportion of all plants in near-real time, projection methods are needed to determine the current feed-in. Today, projections are made primarily based on available real-time measurements of feed-in from wind power and photovoltaic reference systems.

A growing challenge is the steady increase in photovoltaic own consumption, combined with battery storage, electric vehicles and flexible loads used initially to maximize local own consumption. This will lead to fundamental changes in photovoltaic feed-in profiles. While photovoltaic feed-in was previously largely determined by the weather, the interaction of generation with different types of consumption and control strategies at the individual system level is now becoming increasingly important.

4.5 Cybersecurity in the energy system

The advancing digital transformation of the energy system has made protecting energy supply infrastructures from cyberattacks increasingly important in recent years. Due to the central role of energy supply as critical infrastructure, a growing threat situation from cyberattacks results in huge challenges with regard to ensuring permanent security of supply.

These challenges are amplified by the nature of the energy system as a complex, integrated and geographically distributed infrastructure whose operational management spans multiple physical and IT levels. These IT levels, which are mostly divided into "company IT" and "process-related OT" (operational IT — operational technologies, systems for controlling industrial plants), are characterized — with respect to the state of the art — by a great divergence in terms of the description of cyber threats, the monitoring and surveillance of security-related information, and the safeguarding of the respective components and communication pathways. This makes it much more difficult to implement end-to-end risk assessments and consistent IT security measures.

In addition to the changed threat situation due to cyberattacks, the continuously evolving legal framework in the area of cybersecurity also poses challenges for energy supply companies.

The changed threat situation due to cyberattacks

The digital transformation of the energy supply, strongly driven by decentralization and liberalization and the associated new market partners and market processes, has led to a huge increase in the number and complexity of the information and communication systems needed to ensure the functioning of the energy supply. The scope for attack from cyber threats, which is constantly increasing due to this digital transformation, is again greatly increased by new decentralized technologies and trends, such as the Industrial Internet of Things (IIoT) or smart city and smart home. In the same context, the dependence of the energy supply on an information and communication infrastructure that functions at all times is growing. At the same time, cyberattacks on all sectors of the economy, administration and public infrastructures are increasing worldwide, in some cases dramatically in recent years [106].

The motivations for cyberattacks vary, as do their complexity and possibility of imitation, e.g., through known vulnerabilities and corresponding available tools or availability as services, such as "ransomware as a service" (RaaS). In quantitative terms, cybercrime plays the largest role as a driving force, and among the attack methods used for this purpose, ransomware attacks in particular — so-called extortion Trojans — have increased drastically in recent years [106]. Direct attacks on the process infrastructure do not usually take place as a result of these attacks, or at least are not the direct target of the attack. However, the impact of encrypting IT infrastructure, such as file or email servers, for the execution of market processes is huge and can also indirectly sabotage the supply process. Due to the dependencies of companies, supply chain attacks also occur, in which dependent companies can become the direct or indirect target of such an attack. For companies in the energy supply sector, this type of attack can also pose the risk of company or customer data being published. In addition to the economic damage, it is primarily the loss of trust that can lead to a permanent market disadvantage.

In the area of OT, the situation is somewhat more differentiated. Here, it is primarily complex, multi-stage attacks that target the OT infrastructure and thus directly influence the supply process. In contrast to company IT, these attacks are mostly zero-day attacks, i.e., attacks that exploit unknown vulnerabilities in the product. Advanced persistent threats (APT) pose a particular threat to companies, as attackers are able to remain unnoticed in the victim's IT infrastructure for a very long period of time and collect information. The attack on Ukraine's power supply in 2015 [107] represents this kind of complex approach and is an example of the effort required in the preparation and execution of such complex cyberattacks. It can therefore be concluded that such attacks must mainly be financed by state actors and are therefore motivated by politics or terrorism. In this context, the development of the malware used continues to move in the direction of the special circumstances of OT infrastructure and also of remote-control technology. Cyber frameworks such as Pipedream [108] now represent a new level of threat to OT infrastructures.

Another cyber threat to the energy supply arises from the increasing use of public communication infrastructures. Although data transmission is usually secured via VPN and encrypted, if the communication channels or infrastructure are sabotaged, the data transmission will still be disrupted. A recent example of this is the attack on the communication infrastructure of the KA-SAT satellite internet network. As an impact that was not the direct target of the attack, the modems of at least 3,000 wind turbines were infected by malware, disrupting remote access to the turbines' control system.

Legal framework for cybersecurity

The increase in the cyber threat is countered by government measures to prevent cyberattacks. However, the legal framework resulting from various legal principles also poses a challenge for many companies, both with regard to the creation of the technical prerequisites, as well as regarding the availability and financing of qualified personnel. The legal requirements for companies from the energy sector comprise the combination of various laws and regulations at different EU and national levels.

The development of the legal framework was actively supported by the white paper from the German Association of Energy and Water Industries (BDEW), with version 1.0 published in 2011 and the current version dating from 2018 [109].

In 2015, the German Federal Act to Increase the Security of Information Technology Systems (IT Security Act) [110] came into force as part of the German federal government's Digital Agenda. In addition to the goal already clearly set out in the name, it essentially concerns the prevention of failures with dramatic consequences for the economy, the state and society.

The Act on the Federal Office for Information Security (BSI Act) [111] assigns the BSI the role of the central reporting office for the IT security of critical infrastructures, as well as regulating the obligation to provide proof for operators of critical infrastructures with regard to IT security compliance. The BSI Kritis Regulation [112] then defines the critical infrastructure (KRITIS) sectors and KRITIS thresholds for plants.

At the European level, the Directive on security of network and information systems (NIS Directive) came into force in 2016 [8]. This directive was updated in 2019 with the EU Cybersecurity Act [9].

The IT security catalogs according to EnWG define the IT requirements for grid operators (electricity and gas) and operators of energy plants, and include the mandatory introduction of an information security management system (ISMS) according to ISO/IEC 27001.

The most recent iteration of the legal framework, the IT Security Act 2.0 (IT-SiG 2.0) [113], came into force in May 2021. Among other things, this extends the instruments of the BSI, obligates companies to use systems and processes for attack detection from 2023, and regulates trustworthiness along the supply chain for IT products. At the European level, the EU Cybersecurity Act has been in force since 2021.

> "Increasing digital transformation and advanced cyberattacks make the energy system vulnerable, while security measures are often still inadequate."

5 The digital transformation of the energy system — 14 theses for success

Based on the previously described state of the digital transformation of the energy transition and a literature-based gap analysis regarding the potential of digital transformation approaches, Fraunhofer experts have drawn up a series of theses that result in concrete recommendations for action for the efficient and sustainable use of digital tools in the decarbonization of the energy system.

External experts from industry and research were consulted in the course of expert workshops and interviews. During this process, the collected theses were discussed, sharpened and validated. The final results of this process are the following 14 theses, which Fraunhofer Energy Research considers essential for the implementation of the energy transition. As already mentioned at the outset, the theses do not claim to cover every eventuality — together with the recommendations for action derived from them, they were selected by the experts on the basis of their relevance and the option of feasibility in the next five years.

The theses build on the analyses of the previous chapters and formulate success-critical recommendations, structured according to the thematic focus areas of data economics, sector coupling, plant communication, grid operation and planning, and cybersecurity. Finally, a light is shone on the European dimension in the digital transformation of the energy system — since the digital energy transition in Germany is embedded in a European strategy and a European system of regulations and should not be planned and implemented exclusively at national level.

5.1 Focus on data economy

Modern AI processes for identifying and leveraging efficiency potentials, as well as for managing complex interactions between a multitude of stakeholders, require new ways of sharing information between these stakeholders. In the future, a significant acceleration of the energy supply transformation will be necessary, which would be difficult to achieve with existing processes. One approach to meeting this challenge is to create an openly accessible and trustworthy data economy that enables independent energy supply with the aid of resilient ICT infrastructures, despite new global political conditions.

Thesis 1:
In the future, the value of energy will depend on linked data

Brief explanation

Both with the increase in hours thanks to high shares of renewable energy from wind turbines and photovoltaic systems, as well as the general, presumably longer lasting, increase in the price level on the electricity market, the importance of price spreads is increasing significantly. The background to this is, in particular, generation from wind and solar energy, which has near-zero marginal costs and influences market events due to natural fluctuation. As a result, the value of the energy essentially depends on a large number of time-dependent factors and on the data behind them. Consequently, there is a greater focus on when energy is used than on the exclusive consumption of primarily zero-marginal-cost renewable electricity or energy flows based on it [114, 115].

In addition to the above factors, uncertainties are of particular relevance to the value of energy. The higher the level of uncertainty (especially in the electricity market), the higher the balancing costs of the power imbalance. A historical example of such a situation is the solar eclipse on March 20, 2015. Due to the increased uncertainty regarding the effects on photovoltaic generation, increased — and consequently very costly — control reserve capacity was provided. As more useful data becomes available — from meteorology or photovoltaic generation data, for example — it will be possible to take a more effective course of action, as the latest forecasting method developments show. In addition, larger, high-quality datasets supported forecasting in general; for example, to improve the marketing of fluctuating renewable energies [116–119].

In addition to the electricity sector, the guiding principle of the thesis applies equally to other sectors, such as evidencing the type of hydrogen used (green, gray, blue, etc). A concrete example of this in production is low-CO_2 steel [120]. In order to maintain the value of the end product, it must be proven beyond any doubt that the hydrogen used has been produced entirely on the basis of renewable electricity [121].

Significance for key stakeholders in the energy sector

Operators of decentralized energy systems

For the operators of decentralized energy systems, the importance of sensor and data quality, as well as data availability, is increasing. At the same time, this has to be implemented as cost-efficiently as possible. If these conditions are not in place, there are potential economic disadvantages or reduced revenue over the entire life cycle of a plant. In this respect, the operational phase is of the utmost relevance [122–125].

Energy traders and grid operators

As already shown in the forecast example, a comprehensive data basis is becoming more important both in electricity trading and in the planning of associated market system services, such as control reserve capacity. In addition, the interconnection with the electricity sector — with e-mobility or the hydrogen sector, for example — creates new challenges in the management of these interdependencies, which can only succeed with new and expanded simpler data exchanges and the analysis of the information they contain. You can find further details about this below in theses 4 and 6 under "Focus on sector coupling" [21, 126].

End consumers and grid operators

A large number of new stakeholders, especially prosumers and flexsumers, are becoming more integrated into the energy system with their data; for example, when they gain new relevance for distribution grid operation with (flexible) decentralized energy systems in the context of Redispatch 3.0[2]. The value of the associated data is increasing, while at the same time, it may only be possible to process this with a (very) high level of data protection. Above all, this processing will require data ownership solutions such as data space approaches as well as the application of secure options for removing references to people, e.g., machine learning (ML) methods based on large datasets [127–129].

Key messages to political actors

In principle, the regulatory side must establish various incentives so that there is ultimately a very active exchange of data between the various stakeholders. The following issues in particular need to be addressed at this point [130–133]:

1) Unresolved questions of data ownership regarding decentralized energy system data must be clarified so that there is a legally secure basis for data trading.
2) Building on this, there should be legal security so that, in principle, operators of decentralized energy systems in particular can access certain datasets for their systems. Here, the relevant applications in the area of plant flexibilization are to be enabled in particular.
3) For these datasets, as well as in general, the FAIR principle (findability, accessibility, interoperability and reusability) should be prescribed as far as possible for every data exchange so that the costs of a data transfer are as low as possible at scale. This relates in particular to public data and open data.
4) As a data space also becomes more attractive if a lot of useful data is available and this data also costs as little as possible, the principle of "public money — public data" should provide a free foundation of data that can be used for a variety of commercial as well as scientific purposes.

[2] Redispatch 3.0 involves the integration of decentralized energy systems into the low-voltage grid that have not yet been covered by Redispatch 2.0 (usually generation plants with an installed capacity of 100 kW or more).

Key recommendations for action

The current process landscape is characterized by many bilateral and individual central platforms such as Connect+ in the Redispatch 2.0 context. In this area, proprietary and (partially) standardized solutions are in use that do not meet the requirements of an energy data space within the meaning of the European directional decision to establish a European Energy Data Space (EDS).

Nevertheless, an EDS is not a final solution in itself, but must be integrated into the existing ICT landscape and used especially where a large number of stakeholders meet, and data ownership is a core requirement. Here, new options for creating a data economy are emerging in the area of energy supply with its sectors, which are being newly or increasingly linked (mobility, housing industry, ICT, etc.).

For the development of an EDS, governance, standardization and related certification activities are to be promoted initially, as demonstrated by the advanced data space initiatives Catena-X, for the organization of the automotive value chain, as well as the Mobility Data Space (formerly Datenraum Mobilität) for the exchange of mobility-related data (weather, infrastructure data, etc.) [78, 134, 135].

Thesis 2:
Digitally driven value creation networks are the future of the energy system

Brief explanation

Digital transformation not only (partially) automates existing processes, but also offers the opportunity to redesign the existing process landscape to adapt to the "new energy world" [136]. Concrete examples of this advancing development are detailed below:

- An increase in the level of automation in all areas of grid operational management is to be expected. Specifically, the German Association for Electrical, Electronic & Information Technologies (VDE) generally envisages systems that react fully autonomously in a limited application scenario without the need for any human interaction, which is referred to as "autonomy level 3 — condition automation" [137]. An example is the conditional automated control of island networks in the distribution grid in the event of a blackout. This allows individual grid areas to be operated independently of the higher-level grid and is generally known as "micro grid" functionality [137].
- Digitally driven aggregators are challenging the traditional commodity business model of previous energy suppliers. The core element of this development are the options of decentralized energy systems, which are interconnected by aggregators. Original equipment manufacturers of decentralized energy systems in particular now supply suitable ICT-based energy services in addition to pure hardware [138–140].
- Due to the increasing shortage of skilled workers, new start-ups are relying in particular on increasing digital transformation in the skilled trades in order to bring about the necessary acceleration in the number of new installations, especially involving photovoltaic and heat pump technology [141, 142].

- Customer-centric business models that consistently rely on IT tools can achieve significant market share in electricity sales in short periods of time, as demonstrated by company examples from the UK which have achieved a market share gain of 1 percent per year. From an ICT perspective, self-developed, cloud-based platforms play a central role here, for example [143].

Significance for key stakeholders in the energy sector

As the above case studies make clear, it is now impossible to imagine the energy system without the influence of digital transformation. Consequently, all companies in the energy sector that do not invest consistently and purposefully in digital transformation are very unlikely to be competitive in the future. It should be noted that the conventional digital transformation of individual processes or stages of the value chain is no longer sufficient. The task now is to form digitally supported value creation networks that go beyond individual stakeholders to link resources and capabilities in a profitable manner.

Key messages to political actors

Authorities that act as central bodies for the practical implementation of the energy transition must also consistently digitalize their administrative processes, as only then will they be in a position to accompany the speed of process redesign in energy-relevant companies in a target-oriented manner. A suitable target could be the complete, automated building permit of a public charging facility, for example.

Key recommendations for action

Every stakeholder relevant to energy supply should consider digital transformation as an iterative "core business" because it will make a significant contribution to bringing about an efficient and effective implementation of the energy transition. The guiding principles of a real-time energy system must be the defining orientation.

As a legislator, it is essential to demand digital transformation with a focus on regulated processes. One practical example, which has recently been taken into account in section 14e EnWG, is the increasing use of web portals for processing grid connection requests (e.g., for renewables-based plants up to 30 kilowatts). Here, approval was able to be reduced from around eight weeks of processing time to as little as one minute, according to users' experiences.

When introducing such instruments, it should generally be noted that regulation should be open to new technologies, so that the energy industry is as free as possible to develop its own solutions that are as cost-effective as possible. Alternatively, it is possible, as with section 14e EnWG, to transfer successful approaches of individual stakeholders to the entire industry. After implementation, the corresponding solutions must still be regularly scrutinized and, if necessary, renewed [144, 145].

Thesis 3:
An independent and resilient European energy system requires a base EU ICT system

Brief explanation

Assuming that the digital transformation in the energy sector will continue, it can be assumed that the dependence of a secure energy supply on the functionality of a base ICT system will increase. In this case, this specifically includes the following components: platforms, infrastructure components, data models, security architectures and interface solutions (e.g., ICT components of the International Data Spaces Association in the data space environment).

To the extent that these components must meet European requirements (e.g., in the sense of the GDPR), and are also created with driving European participation at least, they each form an important building block that leads step by step to European energy sovereignty and resilience. The following key factors should play an exemplary role in this process:

- Application of the "public money — public code" principle to support public infrastructures and sustainable ICT infrastructures [146].
- Open source helps to minimize dependency on individual stakeholders ("bottlenecks"), especially in the area of critical infrastructure.

European expertise is to be seen as a basic prerequisite for this development and requires action from both an economic and political perspective. At the heart of these activities is a reduction in supply dependencies on non-European countries, especially in critical infrastructures such as the energy sector. In the best-case scenario, these dependencies should be completely eliminated, especially in the case of critical processes, or, as an alternative, strongly diversified.

Significance for key stakeholders in the energy sector

At present, the active (further) development of open-source ICT components is not part of the core business of the energy sector. Here, a transformation toward more IT expertise is underway, as only then can it be ensured that continuous further development is available as an option should non-European stakeholders withdraw their support at short notice.

This dependence on non-European stakeholders should be taken into account when weighing investment decisions for new ICT components. This explicitly does not rule out non-European cooperation, but both sides must take on a substantial role in the joint activities.

Key messages to political actors

Sovereignty and resilience are two approaches that are very much intertwined and therefore support each other; however, this also means that they are interdependent. The COVID-19 pandemic and Russia's war of aggression on Ukraine have significantly changed the social context. In particular, the increase in uncertainty regarding the reliability of supply chains, which among other things specifically affects digital transformation in the form of semiconductor shortages, is currently causing production delays. To ensure that these new conditions remain manageable, a new guiding principle must also be formed in the area of digital transformation, resulting in the emergence of a base EU ICT structure [147, 148].

Key recommendations for action

It is necessary to identify the non-European dependencies within the critical infrastructure to preserve sovereignty while also increasing resilience. This primarily concerns critical processes. With the aid of action plans for emergency situations to be developed by the relevant stakeholders, it is possible to continue to guarantee the continuous provision of software and hardware for the base ICT structure. As a result, ICT systems or associated supply chains in the energy sector are more likely to remain functional or intact.

At the same time, measures already initiated to reduce primarily singular dependencies must be sustained and expanded. A topical example is the European Chips Act, which is currently under discussion as an instrument to help alleviate the ongoing semiconductor shortage. With a view to expansion, the legal requirement should be that all critical process flows of energy supply take place exclusively in EU member states, so that an enforcement of European principles can be ensured.

Furthermore, the functionality of ICT within the energy sector should be ensured at all times in crisis situations. This includes both the continuation of identification and promotion of solutions involving no or little ICT as a final fallback approach for (partially) securing the energy supply in extreme scenarios [149, 150].

In addition, there should be greater investment on the regulatory side for a base EU ICT structure. This should include the following measures:

- Orienting the upcoming digital funding policy, e.g., within the framework of research programs or investment programs, toward a stronger open-source orientation in the context of the base ICT infrastructure
- Direct support of the energy sector through accompanying open-source programs
- Strengthening European value creation in the ICT sector, in particular through the in-house use of EU-based ICT within in-house administration processes

5.2 Focus on sector coupling

Through the smart interconnection of the electricity, heating, gas, industrial and transportation sectors, flexibility potentials arising through synergies can be harnessed. These make it possible to better coordinate the availability and demand of energy in terms of both time and space and to effectively compensate for fluctuations in renewable energies [151]. Electrification is a key aspect of this, enabling the electricity sector to supply as great a proportion of the other sectors as possible with renewably generated energy [86]. Digitalized and automated sector coupling therefore represents a key technology for the efficient success of the energy transition [152].

Thesis 4:
Without digitalized sector coupling, the costs of transforming energy systems will rise significantly

Brief explanation

Digitalized sector coupling opens up opportunities to create financial incentives for flexible, grid-serving behavior (variable electricity tariffs, avoidance of infrastructure and grid usage costs), demand-side management, vehicle-to-grid and power-to-X technologies. Only by expanding digital transformation will it be possible to economically and quickly implement sector coupling. This necessary digital transformation expansion can involve consistent ICT integration between sectors (including standardized data spaces, smart metering systems, fully digitalized and automated processes, high data availability, digital tools, and energy management and control systems). This also helps to manage the increasing complexity of the energy system. Without digital transformation, these tasks cannot be accomplished; inadequate digital transformation also leads to significant inefficiencies and additional costs [153].

Significance for key stakeholders in the energy sector

In order to network the electricity, heating, industrial and transportation sectors sustainably and efficiently, key stakeholders must use technologies that enable the different sectors to be integrated with energy systems and view energy in an integrated manner.

The use of digital technologies helps to reduce the costs of the energy transition, to make better use of scarce resources across sectors, and to exchange information more quickly. Barriers such as lack of interoperability, lack of opportunities for coordinated operation of technologies from different sectors, insufficient deployment and marketing opportunities of sector coupling technologies, lack of acceptance [86], as well as control of plants based on them, are therefore moving into focus for stakeholders such as generators, providers, grid operators, suppliers and users of technologies for sector coupling and planning services.

In this context, a digitally supported use of synergies between sectors, with the provision options of renewable energies and cross-sectoral energy requirements, is to be aimed for. The goal is direct energy use as it is generated, resulting in less need for intermediate storage and associated losses. With efficient and spatially coordinated digitalized sector coupling, there are a number of opportunities for new, future-proof business models, for increasing the transmission capacities of the electrical supply network and for improving the resilience of the overall energy system [86].

Key messages to political actors

Primary energy demand and energy-related CO_2 emissions must be reduced and independence from fossil fuels increased. In this regard, the basic prerequisite is that digital transformation in the area of energy infrastructures is accelerated. This would be possible, for example, by creating incentives and business models for extensive roll-out of ICT structures and technologies for sector coupling, or by promoting technological development. It is also recommended that the smart meter infrastructure, as the basic digital infrastructure for all sectors, should be developed further without delay and that alternatives are considered (see thesis 7). The creation of an innovative framework for sustainable digital transformation and the advancement of open data are also necessary. Not least, emphasis should be on the design of a competitive use of data and a personnel and modernization offensive of public administration at all levels, as well as the firm anchoring of digital expertise in education, research and management. Only once these prerequisites are met can energy-efficient and economically effective sector coupling succeed, accompanied by the integration of high proportions of renewable energies into the energy system.

Key recommendations for action

Digital sector coupling and comprehensive consideration of the energy system are what we should be aiming for. In doing so, consistent ICT integration between sectors, fully digitalized processes with a high degree of automation, and an increase in data quality and quantity in the energy system must be demanded and promoted.

Controllability should be a prerequisite for all relevant applications and systems, while projects that take into account and interconnect all energy-relevant sectors should receive significant funding. In addition, the creation and expansion of educational opportunities to promote systemic understanding of planning and implementation for digitalized cross-sector approaches is essential.

Thesis 5:
Viable energy business models for digitalized energy systems integration at the district level are currently failing due to regulatory hurdles

Brief explanation

At the district level (understood here as the smallest scale level of the energy system, containing several spatially connected buildings including public infrastructure), the sectors (electricity, heating, mobility, and currently gas) all come together. For efficient operation of the energy system, it is important to make use of sector coupling to tap into the necessary decentralized flexibility of the small-scale supply structure with geographic diversity.

By balancing energy flows locally and increasing the quota for own supply, synergies can be used and economic advantages can be achieved by increasing efficiency and avoiding infrastructure and grid usage costs of higher infrastructure levels. In order to establish solutions for local energy management, a high degree of automation and digital transformation is a prerequisite to minimize costs and effort for operators and therefore achieve competitiveness. However, viable digital business models for the energy sector at the district level are currently severely hampered by regulatory hurdles or fail completely as a result of them (e.g., grid charges do not reflect actual grid usage, taxes, levies or apportionments are inconsistent across different energy sources, switching between marketing models for renewable energy plants is not possible, double levy burden for decentralized storage, confusing multitude of different laws and funding mechanisms). The regulatory prerequisites for business models at the district level are currently not in place, meaning that digital solutions as the basis of business models are unable to exploit their advantages in terms of the degree of automation and smart methods, therefore inhibiting the development of flexibility potential at the district level [154–157].

Significance for key stakeholders in the energy sector

District solutions increase the integration capacity of renewable energies for the entire energy system [156, 157] and enable grid-compatible district behavior. However, innovations are hampered by the current regulatory framework and organizational efforts for market participants. For example, a combined heat and power district approach, in which electricity and heat are exchanged between buildings within the district, has not yet been possible due to the existing regulatory framework.

From the perspective of the stakeholders, the relevant laws of the legal framework (in Germany: EnWG, StromStG, GEG, GEIG, EWG and KWKG) are characterized by major differences on a district level and different legal consequences depending on the law. At present, no law aims to exploit local potentials at this district level, although potential for a climate-neutral energy supply is lacking here.

Laws relevant to the district are subject to different regulatory objectives, so districts must accommodate all stakeholders [158]. Stakeholders such as district operators, public utility companies, municipalities, grid operators, providers and users of technologies for sector coupling and energy and planning services currently only have the option of finding viable digitalized district concepts with integrated energy systems within the existing legal framework and closely monitoring amendments to the regulatory framework.

Key messages to political actors

Districts can play an important role in the success of the energy transition, as they open up new efficiency potential and options for action at local and regional level. Economically viable district concepts are necessary for the transformation process of the energy system and demonstrably increase its social acceptance [158].

In implementation, however, district solutions have so far only been a marginal phenomenon with narrow limits in terms of approval procedures and additional requirements. Energy business models at the district level are not yet viable as currently there are no economically viable options for the local exchange and balancing of energy (e.g., infrastructure and grid usage costs when using the public power grid are currently not limited to the corresponding grid level). Therefore, there is currently no motivation for grid-compatible and grid-serving behavior at the district level. The current regulatory and organizational framework and its lack of clarity represent an off-putting hurdle for market participants.

Key recommendations for action

The energy sector is more heavily regulated than almost any other industry. The breakthrough of digital innovations is hampered by these narrow limits imposed by regulation — including at the district level. Regulatory and organizational requirements must be standardized and reduced.

Conditions must be created to motivate grid-compatible behavior with district solutions (e.g., limit infrastructure and grid usage costs to the appropriate grid level when using the public power grid). Furthermore, an innovation-friendly regulatory framework for viable energy sector business models must be implemented at the district level. In order to achieve the increase in user acceptance necessary for the success of the “local energy transition”, innovations for user-friendly and consumer-friendly business and tariff models must be promoted; for example, those that strengthen the priority use of locally generated renewable energies.

Thesis 6:
Efficient decarbonization of the heating sector can only be achieved with digital transformation

Brief explanation

To efficiently decarbonize the heating sector, it is necessary to control plants in a networked and smart manner, thereby unlocking synergies and flexibility through electrification of heat supply, heat storage and power grid compatibility in combination with smart management. This is the only way that the integration of renewable energies and CHPs can be successful on a large scale and also requires the integration of key technologies (low-temperature heating networks, efficient heat pumps, solar collectors, decentralized feed-in and waste heat utilization). To date, however, there has been virtually no digital transformation in the heating sector in the operation of heating networks, generators and storage facilities or in the area of infrastructure planning [159–163].

Significance for key stakeholders in the energy sector

The heating sector accounts for just under half of Germany’s energy consumption. A key starting point for decarbonization is increased integration of renewable energies and CO_2-free heat into the heating sector. Heat suppliers, generators and network operators are faced with the task of integrating decentralized, partly fluctuating supply. The transformation toward 4th generation heating networks [164] poses challenges for stakeholders in terms of increasing energy efficiency, increased integration of sustainable heat sources (e.g., renewable energies or waste heat from industry), moving away from centralized generation concepts, third-party or prosumer access, or integration into other energy-related sectors.

Diversification, decentralization, flexibilization and decarbonization of heat supply will require far-reaching restructuring measures [163]. In order to handle large volumes of data and smart controls, stakeholders will have to deal with the increased deployment and use of smart metering systems and the digital mapping of the grid infrastructure based on them, as well as digital technologies for the heating market [160].

The heating sector has an immense need for digital transformation along the entire value chain. The basic prerequisite for using digital technologies is well-managed data collection that is as automated as possible. In addition, the targeted use of modern digital transformation tools means that operational optimizations and interactions between systems as well as adapted business models can be planned and controlled [163].

Key messages to political actors

Digital transformation and networking in the heating sector is forward-looking and should be pursued as quickly as possible, although major efforts are still needed in terms of education, dissemination and implementation, which must be addressed as soon as possible. Stakeholders must first build up their expertise in digital transformation, which is currently still lacking.

These stakeholders are motivated to implement digital transformation measures quickly; however, bringing about digital transformation projects without funding for innovation and investment is problematic. For example, there is a need to promote research and development in the areas of sensor technology, actuator technology, control and regulation, and to continue and expand the relevant funding instruments, such as the German federal funding for efficient heat networks scheme (BEW). In addition, the implementation of digital transformation projects should be promoted and tested — in real laboratories, for example.

Key recommendations for action

Digital transformation measures can significantly improve knowledge about the status of the grid, allowing optimization potential to be leveraged. In particular, potential can be tapped into through the use of digital technologies in conjunction with the increased use of smart metering points [161]. However, there is a need for action when it comes to increasing rates of digital transformation.

Promoting innovation and investment in sustainable supply concepts at the municipal level can help here. The same applies to improved planning certainty for improving the metering and ICT infrastructure, and for expanding the district and local heating infrastructure. Further recommendations for action are to increase the promotion of research and development as well as investments and research activities in the digital transformation of the heating sector (such as linking promotional bank KfW's energy efficiency programs with smart home energy management systems or linking incentives for building refurbishment with digital transformation approaches).

5.3 Focus on plant communication

Plant communication, which connects future stakeholders in the energy system, will be subject to even higher reliability and resilience requirements in the future. An energy system based on the orchestration of renewable generators and controllable loads requires a reliable control system that has low failure rates and resilient fallback levels in case of failures.

Thesis 7:
The smart metering system will be overtaken by other solutions in plant communication

Brief explanation

The effectiveness of the smart meter roll-out will depend largely on the added value it creates. Apart from planning, the added value for power grid operators lies in the increased ability to observe and control the grids across all voltage levels. However, despite technical feasibility, current generation lacks straightforward options for using the collected data in live operation. Symptomatic of the failure to achieve the roll-out target is the fact that parallel channels (e.g., manufacturer-side backend systems or home energy management systems outside the SMGW) are increasingly being used to collect transaction data from plant operation.

In this context, the costs of rolling out smart metering systems are not aligned with the potential impact, which in the current generation is mainly seen in savings in personnel deployment in metering point operation. The smart metering system is primarily being considered in the electricity sector, while the other sectors (gas, heating, water) have so far been treated as secondary to electricity.

Significance for key stakeholders in the energy sector

Grid operators cannot rely solely on the smart meter roll-out as an efficient data source, but should also consider parallel data channels, e.g., cloud backend systems from equipment manufacturers. If necessary, individual support points from datasets of smart metering systems should also be sufficient for grid operators. As part of this, however, it is also necessary to simplify access to this metering data.

Together with policymakers and regulators, practicable concepts should be developed that enable efficient data communication while still maintaining protection goals such as data confidentiality. It should be practical and economical for grid operators to use plant master and transaction data for the purposes of grid planning and operation. For data protection reasons, it is important to identify a temporal and spatial granularity that is in line with requirements.

Key messages to political actors

The role of the smart metering system and, in particular, the smart meter gateway, which was developed and launched on the market with high security requirements, should be further developed against the backdrop of roll-out challenges and the market penetration of parallel communication channels that may take place in the meantime. The smart meter gateway can continue to play the role of trust anchor in a system architecture in which transaction data from plants is also routed through other channels.

Key recommendations for action

Based on the initial situation described above, the following key recommendations were identified:

- The implementation of technical solutions for cross-operator communication (e.g., between control systems and manufacturer backend systems) should be promoted
- The fundamentally important requirements for security and data protection that apply to smart meter gateway infrastructure should also apply to the parallel infrastructures described — if necessary in an adapted form
- The smart meter gateway should be seen as working alongside parallel infrastructures emerging in the marketplace

Thesis 8:
The energy transition requires plant communication based on the latest IT technologies and open documentation

Brief explanation

Standardization in the area of plant communication is not keeping pace with current or future communication needs. While non-interoperable, proprietary implementations on the part of individual stakeholders must be avoided, current efforts toward standardization are far too slow, with a few exceptions. Currently, plant communication is based on the implementation of proprietary data models based on outdated communication protocols (IEC 60870-5-104, Modbus TCP). The results of recent standardization efforts (IEC 61850, IEC 61400-2) have not seen much use in practice [165]. For this reason, a large proportion of the time and therefore also the budget of digital transformation projects often goes into establishing communication with plants. As a result, many new technologies cannot be evaluated in their entirety for the energy sector.

To implement the energy transition as quickly as required, it is necessary for standardization to support the innovation speed of technological advances. In other sectors, the industry-wide enforcement of expandable de facto standards has become increasingly established as the way to proceed (e.g., web technologies).

Significance for key stakeholders in the energy sector

The stakeholders involved, in particular manufacturers and infrastructure and platform operators, must also be prepared for increased innovation speed in the area of plant communication, as future requirements will only become more concrete in the next few years. To enable interoperability between components, operators should emphasize that components use expandable, well-defined standards and that the data models and semantics used are openly documented. With regard to communication protocols, a switch should be made to flexibly deployable web technologies in order to be able to respond to emerging requirements.

Key messages to political actors

Standardization processes that cannot keep up with the required pace of the digital transformation of the energy system are to be viewed as obstacles. Standardization that responds quickly to new requirements and is developed significantly by manufacturers and operators together can increase interoperability. However, it remains essential that interfaces for plant communication are based on modern communication technologies and that the data models used are disclosed.

Key recommendations for action

The development of interoperable data models and communication interfaces should be encouraged, and manufacturers should build on established technologies. The documentation of data models also enables third parties to create interoperability between components, even if data models do not follow uniform semantics.

Thesis 9:
Modern plant communication enables plug-and-play and cross-stakeholder process automation

Brief explanation

The continuously increasing number of heterogeneous plants in the energy system must be increasingly better coordinated to ensure safe, secure, reliable and ecological system operation. Reconciliation is increasingly algorithmic, with different goals in mind for plant owners. The integration of plants into the overall system and the variety of deployment and marketing options, between own consumption optimization and grid/system services (also known as multi-use plant deployment), requires simplified processes that can be automated.

One way to offer plant owners participation in different coordination processes and markets is to exploit machine identities to automate participation processes (e.g., qualification for system services, logins and logouts) and to reliably map transaction data to plant master data [166]. In the future, these processes will enable plug-and-play integration of components in the energy system and participation in different coordination processes during operation.

Significance for key stakeholders in the energy sector

The future marketing platforms for system services must be prepared for the fact that plants providing system services will switch between different platforms and products. Markets and marketing platforms should support these switches with interfaces that can be automated, enabling logins, logouts and qualification for the appropriate system services without user interaction from the plant owner. In particular, the identification and verification of the plants involved must be automated and double marketing must be ruled out.

A competitive advantage for manufacturers may be the ability to support different products in energy and system services markets. Therefore, when developing components, the possible applications from the prosumer’s point of view must be taken into account and appropriate technical options must be provided.

Key messages to political actors

Regulatory framework conditions must be created for technologically feasible and economically attractive deployment models in an energy system consisting of millions of decentralized energy conversion plants. The processes for market participation and for changing marketing variants must be automated and the associated bureaucracy removed.

The foundation created with the market master data register should be built upon. In addition to master data, transaction data will become more important in increasingly dynamic mapping between plants and marketing options.

Key recommendations for action

Future market and system concepts for a decentralized energy system must be tested. Particular attention should be paid to the interoperability, scalability and security of the overall networked system.

Research on data spaces and digital identities for plants can help develop today's prescribed regulatory processes and enable system dynamization.

5.4 Focus on grid operation and planning

Power grids are the backbone of the energy system. Transmission system operators (TSOs) and distribution system operators (DSOs) are responsible for grid operation. However, this responsibility encompasses much more than simply ensuring the operational capability of technical equipment. In Germany, there are four transmission system operators who have system responsibility for operational management, i.e., procuring and providing balancing mechanisms in the event of grid fluctuations, ensuring that maintenance and expansion measures are carried out in line with demand, and organizing restarts in the event of a blackout. Distribution system operators, of which there are currently 872 in Germany, operate high-voltage, medium-voltage and low-voltage grids. They are responsible for ensuring protection, safety and security, as well as for the far-sighted planning and implementation of grid expansion and connection requests and must cooperate closely with the TSO in many situations. With the introduction of Redispatch 2.0, the task of eliminating regional grid congestion will be shared between TSOs and DSOs. It is now mandatory to connect renewable energy plants and combined heat and power plants of 100 kilowatts or more in a way that can be remotely controlled for these purposes. Overall, the tasks of TSOs and DSOs are becoming significantly more complex and yet must be mapped in a structured manner in processes and interfaces — this represents an enormous challenge.

Thesis 10:
Digital transformation is a core area of expertise in future power grid operations

Brief explanation

The decentralized energy transition means that the remit of distribution system operators is changing. While plants today are mostly operated passively and generally contribute only to a limited extent to system stability and security, grid operation will become more demanding in the future, and complexity will increase significantly. Grid resources can and must be configured differently depending on the weather or the time of year, for example, in order to keep the voltage within the permitted limits in the event of changing feed-in power, while failures or bottlenecks of resources can, if necessary, be remedied by connecting or disconnecting grid lines [167–169].
At the same time, the relevance of the lower voltage levels for stable operation of the power supply system is increasing significantly; separation of a distribution grid mesh from the interconnected grid has a greater impact on the higher levels than before. Passive or even blind grid operation is no longer possible and for active operational management, plants, grid levels and grid areas must be included in grid operators' digital grid models, and processes for control and coordination must be introduced. With the necessary incentive regulation in the direction of active operation and high automation, core processes, value creation and dependence on grid operators' expertise in the digital transformation are changing fundamentally. Grid operators must be prepared to set up and implement their own processes or enter into cooperative ventures.

Significance for key stakeholders in the energy sector

The digital transformation of processes in operational management is a complex task that is particularly difficult for smaller grid operators. With limited personnel resources and a lack of expertise, these activities are outsourced or completed in cooperation with others. Smaller grid operators in particular will have to join together to form larger communities in order to share resources and expertise, exploit synergies in processes, and also to remain or become competitive with existing large grid operating companies.

Consequently, this will in all likelihood lead to consolidation. As a result of the switch to standardized, largely automated operational management processes, the core task of public utility companies and municipal grid operators in particular will essentially be to manage and operate grid elements, i.e., asset management. Dependence on digital processes and therefore on their providers is increasing significantly and is something that may become critical for independent grid operation.

Key messages to political actors

Currently, not enough is being invested in digital transformation, especially by smaller and municipal grid operators. There are a lack of inducements and opportunities when it comes to allocating and crediting costs and investments to incentivize progress in this area [170]. The joint work of the relevant stakeholders who are already involved in the digital transformation of grid operation and who will be involved in the future should also be even more motivated to make the different areas of grid operation (including the technologies in the field) more aligned and interoperable. This is an important building block for responding to the challenges of the energy transition, especially in low-voltage grids.

Model projects can be more strongly encouraged and supported, and these can then serve as a template and role model for grid operators and manufacturers. Furthermore, it is of great importance to train skilled junior staff and to further educate current personnel so that they can handle this new digital challenge.

Key recommendations for action

1) Greater cooperation and joint digital products among grid operators are conducive to accelerating the energy transition
2) In the future, incentives, funding and planning security need to be created for investments in digital transformation and to develop skills among grid operators and all other stakeholders.
3) To this end, we continue to propose programs for collaboration and strategic partnerships to promote acceleration through mutual exchange of experiences and best practices.
4) The development of expertise and expansion of personnel must happen as quickly as possible. Corresponding capacity in vocational training and higher-education programs must be expanded.

Thesis 11: Decentralized energy transition equals comprehensive digital transformation right down to the lower grid levels

Brief explanation

Distribution grids are facing significant changes. Until now, load flows were unidirectional and easy to forecast; accordingly, the grids could be planned and operated “blind”. The change in the energy system from centralized large-scale power plants to small-scale volatile generation, new high-performance consumers and decentralized electricity storage systems requires dynamic, highly automated grid operational management, across all voltage levels. In particular, high voltage and extra-high voltage will increasingly require detailed information on the current and planned operation of the superimposed and subordinate grids in the coming years. This represents a new paradigm, especially at medium-voltage and low-voltage levels. Fundamental prerequisites for active and plannable grid operation are the creation of more grid transparency and controllability, including for the low-voltage level (see also section 14a,b EnWG). The monitoring of assets and grid structures, as well as the determination of the grid status in real time, are essential functionalities that have not yet been implemented in the distribution grids due to cost/benefit considerations. A complete digital transformation of all assets, the available capacity of the grid of the current load flows, the communication interfaces as well as all necessary processes can form the necessary basis for this.

In the event of congestion or faults, the grid operator must be able to intervene. To do this, they need operating data and controlling access to relevant systems. The rapid introduction of sensors for grid status recording, including smart metering systems, is necessary to create a reliable data basis and establish a secure control channel for load flexibilization in households (see thesis 7). However, we are currently seeing data protection stand in the way of extensive and cost-efficient use of smart meter data and other data sources (IoT) for grid operation [33].

Significance for key stakeholders in the energy sector

While transmission grids have been monitored digitally for a long time, the level of metering equipment and observability of low-voltage grids is very low [171]. Significant investment in metering, communication and control technology is necessary here. Distributed smart systems for monitoring, status determination and local power management are also future components of the digitalized grid infrastructure.

As a result, the remit of distribution system operators is changing substantially and with a high level of urgency. At the same time, incentive regulation and business models are not yet designed with this in mind. AI technologies can help, for example, to assess the status of the grid with comparatively few data points. However, metering data must also be available to all relevant stakeholders. Should the transmission system operator (TSO) assume the role of data hub, distribution of data to all relevant stakeholders would need to be ensured. These are, in particular, the DSOs, but also future third-party providers who will take over network operation and planning tasks within the digital transformation (see thesis 10).

The end-to-end digital transformation of processes in energy supply grids requires new approaches to communication and organization between all the stakeholders involved in the value chain. This will require amendments in the regulatory framework for the provision, use and availability of energy data for dynamic grid operation.

Key messages to political actors

Today, there are insufficient incentives for grid operators to invest in digitally connectable systems (smart local grid stations, smart actuators) [170]. Investment in modern metering, communication and control systems as well as in the use of AI is currently too low to be able to face future challenges. Knowledge and expertise need to be expanded in the short term and be sustainable. An overarching, binding strategy for automating distribution grids and making them more flexible is urgently needed. Market elements to leverage flexibility potential, especially on the consumption side, need to be strengthened and intensified; for example, by revising section 14a EnWG (controllable consumption devices).

Key recommendations for action

1) Legal regulations must create incentives and planning security for investments in digitally connectable systems (e.g., smart local grid stations, metering technology, communication technology, control technology)
2) Clarity must be ensured between the GDPR and the necessary data collection for grid operation, and the regulatory framework for real-time monitoring must be adapted. This is particularly the case in the following areas:
   a) Data protection
   b) Digital metering at household level
   c) Use of additional data sources for grid operation
   d) Cybersecurity aspects and technical regulations
3) Incentives should also be provided for end users to purchase and set up controllable devices that enable generation and load management.

Thesis 12: Timely implementation of the energy transition can only succeed by ensuring the complete digital transformation of planning and approval processes

Brief explanation

The number of grid connection requests has seen a dramatic increase in recent years. This trend is currently leading to individual software companies and start-ups [172] already providing digitalized solutions for (semi-)automated connection request processing. This still entails manual work and individual communication for the grid operator. Given the sheer scale, automation in conjunction with digital transformation is inevitable, which should also lead to a reduction in the administration work required.

That said, the tasks for grid planning are becoming increasingly complex due to the large number of decentralized energy systems. Planning and an understanding of the planning process must therefore meet the needs of the complex energy system, meaning that the planning tools must be able to solve significantly more complex tasks with more parameters to take the burden off human grid planners. Ultimately, the expansion requirements must be automatically identified as a result of the connection requests and the connection potentials. Potentially, with an end-to-end digitalized process, the processing time for a connection request can be reduced from several weeks — which is typical currently — to just a few minutes.

Significance for key stakeholders in the energy sector

For most grid operators, manual (target) grid planning should no longer be necessary but should emerge fluidly in the future through the automation of the various processes (connection requests, approval procedures, etc.).

In municipal administrations, authority data must be digitalized and made available for use within the planning process. This means that joint development plans of all stakeholders (demographic developments, income structures, electric vehicles, etc.) must be networked in an automated approval process.

If grid operators are not able to set themselves up digitally in a timely manner and implement digital grid planning themselves, new providers from the digital environment will take over these relevant tasks and be able to perform them in a more (cost) efficient manner (see thesis 10).

Key messages to political actors

To avoid planning backlogs or bottlenecks in the processing of connection requests and in the implementation of the measures, previous administrative processes must be accelerated significantly to ensure effective and efficient grid expansion. Incentives promoting digital transformation and automation must be strengthened. An exchange of information from demographic and structural urban/rural planning and development between the states and municipalities and the respective grid operators is essential for grid expansion planning and must be integrated into energy supply.

Key recommendations for action

1) A comprehensive data basis for authorities/municipalities and grid operators/planners should be created in order to better coordinate future planning processes.
2) Conditions and incentives must be created so that administrative processes can be automated and therefore accelerated — section 14e EnWG in particular should be taken into account here.
3) In order to quickly coordinate political course-setting with industry stakeholders, the implementation of initiatives such as the Federation of German Industries' "Thinking about approval processes digitally" is highly recommended, which is why these should be expanded.

5.5 Focus on cybersecurity

The digital transformation and decentralization of the energy system is accompanied by an increasing number of information and communication technology systems and components in the energy supply infrastructure. This inevitably increases the scope for attack from cyber threats and the volume and complexity of potential attack vectors on the energy system's IT and OT infrastructures. Due to the huge significance of energy supply as critical infrastructure for the economy and society, the energy system is an increasingly attractive target for white-collar crime and also politically motivated cyberattacks from state-sponsored actors. The complexity of such attacks will continue to increase and require a reorientation of cyberattack prevention. Coordinated attacks, such as advanced persistent threats (APTs), are multi-stage approaches that require the attackers to be present on the network for an extended period of time until the target is reached. Such methods of attack therefore require new approaches and orientations in the field of energy system cybersecurity. First and foremost, it will be necessary to increase the robustness of IT and OT infrastructures against attacks. This involves the creation of cyber resilience through appropriate methods and procedures, as well as structural redundancy, especially when it comes to the necessary communication in the energy system.

Thesis 13:
Cyber resilience will replace cybersecurity

Brief explanation

The concept of cyber resilience assumes that fully securing information technology (IT) and operational technology (OT) infrastructures against cyberattacks will not be possible, and that advanced attackers will be able to bypass any cybersecurity measures or maintain a long-term presence within systems. Therefore, it is important to ensure that critical functions remain operational even in the event of disruptions caused by adverse conditions, including cyberattacks (see NIST SP 800-160v2). Modern cyber resilience is based on a circle of five functions (NIST, The Five Functions): 1) Identifying risks and threats, 2) Protective measures, 3) Detecting attacks and incidents, 4) Responding to incidents and 5) Recovering systems and components (NIST, TN2051).

The design approach to resilience therefore complements the security approach with the addition of attack detection, response and recovery. The idea is primarily driven by the fact that security mechanisms fail, systems are attacked and still need to remain in operation, or operations need to be resumed as quickly as possible.

Significance for key stakeholders in the energy sector

Making critical energy infrastructures cyber resilient requires a fundamental understanding of energy suppliers' and grid operators' own IT/OT infrastructure. This includes basic assessments of cyberattack risks and threats, and an assessment of asset vulnerabilities and the impact of IT/OT network and component failures on the electric energy supply process.

To detect attacks, systems and processes must be established that enable concrete and efficient detection of anomalies and the penetration of attackers into the IT/OT systems. IDS systems, which will be required by law in the future, and SIEM systems can form the basis for this. Due to the current heterogeneity and the specificity of communication systems, this represents a particular challenge for OT infrastructures, such that in-depth knowledge of the infrastructures and the communication protocols is an essential requirement here.

To ensure secure operation and maintenance of primary energy supply tasks while detected or undetected cyberattacks occur, robust and semi-autonomous functionality of systems and components must be implemented. This also includes establishing the ability to respond to detected attacks through appropriate action plans and contingency systems.

To recover attacked components and systems, processes and tools must be established that enable a trustworthy state to be quickly established so that the affected systems can be made operational again.

Key messages to political actors

The paradigm shift away from the pure consideration of cybersecurity and toward cyber-resilient energy infrastructures must be accompanied accordingly with regard to legal requirements and guidelines. Here, the latest findings from security and resilience research must be incorporated into binding specifications, while at the same time, existing official structures for recording and managing incidents must be further developed and designed in such a way that all phases of the cyber resilience model are adequately considered. For example, this includes preparing companies for attack situations, including through test scenarios or coordinated stress tests in conjunction with key stakeholders in the energy market.

Key recommendations for action

In the coming years, we need a strong focus in industry and research on long-term, reliable strategies in order to deal with successful attacks, contain their effects on operational security and repair any damage. The companies concerned need both clear guidelines and contacts for consulting and implementing holistic security concepts to increase cyber resilience in their IT and OT infrastructures.

A further focus must be on the education and training of energy supply personnel. Starting with the creation of the necessary awareness, the necessary knowledge to secure infrastructures as well as cyber resilience of energy infrastructures needs to be established.

Thesis 14:
Reliable energy infrastructures require reliable communication networks

Brief explanation

The operational management of our energy supply grids is becoming increasingly dependent on reliable communication infrastructure. Communication channels are already indispensable in plant and system control when integrating renewable energies and are a basic requirement for the efficient operational management of our energy supply grids. However, as the number of producers and consumers in the system grows, communication channels will become essential to maintaining operations.

This means that communication networks are increasingly becoming an integral part of the energy infrastructure. Paradigms of secure and reliable energy supply, such as the N-1 principle, must also be taken into account in the planning and operation of the necessary communication infrastructures in the future and various communication technologies (e.g., 450 megahertz as backup) will be used for this.

Significance for key stakeholders in the energy sector

Efficient options must be created to interlink the communication technology of decentralized plants in order to realize secure data transmission and integration into operational management. In the future, more information will also be available from heterogeneous data sources from the networks and transmitted via different communication channels and technologies — examples of this include IIoT data channels via LoRaWAN communication. This requires secure, encrypted and tamper-free transmission, including over public communication networks. The communication pathways must be integrated into a comprehensive monitoring system to ensure that tampering attempts and malfunctions can be detected.

For the operational management of energy supply systems, security paradigms such as the N-1 principle must also be applied to the communication pathways as an integral part of the supply infrastructure. This means setting up additional communication structures to take over data transmission when needed. The 450 megahertz radio transmission, which is being established by grid operators with a view to black start capability, can be an important building block here, but it must be ensured that coverage is as comprehensive as possible, even for smaller, decentralized networks, for example. When designing and planning such backup networks, attention must be paid to scalability in transmission bandwidth and the number of participants.

Key messages to political actors

In order to develop the communication networks accordingly and to build redundant structures, planning reliability is a basic prerequisite for grid operators and energy suppliers. To this end, questions regarding investment opportunities in such redundant structures must be clarified and made legally binding, and there is also a need for continuous further development of the legal requirements for communication security, including for new technologies and transmission pathways. This includes measures to protect communications and must take endpoints and end-to-end security into account. In addition, these communication pathways must be taken into account in the specifications for monitoring and for anomaly and attack detection.

Key recommendations for action

Communication infrastructures must be considered an integral part of critical energy supply infrastructures and paradigms such as N-1 security must also be applied in this area. This requires the use of various technologies that are optimally suited to the particular application and can provide a backup solution.

The expansion of a redundant communication infrastructure must be understood as a necessary investment in a secure and reliable energy supply and must be specified or incentivized accordingly.

By including the various communication technologies in the underlying norms and standards, system manufacturers must be encouraged to develop appropriate solutions and products.

5.6 The European dimension

Finally, the authors would like to emphasize that, in many cases, energy provision already operates at a pan-European level. In the future, the exchange of energy and flexibilities across borders both within and outside of Europe will play an even greater role (see long-term scenarios [169]). This is already particularly evident today in the current energy crisis, which can only be resolved by a joint European response [173].

However, the EU harmonization of the European energy system not only affects regulation or actual energy flows, but also the associated ICT domain. If, for example, the new IT platforms — Manually Activated Reserves Initiative (MARI) or Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) — enable Europe-wide tenders for control reserve, opportunities will arise for standardization-related process simplifications and competition-related cost reductions on a large scale. This is just one of many examples where European solutions and the development of common platforms and systems are more successful than simply national solutions. A Europe-wide networked energy system should also be accompanied by uniform IT standards and shared solutions in order to drive forward a successful pan-European energy transition [174, 175].

6 Conclusion

The study concentrates on five main areas of focus in the energy system where there is an urgent need for action when it comes to the digital transformation in the short to medium term (up to 2030). The authors believe that the most relevant topics for the digital transformation of the energy sector are in the areas of data economy, sector coupling, plant communication, cybersecurity and digitalized grid operation. Based on an analysis of current trends in energy sector development and digital transformation, these topics were identified as key areas of focus and confirmed in discussion with experts from industry and research. Taking the current state of the digital transformation in these areas and the potential for progression into account, a total of 14 theses have been developed to contribute to this discussion and create momentum for it to continue in the coming years. To this end, the significance for individual key stakeholders for each thesis and more concrete recommendations for action have been derived. The recommendations for action are addressed to the various stakeholders within the energy sector, as well as to political decision-makers, so that they can be echoed across the board in the upcoming decision-making processes.

In the future, a data-centric view will be particularly important as an essential component of a digitalized energy sector, but to achieve this — first and foremost — more data must be collected, and then made transferable, as cost-effectively as possible. This approach involves plant communication, which still accounts for a significant part of the costs of digital transformation projects. By using existing data channels, open interfaces for interoperable data exchange and extensive automation when setting up communication solutions (plug and play), plant communication complexity can be drastically reduced, and data-based business models can become profitable much more quickly. Here, it is important that the many stakeholders in the energy sector work together and form data-driven value creation networks. In this context, a shared data economy creates value for all stakeholders and enables the use of modern AI-based methods on a large database that individual stakeholders usually do not have access to. The information gained from this enables ecological and cost-effective optimization of the energy system.

As a regulated part of the energy sector, grid operation in particular faces its own specific challenges. As yet, the current incentive regulation has not been geared toward the digital transformation as a core component to the necessary extent (in addition to the urgently needed grid expansion). Consequently, the traditional asset business of grid operators focuses on long-term investments and therefore tends to focus on standardized and proven technologies. As it boasts much faster development cycles, digital transformation often creates considerable tension in this regard. Nevertheless, there is very much a need for grid operation to undergo extensive digital transformation, especially at the lower grid levels, in order to meet the new requirements. Digital transformation is therefore becoming a new core area of expertise for grid operation, which, in addition to affecting operational processes, also has an impact on time-critical planning and approval processes. In particular, the BNetzA, the BMWK and other regulatory stakeholders are called upon to provide adequate interfaces for these processes.

The energy sector is not just the electricity sector. Accordingly, the digital transformation must play a key role in particular where there is a crossover with other sectors, as well as within these other sectors themselves. Efficient sector coupling requires a cross-sector view of processes and an exchange of the associated data. Research projects show that renewable energies can be integrated more efficiently through interoperability and controllability, but — at the same time — there are a lack of incentives or regulatory hurdles stand in the way of enabling concepts for combining local energy generation with CO_2-free heat supply in heating networks at district level, for example. With revised regulation, feasible cross-sector business models could already be possible today. The heating sector in particular has a great deal of ground to make up in terms of digital transformation, as there is significant potential in the area of district heating as well as in the optimization of properties. This potential can be leveraged with the aid of networked, renewable heating concepts.

The energy system represents a critical infrastructure, so the issues of energy supply security and cybersecurity are of particular importance. Data networks must be awarded critical infrastructure status comparable with that of energy supply grids. In addition to traditional cybersecurity, the approach of cyber resilience will become more relevant in the future, as due to the huge potential for attacks, it cannot merely be assumed that a system is protected against any and all failures and tampering attempts. Accordingly, systems must be created that can resiliently handle attacks and disruptions.

In summary, the authors believe that digital transformation is integral to implementing the energy transition. A timely and economically viable transformation of the entire energy supply is only possible through consistent digital transformation of the entire value chain. Consequently, delays in the digital transformation will also lead to delays in the entire energy transition. This correlation must be taken into account, especially in the coming phase of system transformation, if the decarbonization of all sectors is to succeed in a timely manner. To this end, it is important that expertise in the digital transformation is significantly boosted across the entire industry over the next few years and that energy companies and public authorities view the digital transformation as an essential core area of expertise. Despite their necessity, not all technologies generated by the IT sector are relevant in the energy system. The digital transformation is, and will remain, an important tool and does not have a purpose in and of itself. This makes it necessary to balance the technological possibilities with the needs of the energy sector during every step that is taken.

7 List of figures

8 Bibliography

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