SteuerBoard Energie
Governance Mechanisms in a Future Polycentric Energy System

# WORKING PAPER

Swantje Gährs, Hannes Bluhm, Leonie Kütemeyer

# SUSTAINABLE DIGITALIZATION OF A DECENTRALIZED ENERGY TRANSITION

State of research, relevant issues and current challenges

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PROJECTPARTNER

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**Authors:**
Gährs, Dr. Swantje (Institute for Ecological Economy Research); Bluhm, Hannes (Institute for Ecological Economy Research); Kütemeyer, Leonie (ECOLOG)

**Project Lead:**
Institute for Ecological
Economy Research (IÖW)
Potsdamer Str. 105, D-10785 Berlin
www.ioew.de/en/

Leuphana University of Lüneburg
Institute of Sustainability Governance
Universitätsallee 1, D-21335 Lüneburg
www.leuphana.de/en/institutes/insugo.html

Dr. Swantje Gährs
Phone: + 49 (30) 884 594 59
Fax: + 49 (30) 882 54 39
E-mail: swantje.gaehrs@ioew.de

Dr. Lars Holstenkamp
Phone: + 49 (4131) 677 1931
Fax: + 49 (4131) 677 2167
E-mail: holstenkamp@leuphana.de

**Cooperation Partner:**
**ECOLOG** – Institut für sozial-ökologische Forschung und Bildung
Office Lüneburg
Wichernstraße 34, D-21335 Lüneburg
www.ecolog-institut.de

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For more information on the project: www.steuerboard-energie.org/english/

## Summary

This working paper deals with the sustainable digitalization of a decentralized energy transition and the effects on technical processes, business models and participation processes. It aims to present the current state of research and to shed more light on relevant aspects from a sustainability perspective. Depending on the actor and implementation, the use of digitalization pursues different goals such as reducing complexity, increasing efficiency or digital participation. Depending on the primary goal, the use of certain digital technologies, tools and methods makes sense at different points in the energy system. For example, existing processes in the energy industry are digitalized and optimized, business models are further developed or newly developed through the use of digitalization, and digital tools are used in energy transition processes. In addition to business interests, the motivation for this is often environmental (e. g. more efficiency or sufficiency) or social (e. g. more participation and transparency). However, from a sustainability perspective, the effects are diverse and often not yet fully researched. For example, the use of energy and resources through digitalization is a relevant variable for assessing the environmental life cycle, but the question of resilience and vulnerability through the linking of digital and electrical infrastructures is also important for assessing the use of digitalization. With regard to social aspects such as co-determination, transparency, diversity of actors and participation, positive and negative trends can currently be observed. Here in some use cases, digitalization creates added value. However, there is also a risk of unintentional lack of transparency or exclusivity.

## About the junior research group

For the energy transition in Germany to succeed, the energy system must be redesigned: On the one hand, many decentralized actors must be integrated, both technically and organizationally. On the other hand, the newly emerging polycentric energy system must be designed in a sustainable way – in other words, higher-level rules should focus on environmentally, economically and socially just implementation. How do current framework conditions and institutions have to change for this? The junior research group "SteuerBoard Energie", funded by the Federal Ministry of Education and Research (BMBF) within the funding program "Junior Research Groups in Social-Ecological Research", is investigating this question in six qualification theses. Based on the concept on polycentric governance, the researchers are investigating two particularly relevant influences in the transformation as key topics: digitalization and financing. In the area of digitalization, the question is which sustainability potentials digitalization contributes to the energy sector and, in particular, to what extent these sustainability potentials support or enable polycentric approaches. With regard to financing of the energy transition, the research team is examining institutions and actors, legal framework conditions and, in particular, looking at possible financing solutions for the expansion of decentralized renewable energies.

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| | |
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| AI | Artificial Intelligence |
| AR | Augmented Reality |
| BDEW | Federal Association of the Energy and Water Industries |
| BNetzA | Federal Network Agency |
| BSI | Federal Office for Information Security |
| CLS | Controllable Local System |
| EU | European Union |
| GIS | Geographic Information System(s) |
| HTML | Hypertext Markup Language |
| ICT | Information and Communication Technology |
| IoE | Internet of Energy |
| IoT | Internet of Things |
| MSR | Measurement and Control Technology |
| PV | Photovoltaics |
| P2P | Peer-to-Peer |
| SMGW | Smart-Meter-Gateway |
| VR | Virtual Reality |

# 1 Introduction

The socio-ecological transformation of the energy system can be viewed in terms of the so-called four D's: decarbonization, decentralization, democratization and digitalization (Di Silvestre et al. 2018; Götz 2020; Soutar 2021; Stephens 2019). In Germany, the Climate Action Program 2030 aims to expand renewable energies by 65 percent by 2030, and the new federal government has even committed itself in the coalition agreement to expand renewable energies by 80 percent by 2030 (Anon 2019; SPD/GRÜNE/FDP 2021). The Energy Efficiency Strategy 2050 also aims to reduce energy consumption by 30 percent by 2030 (BMWi 2019). Decentralization has already progressed through the expansion of renewable energies at the producer level and must increase significantly to achieve the expansion goals. This is also accompanied by the fact that local energy supply in form of microgrids, prosumers and energy communities require significantly more control at the distribution grid level. How decentralized the energy transition should or must become in the end is still a highly controversial question (Bauknecht et al. 2015; Witte et al. 2020). The same applies to the issue of democratization, which describes a very broad field. On the one hand, this also includes prosumers or energy communities that produce their own energy (Horstink et al. 2020; Wittmayer et al. 2022; Wittmayer et al. 2021). On the other hand, questions of co-determination, transparency and acceptance of citizens must also be addressed for a transformation (Holstenkamp and Radtke 2018; Knodt et al. 2019; Schönhuth and Jerrentrup 2019). Closely linked to all these issues is digitalization, which is often discussed as a hope for the implementation of a renewable, decentralized, democratic energy supply and as a "megatrend" (cf. BDEW 2017a; BMWI 2015; iea 2017; Lied 2017; Maier 2018; Roth 2018). Digitalization is supposed to enable a decentralized energy system through the intelligent control of power plants, enable decarbonization with an energy system based entirely on renewable energies through forecasts and flexibilities, and also advance democratization through the integration of significantly smaller producers both technically and in the market. The possibilities of digitalization in the energy system, its interdependencies with other topics, but also the risks that digitalization implicates in some places, are discussed in this working paper based on various focuses.

In order to approach the topic of "digitalization", it is first necessary to take a differentiated look at what is meant by the term digitalization. For this purpose, this working paper distinguishes between the terms digitization, digitalization and digital transformation (cf. Figure 1). Since these terms are not used clearly in the literature, the differences will be presented again here.

– The term **digitization** is initially understood to mean only the change from analog signals to digital data (Bengler and Schmauder 2016; Bonn 2018), for example, the digital recording of electricity consumption with smart meters as opposed to analog Ferraris meters.

– **Digitalization**, on the other hand, describes changes in the economy or institutions that result from digitalization or are made possible by it in the first place (Doleski 2017). Examples of this are the automated reading and billing of energy consumption, online solar registers or smart grids. Digitalization can take place for companies, business models, processes, relations and products (Schallmo et al. 2017).

– The term **digital transformation** is used as the social level of change (Bär 2018). This is primarily about the effects and consequences of digitalization on society, e. g. opportunities for participation, economic participation or self-organization through the dissemination or simple use of big data, platforms or blockchains, but also their negative effects such as a lack of inclusion or justice.

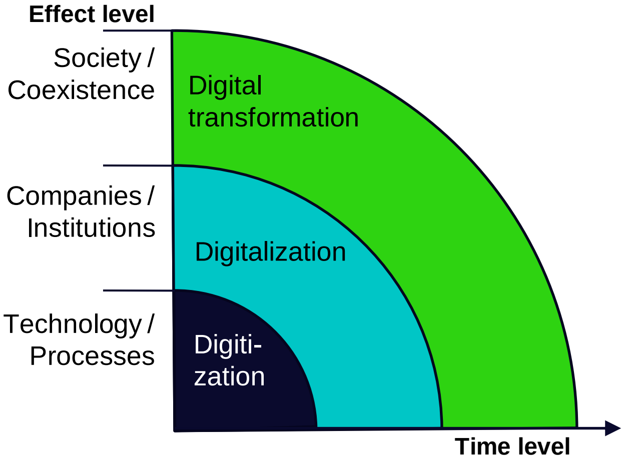


**Figure 1: Dimensions of digitalization and its effects**

The considerations in this working paper refer primarily to the digitalization that is being carried out in the institutions and companies which are in contact with the energy industry, and to the social effects that result from the implied digital transformation when it diffuses across society. The starting point is the question of how far digitalization contributes to a decentralized, or rather polycentrically controlled, energy system and what kind of positive or negative socio-ecological effect can be expected.

The second Chapter first provides an overview of the background and the effects of digitalization on the energy system. Chapters 3, 4 and 5 each focus on an exemplary topic in which the digitalization plays a special role and can be decisive for the transformation or is at least addressed as a game-changer. In Chapter 3, the digitalization of processes in the transformation is addressed in particular, as it occurs, for example, in the automated flexibilization of decentralized actors in the context of smart grids or grid-serving, controlled end-consumers. The various digital technologies that are used in this context are also examined. Chapter 4 discusses digital business models, particularly in the area of digital energy communities. These forms of virtual cooperations of decentralized actors are particularly interesting for the consideration of the socio-ecological impact because they are disruptive innovation approaches that differ from the proven business models in the energy sector. This way they can contribute, among other things, to the provision and coordination of renewable energy and flexibilities through the action of enterprises. Digital products and tools that municipalities can use for the decision-making and participation of citizens are the focus of Chapter 5. Here, digital transformation takes place on a communicative level and the municipalities and citizens are at the center as decentralized actors.

# 2 Transformation of the energy system and the role of digitalization

Digitalization is seen as an enabler for the energy transition, but also as the only way to manage complexity in an increasingly decentralized renewable energy system. The complexity arises not only from the high number of fluctuating renewable energies at distributed locations but also from the large number and diversity of actors along the value and process chains. Thus, solutions for infrastructure must be found for small actors such as prosumers or energy communities and also operators of larger decentralized plants such as regional power plants or wind farms. And for the further expansion of renewable energies, many local citizens must also be involved in order to achieve sufficient acceptance (Knodt et al. 2019). Politicians see digitalization as a necessity for the energy transition and therefore passed the Act on the Digitalization of the Energy Transition in 2016 (Bundestag 2016) and defined the gradual smart meter rollout, which is intended to enable both extensive data collection on electricity consumption and, in the future, heat consumption as well as secure data communication.

**General opportunities and potentials of digitalization**

Against this background, digitalization is said to have many positive attributes. These include connecting local and regional energy systems with each other to make them smarter, more reliable, more efficient and more sustainable, for example by coupling sectors (e. g. Henning 2018; Mega 2019; Rehtanz 2015) as well as through the enhancement of flexibility (Alizadeh et al. 2016; Kondziella and Bruckner 2016). Digital technologies in the energy sector offer numerous opportunities for companies to improve the existing business model or to develop new business models and thus create new income opportunities (Clauß and Laudien 2017; Loock 2020). In addition, through the transmission of data without time delay, digitalization enables a mapping of the physical conditions in the grid also in the electricity market and dynamic tariffs for end consumers (e. g. time-, load-, event- and consumption-variable tariffs) (BDEW 2017a; Vortanz and Zayer 2017).

By automating and optimizing processes, environmental advantages can be gained over non-digitized processes (e. g. through weather forecast control or predictive maintenance, live condition monitoring of grid elements). But also, more efficient use of energy technologies can be achieved through digitalization (e. g. multi-use of storage). In addition, digital technologies can lead to users replacing devices or saving energy on their own initiative (e. g. through visualizations and information on inefficient devices) and thus behaving more environmentally consciously in other areas of life and consumption (Gährs et al. 2021b; Pohl et al. 2019).

Digitalization also offers the potential to use digital tools to better involve affected actors and other stakeholders in energy policy and energy industry processes. Digital platforms and tools for information, participation in political decision-making or customer loyalty in new digital business models are seen as being able to simplify and promote the networking and involvement of a large number of actors (Deckert et al. 2020; Rieger and Weber 2017; Spieker 2018).

**General barriers, risks and challenges of digitalization**

At the same time, however, there are currently still many obstacles, risks and challenges to digitalization in the energy sector. This concerns economic, ecological, social and technical aspects. One aspect is the vulnerability of a digitized energy system. Through the digital linking of systems and actors, the risks and the effects of attacks on the energy system are significantly larger and take on a new quality due to the dependence of the energy system on the digital infrastructure (Aretz et al. 2017; Blank-Babazadeh et al. 2021). One possible approach to counteracting this can be decentralized and cellular approaches (Hirschl et al. 2018), data sufficiency, i. e. the use and collection of data only where it is necessary (Hirschl et al. 2018), and the diversification of infrastructure and technologies (Gährs et al. 2021a).

Digitization goes hand in hand with direct energy and resource consumption for the production, operation and disposal of information and communication technology (ICT) and background processes such as data transfer or the infrastructure operation of service providers (Bordage et al. 2021; Coroama 2021; Gährs et al. 2021b). Digitalization thus poses an environmental risk if an application is not matched by sufficiently large energy and resource savings.

In addition to these direct environmental impacts, further risks can arise from the indirect effects of digitalization. A change in the way energy technologies are driven, triggered by automation and optimization processes, can result in advantages at one point (e. g. additional revenue for service providers through multi-use of storage), which in turn can unintentionally result in technical disadvantages at another point (e. g. shortening of the service life of technical components or efficiency losses). In addition, usage-related effects can occur in the course of the acquisition of digital components. Rebound effects describe the fact that financial benefits generated by digital applications through efficiency gains are used for additional expenditures on environmentally harmful products. Demand-inducing effects describe the situation that the purchase of devices can generate completely new demands (e. g. purchase of tablets for general internet access and subsequent intensive use for online games). Finally, effects at the level of individual households and persons can add up to systemically relevant effects due to strong diffusion of the application (Frick and Nguyen 2021; Gährs et al. 2021b; Lange et al. 2020; Pohl et al. 2019).

On the one hand, digital business models are characterized by certain advantages and new income opportunities. On the other hand, the interest in a market entry is currently limited due to high market entry barriers for certain services in the energy sector (Gährs et al. 2021b). As is often observable with business models, network effects and "first mover advantages" can also be achieved, which hinder the market entry of further providers and lead to a market concentration on a few players (Aagaard 2019; Hages et al. 2017).

In some cases, the lack of infrastructure and the sluggish broadband expansion are already hampering the preconditions for widespread digitization. According to the Federal Ministry of Transport and Infrastructure (BMVI 2019), there is still an urban-rural divide in broadband availability. While the differences are smaller for the lower bandwidths (<16 Mbit/s), significant differences can still be seen for higher bandwidth classes (>1,000 Mbit/s). In addition to the technological preconditions, access to digital technology and the associated digital media, such as the internet, software programs or social media, as well as the skills and competencies in using them are still unequally distributed in society. The level of access is often related to socio-demographic characteristics and can contribute to disadvantages in participation in social processes (Rudolph 2019). Therefore, this phenomenon is often called a "digital divide".

In addition, the roll-out of smart meters is also increasingly delayed. After the Act on the Digitalization of the Energy Transition was passed in 2016, the certification of three smart meter gateways (SMGW) required for the start of the rollout was not achieved until the end of 2019 and the associated market declaration by the Federal Office for Information Security (BSI) was published at the beginning of 2020. However, after a lawsuit, the rollout was stopped again by the OVG Münster in spring 2021. Currently, the law is being revised to restore legal and planning security.

**Connections between digitalization and polycentricity**

In addition to individual aspects of decentralization, polycentric governance in which actors act in a self-organized manner can also be interesting for the energy system. Digitization can also be a supporting technology here, in that automated decisions are made taking into account higher-level rules and limits, for example in the transmission grids. Explicitly or implicitly, connections between digitalization and polycentricity were also analyzed in the literature. For example, the Horizon 2020 project Newcomers looks at the importance of new energy communities enabled by digitalization for polycentricity (cf. Mlinarič et al. 2019; van der Grijp et al. 2019). The focus of the research is on practical recommendations for action and the implementation of innovative energy communities in various European countries. Moroni et al. (2019b) have also dealt with aspects of polycentricity in the energy sector and investigated the transition from passive to active, self-organized consumers. Furthermore, Bauwens (2017) analyzed the extent to which self-organized communities push technological innovations for production, storage and community energy consumption. Past and planned efforts to decarbonize urban spaces through digitization and decentralization were the focus of the research by Webb et al. (2020).

In the following, the challenges and opportunities of digitalization are examined in more detail based on the use of digital technologies for technical control, digital energy communities and digital tools in municipal processes.

# 3 Digitalization of processes in the energy system

## 3.1 Data, digital technology and infrastructure

Digitalization is an important business area for the future, especially for the energy industry, in order to improve both internal and external processes. Already in a survey from 2016, 69 percent of the energy supply companies stated that they had or were planning a digitalization strategy (BDEW 2016). In 2021, more than every second energy supplier had already implemented one (BDEW et al. 2021). A major driver here is the development of new digital technologies and the increasing data base (BDEW 2016).

The federal government also sees the need for digitalization and therefore passed the Act on the Digitalization of the Energy Transition in 2016. At its core, this law regulates the rollout of smart metering systems (iMSys), i. e. the combination of modern metering devices and smart meter gateways. § 29 stipulates that end consumers with more than 6,000 kWh/a and system operators with an installed capacity of more than 7 kW must be equipped with an iMSys. The law also sets deadlines within which the rollout should take place. According to this, the rollout should begin in 2017 and be largely completed by 2025. However, § 30 stipulates that the rollout will not begin until the BSI has certified at least three smart meter gates, that meet the security requirements of the federal government, and that a corresponding market analysis has been carried out by the BSI. Due to delays in certification, this situation was only established with the published market analysis in January 2020, i. e. with a delay of three years. This means that the deadlines for the rollout have started for the first time. Currently, however, these are paused, as it was determined in a lawsuit filed with the Münster Higher Administrative Court in March 2021 that the implementation is not legally secure. However, it can be assumed that the mandatory rollout will be continued shortly.

**Data as the basis of all digital technologies**

The basis of digitalization is data that is collected, transmitted, processed or transferred. This applies not only to the energy system but in general. In the energy system, however, there are some special features due to its history and relevance to services of general interest. Due to the original centralized set-up of the energy system, only little data was needed and the power grid could be controlled using analog signals. In the meantime, the collection and use of large amounts of data has already become part of everyday life in the energy system in some areas, such as plant control in virtual power plants or customer data for sales (cf. also BDEW 2016). As a result of the law on the digitalization of the energy transition and the associated efforts of the federal government to strive for intelligent control of the energy system, the proportion of data that is collected in the energy system is increasing daily. As early as 2016, the BDEW stated that "the daily cross-company data exchange of a medium-sized energy supply company generates up to 30,000 messages with approx. 1.6 TB of data volume" (BDEW 2016, p. 31).

Roughly, the data in the energy system can be divided into two categories: system data and customer/producer data (Corusa et al. 2021; Rhodes 2020). This division is helpful because these data types have different tasks in the energy system and therefore different objectives. All data that relates to the entire energy system or relevant parts of it is grouped under system data. This includes weather forecast data, market data, e. g. of the balancing energy market, plant locations or production quantities. Customer and producer data includes the data of the connection users. This includes personal data, consumption data, production and load profiles or data on load shifting (Rhodes 2020). The data also vary in terms of data protection, which was examined in detail by Corusa et al. (2021) differentiated. The question of how far data protection applies to the individual data cannot be answered only based on the type of data, but must also include the purpose for which the data is to be used. In addition, there is data, especially in the case of system data, which may not be passed on, for example, for reasons of unbundling, in order to avoid competitive advantages. As data plays an important role in an increasingly digitalized energy system, Corusa et al. (2021) identify new business models for procurement, processing and dissemination of data.

**Digital technology for the collection, processing and storage of data**

Various digital technologies are used to collect data. Smart metering systems (iMSys) are the central instrument for collecting consumption and generation data. In the long term, the iMSys is also the communication interface for controlling and integrating other generation and consumption technologies from the heat or mobility sectors via the CLS channel (Controllable Local System) (cf. Gährs et al. 2021b). The smart meter thus divides the digital technology between the technology installed behind the meter at the end customer and the technology in front of it. The technology in front of the meter consists primarily of sensors (e. g. weather data, grid status data, data on the status of the generation and storage systems) and actuators (e. g. pneumatic, hydraulic, thermal or electric) for grid and system control. Behind the smart meter, however, there are several other sensors (e. g. temperature, humidity, brightness, movement, distance), actuators and end devices (e. g. smartphones, tablets, monitors) used by increasingly networked end customers to collect data manually or automatically (Motlagh et al. 2020). This data is then either used for a purpose within the internal network (e. g. monitoring) or passed on via the smart meter for other services. However, the energy generation technologies, as well as large consumers such as heat pumps or electric cars, are also already frequently installed via inverters, heat meters and wallboxes with corresponding data loggers, and the data is thus collected and stored.

Due to the increasing amount of data, data centers and cloud computing, i. e. the virtual combination of several data centers, are often used for processing and storing the data. According to BDEW et al. (2021), 85 percent of energy utilities already use cloud services. Cloud-based software services (Software-as-a-Service, SaaS) are used the most, followed by the provision and use of computing infrastructure (Infrastructure-as-a-Service, IaaS). Platforms for the development of their own services have been the least used so far (Platform-as-a-Service).

**Digital infrastructure for data transmission**

To transmit the data, an infrastructure is also necessary that transports the collected data on a decentralized level to the actors, who process or use this data. For this purpose, a distinction can be made between different transmission media (grid-bound or radio) and distances (Blank-Babazadeh et al. 2021). In addition, communication in the energy system can be differentiated between transmission up to the smart meter and from the smart meter to the grid operator, energy supplier or energy service provider (Gungor et al. 2011). Behind the meter, home, neighborhood or local area networks (HAN, NAN, LAN) are usually used, which exchange grid-bounded data via the existing telecommunications channels (fixed network, cable network). Outside this local zone, transmission is usually via the Wide Area Network (WAN), often the existing grid-bound internet. Figure 2 shows how the communication infrastructure between the grid operator and decentralized generation plants can look. This Figure represents the physical data path. Other actors such as metering point operators and smart meter gateway administrators are also involved in the market organization.

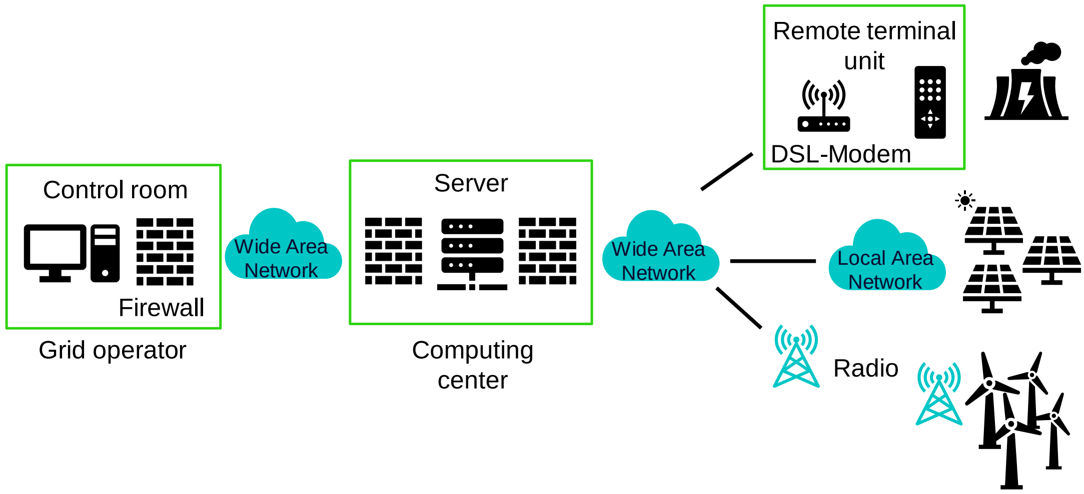


**Figure 2: Example of the communication structure between grid operator and decentralized energy plants, own representation adapted from Zajc et al. (2019)**

Mobile radio enables the transmission of data via radio signals and is thus not grid-bound. An infrastructure in the form of radio masts is required, which in turn is also connected over longer distances via the internet (Blank-Babazadeh et al. 2021). With mobile radio, data is transmitted via different frequency bands or -ranges. These frequency bands can be used in parallel and are allocated to telecommunications network operators by the BNetzA. As a critical infrastructure, the stability of the communication infrastructure is particularly important for the energy industry. For this reason, the BNetzA decided in November 2020 that the 450 MHz frequency may be used preferentially by the energy industry (Fleischle et al. 2021). Based on this decision, the expansion of the corresponding infrastructure is necessary. 540connect GmbH, which was awarded the frequency usage rights in March 2021, plans to put 1,600 radio sites into operation nationwide by the end of 2024 (Fleischle et al. 2021).

## 3.2 Digital technologies and their possibilities

Digital technologies use existing data, digital technology and infrastructure to automate and optimize processes. The spectrum ranges from rather simple technologies, such as desktop applications for end users or automated communication, to the current major trends that are hidden behind the buzzwords blockchain, artificial intelligence, big data, platforms or the Internet of Energy. These are presented below.

**Blockchain technology**

A blockchain or distributed ledger technology (DLT) is a database whose data is stored in a decentralized distributed manner, enabling a secure transaction between two parties without a third party authority (e. g. a bank or government agency) (e. g. Pilkington 2016). A transaction can be a transfer of goods or information that is refunded, e. g. an electricity trade. To check whether a transaction is valid, i. e. whether, for example, the identities and payment methods are correct, a data block is generated for the transaction and this is checked by several decentralized instances using cryptographic procedures and then appended to an existing blockchain and stored. Various so-called consensus mechanisms are available for verification, the best known being the proof-of-work method, which is also used in the case of bitcoins. In addition, there are now other methods that above all try to work in a more resource-efficient way. Thus, Blockchain technology is characterized by the fact that it is forgery-proof, independent and traceable.

Whether the use of a blockchain makes sense for a use case depends on several factors. Andoni et al. (2019) mention here, on the one hand, that the assets should be representable in the form of a digital database and, on the other hand, that this database must be exchanged between the parties and parallel calculations must be carried out so that the transactions are independent. It may be useful, according to Andoni et al. (2019), to consider why this form of decentralization is necessary or helpful in a particular case. This could be, for example, cost reductions, faster and more secure transactions, the traceability of transactions or the desire to do without an authority. In the best-known case of Blockchain technology, bitcoins, a currency with transactions were realized without the use of banks.

The most common use case of blockchain in the energy sector is currently the trading of energy between individuals (peer-to-peer trading) (cf. Andoni et al. 2019; Thasnimol and Rajathy 2020). However, the literature also contains a number of other examples in the energy sector where blockchain is already in use or where there is corresponding potential. Andoni et al. (2019) identifies the following use cases in the literature:

– *Billing:* automatic billing in the case of smart contracts, micropayments for energy, pay-as-you-go solutions or prepaid payments and meters;
– *Sales and marketing*: individualized tariffs based on personal preferences (in combination with artificial intelligence);
– *Trading and markets*: trading platforms, risk management, certificate trading;
– *Automation*: micro-grid control, P2P trading with optimized generation and consumption;
– *Smart grid applications and data transfer*: communication between smart applications (smart meters, sensors, monitoring systems);
– *Grid management*: flexibility and plant management;
– *Security and identity management:* security of transactions in terms of privacy, data protection and identity management;
– *Shared use of facilities:* shared charging infrastructure or shared use of storage facilities;
– *Competition*: simplified and faster switching of energy supplier;
– *Transparency*: increased transparency for audits and regulatory obligations.

So far, there are many examples of pilot and research projects with blockchain applications in the energy sector and a large number of energy suppliers are testing the use of blockchain (cf. Andoni et al. 2019; BDEW 2017b). However, the promised benefits of blockchain, such as security, speed and scalability, have yet to be verified in practice. This also has implications for the consensus mechanisms applied to blockchain. A major point of criticism has been the efficiency of the technology. This is often countered by newer implementations with simplified proof methods such as Proof of Stake (Andoni et al. 2019). At the same time, however, the technology is still seen as having great potential as a solution for decentralized trade.

### Big Data

The term "Big Data" indicates that a large amount of data is available to be processed. In the scientific literature, three characteristic features of "Big Data" are mentioned: the large amount of generated and available data in a data set, the high speed at which the data set grows with new data and the large variety of formats in which data are available (e. g. images, text and videos) (cf. Rhodes 2020). When data are available in such abundance and diversity, new analytical methods are needed for processing and utilization that go beyond the usual data processing in order to extract, type and characterize the data (cf. Jiang et al. 2016). In the energy sector, these analyzes can be relevant, for example, in the control of smart grids, when weather data, grid condition data, market data and data from geographic information systems (GIS) come together (cf. Jiang et al. 2016). The ongoing digitalization is expanding this data to include data made available via the smart meter gateway. Jiang et al. (2016) identify four fields in which Big Data is used: plant management, operational planning, failure detection/prevention, decentralized generation and electric vehicles. Big data is often combined with other analytical methods (e. g. optimization algorithms or artificial intelligence).

### Artificial intelligence and machine learning

Artificial intelligence (AI) is not a clearly defined term. It basically describes the characteristic of an IT system to "exhibit human-like, intelligent behaviour" (Anon 2017, p. 28). An artificial intelligence has four core capabilities: noticing, understanding, acting and learning. Unlike other IT systems, the goal of artificial intelligence is not only to process data but also to learn and understand (Anon 2017). A distinction is often made between strong and weak AI, whereby strong AI refers to intelligence comparable to humans and is still a theoretical concept today. In the following, a weak AI is therefore always meant, which is only trained for a specific application. For an AI to be able to derive decisions independently from new data, the AI must first be trained. Machine learning is a method for learning from large amounts of data. The system is trained with a test data set and can then apply the knowledge to unknown data and situations. The BDEW (2020) distinguishes between four fields of application in which AI can be used in the energy industry:

– *Plant planning*: e. g. optimization in plant planning based on forecasts, image material, measurements;
– *Maintenance, servicing and plant management*: e. g. more efficient maintenance of energy plants by evaluating forecasts, image data, utilization data and staff availability;
– *Grid and plant operation*: e. g. optimized feed-in management or more efficient grid operation through weather forecasts and predictions based on historical data;
– *Sales and customer interface*: e. g. prediction of consumption patterns or evaluations for customer communication.

According to BDEW (2020), whether the use of an AI makes sense can be assessed based on a number of core criteria. For instance, there should be many measurable data points for the intended use, a high optimization potential should be assumed, human-like abilities (hearing, seeing, speaking) should be required and there should be a desire for an independently optimizing system. An AI is not suitable if there exist only small amounts of data or training data could be biased. However, from a sustainability point of view, the amount of data that an AI requires is always a point of criticism. Processing and storing large amounts of data requires a lot of energy itself (Lange and Santarius 2018).

### Internet of Energy

Analog to the Internet of Things (IoT), the Internet of Energy (IoE) refers to the interconnection of sensor technology, the internet and efficient algorithms for data processing in the energy sector. The goal, or rather the vision, is to centrally collect, process and return the results of the multitude of data collected via the internet, e. g. in the home, electricity grid or generation plants, in order to enable efficient and resource-saving operation of plants. In the process, the data is only collected once at a time and further used in a decentralized manner. IoE is therefore sometimes referred to as a combination of smart grid and IoT (Bui et al. 2012). A good and reliable communication infrastructure is relevant for the functioning of the IoE or individual use cases (Rana 2017; Song et al. 2017). IoE approaches are currently being used in particular in the context of smart grids (Jaradat et al. 2015; Kabalci and Kabalci 2019; Nefedov et al. 2018; Strielkowski et al. 2019) or energy management systems (Hannan et al. 2018).

### Digital platforms

Digital platforms represent a technical way to offer products, services or technologies (Baums 2015). In the energy sector, digital platform markets are mostly used, i. e. transactions are carried out via the technical digital structure of the platform. Unlike two-sided markets, where there is a supply side and a demand side, digital platforms enable a network of actors with varying roles in supply and demand. Until 2017, Duch-Brown and Rossetti (2020) had already identified 217 such digital energy platforms in the EU, 25 of them located in Germany. Among these, financing platforms for renewable energies form a large example class. The relevance of digital platforms in the energy sector is related to the fact that the decentralized structure fits particularly well with the decentralized change in the energy system. Borghesi and Glachant (2019) even go so far as to say that electricity grids should become an open, digital platform that supports all other initiatives (upstream or downstream of the meter). Heinemann et al. (2019) have analyzed two use cases in more detail that require a lot of decentralization, regionalization and involvement of many actors and are therefore interesting for the use of digital platforms: flexibility platforms and P2P trading. The flexibility platforms would be particularly helpful for grid management in order to keep the curtailment of renewable energies low, even with increased expansion. This can be achieved primarily through the increased reaction speed in trading via digital platforms. Concerning P2P trading, digital platforms can enable very flexible electricity purchases in terms of time and location, also taking consumer interests into account (Heinemann et al. 2019). Positive effects here can also be the marketing of RE plants that are no longer funded.

### Digital twin

The concept of a digital twin was first coined by NASA in 2003 and has since been used in a variety of contexts. In general, a digital twin is a digital or virtual representation of a physical system and how it looks and behaves, with the aim of optimizing or deciding for some time horizon (Yu et al. 2022). The advantages of a digital twin are to test the impact of scenarios or new physical assets in a virtual environment and thus realize either more efficient use or implementation. Yu et al. (2022) have identified three areas of application for digital twins in the energy industry:

- Design: virtual tests, optimization;
- Process: optimization, prediction, monitoring, control, training;
- Service: failure detection and -diagnosis.

Since a digital twin is a method to calculate physical impacts without intervening in reality, they are very often used in research to implement changed framework conditions. These can be, for example, changed climatic conditions or expanded power grids (Onile et al. 2021). Since the construction of a digital twin is initially associated with high expenditure, they are often used in practice in connection with high-investment measures (Sleiti et al. 2022). In research, the three main drivers for the use of a digital twin are the improvement of energy efficiency or energy consumption, decarbonization of the system under study and economic optimization (Yu et al. 2022).

**Examples of the use of digital technologies in the value chains of the energy industry**

The use of the following digital technologies is diverse. In some complex cases, a combination of technologies may also make sense. Table 1 provides an overview of typical use cases of digital technologies, divided according to the classic value creation stages of energy supply.

**Table 1: Examples of the use of digital technologies in the energy system, own extended representation based on Rhodes (2020)**

| Digital technology | Generation | Trade | Transmission | Distribution / end customers |
|---|---|---|---|---|
| **Blockchain** | Validation in emissions certificate trading | Implementation of smart contracts | Transactions in microgrids and local markets | Simplification and automation of billing and metering |
| **Big Data** | Increase process efficiency through data analysis | Forecast of future load and prices | Data analysis to optimize generation and storage in communities | Advice for energy saving |
| **AI & machine learning** | Optimization of wind farms through wind forecasts | Energy trading by autonomous agents | Protection of grids against power outages | Automation of load shifts |
| **Internet of Energy** | Drone inspection of technical equipment | Smart Grid Sensors, Monitoring and Plant mgmt. | Local microgrids through integrated control | Networking of electric vehicles, home automation |
| **Digital platforms** | Crowdinvesting in renewable energies | Peer-to-peer trading | Implementation of flexibility markets | Individualized change of supplier |
| **Digital twin** | Plant design under uncertainties | Virtual power plants | Long-term network planning strategy | Analysis of energy efficiency methods in buildings |

## 3.3 Opportunities and challenges in the use of digital technology and techniques

The use of digital technology raises a number of unanswered questions regarding its sustainable impact. In many areas, the use is still in the period of research and development and the implementation of pilot projects (e. g. Alizadeh et al. 2016; Castagneto Gissey et al. 2019; Kasaei et al. 2017; Kondziella and Bruckner 2016; Schuitema et al. 2017). Therefore, general statements are still difficult. Isolated findings have already been made on the socio-ecological impact of the digital transformation or individual areas (e. g. Mlinarič et al. 2019; Strohmeyer and Reetz 2019; Tagliapietra et al. 2019; Varela 2018). In the following, particularly relevant opportunities and challenges are further pictured from a sustainability perspective.

### Infrastructure, data and resilience

A stable infrastructure and reliable data must be available for digitization to work. Currently, data availability and data quality are not always guaranteed (e. g. O'Dwyer et al. 2019). In addition, access to data is sometimes difficult, and a trade-off must be made between data protection and open data (BDEW 2020). There are, however, a number of initiatives, such as the Open Energy Platform (OEP Community 2022) which advocate Open Data in the energy sector in order to avoid multiple data collection and therefore an efficient use of data. Data protection in Germany is generally rather strictly regulated, but data can also be used for almost any purpose with the consent of the users. Lucha and Meinecke (2019) assume that consumers with a high level of data protection awareness will not prevail over those who value the convenience offered by digital technologies, and that offers with rather low data protection standards and higher added value for customers will therefore become the norm.

Standards are still lacking in some areas, both for data and for communication interfaces, to ensure smooth interoperability and prevent monopoly positions of individual providers (Richard and Vogel 2017). The expansion of ICT is also a risk to the vulnerability of the critical infrastructure. According to Blank-Babazadeh et al. (2021), there are still a number of risks. For example, it is noted that with the large number of plants that are controlled, simultaneous behavior can arise that can become system-relevant. On the other hand, a decentralized structure can also lead to more resilience if these decentralized systems also function autonomously in isolated operation or even in combination with other critical infrastructures such as hospitals and police stations. In order to use this stabilizing effect, however, according to Blank-Babazadeh et al. (2021) it must be possible for the grid operators to access or influence the systems remotely. Here, too, standards and interfaces or platforms are necessary for good interoperability. In the future, digital technologies such as AI could also be used to control the plants in a stable manner in unexpected situations.

In addition, due to the strong interconnectedness in a digital energy system, errors and attacks also have a major impact on trouble-free operation without prolonged critical outages (Blank-Babazadeh et al. 2021). The amplitude of the impact is also increased in particular by the fact that faulty ICT, when used to operate the power system, cannot simply be switched off, as otherwise, the power grid threatens to collapse in the short term. Likewise, the interconnection of the ICT system and the power system can increase the system complexity and predictability, and thus also the complexity of faults that occur (Blank-Babazadeh et al. 2021).

### Energy and resource consumption vs. efficiency gains

One of the big goals in using digitalization is to achieve better efficiency. This can concern several areas, such as more efficient use of generation plants for heat and electricity (Gährs et al. 2021b), the better control of decentralized renewable energy systems (Heinemann et al. 2019) or the more efficient use of the existing infrastructure with the simultaneous expansion of renewable energies (Lucha and Meinecke 2019). In addition, ecological effects at the energy system level are also targeted, such as less regulation of renewable energies or the avoidance of calling up conventional reserve capacities (Heinemann et al. 2019). On the other hand, this goal of savings is partly offset by a high consumption of energy and resources. This applies above all to the high energy consumption of complex digital technologies such as blockchain, artificial intelligence or the Internet of Energy (Lucha and Meinecke 2019; Motlagh et al. 2020). In addition, the use of resources and sometimes raw materials for the additional digital infrastructure must also be taken into account. In addition, there may be positive or negative user-induced effects. One example is rebound effects, which lead to additional consumption and thus level out the savings or even exceed them (Gährs et al. 2021b; Lucha and Meinecke 2019).

**Higher investments and lower costs**

The higher efficiency in digital technical implementation goes hand in hand with lower running costs in most cases. However, high initial investments are sometimes necessary for the digital infrastructure as well as the development and adaptation of digital technologies (Richard and Vogel 2017). However, digital technologies in particular can usually be transferred or expanded to other areas without major effort. This means that the methods can also be applied to smaller problems without major costs and, for example, efficiency potentials can be tapped that would otherwise not be economically viable individually (Richard and Vogel 2017). Whereby, according to BDEW (2020), there are currently few economic incentives for optimizations in electricity grid management, which are often the goal when using digital technologies, due to regulation.

**Participation, transparency and social impact**

The use of digital technologies can not only technically increase decentralization through the integration of distributed renewable energy, but also increase the opportunities for co-determination and participation (O'Dwyer et al. 2019) (cf. also Chapter 5). In this way, decentralized actors can be involved in both, smart grids (Lucha and Meinecke 2019) as well as in new energy markets (Heinemann et al. 2019) and increase diversity there. Digitalization can also lead to more transparency in some areas, for example in the origin of electricity on digital marketplaces (Heinemann et al. 2019).

On the other hand, increased costs due to individual elements, such as the installation of smart meters, can also end up with consumers without them benefiting from the efficiency gains (Gährs et al. 2021a). In addition, digitalization does not always lead to more transparency; on the contrary, it can lead to a lack of transparency in processes if the technologies are too complex (BDEW et al. 2021). The complexity of the use of digitalization can also lead to employees being overtaxed (BDEW et al. 2021), especially in the case of smaller energy suppliers who do not have staff specialized in digitalization. In addition, there are some ethical concerns about the use of artificial intelligence, such as the complete replacement of jobs, which must be addressed to ensure acceptance (BDEW 2020).

# 4 Digital business models and digital energy communities

## 4.1 Effects of digitalization on business models in the energy industry

Business models describe the principle of how an organization creates and provides benefits or value, and generates income based thereon (Osterwalder and Pigneur 2010). According to Schallmo (2018), business models are logic of a company that describes which benefits are created in which way for customers and partners.

According to Clauß (2017), three dimensions play a central role in the description and design of business models: value proposition, value protection and value creation of a company. Schallmo makes a division into five dimensions (2018): customers, benefits, value creation, partners and finance. These systems are used in the following sections to classify the effects of digitalization on business models in the energy industry.

Key trends (changes in technology, regulation, socio-cultural and socio-economic changes) and other drivers in the dimensions of market forces, macro-economic forces and industry forces are changing business models (Osterwalder and Pigneur 2011). This is also the case in the energy industry.

In the pre-liberalized energy industry, the predominant business model was the vertically integrated energy utility, comprising generation, grid, and distribution and trading in one supply area. Therein, the utility held a monopoly position (Doleski 2017). From 1996 onwards, the EU initiated the liberalization of the energy markets and thus, the unbundling of the above-mentioned business units, opening up the electricity and gas markets to competition (Konstantin 2013). Until about 2012, this was mainly characterized by price competition between the established and new suppliers. The business model of the incumbent utilities, however, remained essentially unchanged: they had a focus on low-cost and fossil energy supply, high market shares and use of economies of scale (Doleski 2017; Wagner et al. 2020). In the following years, the service orientation towards customers increased in the utilities. Since 2015, this development has been additionally underpinned by advancing digitalization (Doleski 2017).

The global upheavals of decarbonization, decentralization, democratization and digitalization result – also in the energy industry – in necessities and opportunities for new services and thus, also the chance to develop new business models (Giehl et al. 2020; Löbbe and Hackbarth 2017; Wagner et al. 2020). This development goes beyond a simple adaptation of existing models (Specht and Madlener 2019). In this context, according to Veit et al. (2014), one can speak of digital business models when changes in digital technologies are accompanied by fundamental effects on the conduct of business operations as well as on the generated revenues of a company. In that sense, digitalization or information technologies are an integral part of the value creation dimension or even enablers of the business model (Boston College et al. 2014; Clauß and Laudien 2017). In addition, according to Loock (2020), digitization-based business models are characterized by three features: a strong focus on the relationship between the company and its stakeholders, the pursuit of approaches with as little ownership of assets as possible (asset-light strategy), and a high degree of scalability.

The new design options that can arise for business models as a result of digitalization are shown by the adapted Table 2 according to Clauß and Laudien (2017). Furthermore, we give examples that can be observed in the energy industry. Changes occur in the dimensions of value creation, value offering and value protection, which in turn can be divided into three impact levels of digitalization:

– *Internal focus*: concerns processes that are digitized or digitally supported within the company;
– *External focus*: includes digital linkages with clients and partners;
– *Outcome focus*: refers to products and services provided to customers.

**Table 2: Systematization of design options for digital business models, adapted from Clauß and Laudien (2017)**

<table>
<tr><th></th><th></th><th colspan="3">Dimensions of digitalization</th></tr>
<tr><th></th><th></th><th>Internal focus</th><th>External focus</th><th>Focus on results</th></tr>
<tr><th rowspan="3">Dimensions of the business model</th><th>Value creation</th><td>– Increased efficiency of internal processes<br>– Improved networking of company divisions<br><u>Examples:</u><br>– Use of Enterprise Resource Planning systems with utilities</td><td>– Expansion of the range of services through integration of external partners in the provision of services<br>– Waiving of the use of physical assets<br><u>Examples:</u><br>– Aggregator role for pooling of decentralized energy technologies</td><td>– Automation of the service provision<br>– Access to customer data reveals room for service design<br><u>Examples:</u><br>– Acquisition and processing of high-resolution feed-in and consumption data through smart meters and smart meter gateways</td></tr>
<tr><th>Value proposition</th><td>– Higher transparency and influence of the service provision<br>– Possibility to individualize the value proposition<br><u>Examples:</u><br>– Offer of different tariff use cases through the use of smart meters</td><td>– Joint value proposition of different providers via platforms<br>– Developing new partners and markets by offering linkable processes<br><u>Examples:</u><br>– Tariff comparison portals<br>– Offer of e-car subscription provided via green electricity tariffs (cross-selling)</td><td>– Development of product service systems<br>– Creation of digital offers<br><u>Examples:</u><br>– Data visualization and data analysis of energy consumption and feed-in via customer portals of technology providers</td></tr>
<tr><th>Value protection</th><td>– Cost reductions through process automation and standardization<br>– Digitization of payment<br><u>Examples:</u><br>– Blockchain and smart contracts for processing contracts and payments in peer-to-peer energy trade</td><td>– Indirect cross-subsidies via third parties<br>– Two- and multi-dimensional platform business models<br>– Crowdfunding<br><u>Examples:</u><br>– Sale of electricity storages and subsequent pooling for energy system services</td><td>– Software as a Service<br>– Freemium business models<br><u>Examples:</u><br>– Internet-of-Things platforms for energy-consuming end devices as a chargeable service</td></tr>
</table>

Business models resulting from these potentials in the energy sector are discussed by Giehl et al. (2020). With the aim of a full survey, the authors present both the existing and the new business models of the energy industry resulting from the trends and structural upheavals. The models are categorized in so-called classes. The models are further classified along the dimensions of "proximity to end consumers" and of "core activities" of the classic value chain of the energy industry (see Figure 3).

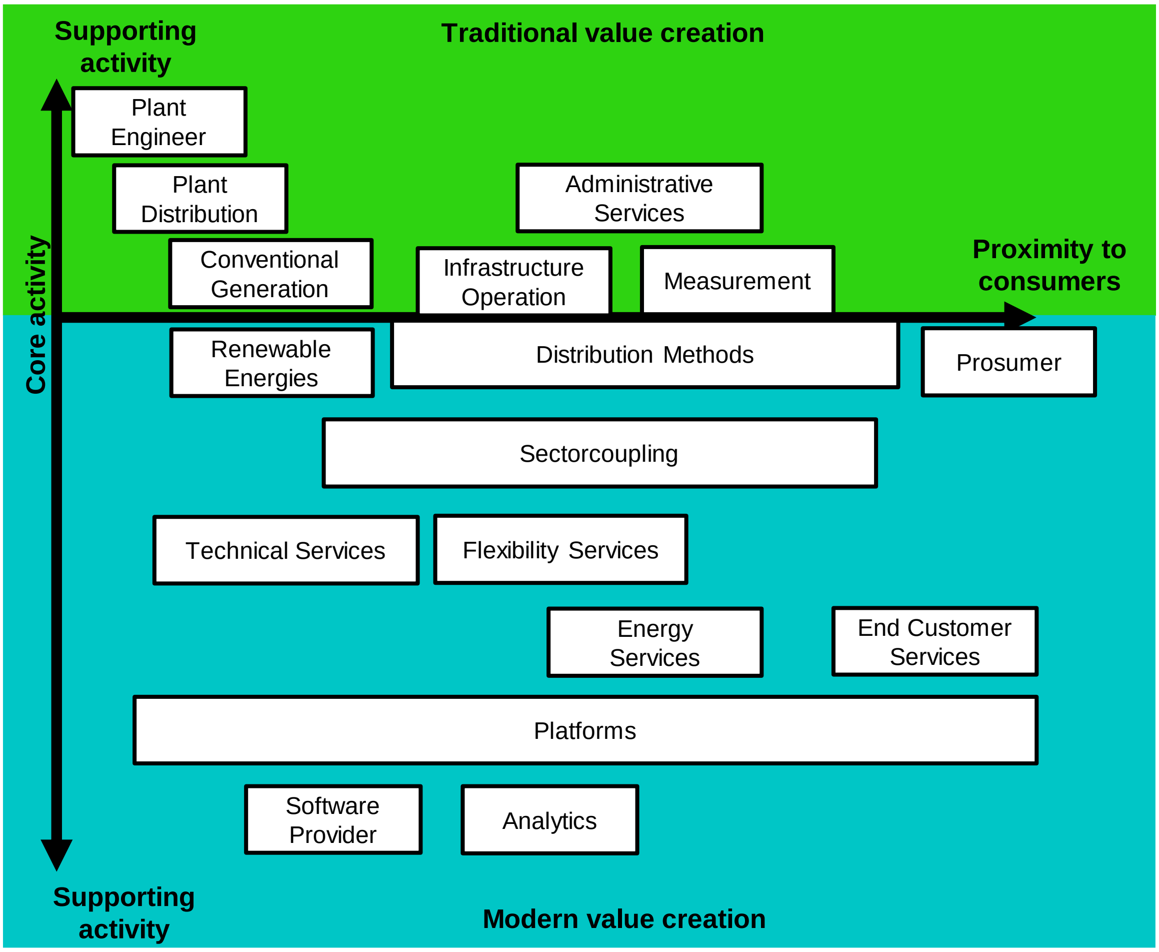


**Figure 3: Overview of business model classes of the energy transition, own representation according to Giehl et al. (2019b)**

Giehl et al. (2020) emphasize that, on the one hand, all business models in the energy industry are affected by digitalization, which is ultimately also seen as a driver and enabler of the energy transition. On the other hand, digitalization has enabled the new business model class of "platforms", which are characterized by the networking of people and companies, the use of software and data platforms, and the integration of decentralized measurement and control technologies, as well as artificial intelligence (Giehl et al. 2019a; Giehl et al. 2019b).

## 4.2 Forms of digital energy communities

The trends of decarbonization, especially in connection with the spread of renewable energies, decentralization and democratization, have also contributed to the emergence of the concept of energy communities. They are already widely implemented in practice (partly under different names) and are subject to further development and improvement in science. According to Blasch et al. (2021), energy communities can be seen as a kind of sustainable business model that provides social, economic and ecological benefits for the actors involved.

A number of definitions exist for the concept of energy communities (Blasch et al. 2021; Gui and MacGill 2018; Moroni et al. 2019a). Moroni et al. (2019a) for example, propose the following general understanding of the term: “groups of individuals who voluntarily accept certain rules for the purposes of shared common objectives (only or also) relating to energy; that is: (1) purchasing energy as collective groups (2) and/or managing energy demand and supply, (3) and/or generating energy.”

With the adoption of the EU winter package "Clean Energy for All Europeans", the concept also found its way into European legislation under the keywords of "jointly acting renewables self-consumers ", "renewable energy communities" and "citizen energy communities", which differ, among other things, in requirements regarding the purpose, the type of actors involved, their spatial distribution and the scope of activities. The latter is broadly defined in the case of citizen energy communities: "generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or […] other energy services” (EU 2019). According to the provisions of the Winter Package, corresponding concepts for energy communities were to be implemented in the countries of the European Union by 31 December 2020 (Electricity Directive) and 30 June 2021 (Renewable Energies Directive).

With the use of information and communication technology (ICT) and digital measurement and control technologies, individuals and companies can be networked and community models can leverage additional flexibility potential. In this way, important energy services can be provided for the energy transition (Mlinarič et al. 2019; Zhou et al. 2020), which are needed to integrate the increasing share of decentralized and volatile renewable energies (Witte et al. 2020). An essential factor is that the coordinator of such a community and its members have the possibility of bidirectional communication and automated measurement, control and regulation in order to be able to react automatically to signals from outside (e. g. price signals or direct control signals) (cf. Giehl et al. 2019a). This opens up new possibilities for providing and sharing energy services that were previously reserved for central actors due to certain conditions (e. g. minimum sizes, response time or communication channels) (Loock 2020). We refer to energy communities that use digital technologies in this way as "digital energy communities" and understand them as a subset of energy communities in general.

Since energy communities using digital technologies represent fundamentally new approaches to the implementation of established energy industry processes, they are, according to Loock (2020), not to be understood as incremental but as transformative business model innovations that enable both, the independence of individual actors from these processes (e. g. through self-supply of energy), and the integration into existing markets to address system-wide challenges (e. g. integration of renewables through the provision of flexibility). These models thus use digitalization to develop new markets, roles and services, and have the potential to overtake and even replace existing business models in the energy industry (cf. Loock 2020).

In the scientific literature, various concepts are discussed that can be understood as digital energy communities when bidirectional ICT and MSR technology are used. An implementation of the models in practice has been observed in the past ten years or so in the form of pilot projects, but also economic implementations. Four concepts and corresponding practical examples with technical implementation of digital, bidirectional elements are presented below. The four types of energy communities presented are often not without overlap in practice, as the associated examples demonstrate[1].

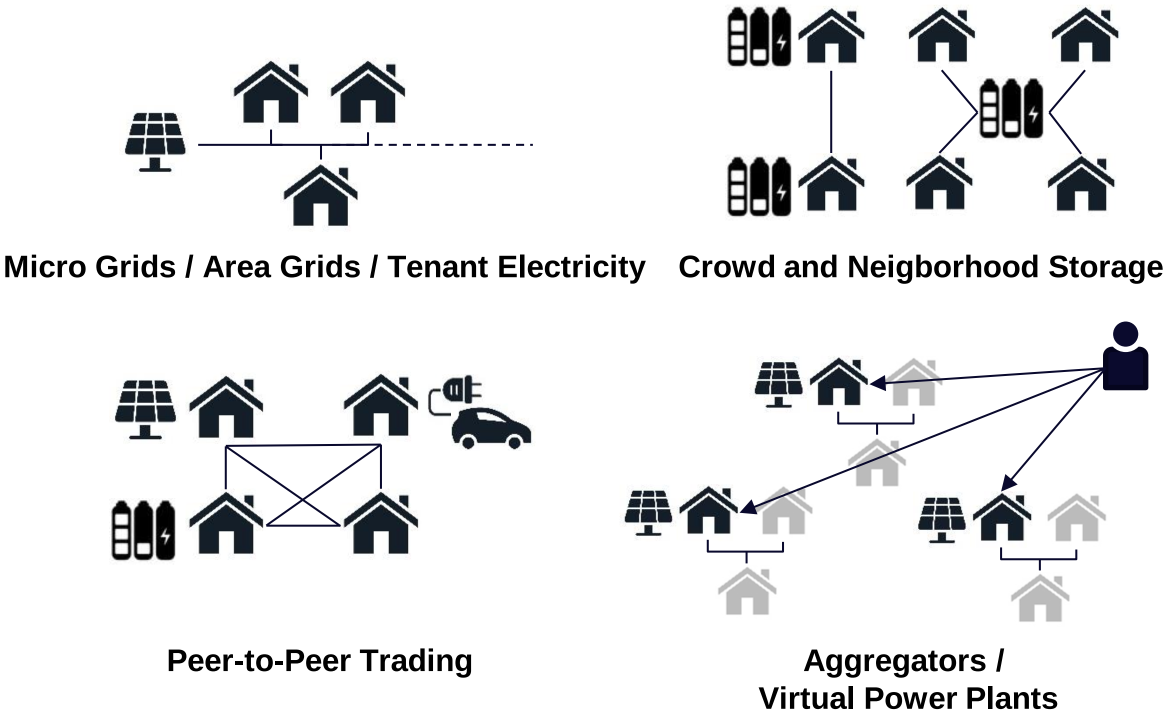


**Figure 4: Forms of digital energy communities, own representation**

**Local supply with renewable energies; microgrids**

The concept of local renewable energy supply can involve, for example, local heating grids, individual Photovoltaics (PV) or battery owners, or cogeneration plants, often interconnected via private grid infrastructures. A well-known form are local microgrids (formerly sometimes referred to as area and property grids), which can be self-contained or connected to the public electricity grid (Gui and MacGill 2018; Mlinarič et al. 2019).

A practical example from the commercial context is the microgrid on the company site of Siemens in Vienna. By linking various generation and consumption units, electricity and heat supply are optimized. A 312 kWp photovoltaic system, a 500 kWh battery storage system, a building and energy management system, as well as the possibility for load control and optimized charging of electric

[1] For example, aggregators can also appear in microgrids, storage concepts and in peer-to-peer platforms, or locally oriented concepts can be organized with a decentralized trading platform.

cars are integrated. A private 5G mobile network is used for communication between the technical units. The microgrid is connected to the public electricity grid. This makes it possible to provide system services such as control energy (Siemens 2020).

One project for integrating private consumers is the "Smart Quarter Durlach" in Karlsruhe. Five existing multi-family buildings with a total of 175 residential units are equipped with two heat pumps and five PV systems (193 kWp in total) in an area grid, as well as with two cogeneration plants (100 kW in total) and a local heating pipeline to supply the residents with electricity and heat. An intelligent energy management system optimizes self-consumption and the economic efficiency of the plants. For this purpose, the schedules of the heat pumps and cogeneration plants are adjusted with the help of artificial intelligence, taking into account consumption, weather forecasts, storage levels and the current PV output (Fraunhofer ISE 2020; Lämmle 2020).

Other microgrid concepts are for example the "Mobility2Grid" project, which is being implemented with the help of electric vehicles on the EUREF campus in Berlin. A combination of microgrid and peer-to-peer trading for 20 households is the "Landau Microgrid Project" (LAMP). Other examples of smart neighborhoods are the "Synergie Quartier" in Walldorf or the "Smart East" project in Karlsruhe's Oststadt.

**Crowd and neighborhood storages**

Electric vehicles, larger battery storages and decentralized storages can be used collectively in the concept of crowd and neighborhood storages. This can be a collection of individually owned batteries or single larger batteries in communal ownership. This can be used to provide different types of flexibility services, e. g. for general energy supply, for the integration of renewable energies, for the provision of system services, for the avoidance of transmission grid and distribution grid expansion, and for the energy management of customers (Giehl et al. 2019a; Mlinarič et al. 2019; Schnabel 2020).

One practical example is the new housing development "Am Umstädter Bruch". Here, the energy supplier Entega has installed a battery storage system with a capacity of 274 kWh, which can be accessed by 25 households that are equipped with PV systems (min. 5 kWp) and partly with heat pumps. For this purpose, the participants conclude a capacity rental tariff with the supplier and can temporarily store PV electricity surpluses for 24 hours. Necessary information about the households' electricity consumption is collected every 15 minutes with the help of smart meters. With this solution, households can achieve a degree of self-sufficiency of up to 70 percent without having to invest in a storage system or take technical risks. The energy supplier markets storage capacities that are not booked elsewhere, regionally and nationally. The neighborhood storage model is intended to relieve the distribution grid structures (Entega Plus 2020; IÖW 2022; Petermann 2020). Similar concepts have been implemented with MVV Energie's "Strombank" or in the "Energy Supply Cooperative Franklin" neighborhood in Mannheim.

A combination of central storage (750 kWh) and several decentralized PV battery storage systems is being tested by the distribution grid operator Avacon Netz in the community of Abbenhausen in Twistringen. Heat pumps and night storage heaters are also integrated into the technical concept. The aim of the project is to test several use cases for the energy community in the supply area and to determine the benefits for the distribution grid. Firstly, these include island grid operation, in which surplus electricity is temporarily stored within the energy community, secondly, the provision of power for the upstream grid in order to stabilize the interconnected grid with the technical units, and thirdly, so-called package-based energy supply, in which remaining energy requirements of the community are forecasted and supply along a supply line is planned with the help of weather forecasts. For the implementation, an energy management system is used that takes into account the flexible consumers and producers in an active power grid management by the distribution grid operator (Avacon Netz 2022; Glennung et al. 2020; Schmidt 2021). Other supraregional examples of crowd storages are the business models of Sonnen and Lichtblick, which are presented in the section on aggregators and virtual power plants.

**Peer-to-peer energy trading**

According to the EU Renewable Energy Directive II (RED II), the concept of peer-to-peer trading describes "the sale of renewable energy between market participants by means of a contract with pre-determined conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator" (EU 2018). The basis for this is an online software platform that brings customers and suppliers together. This can be realized with or without the participation of aggregators (Gui and MacGill 2018; Mlinarič et al. 2019; Zhou et al. 2020).

In the Viennese neighborhood "Viertel Zwei" and the associated research project, 100 residents were able to trade electricity from a 100 kWp rooftop PV system among themselves in order to use it more effectively on site or to sell it on the stock exchange. A capacity of 1 kWp was assigned to each participant and the corresponding electricity output was at their disposal. Furthermore, e-charging points and a 70 kWh battery storage were integrated into the concept. The members of the energy community were able to determine the conditions for the purchase and sale of the electricity themselves via an app on a platform and choose between different dynamic or static electricity tariffs. A blockchain was used to enable trading among the actors. It was used to realize the transactions and settlements, as well as the tracking and identification (Christof 2021; Wien Energie 2022).

The peer-to-peer platform "Tal.Markt" of the Wuppertal Stadtwerke has a broader geographical focus. Initially regionally and now also nationwide, customers can select and combine individual offers from individual operators of renewable energy plants to cover their consumption, which can also be changed at short notice. If a smart meter is available, the customer's consumption data can be evaluated every 15 minutes. Thus, in comparison with the use of standard load profiles, consumption can be matched better with the generation side. However, direct control of consumption and plants has not yet taken place. The transactions are carried out via blockchain (ContextCrew 2019; WSW Wuppertaler Stadtwerke 2022). Another example of peer-to-peer trading is the "Altdorfer Flexmarkt", where decentralized flexibilities can be procured in a cost-optimized manner for distribution grid stabilization from a supply pool of different producers and consumers.

**Aggregators and virtual power plants**

Aggregators are a new type of energy service provider that can increase or decrease the electricity consumption of a group of consumers depending on demand and grid conditions. Via a suitable communication interface, they can influence and control connected technical units in such a way that they form a portfolio with which the aggregator can be active in the wholesale electricity and system services markets. Units can be decentralized market actors such as consumers, prosumers, active customers (e. g. with price-dynamic tariffs) and energy communities. Aggregators also form the basis for broader flexibility platforms, where plants such as PV, heat pumps, batteries and thermal storage and EV batteries are combined into virtual power plants and are remotely controlled (Giehl et al. 2019a; Gui and MacGill 2018; Löbbe and Hackbarth 2017; Mlinarič et al. 2019).

On a supraregional level, the Sonnen company organizes several thousand PV battery storage units under 25 kW capacity in a virtual power plant that is prequalified for the provision of power system services like Frequency Containment Reserves. The basis is a self-developed software that coordinates the plants and enables secure communication with the transmission grid operators via the public internet. The functionality of the virtual power plant is ensured even if the communication infrastructure fails. In the future, other small-scale systems such as heat pumps, EVs or air-conditioning systems can be included in the pool. Other applications for the virtual power plant were also demonstrated: grid management in distribution grids, redispatch and "use before curtailment" of renewable energies. Here, the transactions with the flexibility demanders are sometimes carried out via smart contracts, documented in a blockchain and settled via cryptocurrency (Palla 2020; Palla 2018; Preiß 2020; Preiß 2017). The company Lichtblick offers a similar model for private battery storage with the so-called "swarm battery". An example of the aggregation of heat pumps for the provision of system services is the ViFlex project by the company Viessmann. It can be observed that the aggregators of small-scale technical units are often also providers of the associated energy technology (storage, PV system or heat pumps).

The virtual citizen power plant of the EWS Schönau has a smaller geographical focus. It links around 30 private and commercial participants from five distribution grid areas equipped with PV systems (370 kWp in total), storages, electric vehicles, fuel cells, heat pumps, heating rods and smaller cogeneration plants into a virtual unit. Tenant electricity properties and local heating networks are also represented. An energy management system, smart metering systems and CLS boxes for system control are used as digital elements. Furthermore, users can track the energy flows live via an app and internet portal. The basis is a 15-minute accurate measurement and data transmission via the smart meter gateways. In addition to optimizing self-consumption, the declared goal of the project is to organize flexibility in such a way that electricity surpluses are used and the systems are controlled in a way that serves the grid (Coneva 2020; EWS Schönau 2022; 50,2 online 2020).

The overarching view of the examples makes clear the ranges for the design along certain business model dimensions between and within the concepts:

- Benefit dimension: The services provided can focus on pure energy provision for small actors (including the sale of energy technology, if applicable), on system services and energy provision for upstream energy markets, or both can be served. Thus, the geographical reference of the value proposition can be local, regional or supraregional.
- Partner dimension: Actors from different sectors can be involved as partners for the representation of service provision. Manufacturers of ICT and energy technologies, software development companies, classic energy suppliers as well as start-ups acting as energy managers and platform operators can be observed.

– Customer dimension: Customers or the actors that provide the decentralized energy resources can be private households or small and medium-sized enterprises that provide, consume and store energy. On the other hand, there are customers outside the community, such as transmission system operators or wholesale customers on the energy markets.
– Value creation dimension: The range of integrated energy technologies includes a number of demand-side systems (heat pumps, night storage heaters, heating rods), supply-side technologies (PV systems, cogenerations plants, fuel cells), storages (large and small battery storage, electric vehicles) and electricity and heat grids for transmission. The bundling of the integrated energy technologies can be local, regional or supraregional. Digital systems that are integrated as enablers include smart meters, smart meter gateways, CLS boxes and energy management systems for measurement, information transfer and control of energy flows, smartphone applications and internet portals for customer communication, as well as blockchains, cryptocurrencies and smart contracts for the financial management of processes.

## 4.3 Challenges and risks of digital energy communities

The comparatively innovative concepts of digital energy communities face a number of challenges that need to be overcome in the coming years in order to take the models into the mainstream and make an effective and sustainable contribution to the success of the energy transition.

**Economic challenges**

The implementation of energy communities faces the limited investment opportunities of the participants, which restricts the scope of action and scale of the projects. Cost-related economies of scale are thus difficult to leverage (Gui and MacGill 2018). The economic interest of third parties (e. g. technology manufacturers, grid operators) in such business models is therefore not particularly pronounced (Sousa et al. 2019).

The necessary regulatory framework for widespread implementation of energy communities or full exploitation of the associated potentials is often not yet in place (Blasch et al. 2021). Necessary changes affect a large number of actors along the traditional energy value chain and therefore do not develop at the speed at which new technologies and business models emerge (Zhou et al. 2020). Moreover, as the business models of the classic energy suppliers can be endangered by energy communities, support for regulatory adjustments is hardly to be expected (Gui and MacGill 2018).

The regulatory barriers that currently still exist for energy communities can also have financial implications for participating actors. In Germany, the current structure of grid fees, taxes, levies and charges often prevents the economic operation of energy communities, especially of supraregional models such as virtual power plants (Gährs et al. 2021b). Against this background, it must be examined to what extent these electricity price components are appropriate in the case of energy communities and the services provided. Furthermore, the regulatory definitions of energy communities implemented nationally vary in their restrictiveness and complexity. For example, regulations may not cover all forms of energy communities presented, or they impose high bureaucratic hurdles that make projects unattractive or uneconomical, which in total hinders the expansion of the concepts (Palm 2021).

**Technical challenges**

One technical challenge is the connection and integration of the models into the existing electricity grid infrastructures. Here, certain quality and safety requirements must be met and continuous availability must be ensured, e. g. for the provision of primary control power (Gährs et al. 2021b). In addition, there is the technical complexity, which is challenging due to the coordination of the large number of actors and decentralized technical units that need to be integrated (Gui and MacGill 2018; Sousa et al. 2019).

Collective action can lead to simultaneity effects, e. g. through the synchronous charging of batteries, which can put additional stress on grids and trigger demands for grid reinforcements (Mlinarič et al. 2019) (see also Chapter 3.3). In the absence of central, coordinating actors for the community, the predictability of behavior is another problem for grid operators (Sousa et al. 2019). The example of simultaneity effects also shows that energy communities are dependent on the current and future technical grid infrastructures (Gui and MacGill 2018).

A further technical challenge is the implementation, use and maintenance of the necessary communication and control infrastructures, which, in addition to the requirements for functionality, must fulfil the guidelines for data protection and security (Sousa et al. 2019).

**Environmental challenges**

The environmental benefit of energy communities can be to build and better utilize energy plants and provide flexibility. This should better integrate renewable energies, displace conventional energy sources and avoid grid expansions, thereby providing environmental benefit primarily at the system level and to households (Gährs et al. 2021b). On the other hand, the production and operation of the necessary ICT and technology for measuring and control requires additional resources and energy (Gährs et al. 2021b; Sousa et al. 2019). This also includes expenses for background processes, such as transactions via blockchains and the use of cryptocurrencies, which can mean high environmental burdens (Schinckus 2021). Rebound, sufficiency and other use-related effects can also have a significant impact on the environmental outcome of digital applications in general (Pohl et al. 2019), and for renewable energy approaches in particular (Galvin et al. 2021; Galvin et al. 2022). Holistic studies on the environmental burdens and benefits of digital energy communities are scarce to date (Gährs et al. 2021b).

**Social challenges**

The presented models of (digital) energy communities require different degrees of cohesion between the participating actors. In particular, the locally oriented concepts require a higher degree of cohesion between the participants of the energy community, which has to be established in advance in order to be successful. On the other hand, a high level of cohesion and coordination may imply a lower capacity for social and technical innovation (Gui and MacGill 2018).

The behavior of participants in the operation of communities is very complex and difficult to predict (Zhou et al. 2020). There is also a concern that the motivation to actively participate in trading schemes is not very strong, as is generally the case with electricity products (Sousa et al. 2019). This raises the question of how lasting the potential positive effects of energy communities are and what measures can be taken to ensure their long-term success.

One barrier to the widespread implementation of digital energy communities is the reservations of potential participants about additional ICT infrastructures in the household and the control of private technical systems by third parties from outside (Moshövel et al. 2015).

# 5 Digital products and tools in municipal processes

## 5.1 Forms of participation and the role of digital tools

In the context of the digital transformation and the associated digital change, new digital opportunities, methods and tools are opening up for the involvement of local actors in various areas of impact, such as the planning, development and implementation of new energy supply structures. In the field of urban planning, a variety of digital tools and products are already extensively used and deployed to involve the public and citizens in planning and decision-making processes (Hasler et al. 2017; Kleinhans et al. 2015; Seltzer and Mahmoudi 2013). Many cities have their own web-based platforms that integrate various functions ranging from a pure information base to collaborative design. Functions among others include surveys, the possibility to submit comments or even map-based spatial planning. Mapping or crowdsourcing tools are used here to integrate the opinions and knowledge of the local population into municipal decision-making processes (Stadt Hamburg 2022; Stadt Würzburg 2022). Furthermore, in recent years – also due to the pandemic – more workshops, citizens' councils and other events have been held digitally (Schiebe 2020). Energy and climate issues also often play a role in this context. Digital tools are used here at the political-social level for (mutual) information, consultation or cooperative decision-making, but also in the energy industry context, e. g. to promote financial participation processes for infrastructure projects for renewable energies or for internal networking of energy communities at the local level. Digital tools and products can be used in a variety of ways for participation in municipal decision-making processes and can therefore be differentiated and categorized in different ways.

**Degree and depth of participation**

Based on Arnstein's concept of the "Ladder of Citizen Participation" (1969), (digital) participation tools can be categorized according to the degree or depth of participation. The ladder of participation consists of eight levels, ranging from so-called manipulative processes to consultation and citizen self-direction, and is summarized in three major groups: "no participation", "sham participation" and "citizen power" (Arnstein 1969). Today's evaluation schemes often make use of Arnstein's considerations and adapt them to their respective analytical considerations (Hasler et al. 2017; International Federation 2018). Hasler et al. (2017) extend Arnstein's concept with digital aspects according to type, direction and intensity of exchange. At the lowest levels, the information levels, communication is one-way. Information is shared, but no exchange takes place. At the consultation level, citizens answer questions from local governments, e. g. through online surveys. At the contribution level, citizens are enabled to share opinions or knowledge on specific topics and projects via platforms or apps with comment functions. These are not limited to closed questions and an exchange can take place. At the collaboration level, citizens can interact freely, exchange ideas and proposals, and comment on or evaluate other proposals. The highest level is what Hasler et al. (2017) as empowerment, an empowerment of citizens in the decision-making process. Mukhtarov et al. (2018) differentiate the use of digital tools and products not by level, but by forms of interaction between government and citizens. They distinguish between

– Government as platform (G2C): governments provide data for informed decision-making to increase transparency, trust and legitimacy;

– Citizen Sourcing (C2G): citizens share (bottom-up or top-down) opinions with each other and with governments for planning and planning purposes (crowdsourcing);

– "Do it yourself" government (C2C) is characterized by self-organized citizens with little or no government involvement; and

– Collaborative planning and groupware (GwC) involves collaborative problem solving using visualizations, scenario building and continuous face-to-face contact.

These classifications refer to the type and intensity of communication, exchange and participation.

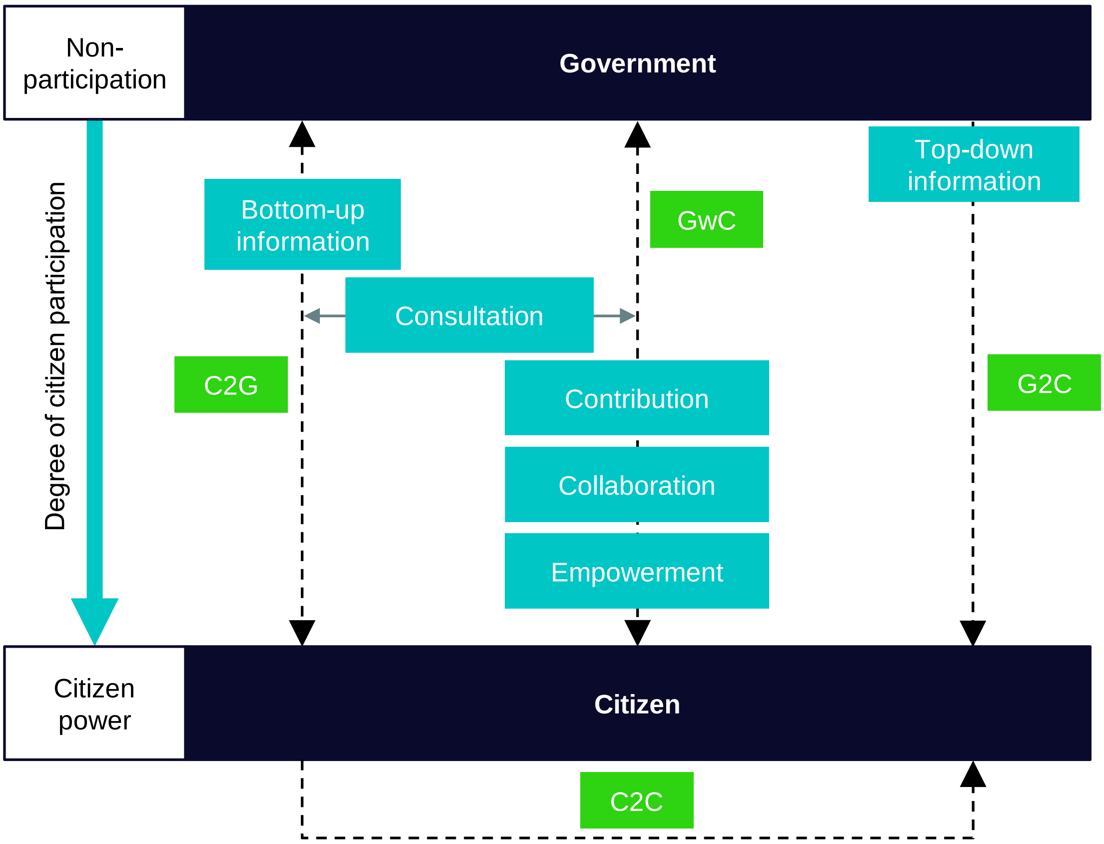


**Figure 5: Categorization of (digital) participation elements, own representation according to Hasler et al. (2017) and Mukhtarov et al. (2018)**

Further possibilities of classification include differentiation according to the type of tool, e. g. web-based participation platforms and mobile participation apps, as well as their possibilities and functions (Gün et al. 2020). Web-based participation platforms include digital participation portals, games and desktop-based application platforms that aim to collect, analyze, visualize and disseminate information, expertise and proposed solutions. Features include 2D and 3D geovisualizations, Web 2.0 collaboration tools such as collaborative mapping and interactive sketching, evaluation and classification of proposals so that users can visualize, influence and discuss (urban) projects in a collaborative environment.

**Goals of participation**

Digital tools and products can also be differentiated according to the respective phase of the planning process and the related objectives (Gün et al. 2020; Hasler et al. 2017). In the early or diagnostic phase of a planning process, the goal may be to identify opinions, barriers and shortcomings, for which crowdsourcing tools or collaborative mapping tools (e. g. PPGIS) can be used. In the development phase of a project, a vision or new urban or regional development plans, modelling, simulation or scenario development tools provided to participants for information or collaborative design can be useful to make forecasts and weigh preferences and proposals. The decision phase is about evaluation and feedback on already developed plans or project designs. In this later phase, according to Münster et al. (2017), visualization techniques, such as 3D environments and augmented reality (AR), become more important to make projects more tangible for stakeholders. In addition to these content- and outcome-oriented goals of participation, such as the identification of information about local conditions or opinions of the population, higher-level goals can also be pursued. Newig et al. (2013) mention here, among others, information, sensitization, education, motivation of potentially affected people/citizens, achieving (democratic) legitimacy, conflict reduction, conflict resolution and compromise, or disseminating or implementing knowledge, empowering action or networking. Klessmann et al. (2014) differentiate here between

1. the achievement of solution-relevant information,
2. the aim to reach as many participants as possible,
3. the aim to reflect the preferences and opinions of citizens, to balance different interests and to correspond as closely as possible to the socio-demographic structure of the target group,
4. making the background for decisions clear and increasing satisfaction with planned measures (acceptance) and
5. promoting the political engagement of the participants and strengthening their trust in the democratic processes.

## 5.2 Differentiation of digital tools for participation in the context of the energy transition

Digital tools can be used in various contexts in energy policy participation processes at the municipal level. First of all, it can be considered which local policy options exist for the expansion of renewable energies and how citizens can be involved in this. Municipal policy options for the expansion of renewable energies include overarching measures such as the development of energy and climate protection concepts and local objectives, the designation of suitable areas for renewable energies through land use plans, participation in regional plans or the joint inter-municipal designation of wind energy priority areas. In the area of regulation and planning, energy-related specifications can be made for development plans or buildings. Municipal enterprises or private-law companies owned by municipalities can offer their own (renewable) energy through municipal energy utilities. They can also be active in public relations and education work or promote and support investments in renewable energy projects. The possibility of financial participation of citizens in renewable energy systems can also have an impact on political decision-making processes and the successful implementation of the municipal energy transition (u. a. Holstenkamp et al. 2018). Some of the tools and products used, from purely informative websites to augmented & virtual reality applications, will be presented here in an energy-specific context.

**Project website / municipal website**

On a purely top-down information level (G2C), digital tools, such as websites in municipalities, are already used to inform about decision-making processes and planned infrastructure projects, such as the construction of renewable energy plants, and potentially also to visualize them (Energieagentur Ebersberg-München 2022; Stadt Bornheim 2022). Websites can also be used to inform about political, but also financial participation options.

*Excursus: Participation platforms for financial participation*

In the area of financial participation, digital tools are also used to reduce complexity, potentially reach a majority of local actors and actively involve them in shaping the energy transition. They can also aim to standardize financial participation processes and reduce the organizational effort. This can be done via external platforms (e. g. from banks) or the respective providers' own participation platforms (e. g. municipal utilities or energy supply companies) can be created. These platforms can also be used to survey citizens' interest and participation levels. Digital citizen participation also enables municipal energy utilities and energy supply companies to make future or recurring offers of financial citizen participation scalable (Eueco 2021).

**Discussion boards / online forum / online surveys**

Discussion boards and online forums are virtual places on the internet that serve to exchange and archive opinions, thoughts and experiences; these can be used for consultation (C2G), but also for participation and cooperation (GwC). Here, communication takes place asynchronously, i. e. with time-delayed reactions. The independence of time and place of such formats is seen as a way of integrating a larger or more diverse group of people into the participation process. They can thus contribute to the discussion at a later stage. Online surveys are used for empirical opinion research and are primarily used for consultation (C2G or GwC). They can be used to generate mood picture and opinion statements on specific project ideas and drafts. The questionnaire to be filled out is stored on a web server, either as Hypertext Markup Language (HTML) or within the survey software used on the server (Schiebe 2020). Climate and energy issues are increasingly addressed in such participatory portals or on municipal websites with feedback functions, surveys or discussion forums in cities and regions (Stadt Würzburg 2022; Zebralog 2015).

**Mapping**

Mapping is the process of locating content on georeferenced maps. For example, in a participation process, certain locations can be noted and displayed on a previously prepared map. This is also referred to as a form of Public Participatory Geographic Information Systems (PPGIS) method. Afterwards, this information can be analyzed by planners in order to gain a variety of information on site-specific projects. The exchange therefore usually takes place on a participation and collaboration level (GwC). PPGIS are used in the energy context, e. g. for the identification and suitability of wind priority areas (Mekonnen and Gorsevski 2015) or also for participation in energy and climate protection concepts and for the spatial localization of concrete ideas and measures in this context.

These can also be integrated accordingly on project or municipal websites and combined with other formats (Stadt Dresden 2022).

**Video call / conference**

Video calls and conferences are suitable for allowing a large number of people to communicate with each other in real time and to engage in exchange. Video conferences or video calls can be used in a variety of digital or hybrid formats (Schiebe 2020). In the energy and climate sector, projects have been moved into the digital space due to the Covid-19 pandemic, such as the digital results conference and panel discussion on the West-coastal dialogue in Schleswig-Holstein (TenneT 2020). Likewise, at the national level, the "Citizens' Climate Council", in which randomly drawn citizens discussed possible measures to deal with the climate crisis and developed policy recommendations to meet the Paris climate targets (Bürgerrat Klima 2022). Even though video conference formats can be used for pure top-down information transfer (G2C) in planning processes, in the context of the above-mentioned examples they can primarily be assigned to the participation and collaboration level (GwC).

**Virtual & augmented Reality**

"Augmented reality" (AR) stands for a visualization method that creates an image of reality with the help of computer-based simulation. Virtual and physical reality can be linked, e. g. to project designs of infrastructure projects onto their later locations. In augmented reality, virtual information is added to the real environment, while in virtual reality a completely virtual space is created (Schiebe 2020). There is increasing reference in the energy policy context to the potential of visualization tools from the fields of virtual reality (VR) and augmented reality (AR) to enable a realistic representation of planning and to reduce access barriers and complexity in the planning of RE infrastructure projects, thus promoting inclusivity and representativeness in planning and participation processes (Deckert et al. 2020; Kauling et al. 2021; Spieker 2018; Spieker et al. 2017). They can thus serve purely to convey information (G2C), but can also be used interactively to integrate suggestions and opinions (GwC). In the project on the pumped storage power plant in Forbach, participating citizens confirmed that complexity was reduced by virtual reality tools. Project managers mentioned the early identification of conflict potential as a further potential of these tools (Deckert et al. 2020).

**Simulation and calculation tools**

The use of simulation-based tools in participation processes is a new approach and offers the possibility to establish and clearly present connections between the individual sectors (electricity, heat, mobility), climate impacts and generation technologies (Fiukowski et al. 2019). In the online potential calculator ERNEUERBAR KOMM! for example, classic basic geodata from the cadastral administration (ALKIS) and information from the Digital Landscape Model (DLM) are evaluated and overlaid together with other spatial data - for example on wind speeds, solar irradiation values, protected areas. On the online calculator, every citizen, local councilor or mayor can not only look at the theoretically available technical potential, but also put together the desired energy mix themselves using the so-called "mobilisation factor" (Klärle and Langendörfer 2011). On the one hand, this can serve as information (G2C), but it also enables the collaborative involvement of stakeholders in the development of energy scenarios (GwC). The participatory design of energy scenarios can help to balance out inequalities in the level of knowledge, clarify complex interrelationships of the local energy system and provide stakeholders with an insight into new perspectives (Fiukowski et al. 2019).

*Excursus: Implementation of (digital) energy communities*

In the implementation of decentralized, digital energy communities at the municipal level, digital tools and service platforms can be used to network, conduct local energy trading and efficiently manage energy production and consumption. In the Oldenburg Fliegerhorst energy neighborhood in the Helleheide neighborhood, this is being implemented in the form of a digital twin of the physical infrastructure (OFFIS e. V. 2021). This can be seen as a product that aims to promote the self-organization of residents and the local exchange of resources.

**Gamification**

Gamified approaches can be used to integrate a variety of content into participation processes. Gamification describes the application of game-typical elements in a non-game context. These elements include, for example, experience points, high scores, progress bars, leaderboards, virtual goods or awards (Schiebe 2020). Many games in the energy context focus on energy savings in households and the consumer level (e. g. "Energy Chickens", "Energy Cat") (Romanov and Holler 2021). Unconventional methods, such as gamification, can contribute to increasing public awareness of this topic and the motivation to deal with it. The focus here is on low-threshold information transfer (G2C), which can also inspire other target groups, such as children or young people, concerning planning content (Romanov and Holler 2021; Schiebe 2020). Some processes and case studies from the energy policy context in which digital tools were used for participatory design are listed in Table 3. These illustrate the diversity of the tools used and the associated objectives.

**Table 3: Examples of the use of digital tools in the energy policy context, own representation**

| Digital format | Example projects | Techno-logy(s) | Type of participation | Target(s) | Planning context |
|---|---|---|---|---|---|
| **Discussion board / online forum / online survey** | Dialogue-oriented participation platform on sites for wind turbines in Heidelberg, Germany (Zebralog 2015) | Wind | Information level (G2C) and participation level (GwC); tool can be used online | Record preferences and reasons for priority areas of different citizens | Definition of concentration zones in the land use plan |
| **Video call / video conference** | Dialogue procedure West Coast line: Klixbüll (Niebüll) – Danish border – Digital results conference (TenneT 2020) | Power grid | Information level (G2C) and participation level (GwC); tool can be used online | Evaluation and feedback on plans or project designs | Route planning; spatial and infrastructure planning |
| **Mapping** | Interactive and collaborative determination of priority areas for RE in Dalfsen, the Netherlands (Flacke and De Boer 2016) | PV & wind | Participation and collaboration level (GwC); Stakeholder workshops with tools as offline support on site | Capture preferences and reasons for priority areas from different stakeholders | Land use plan (spatial and infrastructure planning) |
| **Virtual Reality (VR) / augmented Reality (AR)** | Expansion of pumped storage power plant in Forbach, Baden-Württemberg (Deckert et al. 2020) | Power storage | Top-down information and participation level (G2C/GwC); tools as offline support on site | Involve different stakeholders; identify opinions, barriers | Spatial and infrastructure planning (regional planning procedure) |
| **Simulation-based tools** | Stakeholder Empowerment Tools (StEmp) in the energy transition in regional contexts in Germany (Fiukowski et al. 2019) | Divers | Information, consultation and cooperation level (G2C/GwC); tools primarily usable online | Inclusivity & representativeness (balancing access and knowledge asymmetries); empowerment | Preparation of regional climate protection concepts |
| **Gamification** | "Changing the Game" app was designed in the Energetic Neighborhood Quarter Fliegerhorst Oldenburg and is intended to make complex contents of the energy transition tangible (OFFIS e. V. 2022) | Divers | Information level (G2C); tool can be used online | Inform, motivate, sensitize | Designing the energy supply of a residential neighborhood (fictitious) |

## 5.3 Opportunities and risks of digital participation formats

To promote legitimacy or even the effectiveness of planning processes, participation and public involvement are emphasized as successful strategies for conflict management and the promotion of legitimacy and effectiveness in energy transition planning processes. The discussion about the role of digital tools in this context often depicts two extreme points: between techno-optimism (or techno-determinism) and -pessimism (Schoßböck et al. 2018).

The techno-optimistic view and corresponding studies see digitalization as an opportunity for better participation opportunities for society and the internet as a potential to promote democracy through innovative decision-making (Schoßböck et al. 2018). Some authors argue that, under certain conditions, the use of digital tools can have a positive impact on factors such as inclusivity and representativeness or democracy promotion and empowerment (Deckert et al. 2020; Fiukowski et al. 2019; Ruddat and Mayer 2020; Spieker 2018). Deckert et al. (2020) name three potentials of digital tools as a supplement to analog participation processes:

1. Contribute to the diversification of participants through better communication and information of participation opportunities as well as the mobilization of new digitally affine target groups through the use of new visualization and simulation tools;
2. Reducing complexity and lowering access barriers to participation, especially through visualizations, and thus integrating local knowledge that can improve the quality of decisions;
3. Improved presentation of results through the visualization of participation results, which also enables decision-makers to interpret results more easily and make them understandable.

Kauling et al. (2021) also highlight the potential of visualization technologies such as GIS, virtual and augmented reality. These include making planning content accessible to the public discourse at an early stage through planning-integrated, flexible visualizations and making visualizations accessible to a broad group of the population through the provision of visualizations via everyday technologies.

On the basis of research findings on "digital inequality", on the other hand, it is argued that there are systematic differences with regard to the degree of participatory use of digital media and that socio-economic inequalities of the analog world can be mirrored or even reinforced in the digital world (Hoffmann 2020; Leitner 2018). Digital access, both physical and in terms of usability, is often unequally distributed spatially and socially (Hoffmann 2020; Pham and Massey 2018; Thonipara et al. 2020). Federal states and municipalities differ in terms of their political-institutional frameworks and goals, their financial and human resources, their digital skills and preconditions for social participation (Leitner 2018). Contextual differences, both in the application and use of digital tools in participatory decision-making processes, must therefore be considered more comprehensively in order to identify structural barriers and develop solutions for the successful use of digital tools. Concerning cybercrime and data security, Leitner (2018) also emphasizes that aspects of security and privacy must be taken into account in the development of systems for citizen participation. This is necessary to enable a protected space for exchange, to secure electronic identities and to strengthen the public's trust in the use of technology (Leitner 2018). Digital media, especially the so-called social media, can also have implications for political discourse. Incivility, the spread of "fake news" or the formation of "echo chambers" can have ambivalent effects on political participation. According to studies, "fake news" can encourage people to engage more intensively in political debates, while at the same time misinformation can increase mistrust and have a negative impact on the quality of participation (Hoffmann 2020).

To what extent and under which contextual conditions the use of digital tools in participation processes actually promotes inclusivity and representativeness as well as the quality of results of decision-making processes, and what significance this has for process results in the field of climate and energy planning, has hardly been investigated so far under real-life conditions (Deckert et al. 2020; Ruddat and Mayer 2020).

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