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The Digitalization of the Electricity System

Impact Assessment of Digital Technologies on the Electricity System and its Main Stakeholders

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Abstract

This work explores the state of digitalization of the European electricity sector and assesses the impacts of digital technologies on the electricity system and its main stakeholders. Digital technologies, such as smart meters and 5G connectivity, represent a powerful tool for system operators to face the new challenges brought about by the decarbonization of the energy sector.

By means of an extensive literature review, the position of the energy community on the topic of digitalization, the regulatory framework around it, as well as the state of deployment of digital technologies in Europe are assessed. With the use of a survey as research tool, the impacts of digital technologies on the main stakeholders of the electricity system (namely, transmission and distribution system operators) are assessed. These are based on seven predefined Key Performance Indicators (KPIs) and classified into four main impact categories – technical, economic, environmental, and social.

The results of the survey show not only a positive stand of system operators on digital technologies, but also highlight specific benefits and challenges brought about by their integration. By improving electricity networks observability and monitoring, digital technologies are enhancing electricity systems' stability and reliability and improving operational efficiency, while at the same time favoring customer engagement and the integration of more renewable generation. The increased amount of data shared, however, comes with additional threats related to cyber-security and privacy. An extensive discussion of these and other benefits and challenges experienced by system operators due to digital technologies is provided in this work.

Glossary

Artificial Intelligence (AI) – The ability of a machine to learn from experience, adjust to new inputs and perform human-like tasks. AI systems use algorithms and statistical models to analyze large amounts of data, identify patterns, and make predictions or decisions based on that analysis.

Blockchain - Decentralized, distributed digital ledger (i.e., record keeping system) that exists across a network. By utilizing a chain of validated and interlinked blocks, blockchain allows to record transaction in a secure and tamper-evident manner.

Data Space - A decentralized infrastructure for trustworthy data sharing and exchange in data ecosystems, based on commonly agreed principles. (OPEN DEI, 2021)

Demand Response - The practice of adjusting electricity usage in response to changes in energy prices or grid conditions. This can be done by reducing, increasing, or shifting electricity consumption to balance the supply and demand of energy from the power grid.

Digital Twin – A computer-based model that integrates real-time data from sensor, devices, and other sources to create an accurate virtual replica of a physical object, system, or process. Thanks to a digital twin, simulations and tests can be performed in the virtual environment before making changes in the physical world.

Edge Computing – Distributed computing architecture that brings computation and data storage closer to the data source. The processing of data at network edge reduces the latency and bandwidth requirements for data transfer, improves the speed and efficiency of data processing, and enables real-time analysis and decision-making.

Internet of Things (IoT) – A network of physical objects ("things") embedded with sensors, software, and network connectivity that allow them to exchange data and interact with each other and their environment.

Interoperability – The ability of different systems – i.e., software, hardware, or networks - to exchange data and information seamlessly, regardless of their platforms, languages, or protocols. Enabling effective, accurate, and efficient communication, interoperability constitutes the basis for systems integration.

Load Shifting - A load management technique that aims at redistributing energy demand from periods of high demand (peak hours) to periods of low demand (off-peak hours) during the day.

Peak Shaving - The process of reducing peak demand for electricity or other forms of energy during times of high usage. This is typically achieved by implementing measures (such as demand response or energy storage) that reduce energy consumption during peak hours. It is also referred to as load shedding.

Smart Meter – A device that can measure and record energy consumption data in real time. A smart meter differs from a traditional one for it can send data directly to utility companies and provide consumers with real-time data about their energy usage. Smart meters constitute an important part of the smart grid infrastructure.

5G Connectivity – The fifth generation of mobile network technology that provides faster data transfer rates, lower latency, and greater network capacity than its predecessors.

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1 Introduction

Electricity systems have come to the center of attention of the energy sector for the key role they play in the process of transitioning towards a net-zero economy. Transmission and distribution networks, in particular, represent the backbone of electricity systems and they bear the heaviest weight moving forward. The trend ignited by the net-zero commitments and plans set forth by economies and societies in recent years is reshaping the electricity landscape, and in doing so, posing new challenges to electricity grids. The electrification of processes and activities is increasing the demand for electricity; the integration of variable renewable generation is challenging the stability of the system; the rise of distributed generation is reshaping the balancing of supply and demand. System operators are left to face these challenges to ensure the security of supply and maintain the stability of the grid, while moving towards its decarbonization. Against this background, digital technologies can come to the help of system operators. As discussed in the ENTSO-E vision paper "A Power System for a Carbon Neutral Europe" (ENTSO-E, 2022), deep digitalization is regarded as a promising, high-impact game changer in the process of energy transition, especially from the perspective of electricity systems operators (Figure 1).

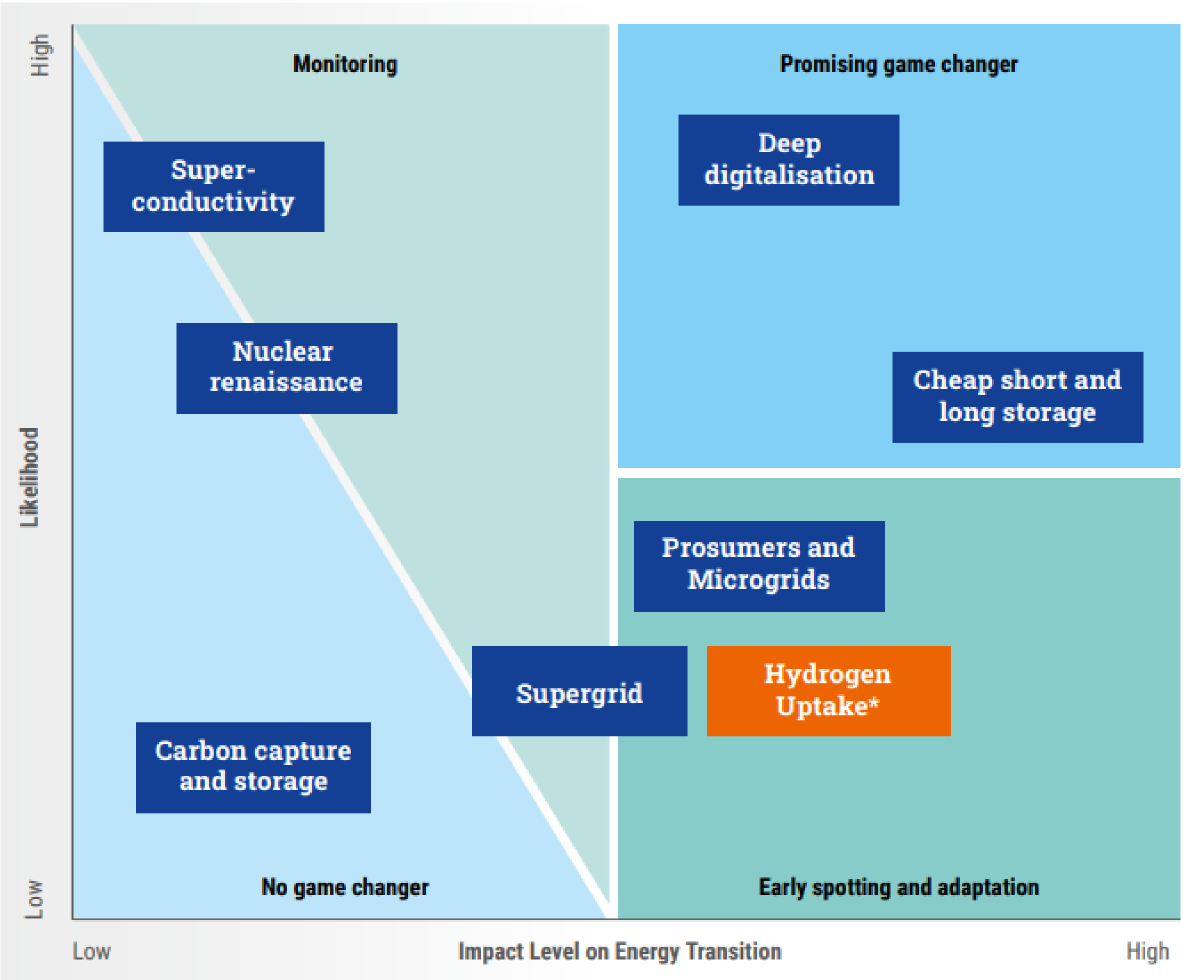


Figure 1 – Potential game changers for the decarbonization of the energy sector, *(ENTSO-E, 2022).*

The process of digitalization builds upon the wide deployment and utilization of digital technologies. These comprise a vast array of devices and technologies, such as smart meters, Artificial Intelligence (AI), 5G connectivity, and many more. Such technologies are transforming societies and economies and affect every aspect of people's life. At the same time, they are supporting the energy and electricity sectors in facing the new challenges brought about by decarbonization. By improving electricity networks observability and monitoring, digital technologies are enhancing electricity systems' stability and reliability and improving operational efficiency, while at the same time favoring the integration of more renewable generation. The digitalization of electricity systems is therefore a hot topic in the general discourse of the decarbonization of energy.

The primary objective of this work is to provide an assessment and evaluate the impacts that digital technologies are having on the European electricity system and its main stakeholders. Said impacts can come in the form of benefits, challenges, and opportunities that need to be taken advantage of, faced, or seized in the process of digitalizing electricity systems. The goal of this work is achieved with a systematical approach that, starting from an historical excursus about the stand of the energy community on digitalization and the main regulatory initiatives around it, foresees the active involvement of European system operators for a reliable and real-life testimony on digitalization and its impacts. The scope of the work includes the following points.

- Understanding the stand of the energy community on the digitalization of electricity starting from, but not restricted to, the position of the International Energy Agency (IEA) on the topic.
- Analyzing the main regulations and initiatives from European institutions for incentivizing digitalization.
- Assessing the state of digitalization in Europe, focusing on two technologies considered as key for the digitalization of electricity systems – smart meters and 5G connectivity.
- Assessing the impacts of digital technologies on the electricity system and its main stakeholders.
- Identifying the impacts of digital technologies deemed as the most relevant by system operators.
- Understanding system operators' stand on the topic of digitalization.

The methodology used to carry out this work is presented in chapter 2. After that, the work is divided into three main sections.

The first section provides the results of a literature review that sets the background and framework for this study. Firstly, three reports by the International Energy Agency (IEA), amongst others, are reviewed to paint a picture of the stand of the energy community on the topic of digitalization. In particular, an analysis of the main reasons behind the energy community's push for a more digitalized electricity system is presented. Secondly, three main communications from the European Commission are reviewed, providing an historical excursus of the position of regulators and institutions on digitalization. The directives established and actions taken to push digitalization forward, culminate in the fourth reviewed regulation, the "Digitalizing the energy system – EU Action Plan", which represents the most complete plan for the effective digitalization of the electricity system. Thirdly, the state of digitalization in Europe is assessed, with particular focus on smart meters and 5G connectivity. This provides a more technical framework for the development of this study's research.

The second section presents the development of the research from a methodological point of view. For the assessment of the impact of digital technologies on the electricity system and its main stakeholders, it is chosen to utilize a survey as the main research tool. Firstly, the relevant stakeholders to be used as respondents to the survey are identified in the Transmission and Distribution System Operators (TSOs and DSOs) of the European electricity system. Secondly, seven Key Performance Indicators (KPIs) are defined to be used as a basis for the creation of the survey and the assessment of its outcomes. Finally, the survey is drafted and submitted to the identified stakeholders.

The third section presents the results of the survey and discusses their implications. Firstly, the raw results as obtained from the survey are reported for the most relevant questions. Secondly a methodology for the assessment of the KPIs is created and based on the outcomes, these are evaluated accordingly. Thirdly, based on the defined KPIs, four impact categories are created for the classification of the survey's results. These are technical, economic, environmental, and social. Finally, starting from the survey outcomes, the impacts are analyzed and discussed within each of the defined impact categories.

As it will become clear from the reading of this work, the scope of the research and the methodology used to carry it out present some unique features that are not found elsewhere. Firstly, the focus of this work is placed solely on electricity systems, as opposed to the entire energy sector – as in (Nazari & Musilek, 2023) – or the broader society in general – as in (IEEE) or (Małkowska, Urbaniec, & Kosala, 2021). Secondly, the tool chosen for the research development – a comprehensive and centralized survey – also proves not to have been previously employed around this topic. Works such as (Nazari & Musilek, 2023) try to paint a picture of the impact of the digital transformation on the energy sector by means of literature reviews only. Finally, the restriction of the investigation to only a few, significant stakeholders provides a very focused approach and accurate assessment of the explored subject. This also proves to be a first attempt for the field, geographical scope, and topic.

In the next chapter, the methodology used to carry out this work and achieve its objective is presented.

2 Methodology

The research carried out in this work aims at providing an overview of the digitalization of the electricity system in Europe and assessing the impacts (both positive and negative) that digital technologies are having on electricity networks and their main stakeholders. To achieve this objective, the methodology hereby presented is followed.

To set the background for the development of the research constituting the backbone of this work, insights on the state-of-the-art of digitalization are gathered by means of an extensive **literature review**. Firstly, information about the stand of the energy community on digitalizing the electricity system is obtained through the analysis of several scientific papers retrieved from the web. The main sources of data are identified in three reports by the International Energy Agency (IEA) from the past twelve years, which are used as the backbone of this first review part. More specifically, *Technology Roadmap, Smart Grids* (2011), *Digitalization & Energy* (2017), and *Energy Efficiency and Digitalization* (2019). These and many other scientific reports are read, examined, and compared to obtain a clear picture of the position of the energy community on digital technologies and the reasons behind it. Secondly, insights on the regulatory framework surrounding the topic of digitalization are gathered through the review of four communications of the European Commission (EC) from the past eight years retrieved from the official EC website (European). These are, *A Digital Single Market Strategy for Europe* (06/05/2015), *A European Strategy for Data* (19/02/2020), *Powering a Climate-neutral Economy: An EU Strategy for Energy System Integration* (08/07/2020), and *Digitalizing the Energy System - EU Action Plan* (18/10/2022). The main actions and decisions from the institutions to incentivize a more digitalized electricity system are identified and presented. Finally, to assess the status of digitalization in Europe, web research is performed to identify the main scientific papers, articles, and websites providing relevant data. Such data isn't readily available for many technologies; therefore, the research is restricted to smart meters and 5G connectivity. These are not only the technologies whose level of deployment presents the highest amount of statistical data but are also the most enabling ones in the process of digitalization of electricity. Such information is therefore obtained through the analysis and comparison of different literature and statistical sources.

With the described literature review, the framework for the research development is defined. The next step is to set up the research for the assessment of the impact of digital technologies on the electricity system and its main stakeholders. The tool chosen for this purpose is an online **survey** drafted with the use of the online tool **Microsoft Forms**. The choice of a survey as the preferred research tool is driven by the aim of the study of gathering feedback on the real-life experience of system operators when dealing with digital technologies. Such tool is preferred to, for instance, personal interviews for several reasons. First, a survey ensures a higher degree of objectivity compared to one-to-one interviews, therefore leading to more reliable outcomes. Second, the time required to fill out a survey is generally shorter than that required for an interview, thus allowing for a smoother and less demanding experience for the respondents. Third, a survey offsets the logistic burdens of reaching out to the potential respondents one by one, waiting for a reply, and finding a suitable time for carrying out the interview. In conclusion, within a time constraint, a survey allows for reaching a large audience in an effective manner with the potential of obtaining a reasonably high response rate. The steps that led to the creation and submission of the survey are the following.

1. **Stakeholders identification.** The relevant stakeholders to be targeted through the survey and to be used as respondents are identified in the Transmission and Distribution System Operators (TSOs and DSOs) of the European electricity system. This is intended to gather expert, technical feedback, as well as to reach a wide geographical and sectoral coverage.

2. **Key Performance Indicators (KPIs) definition.** The aspects of electricity systems deemed as most relevant from the standpoint of system operators, as well as directly impacted by digital technologies, are identified in seven KPIs. Grid reliability and stability, Grid management, Operational efficiency, Data quality, Costs savings, Customer engagement, and Environmental Performance. Such KPIs directly lead to the four impact categories – technical, economic, environmental, and social – used for the assessment of the results.
3. **Questions drafting.** Based on the defined KPIs, the questions of the survey are created keeping in mind the main objectives and the target audience. 20 multiple-choice questions inquiring on the observed impacts of digital technologies, with particular focus on smart meters and 5G connectivity, are compiled. These are also discussed with some experts in the field of energy engineering to ensure their relevance and effectiveness towards the goal of the survey.

The drafted survey is therefore submitted to the identified stakeholders, and anonymity is guaranteed to the respondents upon submission. A deadline is set after three weeks to allow enough time for the stakeholders to respond, as well as for this author to process the results.

Upon reception of the **survey's results**, the natural next step is to process and evaluate them. This is done through several stages of growing analytical depth. Firstly, the response rate obtained for the survey is computed to get an idea of the representativeness of the results. Secondly, a high-level assessment of the outcomes is performed via an overview of the statistics automatically generated by the Microsoft Forms tool. Attention is placed on the number of responses obtained for each possible answer. This allows for a first assessment of trends in the digitalization of electricity and priorities of system operators. Thirdly, the previously defined KPIs are assessed according to the results, following a methodology specifically outlined for this task. For each KPI, the relevant questions and, within them, answer options, are identified. The number of selections of each option is recorded and the average selection rate is computed. If the selection rate represents a number equal or greater than the 70% of the respondents, the KPI is considered to be highly impacted; if it falls between the 30% and 70%, the KPI is assessed as mediumly impacted; if it is equal or lower than the 30% of the respondents, the impact is evaluated as low. Such methodology for the KPIs assessment is explained in more details in the relevant section (8.2). Finally, the KPIs are grouped in four main areas of interest, and impact categories are defined accordingly. Grid reliability and stability, Grid Management, Operational efficiency, and Data quality lead to the technical impact category; Costs savings and Operational efficiency to the economic one; Environmental performance to the environmental one; Customer engagement to the social one. The results are therefore analyzed in depth, their relevance within each impact category is discussed, and their implications linked to the insights obtained from the literature review.

It is worth mentioning that this study presents some limitations within its scope due to external circumstances and methodological choices. Firstly, the time constraint due to this study being the subject of a master's thesis didn't allow for an extension of the deadline established for filling out the survey. Such an action could have given more stakeholders the possibility to take part in the survey, thus resulting in a higher response rate. Secondly, the request of the stakeholders to be guaranteed full anonymity upon participation in the survey prevented this author from drawing more accurate conclusions from the survey's results. The answers to the survey couldn't be traced back to the individual respondents, thus hindering any geographical or technical distinction. Such differentiation would have been important to isolate the perspective of TSOs and DSOs, as well as to acknowledge how geographical and technical development differences affect the perceived impacts. Finally, the choice of an online survey as research tool, while providing the advantages mentioned earlier, doesn't leave space for more personalized nor targeted questions to the individual stakeholders. This can indeed affect the specificity of the results, as well as limiting the respondents' personal contribution.

The next chapter marks the beginning of the literature review part and presents the results of the analysis of three IEA reports, as well as other scientific papers, aimed at understanding the position of the energy community on the topic of digitalization.

3 The Energy Community Stand on Digitalization

The energy transition as it is known today, started taking place in the late 1990s and early 2000s, with the first efforts to intensify the deployment of renewable energy technologies such as PV panels and wind turbines. Although such technologies, together with many others, were already available well before then, the realization of the consequences of CO_2 emissions and the threats brought about by climate change put new pressure and urgency on the transition to clean energy sources. Renewable energy generation constituted the first enabler of the electrification of energy services in the effort of phasing-out fossil fuels. As a consequence, electricity systems started facing growing challenges due to this shift, challenges that carried on through the years and are still very much present today.

Given the central role that electrification is playing in the energy transition, and the many opportunities that this opens for the application of digital technologies, the focus of this review is placed solely on electricity systems.

3.1 IEA – Technology Roadmap, Smart Grids, 2011

Already back in 2011, the International Energy Agency (IEA) identified some of the biggest challenges to be endured by electrical systems during the energy transition. The main ones were identified in **ageing infrastructure**, the continued **growth in demand**, the **integration of an increasing number of variable renewable energy sources** and **electric vehicles**, and the need to improve the **security of supply** (IEA, 2011). In that same instance, the IEA envisioned smart grids as a way forward in tackling these challenges. A **smart grid** is "*an electricity network that uses digital or other advanced technologies to monitor and manage the transport of electricity from all generation sources to […] end-users*." Such concept can be applied to other types of commodity infrastructures, such as water, gas, or hydrogen, however, as previously mentioned, the focus of this review is solely placed on electricity systems.

The main reasons for pushing forward the implementation of smart grids, and therefore of digital technologies, as also corroborated in a later instance by Anderson, Ghafurian and Gharavi (Anderson, Ghafurian, & Gharavi, 2018), lay in the increased **flexibility**, **stability,** and **efficiency** they enable in electricity systems. By **reducing transmission and distribution losses** and **optimizing the use of existing infrastructure**, smart grids can indeed improve the efficiency of the supply system thus supporting it in facing the increasing electricity demand. Additionally, by providing end-customers with real-time data about their consumption and energy-related costs, they can **enhance demand side management**, with the multiple benefits of **releasing stress from the system** (peak shaving and load shifting), **improving system planning**, **reducing operational costs**, and even taking advantage of new, additional loads (such as electric vehicles). Finally, as also discussed by Hu et al. (Hu, et al., 2014), smart grids can support the deployment of variable generation technologies (renewables), by enabling system operators to **better manage generation and power quality and maintain stability and balance**. This further contributes to the CO_2 emissions reduction and the overall energy transition.

For all this to be achievable, governments and industries need to establish regulations, protocols and standards for equipment, data transfer, interoperability, and cyber-security. Governments and regulators, in particular, are responsible for planning and implementing a strategy for the evolution of regulations in tandem with technological advancements. In doing so, they must collaborate with stakeholders from the private and public sector to determine the optimal regulatory and market solutions for the implementation of the digitalization agenda.

3.2 IEA – Digitalization & Energy, 2017

In a later report from 2017, the International Energy Agency (IEA) painted a more comprehensive picture of the meaning of digitalization for the energy sector, together with its implications and challenges. In particular, the analysis was aimed at providing clarity on the topic for decision-makers and giving recommendations on how to establish a strong and safe regulatory framework around it.

Once again the focus is placed solely on the electricity sector, which, in the IEA words, "*is likely to be the first energy sector to see the impact of this deeper transformation* [digitalization] *and the one that will ultimately be most affected*" (IEA, 2017). Adding onto what already mentioned in the previous section, digitalization is enabling the match of demand to the needs of the overall electricity system, thus opening the opportunity for both consumers and producers to actively participate in the system operation. By blurring the distinction between supply and demand (Figure 2), new actors can play a role in the real time balance of the system, thus changing stakeholders' roles. Such aspect is also addressed by Reinders et al. (Reinders, et al., 2018) and constitutes one of the focuses of the Three-Layer Model they utilize to assess the performance of residential smart grids.

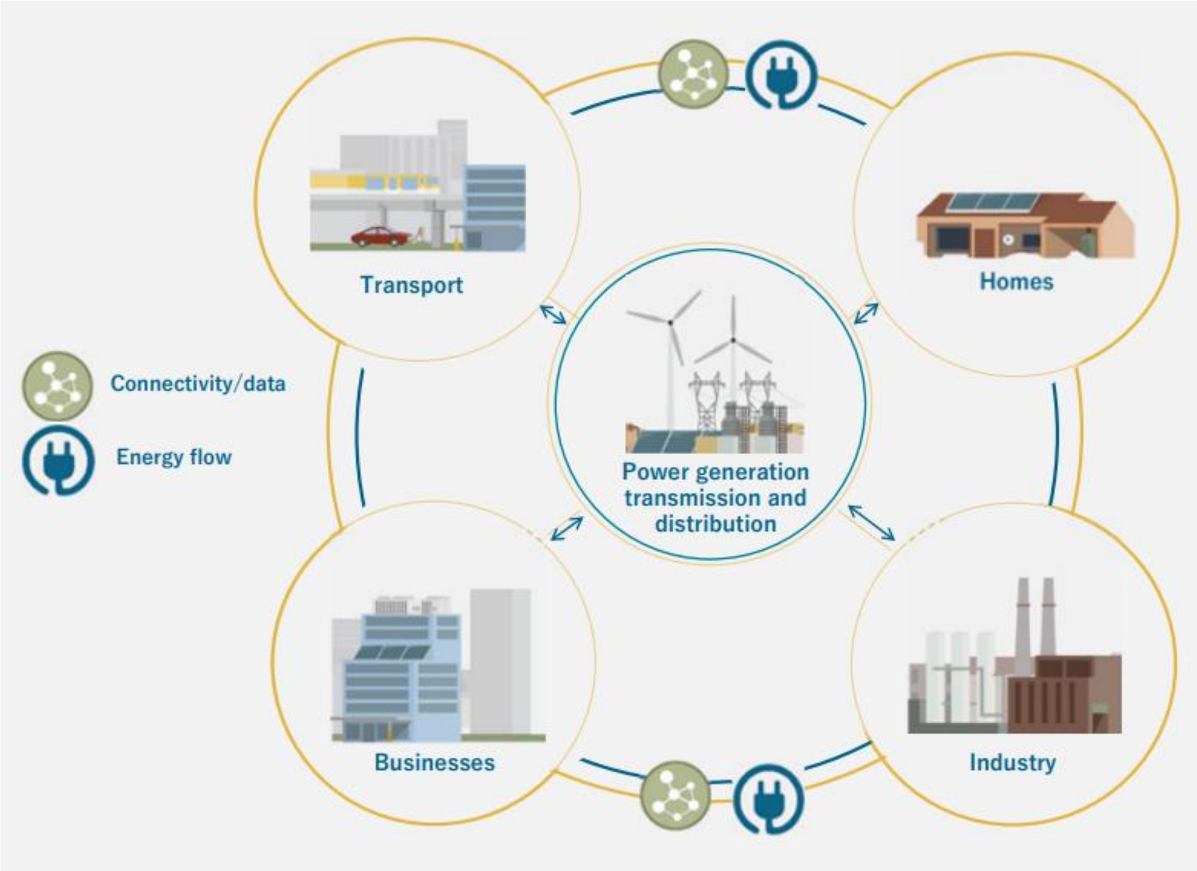


Figure 2 - Thanks to connectivity, new actors arise and the distinction between supply and demand becomes blurrier, *(IEA, 2017).*

The expansion of **electrification** and **decentralization** is transforming **consumers into prosumers and suppliers**, leaving traditional centralized grids and system operators to act as the backbone that balances the entire system. In particular, Distribution System Operators (DSOs) must accommodate a growing number of heterogeneous, distributed energy resources, including EVs and battery storage, and integrate these into their supply and demand balancing operations. For this purpose, interaction and cooperation between DSOs and Transmission System Operators (TSOs) need to be strengthen in the pursue of full interoperability. This requires technical, market, and institutional changes.

The main change driving technologies for electrical systems can be identified in the following three.

1. **Smart demand response.** Demand response is the mechanism through which electricity consumers respond flexibly to signals from the system to help maintaining security of supply at the lowest cost**. Digital connectivity**, with appliances and equipment monitored in real time, allows to utilize the collected data to shape the demand to optimally match the supply. This can translate into **peak shaving**, **load shifting**, or other load management schemes, as thoroughly explained by Hussain and Gao (Hussain & Gao, 2018). Smart demand response is enabled by the penetration of **automation**, **Internet of Things (IoT)**, and **Artificial Intelligence (AI)** both in the residential and commercial sector.

Demand response usually works through financial incentives granted to consumers for flexibly adjusting their demand. If the potential benefits to the system are considerable, however, the financial benefits to individuals might not be enough to have them participate in the mechanism. For this reason, it is important that regulatory and policy frameworks are established, to adequately distribute costs and benefits through the right incentives.

2. **Smart EVs charging.** Similarly to smart demand response, **smart charging** of EVs consists in the coordination of charging strategies through digital technologies to contribute to the balance of electricity systems - as extensively explained by Spencer et al. (Spencer, Fu, Apostolaki-Iosifidou, & Lipman, 2021). By strategically scheduling charging patterns, consumers can benefit from lower electricity prices or other financial incentives, while system operators can more carefully **forecast the system's behavior** and **avoid congestion**. Smart charging requires digital infrastructure to enable communication between charging points and back-end systems.

The potential of EVs in enhancing systems' flexibility, however, isn't limited to smart charging. The development and deployment of **Vehicle-to-Grid (V2G)** technologies for bidirectional charging, allows for the utilization of EVs as energy storage and can therefore greatly support the balance and reliability of the system, as well as the quality of the delivered power.

3. **Distributed generation, mini-grids, and prosumers.** The proliferation of distributed energy resources connected directly to local distribution grids is making the electricity sector ever more decentralized. Although renewable generation is always welcome at any scale, the rise of small-scale producers which inject into or withdraw from the grid at their own convenience (the so-called "prosumers"), might drive down revenues for traditional utilities and system operators. Therefore, digital technologies need not only to enable the rise of such decentralized systems, but also to guarantee the sustainability of the grid infrastructure from an economic perspective. In this sense, blockchain can represent a powerful tool in coordinating the increasing number of devices, owners, and operators in smart grids. This can facilitate the need for effortless and automated trading to allow for adaptability.

The process of digital transformation of the electricity system implies an enormous amount of data shared between several devices and actors through different communication platforms. Within electricity systems, particularly, thanks to the expansion of IoT and the diversification and decentralization of energy technologies, this translates into millions of small-scale prosumers and billions of devices linked together. Such transformation is turning the operational foundation of electricity systems into a massive surface suddenly vulnerable to **cyber-attacks**. To face this new threat, the new digital energy security should be built around three key concepts: **resilience** - the ability of a system to adapt to changing conditions and quickly recover from shocks, while maintaining the continuity of critical infrastructure operations- **cyber hygiene** - the basic set of precautions and monitoring that all ICT (Information and Communication Technologies) users should undertake- and **security by design** - the incorporation of security standards as a core part of the research and design process (IEA, 2017).

Another question raised by the growing use of digital technologies in the electricity sector is that of **data privacy and ownership**. As smart grids get implemented and demand response technologies become more widespread, vast amounts of consumer-specific, real-time electricity usage data become available. It is therefore important to set in place laws and regulations that fully guarantee governance and transparency about consumers' data use and privacy.

3.3 IEA – Energy Efficiency and Digitalization, 2019

The International Energy Agency (IEA) report on energy efficiency from 2019 (IEA, 2019), addresses the topic of digitalization and its contribution to increased energy efficiency and impacts on the energy system as a whole.

Digitalization has the potential of enhancing energy efficiency through technologies that gather and analyze data to make changes to the physical environment. As Figure 3 shows, this is made possible by **digital communication networks** that represent the common denominator of all digital technologies.

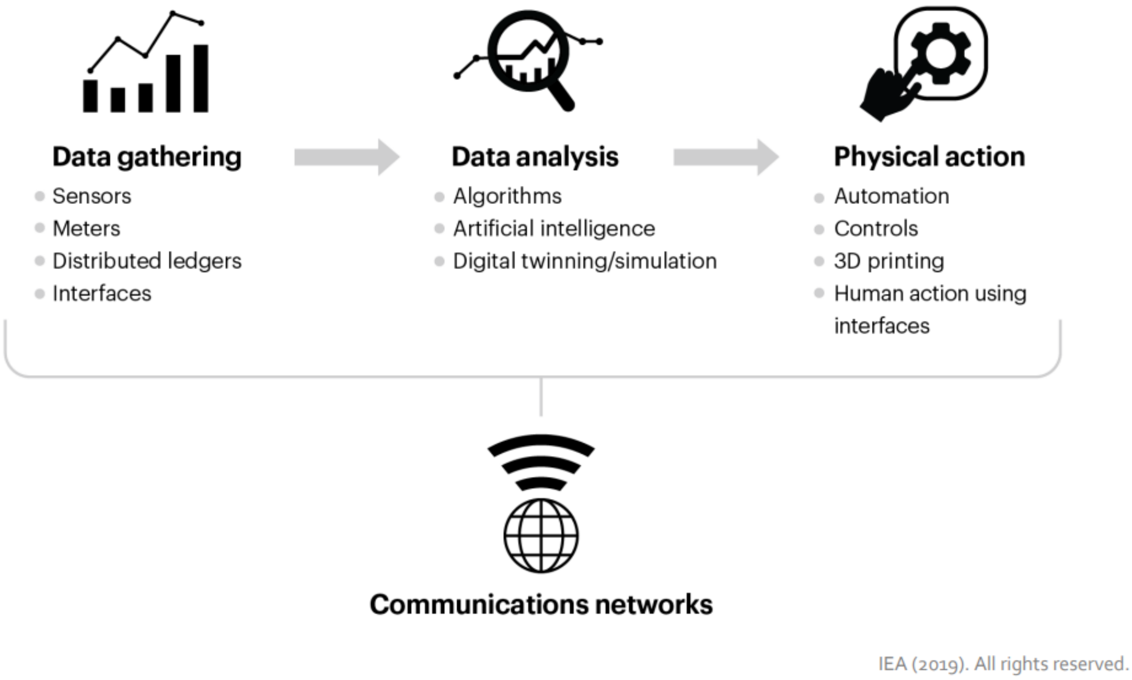


Figure 3 – Communication networks constitute the basic condition for digitalization, *(IEA, 2019).*

The power of data can be harnessed through data gathering and processing technologies that span from the familiar sensors and meters to the more innovative digital twins.

The implementation of digital technology is anticipated to result in energy conservation by **enhancing energy efficiency**, **intelligent energy management**, and **more adaptable supply and demand**. This has a direct and positive impact on the amount of carbon emissions connected to energy usage across various sectors. For instance, in buildings, digitalization has the potential to decrease total energy consumption by up to 10% by 2040, even with limited rebound effects in customer energy demand from the use of digital technologies. In industry, in addition to the benefits that can be achieved with an "energy efficiency first" approach, digitalization can contribute to an extra 5% reduction in final energy demand. Furthermore, digitalization is projected to increase the available demand response capacity from 40 GW in 2019 to 450 GW, and extend its range from just industry, to include buildings and transportation as well (IEA, 2019). Several examples of already existing digital solutions contributing to the energy efficiency and management in buildings, industry and mobility are presented by Dekeyrel and Fessler in the discussion paper: "Digitalization: An enabler for the clean energy transition" (Dekeyrel & Fessler, 2023).

On top of this, digitalization can help highlight the benefits and value of energy efficiency in a more accurate and faster manner. If end-use efficiency has always been beneficial for energy systems, its benefits have seldom been recognized, or at least recognized in a timely enough manner to allow decision makers to take them into consideration when planning generation and network infrastructure investments. Part of the problem has been related to the difficulty in predicting or measuring the impacts of increased end-use efficiency on the overall system, as well as to the inconsistency of demand response services provided by households and commercial buildings until now. Digitalization, however, can help address these issues, offering a more **predictable and measurable** type of **energy efficiency** thus allowing system operators to more accurately value energy efficiency that helps decarbonize the grid. More accurate forecasts of future demand enables more precise estimation of the infrastructure to be build and avoids overspending. Additionally, this information can assist in rewarding energy users for their actions in addition to the benefits they obtain themselves from increased energy efficiency.

In the next chapter, a review of the main European regulations that paved the way for the digitalization of the energy system, leading to the most recent "Digitalizing the Energy System- EU Action Plan", is presented.

4 Regulatory Framework

The rapid development of digital technologies and the way they affect modern societies and economies, have put pressure on governments and regulators for the creation of regulatory frameworks aimed at enabling the integration of these technologies in every sector, and create the right conditions for a digitalized European Union. Such step is fundamental for unlocking the potential of digitalization, while at the same time guaranteeing safety, security, and fairness during the process.

An excursus of the main communications from the European Commission (EC) that led to the creation of regulations and programs regarding digitalization is here presented. Although in some cases the focus of the communications is not the energy sector itself, the resulting legislations and initiatives acted as enablers of the digitalization of economies and societies, thus preparing the ground and providing incentives for the digitalization of energy as well.

4.1 A Digital Single Market Strategy for Europe, 06/05/2015 – Communication SWD(2015) 100

The goal of the European Commission (EC) Communication SWD(2015) 100 is to impulse the creation of a Digital Single Market for Europe, a market which, taking advantage of ICT and other digital technologies, ensures the free movement of goods, persons, services and capital. Although the Communication doesn't target the energy sector per se, it highlights the importance of digitalization for modern societies and economies and sets the foundation for its realization. The regulation represents the first effort for the creation of **reliable, trustworthy, high-speed, and affordable networks** that safeguard consumers' rights to privacy and personal data protection while also encouraging innovation (European Commission, 2015). This is a clear advancement in setting the basis for a digitalized energy sector.

From a technical point of view, the EC places the focus on the implementation of a harmonized framework for broadband services and their deployment in rural areas. This is of vital importance for enhancing devices connectivity across all European country members and enabling the rollout of **4G mobile networks**.

The question of scaling up Big Data, cloud computing, and the IoT is also addressed, as these technologies are catalysts for economic growth, innovation, and digitalization across all economic sectors. In this sense, the EC pushes for the creation of open and interoperable systems and services, and for data portability between services. The adoption of the data protection reform package (2012) ensures uniformity across the Union in the way personal data are processed.

Finally, the EC, aware of the importance of interoperability, pushes for the update and expansion of the European Interoperability Framework of 2010. In this sense, particular attention is placed on standardization. This plays an essential role in increasing interoperability and can help accelerate the development of new technologies such as 5G wireless communications, data driven services, and cyber-security. The EU Rolling plan for ICT Standardization (European Commission, 2020) is a powerful instrument in this regard.

4.2 A European Strategy for Data, 19/02/2020 – Communication COM(2020) 66

The EC Communication COM(2020) 66 outlines a strategy to unlock the full potential of a data-driven economy in Europe and enable the EU to become an attractive, secure, and dynamic data-agile environment. The Communication additionally enumerates the series of policy measures and investments necessary to achieve this goal. The key actions to be taken to create a **single European market for data** combine fit-for-purpose legislations and governance to ensure data availability and investments in standards, tools, and infrastructure, as well as competences for data handling (European Commission, 2020).

The main idea behind the strategy is to prevent the single market from becoming fragmented due to inconsistent actions by different sectors and Member States. This will be achieved by creating a **cross-sectoral framework**, which includes governance structures for the use of data across different sectors and common sectoral data spaces. The framework includes mechanisms to prioritize standardization thus ensuring a safe environment for sharing data and interoperability. Additionally, there will be **investments** of €4-6 billion in infrastructure, data-sharing tools, architecture, and governance mechanisms to facilitate data-sharing and Artificial Intelligence (AI) ecosystems. The strategy also aims at building **competences** through education and empower individuals to enhance their right to data portability.

Such horizontal framework is to be complemented with the creation of **common European data spaces** in nine strategic economic sectors and domains of public interest – namely, manufacturing, Green Deal, mobility, health, finance, energy, agriculture, and public administration. Amongst them, the **Common European Energy data space** is aimed at promoting a stronger availability and cross-sector sharing of data in a customer-centric and secure manner. This is achieved by establishing clear directives regarding customer access and portability of their meter and energy consumption data, as well as electricity network operators' obligations in data-sharing. The final goal of the creation of a common energy data space is to **facilitate innovation** and **support the decarbonization** of the energy system.

4.3 Powering a Climate-neutral Economy: An EU Strategy for Energy System Integration, 08/07/2020 – Communication COM(2020) 299

Within the context of the European Green Deal (EGD) (European Commission, 2019), the EC Communication COM(2020) 299 highlights the crucial role of the energy sector towards the achievement of the EGD goal of carbon neutrality by 2050. In particular, this document focuses on the necessity for energy system integration – i.e., the coordinated planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructures, and consumption sectors. This is regarded as the only pathway towards an effective, affordable, and deep decarbonization of the European economy. Several factors are listed as proof of such integration trend, amongst them, the declining cost of renewable energy technologies, the rapid innovation of storage systems, electric vehicles and, most importantly, digitalization. In this Communication the EC touches on all the ways that digitalization can support system integration and on the questions that need to be tackled through legislations and coordinated actions at European level.

Digitalization can enable dynamic and interlinked flows of energy carriers and provide the necessary data to **match supply and demand with more time and space granularity**. (European Commission, 2020) Technologies that make use of Big Data, Artificial Intelligence (AI), 5G connectivity, and distributed ledger technologies (blockchain) can **enhance forecasting**, allow **remote monitoring of distributed generation**, and **improve assets optimization**. On the other hand, however, digitalization brings on new challenges due to the increased energy demand for ICT equipment, networks, and services, and poses questions regarding ethics, privacy, and cybersecurity.

To enable and accelerate the implementation of digital solutions, and face the challenges that a digitalized, data-based energy system poses, the EC calls for a **system-wide Digitalization of Energy Action Plan**. This could build on the Common European energy data spaces announced in the European Data Strategy, and contribute to smart-metering roll-out, demand response enhancement, and energy-related data interoperability. Additionally, such action plan should foster research and innovation to enable lower maturity technologies to come to the market and more mature ones to scale up at a faster rate.

These communications paved the way for the creation of legislations and programs at European level targeted at accelerating the decarbonization and digitalization of the energy sector, amongst others. A few examples of such programs that have helped innovation and technological development through public funding are:

1. Horizon Europe, 2021 (European Commission, 2021)
2. Connecting Europe Facility, 2021 (INEA, 2014)
3. The Digital Europe Programme, 2022 (European Commission, 2022)
4. The Data Act, 2022 (European Commission, 2022)

5. Digitalising the Energy System – EU Action Plan, 2022 (European Commission, 2022)
6. Network and Information Security (NIS) Directive, 2023 (European Commission, 2023)

In the next chapter, the EU action plan for the digitalization of the energy system is analyzed in more detail.

5 Digitalizing the Energy System - EU Action Plan

On October 18, 2022, the European Commission published an EU action plan for the digitalization of the energy system. This can be regarded as the culminating point of all programs and initiatives about digital technologies and data set forth throughout the previous months and years. Such action plan **represents the first EU-wide coordinated effort for the digital transition of the energy sector in pursuit of the realization of the goals of the European Green Deal and REPowerEU**. Amongst such goals are the reduction of greenhouse gas emissions by 55% and the increase of the share of renewables to 45% by 2030. These objectives will be reached through, amongst other things, the installation of solar PV panels on residential, public, and commercial buildings and the massive deployment of heat pumps and adoption of electric vehicles. For the energy system to be ready for such changes, **EUR 584 billion of investment in the electricity grid** will be required between 2020 and 2030. In particular, it is estimated that EUR 400 billion will have to be dedicated to the distribution grid and that out of these, **EUR 170 billion will have to go to digitalization**.

The European Commission identified six key areas where concrete actions are needed for the digitalization of the European energy system.

1. **Data exchange**: promote connectivity and interoperability while respecting privacy and data protection.
2. **Investments in the electricity grid**: enable a smarter and more resilient energy system to accelerate the deployment of digital solutions.
3. **Consumers protection and empowerment**: enable consumers to engage with digital technologies and benefit from them.
4. **Cyber-security:** enhance the security of digital technologies and their applications.
5. **Sustainability of the ICT sector:** reduce the energy consumption of digital technologies by promoting greater efficiency and circularity.
6. **Effective governance:** perform strategic and joint planning between public and private sector, and support Research and Innovation (R&I).

As previously mentioned, addressing all these topics will require an EU-wide coordinated approach and a long-term strategic vision. Following is a description of the key actions to be taken within each of these areas.

5.1 Data Sharing Framework for Energy

Quoting from the action plan itself, *"[..] the aim of this action area is to establish a common European energy data space and to ensure a solid governance for it, in the form of a coordinated European framework for sharing and using energy data*." (European Commission, 2022) The deployment of such common energy data space will start no later than 2024 and will facilitate the participation in the wholesale markets of more than 580 GW of flexible energy resources that use digital solutions by 2050. It is estimated that this could cover up to 90% of flexibility needs in the EU electricity grid by **enabling smart and bidirectional charging of EVs**, **integrating virtual power plants (VPPs)** and exploiting the potential of **energy communities**, amongst other things.

To promote this action, the Commission established a '**Smart Energy Expert Group'**, within which, by March 2023, a '**Data for Energy**' (D4E) working group was set up. The D4E working group will mainly focus on developing a collection of high-level use cases for data exchange in energy across Europe, with a particular emphasis on flexibility services for energy markets and grids, smart and bi-directional charging of EVs, and energy-efficient buildings. Under the guidance of D4E, the Commission will adopt an implementing act on interoperability requirements and transparent procedures for access to metering and data consumption, as well as data required for demand response and customer switching.

For the D4E initiative to be effective, a crucial prerequisite is the presence of **smart electricity meters** in consumers' homes. For this reason, it is important not only that Member States speed up the process of smart meters rollout, but also that such digital tools are made available to all consumers at an affordable price. This will be crucial to enable and accelerate the digital transition without leaving anyone behind.

5.2 Investments in Digital Electricity Infrastructure

As already mentioned, smart and digital energy infrastructure is a key requirement for the implementation of the actions contained in the action plan. Massive investments are therefore needed to smarten the European electricity grid and push forward the digitalization process. It is for this reason that the Commission will support the European Union Agency for the Cooperation of Energy Regulators (ACER) and the National Regulatory Authorities (NRAs) in their work to define **common smart grid indicators**: these will enable NRAs to monitor smart and digital investments in the electricity grid every year and measure progress in this process. Additionally, the Commission will support the EU Transmission System Operators (TSOs) and Distribution System Operators (DSOs) in the creation of a **digital twin of the European electricity grid**, i.e. a virtual model of the European electricity grid. The objective of the digital twin is to enhance the efficiency and smartness of the grid as to make the whole energy system more intelligent. The creation of such digital twin will be achieved through investments in five strategic areas:

1. Observability and controllability
2. Efficient infrastructure and network planning
3. Operations and simulations for a more resilient grid
4. Active system management and forecasting to support flexibility and demand response
5. Data exchange between TSOs and DSOs

The creation of the digital twin will require a continuous investment and innovation effort for years to come. A Declaration of Intent to kick-start this process and enhance collaboration between the different stakeholders was signed between the European Network of Transmission System Operators for Electricity (ENTSO-E) and the EU DSO Entity on December 20, 2022.

5.3 Legal Framework to Empower and Protect Consumers

In light of the digitalization of the energy sector, consumer protection needs to be taken into careful consideration and adequately addressed. For this purpose, the Commission has launched a **Fitness Check of EU consumer law on digital fairness**. Such evaluation will examine whether the existing rules are still adequate and effective in a more digitalized energy sector, and that issues such as consumer vulnerability in the digital environment and manipulation of choice are properly addressed.

In addition to this, it must also be considered that not all consumers are able or interested in participating in the energy transition to the same degree. To ensure that no one is left behind in the digital transition, it is necessary to create consumer-focused digital tools designed to meet the needs, skills, habits, and expectations of different categories of consumers. "*The tools created should reflect the reality of demographic change with increasing numbers of older consumers who need to be specifically supported in the digital transition*." (European Commission, 2022). Towards this goal, the Commission will make sure to identify strategies to engage consumers in the design and use of **accessible and affordable digital tools**. In this sense, the Commission is in parallel carrying out dialogues with Member States to foster commitments and reforms in digital education and skills. This will contribute to the creation of a skilled workforce and consumers audience to accelerate the digital transition.

Finally, **energy communities** and local energy initiatives can greatly benefit from digital tools if properly integrated in developing collective energy schemes. Towards this goal, the Commission will identify digital tools and provide guidance on energy sharing to policy makers, regulators, and local communities. Additionally, it will develop a first-of-its-kind experimentation platform to test and simulate energy communities in combination with innovative activities such as blockchain-based energy trading.

5.4 Cybersecurity and Resilience in the Energy System

The energy sector is regarded as one of the EU's critical infrastructures and, as such, a systemic approach is required to strengthen its cybersecurity. The NIS 2 Directive (European Parliament and Council, 2022) defines cybersecurity obligations related to supply chain security and risk-management measures. Particular attention is paid to renewable energy and grid supply chain: they are considered as priority areas on which to perform technical and non-technical risk assessments. Additionally, to increase the resilience of the electricity system against cybersecurity risks, the Commission (in collaboration with ACER, ENTSO-E, and EU DSO Entity) will propose a network code for cybersecurity aspects of cross-border electricity flows.

5.5 Energy Consumption of the ICT Sector

The ICT sector accounts today for approximately 7% of global electricity consumption and this share is expected to increase to 13% by 2030. It is therefore of outmost importance to perform comprehensive planning to manage the substantial load it puts on electricity grids and to make sure that its energy needs don't offset the benefits it brings to the energy system and to the economy in general. As a first step, the Commission will work on boosting transparency regarding the environmental footprint of electronic communication services by developing common indicators. Additionally, an EU Code of Conduct for the sustainability of telecommunications networks will help steer investments towards energy-efficient infrastructures.

With an ever-increasing number of tasks and calculations performed over the cloud or High-Performance Computers (HPC), **data centers** are of particular interest to this area of the action plan. Having become a core infrastructure of ICT systems, EU data centers' energy consumption is expected to increase over 200% between 2020 and 2030. To tackle this situation, the Commission will, by 2025, introduce environmental labelling schemes specific for data centers, improve the requirements on the operating conditions of servers and data storage products, and promote the reuse of waste heat from data centers to heat homes and businesses.

5.6 An EU-wide Coordinated Approach

The process of digitalization is rapidly changing the society and the energy system, and as already mentioned, careful planning and a dedicated political dialogue at all levels are necessary to enhance the benefits it brings and face the challenges it encounters. In this regard, the Commission is pushing to exploit the synergies between the green and digital transition with two main instruments at EU level, namely the European Green Deal and the Digital Decade Policy Programme 2030. For this purpose, the Commission is engaging with Member States and through the Smart Energy Expert Group will set up a structured dialogue with national representatives on **'Digitalization of energy: state of play, progress, opportunities and challenges'**. From this, a common agenda and roadmap will be drawn to improve the digitalization of the energy system through a coherent planning and monitoring framework at EU level.

In addition to this, the Commission is interested in fostering an innovation ecosystem where many digital and energy actors at European, national, and regional level can cooperate and exchange best practices. For this purpose, it will create the **'Gathering Energy and Digital Innovators from across EU'** platform to enhance a cooperation environment and create an EU network of innovators and research institutions in the digital and energy sectors.

As a result of this action plan for the digitalization of the energy system, the European Commission will initiate and support the actions and programs presented in this review. These, however, are only a part of the initiatives that the Commission intends to push forward in the coming years.

In the next chapter, an assessment of the state of digitalization in Europe is presented.

6 State of Digitalization in Europe

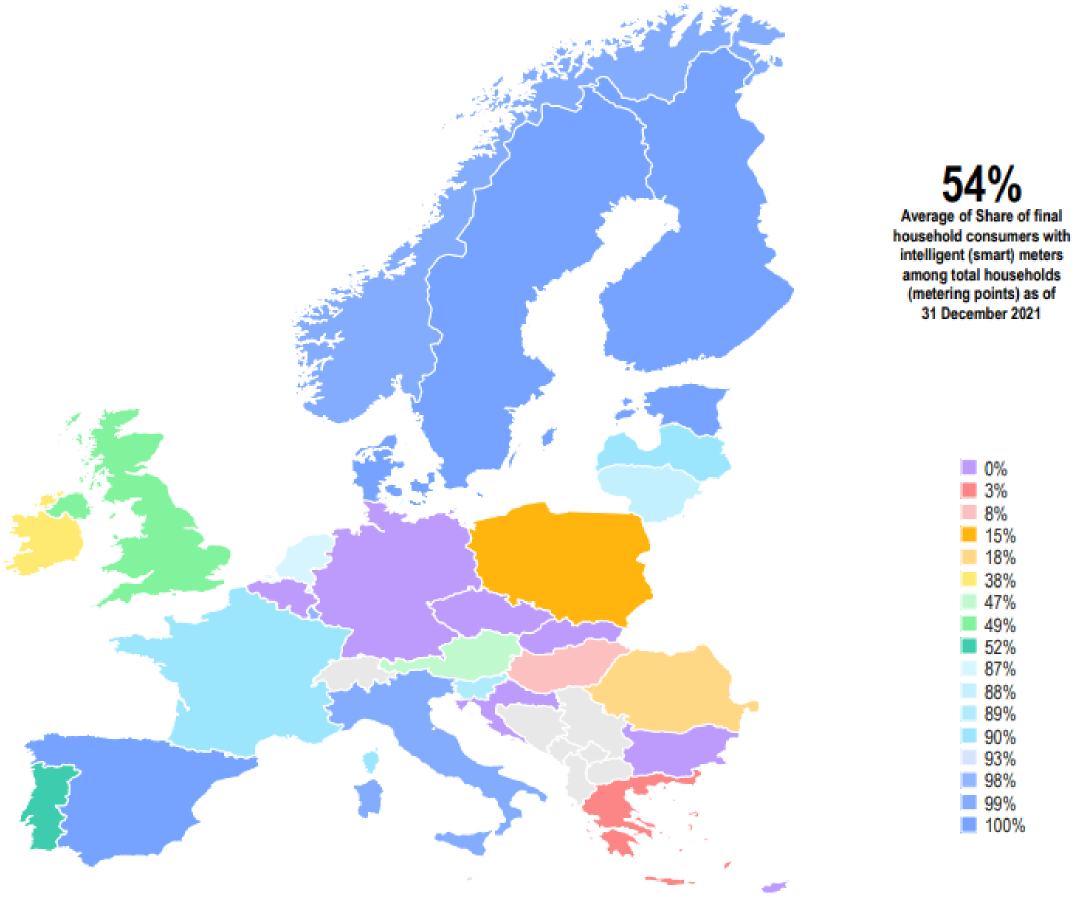
Assessing the state of digitalization across the European Union is no easy task. Firstly, considerable geographical, economical, and societal differences are present across the Union, thus making it difficult and possibly not very valuable to have an overall evaluation of the state of things. Average figures and statistics can indeed be drawn, but these, however, cannot be taken as representative without considering all the national differences as well. Secondly, the variety of technologies involved in the process of digitalization cannot be restricted to a single word, and a realistic picture of the state of digitalization should take into account the level of development and deployment of each of them. Finally, the interconnection and dependencies between said digital technologies, where one's development and deployment can deeply depend on another one's, make it hard to clearly separate them and assess their maturity individually.

For these reasons, and for the larger amount of data and statistics available, the assessment of the state of digitalization across the EU is carried out focusing solely on the stage of deployment of two key digital technologies: smart meters and 5G connectivity. As previously mentioned, these technologies are enablers of the digitalization of the electricity system and as such, particularly crucial to its progress. Therefore, an assessment of their level of advancement can give a good, although non exhaustive, picture of the state of digitalization overall.

6.1 Smart Meters

As already mentioned in this work, and explicitly highlighted in the EU Action Plan (see 5.1), smart meters are essential for the digitalization of the energy system as a whole, and the utilities sector in particular. While giving households and businesses more control over their energy usage, smart meters help reshape the energy infrastructure enabling greater flexibility, thus lowering operational costs and the need for new investments. Early studies conducted by the European Commission (Banks, 2013) found that **smart meters could help households reduce their electricity bills by an average 12% annually**, with **commercial consumers reducing consumption by as much as 58%**.

In the Third Energy Package of 2009 (European Parliament and Council, 2009), the Commission mandated Member States to install electricity smart meters in consumers' homes so as to reach at least 80% coverage by 2020. As of 2021, several EU countries have surpassed that target, while others are still trailing behind. Figure 4 provides an overview of the status of electricity smart meters rollout at the end of 2021. The average penetration rate reaches 54%, corresponding to about 163 million devices installed (ACER, 2022), with, however, great discrepancies between countries. It is therefore interesting to highlight a few remarkable cases both amongst the market leaders and laggers.



Source: CEER 2022

Note: No data for Ireland provided, data gathered from ESB Networks.

Figure 4 - Status of electricity smart meters rollout at the end of 2021 (%), *(ACER, 2022).*

Amongst the leading EU countries for households' smart meters rollout, **Spain was the first to reach 100% installation in 2018** following a governmental mandate. Additionally, Spain achieved this result at one of the most efficient costs for costumers, at about 40% less than the EU average (triPica, 2021). **Sweden and Italy also reached 100% coverage**, having begun the deployment of automated smart meters already back in 2003 and 2000 respectively. In Sweden, in particular, thanks to the push of power company Vattenfall, by June 2008 every home had a first-generation smart meter installed, and the country is now in the process of replacing them with more modern models. The same can be said for Finland, which, after reaching 100% rate of deployment, is now deploying a second rollout which will enable the collection of consumption data every 15 minutes and its storage in a centralized data hub.

Amongst the lowest performers, particularly interesting is the case of **Germany**, where the government decided against a national smart meters' rollout, citing possible noncompliance with legal requirements (triPica, 2021). An equivalent decision was taken in **Czech Republic, Greece, Croatia, and Cyprus**. In France, although trial rollouts already started in 2010, the official launch of the nation-wide rollout only began in 2018, and despite the interruptions caused by the COVID-19 pandemic, the country managed to reach its 80% rollout target by the end of 2021. Portugal was also a late starter, as were Ireland and Lithuania, and it expects to reach full coverage by 2025 with 2.5 million smart meters installed.

Going back to Union level and projecting the figures one year into the future, **by the end of 2022 more than 56% of electricity customers in Europe and the United Kingdom (the EU27+3) had a smart meter installed** (Jones, 2022). Additionally, the market is expected to experience robust growth in the coming years, with a total of 106 million smart electricity meters forecasted to be deployed across the region in the period 2022-2027 (Jones, 2022), amounting to an annual growth rate of 5.8%. **By the year 2027 the penetration rate is expected to reach 74%**, driven by the large rollouts in the UK, Poland, and eventually Germany and Greece. Finally, the market trends are expected to change, as first-generation smart meters will start to be deployed in Central-Eastern and South-Eastern Europe, whereas Northern and Western

Europe, especially in the Netherlands, Spain, Italy, and the Nordics, will experience the spread of second-generation meters.

6.2 5G Connectivity

The fifth generation of telecommunication systems, 5G, is a new global wireless standard. On top of offering much greater data capacity and transmission speeds compared to its predecessors, 3G and 4G, 5G is forecasted to connect more devices than ever before through the Internet of Things (IoT) (European Court of Auditors, 2022). 5G services are essential for a wide range of applications that will impact many sectors of the EU economy, and it is estimated that the introduction of 5G in four strategic industrial sectors – automotive, health, transport and energy - will generate as much as EUR 113 billion in benefits between 2021 and 2025 (Tech4i2, Real Wireless, CONNECT, InterDigital, 2016). To enable such benefits to take place, back in 2016 the European Commission launched a 5G Action Plan (European Commission, 2016), where it set clear goals for the deployment of 5G networks across Europe. As of today, however, the EU is not on track to meet those objectives, and in a special report from March 2022 (European Court of Auditors, 2022), the European Court of Auditors (ECA) warned that the EU was especially falling behind the targets of 5G rollout across all urban areas and major transport routes by 2025, and achieving a EU-wide 5G coverage by 2030. This already not so optimistic situation looks even more worrying when zooming in from Union to national level.

Figure 5 shows the percentage of the EU27 population covered by 5G as of August 2022 (such estimated coverage figure - 72% - is based on the sum of total number of people covered in each country divided by the total EU27 population (European Court of Auditors, 2022)). If this number doesn't appear to paint an overly negative picture of the level of deployment of 5G connectivity across Europe, this does not hold true when looking at the national realities.

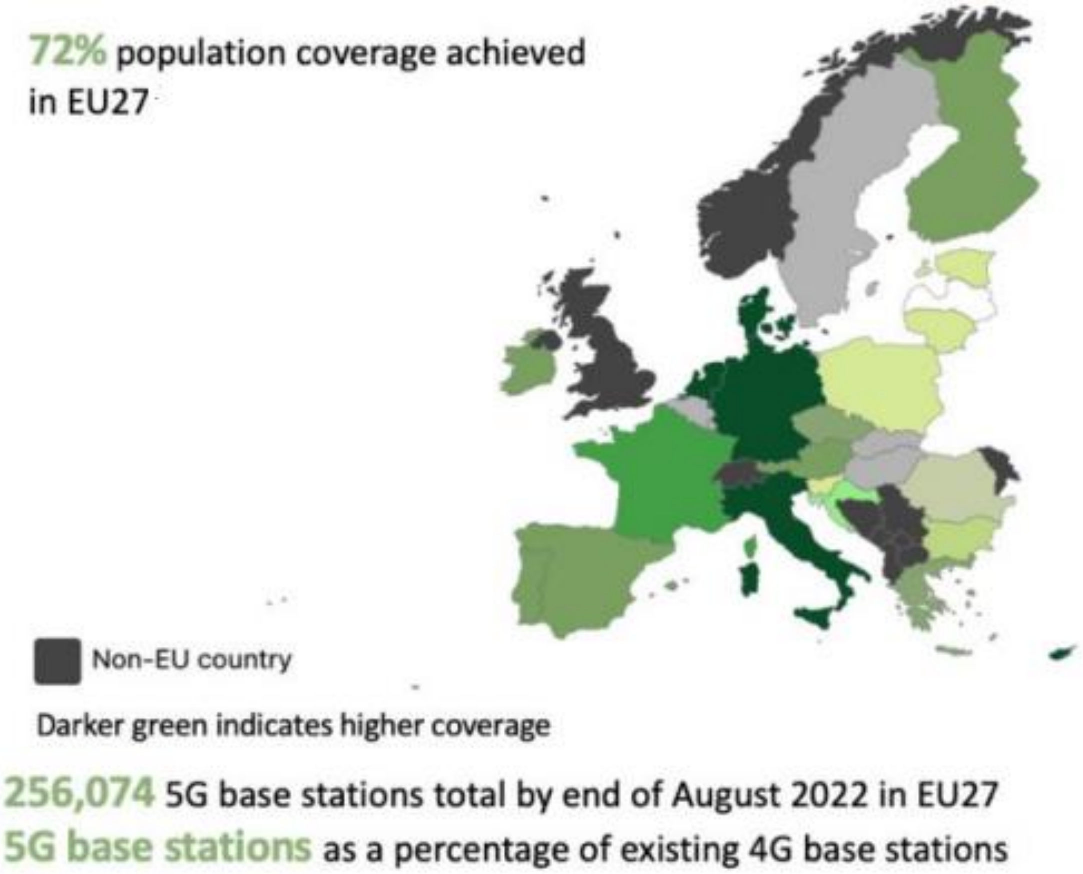


Figure 5 - EU-27 countries 5G coverage by August 2022, *(European Commission, 2022).*

The European 5G Observatory report of October 2022 (European Commission, 2022) shows that some countries perform particularly well in terms of percentage of population covered by 5G, with **Cyprus reaching as much as 100% coverage, followed by Italy with 99.7%, Denmark with 99.3%, the**

Netherlands with 97%, and Germany with 91%. Most European countries, however, are not quite near those positive results. A group of eight countries hovers in the 60 to 85 percentiles, thus more or less in line with the European average. To such group belong, for instance, France with 84%, Spain with 80%, and Greece with 70%. A big gap separates such countries to all the remaining ones, which present an astonishingly low coverage of 40% or lower, with extreme cases such **as Luxemburg, Belgium, and Latvia having respectively 12.7%, 4.3% and 0% of 5G coverage**. It is indeed quite impressive that the majority of EU27 countries does perform much worse than the European average and that considerable differences amongst Member States exist.

Ultimately, however, although slower and with many regional differences, 5G connectivity is on its way to become the main technology in the mobile industry, as it is expected to overtake 3G and considerably reduce the gap with 4G technologies by 2023 (Figure 6).

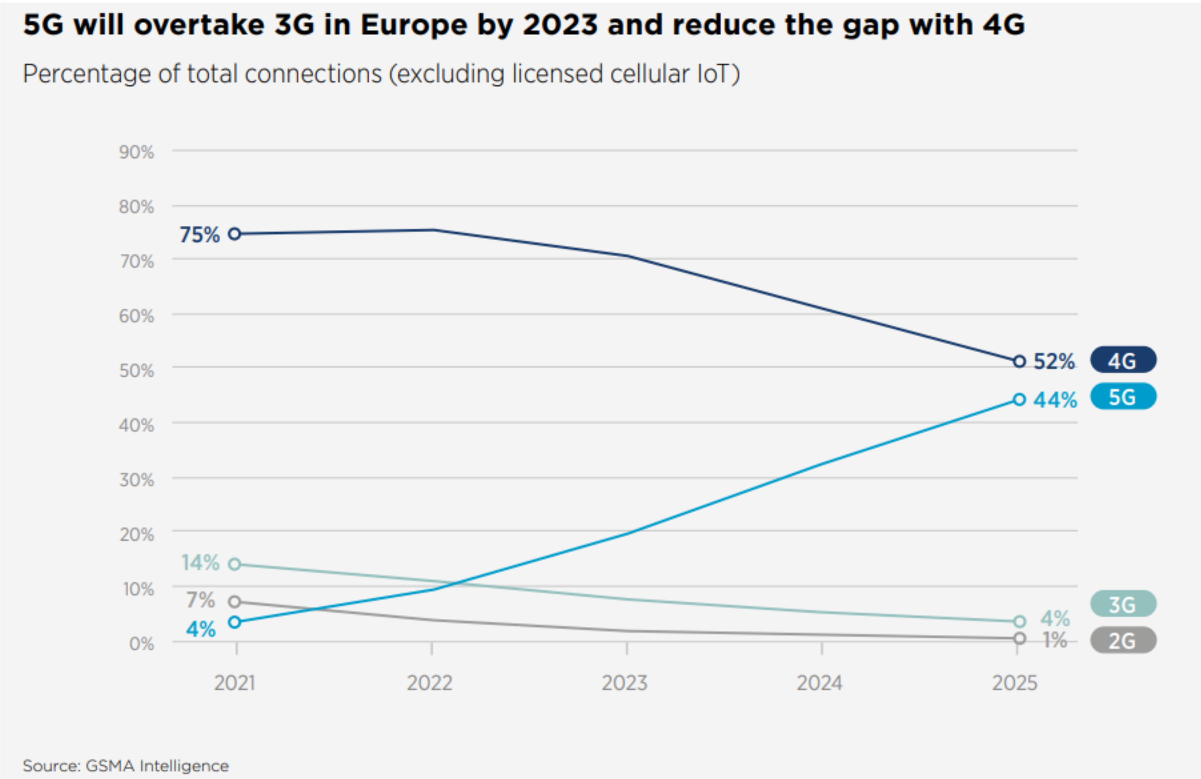


Figure 6 – Projections for the deployment of 5G compared to its predecessors, *(GSMA, 2022).*

This fact is particularly important because, on top of the already mentioned benefits that it provides, the uptake of 5G connectivity is also a key factor in the process of improving the sustainability of the European telecommunication networks. As mentioned by the European Telecommunications Network Operators (ETNO) in a recent report (etno, 2022), **5G technology can indeed be up to 90% more efficient than 4G in terms of mobile data transmission per one kilowatt-hour of energy used**. Therefore, 5G deployment is crucial to reduce power consumption and improve telecommunication network efficiency, especially in sight of the increasing number of mobile and IoT devices that are constantly entering the market.

The previous chapter constitutes the end of the literature review part of this work. The next chapter marks the beginnings of the research development section.

7 Research Development

The literature review presented in the previous chapters provides an overview of the key concepts and milestones towards the digitalization of electricity systems. The last chapter, in particular, paints a picture of the state of deployment of digital technologies in Europe and provides the background against which the research developed in this work is built.

The primary objective of this study is the assessment of the impacts of digital technologies on the electricity system and its operators. The investigation is conducted at European level and carried out through the submission of a survey to transmission and distribution system operators within the European electricity network. Focus of the survey is the impact of digital technologies, with particular attention to smart meters and 5G connectivity, on the electricity system and its daily operation from the perspective of system operators.

In the following sections the research development is presented in more detail. First the stakeholders involved in the study are identified and listed. Secondly, the Key Performance Indicators (KPIs) providing the basis for the survey creation and results assessment are defined. Finally, the survey submitted to the identified stakeholders is described.

7.1 Stakeholders Identification

The stakeholders identified as relevant for this study are the transmission and distribution system operators (respectively, TSOs and DSOs) of the European electricity network. To reach a wide geographical and sectoral coverage, all TSOs members of the European Network of Transmission System Operators for Electricity (**ENTSO-E**) are considered. This is possible thanks to the involvement of this author in the ENTSO-E association as an intern during the development of this work. As of December 2022, ENTSO-E gathers 39 members TSOs from 35 different countries and 2 observer members. The full list of the TSOs members considered in this study is provided in Table 1.

Table 1- List of Transmission System Operators (TSOs) involved in the survey.

Country	TSO(s)	Website link
Albania	OST sh.a – Albanian Transmission System Operator	OST
Austria	Austrian Power Grid Vorarlberger Übertragungsnetz GmbH	APG VUEN
Belgium	Elia System Operator SA	Elia
Bosnia and Herzegovina	Nezavisni operator sustava u Bosni i Hercegovini	NOS BiH
Bulgaria	Electroenergien Sistemen Operator EAD	ESO
Croatia	HOPS	HOPS
Cyprus	Cyprus Transmission System Operator	Cyprus TSO
Czech Republic	ČEPS	ČEPS
Denmark	Energinet	Energinet.dk
Estonia	Elering	Elering AS
Finland	Fingrid Oyj	Fingrid
France	Réseau de Transport d'Electricité	RTE
Germany	TransnetBW GmbH TenneT TSO GmbH Amprion GmbH 50Hertz Transmission GmbH	TransnetBW TenneTDE Amprion 50Hertz
Greece	Independent Power Transmission Operator	IPTO

Hungary	MAVIR	MAVIR ZRt.
Iceland	Landsnet hf	Landsnet
Ireland	EirGrid plc	EirGrid
Italy	Terna - Rete Elettrica Nazionale	Terna
Latvia	AS Augstsprieguma tīkls	AST
Lithuania	Litgrid AB	Litgrid
Luxembourg	Creos Luxembourg	Creos Luxembourg
Montenegro	Crnogorski elektroprenosni sistem	Crnogorski elektroprenosni sistem
Netherlands	TenneT TSO	TenneT NL
Northern Ireland	System Operator for Northern Ireland Ltd	SONI
Norway	Statnett	Statnett
Poland	Polskie Sieci Elektroenergetyczne	PSE S.A.
Portugal	Rede Eléctrica Nacional	REN
Republic of North Macedonia	Transmission System Operator of the Republic of North Macedonia	MEPSO
Romania	C.N. Transelectrica	Transelectrica
Serbia	Akcionarsko društvo Elektromreža Srbije	EMS
Slovak Republic	Slovenská elektrizačná prenosová sústava	SEPS
Slovenia	ELES	ELES
Spain	Red Eléctrica de España	REE
Sweden	Svenska Kraftnät	SVENSKA KRAFTNÄT
Switzerland	Swissgrid	Swissgrid
Turkey*	Turkish Electricity Transmission Corporation	TEİAŞ
Ukraine*	National Power Company Ukrenergo	Ukrenergo

*Observer Members

DSOs are higher in number (more than 2 500 DSOs are currently active in Europe) and lack a single Europe-wide association that gathers all of them. To face this challenge, the pool of participants to the survey is restricted to a group of 20 DSOs members of **EU DSO Entity**, the new Association of European Distribution System Operators. This is done to enable a smoother communication process and to ensure a higher response rate. The list of DSOs participating in this study is presented in Table 2.

Table 2 – List of Distribution System Operators (DSOs) involved in the survey.

Country	DSO(s)	Website link
Austria	Wiener Netze GmbH Energienetze Steiermark	Wiener Netze E-netze
Belgium	Synegrid	Synergrid
Bulgaria	ERM zapad	ЕРМ Запад
Germany	E.ON	E.ON

	SWM Infrastruktur	SWM Infrastruktur
Greece	HEDNO	ΔΕΔΔΗΕ
Italy	Enel Areti INRETE Distribuzione	Enel Energia Areti INRETE Distribuzione
Latvia	Sadales tīkls	Sadales tīkls
Lithuania	ESO	ESO
Netherlands	Alliander Stedin	Alliander Stedin
Poland	PGE Dystrybucja TAURON Dystrybucja	PGEdystrybucja TAURON Dystrybucja
Portugal	E-REDES	EDP
Slovenia	SODO	SODO
Spain	Cuerva energía UFD	Cuerva UFD

It is worth mentioning that, for privacy reasons, full anonymity was guaranteed to the participants upon submission of the survey.

7.2 Key Performance Indicators (KPIs) Definition

For the creation of the survey, seven Key Performance Indicators (KPIs) are identified. These serve as the basis for the drafting of the survey's questions, as well as for the assessment of the results. The KPIs are here described.

1. **Grid Reliability and Stability**: This KPI measures the reliability and stability of electricity supply, including the frequency, voltage, and duration of outages. Digital technologies can improve grid reliability by enabling better monitoring, control, and predictive maintenance.
2. **Grid Management**: This KPI measures the ability of digital technologies to help system operators in their grid management services. These include outage detection, peak load management, and remedial actions performance. By obtaining real-time data on energy usage, utilities can predict the status of the grid in a more accurate way and perform interventions in a timelier manner.
3. **Operational Efficiency**: This KPI measures the impact of digital technologies, especially smart meters, on the operational efficiency of utilities. By obtaining real-time data on energy usage, utilities can better manage resources, thus reducing costs and improving efficiency.
4. **Data Quality**: This KPI measures the quality and accuracy of data collected by smart meters. Accurate data is essential for utilities to make informed decisions and provide high-quality services to customers.
5. **Costs savings**: This KPI measures the costs savings achieved with the use of digital technologies. By enabling more efficient management of the grid and more accurate planning, system operators can achieve significant costs savings.
6. **Customer Engagement**: This KPI measures the engagement of customers with their electricity supply and demand. Digital technologies can improve transparency about electricity consumption, empowering costumers to make more conscious choices about their electricity usage.
7. **Environmental Performance**: This KPI measures the environmental performance of electricity systems. Digital technologies can enable the integration of more renewable energy sources into the grid by improving forecasting and managing variability. Additionally, by improving energy

efficiency and peak load management, they can help reduce the need for expensive and environmentally damaging peak power generation.

The identified KPIs lead to the definition of the four impact categories - technical, economic, social, and environmental - that are used to assess the results of the survey (see 9).

7.3 Survey Creation

Based on the identified KPIs, the survey is created using the online tool **Microsoft Forms**. As previously explained, the questions are targeted to transmission and distribution system operators working within the European electricity network. For privacy reasons, no personal identification is required other than the name of the organization and the country of operation, which are further disregarded upon processing of the results. The survey contains a total of 20 questions divided into three main sections that aim at assessing the impact of **digital technologies**, with particular focus on **smart meters** and **5G connectivity**, on the electricity system and its operators. At the beginning of each section, a question to assess the status of deployment of the investigated technologies is presented to the participants to set the background for a correct assessment of the answers. For each question, multiple choices are provided, and a maximum number of possible answers is established. This is intended to encourage the participants to select the options that they deem most relevant in the context of each question, thus indirectly creating a priority classification of the possible answers. Automatic statistics are created by the online tool upon reception of the answers. These first raw results are shown in a later section (see 8.1). The complete survey submitted to the participants is reported in Annex A.

The next chapter marks the beginning of the research conduction section of this work, where the results obtained from the survey are analyzed and discussed.

8 Research Conduction

The presented survey is submitted to the identified stakeholders on April 5th, 2023. A deadline for answering the survey is set to April 28th, 2023: this is deemed necessary to allow enough time for the post-processing of the answers and the analysis of the results. Within this time frame 11 TSOs and 5 DSOs answered the survey, for a **response rate** of respectively **28%** and **25%**, and an overall one of **27.1%.** Such a result can be deemed as positive, considering that the usual response rate for surveys hovers between 5% and 30%

In the next sections some of the raw results gathered from the survey are presented and briefly discussed, and the defined KPIs assessed accordingly.

8.1 Survey Results

The results of the survey painted a positive picture of digital technologies with respect to their impact on electricity systems and system operators. The most relevant results are extracted from the survey and are here reported as they are received.

By looking at the answers to question 4, presented in Figure 7 below, it can be seen that the biggest benefit of digital technologies is the improvement in **network observability**, with 15 selections out of 16. As a consequence, **grid's reliability and stability** are also enhanced, as corroborated by the similarly high number of selections (13) received by this option.

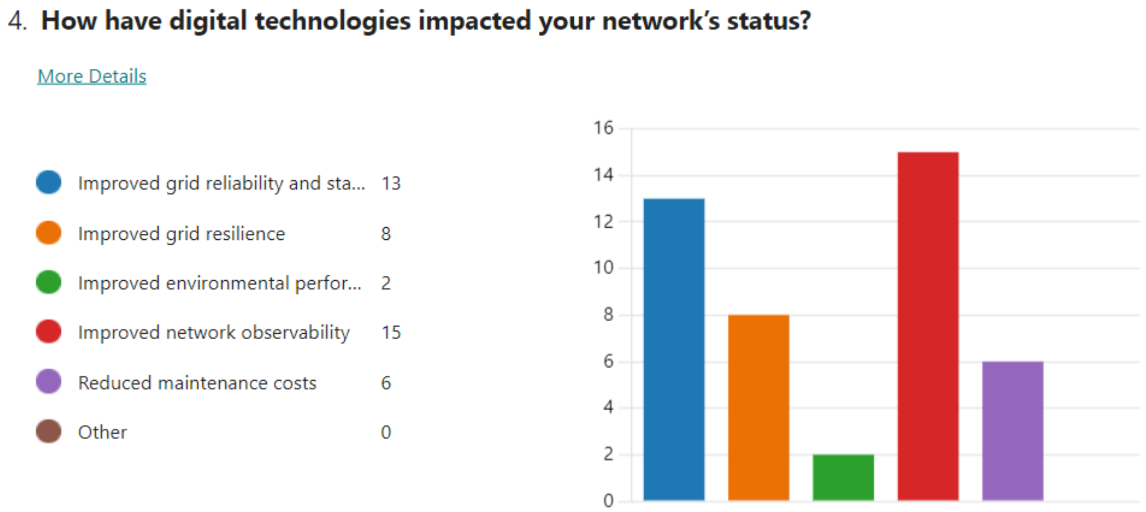


Figure 7 – Outcomes of question 4 of the survey.

When studying the results of question number 5, shown in Figure 8 below, it can be concluded that thanks to digital technologies, system operators are better equipped in their **monitoring and maintenance operations**, as well as overall **grid management**. This has the further benefit of improving **operational efficiency** as a whole, as testified by the high number of selections (11) of such option. It is also worth noticing that, by enabling better communication and electricity data sharing, an improvement in the interaction between different TSOs is additionally experienced.

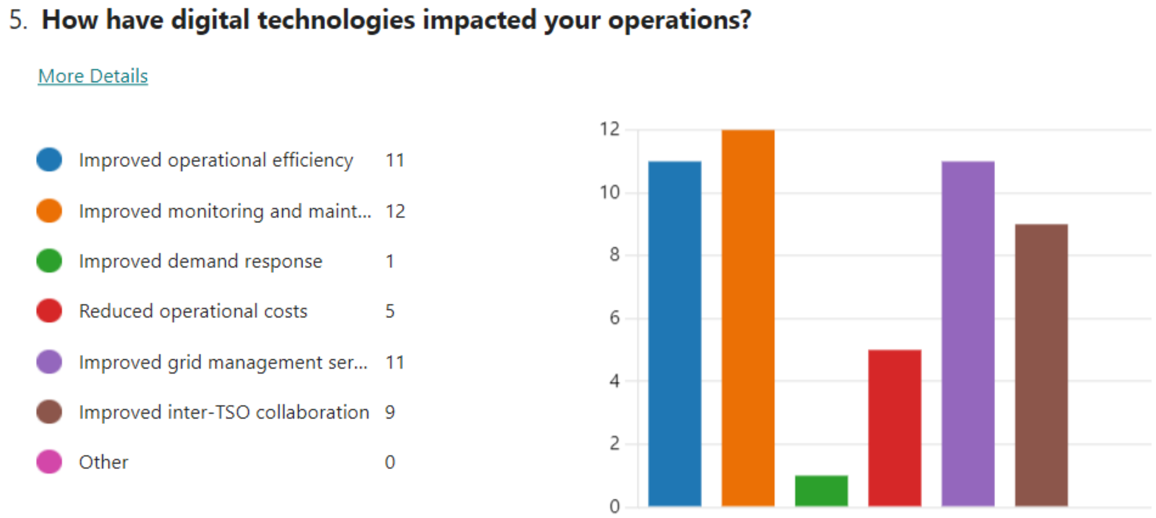


Figure 8 – Outcomes of question 5 of the survey.

The results of question 6 reported below, give insights regarding changes in customers' behavior due to digital technologies. Here it can be seen that the results aren't as unanimous as for the previous questions, and several different impacts are observed, with the highest-ranking being customers' increased **energy consumption flexibility** and **participation in the electricity system**. The wider diversity in the collected answers might be explained by the national differences present amongst the respondents, with great disparities in terms of population, as well as digital maturity level.

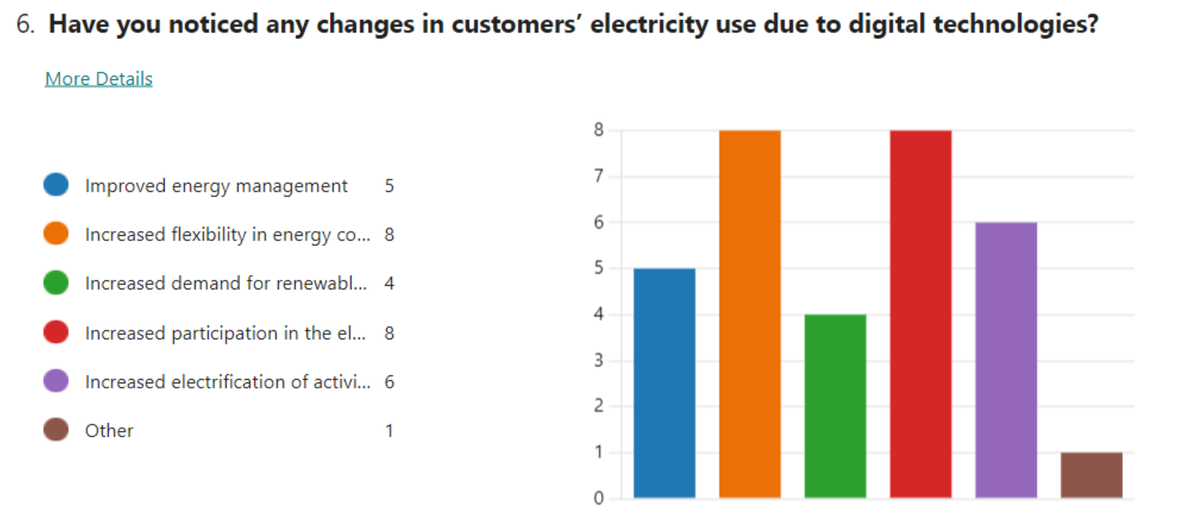


Figure 9 – Outcomes of question 6 of the survey.

Questions 12 and 13, whose results are presented in Figure 10 below, clearly show the immense benefit that digital technologies, with special focus on smart meters, have on electricity data. If the overall data sharing experience is indeed positively affected, the biggest improvement observed, with as high as 14 selections out of the 14 respondents who agree with the statement, is related to **data quality**. The **time granularity** of the shared data, as well as its **accuracy**, are particularly worth of mention.

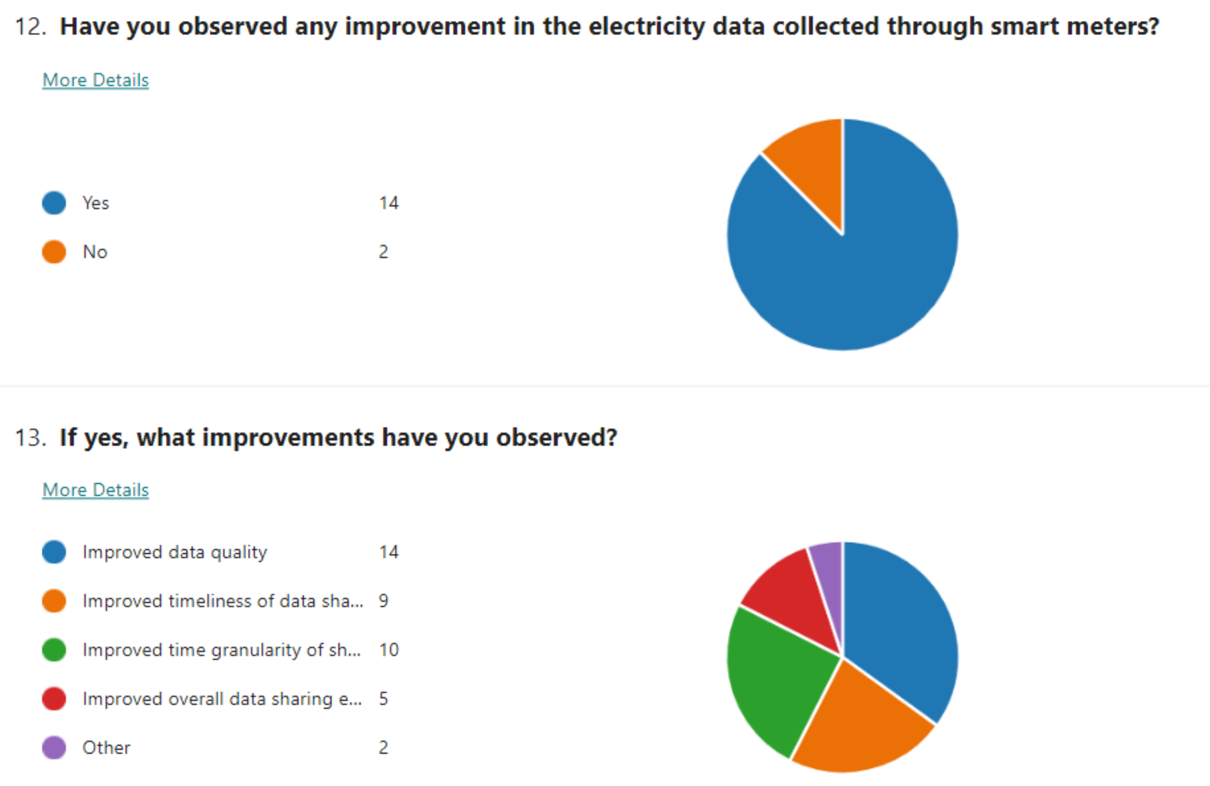


Figure 10 – Outcomes of questions 12 and 13 of the survey.

Finally, by looking at the results of question 14 shown below, it can be said that the assessment of the impact of digital technologies, and smart meters particularly, on the environmental performance of electricity networks is overall positive.

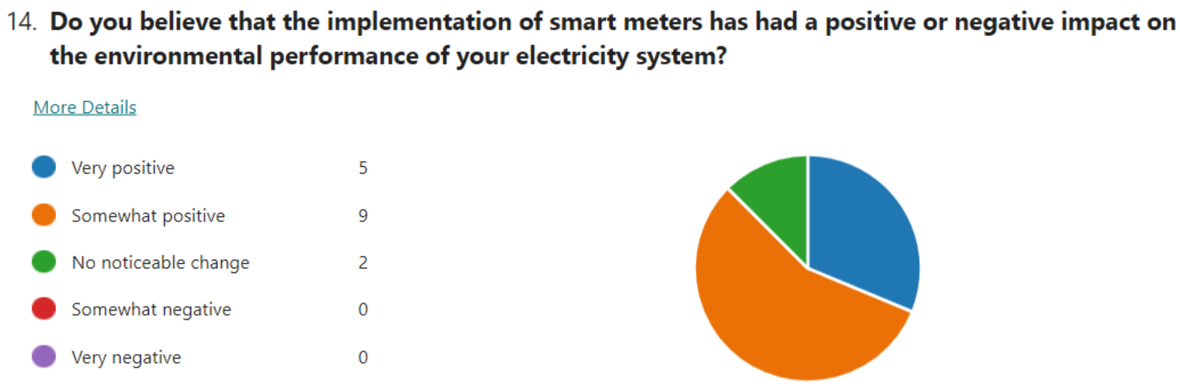


Figure 11 – Outcomes of question 14 of the survey.

In the next section the Key Performance Indicators defined for the survey are assessed according to the results obtained.

8.2 KPIs Assessment

The KPIs assessment aims at evaluating the level of impact that digital technologies have on the different aspects of electricity networks and their operation. It is performed with a **traffic light system**, according to which the color red corresponds to low impact, yellow to medium impact, and green to high impact. In order to assign the impact levels, for each KPI, the following methodological steps are followed:

1. The questions addressing aspects relevant to the KPI are identified
2. Within each identified question, the relevant answer options are recognized
3. The number of participants choosing each option is collected
4. The average of the number of participants who chose each option is computed
5. The criterion for the assignment of the impact is applied:
   - If the relevant options were selected by an average number of participants equal or greater than 70% of the maximum possible (being it 16, as the number of respondents): high impact
   - If the relevant options were selected by an average number of participants equal or greater than 30% of the maximum possible, whilst lower than 70%: medium impact
   - If the relevant options were selected by an average number of participants lower than 30% of the maximum possible: low impact

The maximum number of selections that could occur for each answer option is represented by the total number of respondents – 16. Starting from this figure, the 70% of respondents corresponds to 11.2, while the 30% to 4.8. Therefore, a KPI is considered as highly impacted, when the average number of selections of its relevant options exceeds 11.2, medium when it lays between 4.8 and 11.2, and low when it is below 4.8. To assess the results with more accuracy, the impact levels of medium-high and medium-low are also utilized for results respectively between 9 and 11.2, and between 4.8 and 6.

It is worth noticing that the conditions to be fulfilled for the determination of a high impact are quite restrictive. This is an intentional choice of this author to account for the limited scope of the survey and the small pool of people it was submitted to.

Based on this methodology, the KPIs assessment is performed. The results obtained through this procedure are shown in Table 3.

Table 3 – Results of the KPIs assessment.

KPI	Average Number of Selections	Impact Assessment (High/Medium/Low)	Color
Grid Reliability and Stability	6.4	Medium	

Grid Management	6.7	Medium	
Operational efficiency	10.1	Medium/High	
Data Quality	8.2	Medium	
Cost Savings	9	Medium/High	
Customer Engagement	6.2	Medium	
Environmental Performance	6	Medium/Low	

Such results are further visualized through the spider chart reported below.

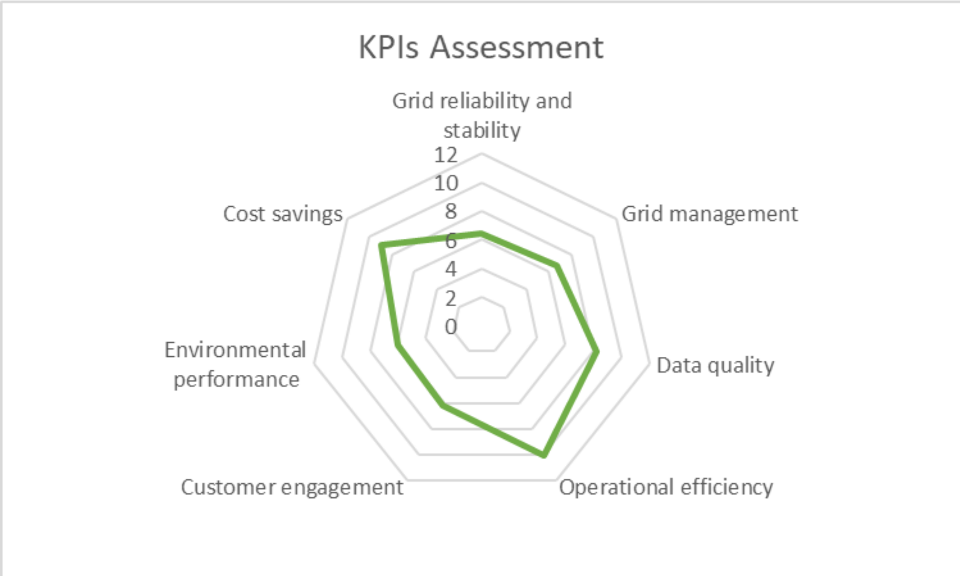


Figure 12 – Spider chart with the KPIs assessment results.

As seen in the results table, most KPIs are mediumly impacted by the investigated digital technologies. Only exceptions are represented by Operational efficiency and Costs savings, which are impacted in a medium to high manner, and Environmental performance, which is affected by digital technologies to a medium to low extent. Such results can be regarded as a reasonable representation of the reality of things, where no extreme positions are yet taken on the impact that digital technologies have on electricity networks. This is due to several different reasons, that must be kept in mind when analyzing these results.

Firstly, the level of deployment of the investigated technologies understandably plays a crucial role in the definition of the position of system operators on them, and therefore on their answers. As the graphs below, extracted from the survey itself, show, the level of deployment of digital technologies is quite heterogeneous across the respondents' networks and therefore, in several cases, their impact might not be visible or even present at all yet. The results of question 8 – status of smart meters rollout – are particularly interesting as they paint a very polarized picture of the level of deployment of smart meters. On one hand, this proves to be in line with the state-of-the-art assessment performed in the literature review (see 6.1), with a group of countries presenting a very advanced level of implementation, another one a very poor one, and a third one falling in the middle. This also corroborates the misalignment between the goals set at European level by the Commission for smart metering rollout (80% coverage to be achieved by 2020 - see 6.1) and the actual reality of things. On the other hand, such ununiform results greatly affect the survey's answers, making it very difficult to define a clear position on the impact that smart meters have on electricity systems.

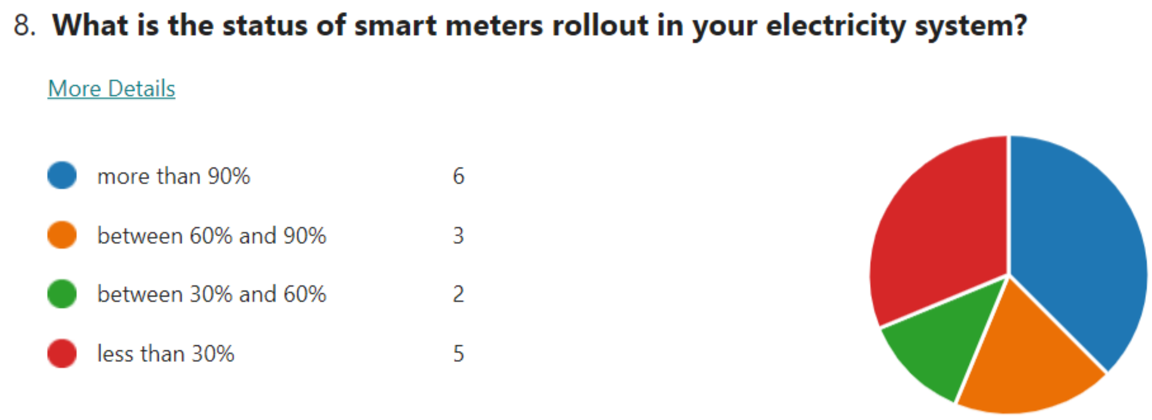


Figure 13 – Outcomes of question 8 of the survey, regarding the status of smart meters rollout.

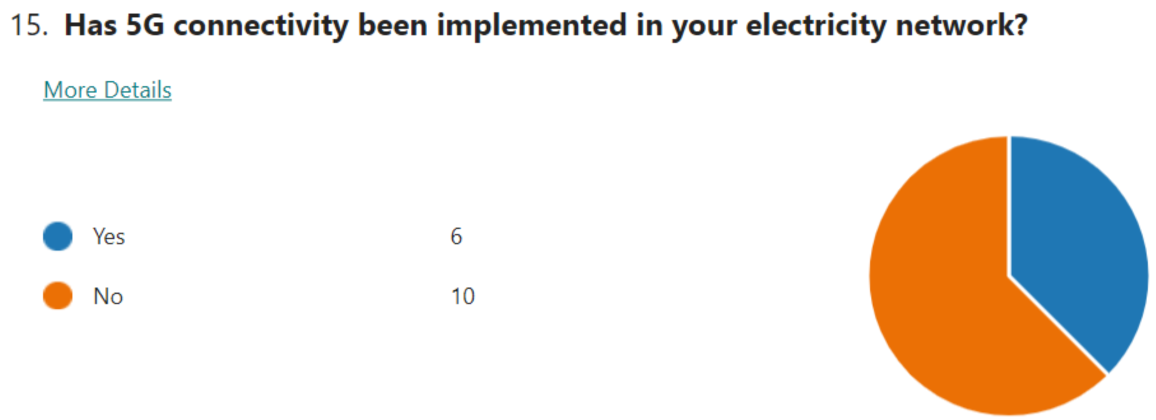


Figure 14 – Outcomes of question 15 of the survey, regarding the status of 5G connectivity implementation.

Secondly, the reality of electricity systems, where many actors and devices operate in an extremely interconnected manner, makes it very difficult to identify the benefits and drawbacks associated with a specific technology, let alone quantifying them. For this reason, system operators might have given conservative answers when asked to pinpoint the specific impacts of the investigated technologies on their networks and operations. If digital technologies have indeed contributed to the improvement of the overall status and management of electricity systems, as the results show, it is quite hard to directly link such benefits to a single specific technological implementation.

Finally, the limited number of answers allowed for each question, whilst on one hand helps identifying system operators' priorities and classifying the options accordingly, on the other hand prevents some options from receiving more selections. At the time of applying the methodology and calculating the average, options with low scores obviously affect the final results and therefore the assessed impact level.

This section provided an assessment of the defined KPIs, thus allowing to determine the level of impact of the investigated digital technologies on several aspects of electricity systems and their operations. In the following chapter, such KPIs are linked to four impact categories, and the survey's results are framed and discussed according to them.

9 Results Analysis: Impact Assessment of Digital Technologies

The assessment of the impact of digital technologies on electricity systems requires a thorough analysis of the results obtained from the survey. Such results need to be methodologically sorted and organized according to their area of interest. For this purpose, four impact categories are defined based on the identified KPIs. These categories create the framework for the classification of the results and a more punctual and deep discussion about them. The four impact categories defined, together with the KPIs leading to their creation are listed in Table 4.

Table 4 – Impact categories and KPIs involved in their definition.

Impact Category	KPIs Involved
Technical	Grid reliability and stability Grid Management Operational efficiency* Data quality
Economic	Costs savings Operational efficiency*
Environmental	Environmental performance
Social	Customer engagement

*The KPI "Operational efficiency" is shared between two different impact categories - technical and economical. This is because operational efficiency refers to both technical and economic efficiency.

Based on the KPIs evaluation presented in the previous section, a high-level assessment of the four impact categories can already be done. Considering the level of impact registered for each KPI (see Table 3), it can be said that the category that presents the most positive results is the Economic one, as both KPIs defining it were assessed as medium to highly impacted. On the opposite hand, the Social and Environmental categories register the least benefits since both their KPIs were evaluated as modestly impacted. Finally, the Technical category lays in between, with its KPIs presenting medium impacts. This high-level evaluation is visualized in the spider chart below.

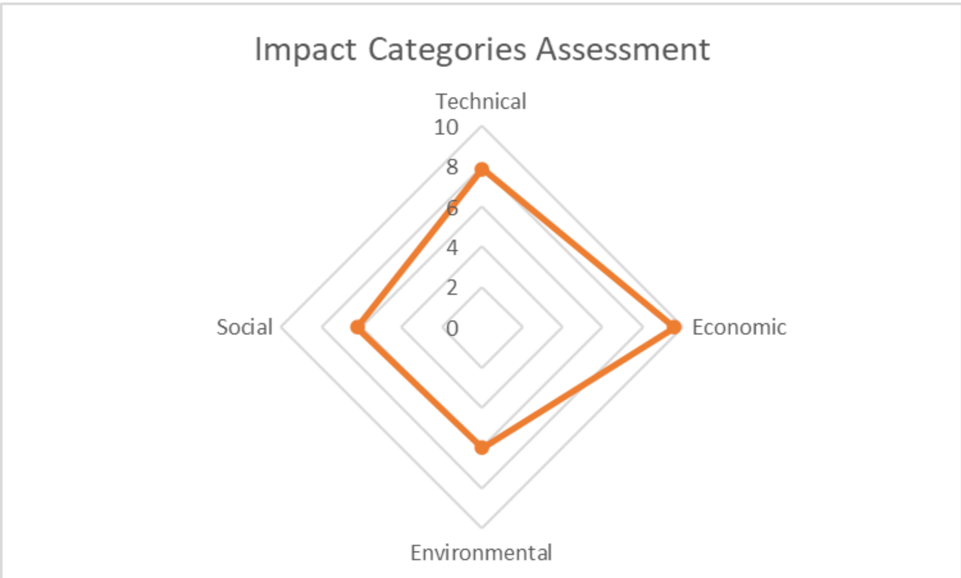


Figure 15 – Spider chart with the impact categories assessment.

The following sections provide the analysis and discussion of the outcomes of the survey within each impact category.

9.1 Technical Impact

The impact category related to technical aspects is the one with the highest number of representative KPIs. This is due to the fact that the impacts of digital technologies on the operation and management of electricity systems from a technical point of view are the easiest to detect, especially from the perspective of system operators.

Digital technologies prove to have substantial and very concrete positive impacts on the technical aspects of electricity networks and their operation. First of all, digital technologies allow for an increase in the **amount of electricity data** flowing to and from system operators. This, together with the improved granularity and the real-time nature of such data, provides the direct benefit of enhancing the **observability** of the network. The importance of data accessibility in grid management shouldn't come as a surprise, and the communication "A European Strategy for Data" of 2020 (see 4.2) already represented an effort in the direction of improving data quality and availability. The improved observability of electricity networks enabled by better quality data additionally benefits **network monitoring and management**, thus affecting its maintenance and improving operational efficiency. An enhanced control over electricity assets allows system operators to extend their lifetime through **predictive maintenance**, thus reducing the need for investments for their care and replacements. This was also mentioned in the communication "Powering a Climate-neutral Economy: An EU Strategy for Energy System Integration" of 2020 (see 4.3) as a reason for pushing forward the deployment of 5G connectivity, Artificial Intelligence (AI), and Big Data.

The greater accuracy and time granularity of electricity data collected via smart meters and other intelligent devices running on different connectivity technologies also allows system operators to forecast the network demand more precisely. This has the direct benefits of improving the match of the supply with such demand, as well as intervening in a timely and effective manner on the network status and implementing measures for peak load management. The introduction of schemes for demand response or load management increases networks' flexibility and reduces the risk of outages, while also improving their detection. All these benefits, while enhancing operational efficiency and reactivity, ultimately contribute to **a more stable and reliable grid**, which is the primary goal of system operators.

The above-discussed aspects were already mentioned as necessary for the optimization of present and future electricity grids in the IEA "Technology Roadmap, Smart Grids" of 2011 (see 3.1) and further taken into consideration for the communication "Powering a Climate-neutral Economy: An EU Strategy for Energy System Integration" of 2020 (see 4.3). Indeed, the aspects of observability and controllability, efficient infrastructure and network planning, operations and simulations for a more resilient grid, active system management and forecasting to support flexibility and demand response, and data exchange between TSOs and DSOs are what constituted the basis for one of the actions of the EU Action Plan of 2022 discussed in section 5.2. The creation of a digital twin of the European electricity grid represents the ultimate mean to unlock the full potential of digital technologies and enhance the numerous benefits they carry with them. It can therefore be said that the perceived and forecasted technical impacts of digital technologies on electricity systems provide a reason for their quick and effective deployment.

9.2 Economic Impact

The impact category related to economic aspects is the one represented by the highest scoring KPIs. The economic impact of digital technologies is mainly experienced by system operators as a **reduction in operational and maintenance costs**. More concretely, through the enhanced observability and controllability of the network in real time, system operators can manage resources and assets more efficiently, thus reducing the investments needed for the operation, maintenance, and upgrade of the system. Such economic impact of digital technologies was already forecasted by the IEA in its "Energy Efficiency and Digitalization" report of 2019 (see 3.3) as one of the benefits that digitalization would bring about. Such expectation is therefore corroborated by the real-life experience of system operators.

The overall improvement in operational efficiency registered by system operators, is also reflected on the consumers' side. Digital technologies such as smart meters unlock electricity saving potentials for consumers through the enhanced transparency about their electricity consumption. This not only allows them to increase their **energy efficiency** by making more conscious choices about their electricity consumption, which immediately translates into savings on the electricity bill, but also gives them the possibility to participate in demand response programs, thus creating **new revenue streams**. Additionally, as mentioned in the IEA "Energy Efficiency and Digitalization" report of 2019 (see 3.3), digital technologies allow for a more accurate quantification of the economic benefits brought about by increased energy efficiency, thus creating a virtuous cycle in costumers' behavior.

In conclusion, the economic benefits discussed above represent a great incentive for all electricity systems' stakeholders to accelerate the deployment of digital technologies.

9.3 Environmental Impact

The clearest and most important way in which digital technologies impact the environmental performance of electricity systems and their operations regards the **integration of variable, renewable technologies**. As already mentioned in the IEA report "Technology Roadmap, Smart Grids" of 2011 (see 3.1), improving the management of power production and quality contributes to the stability and balance of the electricity grid, which in turn favors the deployment of renewable technologies. This holds true for both centralized and distributed renewable generation. Such trend has the double benefit of greening the electrical system and encouraging electricity consumers to invest in renewable technologies to become themselves small-scale producers. From the point of view of consumers, in particular, this last trend, together with the improved accuracy of electricity consumption monitoring enabled by digital technologies, represents an additional incentive for the **electrification** of activities, processes, and appliances. All these steps are necessary for the decarbonization of electricity grids moving forward.

In addition to the most obvious benefit of increasing the capacity of renewable generation, the environmental performance of electricity networks is also improved through the increased energy efficiency enabled by digital technologies. This, as already explained in the previous section, allows for a better resource management, and decreases electricity consumption, therefore reducing the amount of primary energy sources needed for electricity generation.

In conclusion, the benefits provided by digital technologies to electricity networks and their technical operation, directly impact their environmental performance and offer reasons for a more ample adoption.

9.4 Social Impact

The social impact of digital technologies is hard to evaluate from the point of view of system operators. This is even more true for TSOs, as they don't have direct vision nor control over small customers' electricity consumption habits. DSOs, on the other hand, while managing the distribution grid, have direct connection to households and small production and consumption facilities, which enables them to have a clearer idea of trends and changes at consumers' level.

This being said, the most relevant impact that system operators notice on customers since the introduction of digital technologies in their networks, is their increased **active participation** in the management of the electricity system. By being able to monitor their electricity consumption through smart meters and other intelligent devices, consumers are better equipped to participate in demand response and other load management programs, which have effects on the entire electricity network. This has the triple benefit of generating new sources of revenues for consumers (as explained in 9.2), allowing system operators to manage the grid more effectively, thus increasing operational efficiency and costs savings as previously discussed, and to **empower** customers to take ownership of their own electricity consumption. This last fact, in particular, directly ties with the other major impact observed by system operators, which regards costumers' increased **flexibility** in their electricity consumption. As discussed in 5.3, one of the actions of the EU Action Plan, is indeed focused on making sure that in the process of digitalizing the energy system no one is left behind, and that all consumers are engaged and empowered to contribute to the stability of electricity systems to the extent they see fit.

Another impact observed on consumers as a result of digital technologies, although to a smaller extent according to the respondents, is the increased **demand for renewable energy**. This positive behavior sets the stage for an increase in distributed renewable generation installations, such as rooftops PV panels, and the transformation of passive consumers into active prosumers. As already explained by the IEA in its

"Digitalization & Energy" report of 2017 (see 3.2), prosumers and energy communities are set to play an increasingly important role within electricity systems and their operations moving forward.

The social impacts of digital technologies aren't however entirely positive, as the new interconnectedness and transparency pose questions about data privacy and customers protection. These and other concerns are discussed in the following chapter.

10 Further Discussion

To allow for an unbiased evaluation of the stand of system operators on the topic of digitalization, the survey includes two questions that transcend the main scope of assessing the impacts of digital technologies on electricity systems. One of them concerns system operators' view on the future of digital technologies within the electricity system, while the other openly asks about experienced negative impacts of digital technologies. The outcomes of these questions are here discussed.

10.1 Future Impacts

Question 7 of the survey asks the participants about how they foresee digital technologies to shape the future of electricity systems. Almost all respondents agree that a more digitalized electricity grid will allow for **greater efficiency and optimization of energy usage**. This comes at little surprise since it is already mentioned as one of the main benefits brough about by digital technologies in the present. Additionally, together with another foreseen improvement regarding **grid reliability and stability**, this is one of the main areas of investment for the action of the EU Action Plan aimed at the creation of the digital twin of the European electricity network (see 5.2). Therefore, its importance and direct correlation with the process of digitalization is commonly understood.

Another strong position is taken by system operators on the enabling role that digital technologies will play in the deployment of **distributed generation**, that, in exchange, will make electricity systems increasingly decentralized. Such crucial aspect of the grid of the future is also not new. The enhancement of flexibility, integration of Virtual Power Plants (VPP), and exploitation of energy communities are indeed some of the benefits foreseen with the creation of an European Energy Data Space, as established in "A European Strategy for Data" (see 4.2), and further reiterated as one of the actions of the EU Action Plan (see 5.1).

Finally, most respondents agree that digital technologies will promote and enhance **customers engagement** and participation in the electricity system. Since greater customers active participation is already observed by system operators nowadays, it is just logic to expect this trend to intensify even more in the future. Again, this expectation is shared amongst the energy community and regulators, and consumers empowerment and protection constitute the focus of another action of the EU Action Plan, as discussed in 5.3.

In conclusion, system operators expect digital technologies to accelerate and enhance the trend and changes already taking place within the electricity system. Therefore, it can be said that an increased digitalization of electricity networks is supported and encouraged by them.

10.2 Negative Impacts

Question 20 of the survey is aimed at gathering open feedback from system operators about the negative impacts of the implementation of digital technologies that they observe in their electricity networks. Being this an open, non-mandatory question, not all respondents contributed to it, but 13 out of 16 did. Out of these 13 answers, 6 state that no negative aspect is recorded. However, several other entries provide interesting insights on the experience of system operators with digitalization.

A group of respondents (4) mention the increased **cybersecurity threats** as the main negative impact of digital technologies. The large amount of shared data and the different platforms used for it, expand the surface area vulnerable to cyberattacks, thus endangering system operators and consumers' practices and safety. The question of cybersecurity is indeed at the center of attention in the process of digitalization of energy, and regulators are aware of the importance of establishing safety guidelines and frameworks to ensure the principle of "safety by design". One of the actions of the EU Action Plan (see 5.4) is indeed solely focused on guaranteeing cybersecurity and resilience in the process of digitalization moving forward.

Another negative aspect mentioned by a few respondents (2) concerns the topic of **privacy** at the time of sharing personal data, as it happens with smart meters and other intelligent devices. The question of data privacy is indeed a hot topic in the general discourse of digitalization, and, by affecting every party involved, raises questions regarding ethical aspects. Which data is shared? Who has access to it? How is the data used? These are just some of the many questions that need to be carefully considered during the process of digitalization. Once again, regulators and policymakers are aware of the importance of such matters, and efforts have indeed been made in this sense. From "A Digital Single Market Strategy for Europe" (see 4.1) which aims at guaranteeing customers' rights to privacy and personal data protection, to one of the actions of the EU Action Plan (see 5.3) which addresses the topic of customers vulnerability, the question of privacy is surely kept under close attention.

A third issue that some respondents (2) mention in their feedback is related to the lack of a digitally skilled workforce. Citing directly from one of the respondents' answer, "*The amount of data collected is growing faster than we are able to grow the digital skills of our people*". This experienced **lack of competences and skills** clearly represents an impediment in the effort of expanding and improving the digitalization of electricity systems. Such an issue is taken into consideration by regulators who, in "A European Strategy for Data" (see 4.2) first and in one of the actions of the EU Action plan (see 5.3) later, envision plans to build digital competences and skills through education. These, however, need immediate implementation if the process of digitalization is to be realized in a timely and effective manner.

Finally, an interesting remark from one of the respondents places the focus on the human aspect of digitalization. Digital technologies require many changes in the roles, functions, and missions of IT and business experts, therefore, it is important to address the question of **change management** not only from a practical, but also from a psychological point of view. Change is experienced differently across individuals, organizations, and cultures, and it must be dealt with properly for a productive and comfortable digital transition. Therefore, the human impact of digital technologies must not be underestimated.

In conclusion, the feedback provided by system operators regarding the negative impacts of digital technologies, aligns with regulators' concerns and plans of action. It is therefore fair to wish for an improvement in such matters moving forward.

11 Conclusions

The study presented in this work aimed at providing an assessment of the digitalization of electricity systems. From the performed literature review it emerged that the energy community has long been advocating for a faster and deeper digitalization of energy and electricity. This is also corroborated by the regulatory framework built around digitalization that aims at fostering a data driven European economy and society. From a technical point of view, digital technologies can indeed assist electricity networks in facing the new challenges brought about by decarbonization. These challenges were identified in ageing infrastructure, the increased demand due to electrification, the integration of large amounts of variable, renewable generation, and guaranteeing security of supply. The energy community highlighted several solutions to such challenges to be unlocked by digital technologies. Amongst these were: enhanced flexibility and demand side management, improved system planning and stability, optimization of infrastructure and reduced operational costs, and improved energy efficiency and management. Such benefits are as well the focus of the recent EU Action Plan for the digitalization of the European energy system, which aims at establishing an EU coordinated effort for a faster and deeper digital transformation. Indeed, the state of digitalization in Europe proved to be lagging compared to the goals and expectations set by regulators, with only 56% of smart meters rollout and 72% of 5G connectivity coverage as of 2022.

Against this background, the research conducted in this work aimed at gathering feedback from transmission and distribution system operators about the experienced impacts of digital technologies on their networks and operations. This was done by means of a survey created based on seven defined KPIs that cover several aspects of electricity networks, from grid management and operational efficiency to customer engagement.

Such KPIs led to the creation of four impact categories - technical, economic, environmental, and social – used for the assessment of the survey's outcomes.

The survey presented a response rate of 27.1%. The results proved to be in line with the findings from the literature review, with the economic category resulting the most highly and positively impacted. Indeed, according to the survey's results, digital technologies are not only reducing operational costs and improving resources and assets management for system operators, but they're also providing economic benefits to costumers through increased energy efficiency and the participation in demand response programs. From a technical point of view, the main benefit unlocked by digital technologies is the improved network observability and monitoring thanks to the increased amount and quality of electricity data available. This carries with it the improvement of system management for a more stable and reliable electricity supply. In terms of environmental performance, as already anticipated, digital technologies are enabling the integration of more renewable generation, while at the same time reducing the need for primary energy sources thanks to improved demand management and energy efficiency. Finally, from a social standpoint, digital technologies are empowering costumers to participate in the electricity system management more actively and to make more conscious and flexible choices about their electricity consumption.

During the study, some negative impacts of digital technologies were also registered. These were mainly identified in increased cybersecurity threats, data privacy concerns, and the lack of digital competences and skills. Once again, these aspects were already found as crucial action points for the energy community and regulators.

In conclusion, digital technologies support system operators and electricity consumers in their short and long-term plans and activities, and act as enablers of the process of decarbonization of electricity. Therefore, digitalization, while carefully managed, should be welcomed as a new, integral part of everyone's reality.

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Annex A – Survey

Impact of digital technologies on the electricity system

The survey will take approximately 5 minutes to complete.

'Research on the impact assessment of digital technologies on the electricity system and its operators.'

Digital technologies are reshaping the way we produce, consume and manage electricity. System operators, in particular, have the responsibility of integrating digital technologies in their operations to enable the digital and green transition.

This study aims at providing an overview of the main benefits and challenges brought about by digital technologies on the management and operations of electricity networks. Particular focus is placed on smart meters and 5G connectivity, as the main enablers for the digitalization of electricity systems.

The results of this survey will be used as the basis for a discussion for master study purposes.

...

* Required

1. What is your role within the electricity sector? *

- ○ TSO
- ○ DSO

2. Please provide the name of your organization and country of operation. *

Enter your answer

3. What is the level of maturity of the following digital technologies in your electricity network? *

	High	Medium	Low
Advanced Metering Infrastructure (AMI)	○	○	○
5G Connectivity	○	○	○
Distributed energy resources management systems	○	○	○
Cybersecurity systems	○	○	○
Digital substations	○	○	○
Digital Twin	○	○	○

4. **How have digital technologies impacted your network's status?** *

Please select at most 3 options.

- ☐ Improved grid reliability and stability
- ☐ Improved grid resilience
- ☐ Improved environmental performance
- ☐ Improved network observability
- ☐ Reduced maintenance costs
- ☐ Other

5. **How have digital technologies impacted your operations?** *

Please select at most 4 options.

- ☐ Improved operational efficiency
- ☐ Improved monitoring and maintenance
- ☐ Improved demand response
- ☐ Reduced operational costs
- ☐ Improved grid management services
- ☐ Improved inter-TSO collaboration
- ☐ Other

6. **Have you noticed any changes in customers' electricity use due to digital technologies?** *

Please select at most 3 options.

- ☐ Improved energy management
- ☐ Increased flexibility in energy consumption
- ☐ Increased demand for renewable energy
- ☐ Increased participation in the electricity system
- ☐ Increased electrification of activities/operations/appliances
- ☐ Other

7. **How do you see digital technologies shaping the future of the electricity system?** *

Please select at most 4 options.

- ☐ More decentralized and distributed energy systems
- ☐ Increased reliance on renewable energy
- ☐ Greater efficiency and optimization of energy usage
- ☐ Improved grid reliability and resilience
- ☐ Increased customer engagement and participation
- ☐ Enhanced data quality
- ☐ Increased cost savings
- ☐ Other

8. **What is the status of smart meters rollout in your electricity system?** *

- ○ more than 90%
- ○ between 60% and 90%
- ○ between 30% and 60%
- ○ less than 30%

9. **If you have implemented smart meters, what benefits have you seen in your operations?** *

Please select at most 5 options.

- ☐ Improved accuracy of meter readings
- ☐ Reduced manual meter reading costs
- ☐ Reduced remedial actions interventions
- ☐ Improved network monitoring
- ☐ Improved demand forecast
- ☐ Improved load balancing
- ☐ Improved outage detection
- ☐ Reduced outage response times
- ☐ Other

10. **Have you implemented any demand response programs or other load management initiatives as a result of smart meters?** *

- ◯ Yes
- ◯ No

11. **If you have implemented demand response programs or other load management initiatives, what impact have they had on your electricity network?** *

Please select at most 3 options.

- [ ] Reduced peak demand
- [ ] Reduced overall energy consumption
- [ ] Improved grid stability
- [ ] Reduced outages
- [ ] Other

12. **Have you observed any improvement in the electricity data collected through smart meters?** *

- ( ) Yes
- ( ) No

13. **If yes, what improvements have you observed?** *

Please select at most 3 options.

- [ ] Improved data quality
- [ ] Improved timeliness of data sharing
- [ ] Improved time granularity of shared data
- [ ] Improved overall data sharing experience
- [ ] Other

14. **Do you believe that the implementation of smart meters has had a positive or negative impact on the environmental performance of your electricity system?** *

- ◯ Very positive
- ◯ Somewhat positive
- ◯ No noticeable change
- ◯ Somewhat negative
- ◯ Very negative

15. **Has 5G connectivity been implemented in your electricity network?** *

- ◯ Yes
- ◯ No

16. **Have you observed any improvement in the electricity data collection process thanks to 5G connectivity?** *

- ◯ Yes
- ◯ No

17. **If yes, what improvements have you observed?** *

Please select at most 3 options.

- [ ] Increased data sharing speed
- [ ] Increased data processing speed
- [ ] Increased shared data quantity
- [ ] Improved data quality
- [ ] Other

18. **Have you observed any benefits enabled by the implementation 5G connectivity in your electricity network?** *

- ( ) Yes
- ( ) No

19. **If yes, please specify the benefits observed.** *

Please select at most 2 options.

- [ ] Improved network reliability
- [ ] Reduced outage times
- [ ] Enhanced grid management and monitoring
- [ ] Improved load balancing
- [ ] Other

20. **Have you observed any negative impact from the implementation of digital technologies in your electricity network? If yes, can you please specify?**

Enter your answer

You can print a copy of your answer after you submit

Submit

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