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# Digitalization in decarbonizing electricity systems – Phenomena, regional aspects, stakeholders, use cases, challenges and policy options

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## ABSTRACT

Digitalization is a megatrend that affects and transforms societal, economic, and environmental processes on a global scale. Driven by a combination of technological advances as well as shifting societal demands, digitalization also affects the operation and planning of the electricity sector. This paper uses megatrend analysis framework to analyze digitalization phenomena, its regional differences, technologies, use cases and challenges. It highlights potential system-level benefits (e.g., increased efficiency, transparency, consumer participation) and challenges (e.g., electricity demand growth, autonomy loss, increasing cyber risks) currently reported in the literature. Eventually, building on the thorough analysis, we present a menu of policy options to exploit its full potential of digitalized electricity systems while mitigating adverse effects on decarbonization goals and consumers.

## 1. Digitalization in the electricity system

Digitalization, along with decarbonization and decentralization/deregulation, is a key phenomenon affecting the electricity sector [1]. It can be described as the increasing convergence of and interaction between digital and physical agents and infrastructures, particularly in the application of information and communication technologies (ICT) across the economy (including energy) [2]. It is driven by various technological factors, such as exponential data availability, advances in computing power and capacity for improved analytics, and expansion of connectivity through advances in communication networks [2,3]. In addition, investment by governments and private companies in digitalization technologies (either due to market pull from demand or push from new innovations) may also have accelerated the phenomenon [6, 5].

Positive implications of applying digital technologies to various use cases throughout the economy and the value generated can come as economic gain (e.g., from improved efficiencies) or societal benefit (e.g., more reliable, decarbonized electricity generation) [2,6]. A recent study based on an E-survey [7] found that expected improvements in economic performance is the main driver for the uptake of digital

technologies in the Polish energy sector. The EU's assessment and roadmap for the digital transformation of the energy sector summarizes the potential of digital technology applications along the energy value chain [69]. Recent research [3] outlined how digital technologies may support electricity system decarbonization and process optimization. The report delineated various use cases employing big data (BD) [9,10], digital twins (DT) [11,12], artificial intelligence (AI) [13,14], internet of things (IoT) [15], distributed ledger (DL - incl. blockchain [16,17]), and cloud computing (CC) among others [18]. But digitalizing the electricity sector also brings risks, such as increasing electricity consumption [19, 20] and resource use [21,22], cyber security issues [23,24], and data privacy concerns [25].

The high pace of technological advancement may require dynamically adjusting electricity regulation [26] to exploit the full benefits that digitalization may bring to the electricity sector. Such benefits and potential contributions to fulfill the Sustainable Development Goals have been surveyed in a recent study [27]. Reported benefits also include further electrification and thus less reliance on fossil fuels [28]. Furthermore, some countries have introduced protected test-beds, so called regulatory sandboxes, to further assess the advantages of digital technologies and business models [29] in highly regulated sectors. An

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international comparison of currently used regulatory sandboxes and examples on how they support the use of digital technologies or business models is provided in Ref. [30].

Despite the growing interest on the impact of digitalization on electricity systems, there is a lack of a comprehensive overview that analyses digitalization phenomena, expected benefits, challenges and policy options from a broader, global scale. Finally, the diversity of the use of the term “digitalization” showcases the growing need to synthesize the existing range of definitions and concepts.

Hence, this work addresses the identified gap, providing:

- A) the first, consistent review of digitalization phenomena, stakeholders, regional differences and digitalization’s impact on electricity systems by applying a megatrend analysis framework.
- B) a detailed overview of digital technologies and business models as well as their potential benefits and new challenges they may pose to electricity system planning and operation.
- C) a technology-oriented menu of policy options that can help to exploit digitalization’s full benefits while mitigating adverse system-level effects.

The presented study will prove a useful source to policymakers, researchers and industry practitioners that seek consistent information on digitalization phenomena, its potential benefits and adverse effects on electricity systems.

## 2. Megatrend analysis applied on digitalization phenomena

In this study, we apply a megatrend analysis framework to study the effects of the megatrend of digitalization on electricity systems. A megatrend has been defined as global challenges that “are generated by macroeconomic forces that manifest themselves in cycles ranging between 20 and 50 years and that act on extended geographical areas by generating an important shift in the progress of a society” [31]. It is an internationally widely used analysis framework for foresight studies on emerging technologies and business models [32]. Many works have categorized the spread of digital technologies, business models and increasing connectivity as a megatrend [33,34]. The results of a bibliometric analysis on technological megatrends from 1982- to 2021 [31] even suggest that digital technologies have been at the center of megatrend research.

Our work builds on previous studies on megatrends, such as the work of [32], who introduced a megatrend analysis framework aimed at product or service developers. The framework consists of seven stages, comprising definition building, information review, definition review, opportunity screening, megatrend implications, expert consultation and a commercial and technical feasibility check. Another recent study conducted a regionalized megatrend analysis on the case of European agriculture [35]. The work considers the megatrends climate change, demographic change, environmental degradation and shifts in consumer & producer preferences. While the uptake of digital technologies and business models is not considered, the study presents a comprehensive analysis of one single economic sector (agriculture).

In this paper, we apply an novel megatrend analysis framework for policy makers, researchers and industry practitioners that builds on previous advances [32,35]. The developed framework consists of five stages, that allow for holistic analysis of any megatrend and its impact on a specific economic sector. The stages include: 1) Megatrend definition, 2) Phenomena and stakeholders, 3) New technologies and business models, 4) Opportunities and challenges and 5) Policy options (Fig. 1). While stages 1)-4) are particularly interesting for industry practitioners and researchers, stage 5) is particularly interesting for professionals that shape energy policy and regulation.

Thus, in this study, we apply the herein introduced megatrend analysis framework to study the phenomena of digitalization and its effects on electricity systems. The core aspects that guide our analysis at



Fig. 1. Developed megatrend analysis framework.

each stage are listed in the following.

**Stage 1: Megatrend definition** (in Section 3). This step involves the definition of the megatrend and place it in a consistent manner along similar, connected concepts.

**Stage 2: Phenomena and stakeholders** (in Section 3). At this stage, the questions of “What drives the megatrend forward?“, “Which technologies does the megatrend build on?” and “Which stakeholders influence the unfolding of the megatrend” are put forward and shall be answered.

**Stage 4: Opportunities and challenges** (Section 4, Section 5.). This stage investigates upon the different use cases that are enabled through the megatrend. Which social, economic, technical or ecologic benefits does the megatrend bring? And, which challenges or risks does it introduce in the aforementioned dimensions? This step is particularly interesting for industry practitioners that seek to understand the value of new technologies and business models.

**Stage 5: Policy options** (Section 5.). This stage is typically strongly linked to the previous stage. It addresses each challenge/risk through different policy options. In other words, the final step of the presented megatrend analysis maps the action space for policy makers and regulators to pull the megatrend towards desired political goals.

To our knowledge, there has been no previous study thoroughly studying the effects of digital technologies and business models in the electricity sector applying megatrend analysis. Thus, the results will provide valuable inputs for energy policy makers, industry experts, researchers and regulators that aim to support the decarbonization of the electricity industry through the use of digital technologies and business models.

### 3. Digitalization: definitions and phenomena

#### 3.1. Defining digitalization

There is currently not a common set of definitions of digitization, digitalization and digital transformation in the electricity sector. Digitalization, for example, has been defined both from a data-centric perspective [36,37] (“digitalization as exploiting novel, large-scale data flows for optimizing some processes”) and a rather process-centric perspective [2,7] (“digitalization as wide application and uptake of ICT converging physical and digital spheres”).

However, a clear, consistent definition is a fundamental basis for further analysis. Hence, building on previous findings of [2,7,38], and differentiating by process duration and involved agents, we define:

- **Digitization** as the conversion of analogue to digital data. It is a rather quick process and can occur on the level of an individual electricity sector agent. It involves single actors (companies) and can be realized within the timeframe of months. *Example: a distribution network company digitizes its network plan into a digital version.*
- **Digitalization** as exploitation of novel data sources through the application of digital technologies (i.e., ICT) across all agents in one economic sector, in order to improve safety, efficiency and productivity. Digitalization involves structural changes in a whole economic sector over the several years. *Example: all distribution network companies digitize their network plans and assets.*
  - **Digital transformation** as large-scale, cross-sectoral networking of all economic and social agents towards an interlinked, digital system, which exploits enhanced data exchange, analysis, and decision capabilities. Over the period of years to decades, digital transformation changes the interactions between all market actors. *Example: all network companies of the gas, electricity and heating sector digitize their network plans and assets and provide the data on a central data platform for multiple users and novel business models.*

The above-cited set of definitions differ from those presented in Refs. [39,40], whose definition of “digital transformation” is almost interchangeably used with the more common definition of “digitalization” put forward (e.g., by Refs. [1,36]). The problem of using “digital transformation” for describing company or sectoral uptakes of digital technologies and business models interchangeably with “digitalization” is, that it renders it impossible to separate such process with an overall, macroscopic, economy-wide progress. The use of digital technologies and business models is still very uneven across economic sectors (e.g., electricity vs. gas and oil sector [40]) and even between countries (e.g. Ref. [7]) As such, overlapping definitions obfuscate a rigorous analysis of structural differences across countries and economic sectors.

In recent research on digitalization and energy, the historical roots of digitalization are typically attributed to technological advances, in particular the introduction of computer technology [36,44]. Interestingly, this perspective is not widely shared among social scientists. For example, Nasseni [42] argues that digitalization has emerged to satisfy societal needs for enhanced organization and planning capabilities in an increasingly complex world. Hence, digitalization has originated already from the early beginnings of population statistics and city planning, i.e. the 19th century (e.g., Quetelet and his “homme moyen” [43]).

According to Ref. [44], the process of digitalization is accompanied by five major phenomena that affect the overall social and economic conditions of human life. These are:

- **Interconnectedness.** The strong level of interconnection between all societal actors on different levels of economic, social and political life.
- **Cognition.** Technical systems able to perceive, learn, analyze, evaluate and act autonomously.

- **Autonomy.** Independent control, optimization of complex processes and decision making through technical systems.
- **Virtuality.** The evolution of new, virtual (non-physical, at times simulated) spaces for human societies.
- **Knowledge explosion.** Dynamic increase in human knowledge through novel data acquisition, processing, analysis, modeling, simulation and visualization capabilities.

#### 3.2. Regional developments in digitalization

Progress in digitalization does depend on several factors, such as quality of and access to ICT infrastructure and electricity, economic prosperity, skill sets of the work force, among others [44]. Thus, digitalization progress differs across the world’s regions. An overview of digitalization trends across world regions [45,46] is shown in Table 1. For metrics of overall digitalization, the table summarizes the European Union (EU) Digital Economy and Society Index (DESI) [47] and the ICT index values [48]. Enablers of digitalization are assessed by electricity access [49], gross domestic product (GDP) per capita [50], high speed internet access [51], and median SAIDI value [52]. The existing ICT network is described by on the network route, transmission links and node [53].

Results show highest digitalization progress in North America, Europe and Oceania, both in indices such as the EU DESI and the ICT index from the International Telecommunication Union (ITU) (see Table 2). This comes without surprise, as these continents also have highest electricity access rate and are in the upper range of GDP. In addition, ambitious policies further drive digitalization across the continents. For example, the EU has defined the coming decade as a “Digital Decade”, with numerous novel policies and ambitious digitalization targets towards 2030 [54]. Similar strategies have been formulated for creating a competitive digital economy in Australia by 2030 and for a digitalized government in the United States, with the latter already having been drafted in 2012 [55,56]. China has developed a Digital Silk Road policy (DSR) [20], and has emerged as one of the global leaders of digitalization, hosting almost half of the smart cities in the world [57].

On the African continent, economic power and electricity access, as well as reported performance indicators for digitalization, are lower than in all of the other continents. Both Europe and Asia (specifically China) have shown a major interest to promote digitalization in less developed regions through investment initiatives. Here, Africa is a key beneficiary of such investments, e.g., through the European Digital4-Development initiative [58] and the Chinese Digital Silk Road (DSR) initiative [59].

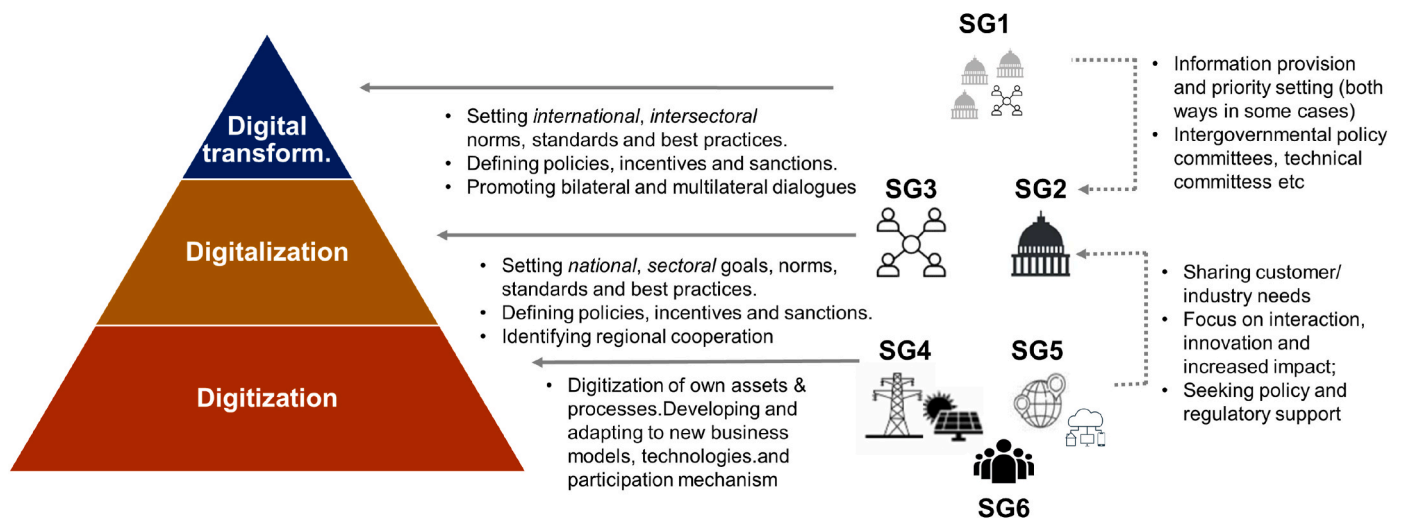
It remains to be seen if such initiatives can decrease existing regional differences in digitalization, due to the diversity in policies, economic prosperity and electricity and ICT backbone, or if the uneven adoption of digital technologies will aggravate the global digital divide [44].

#### 3.3. Digitalization stakeholders

Digitalization of electricity systems is a complex process that may involve various actors. Similar to energy policy processes, actors include international and governmental actors, non-governmental organizations (NGO), civil representatives and electricity companies and company associations from the electricity sector [60,61]. As the digitalization processes strongly relies on and relates to services and products of the digital economy, it is clear that digital companies (e.g., software companies, hardware developers, communication providers and their associations) also have a stake in the digitalization of the electricity sector. Different stakeholder groups (SG), each playing a crucial role in transforming the electricity sector, are shown in Fig. 2 and briefly discussed below:

**Table 1**  
Regional differences in digitalization progress across continents and world regions (own compilation).

Overall Digitalization progress	Africa	South & Central America	North America	Europe	Middle East + Asia	Oceania
EU DESI (0–100)	N/A	41 (Chile) to 36 (Brazil)	62 (USA) to 54 (Canada)	65 (Finland, Denmark) to 34 (Poland)	52 (Japan) to 30 (Turkey)	57 (Australia) to 55 (New Zealand)
ITU ICT Index (0–100)	68.6 (Mauritius) to 21.3 (Niger)	80.5 (Uruguay) to 41.2 (Honduras)	90.1 (USA) to 84.9 (Canada)	93.4 (UK) to 59.3 (Bosnia and Herzegovina)	94.8 (Rep. of Korea) to 25.4 (Lao PDR)	90.6 (New Zealand) to 88.3 (Australia)
<b>General enablers for digitalization</b>	<b>Africa</b>	<b>South &amp; Central America</b>	<b>North America</b>	<b>Europe</b>	<b>Middle East + Asia</b>	<b>Oceania</b>
Electricity Access (%)	100 (Egypt) to 8.4 (Chad)	100 (Chile) to 45 (Haiti)	100 (all countries)	100 (all countries)	100 (e.g., Singapore, China) to 49 (N. Korea, D.P.R.)	100 (Australia) to 63 (Papua New Guinea)
GDP/capita (USD)	<10,000	<10,000	40,000 to >60,000	<10,000 to >60,000	<60,000	<10,000 to >50,000
High Speed Internet Access (Mbps)	32.0 (Côte d’Ivoire) to 2.2 (Yemen)	200.0 (Chile) to 1.9 (Cuba)	151.2 (USA) to 106.8 (Canada)	166.1 (Denmark) to 26.8 (Bosnia and Herzegovina)	207.6 (Singapore) to 1.8 (Afghanistan)	121.9 (New Zealand) to 10.1 (Marshall Islands)
SAIDI (median)	17.8	6.3	0.58	0.63	2.21	7.28
<b>Digitalization backbone: ICT network</b>	<b>Africa</b>	<b>LAC</b>	<b>North America</b>	<b>Europe</b>	<b>CIS</b> <b>Arab States</b>	<b>Asia Pacific</b>
Route (total km)	542,365	1,729,429	1,612,600	3,986,769	1,466,907	417,034
Transmission links	5771	7590	3634	11,922	1573	1891
Nodes	3874	4921	2479	7326	867	1068



**Fig. 2.** Stakeholder interaction and influence along digitization, digitalization and digital transformation processes.

**3.3.1. Supra-national, governmental organizations (SG1)**

The main interest of this group is to protect consumer and business, and articulate, synthesize and protect the common interests of its group members (e.g., nation states). They further seek consensus and alignment of national frameworks to the common international viewpoint. An example for such a stakeholder is the Internet Governance Forum (IGF), which is a multi-stakeholder forum, with annual meetings and discussions on the regulation of the internet [62].

**3.3.2. National and regional governments (SG2)**

This groups role is to drive overarching national or regional interests through relevant policies and regulations, and to provide consumer and business protection. A further priority is the alignment of international frameworks to national viewpoints. An example would be the UK government, that, together with its national regulator, developed a countrywide “Energy Digitalization Strategy”, setting out a vision and suite of policies to digitalize the energy system [63].

**3.3.3. Non-governmental international, national and regional interest groups (SG3)**

Such groups articulate, consider and protect the interests of their

group members, while seeking consensus. An example would be AlgorithmWatch, a Swiss/German non-profit research and advocacy organization that analyzes automated decision-making (ADM) systems and their impact on society [64].

**3.3.4. Electricity companies’ (SG4)**

Major targets include maintaining profitability and revenue generation, quality of service and consumer satisfaction as well as regulatory compliance. One such example is Iberdrola, a Spanish energy company, that uses AI applications for almost 20 years to predict the production of the group’s renewable facilities by analysing meteorological variations [65].

**3.3.5. Digital economy companies (SG5)**

Share all above-mentioned targets with electricity companies. One example is Google, a major owner of data centers, which plans to decarbonize its electricity supply while operating on 24/7 carbon-free, inexpensive energy by 2030 [66].

**3.3.6. Customers, communities, and cooperatives (SG6)**

Group all kinds of end users of the digitalized, decarbonizing

electricity system. Their aim is to have seamless system integration while unlocking the benefits of small-scale on-site generation and new digital business models.

All identified stakeholder groups typically try to influence policy-making and regulation through distinct mechanisms:

**Horizontal influence** is influence within one layer of power, i.e., equally potent decision makers, and can be performed for example between national governments that collaborate on a certain policy domain (e.g., energy policy). Here, one country can, through agenda setting or knowledge transfer, try to nudge its collaborating, neighboring or partner country to adopt a similar policy in the given domain.

**Vertical influence**, on the other hand, occurs, if one stakeholder influences vertically, that is, towards larger representative bodies or smaller, single actors. This could be for example a national government that tries to influence the common strategy of an intergovernmental body. Another example is a company that lobbies its own interests in a larger company association or an association lobbying with government for a particular set of policies. In particular, member companies could, e.g., through delegates or funding, influence the joint position of an organization which is included in a policymaking process.

In reality, the stakeholder influence and policymaking process is much more complex, as shown by the existence of several different policy process models [67], with simultaneous or delayed vertical and horizontal influences that may weaken or reinforce opinions and agenda setting [68]. However, a more detailed description of the mechanisms of and incentives for stakeholder participation in the energy policy process, as well as a finer decomposition of power structures, for example using the RACI framework (Responsible, Accountable, Consulted, Informed) (e.g. as in Refs. [60,61]), lies outside the scope of this paper.

### 3.4. Digital technologies and energy sector business models

There are a set of digital technologies that are currently used in the electricity sector, which allow the uptake of digitalization-enabled business models [36,37] and applications [3,69]. Based on a strong agreement across all sources (e.g. Refs. [3,7,44]), and also considering the definitions in Ref. [13], we define the following as **primary digital technologies**, being a foundation of most applications business models in the electricity sector:

- **Big data (BD)**. Duplication of real world through large amounts of machine-readable, at times real-time, data.
- **Artificial intelligence (AI)**. Methods used to mimic human capacities such as cognition, learning and problem-solving.
- **Internet of Things (IoT)**. Fusion of digital and physical infrastructures, mainly through internet-connected devices.
- **Distributed Ledger (DL)**. Distributed, transparent transaction storage expanding along chronological order of transactions.

**Secondary digital technologies**, i.e., those with less documented use cases and/or minor agreement across the analyzed sources, include:

- **Digital Twins**: It can be seen a simulated model of a single asset up to an entire electricity system. It is enabled by IoT and can eventually optimize operational processes [70].
- **Robotics (RB)**. Use of robots for design, construction, operation processes.
- **3D printing (3D)**. Manufacturing based on a 3D computer model through sequential layering.

- **Augmented & virtual realities (VR)**. Augmented real or entirely virtual worlds allowing human interaction simulated through computers.
- **Cloud computing (CC)**. On-demand access to a shared pool of large-scale computing resources.

In contrast to Ref. [44], we do not consider “monitoring” and “cyber security” as technology but rather as a large-scale application of identified primary digital technologies (IoT, BD) and a digitalization-enabled risk, respectively.

The development and wide uptake of the afore-mentioned digital technologies also allowed the creation of new business models in the energy sector (e.g. Refs. [37,71]). Reported examples can be coarsely grouped into the following business models:

- **Optimized building energy management**. This involves various methods that use digital technologies bringing financial gain through an increase in energy efficiency and energy savings by optimizing the use of domestic applications.
- **Local energy communities**, including peer-to-peer (P2P) energy trading. These business models benefit from a partial exemption of network tariffs as well as locally produced cost-inexpensive renewable energy.
- **Optimized grid services**. This includes a multitude of concepts such as dynamic network tariffs, flexibility provision and aggregation or electric vehicle (EV) charging, providing novel monitoring and management capabilities to mitigate electricity network imbalances or asset degradation.
- **Energy data management**, summarizing, in a broader sense, all novel forms of energy data (e.g., smart meter data or consumer data), which is structured and made accessible for new services (analytics, business insights) via digital platforms.

## 4. Use cases in the electricity sector

Building on these practical business applications of digital technologies in the energy sector, as well as on previous findings (e.g. Refs. [7, 36]), we further expand and structure all identified potential applications into a set of use cases, categorized along the electricity value chain Table 2.

### 4.1. Generation

The planning of electricity generators does benefit from the rising use of BD and AI, for example in siting decisions [72]. For operation and maintenance, forecasts are widely used, including applications that employ AI and BD, to forecast the location and output of renewable generators and electricity market prices [73,74]. Forecasts can also serve as inputs on decisions of curtailing output from electricity power generators [36] and applications may also employ IoT [75] and cloud computing [18] or VR, for example for guiding maintenance decisions in nuclear power plants [76]. In addition, novel 3D printing applications allow to “print” electricity system components such as batteries, capacitors, photovoltaic (PV) cells among many others [107,108] [], achieving shorter production durations and material savings.

### 4.2. Transmission and distribution

Transmission [80,] and distribution [15,82] network planning benefit at large from the evolution of digital technologies. Likewise, such technologies are used for the operation and maintenance of electricity

**Table 2**  
Digitalization use cases along the electricity value chain (own elaboration).

Energy Value Chain	Use Cases	Related digital technologies									
		BD	AI	IoT	DL	DT	RB	3D	VR	CC	
Generation	Improved planning	■	■								■
	Improved O&M	■	■	■							■
	Reduced resource use	■						■			■
Transmission	Improved planning	■	■								■
	Improved O&M	■	■								■
	TSO-DSO coordination	■	■								■
Distribution	Automated grid operation	■	■	■							■
	Improved planning	■	■								■
	Improved O&M	■	■								■
Market Operations/Trading	Data platforms (e.g., flexibility)	■	■	■	■						■
	Automated grid operation	■	■	■							■
	RES origin tracking	■	■								■
Retail	Flexibility markets & aggregators	■	■		■						■
	Automated trading (incl. P2P)	■	■		■						■
	Optimized DER use	■	■	■							■
Retail	Electrification planning	■	■	■							■
	Building energy optimization	■	■	■							■
	Community energy systems	■	■	■	■						■
	Customer data analytics	■	■								■

**Table 3**  
Digitalization challenges and policy options.

Category	Challenges	Policy options
Direct Consequences	Increased cyber risk	<ul style="list-style-type: none"> <li>• Create awareness around vulnerabilities and provide guidelines for assessing risks</li> <li>• Develop preventive and corrective policies</li> <li>• Define general security risks, roles, responsibilities, and expectations from energy businesses</li> <li>• Policies and standard around firewalls and antivirus software</li> <li>• Create incentives for cyber security initiatives</li> <li>• Develop cyber security quality certifications for energy businesses</li> <li>• Government mandated cyber security inspection for critical areas</li> </ul>
	Strongly increasing energy demand due to higher digitization and digital services	<ul style="list-style-type: none"> <li>• Promote data efficiency and sufficiency</li> <li>• Promote energy efficiency in data centers, e.g., through labelling schemes, Renewable power contracts, etc.</li> <li>• Improve the efficiency of digital devices and overall infrastructures</li> </ul>
	Accountability loss through autonomous decision agents	<ul style="list-style-type: none"> <li>• Develop appropriate standards to ensure accountability of various participants and mitigating potential harm</li> <li>• Support and increase transparency of the automated decision-making process</li> </ul>
Indirect Consequences	Technological progress outpaces regulatory and policy response	<ul style="list-style-type: none"> <li>• Support policy research and development to support technological innovation and funding for regulatory sandboxes</li> <li>• Provide R&amp;D tax incentives and encourage free trade for cross-border innovation</li> <li>• Provide direct grants for technology policy R&amp;D</li> </ul>
	Increased geopolitical complexity around data ownership and storage	<ul style="list-style-type: none"> <li>• Create detailed assessment of data supply chain risks</li> <li>• Develop data governance framework</li> <li>• Explore treaty and agreements between nations on data ownership and use</li> </ul>
	Disrupting existing business models	<ul style="list-style-type: none"> <li>• Promote the benefits of digital technologies</li> <li>• Redefine the role of existing stakeholders and provide necessary training support</li> <li>• Encourage addressing existing challenges and provide necessary incentives</li> </ul>
	Compromised data privacy	<ul style="list-style-type: none"> <li>• Provide necessary policy and regulatory support for new innovative business models</li> <li>• Provide clear guidelines on personal data collection, storage and processing</li> <li>• Develop data breach related policy</li> <li>• Develop non-compliance penalty mechanism</li> <li>• Develop standard data management tools</li> </ul>
	Shortage of relevant skillsets	<ul style="list-style-type: none"> <li>• Provide training to stakeholders on data privacy laws</li> <li>• Bring digital focus at all levels of education system</li> <li>• Support life-long learning initiatives</li> <li>• Train existing workers with new digital skill sets</li> <li>• Support cross-cutting and interdisciplinary conferences and partnerships</li> </ul>

networks [83–87], including applications that use distributed sensors (to increase situational awareness) or drones [88,]. Digital technologies will also facilitate the coordination at the DSO-TSO boundary, providing additional means for automation and enhanced control [90,91]. Eventually, digital technologies may be used to support automated distribution and transmission grid operation and reconfiguration [90,92], also through digital replication and modeling of system behavior using DT [12,93]. The latter also proves useful for electrification planning [94, 95].

Emerging energy data platforms (including the provision balancing power), which are increasingly interwoven with distribution and transmission grid operation [96], build especially onto IoT-derived data infrastructure, also using AI and BD capabilities [97,98].

4.3. Market operations/trading

Several primary digital technologies are also used in electricity trading and market operation, such as AI, BG and IoT. Exemplary use

cases include: tracking the origin of generated electricity with marginal greenhouse gas emission estimates [99,100], automatic algorithm-based market trading [101,102] and the aggregation and provision of flexibility on electricity markets [103,104].

#### 4.4. Retail

In electricity retail, many studies have applied AI, BD and IoT to study and characterize electricity consumers or energy technology adopters [81,105] to assist in electricity tariff design [106], optimize building energy demands [77–79] or help with sizing and optimizing community energy systems [10]. Latter studies, at times, may also use DL for storing peer-to-peer transactions [109]. Furthermore, the optimized use of distributed energy resources (DER) such as EV, PV or heat pumps is strongly facilitated through primary digital technologies, e.g. in integrating prosumers into distribution networks [81,110] and electricity markets [111]. Most popular primary digital technologies (AI, BD, IoT) are also employed to support electrification planning tools, as in Refs. [112–114].

Apart from the above-mentioned business use cases, it should be added that digital technologies also bring new capabilities to energy policy and regulation. Such extended capabilities include increased transparency and policy analysis capacities [115,116], ex-ante policy evaluation through simulations [117,118] and improved understanding of welfare effects and social inequality [119–121] (see Fig. 2).

### 5. Challenges and policy options

Policy and regulation are essential tools to address the emerging challenges of digitalization of the electricity sector [2,122]. The role of digitalization in the electricity sector and its relation to other larger-scale sectorial trends such as deregulation, decarbonization and decentralization will be further analyzed (See Fig. 3).

Policy goals have driven electricity sector deregulation and decarbonization, since the unbundling of vertically integrated electricity companies and the energy transition towards a decarbonized electricity sector became common targets worldwide, as in the European Union [123].

Digitalization, through novel or optimized planning and operation processes, can support the integration of renewable energy sources and thus facilitate decarbonization [2,71]. Likewise, digitalization, through the increasing use of ICT, could also contribute in complication of current decarbonization efforts. For example, the studies of [124,125]

show, how the increased use of data and the reliance of data infrastructures can increase electricity consumption. If such demand growth cannot be offset through efficiency gains, digitalization may require additional renewable generation capacities to reduce greenhouse gas emissions in line with climate goals [126].

Digitalization can also support decarbonization through spatial planning [127], such as for spatial load forecasting [128,129], generation or network siting [130,131]. Such tools are especially useful under the unavoidable decoupling of electricity demand and generation patterns (decentralization) [132]. Such decentralization is driven both through the separation of retail, network planning and generation planning activities under deregulation, as well as by electricity systems with high shares of renewable energy sources. As a matter of fact, the latter are built where the economic potential is highest and are not necessarily located close to demand centers [132]. Thus, it has been argued that the use of digital technologies and their new business models should be seen in the light of energy transitions and its policy changes [71].

As has been suggested by Ref. [2], the shape of policy design can lead to either a strong increase or decrease of energy consumption using the example of the transport sector. This is backed by recent findings of a meta study, which reviewed the greenhouse gas (GHG) emission footprint and reduction potential of several reported use cases of digital technologies in the energy sector [133]. Calculating an enablement factor (quotient of GHG reduction potential and GHG footprint), the study shows that, for many use cases, enablement factors range below 1.0. This highlights the need for well-designed digitalization policies in the energy (and electricity) sector.

The energy sector and environmental impact of digitalization from a systems perspective is shown in Fig. 4 [126]. The presented framework highlights how digital service demand interlinks with a set of drivers and eventually impacts energy and environmental systems via electricity demand and material use. It thus provides a sound basis for deriving structured sets of policy recommendations that aim to reduce digitalization’s impact in energy and ecologic terms.

Several concerns arise when leveraging digital opportunities, which have to be proactively addressed with relevant policies or combination of policies.

First, the surge in generated data translates into higher needs for computing power and data storage capacities. Consequently, the increased number of data centers (DC) is causing higher energy demands [22], while also having the potential of negatively disrupting the energy grids. Other digital technology driven applications, e.g., DL-based bitcoin mining further aggravate electricity demand growth [134]. In this sense, public policy ought to standardize new DCs’ energy efficiency requirements [135], thus keeping their carbon footprint at minimum levels, while also creating the proper framework to use DCs as network flexibility tools. Additionally, circular economy regulations should be implemented, to use DCs’ heat waste for district heating purposes.

As digital technologies and services are deployed, the share of manual labor-intensive activities (e.g., reading meters, manual commands, maintenance, and service actions, etc.) will decrease [136]. However, the digitalization process is also creating new economic sectors, such as manufacturing, installing, operating, maintaining, and servicing these technologies and platforms, and will generate additional jobs on the labor market. In this context, the pace of this transition should be assessed based on the national conditions, since a faster paced digitalization process may cause significant disruptions in the labor market. Additionally, public policy measures should ensure upskilling and reskilling of existing personnel, while also equipping future generations of employees with digital skills [2,136].

Finally, as critical infrastructure, such as the energy sector (including the technical, operational, or commercial subdomains), are increasing their digitalization level, cybersecurity risks as well as data protection concerns are rising [24]. Moreover, considering the current geopolitical context, cyber-attacks can now be considered another layer of the

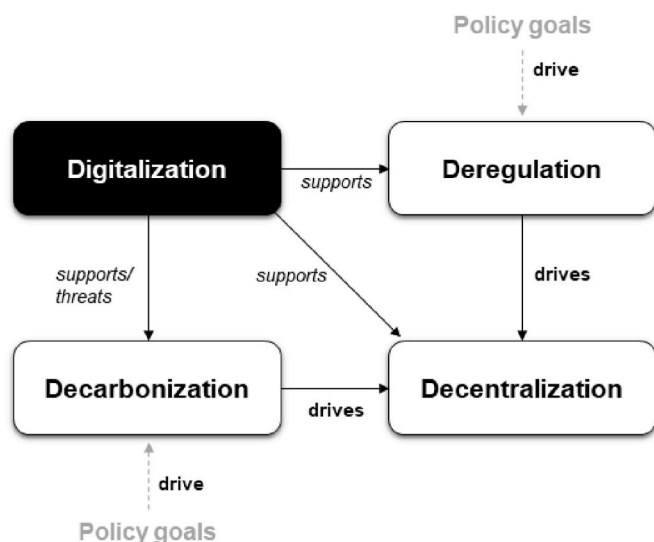


Fig. 3. Interplay of digitalization and decarbonization.

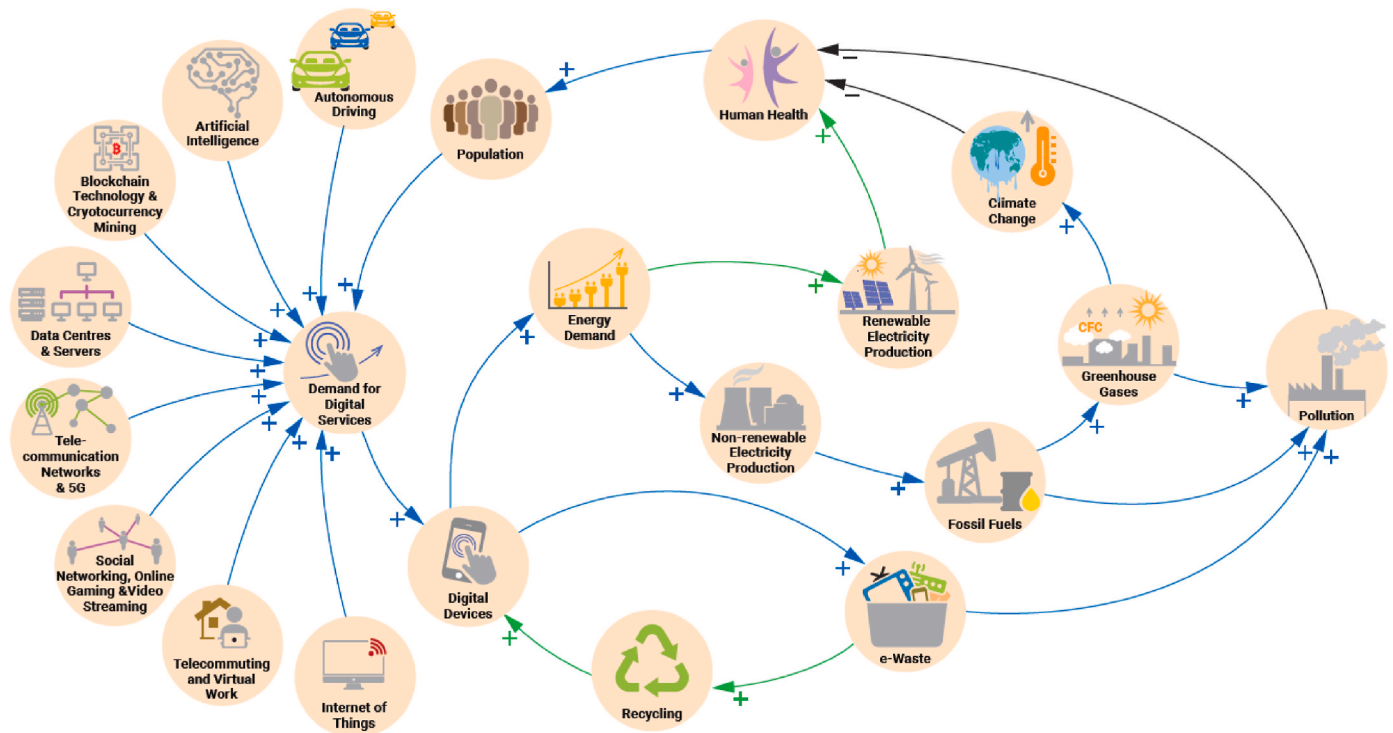


Fig. 4. Energy sector and environmental impact of digitalization – a systems perspective [126].

energy security paradigm. While cybersecurity experts are being increasingly trained and other economic sectors are addressing these concerns rapidly, the energy sector is still behind in developing its mitigation and adaptation strategies for cyber-attacks. Although this process would entail additional costs to the overall energy bills, the associated risks may further disrupt the already-challenged global energy systems. Thus, public policy should develop additional regulatory frameworks, which may also include support schemes, to encourage investments in cyber protection technologies and capabilities, as well as in additional data protection measures [137].

However, policies are very much country specific and must be developed within the existing legal basis to effectively meet the regional challenges associated with digitalization. An overview over currently implemented national digitalization policies has been recently created by the International Energy Agency and is accessible via [122].

## 6. Conclusions

The digitalization of the electricity sector has gained much momentum, as digital technologies and business models are increasingly used in the electricity sector. Transforming the possibilities of electricity system operation and planning, the latest developments have highlighted the need to develop policies that address both opportunities and challenges that come with the transition.

However, the advance of digitalization or mechanisms to address its consequences or unintended consequences are not homogeneous between nations. The progress depends on various factors, such as existing ICT infrastructure, economic development, availability of governmental and private funding, existing skillsets, or capacity for reskilling and upskilling, or investment, as well as other relevant regulations and policy in place. Inherent regional differences in the state of the information, communication, and electricity infrastructure place countries in different segments along the digitalization process.

Electricity system transformation through digital technologies and acceleration of its decarbonization will need a systematic, but contextual, assessment and approach to leverage opportunities while

proactively addressing existing challenges at the same time. Untapping the full potential of digitalization in the electricity sector eventually requires consistent policies and regulations that make sure that digital technologies are used where efficiency potentials can be exploited under minimal (added) risk.

## Author statement

**Fabian Heymann:** Conceptualization, Writing- Reviewing and Editing; **Tatjana Milojevic:** Conceptualization, Writing- Original draft preparation, Writing- Reviewing and Editing; **Andrei Covatariu:** Conceptualization, Writing- Reviewing and Editing; **Piyush Verma:** Conceptualization, Writing- Reviewing and Editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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