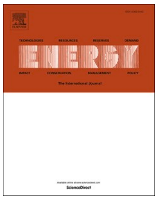
Energy 262 (2023) 125521

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



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

Fabian Heymann [a], Tatjana Milojevic [b,*], Andrei Covatariu [d], Piyush Verma [c]

[a] Center of Energy and Power Systems, INESC TEC Porto, Portugal
[b] Civil Engineering and Environmental Sciences, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[c] Kennedy School of Government, Harvard University Cambridge, MA, USA
[d] Ecological and Circular Economics Research for Action (ECERA), Bucharest, Romania

ARTICLE INFO

*Keywords:*
Decarbonization
Digitalization
Electricity
Energy policy
Megatrend analysis

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

---

* Corresponding author.

*E-mail addresses:* fabian.heymann@feu.up.pt (F. Heymann), tatjana.milojevic@epfl.ch (T. Milojevic), andrei.covatariu@ecera.org (A. Covatariu), piyush_verma@hks.harvard.edu (P. Verma).

https://doi.org/10.1016/j.energy.2022.125521
Received 14 June 2022; Received in revised form 4 September 2022; Accepted 19 September 2022

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 each stage are listed in the following.

**Fig. 1.** Developed megatrend analysis framework.

**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 (GPD) 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) |
| **General enablers for digitalization** | **Africa** | **South & Central America** | **North America** | **Europe** | **Middle East + Asia** | | **Oceania** |
| 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 |
| **Digitalization backbone: ICT network** | **Africa** | **LAC** | **North America** | **Europe** | **CIS** | **Arab States** | **Asia Pacific** |
| Route (total km) | 542,365 | 1,729,429 | 1,612,600 | 3,986,769 | 1,466,907 | 417,034 | 6,655,045 |
| Transmission links | 5771 | 7590 | 3634 | 11,922 | 1573 | 1891 | 11,493 |
| Nodes | 3874 | 4921 | 2479 | 7326 | 867 | 1068 | 6754 |

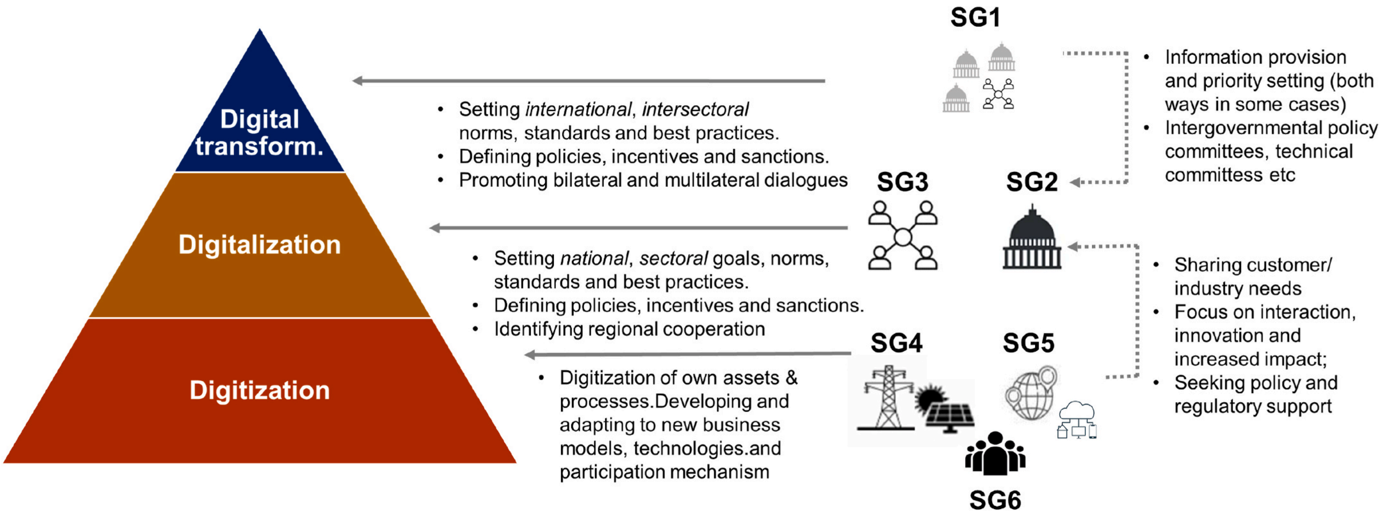


**Fig. 2.** Stakeholder interaction and influence along digitization, digitalization and digital transformation processes.

### 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 policymaking 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 though 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 | ■ | ■ | | | | | | | |
| | Automated grid operation | ■ | ■ | ■ | | ■ | ■ | | ■ | |
| Distribution | Improved planning | ■ | ■ | | | ■ | | | | |
| | Improved O&M | ■ | ■ | | | ■ | | | | |
| | Data platforms (e.g., flexibility) | ■ | ■ | ■ | ■ | | | | | ■ |
| | Automated grid operation | ■ | ■ | ■ | | | | | | ■ |
| Market Operations/Trading | RES origin tracking | ■ | ■ | | | ■ | | | | |
| | Flexibility markets & aggregators | ■ | ■ | | ■ | | | | | |
| | Automated trading (incl. P2P) | ■ | ■ | | ■ | | | | | ■ |
| Retail | Optimized DER use | ■ | ■ | ■ | | | | | | |
| | 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 | • Create awareness around vulnerabilities and provide guidelines for assessing risks<br>• Develop preventive and corrective policies<br>• Define general security risks, roles, responsibilities, and expectations from energy businesses<br>• Policies and standard around firewalls and antivirus software<br>• Create incentives for cyber security initiatives<br>• Develop cyber security quality certifications for energy businesses<br>• Government mandated cyber security inspection for critical areas |
| | Strongly increasing energy demand due to higher digitization and digital services | • Promote data efficiency and sufficiency<br>• Promote energy efficiency in data centers, e.g., through labelling schemes, Renewable power contracts, etc.<br>• Improve the efficiency of digital devices and overall infrastructures |
| | Accountability loss through autonomous decision agents | • Develop appropriate standards to ensure accountability of various participants and mitigating potential harm<br>• Support and increase transparency of the automated decision-making process |
| Indirect Consequences | Technological progress outpaces regulatory and policy response | • Support policy research and development to support technological innovation and funding for regulatory sandboxes<br>• Provide R&D tax incentives and encourage free trade for cross-border innovation<br>• Provide direct grants for technology policy R&D |
| | Increased geopolitical complexity around data ownership and storage | • Create detailed assessment of data supply chain risks<br>• Develop data governance framework<br>• Explore treaty and agreements between nations on data ownership and use |
| | Disrupting existing business models | • Promote the benefits of digital technologies<br>• Redefine the role of existing stakeholders and provide necessary training support<br>• Encourage addressing existing challenges and provide necessary incentives<br>• Provide necessary policy and regulatory support for new innovative business models |
| | Compromised data privacy | • Provide clear guidelines on personal data collection, storage and processing<br>• Develop data breach related policy<br>• Develop non-compliance penalty mechanism<br>• Develop standard data management tools<br>• Provide training to stakeholders on data privacy laws |
| | Shortage of relevant skillsets | • Bring digital focus at all levels of education system<br>• Support life-long learning initiatives<br>• Train existing workers with new digital skill sets<br>• Support cross-cutting and interdisciplinary conferences and partnerships |

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].

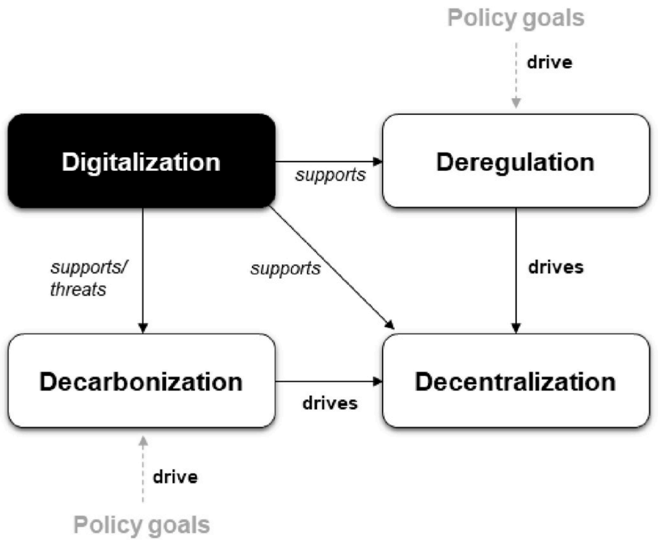


**Fig. 3.** Interplay of digitalization and decarbonization.

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

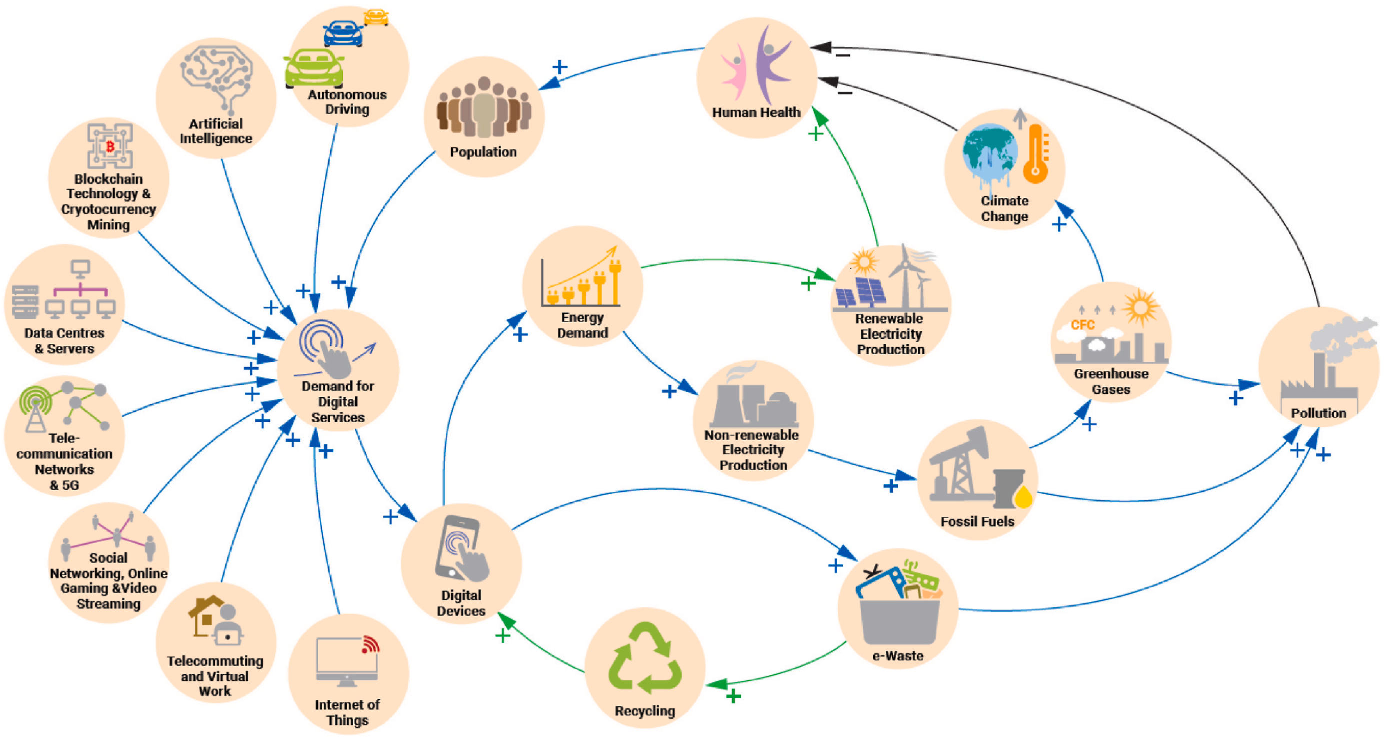


**Fig. 4.** Energy sector and environmental impact of digitalization – a systems perspective [126].

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. Inherit 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.

## Acknowledgments

We would like to thank the anonymous reviewers for their helpful, constructive feedback during the review of this paper. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 754354. F. Heymann would like to express his deep gratitude to Rachid Cherkaoui and Cécile Taverney, for their invaluable help at EPFL to build the doctoral course ENG-601 this paper is building on. Furthermore, he is very grateful for the mentorship and support from Matthias Galus (SFOE), who influenced and consolidated his view on digital energy systems. Finally, F. Heymann would like to thank his fellow researchers Pante Ra., Ann E. and Mafalda, who diligently received and processed his inputs along the writing of this work, refining the latter trough their contrasting, thus enriching perspective.

## References

[1] Di Silvestre ML, Favuzza S, Riva Sanseverino E, Zizzo G. How Decarbonization, Digitalization and Decentralization are changing key power infrastructures. Renew Sustain Energy Rev 2018;93:483–98. https://doi.org/10.1016/j.rser.2018.05.068.

[2] IEA, Digitalization & Energy. Paris: France; 2017. https://doi.org/10.1787/9789264286276-en.

[3] IRENA. Innovation landscape for a renewable-powered future: solutions to integrate variable renewables. Abu Dhabi: United Arab Emirates; 2019.

[5] Borowski PF. Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector. Energies 2021;14. https://doi.org/10.3390/en14071885.

[6] WEF. Digital Transformation of Industries - Electricity Industry. Geneva, Switzerland: WEF; 2016.

[7] Światowiec-Szczepańska J, Stępień B. Drivers of digitalization in the energy sector—the managerial perspective from the catching up economy. Energies 2022;15:1–25. https://doi.org/10.3390/en15041437.

[9] Kezunovic M, Pinson P, Obradovic Z, Grijalva S, Hong T, Bessa R. Big data analytics for future electricity grids. Elec Power Syst Res 2020;189:106788. https://doi.org/10.1016/j.epsr.2020.106788.

[10] IRENA. Artificial intelligence and big data (Innovation landscape brief). International Renewable Energy Agency; 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_AI_Big_Data_2019.pdf.

[11] He X, Ai Q, Qiu RC, Zhang D. Preliminary exploration on digital twin for power systems: challenges, framework, and applications. 2019. p. 1–8. ArXiv. http://arxiv.org/abs/1909.06977.

[12] Palensky P, Cvetkovic M, Gusain D, Joseph A. Digital twins and their use in future power systems. Digit. Twin. 2021;1:4. https://doi.org/10.12688/digitaltwin.17435.1.

[13] Lyu W, Liu J. Artificial Intelligence and emerging digital technologies in the energy sector. Appl Energy 2021;303:117615. https://doi.org/10.1016/j.apenergy.2021.117615.

[14] Quest H, Cauz M, Heymann F, Rod C, Perret L, Ballif C, Virtuani A, Wyrsch N. A 3D indicator for guiding AI applications in the energy sector. Energy AI 2022;9:1–13.

[15] Mahmoud MA, Md Nasir NR, Gurunathan M, Raj P, Mostafa SA. The current state of the art in research on predictive maintenance in smart grid distribution network: fault's types, causes, and prediction methods—a systematic review. Energies 2021;14. https://doi.org/10.3390/en14165078.

[16] Andoni M, Robu V, Flynn D, Abram S, Geach D, Jenkins D, McCallum P, Peacock A. Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renew Sustain Energy Rev 2019;100:143–74. https://doi.org/10.1016/j.rser.2018.10.014.

[17] Albrecht S, Reichert S, Schmid J, Strüker J, Neumann D, Fridgen G. Dynamics of blockchain implementation – a case study from the energy sector. Proc. Annu. Hawaii Int. Conf. Syst. Sci. 2018-Janua 2018:3527–36. https://doi.org/10.24251/hicss.2018.446.

[18] Tam K-S, Sehgal R. A cloud computing framework for on-demand forecasting services. Lect. Notes Comput. Sci.. In: Hsu RCH, Wang S, editors. Internet veh. – technol. Serv. IOV. vol. 8662. Cham: Springer; 2014. n.d. https://doi.org/https://doi.org/10.1007/978-3-319-11167-4_35

[19] Liu Z, Zhang Y, Wang Y, Wei N, Gu C. Development of the interconnected power grid in Europe and suggestions for the energy internet in China. Glob. Energy Interconnect 2020;3:111–9. https://doi.org/10.1016/j.gloei.2020.05.003.

[20] EURASIA Group. The digital Silk Road. Expanding China's Digital Footprint; 2020.

[21] Council on Foreign Relations. Assessing China's digital Silk Road initiative. 2020.

[22] Belkhir L, Elmeligi A. Assessing ICT global emissions footprint: trends to 2040 & recommendations. J Clean Prod 2018;177:448–63. https://doi.org/10.1016/j.jclepro.2017.12.239.

[23] Onyeji I, Bazilian M, Bronk C. Cyber security and critical energy infrastructure. Electr J 2014;27:52–60. https://doi.org/10.1016/j.tej.2014.01.011.

[24] IEA. Enhancing cyber resilience in electricity systems. Paris: France; 2021.

[25] Galus MD. Smart grid roadmap and regulation approaches in Switzerland. CIRED - Open Access Proc. J. 2017;2017:2906–9. https://doi.org/10.1049/oap-cired.2017.0141.

[26] CEER. Dynamic regulation to enable digitalisation of the energy system: conclusions paper. 2019. Brussels, Belgium, https://www.ceer.eu/documents/104400/-/-/3aedcf03-361b-d74f-e433-76e04db24547.

[27] Celik D, Meral M, Waseem M. Investigation and analysis of effective approaches , opportunities , bottlenecks and future potential capabilities for digitalization of energy systems and sustainable development goals. Elec Power Syst Res 2022;211:1–32. https://doi.org/10.1016/j.epsr.2022.108251.

[28] Strüker J, Weibelzahl M, Körner M-F, Kiessling A, Franke-Sluijk A, Hermann M. Decarbonisation through digitalisation - proposals for transforming the energy sector. Germany: Bayreuth; 2021. https://epub.uni-bayreuth.de/5762/.

[29] Heymann F, Schmid J, Vazquez M, Galus M. Regulatory sandboxes in the energy sector - review and learnings for the case of Switzerland. In: CIRED 2021, sep; 2021. p. 6. https://doi.org/10.1049/icp.2021.1730. Geneva, Switzerland.

[30] An A, Chaves Ávila JP, et al. Smart grid case studies: innovative regulatory approaches with focus on experimental sandboxes - casebook. 2019.

[31] Jeflea FV, Danciulescu D, Sitnikov CS, Filipeanu D, Park JO, Tugui A. Societal technological megatrends: a bibliometric analysis from 1982 to 2021. Sustain Times 2022;14. https://doi.org/10.3390/su14031543.

[32] Güemes-Castorena D. Megatrend methodology to identify development opportunities. In: PICMET 2009 proceedings, august 2-6. Portland, Oregon; 2015. p. 2391–6. https://doi.org/10.1109/PICMET.2009.5261829.

[33] OECD. OECD regional outlook 2019 - leveraging megatrends for cities and rural areas. 2019. https://doi.org/10.1787/9789264312838-en. Paris, France.

[34] IIASA. Transformations to achieve the sustainable development goals - report. 2018. https://doi.org/10.22022/TNT/07-2018.15347. Laxenburg, Austria.

[35] Debonne N, Bürgi M, Diogo V, Helfenstein J, Herzog F, Levers C, Mohr F, Swart R, Verburg P. The geography of megatrends affecting European agriculture, Glob. Environ Change 2022;75:102551. https://doi.org/10.1016/j.gloenvcha.2022.102551.

[36] Vingerhoets P, Chebbo M, Hatziargyriou N, Efthymiou V, Huitema G. The Digital Energy System 2016;4.

[37] Küfeoglu S, Liu G, Anaya K, Pollitt M. Digitalisation and new business models in energy sector. United Kingdom: Cambridge; 2019. https://www.repository.cam.ac.uk/handle/1810/294125.

[38] Schallmo DRA, Williams CA. History of digital transformation. Int J Innovat Manag 2017;21:1–17. https://doi.org/10.1007/978-3-319-72844-5_2.

[39] Nadkarni S, Prügl R. Digital transformation: a review, synthesis and opportunities for future research. Springer International Publishing; 2021. https://doi.org/10.1007/s11301-020-00185-7.

[40] Maroufkhani P, Desouza KC, Perrons RK, Iranmanesh M. Digital transformation in the resource and energy sectors: a systematic review. Resour Pol 2022;76:102622. https://doi.org/10.1016/j.resourpol.2022.102622.

[42] Nassehi A. German. In: Beck CH, Litrixde, editors. Patterns. Theory on the digital society; 2019. Munich, Germany.

[43] L.A.J. Quetelet. Du système social et des lois qui le régissent. Paris: France; 1848. http://books.google.fr/books?id=OGcOAAAAQAAJ.

[44] Messner D, Schlacke S, Fromhold-Eisebith M, Grote U, Matthies E, Pittel K, Schellnhuber U, , H. J., Schieferdecker I, Schneidewind K, Augenstein R, Blake-Rath K, Bohnenberger A, Bossy MJ, Dorsch M, Feist J, Gärtner M, Göpel U, Jürschik K, Krause C, Loose M, Messerschmidt R, Müngersdorff I, Paulini N, Petrusjanz J, Pfeiffer B, Pilardeaux T, Schlüter G, Schöneberg A, Schulz B, Stephan P, Szabo-Müller H, Wallis N, Wegener GAC, on G.C. (WBGU). Towards our digital future. Flagship report. German Advisory Council on Global Change (WBGU); 2019.

[45] ITU. World Telecommunication/ICT Indicators Database. ITU; 2022. https://www.itu.int/en/ITU-D/Statistics/Pages/publications/wtid.aspx.

[46] United Nations Statistics Division. Methodology: standard country or area codes for statistical use (M49). 2022.

[47] European Commission. International Digital Economy and Society Index (DESI). European Commission; 2020. https://digital-strategy.ec.europa.eu/en/policies/desi.

[48] ITU. The ICT Development Index. International Telecommunication Union 2021. https://www.itu.int/en/ITU-D/Statistics/Pages/IDI/default.aspx.

[49] Worldbank. Data: access to electricity (% population). Worldbank; 2021. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS.

[50] Worldbank. Data - GDP per capita (USD). Worldbank 2022. https://data.worldbank.org/indicator/NY.GDP.PCAP.CD.

[51] Speedtest. Speedtest global index. Speedtest; 2022. https://www.speedtest.net/global-index.

[52] Worldbank. Getting electricity: system average interruption duration index (SAIDI). Worldbank; 2022. https://tcdata360.worldbank.org/indicators/h2d96dbda?country=BRA&indicator=42570&viz=line_chart&years=2014,2019.

[53] ITU. ITU interactive transmission map. ITU; 2022. https://www.itu.int/itu-d/tnd-map-public/.

[54] European Commission. 2030 digital compass: the European way for the digital decade. 2021. Brussels, Belgium.

[55] Australian Government. Digital economy strategy 2030: a leading digital economy and society by 2030. Commonwealth of Australia; 2021.

[56] U.S Department of State. Digital government: building a 21st century platform to better serve the American people. 2012.

[57] Bu L, Chung V, Leung N, Wang KW, Xia B, Xia C. The future of digital innovation in China: megatrends shaping one of the world's fastest evolving digital ecosystems the. 2021.

[58] European Commission. Digital4Development: mainstreaming digital technologies and services into EU Development Policy. 2017. SWD(2017) 157 final, Brussels.

[59] Arcesati R. The Digital Silk Road is a development issue. Merics; 2020.

[60] Rountree V, Baldwin E. State-level renewable energy policy implementation: how and why do stakeholders participate? Front. Commun. 2018;3. https://doi.org/10.3389/fcomm.2018.00006.

[61] Hirmer SA, George-Williams H, Rhys J, McNicholl D, McCulloch M. Stakeholder decision-making: understanding Sierra Leone's energy sector. Renew Sustain Energy Rev 2021;145:111093. https://doi.org/10.1016/j.rser.2021.111093.

[62] About the internet governance forum. IGF; 2022.

[63] UK BEIS. Digitalising our energy system for net zero: strategy and action plan. UK BEIS; 2021. https://www.gov.uk/government/publications/digitalising-our-energy-system-for-net-zero-strategy-and-action-plan.

[64] Algorithmwatch. Algorithmwatch: what we do. Algorithmwatch; 2022. 2022, https://algorithmwatch.org/en/vision-mission-values/.

[65] Iberdrola. METEOFLOW project: MeteoFlow Project's next challenge? To predict sea conditions. 2022.

[66] Google. A policy roadmap for 24/7 carbon-free energy. Google; 2022. https://cloud.google.com/blog/topics/sustainability/a-policy-roadmap-for-achieving-247-carbon-free-energy.

[67] Chapman A, McLellan B, Tezuka T. Strengthening the energy policy making process and sustainability outcomes in the OECD through policy design. Adm Sci 2016;6:9. https://doi.org/10.3390/admsci6030009.

[68] Weible PAS Christopher M. A guide to the advocay coalition framework. In: Handb. Public policy anal.. first ed. New York: Routledge; 2007. https://doi.org/https://doi.org/10.4324/9781315093192.

[69] European Commission. Assessment and roadmap for the digital transformation of the energy sector towards an innovative internal market. 2019. Final report., Brussels, Belgium.

[70] ENTSO-E. Digital twin (Technopedia techsheets). ENTSO-E; 2022. accessed May 6, 2022, https://www.entsoe.eu/Technopedia/techsheets/digital-twin.

[71] Loock M. Unlocking the value of digitalization for the European energy transition: a typology of innovative business models. Energy Res Social Sci 2020;69:101740. https://doi.org/10.1016/j.erss.2020.101740.

[72] Assouline D, Mohajeri N, Scartezzini J-L. A machine learning methodology for estimating roof-top photovoltaic solar energy potential in Switzerland. In: Scartezzini J-L, editor. Proc. Int. Conf. CISBAT 2015 futur. Build. Dist. Sustain. From nano to urban scale. Lausanne: LESO-PB, EPFL; 2015. p. 555–60. https://doi.org/10.5075/epfl-cisbat2015-555-560.

[73] Petropoulos F, et al. Forecasting: theory and practice. Int J Forecast 2022;38: 705–871. https://doi.org/10.1016/j.ijforecast.2021.11.001.

[74] Heymann F, vom Scheidt F, Soares FJ, Duenas P, Miranda V. Forecasting energy technology diffusion in space and time: model design, parameter choice and calibration. IEEE Trans Sustain Energy 2021;12:802–9. https://doi.org/10.1109/TSTE.2020.3020426.

[75] Rogier JK, Mohamudally N. Forecasting photovoltaic power generation via an IoT network using nonlinear autoregressive neural network. Procedia Comput Sci 2019;151:643–50. https://doi.org/10.1016/j.procs.2019.04.086.

[76] Lee DJ, Salve R, Tecnatom M, de Antonio A, Verdejo Herrero P, Pérez JM, et al. Virtual reality for inspection , maintenance , operation and repair of nuclear power plant. CORDIS; 2004. https://cordis.europa.eu/project/id/FIKS-CT-2000-00114.

[77] Reynolds J, Rezgui Y, Kwan A, Piriou S. A zone-level, building energy optimisation combining an artificial neural network, a genetic algorithm, and model predictive control. Energy 2018;151:729–39. https://doi.org/10.1016/j.energy.2018.03.113.

[78] Ma Z, Clausen A, Lin Y, Jørgensen BN. An overview of digitalization for the building-to-grid ecosystem. Energy Informatics 2021;4. https://doi.org/10.1186/s42162-021-00156-6.

[79] Deng Z, Chen Q. Artificial neural network models using thermal sensations and occupants' behavior for predicting thermal comfort. Energy Build 2018;174: 587–602. https://doi.org/10.1016/j.enbuild.2018.06.060.

[80] Vilaça Gomes P, Saraiva JT. A novel efficient method for multiyear multiobjective dynamic transmission system planning. Int J Electr Power Energy Syst 2018;100: 10–8. https://doi.org/10.1016/j.ijepes.2018.02.020.

[81] Heymann F, Lopes M, vom Scheidt F, Silva JM, Duenas P, Soares FJ, Miranda V. DER adopter analysis using spatial autocorrelation and information gain ratio under different census-data aggregation levels. IET Renew Power Gener 2020;14: 63–70. https://doi.org/10.1049/iet-rpg.2019.0322.

[82] Bernards R, Morren J, Slootweg H. Development and implementation of statistical models for estimating diversified adoption of energy transition technologies. IEEE Trans Sustain Energy 2018;9:1540–54. https://doi.org/10.1109/TSTE.2018.2794579.

[83] Mahmoud MA, Tang AYC, Kumar K, Law NLLMF, Gurunathan M, Ramachandran D. An ontology-based predictive maintenance tool for power substation faults in distribution grid. Int J Adv Comput Sci Appl 2020;11: 397–407. https://doi.org/10.14569/IJACSA.2020.0111151.

[84] Pau M, Patti E, Barbierato L, Estebsari A, Pons E, Ponci F, Monti A. A cloud-based smart metering infrastructure for distribution grid services and automation. Sustain. Energy, Grids Networks 2018;15:14–25. https://doi.org/10.1016/j.segan.2017.08.001.

[85] Angioni A, Lu S, Hooshyar H, Cairo I, Repo S, Ponci F, Della Giustina D, Kulmala A, Dedè A, Monti A, Del Rosario G, Vanfretti L, Garcia CC. A distributed automation architecture for distribution networks, from design to implementation. Sustain. Energy, Grids Networks 2018;15:3–13. https://doi.org/10.1016/j.segan.2017.04.001.

[86] de Sousa R, González Fernández D, Rodriguez Gonzalez J, Tai H. Harnessing the power of advanced analytics in transmission and distribution asset management. McKinsey Co.; 2018.

[87] Kumar NM, Chand AA, Malvoni M, Prasad KA, Mamun KA, Islam FR, Chopra SS. Distributed energy resources and the application of ai, iot, and blockchain in smart grids. Energies 2020;13. https://doi.org/10.3390/en13215739.

[88] IRENA. Dynamic Line Rating (Innovation Landscape Brief). International Renewable Energy Agency 2020. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_Dynamic_line_rating_2020.pdf?la=en&hash=A8129CE4C516895E7749FD495C32C8B818112D7C.

[90] Pilo F, Mauri G, Bak-Jensen B, Kämpf E, Taylor J, Silvestro F. Control and automation functions at the TSO and DSO interface – impact on network planning. In: 24th int. Conf. Exhib. Electr. Distrib. (CIRED), seesion 5 plan. Power Distrib. Syst.; 2017. p. 2188–91.

[91] Gerard H, Rivero Puente EI, Six D. Coordination between transmission and distribution system operators in the electricity sector: a conceptual framework. Util Pol 2018;50:40–8. https://doi.org/10.1016/j.jup.2017.09.011.

[92] Hamidi V, Smith KS, Wilson RC. Smart grid technology review within the transmission and distribution sector. In: IEEE PES innov. Smart grid technol. Conf. Eur. ISGT Eur.; 2010. p. 1–8. https://doi.org/10.1109/ISGTEUROPE.2010.5638950.

[93] Pan H, Dou Z, Cai Y, Li W, Lei X, Han D. Digital twin and its application in power system. In: 2020 5th int. Conf. Power renew. Energy, ICPRE 2020; 2020. p. 21–6. https://doi.org/10.1109/ICPRE51194.2020.9233278.

[94] Lee S, Perrez-Arriaga IJ. Imagining the 'Google' of electrification: how digital twins and computational systems for continuous planning can reinvent century-old practices. Energy Growth Hub; 2022. accessed May 6, 2022, https://www.energyforgrowth.org/memo/imagining-the-google-of-electrification-how-digital-twins-and-computational-systems-for-continuous-planning-can-reinvent-century-old-practices/.

[95] Ciller P, Ellman D, Vergara C, Gonzalez-Garcia A, Lee SJ, Drouin C, Brusnahan M, Borofsky Y, Mateo C, Amatya R, Palacios R, Stoner R, De Cuadra F, Perez-Arriaga I. Optimal electrification planning incorporating on- and off-grid technologies- and reference electrification model (REM). Proc IEEE 2019;107: 1872–905. https://doi.org/10.1109/JPROC.2019.2922543.

[96] Duch-Brown N, Rossetti F. Digital platforms across the European regional energy markets. Energy Pol 2020;144. https://doi.org/10.1016/j.enpol.2020.111612.

[97] Heymann F, Galus M. Digital platforms in the energy sector – a menu of regulatory options for policy makers. In: MEDPOWER Conference. IET; 2022. p. 1045–9. Palmero, Italy.

[98] Kloppenburg S, Boekelo M. Digital platforms and the future of energy provisioning: promises and perils for the next phase of the energy transition. Energy Res Social Sci 2019;49:68–73. https://doi.org/10.1016/j.erss.2018.10.016.

[99] Tranberg B, Corradi O, Lajoie B, Gibon T, Staffell I, Andresen GB. Real-time carbon accounting method for the European electricity markets. Energy Strategy Rev 2019;26. https://doi.org/10.1016/j.esr.2019.100367.

[100] Rüdisüli M, Romano E, Eggimann S, Patel MK. Decarbonization strategies for Switzerland considering embedded greenhouse gas emissions in electricity imports. Energy Pol 2022;162:112794. https://doi.org/10.1016/j.enpol.2022.112794.

[101] Xu Y, Ahokangas P, Louis JN, Pongrácz E. Electricity market empowered by artificial intelligence: a platform approach. Energies 2019;12. https://doi.org/10.3390/en12214128.

[102] ElCom. Algorithmic trading. ElCom; 2020.

[103] Ableitner L, Tiefenbeck V, Meeuw A, Wörner A, Fleisch E, Wortmann F. User behavior in a real-world peer-to-peer electricity market. Appl Energy 2020;270: 115061. https://doi.org/10.1016/j.apenergy.2020.115061.

[104] Villar J, Bessa R, Matos M. Flexibility products and markets: literature review. Elec Power Syst Res 2018;154:329–40. https://doi.org/10.1016/j.epsr.2017.09.005.

[105] Chen TD, Wang Y, Kockelman KM. Where are the electric vehicles? A spatial model for vehicle-choice count data. J Transport Geogr 2015. https://doi.org/10.1016/j.jtrangeo.2015.02.005.

[106] Bregere M, Bessa RJ. Simulating tariff impact in electrical energy consumption profiles with conditional variational autoencoders. IEEE Access 2020;8: 131949–66. https://doi.org/10.1109/ACCESS.2020.3009060.

[107] Tarancón A, Esposito V, editors. 3D printing for energy applications. Wiley; 2021.

[108] Zhang F, Wei M, Viswanathan VV, Swart B, Shao Y, Wu G, Zhou C. 3D printing technologies for electrochemical energy storage. Nano Energy 2017;40:418–31. https://doi.org/10.1016/j.nanoen.2017.08.037.

[109] Antal C, Cioara T, Antal M, Mihailescu V, Mitrea D, Anghel I, Salomie I, Raveduto G, Bertoncini M, Croce V, Bragatto T, Carere F, Bellesini F. Blockchain based decentralized local energy flexibility market. Energy Rep 2021;7:5269–88. https://doi.org/10.1016/j.egyr.2021.08.118.

[110] Schram WL, Lampropoulos I, van Sark WGJHM. Photovoltaic systems coupled with batteries that are optimally sized for household self-consumption: assessment of peak shaving potential. Appl Energy 2018;223:69–81. https://doi.org/10.1016/j.apenergy.2018.04.023.

[111] Iria JP, Soares FJ, Matos MA. Trading small prosumers flexibility in the energy and tertiary reserve markets. IEEE Trans Smart Grid 2018. https://doi.org/10.1109/TSG.2018.2797001. 1–1.

[112] Heymann F, Duenas Martínez P, Soares F, Miranda V. Explorative ex-ante consumer cluster delineation for electrification planning using image processing tools. In: MEDPOWER Conference. IET; 2018.

[113] Mentis D, Howells M, Rogner H, Korkovelos A, Arderne C, Zepeda E, Siyal S, Taliotis C, Bazilian M, De Roo A, Tanvez Y, Oudalov A, Scholtz E. Lighting the World: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa. Environ Res Lett 2017;12. https://doi.org/10.1088/1748-9326/aa7b29.

[114] Sankaramurthy P, Kannan SS, Behera AK, , IoT-Based Smart Electrification System, Komanapalli VLN, Sivakumaran N, Hampannavar S. Adv. Autom. Signal Process. Instrumentation, Control. Lect. Notes Electr. Eng. 2021;700. https://doi.org/https://doi.org/10.1007/978-981-15-8221-9_137.

[115] Deloitte. Big data analytics for policy making. 2016. Brussels, Belgium, https://joinup.ec.europa.eu/sites/default/files/document/2016-07/dg_digit_study_big_data_analytics_for_policy_making.pdf.

[116] Heymann F, Bessa R, Liebensteiner M, Parginos K, Hinojar JCM, Duenas P. Scarcity events analysis in adequacy studies using CN2 rule mining. Energy AI 2022;8:100154. https://doi.org/10.1016/j.egyai.2022.100154.

[117] Benvenutti LMM, Ribeiro AB, Forcellini FA, Maldonado MU. The effectiveness of tax incentive policies in the diffusion of electric and hybrid cars in Brazil, 41st congr. Latinoam. Din. Sist. São Paulo; 2016.

[118] Heymann F, Miranda V, Soares JF, Duenas P, Perez-Arriaga I, Prata R. Orchestrating incentive designs to reduce adverse system-level effects of large-scale EV/PV adoption – the case of Portugal. Appl Energy 2019;256:113931. https://doi.org/10.1016/j.apenergy.2019.113931.

[119] Grover D, Daniels B. Social equity issues in the distribution of feed-in tariff policy benefits: a cross sectional analysis from England and Wales using spatial census and policy data. Energy Pol 2017;106:255–65. https://doi.org/10.1016/j.enpol.2017.03.043.

[120] Picciariello A, Vergara C, Reneses J, Frías P, Söder L. Electricity distribution tariffs and distributed generation: quantifying cross-subsidies from consumers to prosumers. Util Pol 2015;37:23–33. https://doi.org/10.1016/j.jup.2015.09.007.

[121] Heymann F, Soares FJ, Duenas P, Miranda V. Explorative spatial data mining for energy technology adoption and policy design analysis. Springer Lect. Notes Artif. Intell 2019;11804:1–11.

[122] Sung J, Troilo M, Howarth N. Better energy efficiency policy with digital tools – analysis - IEA. IEA; 2021.

[123] Gugler K, Liebensteiner M, Schmitt S. Vertical disintegration in the European electricity sector: empirical evidence on lost synergies. Int J Ind Organ 2017;52: 450–78. https://doi.org/10.1016/j.ijindorg.2017.04.002.

[124] Andrae A, Edler T. On global electricity usage of communication technology: trends to 2030. Challenges 2015;6:117–57. https://doi.org/10.3390/challe6010117.

[125] Masanet E, Shehabi A, Lei N, Smith S, Koomey J. Recalibrating global data center energy-use estimates. Science 2020;367:984–6. https://doi.org/10.1126/science.aba3758. 80.

[126] UNEP. UNEP's Foresight Brief - the growing footprint of digitalisation. 2021.

[127] Resch B, Sagl G, Törnros T, Bachmaier A, Eggers J-B, Herkel S, Narmsara S, Gündra H. GIS-based planning and modeling for renewable energy: challenges and future research avenues. ISPRS Int J Geo-Inf 2014;3:662–92. https://doi.org/10.3390/ijgi3020662.

[128] Aguero JR, Willis HL. Spatial electric load forecasting methods for electric utilities. 2007. Raleigh.

[129] Heymann F, Melo J, Martínez PD, Soares F, Miranda V. On the emerging role of spatial load forecasting in transmission/distribution grid planning. In: MEDPOWER Conference. IET; 2018.

[130] Höfer T, Sunak Y, Siddique H, Madlener R. Wind farm siting using a spatial Analytic Hierarchy Process approach: a case study of the Städteregion Aachen. Appl Energy 2016;163:222–43. https://doi.org/10.1016/j.apenergy.2015.10.138.

[131] Heymann F, Bessa R. Power-to-Gas potential assessment of Portugal under special consideration of LCOE. In: 2015 IEEE eindhoven PowerTech; 2015. p. 1–5. https://doi.org/10.1109/PTC.2015.7232586.

[132] Brisbois MC. Decentralised energy, decentralised accountability? Lessons on how to govern decentralised electricity transitions from multi-level natural resource governance. Glob. Transitions. 2020;2:16–25. https://doi.org/10.1016/j.glt.2020.01.001.

[133] bitkom. Climate protection through digital technologies - risks and benefits. 2020. p. 59 (in German).

[134] Küfeoğlu S, Özkuran M. Bitcoin mining: a global review of energy and power demand. Energy Res Social Sci 2019;58:101273. https://doi.org/10.1016/j.erss.2019.101273.

[135] Banet C, Pollit M, Covatariu A, Duma D. Data centres & the grid - greening ICT in Europe. 2021. https://doi.org/10.1111/fcre.12597. Brussels, Belgium.

[136] Verma P, Savickas R, Buettner SM, Strüker J, Kjeldsen O, Wang X. Digitalization: enabling the new phase of energy efficiency. In: UNECE; 2020. p. 1–16.

[137] National Institute of Standards and Technology. Framework for improving critical infrastructure cybersecurity. 2018.