Digital Applications in Energy Sector

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Digitalization is a transformation process which has already affected many parts of industry and society and is expected to yet increase its transformative speed and impact. In the energy sector, many digital applications have already been implemented. However, a more drastic change is expected during the next decades. Good understanding of which digital applications are possible and what are the associated benefits as well as risks from the different perspectives of the impacted stakeholders is of high importance. On the one hand, it is the basis for a broad societal and political discussion about general targets and guidelines of digitalization. On the other hand, it is an important piece of information for companies in order to develop and sustainably implement digital applications. This entry provides a structured overview of potential digital applications in the German energy (electricity) sector on the basis of a literature review.

Keywords: digitalization ; digital applications ; energy sector ; transformation ; sustainability ; holistic evaluation ; multi-criteria analysis

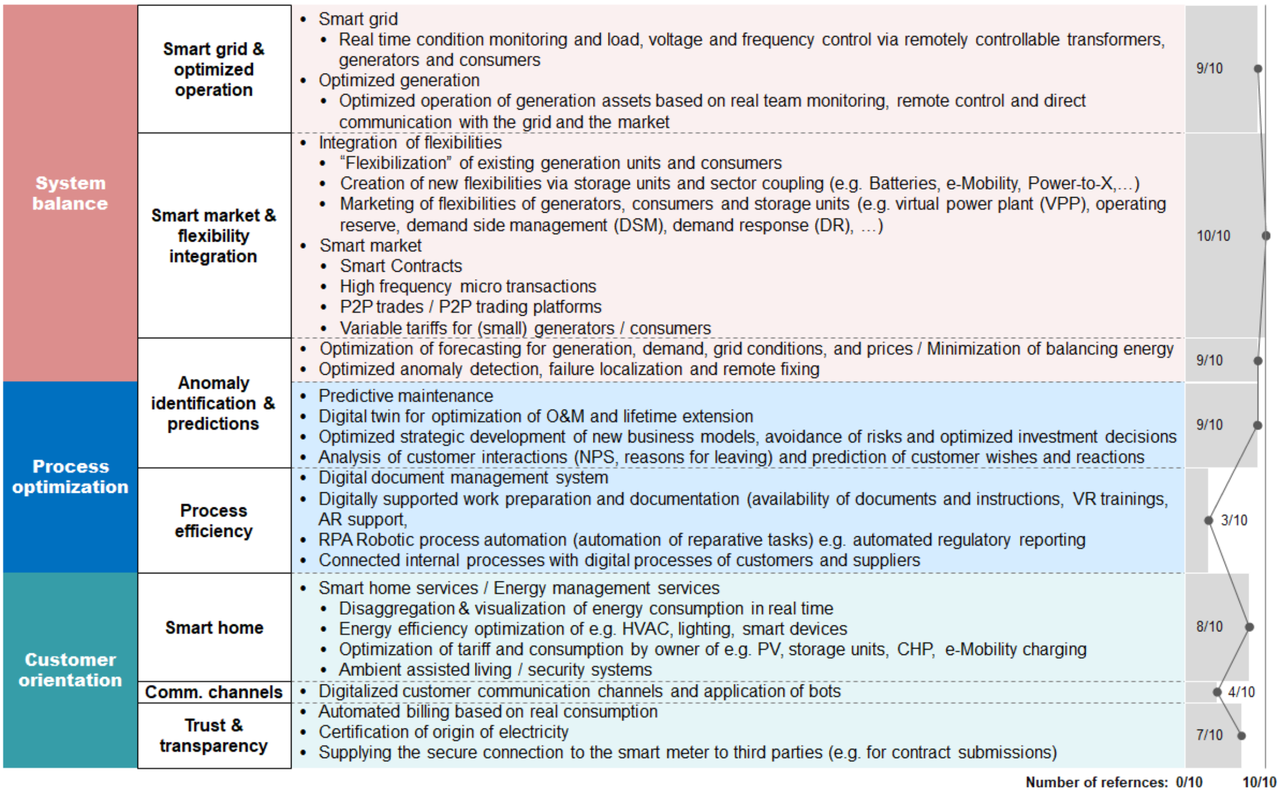
1. Introduction

Digitalization is not a recent phenomenon but started decades ago. First, commercial computers, as well as tests with artificial intelligence, date back to the 1950s [1][2]. Due to the exponential development speed of individual digital technologies (Moore's "law") and the effect of mutual acceleration, the use of digital applications has increasingly accelerated and is expected to continue to accelerate for decades. Many areas of industry and society have already been fundamentally changed by digitalization. The most prominent examples are digital photography and online commerce. According to [3] today, each day 36 million Amazon purchases are conducted and 3.3 billion digital photos are taken [4]. The German energy sector (in particular the electricity sector) has undergone significant changes since the year 2000 [5] mainly due to the liberalization of the electricity market and the introduction of the Renewable Energy Sources Act. Some of the changes have been caused, enabled or accompanied by digital applications. However, the principles of the value chain have not fundamentally changed. In the coming decades, digital applications have the potential to cause significant changes in the energy sector, even affecting the value chain itself.

Good knowledge of the expected digital applications and how benefits and potential downsides affect different stakeholders is an essential basis for a broad societal and political discussion to set targets and guidance for digital transformation. Furthermore, this knowledge is relevant for the development of new business models. Therefore, the benefits, as well as potential risks and bottlenecks from the perspective of different stakeholders, need to be analyzed early on to develop solution options for pitfalls and ensure that the full benefits can be utilized.

2. Discussion of digital applications in current literature

The term "digitalization" is very broadly used with different definitions. In the book "Practical knowledge digital transformation" by Wallmüller [6], digitalization is described as the process of capturing, editing/using, and saving analog information on digital data storage devices, and digital transformation is seen as the application of digital technologies. The International Energy Agency (IEA) states that digitalization describes the growing application of ICT and that it can be seen as the convergence between the digital and the physical worlds [7]. In the publication "The digital energy sector" by the German Association of Energy and Water Industries [8], digitalization in the energy sector is defined as the network of applications, processes, and devices based on internet technologies. The common aspect of these definitions and hence, the definition used in the present study, is that digitalization describes the transformation caused, facilitated or accelerated by digital applications. Digital applications can be based on hardware and software, but in most cases are a combination of both, so-called cyber-physical systems, which use information and communication technology ICT. Based on this definition, already the application of the first computers, which used ICT, were part of digitalization, which is coherent with the authors' initial statement that digitalization is not a recent phenomenon. Examples for digital applications are presented in the following figure. Likewise the frequently used term “smart” does not have a commonly accepted definition. For the authors, “smart” describes the properties of (1) being digital (in contrast to analog), (2) being connected via communication technology, and (3) being able to process information (locally or in the cloud).



Technical and economic aspects of digitalization in the German energy sector are well-covered in the concurrent literature. Both broad views looking at digitalization as an overall trend as well as very specific research about individual aspects or technologies of digitalization have been published. The status quo of the overall digitalization in Germany is analyzed as the digitalization index between 0 and 100 based on survey results in [9]. The energy sector reaches an index of 47 (in 2018), which is midfield compared with other sectors. The same study reveals that the ICT sector is by far the most digitalized in Germany (74 out of 100). Therefore, it is likely that the ICT sector acts as a technology push factor for the digitalization of other sectors, including the energy sector.

Many companies feel a high urgency to “become digital” but simultaneously a high uncertainty around what needs to be done. Therefore, many publications give guidance for companies on how to successfully master the challenges of digitalization. While [10] describes the fundamental functions of digital business models, a general process to develop new digital business models is suggested in [11][12][13]. Approaches to successfully master the digital transformation in the energy sector are described in [14][15][16], e.g., in [16] (pp. 368–379) a digital transformation canvas based on a digital vision and 20 action areas is suggested.

As mentioned, many specific applications and technologies are discussed in the concurrent literature. “Smart grids” and “smart markets”, for example, are described in [17][18]. The position paper “Smart Grid and Smart Market” [18] by the Bundesnetzagentur (German federal grid agency) first clearly defines and distinguishes “smart grid” and “smart market” and describes a target picture for both, including what needs to be done in the grid so that the “smart grid” can support the “smart market”. It is concluded that grid reinforcements are needed on different grid levels as well as the integration of flexibilities and storage units in order to enable the future market logic “demand follows generation”. The definition of “smart grid” and “smart market” given by the German federal grid agency is the basis for the definition used in the current paper. “Smart grid: *The conventional electricity grid will become a smart grid by being upgraded with communication, metering, control, regulation and automation technology and IT components*”. “Smart market: *The smart market is the area outside the grid in which energy volumes or services derived from them are traded among market participants on the basis of the available grid capacity*”. Furthermore, the publication distinguishes between the two based on two questions: Are energy volumes/flows (-> market) or capacities (-> grid) considered? Does a component serve the grid and is financed by the grid (if yes -> grid)? The collected edition “Smart Market” [17] includes articles by researches as well as business representatives covering the aspects stakeholders, components, applications, and business models of the “smart grid” and “smart market”.

A review of "smart home" applications and their challenges is, for example, given in [19][20]. The authors of "Applications, Systems and Methods in Smart Home Technology: A Review" [20] present an overview of "smart home" communication technologies and applications based on a literature review. They conclude that "smart home" systems are especially beneficial for elderly and disabled people. Similarly, the authors of "A review of Internet of Things for smart home: Challenges and solutions" [19] conduct a literature review of "smart home" and IoT (Internet of Things) applications but also present a framework to integrate "smart objects" in a IoT system. Furthermore, challenges regarding the interoperability of communication protocols and security/privacy issues are discussed.

Individual digital technologies such as blockchain, artificial intelligence or cloud computing and their applications in the energy sector are, for example, discussed in [21][22][23][24][25][26][27][28][29]. The collected edition [21] gives a broad overview of the digitalization and cloud applications across different economic sectors based on articles by researchers, journalists, and business representatives. The publications [22][23][24][25][26][27] all discuss blockchain applications in the energy sector. Both [26][27] conclude that decentralized energy markets are possible using blockchain technology. The conclusion is based on market models and simulations. All three publications [22][23][24][25] give a structured overview of blockchain applications in the energy sector and challenges based on a review of research projects/start-ups, expert interviews, and workshops with energy-related companies respectively. The conclusion of the three articles is that blockchain technology offers great potential benefits such as direct peer-to-peer markets and economically feasible integration of small generation and consumption units. For consumers the transparency and level of trust can be increased and for suppliers new business models can be developed. However, some key regulatory and technological challenges have to be overcome.

The use of artificial intelligence in the energy sector is the focus of the publications [28][29]. Both articles give an overview of practical-use cases based on a literature review and conclude that artificial intelligence and machine learning can greatly increase the accuracy of demand, generation, and price forecasting and thereby support the implementation of "smart grids" and the integration of more renewable energy. An assessment and a structure of different machine learning algorithms is presented in [28].

To some extent also potential risks such as cyber security and privacy issues [7][30][31] and a change in the work environment [32][33] are discussed. The IEA (International Energy Agency)/OECD report "Digitalization & Energy" [7] covers among other topics the issue of cyber security, data privacy, and potential societal impacts. The authors present an overview of cyberattacks that impacted the energy system, discuss how different IEA Members approach the topic and suggest that digital resilience should be included early on in research and development as well as policies. Regarding data privacy, the authors see a potential threat for private consumers as well as companies as the energy demand can reveal much information about living habits and production patterns respectively. A suggested solution is that data protection is further regulated by policy. For the electricity sector, the highest impact on labor is seen in the operation and maintenance of power plants where jobs could be automated. However, in some areas also new jobs would be created with a strong skill focus in the IC technologies and data science. In [30] the Energy Expert Cyber Security Platform (EECSP) provides advice to the European Commission on cyber security policy. Based on the expected cyber security threats in the energy sector and existing regulations, a gap is identified and recommendations for actions are given including, for example, the creation of a cyber response framework for the energy sector. The "World Energy Council's" report [31] on "The road to resilience" also provides an overview of cyberattacks with impacts on the energy system. The authors conclude that digitalization increases the complexity of managing cyber risks. The recommended actions include, for example, the implementation of policies and standards, the use of information sharing and collaboration between companies and countries and the implementation of cyber security already in the development of technology. The Hans Böckler Foundation [33] (which belongs to the German Trade Union Confederation) sees the highest risk of job losses in the administrative tasks as well as technical tasks in the grid and generation. Furthermore, a risk of higher stress levels due to multitasking requirements and high performance transparency is identified. The author also points out that a new set of skills will be required, which offers opportunities for employees willing and able to participate in further education programs. Besides that, according to the author, digitalization offers the potential for more flexibility of working conditions and facilitated processes.

Overall, most aspects of the digitalization of the energy sector are to some extent covered in the concurrent literature. However, two aspects are lacking. The first is a structure that allows categorizing digital applications unambiguously (as far as possible) regarding different important aspects. The second aspect is a basis for a holistic assessment and evaluation of digital applications taking into consideration criteria reflecting the different perspectives of all stakeholders.

3. Categorization of digital applications

The objective of the literature review is to identify applications of digitalization in the energy sector with a focus on the German market. In a second step, these applications are then clustered. Therefore, ten publications [7][8][16][34][35][36][37][38][39][40] have been identified which cover a broad view of the digitalization across different technologies and along the entire value chain of the energy sector. For more information on the method of the literature review and further results please refer to [41].

Digital applications in the energy sector are numerous and extremely diverse in their area of application, intended benefit, and functionality. Subsequently, there are many ways to categorize these digital applications. Based on the findings of the present literature review the applications are clustered in three categories and seven subcategories as depicted in the above figure, based on the area where they cause the highest impact. The three categories are:

- System balance—These applications help to level energy generation, demand, and grid capacity;
- Process optimization—These applications improve internal processes and raise efficiency and effectiveness;
- Customer orientation—These applications offer additional benefits to the user and increase revenues.

These three categories and seven subcategories allow a mostly unambiguous allocation of applications into the different clusters. Nevertheless, some applications exist which could be allocated in more than one category or subcategory. This is mainly the case for “Process optimization” applications, such as the “digital twin” which, depending on its area of utilization, can also help to improve the balance of the overall system.

Furthermore, an indication of how often the applications of the subcategory are mentioned is given (i.e., from 0 out of 10 to 10 out of 10). It becomes apparent that the discussion about digital applications in the energy sector are mainly focused on applications which support the balancing mechanisms of the system, i.e., “smart grid”, “smart markets”, and integration of flexibilities. This coincides with one of the main current challenges of Germany’s electricity system—to cope with the rising integration of volatile generation. The applications in the subcategory “anomaly detection and predations” are mentioned in the context of both application categories “System balance” and “Process optimization” and, based on their frequent reference, are identified as important parts of the digitalization of the energy sector. Contrastingly, the process efficiency applications based on process automation are less frequently mentioned. These are the least energy-specific applications, which might be a reason why they are discussed less in energy-specific literature. Customer orientation applications of all three subcategories are frequently mentioned in the analyzed literature, however not as frequently as the “System balance” applications. In the following, the identified digital applications are described.

- System Balance

Digitalization is mostly based on technology which captures, transmits and analyses data, which can then be made usable. The current German/European energy system is already highly complex. However, with a growing number of decentralized volatile electricity generators, the complexity rises drastically. The number of PV units installed in Germany, for example, almost tripled between 2009–2018, resulting in >1.7 million grid-connected units [42]. To cope with this complexity and the high ratio of volatile energy generation, either high inefficiencies in grid and generation capacities need to be accepted as safety buffers or the information about actual and predicted demand, generation, and grid capacities is used to actively control the balance of the system. This is where digitalization can bring massive benefits [7][8][16][34][35][37][38][39][40]. By applying digital sensors, digital control units (actuators) and network connections to electricity generators, consumers and grid units, and using the availability of information and remote control capabilities, the system can be controlled and kept in balance (i.e., actively manage demand and generation, also considering grid capacity restraints) in a more efficient way. For the grid, for example, temperature sensors are one important aspect for real-time condition monitoring and remotely controllable transformers and switchgear enable load, voltage, and frequency control even on low voltage distribution grid levels. This is often referred to as “smart grid”.

Besides optimizing the balancing mechanisms between generation, demand, and grid conditions, also the individual steps of the value chain can be optimized based on digital applications. For example, the operating point of power plants can be optimized based on data driven algorithms taking into account e.g., electricity and fuel prices. Safety factors used in the grid can be reduced based on a higher density of condition data points (e.g., digital temperature sensors), and the charge–discharge cycle of batteries can be optimized to, for example, maximize overall battery lifetime. If incentivized correctly the optimization of the individual steps of the value chain overall support the system stability [7][8][16][35][37][38].

While in the past, the generation followed the demand, digitalization will enable demand to follow generation (to a certain extent) by providing the necessary information and control infrastructure [7][16][34][35][38][39][40]. These applications are summarized as Demand Side Management. While the flexibility of industrial electricity demand (e.g., heating and cooling processes) is already partly used today, the potential of residential demand (e.g., night storage heating, heat pumps, dishwasher, cleaning robots) relies on one of the major digitalization steps, the “smart meter” roll-out. Beside the “smart meter” roll-out as the central communication device the household appliances which are used to offer demand flexibility need to be network-connected and remotely controllable. The total potential for flexibility of the German residential electricity demand is estimated to be ~7% of the net consumption [38]. However, more demand flexibility can be achieved via batteries or sector coupling, such as with e-mobility or the gas sector via power-to-gas technologies [7][16][34][35][37][39][40]. The required hardware to make use of these flexibilities can be integrated and utilized in the energy sector based on digital data acquisition, transmission, and analysis infrastructure as well as remote control systems. One crucial aspect however, is the definition of universal device communication standards to ensure interoperability between consumers, generators and communication devices. Due to the demand flexibility, the share of renewable energy of the total consumption can be increased while maintaining grid stability [7][16][34][35][37][39][40]. Logically, the flexibility of generation units, especially renewables, can also be increased due to digitalization [7][35][37][38], however in Germany this is rather an issue of renewable energy regulation. The flexibilities can be either part of the “smart grid”, if controlled by the grid operator, or of the “smart market” if they are “controlled” via a price signal. These price signals could be variable tariffs for residential customers or direct market participation of industrial customers, enabled by “smart meters” and the previously described information and communication infrastructure [8][16][37][38][39]. Flexibilities can be bundled to form Virtual Power Plants, offering financial benefits for the participants and new business possibilities for the service provider [7][8][16][34][35][37]. Overall, the digital data acquisition and transmission infrastructures enables trading and generation/consumption/grid controlling with a higher frequency, thus improving system stability.

Besides converting the current electricity market into a “smart market” as indicated above, digitalization could also cause more disruptive changes such as a true peer-to-peer market, where decentralized prosumers (generator and consumer, e.g., household with photovoltaic units) exchange energy in a mostly regional setup [7][8][35]. This would require a digital platform, which offers basic market functionalities as well as direct communication and transaction channels between the control devices (e.g., “smart home” system) of the participants. By using “smart contracts”, a high level of automation can be reached such that the user is not required to give frequent input [16][35][37]. A blockchain technology could (if the technical challenges of high energy consumption and low transaction speed can be solved) offer an economically feasible way to perform these mini transactions in a secure manner [7][37].

By using advanced analytics based on historical and current energy-related as well as external data, accurate forecasts for generation, demand, and grid conditions can be made. This reduces grid losses and the need of operating reserves, avoids unnecessary grid reinforcements and reduces the instances when renewable generation needs to be curtailed. In its effect, this reduces greenhouse gas (GHG) emissions and the use of resources [8][16][34][35][38][40]. The higher quantity and quality of information on the status of the energy system also allows for faster error detection and in some cases even remote fixing [7][16][34][35][37][38][39]. Besides that, decisions on building further generation units or implementing grid enforcements can be made on a better factual basis [7][8][16][36][38][39].

- Processes Optimization

Besides supporting the balancing of the energy system, digital applications offer great potential to optimize internal processes. Some of the process optimizations are specific to the energy sector while others can be observed across different sectors.

Data analytics and machine learning can improve the understanding of correlations and the ability to identify the root cause of anomalies and thereby help to define predictive maintenance strategies [7][8][16][34][35][36][37]. While predictive maintenance can avoid costs and downtime for any equipment, it is, in particular, relevant for assets with high availability requirements and assets which are difficult to access, such as offshore wind turbines. If data is captured and analyzed thoroughly a digital twin of equipment units, entire assets, and even whole systems can be created. Digital twins help to optimize operations and maintenance activities in line with overall objectives [16][35][36]. These objectives can be, for example: increasing a power plant’s primary energy efficiency, deferring grid investments, reducing energy consumption or increasing expected lifetime. Besides that, digitalization can help to improve the preparation for and the documentation of construction and maintenance work via delivering upfront information on potential issues, relevant (virtual-/augmented-reality based) instructions, and material and tool lists [8][16][36]. A digital document management system can increase accessibility of documents and decrease administrative costs [36]. Many repetitive tasks can be automated based on digital solutions (RPA, robotic process automation). In particular, administrative tasks as well as some regulatory reporting can be automated [36]. The automation of more complex and less standardized tasks might require the application of machine learning. Connecting internal processes and IT systems with customer/supplier/partner processes and IT systems can offer benefits. The benefit of automated processes and connected IT systems is mostly an efficiency increase but they can also lead to higher process quality [36]. Non-energy related processes such as, for example, supply chain [43], human resources/recruiting [44], strategy definition [45], controlling and accounting [46], and legal can also greatly benefit from digitalization in terms of process efficiency or quality of the output.

- Customer Orientation

Historically, electricity was mainly a commodity. Customers wanted electricity to be available and cheap. However, during the last decades, customers in Germany have developed further requirements. Climate-friendly electricity became more important, which can, for example, be seen in the rising number of renewable energy contracts (increase from 5% in 2008 to 24% in 2017 of German residential customers [47]). Furthermore, the experiences of data transparency and convenience in other sectors have changed customer expectations [34]. Customers, for example, become increasingly dissatisfied with receiving estimated monthly energy bills and an adjustment payment after a physical meter read rather than having full transparency of consumption and costs. These customer requirements (cheap, renewable energy with high transparency and convenience) are where digital applications can create benefits. “Smart meters” are one of the most crucial components for “smart home” applications. “Smart home” systems offer the possibility to continuously measure energy consumption (and therefore automatically issue bills based on actual consumption), disaggregate the consumption to distinctive household appliances and visualize this information [8][16][34][35][36][38][39]. This creates transparency and subsequently offers possibilities to identify energy-saving potentials. “Smart” devices can be integrated into the “smart home” system, and their operation can be remotely controlled and manually or automatically optimized. These devices can be energy consumers (e.g., washing machines), energy generators (e.g., PV units), or energy storage units (e.g., batteries or e-cars). The optimization of these devices can reduce energy consumption or minimize the cost of the consumed energy as well as maximize the revenues of the electricity generation [7][8][16][34][35][38]. Overall, “smart home” systems and its components can use neural networks to learn the customer’s habits and adapt to them, e.g., heating adapts to the customer´s habit of working and sleeping. Furthermore, new digital customer interaction channels can be used or created such as WhatsApp, Facebook, online chats and self-service online portals. This not only increases customer satisfaction as it matches their expectations but can also reduce costs, especially if parts of the interaction are performed via bots or self-service portals [8][16][34][36].

Logically, non-energy related services can be included in the “smart home” system as well. By monitoring the usual consumption habits of an elderly person, an ambient assisted-living system could send an alarm if it detects anomalies [16][38][39] which could indicate a potential problematic situation of the user. Further, data from temperature sensors can be used to detect open windows/doors and inform the owner. Ultimately, security systems could also be integrated into “smart home” systems [16][38].

The “smart meter” also offers the potential for another non-energy related service. Since the “smart meter” gateway, including all connections to authorized receivers of data, need to comply with the security standard BSI-CC-PP-0073 defined by the BSI (Bundesamt für Sicherheit in der Informationstechnik/Federal Office for Information Security). This secure connection could also be used to transmit other information such as contracts, bank statements, and replace the hard copy signature. Furthermore, the data itself, gathered by the “smart home” systems, can be used. On the one hand, it can be used to offer customized energy-related services and products and even predict the customer’s reaction to specific offers or events [8][36]. On the other hand, the data can be sold, with the permission of the customer, to data-driven companies, e.g., marketing firms. However, it is not completely clear yet which are the areas where data on energy consumption can be the most valuable [38][40]. As digitalization offers the potential to increase transparency along the entire value chain, cheaper and more trustworthy proof of origins can be implemented, for example as a blockchain. For electricity this could be used for certificates of renewable energy generation [35][37].

4. Conclusion

In conclusion, it can be stated that digitalization is a process that has begun decades ago and is continuously accelerating. It has already drastically changed several industry sectors. In the energy sector, many digital applications have been implemented; however, more drastic changes can be expected in the next decades.

A literature review based on ten publications was performed. The ten publications all take a broad view of the digitalization of the energy sector including all value chain steps. Based on the literature analysis, a structured overview of potential digital applications, expected benefits, and impacted stakeholders is presented.

Three impact areas are identified as categories of digital applications, “System balance”, “Process optimization”, and “Customer orientation”, each containing numerous individual digital applications. The “System balance” applications mainly consist of applications in the fields “smart grid” and “smart market”, which actively control generation and consumption in order to balance both based on data-driven monitoring, control and prediction tools. These applications are found to be the most discussed in the analyzed literature. “Process optimization” applications either optimize processes based on data analytics or automate processes based on robotics. “Customer orientation” applications use a variety of digital technologies and mostly aim at providing a benefit to the customer, which in some cases could be monetized by the service provider.

As the literature review has some inherent limitations, such as limited number of publications, potentially a selection bias, and no qualitative analysis of the content discussed, further steps to validate the results should be taken. These could include an extension of the literature analysis or a survey among stakeholders. Besides that, the focus of the present literature review was on applications, benefits, and stakeholders, and in the further analysis potential risks and used digital technologies also need to be included.

The publication can be found here: https://www.mdpi.com/2076-3417/9/24/5350/htm

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