applied sciences

MDPI

Review

Review and Categorization of Digital Applications in the Energy Sector

Paul Weigel [1,2,*] and Manfred Fischedick [1]

[1] Wuppertal Institut für Klima, Umwelt, Energie gGmbH, Döppersberg 19, 42103 Wuppertal, Germany; manfred.fischedick@wupperinst.org
[2] University Duisburg-Essen, Institute for Environmental Process Engineering and Plant Design, Leimkugelstr. 10, 45141 Essen, Germany
* Correspondence: paul.weigel@uni-due.de

Received: 27 March 2019; Accepted: 2 December 2019; Published: 7 December 2019

Abstract: 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 article provides a structured overview of potential digital applications in the German energy (electricity) sector, including the associated benefits and the impacted stakeholders on the basis of a literature review. Furthermore, as an outlook, a methodology to holistically analyze digital applications is suggested. The intended purpose of the suggested methodology is to provide a complexity-reduced fact base as input for societal and political discussions and for the development of new digital products, services, or business models. While the methodology is outlined in this article, in a follow-up article the application of the methodology will be presented and the use of the approach reflected.

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.

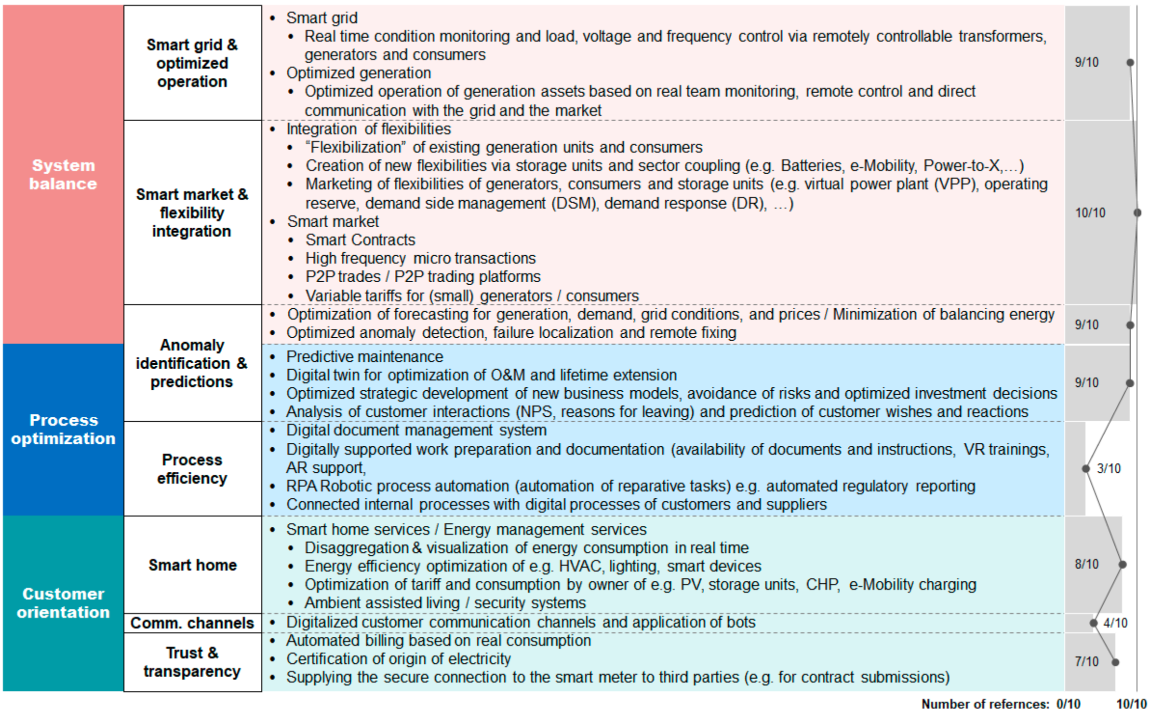
As a first step, transparency on which digital applications can be expected in the electricity sector and why they will/might be implemented needs to be created. Therefore, this article presents the results of a literature review of ten publications with the following three objectives:

1. Identify and categorize the digital applications in the energy sector;
2. Identify the expected benefits attributed to the applications;
3. Identify the impacted stakeholders.

In a second step the identified digital applications need to be holistically analyzed. Therefore, as an outlook, a potential methodology to holistically assess and evaluate digital applications in the electricity sector is suggested. While the methodology is outlined in this article, a follow-up article will present a detailed description, an applied use case of the methodology and a critical reflection of the approach.

2. The Current State of Knowledge

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 Figure 1. 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).



System balance	**Smart grid & optimized operation**	• Smart grid
		  • Real time condition monitoring and load, voltage and frequency control via remotely controllable transformers, generators and consumers
		• Optimized generation
		  • Optimized operation of generation assets based on real team monitoring, remote control and direct communication with the grid and the market
			9/10

	Smart market & flexibility integration	• Integration of flexibilities
		  • “Flexibilization” of existing generation units and consumers
		  • Creation of new flexibilities via storage units and sector coupling (e.g. Batteries, e-Mobility, Power-to-X,…)
		  • Marketing of flexibilities of generators, consumers and storage units (e.g. virtual power plant (VPP), operating reserve, demand side management (DSM), demand response (DR), …)
		• Smart market
		  • Smart Contracts
		  • High frequency micro transactions
		  • P2P trades / P2P trading platforms
		  • Variable tariffs for (small) generators / consumers
			10/10

	Anomaly identification & predictions	• Optimization of forecasting for generation, demand, grid conditions, and prices / Minimization of balancing energy • Optimized anomaly detection, failure localization and remote fixing	9/10
Process optimization		• Predictive maintenance • Digital twin for optimization of O&M and lifetime extension • Optimized strategic development of new business models, avoidance of risks and optimized investment decisions • Analysis of customer interactions (NPS, reasons for leaving) and prediction of customer wishes and reactions	9/10
	Process efficiency	• Digital document management system • Digitally supported work preparation and documentation (availability of documents and instructions, VR trainings, AR support, • RPA Robotic process automation (automation of reparative tasks) e.g. automated regulatory reporting • Connected internal processes with digital processes of customers and suppliers	3/10

Customer orientation	**Smart home**	• Smart home services / Energy management services
		  • Disaggregation & visualization of energy consumption in real time
		  • Energy efficiency optimization of e.g. HVAC, lighting, smart devices
		  • Optimization of tariff and consumption by owner of e.g. PV, storage units, CHP, e-Mobility charging
		  • Ambient assisted living / security systems
			8/10

	Comm. channels	• Digitalized customer communication channels and application of bots	4/10
	Trust & transparency	• Automated billing based on real consumption • Certification of origin of electricity • Supplying the secure connection to the smart meter to third parties (e.g. for contract submissions)	7/10

Figure 1. Categorized digital applications in the energy sector.

Since the status quo, regulations, and driving forces of digitalization differ by country, each country’s energy sector will have a somewhat different digitalization path and will utilize somewhat different digital applications. As this publication aims at structuring the inherently broad topic of digital applications in the energy sector, it focuses on Germany. A similar approach could later be applied to other countries or bigger regions such as the EU.

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 [11–13]. Approaches to successfully master the digital transformation in the energy sector are described in [14–16], 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.

Digital technologies such as blockchain, artificial intelligence or cloud computing and their applications in the energy sector are, for example, discussed in [21–29]. 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 [22–27] 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 [22–25] 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" covers among other topics (see next section) 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 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 (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.

Besides the business view and the publications on specific aspects of digitalization, some publications cover a broad overview of the digital transformation in the energy sector including digital applications. The publications taking a broad view on which digital applications can be expected in the energy sector are used for the literature review performed in this paper (see next section).

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. Furthermore, the literature taken into account and especially the literature analyzed in Section 3 mainly presents the findings of the individual authors, based on their own research, surveys, or analysis of specific literature, however, an overarching overview is missing. Therefore, this study intends to create this overview and summarizes and structures the findings of the analyzed publications.

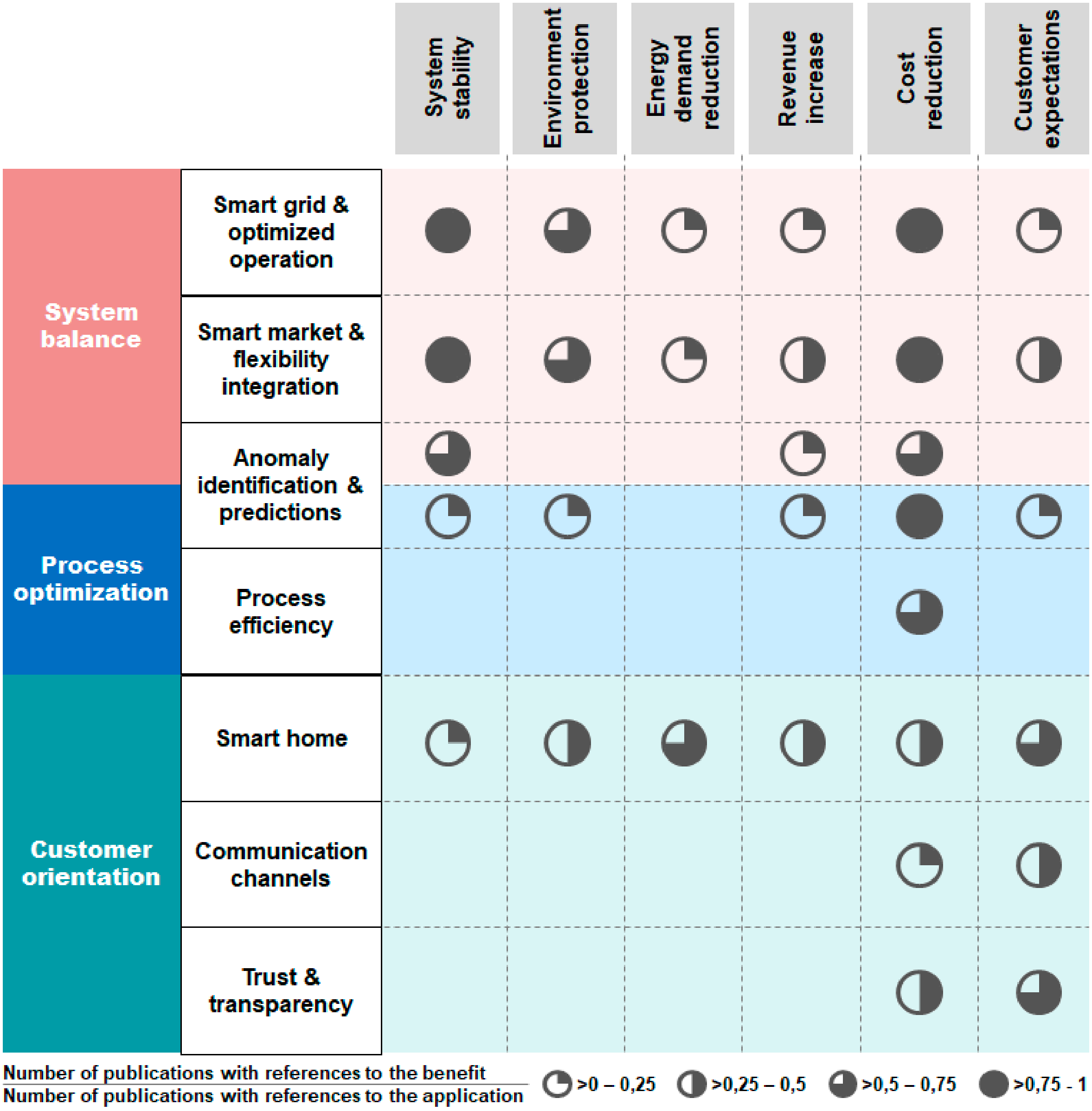
3. Objective and Approach of the Literature Review

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. Furthermore it is analyzed which applications are considered to have which benefits and which are the profiting stakeholders. Therefore, ten publications [7,8,16,34–40] have been identified which cover a broad view of the digitalization across different technologies and along the entire value chain of the energy sector. The ten publications consist of two publications by renowned organizations presenting their views, three collected edition publications from researchers, politicians and business as well as association representatives, one survey conducted among German utilities, one meta-study regarding five specific aspects of the digitalization and three studies of the effects of the "smart meter" roll-out as one important aspect of the digitalization.

The IEA and OECD publication "Digitalization and Energy" [7] offers an exhaustive overview of the impacts of digitalization on various energy-related sectors, among them the power sector. Besides that, it also covers the critical points own-consumption of electricity of ICT, threats due to cyber security and economic disruptions, and policy aspects. The BDEW (German Association of Energy and Water Industries) publication "The digital energy economy" [8] discusses similar aspects with a focus on the electricity sector. The collected edition "Chances and challenges due to the digitalization of the economy" [34] includes statements on the digitalization of politicians and business as well as association representatives regarding various energy-related sectors. All value chain steps of the energy sector are covered and many different stakeholder perspectives represented. A structured overview of business models and digital applications along the stakeholders of the value chain is presented in [34] (pp. 51–58). The publication "Challenge Utility 4.0" [16] also covers all value chain steps of the energy sector but besides mainly describing the impact of digitalization, it also includes suggestions on how to approach the digital transformation for companies. Thus, there are many business representatives among the authors of the collected edition. “Digitalization of the Energy sector” [35] by SETIS (part of the European Commission) naturally focuses more on the political aspects but nevertheless covers a broad spectrum of digital applications along the entire value stream. The authors of the edited edition are mainly politicians and association and business representatives. “Digital@EVU” [36] is a survey conducted by A.T. Kearney on behalf of BDEW among German utilities. Although the utilities cover all value chain steps, the customer-related digital applications have a higher focus. Besides the used digital applications, the survey also analyses the companies’ approach to digital transformation. In the meta-study “The digitalization of the energy transition” [37] different aspects, such as virtual power plants, “smart grid”, blockchain, load management, and electricity own consumption of ICT devices, are analyzed among 38 publications. The three “smart meter” roll-out studies all cover the effect of the “smart meter” on the energy system. Naturally, as the “smart meter” is a device at the customer level, the main focus is on customer-related digital applications. However, since the “smart meter” can have effects across the entire value chain these are also covered. The three publications differ in the regions the “smart meters” are applied. While [38] focuses on Germany and therefore is entirely applicable to this literature review, for the other two studies, which focus on the UK [39] and the US [40], only aspects relevant for Germany are considered.

The analysis is conducted in an iterative manner by identifying digital applications, benefits and stakeholders, clustering them, and analyzing if they are discussed in the considered publications. It is quantitatively analyzed whether or not a particular application, benefit or stakeholder is mentioned. A qualitative evaluation of how a mentioned application is described, e.g., high or low importance, is not conducted. The evaluation is performed on application subcategory level as depicted in Figure 1 (instead of on individual application level) as this is the level of detail that all analyzed publications can provide. Three quantitative analysis are performed:

- Applications (Figure 1)—Number of publications with references to the application (from 0 out of 10 to 10 out of 10);
- Benefits per application (Figure 2)—Number of publications with references to the benefit of a specific application compared to the number of publications which reference this application;



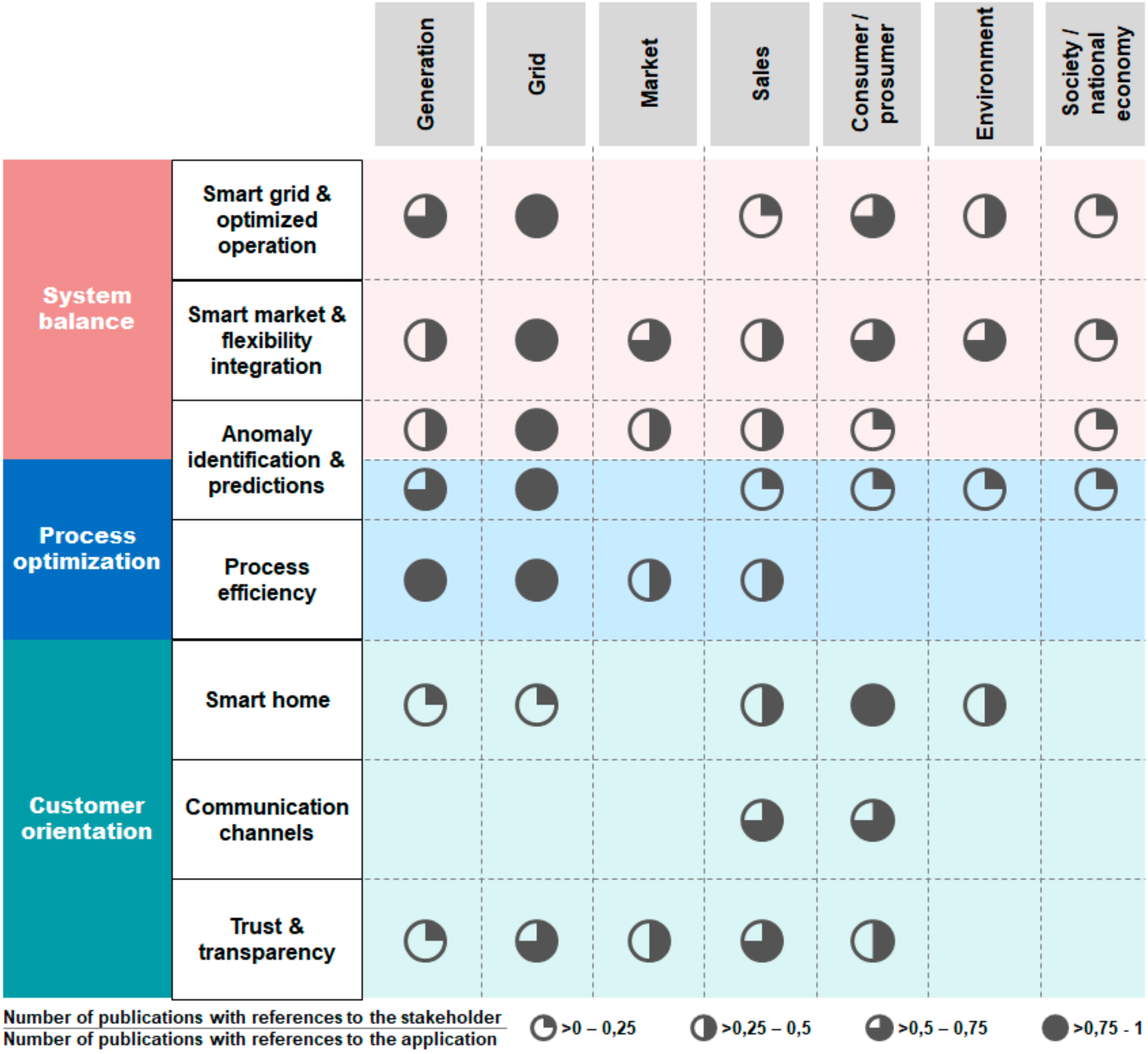
		System stability	Environment protection	Energy demand reduction	Revenue increase	Cost reduction	Customer expectations
System balance	Smart grid & optimized operation	●	◕	◔	◔	●	◔
	Smart market & flexibility integration	●	◕	◔	◑	●	◑
	Anomaly identification & predictions	◕			◔	◕	
Process optimization		◔	◔		◔	●	◔
	Process efficiency					◕	
Customer orientation	Smart home	◔	◑	◕	◑	◑	◕
	Communication channels					◔	◑
	Trust & transparency					◑	◕

$\frac{\text{Number of publications with references to the benefit}}{\text{Number of publications with references to the application}}$ ◔ >0 – 0,25 ◑ >0,25 – 0,5 ◕ >0,5 – 0,75 ● >0,75 - 1

Figure 2. Digital applications and attributed benefits.

- Affected stakeholders per application (Figure 3)—Number of publications with references to the impacted stakeholders of a specific application compared to the number of publications which reference this application.

In order to avoid a double evaluation, the publications analyzed in the meta-study [37] are not reevaluated in the present literature review, with one exception: the German “smart meter” roll-out study [38]. Here, an in-depth analysis was conducted as it is one of the most relevant, comprehensive, and reliable publications in this field.



		Generation	Grid	Market	Sales	Consumer / prosumer	Environment	Society / national economy
System balance	Smart grid & optimized operation	◕	●		◔	◕	◑	◔
	Smart market & flexibility integration	◑	●	◕	◑	◕	◕	◔
	Anomaly identification & predictions	◑	●	◑	◑	◔		◔
Process optimization		◕	●		◔	◔	◔	◔
	Process efficiency	●	●	◑	◑			
Customer orientation	Smart home	◔	◔		◑	●	◑	
	Communication channels				◕	◕		
	Trust & transparency	◔	◕	◑	◕	◑		

$\frac{\text{Number of publications with references to the stakeholder}}{\text{Number of publications with references to the application}}$ ◔ >0 – 0,25 ◑ >0,25 – 0,5 ◕ >0,5 – 0,75 ● >0,75 - 1

Figure 3. Digital applications and affected stakeholders.

4. Categorization of Digital Applications

As discussed in Section 2, potential 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 Figure 1, 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. A visual overview of which benefit is generated by which of the seven subcategories is given in Figure 2. Finally, an allocation of affected stakeholders to the according application subcategory is performed and depicted in Figure 3.

4.1. 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 [41]. 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. 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" [7,8,34,35,37–40].

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 [7,8,35,37,38].

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 [7,34,35,38–41]. 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 [7,34,35,37,39,40]. 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 [7,34,35,37,39,40]. Logically, the flexibility of generation units, especially renewables, can also be increased due to digitalization [7,35,38,41], 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 [8,37–39]. Flexibilities can be bundled to form Virtual Power Plants, offering financial benefits for the participants and new business possibilities for the service provider [7,8,34,35,37]. 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 [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 [8,34,35,38,40]. 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 [7,34,35,37–39]. Besides that, decisions on building further generation units or implementing grid enforcements can be made on a better factual basis [8,38,39,42].

4.2. 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 [7,8,34–37]. 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 [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 [8,36]. 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.

4.3. 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 [8,34–36,38,39]. 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 [7,8,34,35,38]. 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 [8,34,36].

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 [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 [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].

5. Overview of Benefits and Impacted Stakeholders of Digital Applications

Besides clustering the digital applications into the described categories and subcategories, they can be evaluated along numerous different criteria. One of the most relevant evaluation criteria is the expected benefits. In Figure 2 the applications and benefits are synthesized in a visual overview. For this overview also the benefits are grouped into six clusters derived from the reviewed literature. The identified benefits can be allocated to the following six clusters:

- System stability—Improving system stability and controllability;
- Environment protection—Reducing greenhouse gas emissions and resource use;
- Energy demand reduction—Reducing the need for primary energy and the overall consumption;
- Revenue increase—Increasing revenue by developing new business models, products/services and accessing new customer groups;
- Cost reduction—Decreasing the cost to supply energy;
- Customer expectations – Satisfying customer needs and expectations (residential and industrial).

In Figure 2 it becomes apparent that the four subcategories (smart grid & optimized operation, smart market & flexibility integration, anomaly identification and predictions, and smart home) are attributed a broad spectrum of benefits. This is not surprising since these four subcategories are also found to be the most discussed in the literature (compare Figure 1) and they include a high number of individual digital applications.

The single benefit with the most references is cost reduction. At first this does not seem to match the finding that process efficiency applications are among the less discussed in the reviewed literature. However, the potential for cost reduction appears to be inherent to most digital applications independently of its category or subcategory. A potential for cost reduction is identified for every application subcategory. For each subcategory at least one quarter of the publications, which discuss the applications, identify cost reduction as a benefit. The benefit is either based on digitalization's potential to automate processes or on its potential to improve the effectiveness of processes. Following cost reduction, the next most referenced benefits are positive effects on the system stability and on fulfilling customer expectations. The benefit of improved system stability logically is mainly attributed to the applications of the category "System balance". The benefit is based on digitalization's potential to connect formerly separated things (e.g., equipment, machines, assets) into interacting networks. Fulfilling customer expectations is attributed to almost all application subcategories (with the exception of "Process optimization"). Similarly to the benefit cost reduction a potential for fulfilling customer expectations is identified for most digital applications independently of their category or subcategory. The benefit is based on digitalization's potential to increase transparency and improve convenience. Furthermore, the benefit of environmental protection is attributed to four application subcategories. Here environmental protection and system stability appear to be correlated as they are attributed mostly to the same application subcategories. The main cause of this correlation is that with improved system stability a higher share of volatile renewable energy can be integrated. Besides that, a reduction of required hardware (spare parts, grid reinforcements) reduces the need for resources. Lastly, the benefits of "Energy demand reduction" and "Revenue increase" are relatively rarely discussed. It appears that although overall digitalization is believed to have great potential for new business models, when it comes to actual digital applications in the energy sector a positive impact on revenues is relatively rarely identified.

Furthermore, the understanding of who is affected by the impact of digital applications is of great importance for its evaluation. The stakeholders of the value chain (generation, grid, market, sales, customer/prosumer) are extended by the "stakeholders" environment and society/national economy. As explained in Section 3, the analyzed literature is reviewed for references regarding which stakeholders are affected by which digital application. A visual overview of the outcome is depicted in Figure 3.

The stakeholder which is by far most often mentioned as impacted is the grid. While for applications of the category customer orientation the grid is hardly mentioned as impacted, all publications discussing applications of the categories "System balance" and "Process optimization" mention the grid as an impacted stakeholder. This underlines the importance of digitalization for the grid. As the transmission system operators in general already have a high level of digital maturity, most impacts of digital applications can be expected on the level of the distribution system operators. The second most mentioned impacted stakeholder is the consumer/prosumer. Although many applications in the category "Customer orientation" are mentioned with a direct impact on consumers, the overall high impact is also due to the possibilities for formerly passive consumers to actively participate in the energy market as a prosumer or with a demand flexibility, hence the mentioned impacts within the application category "System balance". Thirdly, generation and sales are mentioned as impacted stakeholders. An impact on sales is identified for applications of all categories and subcategories. Naturally, as sales are the interface between energy (service) providers and customers, most references occur for applications in the customer orientation category. The analyzed literature also frequently mentions impact on sales for applications in the "Process optimization" category due to the potential of automation and customer analysis. Applications of the "System balance" category mainly impact sales due to additional services which can be provided to the customer/prosumer such as the marketing of flexibilities. This finding is coherent with the identified potential of increased revenue for "System balance" applications (compare Figure 2). The stakeholder generation is mentioned mostly as impacted by applications in the category "System balance" and "Process optimization". Many applications are mentioned to have the potential to improve operation and maintenance processes, either in isolation or in the context of the energy system. Coherently with the analysis of the benefits, environmental protection impacts on the stakeholder environment are mainly mentioned for applications that improve system stability, hence enable more integration of renewable energy sources as well as applications with the potential to reduce energy consumption and use of resources. The energy market is not frequently mentioned as impacted by digitalization. Most instances that an impact is mentioned are due to the integration of flexibilities via price signals and new direct forms of energy trading such as peer-to-peer platforms. The energy trading itself today already is highly digitalized which might be an explanation why it is not frequently mentioned as impacted. Lastly, the society and the national economy are hardly mentioned as impacted. Most described impacts are an increase in availability hours of electricity (already very high in Germany [47]) and a reduction of the cost to supply energy which is passed through to the consumer. However, further social impacts such as privacy concerns and work conditions are, at least within the analyzed literature, not attributed to digital applications. Yet it is to be mentioned that cyber security risks are generally mentioned in some of the analyzed literature but not specific to any application.

More criteria for analyzing digital applications could be the enabling IC technologies (e.g., artificial intelligence, internet of things, big data, cloud computing, mobile computing, blockchain), the implementation time horizon, interdependencies, the need for governmental implementation support, or the effect on the security of the critical infrastructure.

6. Suggested Evaluation Methodology for Digital Applications

Digitalization has the potential to have a drastic impact on all steps of the energy value chain as well as on all stakeholders, including the environment, the overall society, and the national economy. Good knowledge of the functionality of digital applications and their impact on all stakeholders is necessary.

One the one hand, it enables a broad societal and political discussion to set the general targets and guidelines for the digitalization process and on the other hand, it is an important piece of information for companies to develop and sustainably implement digital applications. A variety of conventional as well as rather recent methods, such as living labs and design thinking, are already applied in the development of new products, services, and business models. However, a holistic analysis of benefits and potential risks of digital applications, taking into account all impacted stakeholders, provides an effective way to identify and solve potential impediments and drawbacks early on.

As an outlook, a methodology is presented in this section which could offer a basic framework to perform this holistic analysis of technical, ecological, social and economic aspects of digital applications. A combination of a multi-criteria analysis (MCA), a life cycle assessment (LCA), and semi-structured interviews is suggested. In Figure 4, the overall concept and basic functionality of the combination of methodologies is depicted. The concept can be adapted to the diverse kinds of digital applications and different analysis depths, and it allows the inclusion of quantitative as well as qualitative criteria. The result is an overall evaluation with reduced complexity including specific highlights, risks and respective solution options.

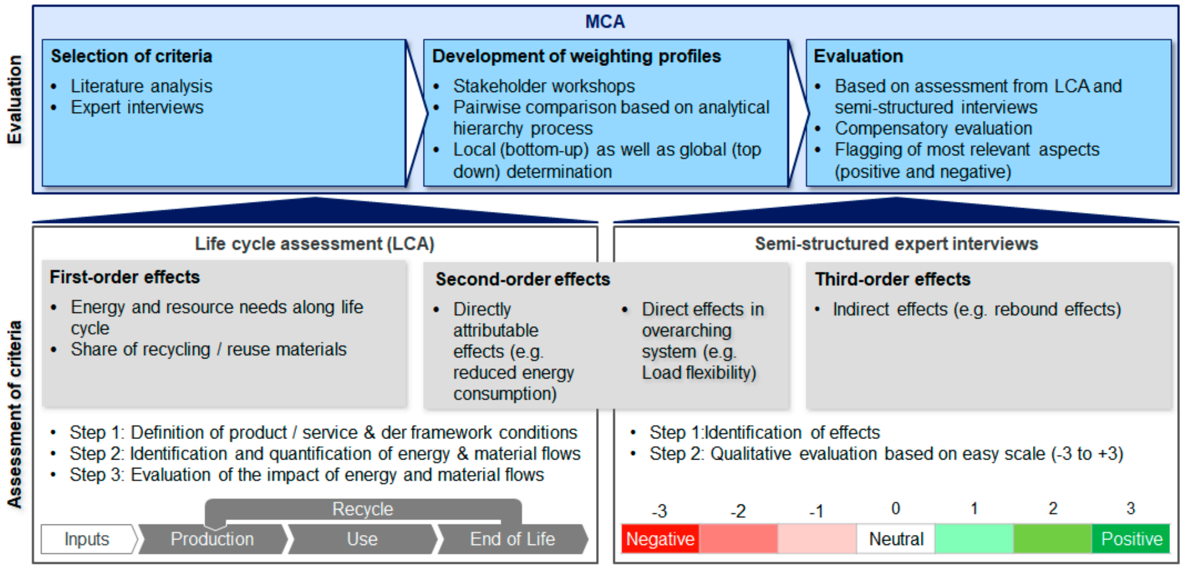


Figure 4. Suggested combination of methodologies for holistic assessment and evaluation of digital applications.

As depicted in Figure 4, the basic structure for the evaluation is a multi-criteria analysis. However, the assessment of the different criteria defined in the MCA is conducted either within the life cycle assessment or via the semi-structured expert interviews. This offers the flexibility to either perform a more qualitative “Quick Check” based mostly on expert interviews (or even literature review) or if required a qualitative “Deep Analysis” via the LCA.

A first test of the described methodology is currently being conducted for the German “smart meter” roll-out in cooperation with “smart meter” manufacturers. While an overall evaluation result cannot yet be given, first risks/bottlenecks have already been identified. One risk is the use of conflict (e.g., tin, tantalum) and scarce/critical (e.g., rare earth elements) materials. However, this risk is not specific to “smart meters” but applies to most modern communication devices. Besides that, some manufacturers of “smart meters” have managed to minimize or even eliminate the use of certain conflict and scarce materials. Another risk is a potential rebound effect. Although field tests have shown a reduction in energy consumption after the implementation of “smart meters”, it is unknown to what extent these reductions are permanent. A lower reduction of energy demand could offset the life cycle GHG balance. This risk could be met in the future with automated demand response mechanisms for “smart” household devices based on, for example, price signals. Furthermore, missing standards such as for “smart home” network communication protocols and interfaces could lower the implementation speed of applications and thereby reduce overall benefits.

Full application of the methodology and discussion of the results, including an evaluation of the suitability of the methodology is yet to come. However, the first experiences of the test suggest that the proposed methodology as such could be suitable for the purpose of a holistic evaluation of digital applications.

7. Conclusions

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. The main benefits identified in the analyzed publications are cost reduction due to more efficient and effective processes and a positive impact on the system stability due to improved balancing of generation, consumption and grid capacity. While the benefits of improved system stability are naturally mainly attributed to the applications of the “System balance” category, the cost reduction benefit is found to be mentioned for all seven application subcategories. Hence, it can be concluded that most digital applications, even those which do not focus directly on cost reduction, have the potential to reduce cost. In other words, cost reduction due to digitalization is not only a matter of process automation. The third most mentioned benefit is the fulfillment of customer expectations which, naturally, is mostly attributed to the applications of the “Customer orientation” category. However, most other application (sub)categories also appear to generate a positive effect for the fulfillment of customer expectations. Environmental protection, as the fourth most often discussed benefit, correlates with the “system stability” benefit, as its main effect is based on a reduction of GHG emissions and resource use due to an energy system, which allows the integration of more renewable energies. Further identified benefits are increase in revenues due to new business models, products and services and reduction of energy demand due to energy-efficiency applications as well as reduced losses. All stakeholders of the energy value chain are impacted by digital applications, including the environment, the society, and the national economy. The main impacted stakeholder identified is the grid. The grid, itself a network connecting generation and consumption, can greatly benefit from monitoring, control and communication technologies. Various applications for system balancing and process optimization with an impact on the grid are identified. Coherent with the finding that most digital application subcategories have the potential to fulfill customer expectations, also the consumers/prosumers are affected by applications of most subcategories. This is mainly due to the changing role from a passive consumer to an actively participating customer who offers generation and flexible demand capacity to other participants or the market. Further impacted stakeholders are (descending order): generation, sales, environment, market and the society/national economy. 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.

Most digital applications do not only cause benefits but also have risks of downsides. Therefore, a good understanding of both benefits and risks from all stakeholders' perspectives at an early stage of development is essential to find solutions to mitigate the risks and make full use of the benefits. A methodology for a holistic assessment and evaluation of digital applications in the energy sector is presented. The methodology consists of a combination of multi-criteria analysis (MCA), life cycle assessment (LCA), and semi-structured expert interviews. Going forward the suggested methodology needs to be further detailed, tested and revised. It could also be adapted to be suitable for digital applications in other, non-energy sectors. Overall, the aim is to create an evaluation basis that provides a structured approach to holistically assess digital applications and provide assessment results with reduced complexity.

Author Contributions: Conceptualization, P.W. and M.F..; methodology, P.W.; literature analysis: P.W.; writing—original draft preparation, P.W.; writing—review and editing, P.W.; visualization, P.W.; supervision, M.F.

Funding: This research received no external funding.

Acknowledgments: The author Paul Weigel receives a scholarship from the Reiner Lemoine Foundation.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Randell, B. The History of Digital Computers. In *Computing Laboratory Technical Report Series*; University of Newcastle upon Tyne: Newcastle upon Tyne, UK, 1974; p. 38.
2. Warwick, K. *Artificial Intelligence: The Basics*; Routledge: New York, NY, USA, 2012.
3. Peña-López, I. *World Development Report 2016: Digital Dividends*; World Bank Publications: Washington, DC, USA, 2016.
4. InfoTrends InfoBlog, September 2018. Available online: http://blog.infotrends.com/our-best-photos-deserve-to-be-printed/#more-24362. (accessed on 21 March 2019).
5. Weigel, P.; Fischedick, M. Rolle der Digitalisierung in der soziotechnischen Transformation des Energiesystems. *Energ. Tagesfr.* **2018**, *68*, 10–16.
6. Wallmüller, E. *Praxiswissen Digitale Transformation: Den Wandel verstehen, Lösungen entwickeln, Wertschöpfung steigern*; Hanser: München, Germany, 2017.
7. International Energy Agency and OECD. *Digitalization & Energy*; IEA publications: Paris, France, 2017.
8. Bundesverband der Energie- und Wasserwirtschaft. *Die digitale Energiewirtschaft—Agenda Für Unternehmen und Politik*; Press center of the Bundesverband der Energie- und Wasserwirtschaft: Berlin, Germany, 2016.
9. Bundesministerium für Wirtschaft und Energie. *Monitoring-Report Wirtschaft DIGITAL*; Publications service of the Bundesministerium für Wirtschaft und Energie: Berlin, Germany, 2018.
10. Stähler, P. *Geschäftsmodelle in der digitalen Ökonomie: Merkmale, Strategien und Auswirkungen*; Joesef Eul Verlag: Lohmar, Germany, 2002.
11. Kraft, P.; Jung, H.H. *Digital vernetzt. Transformation der Wertschöpfung: Szenarien, Optionen und Erfolgsmodelle für Smarte Geschäftsmodelle, Produkte und Services*; Hanser: München, Germany, 2017.
12. Schallmo, D.; Rusnjak, A.; Anzengruber, J.; Werani, T.; Jünger, M. *Digitale Transformation von Geschäftsmodellen: Grundlagen, Instrumente und Best Practices*; Springer Gabler: Wiesbaden, Germany, 2017.
13. Scheer, A.W. Nutzentreiber der Digitalisierung: Ein systematischer Ansatz zur Entwicklung disruptiver digitaler Geschäftsmodelle. *Inform. Spektrum* **2016**, *39*, 275–289. [CrossRef]
14. Doleski, O.D. *Utility 4.0: Transformation vom Versorgungs-zum digitalen Energiedienstleistungsunternehmen*; Springer Vieweg: Wiesbaden, Germany, 2016.
15. Schallmo, D.; Herbort, V.; Doleski, O.D. *Roadmap Utility 4.0: Strukturiertes Vorgehen Für Die Digitale Transformation in Der Energiewirtschaft*; Springer Fachmedien Wiesbaden GmbH: Wiesbaden, Germany, 2017.

16. Doleski, O.D. *Herausforderung Utility 4.0: Wie sich die Energiewirtschaft im Zeitalter der Digitalisierung verändert*; Springer Vieweg: Wiesbaden, Germany, 2017.
17. Aichele, C.; Doleski, O.D. *Smart Market: Vom Smart Grid zum intelligenten Energiemarkt*; Springer Vieweg: Wiesbaden, Germany, 2014.
18. Bundesnetzagentur. *Smart Grid und Smart Market Eckpunktpapier der Bundesnetzagentur zu den Aspekten des sich verändernden Energieversorgungssystems*; Media Center of the Bundesnetzagentur: Bonn, 2011.
19. Stojkoska, B.L.R.; Trivodaliev, K.V. A review of Internet of Things for smart home: Challenges and solutions. *J. Clean. Prod.* **2017**, *140*, 1454–1464. [CrossRef]
20. Robles, R.; Kim, T. Applications, Systems and Methods in Smart Home Technology: A Review. *Int. J. Adv. Sci. Technol.* **2010**, *15*, 37–48.
21. Abolhassan, F. *Was Treibt Die Digitalisierung? Warum an Der Cloud Kein Weg vorbei führt*; Springer Gabler: Wiesbaden, Germany, 2016.
22. 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*, 143–174. [CrossRef]
23. Bundesverband der Energie- und Wasserwirtschaft. *Blockchain in der Energiewirtschaft*; Press center of the Bundesverband der Energie- und Wasserwirtschaft: Berlin, Germany, 2017.
24. Bogensperger, A.; Zeiselmair, A.; Hinterstocker, M.; Dufter, C. *Blockchain—Chance zur Transformation der Energiewirtschaft—Anwendungsfälle*; Publications of the Forschungsstele für Energiewirtschaft: München, Germany, 2018.
25. Bogensperger, A.; Zeiselmair, A.; Hinterstocker, M. *Blockchain—Chance zur Transformation der Energiewirtschaft—Technologiebeschreibung*; Publications of the Forschungsstele für Energiewirtschaft: München, Germany, 2018.
26. Mengelkamp, E.; Notheisen, B.; Beer, C.; Dauer, D.; Weinhardt, C. A blockchain-based smart grid: Towards sustainable local energy markets. *Comput. Sci. Res. Dev.* **2018**, *33*, 207–214. [CrossRef]
27. Wunderlich, S.; Christian Loose, A.; Nachtigall, N.; Bruns, K.; Sandau, A.; Marx Gomez, J. *Energiemarkt Mit Blockchain-Technologie: Ein Marktmodell Unter Berücksichtigung Bestehender Netzkomponenten Und Marktakteure*; Verlagshaus Monsenstein und Vannerdat OHG: Lüneburg, Germany, 2018.
28. Mosavi, A.; Salimi, M.; Faizollahzadeh Ardabili, S.; Rabczuk, T.; Shamshirband, S.; Varkonyi-Koczy, A. State of the Art of Machine Learning Models in Energy Systems, a Systematic Review. *Energies* **2019**, *12*, 1301. [CrossRef]
29. Ramchurn, S.; Vytelingum, P.; Rogers, A.; Jennings, N.R. Putting the 'Smarts' into the Smart Grid: A Grand Challenge for Artificial Intelligence. *Commun. ACM* **2012**, *55*, 86–97. [CrossRef]
30. Energy Expert Cyber Security Platform. Cyber Security in the Energy Sector. In *EECSP Report*; Publications Office of the European Commission: Brussels, Belgium, 2017.
31. World Energy Council. Managing Cyber Risks. In *World Energy Perspectives*; The road to resilience: London, UK, 2016.
32. Lee, J. *The Impact of ICT on Work*; Springer: Singapore, 2016.
33. Roth, I. *Digitalisierung in Der Energiewirtschaft Auswirkungen auf Arbeit und Qualifizierung*; Hans Böckler Stiftung: Dusseldorf, Germany, 2018.
34. Forum für Zukunftsenergien, E.V. *Chancen und Herausforderungen durch die Digitalisierung der Wirtschaft*; Schriftenreihe des Kuratoriums: Berlin, Germany, 2016.
35. Strategic Energy Technology Information System. Digitalisation of the Energy sector. In *SETIS Magazine*; Publications Office of the European Commission: Brussels, Belgium, 2018.
36. Kearny, A.T.; Bundesverband der Energie- und Wasserwirtschaft; IMProve academy. *Digital@EVU 2019*; Press center of the Bundesverband der Energie- und Wasserwirtschaft: Berlin, Germany, 2019.
37. Maier, M. *Metaanalyse: Die Digitalisierung der Energiewende*; Forschungsradar Energiewende by Agentur für erneuerbare Energien: Berlin, Germany, 2018.
38. Edelmann, H.; Kästner, T. *Kosten-Nutzen-Analyse für einen flächendeckenden Einsatz intelligenter Zähler*; Editorial office of the Bundesministerium für Wirtschaft und Energie: Berlin, Germany, 2013.
39. *Department for Business, Energy & Industrial Strategy, Smart meter roll-out (GB): cost-benefit analysis*; UK Government publications: London, UK, 2016.

40. Le Grelle, M. *Cost Benefit Analysis of Smart Meter Deployment for Residential Customers, A Holistic Approach*; ETH Zürich publications: Zürich, Switzerland, 2016.
41. Agentur für Erneuerbare Energien e.V. Anzahl Photovoltaikanlagen-Alle-D-Daten und Fakten zur Entwicklung Erneuerbarer Energien in einzelnen Bundesländern föderal Erneuerbar. 2019. Available online: https://www.foederal-erneuerbar.de/landesinfo/bundesland/D/kategorie/alle/auswahl/664-anzahl_photovoltaika/ordnung/2009. (accessed on 20 March 2019).
42. Peña-López, I. *OECD Digital Economy Outlook 2017*; OECD Publishing: Paris, France, 2017.
43. Glas, A.; Kleemann, F.C. The Impact of Industry 4.0 on Procurement and Supply Management: A Conceptual and Qualitative Analysis. *Int. J. Bus. Manag. Invent.* **2016**, *5*, 55–66.
44. Spitzer, B. HR in the Digital Age. *Workforce Solut. Rev.* **2014**, *5*, 15–17.
45. Hossfeld, S. The Advantage of Digital Decision Making for Strategic Decisions—Proofed by a Supply Chain Case. *Int. J. Manag. Sci. Bus. Adm.* **2017**, *3*, 7–20. [CrossRef]
46. Bhimani, A. *Management Accounting in the Digital Economy*; OUP: Oxford, UK, 2003.
47. *Bundesnetzagentur, Monitoringbericht 2018*; Media Center of the Bundesnetzagentur: Bonn, 2018.