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# Holistic Evaluation of Digital Applications in the Energy Sector - Evaluation Framework Development, Test, and Validation

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***"Gradually and then suddenly."***

Although in Ernest Hemmingway's 1926 novel, *The Sun Also Rises,* this is the answer to the question "How did you go bankrupt?", in a broader sense, it very well describes the dynamics of big changes. The concept is, in particular, applicable to digital transformation due to the exponential development of information & communication technology.

# Acknowledgments

This thesis is dedicated to my unborn child.

First and foremost, I would like to thank PD Dr. Peter Viebahn and Prof. Dr. Manfred Fischedick, who not only supervised my work but also contributed significantly to the successful completion of the thesis through their continuous support and advice. Likewise, Prof. Dr. Klaus Görner (University Duisburg-Essen) supported specific, important parts such as the survey among energy utilities. Furthermore, the financial independence to conduct the research without external commitments was only possible through the generous support of the Reiner Lemoine Foundation, for which I am very grateful. Last but not least, I would like to express my great gratitude to the many experts who participated in the (sometimes lengthy) expert interviews, as well as to the companies who placed a high degree of trust in me by providing detailed information about their products and services, which was necessary to conduct the evaluations carried out in this thesis.

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## List of Abbreviations

| | |
|---|---|
| ADLS | Aircraft detection lighting system |
| BNK | Bedarfsgesteuerte Nachtkennzeichnung |
| CBA | Cost benefit analysis |
| CM | Conventional meter |
| DR | Direct response |
| DSM | Demand side management |
| DSO | Distribution system operator |
| GHG | Greenhouse gas |
| GWP | Global warming potential |
| ICT | Information and communication technology |
| iMSys | Intelligent measuring system |
| ISO | International standard organization |
| IT | Information technology |
| LCA | Life cycle assessment |
| LCC | Life cycle costing |
| LCI | Life cycle inventory |
| LCIA | Life cycle impact assessment |
| LCSA | Life cycle sustainability assessment |

| | |
|---|---|
| MCA | Multi-criteria analysis |
| MCDA | Multi-criteria decision analysis |
| MCT | Matrix of convivial technology |
| MECE | Mutually exclusive and collectively exhaustive |
| mMe | Modern measuring equipment |
| NGO | Non-governmental organization |
| SAW | Simple additive weighting |
| S-LCA | Social life cycle assessment |
| SM | Smart meter |
| TA | Technology assessment |
| TSO | Transmission system operator |
| VPP | Virtual power plant |
| WSM | Weighted sum method |
| WT | Wind turbine |

## Summary

Digital technologies have developed exponentially in recent decades. This trend is expected to continue in the foreseeable future, bringing about massive changes in society and the economy. Although in some industries, digital transformation itself is the driver of change, this is not the case in the energy sector. Due to the need for decarbonization, the energy sector is currently undergoing a fundamental transformation from a demand-driven central system mainly based on fossil fuels to a supply-driven decentral system based on renewable energies. Digitalization is not in itself driving this transformation, yet it may be an enabler and accelerator. Digital technologies are expected to play an increasingly important role in the future energy system. How this role will look like depends on both the emerging requirements of the decarbonization transformation as well as the future development of information and communication technologies. Due to the increasingly significant impacts that digital applications cause, a holistic view on these impacts is imperative to avoid adverse effects while maximizing benefits. Such a holistic view must cover the relevant impact areas, include the relevant stakeholders' perspectives, and involve representatives of the relevant stakeholder groups. However, this holistic view of the digital transformation itself or specific digital applications does not, to the best of the author's knowledge, yet exist in the concurrent literature, constituting a content gap. The assessment of available evaluation approaches and methods reveals a corresponding methodological gap.

Therefore, the goal of this dissertation is to develop a framework for the holistic evaluation of digital applications in the energy sector. To achieve this goal, an approach is defined in line with three research questions. First, potential digital applications are categorized, and their characteristics are identified. Second, evaluation requirements are derived. Third, available evaluation approaches and methods are assessed against the requirements, and a potentially suitable combination of three methods is identified. Subsequently, a framework based on these methods is developed. Lastly, the framework is tested by evaluating two digital applications, improved, and its suitability is validated against the defined requirements. Hence, the main novelty of this thesis is the presented framework

comprised of the combination of the three methods, the adaption to digital applications in the energy sector, and the resulting holistic evaluation results.

The results and conclusions obtained in this dissertation consist of three parts. The first part is the overview and categorization of digital applications in the energy sector, including associated benefits and impacted stakeholders. It is concluded that digital applications are very diverse in nature and can be categorized by their area of impact, system balancing, process optimization, and customer orientation. The categorization is relevant as a basis for further research. The second part of the results is the evaluation framework itself. The framework is based on the combination of three well-established methods, multi-criteria analysis (MCA), life cycle assessment (LCA), and expert interviews, and covers technical, ecological, economic, and socio-political aspects. Based on a suitability assessment, it is concluded that the framework is well suited for the holistic evaluation of digital applications in the energy sector and therefore closes the identified methodological gap. The third part consists of the evaluation of two digital applications, namely the “smart meter” roll-out in Germany and a standalone "ADLS” (Aircraft Detection Lighting Systems) for wind turbines prior to its expected roll-out in Germany. Both applications are very relevant and highly discussed in their respective areas. The evaluation delivers aggregated high-level results as well as detailed insights regarding risks and obstacles. These results are of high relevance for the involved stakeholders to find solutions for the identified risks and obstacles, maximize the benefits and ensure a smooth and quick roll-out. The tests constitute not only the first applications of the framework but also the first holistic evaluations of the two evaluated digital applications and hence contribute to closing the identified content gap.

In a future advancement, the methodology of the framework could be extended by applying fuzzy MCA logic and integrating life cycle costing (LCC) as well as social life cycle assessment (SLCA). Prospectively, with an increasing number of performed evaluations, not only the results of specific digital applications can be discussed and compared, but increasingly, the basis for a broader discussion regarding digitalization as a transformative process is created.

# Zusammenfassung

Digitale Technologien haben in den letzten Jahrzehnten eine nahezu exponentielle Entwicklung gezeigt. Es kann davon ausgegangen werden, dass sich dieser Trend in absehbarer Zukunft fortsetzt und zu massiven Veränderungen für Gesellschaft und Wirtschaft führen wird. Während in einigen Branchen die digitale Transformation selbst der Treiber für Veränderungen ist, ist dies im Energiesektor nicht der Fall. Im Energiesektor führt die Notwendigkeit der Dekarbonisierung zu starkem Veränderungsdruck ausgehend von einem nachfrageorientierten zentralen System, das hauptsächlich auf fossilen Brennstoffen basiert, hin zu einem angebotsorientierten dezentralen System, welches auf erneuerbaren Energien basiert. Die Digitalisierung an sich treibt diesen Wandel nicht voran, sie kann ihn jedoch ermöglichen und beschleunigen. Es wird erwartet, dass digitale Technologien eine immer wichtigere Rolle im zukünftigen Energiesystem spielen werden. Wie diese Rolle genau aussehen wird, hängt sowohl von Anforderungen der Dekarbonisierung als auch von den zukünftigen Entwicklungen der Informations- und Kommunikationstechnologien ab. Aufgrund der zunehmend signifikanten Auswirkungen von digitalen Anwendungen ist eine ganzheitliche Betrachtung der Auswirkungen unerlässlich, um negative Effekte zu vermeiden und gleichzeitig den Nutzen der Digitalisierung zu maximieren. Die ganzheitliche Betrachtung muss die relevanten Wirkbereiche abdecken, die Sichtweisen der relevanten Stakeholder berücksichtigen und Vertreter der relevanten Stakeholdergruppen einbeziehen. Eine solche ganzheitliche Betrachtung der digitalen Transformation oder spezifischer digitaler Anwendungen ist jedoch nach Kenntnis des Autors in der einschlägigen Literatur nicht vorhanden. Dies stellt eine inhaltliche Lücke dar. Einhergehend mit der inhaltlichen Lücke besteht eine entsprechende methodische Lücke bezüglich Bewertungsansätzen zur ganzheitlichen Bewertung digitaler Anwendungen.

Ziel dieser Dissertation ist es daher, ein Framework für die ganzheitliche Bewertung von digitalen Anwendungen im Energiesektor zu entwickeln. Um dieses Ziel zu erreichen, wird ein Ansatz definiert, der sich an drei Forschungsfragen orientiert. In einem ersten Schritt werden potenzielle digitale Anwendungen

kategorisiert und ihre Eigenschaften identifiziert. Im zweiten Schritt werden Bewertungsanforderungen abgeleitet. Im dritten Schritt werden verfügbare Bewertungsansätze und -methoden anhand der Anforderungen bewertet und eine potenziell geeignete Kombination von Methoden identifiziert. Anschließend wird ein auf diesen Methoden basierendes Framework entwickelt. Schließlich wird das Framework durch die Bewertung zweier digitaler Anwendungen getestet, verbessert und seine Eignung anhand definierter Kriterien validiert. Der wichtigste Neuheitswert dieser Arbeit liegt somit in der Entwicklung des Frameworks, bestehend aus einer Kombination dreier Methoden, der Anpassung des Frameworks an digitale Anwendungen im Energiesektor und den daraus resultierenden ganzheitlichen Bewertungsergebnissen.

Die Ergebnisse und Schlussfolgerungen in dieser Dissertation bestehen aus drei Teilen. Im ersten Teil wird ein Überblick über das Thema und eine Kategorisierung von digitalen Anwendungen im Energiesektor, einschließlich der damit verbundenen Vorteile und der betroffenen Interessengruppen gegeben. Die Schussfolgerung ist, dass digitale Anwendungen sehr vielfältig sind und sich nach ihrem Wirkbereich, also der Systembilanzierung, der Prozessoptimierung und der Kundenorientierung kategorisieren lassen. Die Kategorisierung der digitalen Anwendungen ist als Grundlage für weitere Forschung relevant. Der zweite Teil der Ergebnisse ist das Bewertungsframework selbst. Dieses basiert auf der Kombination von drei etablierten Methoden, der multikriteriellen Analyse (MCA), der Ökobilanzierung (LCA) und Experteninterviews, und deckt technische, ökologische, ökonomische und gesellschaftspolitische Aspekte ab. Auf der Grundlage einer Eignungsbewertung wird der Schluss gezogen, dass das Framework für die ganzheitliche Bewertung digitaler Anwendungen im Energiesektor gut geeignet ist und somit die identifizierte methodische Lücke schließt. Der dritte Teil besteht aus der Bewertung zweier digitaler Anwendungen, nämlich des aktuellen Smart Meter Roll-outs in Deutschland und eines einzelnen BNK-Systems (Bedarfsgesteuerte Nachtkennzeichnung) für Windkraftanlagen, bevor diese Art System flächendeckend in Deutschland ausgerollt wird. Beide Anwendungen haben eine hohe aktuelle Relevanz und werden in ihren jeweiligen Bereichen stark diskutiert. Die Evaluierung liefert sowohl aggregierte High-Level-

Ergebnisse als auch detaillierte Erkenntnisse über Risiken und Hindernisse. Diese Ergebnisse sind für die beteiligten Akteure von großer Bedeutung, um Lösungen für die identifizierten Risiken und Hindernisse zu finden, den Nutzen zu maximieren und eine reibungslose und schnelle Einführung zu gewährleisten. Bei den Tests handelt es sich nicht nur um die ersten Anwendungen des Frameworks, sondern auch um die ersten ganzheitlichen Bewertungen der beiden evaluierten digitalen Anwendungen. Die beiden Ergebnisse tragen somit zur Schließung der identifizierten inhaltlichen Lücke bei.

In einer zukünftigen Weiterentwicklung könnte die Methodik des Frameworks durch die Anwendung der Fuzzy-MCA-Logik und die Integration der Lebenszykluskostenrechnung (LCC) sowie der sozialen Lebenszyklusanalyse (SLCA) erweitert werden. Perspektivisch können mit einer zunehmenden Anzahl durchgeführter Bewertungen nicht nur die Ergebnisse spezifischer digitaler Anwendungen diskutiert und verglichen werden, sondern es wird zunehmend die Grundlage für eine breitere Diskussion über die Digitalisierung als transformativen Prozess geschaffen.

# 1 Introduction

## 1.1 The role of digitalization in the energy sector

Before looking closer at the role of digitalization in the energy sector, it needs to be defined what digitalization actually is. In the literature, many authors have developed definitions for different terminologies. An increasingly common set of terms is digitization, digitalization, and digital transformation, used by, e.g. (Heymann et al., 2022; Kraus et al., 2021; Mahraz et al., 2019). In the context of this thesis, the set of these three terms is used and extended, as in (Weigel & Görner, 2020), by the term digital applications.

- Digitization describes the process of making something previously analog digital, i.e., converting a paper databank into a digital databank. Digitization may be a first step of digitalization.
- Digitalization means that information and communication technology (ICT) is used to collect, process, analyze, transmit, and in general, make use of digital data.
- Digital transformation is the socio-economic transformation related to the process of digitalization within companies and society. This includes, for example, the creation of digital strategies, the adaptation of new working methods, changes in business models, and, in a broader sense, cultural and societal changes.
- Digital applications are mostly cyber-physical systems based on ICT, which include hard- and/or software. Throughout the thesis, the term "digital application" is used as a synonym of the semantically more precise term "application of digitalization" to improve readability.

Digitalization itself is not new. In fact, it started decades ago with the first commercial applications of computers for business processes in the second half of the last century (Dornberger et al., 2018; International Energy Agency, 2017; Valenduc & Vendramin, 2017). However, due to the historical and continued exponential development of key information and communication technologies (in an adaption of Moore's "law" - (Denning & Lewis, 2017)), the speed and magnitude of changes caused by digitalization have increased significantly. Key improvements regarding the speed and cost of processors, data storage, and data transmission, as well as the physical hardware size, have made new types of digital technology feasible, such as advanced analytics based on big data, mobile computing, cloud computing, internet of things, machine learning and artificial intelligence (Nadkarni & Prügl, 2020). These technologies, in turn, have caused fundamental changes in many areas of the economy and society (Kraus et al., 2021; Nadkarni & Prügl, 2020). Prominent examples are e-mails, e-commerce, and digital photography – today, each day, 207 billion e-mails are sent, 36 million Amazon purchases are conducted, and 3.3 billion digital photos are taken (Lee, 2018; World Bank, 2016).

Unlike other sectors, which have been changed by digitalization itself, the energy sector is currently undergoing a fundamental transformation driven primarily by the need to decarbonize. The transformation from a demand-driven central system mainly based on fossil fuels to a supply-driven decentral system based on volatile renewable energies is depicted in the multi-level perspective (MLP) analysis of the energy system in Figure 1.

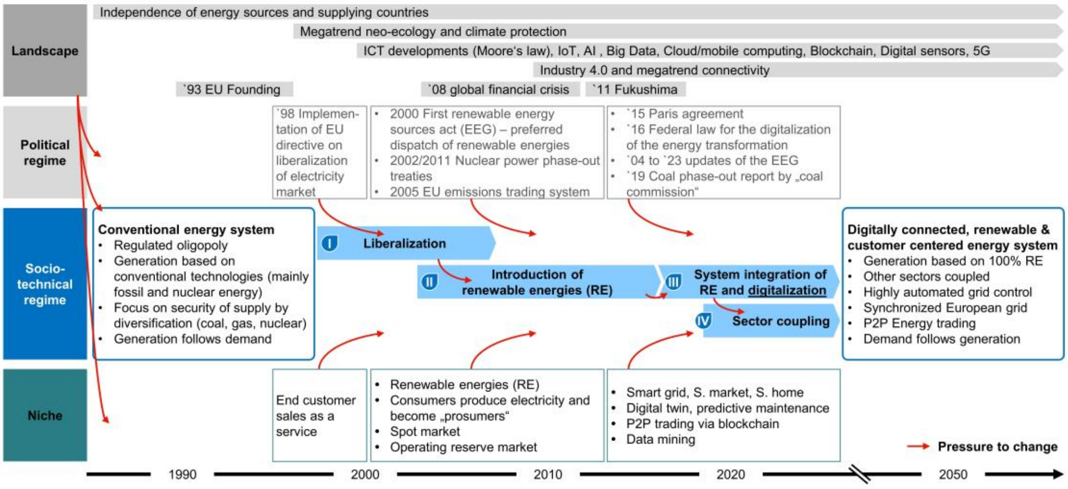


**Figure 1: Multi-level perspective of the energy transformation (source: translated from Weigel & Fischedick, 2018)**

The MLP reveals high-level developments on the "Landscape" level, such as neo-ecology and climate protection, guiding policies such as the "Paris agreement" on the "Political regime" level, and "Niche" developments, such as digital applications, which all contribute to the transformation of the energy system. Therefore, although not driving this change, digitalization can be an enabler and accelerator of this transformation (Veskioja et al., 2022). According to (Singh et al., 2022), digital technologies can play an important role in the future sustainable energy system, which highlights the relevance of the topic. How this role will look like and which digital applications will be implemented mainly depends on the ICT developments (technology push factors) and the requirements and demand arising from the transformation of the energy system (demand pull factors). Figure 2 depicts these push and pull factors as well as additional factors which may influence the course and speed of digitalization.

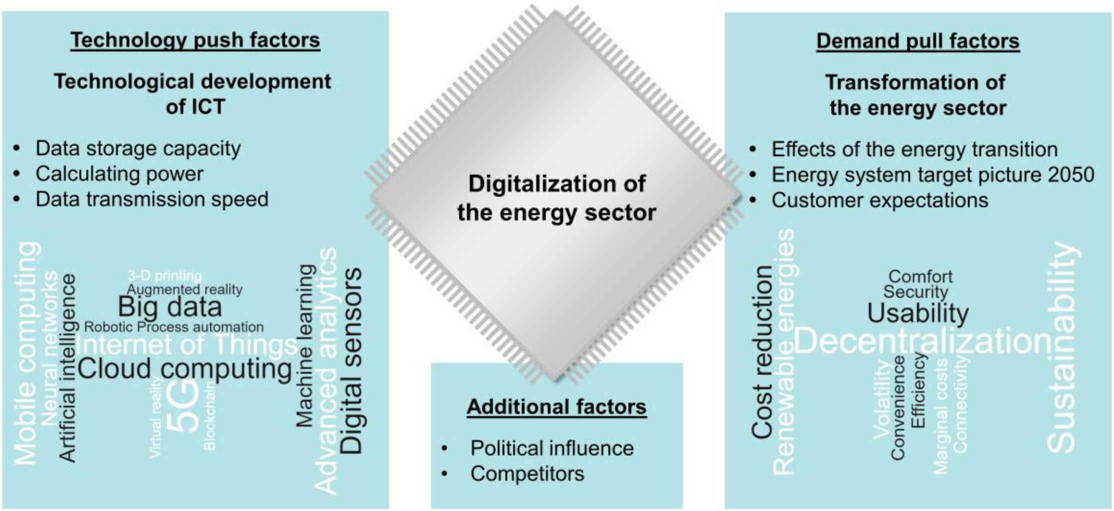


**Figure 2: Drivers of the digitalization of the energy sector (source: adapted from Weigel & Fischedick, 2018)**

Today, the energy sector is already impacted by digitalization to varying degrees. In some parts of the value stream, digitalization has already had a significant impact, e.g., decentral generation and consumption assets can be pooled to virtual power plants (VPP) and jointly offer flexibility and balancing services to the transmission system operator (TSO) while being remotely controlled (Venegas-Zarama et al., 2022). In other areas, digitalization is still in an early implementation stage, e.g., the smart distribution grid (Sai Pandraju et al., 2022) due to a slow smart meter roll-out in Germany (Vitiello et al., 2022). Thus, large future potentials are still untapped, and significant changes can be expected during the next decades.

## 1.2 Digitalization of the energy sector in the concurrent literature

Digitalization and digital transformation are highly discussed topics. Systematic literature reviews (Hanelt et al., 2021; Kraus et al., 2021; Zhu et al., 2021) identify an increasing trend in publications related to digital transformation, and the energy sector is no exception. According to (Heymann et al., 2022), the digitalization of the electricity sector has gained significant momentum. The discourse on digitalization of the energy sector can be clustered into publications that look at the digital transformation as a whole on the one hand and, on the other hand, publications that look at specific aspects, e.g., specific applications, stakeholders, risks, or benefits.

The discourse targeting the transformation as a whole is driven equally by scientific research, which provides overviews of the expected transformation, e.g. (Heymann et al., 2022; Strüker et al., 2021; Wickert et al., 2022) as well as the industry and governmental organizations which provide guidance and prerequisites for a successful digital transformation, e.g. (BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., 2021; German Federal Press Office, 2021; PricewaterhouseCoopers, 2022).

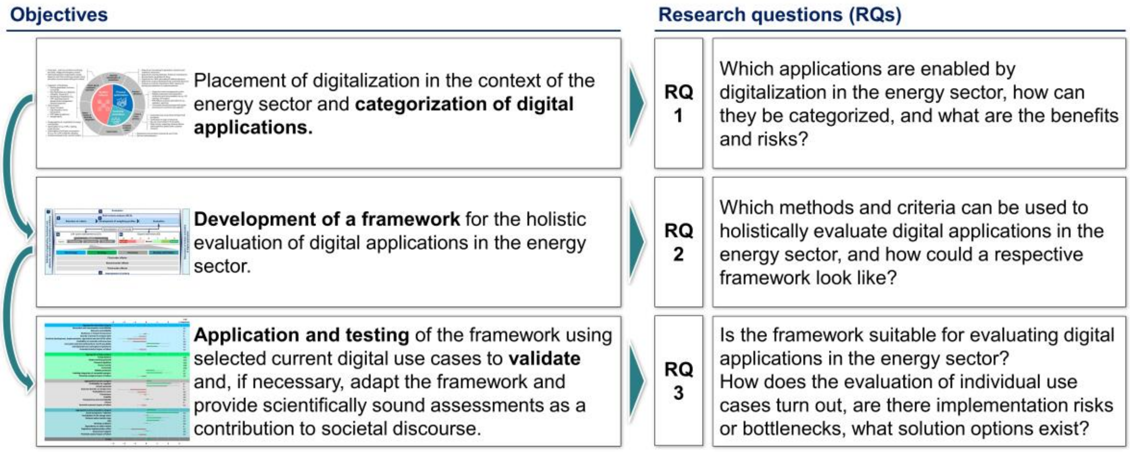
Besides the transformation view, many publications analyze specific facets, such as applications, areas of implementation, digital technologies, and impacts. In (Cali et al., 2021), the digitalization of the power markets is analyzed, and in (Baidya et al., 2021), applications arising from the digital technologies Blockchain and IoT are described. Furthermore, the effects of digitalization on different aspects are assessed, e.g., on sustainability in (Ghobakhloo & Fathi, 2021; Mondejar et al., 2021), on circular economy in (Ramesohl et al., 2022), on the energy transition in (Veskioja et al., 2022), and on energy security in (Thanh et al., 2022). Most of the aforementioned publications include a description of the benefits as the driver for the digital transformation or the specific application. Although some key risks, such as cyber security issues (Ang & Utomo, 2017), the energy demand of ICT hardware (Briglauer & Köppl-Turyna, 2021), and adverse social effects (Grafe, 2021) are discussed, in general, risks and challenges are less commonly and less holistically assessed.

The existing literature covers many relevant aspects of digital applications, yet in a disintegrated manner, without full transparency on benefits as well as risks across all impact areas and all affected stakeholders. Thus, a holistic view on the impacts of digital applications in the energy sector is missing, constituting a content gap. The holistic evaluation of new technologies is essential in order to identify undesired and otherwise unforeseen effects or bottlenecks, find solutions for these issues, and thereby take full advantage of the technology's benefits while avoiding downsides. Due to the fast and accelerating development trend and the potentially far-reaching impacts, the holistic evaluation of digital technologies and their impacts is particularly important.

## 1.3 Objective and research questions of the thesis

To close the identified gap, the goal of this thesis is to develop a framework for the structured and transparent holistic evaluation of digital applications in the energy sector. On the one hand, the results of the holistic evaluations can be part of the basis of a transparent, fact-based discourse between policymakers, businesses, and consumers about general targets and guidelines of digitalization as a transformative process. On the other hand, these results are an important piece of information for companies and organizations in order to develop and sustainably implement digital applications. The intended users of such an evaluation framework are fellow researchers, companies in the energy sector, as well as governmental and non-governmental organizations. Thematically, the focus of this thesis is primarily on the electricity value stream within the energy sector. In specific cases, digital applications may enable sector coupling and hence cause impacts in other sectors, which may need to be considered.

Based on the defined goal, three objectives and resulting research questions are defined, as depicted in Figure 3.



**Objectives**

**Research questions (RQs)**

Placement of digitalization in the context of the energy sector and **categorization of digital applications.**

**RQ 1** Which applications are enabled by digitalization in the energy sector, how can they be categorized, and what are the benefits and risks?

**Development of a framework** for the holistic evaluation of digital applications in the energy sector.

**RQ 2** Which methods and criteria can be used to holistically evaluate digital applications in the energy sector, and how could a respective framework look like?

**Application and testing** of the framework using selected current digital use cases to **validate** and, if necessary, adapt the framework and provide scientifically sound assessments as a contribution to societal discourse.

**RQ 3** Is the framework suitable for evaluating digital applications in the energy sector? How does the evaluation of individual use cases turn out, are there implementation risks or bottlenecks, what solution options exist?

**Figure 3: Objectives and research questions of the thesis (source: own illustration)**

Objective 1: The first objective is to place digitalization in the context of the energy sector and identify and categorize relevant digital applications. The resulting first research question is: Which applications are enabled by digitalization in the energy sector, how can they be categorized, and what are the benefits and risks?

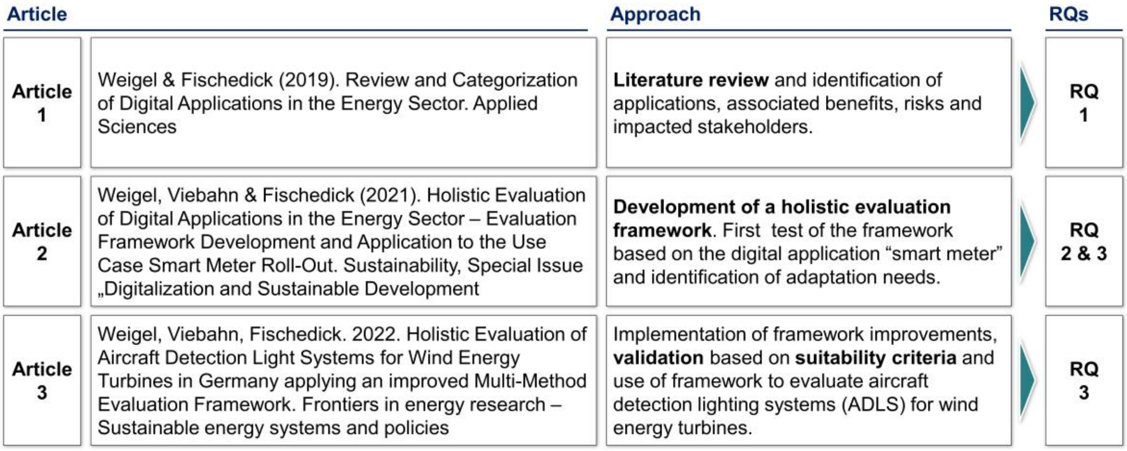
Objective 2: The second objective is the development of a holistic evaluation framework for digital applications in the energy sector while taking into consideration the specific characteristics of the identified digital applications and the state of the art of technology evaluation methodologies. The resulting second research question is: Which methods and criteria can be used to holistically evaluate digital applications in the energy sector, and how could a respective evaluation framework look like?

Objective 3: The third objective is the application and validation of the developed framework based on real digital applications. Based on the insights gathered in the application of the framework, improvements can be identified. The resulting third research question is: Is the framework suitable for evaluating digital applications in the energy sector, and how does the evaluation of individual applications turn out, are there implementation risks or bottlenecks, what solution options exist?

As depicted in Figure 4, these three objectives and the corresponding research question are covered in three peer-reviewed articles:

- Weigel & Fischedick (2019). Review and Categorization of Digital Applications in the Energy Sector.

- Weigel, Fischedick, & Viebahn (2021). Holistic Evaluation of Digital Applications in the Energy Sector – Evaluation Framework Development and Application to the Use Case Smart Meter Roll-Out.
- Weigel, Viebahn, & Fischedick (2022). Holistic evaluation of aircraft detection lighting systems for wind turbines in Germany using a multi-method evaluation framework.



| Article | | Approach | RQs |
|---|---|---|---|
| **Article 1** | Weigel & Fischedick (2019). Review and Categorization of Digital Applications in the Energy Sector. Applied Sciences | **Literature review** and identification of applications, associated benefits, risks and impacted stakeholders. | **RQ 1** |
| **Article 2** | Weigel, Viebahn & Fischedick (2021). Holistic Evaluation of Digital Applications in the Energy Sector – Evaluation Framework Development and Application to the Use Case Smart Meter Roll-Out. Sustainability, Special Issue „Digitalization and Sustainable Development | **Development of a holistic evaluation framework**. First test of the framework based on the digital application "smart meter" and identification of adaptation needs. | **RQ 2 & 3** |
| **Article 3** | Weigel, Viebahn, Fischedick. 2022. Holistic Evaluation of Aircraft Detection Light Systems for Wind Energy Turbines in Germany applying an improved Multi-Method Evaluation Framework. Frontiers in energy research – Sustainable energy systems and policies | Implementation of framework improvements, **validation** based on **suitability criteria** and use of framework to evaluate aircraft detection lighting systems (ADLS) for wind energy turbines. | **RQ 3** |

**Figure 4: Peer-reviewed articles, approaches, and links to research questions (source: own illustration)**

Article 1 answers the first research question. The relevant literature on digitalization and digital applications in the energy sector is reviewed, and applications are identified. The applications are categorized based on their implementation area as well as associated benefits, and impacted stakeholder roles are identified. This article is an introduction to the topic, creates an overview of the content matter, and thereby establishes the basis for the following articles.

Article 2 mainly answers the second research question but also takes up parts of the third question. A holistic evaluation framework for digital applications in the energy sector is developed by identifying, combining, and adapting technology evaluation methodologies taking into consideration the specific characteristics of the digital applications. Subsequently, this framework is used to evaluate the digital application "smart meter" roll-out in Germany. Methodological improvement possibilities are identified.

Article 3 answers the third research question. The framework developed in article 2 is modified and used to evaluate the digital application "ADLS" (aircraft detection lighting system) for wind turbines in Germany. A set of suitability criteria is developed, and the suitability of the framework is assessed and validated against its intended purpose.

The remainder of this thesis is organized as follows: in Section 2, the approach to developing the framework, as well as the framework itself, is described. Subsequently, in Section 3, the results of the three peer-reviewed articles are discussed, and in Section 4, a concise synthesis of the answers to the three research questions is given. Finally, in Sections 5 & 6, conclusions are drawn, and an outlook is given.

Since the central goal of this thesis is the development and application of the evaluation framework, a good understanding of the underlying methods is essential for the understanding of the thesis. Therefore, the framework is described in depth already in the methodology section (Section 2), although it is only developed in the articles 2 and 3 (Section 3).

# 2 Methodology

## 2.1 Approach to the framework development

The main goal of this thesis is to develop a holistic evaluation framework for digital applications in the energy sector. In general, digital applications can be evaluated in a similar way to other technological developments. However, there are some specific characteristics and requirements that need to be considered. Therefore, a three-step approach is applied: (1) Identification of the characteristics of digital applications, (2) Definition of requirements for the holistic evaluation of these digital applications, and (3) Identification of suitable evaluation methods.

### *2.1.1 Identification of the characteristics of digital applications*

First, the characteristics of digital applications are identified in article 2 based on the structured overview of digital applications in article 1. Digital applications are found to have a very fast development speed making it difficult to foresee future developments, obtain reliable evaluation data at an early stage and reach a sound evaluation conclusion within the public discourse in time to actively steer the development. Furthermore, they impact a very broad range of stakeholders and cause very diverse impacts across technical, ecological, economic, and social dimensions.

### *2.1.2 Definition of evaluation requirements*

Secondly, in article 2, a number of requirements for the evaluation method are derived from the characteristics of digital applications and the stated objectives of the framework. The framework needs to be highly adaptable to the variety of different types of digital applications, the varying availability and quality of data, and the practitioners' preferences. Due to the great variety of digital applications, it needs to be easy to adjust the evaluation criteria, either by adding or removing criteria or by changing their weights. The varying availability and quality of data make it necessary that quantitative as well as qualitative, objective as well as subjective, and detailed as well as high-level data can be used. The level of detail of the input data is also influenced by the practitioners' aims, which may range from a high-level quick check to an in-depth analysis. The use of the framework must be feasible in terms of evaluation effort and required expertise. The required effort partly depends on the complexity of the applied methods, which, therefore, should be reasonably low. Other factors which influence the effort can either not be influenced, e.g., availability of data, or directly impact the results, e.g., desired level of detail. Another reason in favor of low complexity methods is that they generally require less expertise of the practitioner, which allows a wider spread usage of the framework. Last but not least, the framework needs to deliver conclusive, i.e., correct and useful results. The methodological setup should foster a holistic (and as realistic as possible) evaluation by covering the relevant impact areas, considering the relevant stakeholders’ perspectives, and involving representatives of the relevant stakeholders. Due to the high impact of the energy sector on the climate and environment, it is of outstanding importance to understand the full environmental and climate impacts of any changes to this system caused by a digital application. To cover all relevant environmental impacts, a life-cycle perspective is necessary. The final result of the evaluation is deemed useful if it allows the derivation of meaningful conclusions and concrete actions.

### *2.1.3 Identification of suitable evaluation methods*

Thirdly, in light of these requirements, the available evaluation methods are reviewed in article 2 in order to identify potentially suitable methods. A variety of different concepts, methods, and frameworks for the evaluation of new technologies exist. Some of the most-used approaches include the technology assessment (TA), the multi-criteria analysis (MCA), the cost benefit analysis (CBA), and the life cycle assessment (LCA). A more recent and still less commonly applied method is the matrix of convivial technology. Furthermore, a variety of business-driven methods for product, service, and business model development exist, including, e.g., living labs and design thinking. The approaches differ greatly regarding their level of theoretical determination, type of evaluation object, input information, and objective. Each approach has a unique set of strengths and weaknesses, which defines the circumstances and cases for which it is used. Combinations of these approaches are commonly applied.

In article 2, the MCA and LCA are found to best match the identified requirements, while the TA and CBA are ruled out. The TA concept is found to be too open, requiring too much methodological knowledge to select an appropriate assessment method, thereby reducing the comparability of results. The CBA, on the other hand, is found to be too limited due to its focus on effects with monetary implications.

The multi-criteria analysis (MCA) is a concept to transparently evaluate alternative options regarding multiple criteria. If the objective is to decide between two options, the concept is referred to as multi-criteria decision making (MCDA). A variety of different methods for assigning criteria weights, criteria evaluation, and result aggregation are established. MCA is particularly applied for complex issues with multiple objectives or stakeholders and if multiple criteria are relevant. The interest in this method has significantly increased in recent years, reflected in the six to seven-fold increase in publications between 2011 and 2022 identified by (Kozłowska, 2022). According to (Basílio et al., 2022), the method is most frequently applied in the area of engineering, computer science, environmental science, and business economics, thus covering a very broad range. Due to the high number of MCA publications, recently, many review studies have been published for MCA approaches in specific areas such as the circular economy (dos Santos Gonçalves & Campos, 2022), energy systems (Bohra & Anvari-Moghaddam, 2022) and sustainability (Lindfors, 2021). The method can also be applied in the field of digitalization, e.g., in (Sung et al., 2022), the authors use a multi-criteria evaluation for the site selection for smart community projects. The MCA is found to be suitable for holistic evaluations since relevant criteria and stakeholders' perspectives can be reflected, and the method offers the required flexibility to evaluate the vast variety of digital applications. However, the approach to assess data and information required for the evaluation is not sufficiently defined to ensure comparability of results, thus, to meet the requirements, the MCA needs to be combined with assessment methods.

The life cycle assessment (LCA) method, as defined in (ISO/TC 207/SC 5, 2006a, 2006b), is designed to identify and quantify impacts along the entire life cycle. The relevant energy and mass flows are identified in the life cycle inventory analysis, and the resulting life cycle impacts are assessed. The final result can be expressed as the total sum of the impacts per analyzed impact category, and high-impact process steps or materials can be identified. While in the classic LCA, mostly environmental impacts are considered, the concept can be extended to social aspects in the social life cycle assessment (S-LCA) and to financial aspects in the life cycle costing (LCC). Together, LCA, S-LCA, and LCC are considered a life cycle sustainability assessment (LCSA). The combination of environmental, social, and economic aspects is sometimes referred to as the triple bottom line of sustainability assessment. A recent example of an LCSA in the energy sector is (Haase, Wulf, Baumann, Rösch, et al., 2022). A growing importance of the life cycle perspective is identified by (Sala et al., 2021) based on the number of legal acts and official communications by the European Union with reference to life cycle results. Similarly (Jordaan et al., 2021) see an increasing trend in the number of life cycle publications in the energy sector and identify a trend towards higher spatiotemporal resolution and accuracy. The LCA, as a stand-alone solution, is found to be too narrowly focused on ecological aspects for the defined requirements. Yet, as an assessment method in combination with the MCA, it is well suited to fulfill the requirement of covering relevant ecological criteria with a life cycle perspective.

A variety of research articles applying an MCA-LCA combination have recently been published for the assessment of, e.g., waste in road asphalt pavements (Russo et al., 2021), technologies and fuels of motorized transport (Haase, Wulf, Baumann, Ersoy, et al., 2022), and circular building design (Rajagopalan et al., 2021). These articles further corroborate the finding made in article 2 that the MCA-LCA combination is commonly applied. This combination already meets several of the requirements identified for the evaluation of digital applications. However, it does not yet allow a holistic evaluation as it lacks the means of assessing non-ecological and qualitative criteria. As discussed in article 2, the MCA is often combined with expert or stakeholder interviews to assess qualitative as well as quantitative data. A recent example is (Masoud et al., 2022). Although these interviews usually do not provide statistically sound results (depending on the number of interviews and the choice of experts), they do provide valuable and well-informed insights. Thus, by adding expert interviews to the MCA-LCA combination, all criteria, qualitative as well as quantitative can be assessed.

The resulting combination of MCA, LCA, and expert interviews fulfills the requirements stated in Section 2.1.2. The approach enables a holistic evaluation by covering the relevant impact areas as criteria with a life cycle view where necessary, considering the relevant stakeholders' perspectives as weighing profiles and involving representatives of the relevant stakeholders in the evaluation process. Furthermore, it offers the flexibility to be adapted to (1) the digital application via the selection of criteria, (2) to the availability of data and the desired level of detail and certainty by choosing the assessment method (LCA or expert interviews) as well as the number of expert interviews and (3) to the perspectives of the practitioners and stakeholders by modifying the criteria weights. The specific combination of these three methods and the adaptions for the evaluation of digital applications in the energy sector constitute the methodological novelty of this thesis. Furthermore, the resulting holistic evaluation results of digital applications are novelties in regard to content.

## 2.2 Methodology of the developed framework

The combination of MCA, LCA, and expert interviews is found to best meet the requirements and is therefore used for the evaluation framework. Figure 5 illustrates how the methods are intertwined in the framework. The MCA is used as the overarching evaluation structure, while the actual assessment of applications is performed within the LCA and the expert interviews.

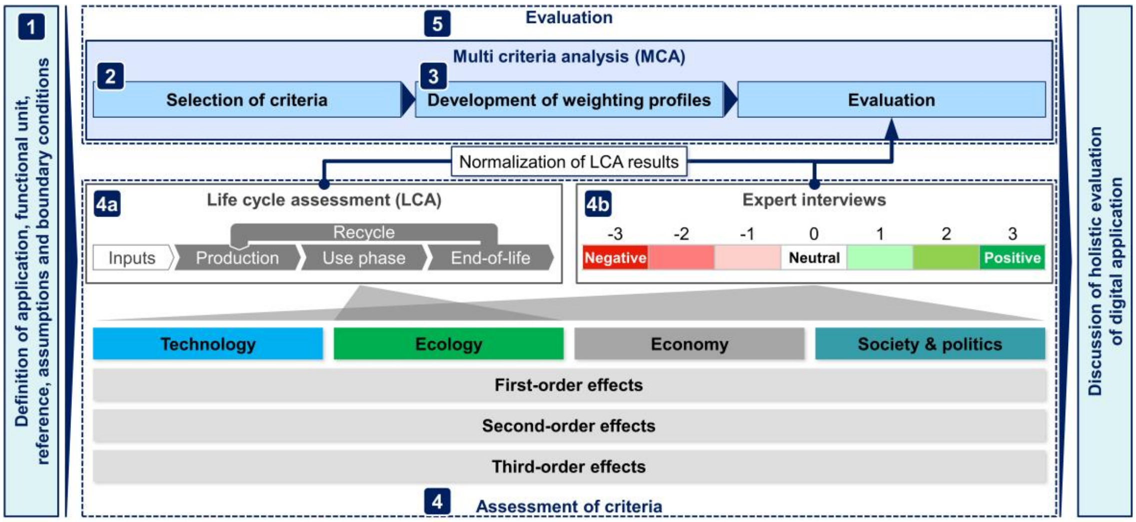


**Figure 5: Schematic overview of the developed evaluation framework and its five assessment steps (source: article 3)**

The developed approach consists of five steps, also numbered in Figure 5. The following description is based on article 3, where an updated version of the initial framework developed in article 2 is used. The five steps are:

1) Definition of application, functional unit, reference, assumptions, and boundary conditions
2) Selection of criteria
3) Development of weighting profiles
4) Assessment of the criteria
    a) Environmental criteria based on LCA
    b) All other criteria based on expert interviews
5) Evaluation of digital application based on criteria assessments and weighting profiles within MCA

The methodological background and the practical application of each step are laid out in the following Subsections 2.2.1 - 2.2.4.

### *2.2.1 Step 1: Definition of application, functional unit, reference, assumptions, and boundary conditions*

The first step is the definition of the application under investigation, the functional unit, the reference for the evaluation, and key assumptions. This step ensures consistency of the frame conditions of the evaluation throughout the entire process and among different involved practitioners. The consistency of the frame conditions is important to avoid quality issues and inefficiencies in the assessment and evaluation process. Although a general definition of digital applications is given in the context of the developed framework, this step needs to be carried out by the practitioner for each specific evaluation.

### *2.2.2 Step 2: Selection of criteria*

The selection of criteria is of particular importance, as it defines the range of effects considered in the analysis. The criteria need to be MECE (Mutually Exclusive and Collectively Exhaustive: No overlap/duplication, fully comprehensive) as well as relevant for the evaluated digital application.

The selection of evaluation criteria, originally described in article 2, is based on three steps. In the first step, a long list of criteria is gathered based on existing literature in the field of evaluations of energy-related topics. The resulting long list of criteria is subsequently extended and structured based on the author's own professional experience of several years in the energy industry and with digitalization endeavors. Lastly, the criteria are refined and validated in expert interviews. Several interviews are conducted with a variety of experts, including an IT security expert, several energy sector experts with a research and business background, a consumer protection representative, and a scientist with expertise in environmental and holistic evaluations. After the first test of the framework in article 2, the original list of criteria is modified to reduce the complexity and eliminate overlaps, as described in article 3. In particular, the number of responses per criterion, the weighting of each criterion, as well as direct expert feedback from the first test are evaluated to identify required adaptations. Based on the findings, the total number of criteria is reduced, and the structure is set to only two levels, categories and criteria. The final list of criteria is shown in Table 1.

**Table 1: List of criteria for the developed framework (source: article 3)**

| Technology | Ecology | Economy | Society & politics |
|---|---|---|---|
| Generation & consumption controllability | Cumulative energy demand | Profitability for suppliers | Social acceptance/ rejection |
| Network controllability | Global warming potential | Growth potential | Participation in the energy sector |
| Resilience of critical infrastructure | Adiabatic resource depletion | Economic barriers to market entry | National value creation steps |
| Security of private & company data | Human toxicity | Profitability for users | Jobs |
| Technical development, implementation, operation, and end-of-life effort | Ecotoxicity | Convenience | Working conditions |
| Availability of materials, capacities, and know-how | Wildlife protection | Usability | Dependence on other nations |
| Innovation potential with /without retrofit option | Enabling integration of renewable energies | Transparency and controllability | Regulatory implementation effort |
| Interdependencies (synergies/competitions) | | Privacy | Government support |
| Potential technical impact of failure | Potential ecological impact of failure | Potential economic impact of failure | Potential societal impact of failure |

However, for each evaluation, the practitioner needs to check the list of criteria in light of the specific characteristics of the application under investigation and, if necessary, integrate new or eliminate existing criteria. This step can be moved up and down in the sequence of steps within limits as long as it is performed after the definition of the application (step 1) and prior to the assessment (step 4).

### *2.2.3 Step 3: Development of weighting profiles*

The weighting of the criteria is necessary to reflect differences in the importance of different criteria. Weighting becomes especially important when the evaluation includes the perspectives of different stakeholders. Either one weighting profile, which covers all stakeholders' perspectives, can be defined, or the stakeholders' different views can be represented in different weighting profiles.

In step 3, these weighting profiles are defined. Similarly to the definition of the criteria, a set of standard weighting profiles for common stakeholders are defined during the development and testing of the framework. In Figure 6, a category-level overview of weighting profiles is provided, and Table 2 in the annex shows a criteria-level example. However, more case-specific adaptations are likely to be required, as different applications may involve different stakeholder roles. The practitioner may decide to simply tweak the existing weighting profiles or develop partly or completely new profiles. If new profiles are to be developed, the approach described in article 3 should be applied.

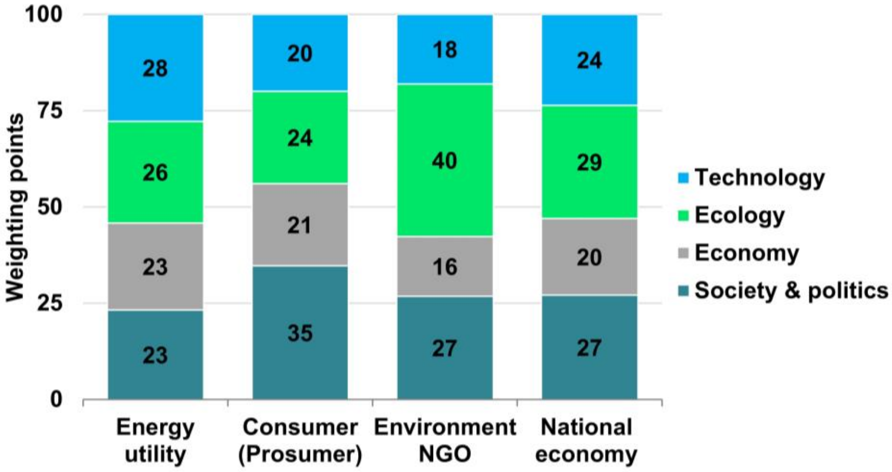


**Figure 6: Weighting profiles derived from weightings developed in articles 2 and 3 (source: adapted from articles 2 and 3)**

Weightings may be determined in specific weighting interviews with relevant stakeholders or as part of the expert interviews in step 4b. If the expert interviews are used, the weighting should be carried out independently by the experts after the actual interview as described in article 3, diverging from the initial approach in article 2. This order meets the experts’ expectations to talk directly about the application itself, shortens the interview, and reduces the interviewer’s influence on the weighting. However, most experts require a good explanation of how to perform the weighting on their own, and not all experts provide (useful) weighting results.

Point allocation, a direct, subjective, and non-compensatory rating method, is applied using 100 allocation points. The 100 points represent 100% importance, a concept that is intuitively understood by stakeholders and experts. The stakeholders or experts selected to perform the weighting are asked to allocate the points sequentially, first on the category level and then on the criteria level. Once all points are allocated, in order to increase the weight of one criterion, the point allocator needs to reduce the weight of another criterion. This forces the point allocator to thoroughly question previously determined weights. After the allocation of all points, a sense check is encouraged by comparing selected pairs of criteria in an iterative process to ensure that both the weighting order and the weighting distances between them reflect the allocator's preference. This sense check is necessary due to the large number of criteria and resembles an update implemented after the initial test in article 2. As the approach starts with weighting the category level, the number of criteria within each category does not influence the overall weight of the category.

### *2.2.4 Step 4: Assessment of the criteria*

Most ecological criteria are assessed by performing an LCA to ensure all life cycle effects are covered. All other criteria are assessed by conducting expert interviews with relevant stakeholder representatives to capture quantitative as well as qualitative information. The practitioner can influence the required assessment effort and the level of robustness by determining the level of detail of the LCA and the number of experts to be interviewed.

#### *2.2.4.1 Assessment of environmental criteria based on LCA*

The LCA approach (step 4a) is based on the standard defined in (ISO/TC 207/SC 5, 2006), including the following steps.

a) Goal and scope definition
b) Inventory analysis
c) Impact assessment
d) Interpretation of the result

The definition of the goal, scope, and functional unit in step a) is already performed in step 1 of the presented framework. Steps b) and c) follow the general LCA approach. In step b) the relevant energy and mass flows are identified and quantified, and a model of the application under investigation is created. In step c) the impacts resulting from the identified energy and mass flows are assessed. Out of the variety of environmental impacts, the ones matching the ecological criteria of the criteria list (Table 1) are selected. Step d), the interpretation of results includes a normalization to the MCA evaluation scale and is subsequently performed within step 5 of the overall framework.

The LCA performed in the context of articles 2 and 3 is carried out using the software openLCA (v1.10.1), the ecoinvent (v3.3) database, and the CML2001, as well as the cumulative energy demand impact calculation methods.

#### *2.2.4.2 Assessment of all other criteria based on expert interviews*

The expert interviews conducted in step 4b are semi-standardized, which ensures comparable results across different expert interviews while providing the flexibility to capture additional detailed information. The list of criteria is used as the interview structure. To minimize the interviewer's influence on the outcome, an approach of minimal interventions is used, meaning that after an initial introduction and explanation, no input from the interviewer is given throughout the central part of the interview as long as the interviewee does not raise any questions or the interviewer identifies any misunderstandings. The interviews can include quantifiable and non-quantifiable first-, second-, and third-order effects. Thus, all criteria can be assessed. The required number of interviews depends on the number of involved stakeholder roles as well as the practitioner's preference regarding the effort-result robustness compromise.

### *2.2.5 Step 5: Evaluation of digital application based on criteria assessments and weighting profiles within the MCA*

In step 5, the results per criterion from the LCA and expert interviews are integrated into the MCA and aggregated based on the weighting profiles. A direct ordinal rating scale, depicted in Figure 7, ranging from -3 (strongly negative impact) via 0 (no/neutral impact) to +3 (strongly positive impact), is used. The scale is intuitive for experts, and the evaluation can be broken down into two questions: 1. Is the impact positive, negative, or neutral (+ or – range)?; 2. How positive or negative is the impact (±1,2, or 3)?

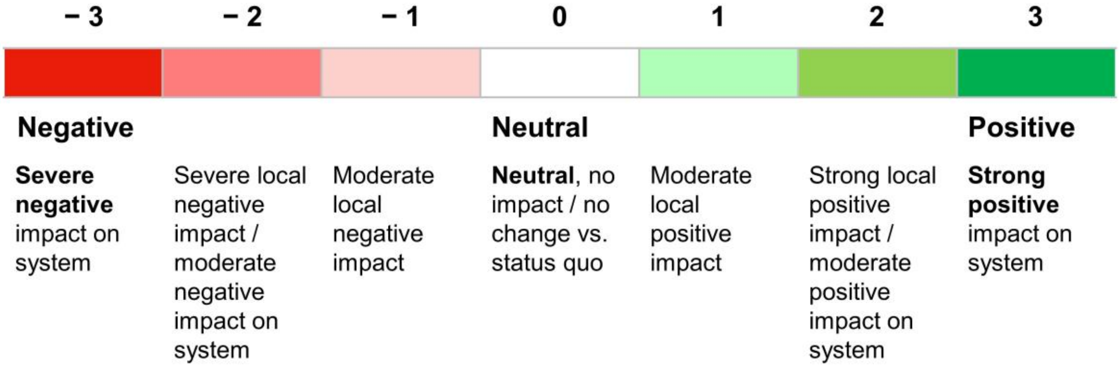


**Figure 7: MCA evaluation scale of the developed framework (source: article 2)**

In the following paragraphs, the calculation of the evaluation result, partly mentioned in articles 2 and 3, is described in a stringent manner. For each criterion, a result $E_i$ is calculated, with $i \in \{1, \dots, n\}$ and $n$ being the number of criteria. For criteria evaluated by experts, $E_i$ for a specific criterion is calculated as the arithmetic mean $\overline{e_\iota}$ of the expert evaluations $e_{i_j}$, with $j \in \{1, \dots, m_i\}$. Here, $m_i$ is the number of evaluations received for the specific criterion. $\overline{e_\iota}$ is defined as

$$E_i = \overline{e_\iota} = \frac{\sum_{j=1}^{m_i} e_{j_i}}{m_i}. \tag{1}$$

While in the expert interviews, all criteria are already evaluated in the MCA evaluation scale, the LCA results need to be normalized by comparison with a reference value. This reference value is a quantification of the reference defined in step 1. The selection of the reference may have a significant influence on how the LCA results affect the MCA. External references (e.g., external targets or system parameters) generally offer more objectivity than internal references (e.g., a specific calculated scenario) but may not always be available. Whether an external or internal reference is used, the evaluation $E_i$ can be calculated by

$$E_i = \frac{I_{LCA_i}}{I_{Ref_i}} \times E_{max} \tag{2}$$

based on the ratio of the impact identified in the LCA $I_{LCA_i}$ and the reference impact $I_{Ref_i}$ and the maximum evaluation $E_{max}$, i.e., -3 or +3. If $I_{Ref_i}$ is an increased impact $E_{max}$ is -3 and vice versa if the reference is a decreased impact.

Subsequently, all assessment results per criterion can be aggregated to the category as well as to a total level. The simple additive weighting (SAW) method, also known as the weighted sum method (WSM), is used, meaning that the aggregated result is calculated in a compensatory manner as the weighted sum of the criteria results by

$$\bar{E} = \frac{\sum_{i=1}^{n} w_i E_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

with $\bar{E}$ being the arithmetic mean calculated based on each criterion's evaluation $E_i$ and the criterion's weight $w_i$. For the calculation of the total result, the sum of the weights $\sum_{i=1}^{n} w_i$ equals 100 if all criteria are evaluated. For the calculation of the category results, only the weights connected to the criteria of the specific category are summed up. The SAW method is simple in its application and provides a high-level of transparency on how results are aggregated.

Last but not least, the results need to be discussed in the context of the accuracy and robustness of the underlying data. While most of the influencing factors can only be discussed qualitatively, an indication of the robustness of the expert interview data can be obtained based on the standard deviation in combination with the number of received evaluations. This quantitative robustness indication is an improvement implemented in article 3. For each criterion, the standard deviation $s_i$ can be calculated by

$$s_i = \sqrt{\frac{\sum_{j=1}^{m_i} \left[e_{i_j} - \bar{e_i}\right]^2}{m_i - 1}} \tag{4}$$

with $m_i$, $e_{i_j}$, and $\bar{e_i}$ as defined in Equation (1). The combination of standard deviation and number of received evaluations is used instead of the margin of error and confidence intervals because normal distribution cannot be assumed for expert interviews, which are conducted in small numbers.

### 2.3 Suitability assessment of the developed framework

Based on the performed evaluations using the developed framework, its suitability is assessed as described in article 3. Three factors are evaluated:

- the conclusiveness of results,
- the feasibility of use, and
- the adaptability of the framework.

The conclusiveness of the results includes both correctness and potential for deriving action. Feasibility of use is based on the effort required for each evaluation as well as the inherent complexity and, thus, the level of expertise required by the practitioner. Adaptability of the framework is required regarding different types of digital applications, the level of data availability, and practitioners' preferences. These suitability criteria are specific to the evaluation of this framework and can only be evaluated qualitatively. The suitability itself depends on how well the requirements defined in Section 2.1.2 are met, in particular, the requirements which enable the holistic nature of the evaluation. Therefore, these are considered essential, i.e., “must-haves”. They include the incorporation of quantitative and qualitative criteria covering the relevant impact areas, the representation of stakeholder perspectives via criteria weights, and the involvement of stakeholder representatives in the evaluation. With regard to all other requirements, the better these are fulfilled, the higher the suitability of the approach is.

# 3 Results and discussion of research articles

In this section, a summary of each peer-reviewed article is provided. If new relevant publications are identified in the field of the articles after their publication date, the findings of these publications are discussed in the context of the respective article.

### 3.1 Article 1: Review and Categorization of Digital Applications in the Energy Sector

#### *3.1.1 Introduction & approach*

As an introduction to the general subject area of digital applications in the energy sector, article 1 (Weigel & Fischedick, 2019) provides a structured overview of digital applications in the German energy (electricity) sector, including the associated benefits and the impacted stakeholders. A literature review based on ten publications is performed. The ten publications all take a broad view on digitalization of the energy sector, including all primary value chain steps. The novelty of the article is given by the exhaustiveness of the digital applications as well as the categorization structure.

### *3.1.2 Results & discussions*

Three impact areas and seven subcategories, each containing numerous individual digital applications, are identified and depicted in Figure 8.

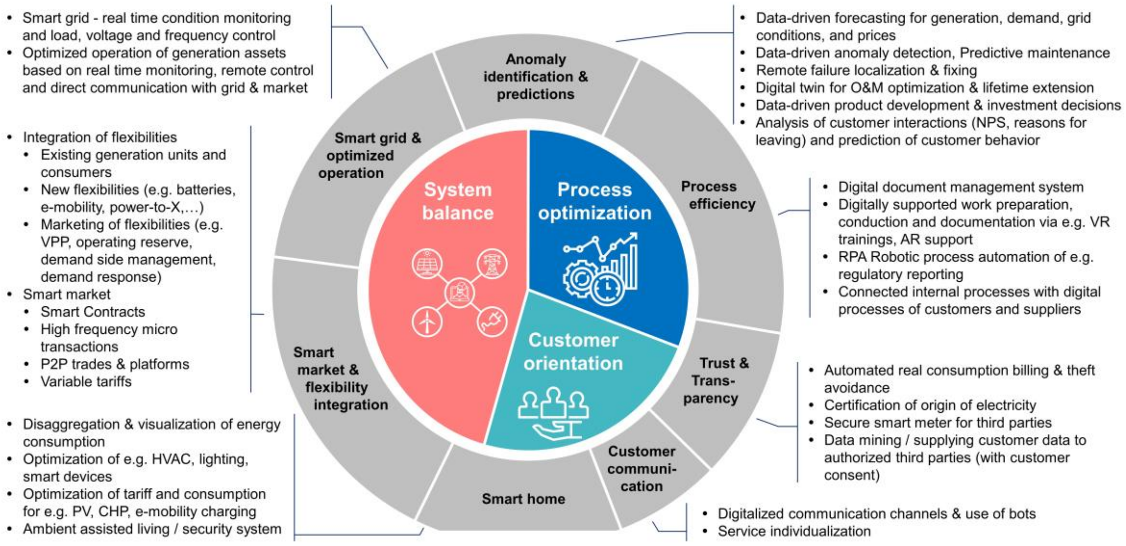


**Figure 8: Categorized digital applications in the energy sector (source: adapted from article 1)**

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.

All analyzed stakeholder roles of the energy value chain, plus the environment, society, and the national economy, are impacted by digital applications. The main impacted stakeholder role identified is the grid, i.e., grid operators. 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. Furthermore, 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 stakeholder roles are (descending order): generation, sales, environment, market, and the society/national economy.

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 costs. 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 on 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 an increase in revenues due to new business models, products, and services and a reduction of energy demand due to energy-efficiency applications, as well as reduced losses.

Within the analyzed literature, risks are not commonly discussed, and if so, the focus is usually on a specific risk (e.g., cyber security) rather than a broad view. The lack of a broad inclusion of possible risks corroborates the identified gap of a missing holistic view on digital applications.

### *3.1.3 Discussion update, based on information published post-submission of the article*

In order to further validate the findings and extend the insights to risks resulting from digitalization, bottlenecks to the implementation of digitalization, and required digital technologies, a survey is conducted among energy utilities in cooperation with *vgbe energy e.V.* (Weigel & Görner, 2020). The survey shows that energy utilities generally work on all of the digital applications identified in article 1 and therefore validates the identification of these applications. In some cases, the topics highly discussed in the literature are the ones for which companies have already achieved a high implementation status. This is the case for condition monitoring, remote control, and optimized operation. In other cases, the relative number of references found in the literature does not coincide with the implementation degree found in the survey. The integration of flexibilities and the use of advanced analytics for predictive maintenance and digital twins are frequently mentioned in the publications but reveal a relatively low implementation level in the survey. This may be due to missing regulatory frameworks or lacking capabilities. Interestingly there are also cases of digital applications, which are rarely discussed in the literature but are highly implemented in the sector, e.g., applications for process efficiency, such as digital document management and automated reporting. The reason for the "under-reporting" of these applications in the analyzed literature might be that they are mostly not specific to the energy sector and hence might not be the focus of the energy-specific digitalization literature. However, both the analyzed literature as well as the survey participants see cost reduction as the main benefit of digitalization in the energy sector. Besides validating the literature analysis results with practical insights from affected companies, the survey adds additional insights into risks, obstacles, and digital technologies. Regarding risks and obstacles, the survey reveals IT security issues as the biggest risk of digitalization and a lack of qualified employees as the biggest obstacle to its implementation. The most relevant digital technologies are found to be Big Data / Advanced Analytics, Internet of Things (IoT), and Mobile Computing.

Since the publication of article 1 in 2019, several new overviews of digital applications in the energy sector have been published. In (Światowiec-Szczepańska & Stępień, 2022), the authors closely follow the structure developed in article 1 and add managerial implications. The digital applications relevant to energy efficiency identified by (Verma et al., 2020) are very similar to the ones of the subcategories "Smart grid & optimized operation", "Smart market & flexibility integration", and "Smart home" of article 1. This corroborates the finding that applications of these three subcategories decrease energy demand. The authors also add further applications in the upstream energy business, such as identifying the best location for renewable energies or coal mining based on the analysis of satellite data. In (Antretter et al., 2022), the Energy Transition Expertise Centre (EnTEC) identified digital applications relevant to the flexibilization of the energy sector, which coincide well with the applications identified in the subcategories "Smart grid & optimized operation" and "Smart market & flexibility integration". The authors further identify which kind of flexibility service the applications can provide and quantify the expected capacity across the European Union. Lastly, the digital transformation working group of the institute for ecological economy research published a working paper (Gährs et al., 2022) about the sustainable digitalization of a decentralized energy transformation in which they categorized digital applications based on the underlying technology, yet the identified applications coincide well with the applications found in article 1. The authors additionally mention the use of drones for remote inspection and crowdfunding of renewable energy projects. Overall, these publications corroborate and extend the findings of article 1.

Furthermore, it is found that the applications identified and the structure developed in article 1 have already been used by other authors as a basis for their research, i.e., by (Kaštelan et al., 2022; Światowiec-Szczepańska & Stępień, 2022; Viet & Kravets, 2022). This highlights the scientific relevance of article 1.

## 3.2 Article 2: Holistic Evaluation of Digital Applications in the Energy Sector—Evaluation Framework Development and Application to the Use Case Smart Meter Roll-Out

### *3.2.1 Introduction & approach*

Based on the insights on digital applications in the energy sector gained in article 1, a framework for the holistic evaluation of these applications is developed and tested for the first time in article 2 (Weigel, Fischedick, & Viebahn, 2021). The framework's methodology is described in detail in Section 2.2. It consists of a combination of well-established methods, namely the multi-criteria analysis (MCA), the life cycle assessment (LCA), and expert interviews. As a first test of the framework, it is applied to evaluate the German smart meter roll-out. This application is chosen due to its high relevance for the overall digitalization of the electricity grid and an identified gap in holistic evaluation results. The obtained result is the first holistic evaluation of the smart meter roll-out in Germany. The term smart meter roll-out comprises the roll-out of intelligent measuring systems (iMSys) and modern measuring equipment (mMe) as defined in the German federal law for "digitalization of the energy transition" BGBl. I 2016 S. 2034 §29. Main assumptions such as the total number of iMSys (16.2 million) and mMe (35.4 million) and the estimated energy and grid reinforcement savings are based on (Ernst & Young, 2013). The LCA is conducted using information about the technical setup and specifications supplied by a smart meter manufacturer. Besides the LCA, seven interviews are conducted with experts, including two representatives of regional energy utilities, one representative of an energy distribution network company, one management consultancy executive, one representative of an environmental NGO, one member of the energy department of the German consumer protection organization and one representative of the German Trade Union Confederation.

### *3.2.2 Results & discussions*

Although the LCA results are part of the subsequently discussed MCA result, they are also discussed separately because detailed insights about life cycle impacts can be drawn. Figure 9 (a) shows a direct comparison of using smart meters vs. conventional meters on the global warming potential (GWP).

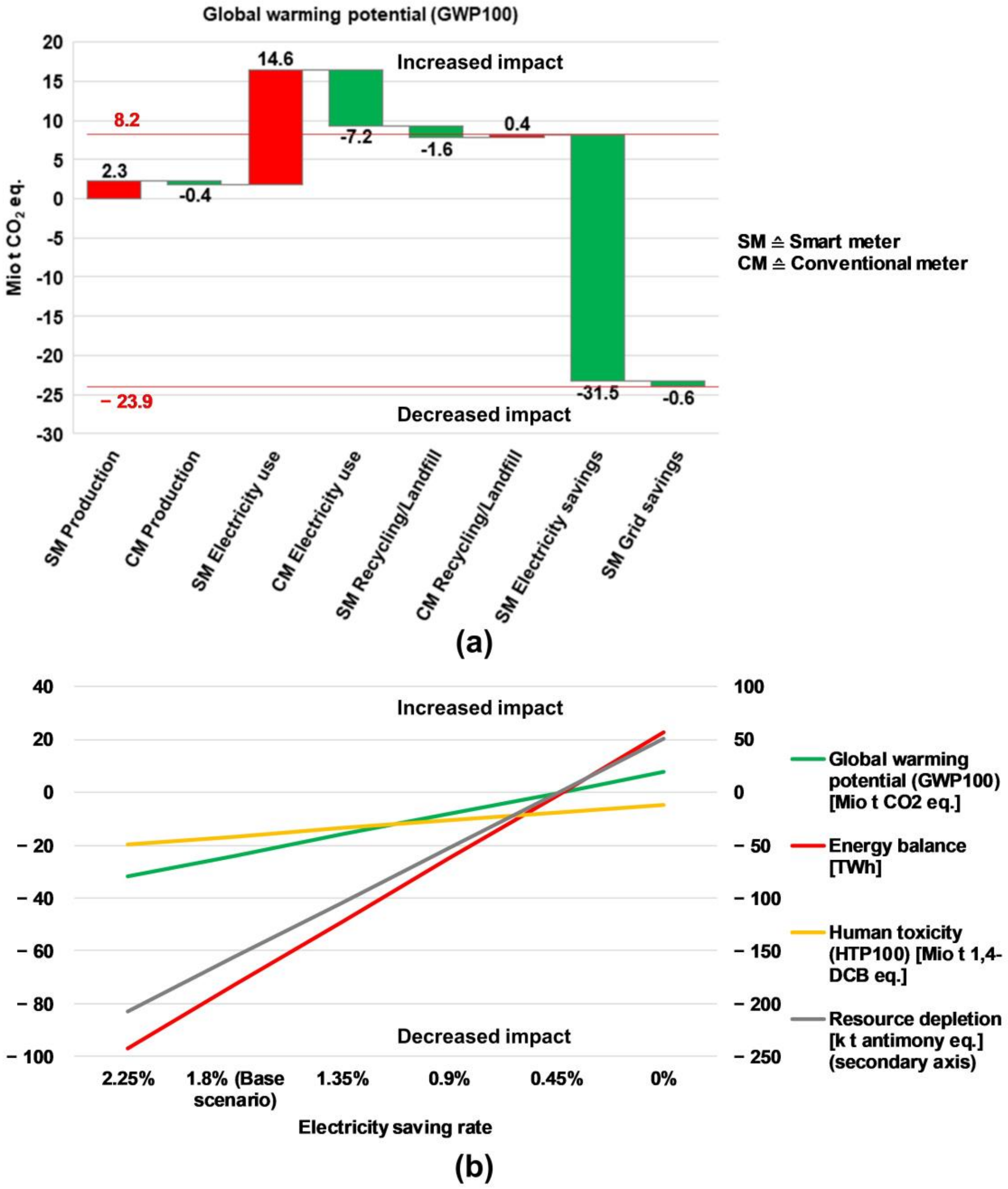


**Figure 9: Life cycle impact of the German smart meter roll-out over 20 years. (a) GWP100 for base scenario (1.8% electricity savings); (b) all assessed impact criteria across different electricity savings (source: article 2)**

It is revealed that, including the expected electricity and grid reinforcement savings, the total GWP impact is reduced (by 23.9 Mio t $CO_2$ eq., see lower red line in Figure 9) due to the smart meter roll-out over 20 years. However, without the expected savings, the smart meter as an electronic device would cause a higher GWP impact (of 8.2 Mio t $CO_2$ eq., see higher red line in Figure 9), mainly due to the high consumption of electricity during the use phase. As the electricity saving is identified as the main impact factor in Figure 9 (a), the sensitivity of the result to changes in the electricity savings is assessed in Figure 9 (b). It is found that in case the smart meter roll-out results in a saving of the users' electricity demand of > 0.43%, the overall environmental impact, including, e.g., the global warming potential (GWP), would be reduced. Therefore, the electricity saving potential should be validated practically in the future, e.g., in pilot projects or by monitoring specific households during the roll-out.

The MCA results include the normalized LCA as well as expert interviews. In Figure 10, the results per criterion are depicted.

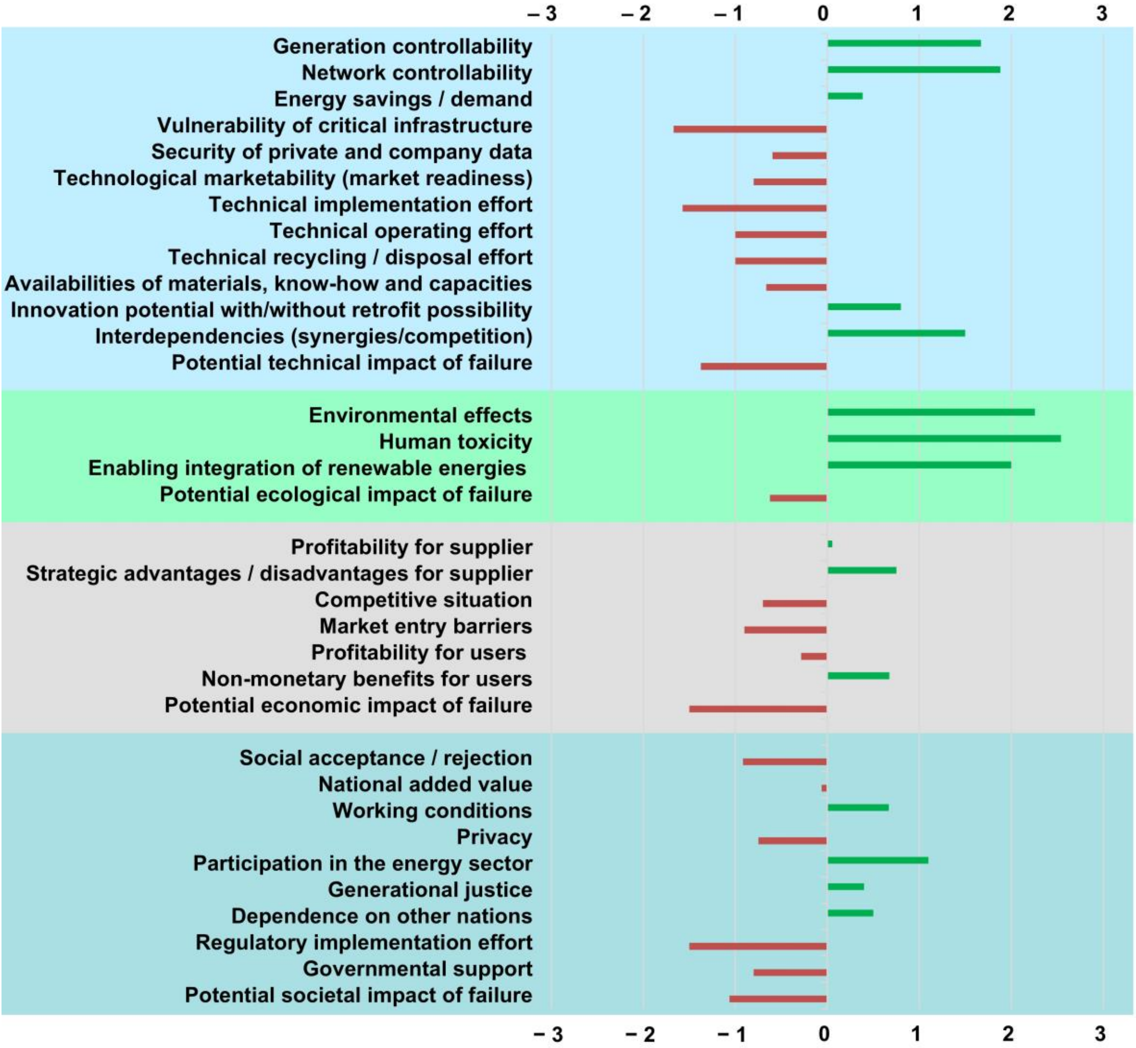


**Figure 10: Smart meter roll-out MCA result on criteria level (source: adapted from article 2)**

On the one hand, the core reasons for the smart meter roll-out, generation/grid controllability, and further integration of renewable energies, are all evaluated very positively. On the other hand, negative evaluations in the area of implementation and operational effort, IT and data security, social acceptance, and added value for the user cause a negative result for the categories Technology, Economy, as well as Society & politics. By finding solutions to these negatively evaluated aspects, the total evaluation result can be improved. This approach ensures that benefits can be fully realized while downsides are minimized.

The criteria level results can be aggregated to category and total levels using the weighting profiles to reflect the perspectives of different stakeholders, as shown in Figure 11. A slightly positive overall evaluation result for all stakeholder perspectives is revealed. This indicates that for all involved stakeholders, the benefits outweigh the negative effects. However, from the energy utilities' perspective (i.e., the stakeholder who implements the deceives), the result is almost neutral, indicating a likely lack of intrinsic motivation to actively drive the roll-out. Energy utilities give more importance, i.e., higher weight, to the negatively evaluated technical and regulatory implementation effort as well as to the social acceptance. Solutions to either decrease the implementation effort or increase the social acceptance are required to improve the result from the energy utilities' perspective. On the other side of the spectrum, the result is the most positive from the perspective of environmental NGOs, mainly driven by the very positively evaluated ecological criteria, which are given higher weights by environmental NGOs.

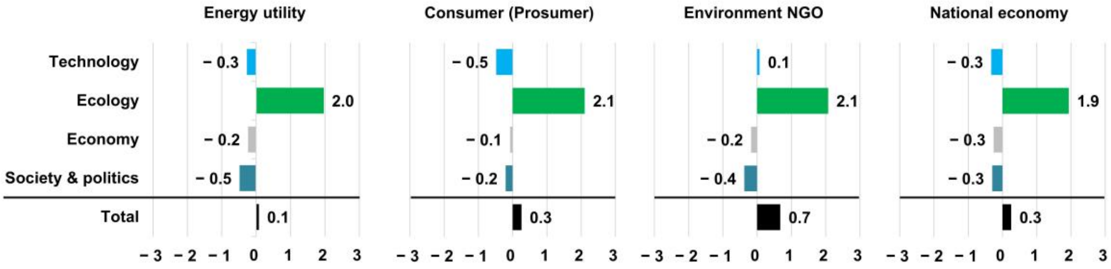


**Figure 11: Smart meter MCA results on category level for different weighing profiles (source: article 2)**

The first test of the framework results in a largely consistent evaluation of the smart-meter roll-out, in line with the relevant existing studies on smart meters for most aspects. Therefore, the overall goal of the developed framework is met, and it is concluded that the framework is suitable for evaluating this digital application. Nevertheless, further improvement potentials are identified in three areas:

1. The list of criteria should be modified. The total number of criteria should be reduced to reduce the complexity, overlaps should be eliminated to reduce double counting, and criteria hierarchy levels should be made more consistent.
2. The weighting process within the expert interviews should be modified. Standard pairs of criteria should be defined for direct comparison to support leveling of criteria weights between categories.
3. The data and evaluation robustness should be indicated, where possible quantitatively, otherwise qualitatively.

These improvements are implemented in the framework and tested in article 3 in Section 3.3.

### *3.2.3 Discussion update, based on information published post-submission of the article*

Since the publication of article 2, new articles on the evaluation of smart meters have been published. In (Wohlschlager et al., 2021), the authors present an LCA on the smart meter roll-out in Germany. The results corroborate the finding that the gateway has a greater global warming potential (GWP) impact than the modern measuring equipment and that end-of-life processes have a very small overall impact. Furthermore, it is shown that the impact on data transmission is negligible, confirming the validity of the assumption made in article 2 to not include it. While in article 2, a minimum energy saving of 0.43% is identified as required for GWP break-even, in (Wohlschlager et al., 2021), the break-even point is found to be at 2,7%. Considering that the study, unlike article 2, includes neither the reduction of grid reinforcements nor the avoided conventional meter production and operation and furthermore assumes a shorter meter lifetime as well as higher energy consumption, the higher identified required savings can plausibly be explained. Similarly, in (Gährs et al., 2021), the authors identify the operation as the biggest driver for GWP impact and a net GWP reduction for the base case of 1.2% electricity savings. These findings, on the one hand, reveal the sensitivity of the LCA to assumptions made by the practitioner, yet they do corroborate the general direction of the LCA results of article 2. To the best of the author’s knowledge, no new, broader, or even holistic evaluations of the smart meter roll-out, particularly for Germany, are available.

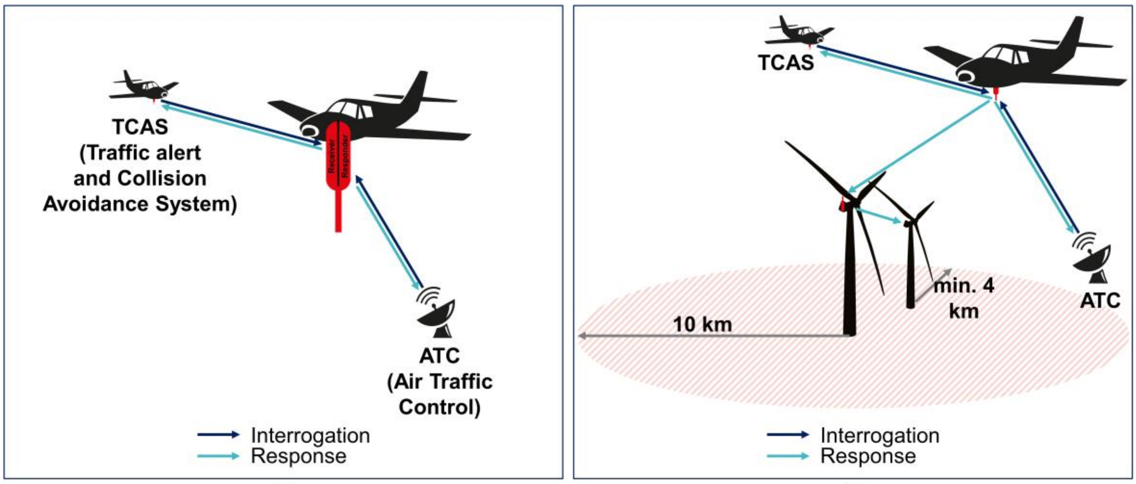
Although, at the time of publication of article 2, the smart meter roll-out was already underway, the achieved knowledge of risks and downsides can be used to improve these aspects and speed up the roll-out process. Besides that, the results, as well as the method, provide a basis for research and public discourse beyond Germany, illustrated by the referencing of the article in the policy brief (Tuominen-Thuesen et al., 2022) in the context of a project to assess environmental impacts caused by digitalization in the public sector services in Finland.

## 3.3 Article 3: Holistic evaluation of aircraft detection lighting systems for wind turbines in Germany using a multi-method evaluation framework

### *3.3.1 Introduction & approach*

In article 3 (Weigel, Viebahn, & Fischedick, 2022), the previously developed framework is modified and again tested based on the evaluation of a digital application, the Aircraft Detection Lighting System (ADLS). Transponder-based ADLS are increasingly used in wind turbines (WTs) to limit beacon operation times, reduce light emissions, and increase wind energy acceptance. The systems use digital technologies such as receivers of digital transponder signals, LTE/5G, and other information and communication technology. Schematic illustrations of the functionality of aviation transponders and transponder-based ADLS are depicted in Figure 12 (a) and (b), respectively.

The use of ADLS will be mandatory in Germany both for new and existing wind turbines with a height of >100 meters beginning in 2024 (At the time of publication of article 3 envisioned start date was January 2023, which was later changed). Therefore, a nationwide roll-out is expected during 2023 making ADLS a highly discussed topic in the German wind energy sector. To fully realize the benefits while avoiding risks and bottlenecks, a thorough and holistic understanding of the efforts required and the impacts caused along the life cycle of an ADLS is essential.



(a) (b)

**Figure 12: Illustrative functionality of (a) a transponder in aviation; (b) a transponder-based ADLS (source: article 3)**

Several studies by different research groups analyzed the impact of ADLS on WT acceptance. All studies find that lighting of WTs has a negative effect on social acceptance, and some studies specifically recommend ADLS as a measure to improve acceptance. Besides the acceptance-focused articles, one study assesses the risk of transponder-based ADLS for aviation safety and comes to the conclusion that the risk of a system failure with consequences for aviation safety is very low. Societal impacts beyond acceptance, non-aviation-risk-related technical impacts, and environmental as well as economic impacts have not yet been analyzed. In particular, neither a life cycle assessment nor an environmental study, or a holistic assessment incorporating multiple perspectives, involving the relevant stakeholders, and considering the relevant impact areas has been conducted so far.

In order to close this gap, the previously developed framework is refined and applied to conduct a holistic evaluation of ADLS. A life cycle assessment is performed to assess several environmental criteria. The required data and information are provided by both an ADLS and a beacon manufacturer. Furthermore, twelve expert interviews, including four wind farm operators, two environmental NGO experts, two policy advisors, one wind farm manufacturer, one ADLS manufacturer, and two scientists, are conducted to assess all other criteria that are not part of the LCA. The experts also provide an allocation of weights to the criteria, and five weighting profiles are derived.

### *3.3.2 Results & discussions*

The results of the LCA for the defined “base case” (8 turbines per ADLS and only one communication module) show an increase in the life cycle impact of all analyzed criteria. Exemplary, Figure 13 (a) depicts the GWP result along the life cycle revealing the electricity consumption of the hardware during the use phase as the biggest emitter of $CO_2$ eq..

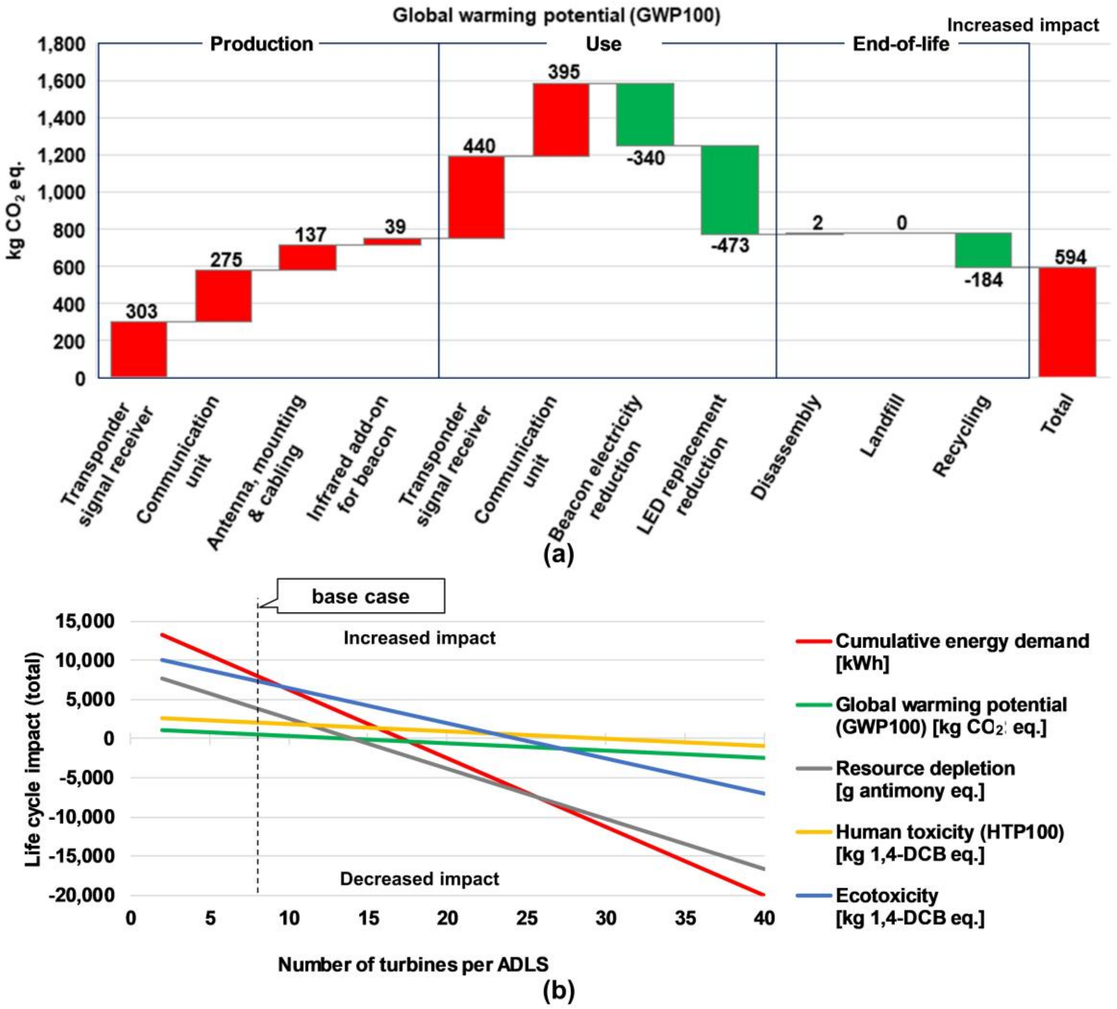


**Figure 13: Life cycle impact of one ADLS. (a) GWP100 for the base case scenario; (b) all assessed impact criteria across different numbers of turbines covered by one ADLS (source: article 3)**

However, the results highly depend on the number of WTs covered by one ADLS, as depicted in Figure 13 (b), and the need to install additional communication units.

Due to the size of offshore wind farms (typically >40 turbines), the ADLS will likely lead to a reduction in life cycle impacts for these assets.

The LCA results of this study can be used by ADLS manufacturers as a starting point for life cycle improvement activities. Put into the context of the life cycle impacts of the turbines covered by the ADLS, the impact of the ADLS itself is negligible, whether it is increased or decreased. Therefore, the LCA results normalized to the MCA evaluation scale result in an almost neutral evaluation score.

The MCA results, including the normalized LCA and expert interviews, are depicted in Figure 14 per criterion.

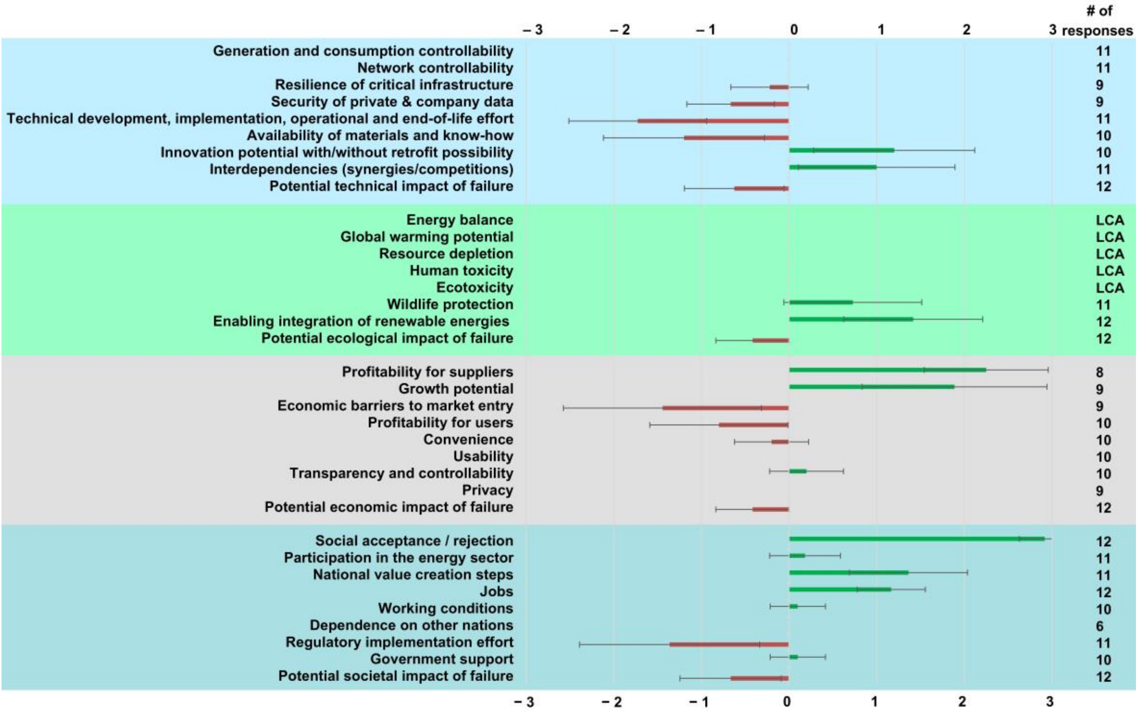


**Figure 14: MCA result of one ADLS on criteria level including standard deviation and number of data points (source: adapted from article 3)**

The most significant benefits are seen in the increased social acceptance of wind turbines as well as the economic (international) growth potential for the providers of the technology and the resulting impact on the national economy. Most negative impacts are of a technical nature, in particular, the effort for the system's development and implementation, including the availability of necessary materials and know-how. Besides that, also the regulatory implementation effort, the economic barriers for new ADLS providers, and the profitability for the users (i.e., wind farm operators) are evaluated negatively.

Furthermore, three main bottlenecks for the roll-out are identified: the shortage of global semiconductor supply needed for production, the lack of trained technicians for installation, and remaining regulatory uncertainties regarding the approval process. Given these bottlenecks, an extension of the roll-out period is recommended in the article. With a similar reasoning, the German Federal Ministry of Economic Affairs and Energy, shortly after the submission of this article, extended the roll-out period by one year for onshore WTs in the federal "Renewables Energy Act" BGBl. I 2022 S. 1237 §9. The remaining time, until the obligation becomes effective, should be used by decision-makers to address the identified bottlenecks. Political decision-makers should drive the administrative process to eliminate regulatory uncertainties and ensure the availability of administrative capacities for the large-scale roll-out. The issues of global semiconductor scarcity and lack of technicians in Germany go well beyond affecting only ADLS but hinder major developments, such as the transition towards renewable energies. Therefore, these issues need to be counteracted on a broader economic-political level by, e.g., researching material substitutions, investing in new production capacities, and supporting continuing professional development. However, smaller measures to mitigate the immediate impact of these bottlenecks on the ADLS roll-out can be taken by business decision-makers. For example, the pooling of ADLS installations for an entire region, as done by the association for renewable energies in the state of North Rhine-Westphalia, could improve the plannability for both ADLS manufacturers and installers. Furthermore, the roll-out period should be used to address two aspects that are found to require further studies. These aspects are (1) wildlife impacts to ensure that potential adverse impacts are identified and addressed and (2) social acceptance impacts to validate and measure wind energy acceptance before and after installing ADLS.

Figure 15 shows the aggregated category and total level results for different stakeholder perspectives, i.e., weighting profiles. The total results are slightly positive for all perspectives. It is concluded that the benefits outweigh the adverse effects. Therefore, a roll-out is expected to be beneficial. Since the evaluation is positive for all stakeholders, resistance from a specific group is unlikely. However, the almost neutral result from the perspective of wind farm operators, who carry out the implementation, indicates a likely lack of intrinsic motivation to do so. In particular, the high implementation effort in combination with the low profitability are the underlying reasons. Hence, reducing, for example, the regulatory effort to install the application would increase the operators' motivation and thereby likely accelerate the roll-out.

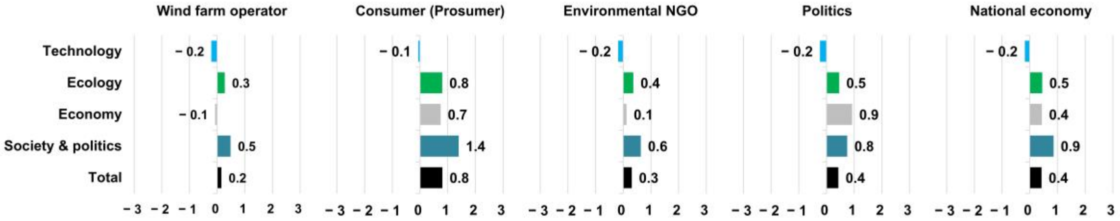


**Figure 15: ADLS MCA results on category level for different weighing profiles (source: article 3)**

The framework delivers a robust evaluation result with an aggregated overview as well as valuable detailed insights, thus proving its' feasibility for this particular case.

Both in articles 2 and 3, the feasibility of the evaluation framework is demonstrated based on the evaluation of two distinct digital applications. In article 3, going beyond the demonstration of feasibility, additionally, a criteria-based suitability assessment is performed. Here the suitability assessment of article 3 is extended to also include aspects of the application of the framework in article 2. This extension results in a broader basis for the suitability assessment and, therefore, a more robust answer to research question 3.

The suitability of the framework is assessed as described in Section 2.3 based on three criteria: conclusiveness of results (correctness and potential to derive actions), feasibility of use (effort and required expertise), and adaptability (to different digital applications, data availability situations and practitioners' preferences) of the framework.

The objective correctness of the results is difficult to assess, but a comparison with available information in the same or similar fields can be used as a proxy. In both articles, the results are discussed in the context of available secondary information. Overall good consistency between obtained results and secondary information is found. In cases of diverging results, plausible explanations for the differences are identified. Another indicator of the robustness of the result is the standard deviation of the responses given in the expert interviews. This indicator is assessed in article 3, revealing a relatively high consistency of responses. Overall, it is concluded that the results obtained with the evaluation framework are very realistic. Furthermore, in both articles 2 and 3, direct measures and recommendations for further studies, life cycle improvement initiatives, as well as regulatory adjustments are identified. It is concluded that the potential to derive concrete measures and actions of the applied framework is high. The overall conclusiveness of the result is therefore considered to be high.

The effort required to collect the necessary data for the LCA and to conduct the expert interviews is relatively high. However, the framework improvement implemented in article 3, to let experts independently conduct the weighting after the interview, decreased the interview effort and time requirement for the research team significantly. Due to the methods chosen, the complexity of the MCA and the expert interviews are rather low, such that these parts of the framework can also be carried out by practitioners without a deep theoretical understanding of the methodology. The LCA, however, requires in-depth expertise. This drawback can be mitigated if existing life cycle results are available and can be integrated instead of conducting a separate LCA. This would also decrease the required effort. However, in particular, for new or even future applications, LCA results are rarely available. Therefore, overall, the feasibility of use of the framework is evaluated as medium.

The adaptability of the framework regarding different types of applications can be assessed by looking at the difference between the applications evaluated in articles 2 and 3, smart meter roll-out vs. a single ADLS. The two applications differ greatly in terms of the energy value stream step in which they are deployed (metering vs. generation), their function (measuring and communicating electric flows vs. recognizing aerial vehicles and managing obstruction lighting), and their main effects (local energy saving and system-wide balancing vs. local social acceptance increase). Furthermore, in article 2, the evaluation subject is a nationwide roll-out of an application, while in article 3, it is a single local application. Both applications can be evaluated equally well using the framework. Hence, the adaptability regarding the type of application is considered to be very high. The availability of information differs considerably between the two studies as well as between individual criteria within the same study, e.g., there are several studies on the social acceptance of ADLS but none on the impact on wildlife. Nevertheless, all criteria can be evaluated either within the LCA or in the expert interviews. This demonstrates the very high adaptability of the framework to different levels of data availability. Finally, the adaptability to practitioners' preferences can only be evaluated once the framework has been applied by different practitioners, which is not the case at this stage. Therefore, the overall adaptability is considered to be very high, but the unevaluated adaptability to practitioners' preferences has to be taken into account.

Considering the high conclusiveness of the results, the medium feasibility of use, and the very high adaptability, it is concluded that the evaluation framework is very well suited for its purpose. Nevertheless, two measures are suggested to further improve the feasibility of use. In addition, the possibility of applying fuzzy sets for the SAW aggregation method is pointed out to improve the handling of uncertainties which could improve the correctness of the result.

### *3.3.3 Discussion update, based on information published post-submission of the article*

Since article 3 was published relatively recently, no relevant new publications in the field of aircraft detection lighting systems have been identified.

The practical relevance of the ADLS evaluation is underlined by the fact that the results were presented and discussed in the context of the 30th wind energy days in Linstow (Germany) and mentioned in a newspaper report (Flatt, 2023) on a current bill to make ADLS mandatory in Washington (USA).

# 4 Synthesis of research questions

The results of the three articles in Section 3, overall, answer the three research questions. Therefore, in this section, a concise answer to each research question is provided as a synthesis. Nevertheless, in the case of research question 3, the answer given in this section goes beyond the short synthesis and extends the individual answers given in articles 2 and 3 by combining them.

## 4.1 Research question 1

RQ1: Which applications are enabled by digitalization in the energy sector, how can they be categorized, and what are the benefits and risks?

In article 1, digital applications in the energy sector are identified and categorized. The results of article 1 are discussed in Section 3.1 of this thesis. Here only a short synthesis is provided.

A wide variety of potential digital applications in the energy sector is identified, in total, 29 applications in seven subcategories of three impact areas. The three impact areas, which are used to categorize the applications, are "system balance", "process optimization", and "customer orientation". Most applications are identified in the area of "system balance". The core of digitalization is the collection, processing, analysis, and transmission of digital data, which makes digital technologies a "natural fit" for making real-time information available and enabling remote control to improve system balancing. The applications within the second impact area, "process optimization", are mainly applying automation and prediction functionalities to increase process efficiency and efficacy. The third area, "customer orientation", is comprised of a variety of different applications, all supporting companies in understanding customers and adapting their products and services correspondingly. A subsequent survey among energy utilities published by (Weigel & Görner, 2020) corroborates that the identified digital applications are indeed relevant and that the list is exhaustive.

Furthermore, benefits are analyzed. The main benefits 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 capacities.

Risks are not covered in article 1 as they are not discussed in a structured manner in the analyzed literature. This finding corroborates the identified gap of a missing holistic view on digital applications.

Digital applications overall comprise a wide variety of functionalities, digital technologies, application areas, benefits, risks, and affected stakeholders. These factors can all be used to categorize digital applications.

## 4.2 Research question 2

RQ2: Which methods and criteria can be used to holistically evaluate digital applications in the energy sector, and how could a respective framework look like?

In articles 2 and 3, a framework for the holistic evaluation of digital applications in the energy sector is developed and tested. The evaluation requirements and the methodological approach are described in detail in Sections 2.1 and 2.2. Thus, here only a short synthesis is given.

The framework needs to be highly adaptable to the variety of different types of digital applications, the varying availability and quality of data, and the practitioners' preferences. The use of the framework must be feasible for researchers, policymakers, and company employees in terms of evaluation effort and required expertise. Moreover, the framework needs to deliver holistic, correct, and useful results.

Based on these requirements, a combination of three well-established methods, i.e., MCA, LCA, and expert interviews, is applied. The MCA is used as the underlying evaluation structure, including an extensive list of relevant criteria in the areas of technology, ecology, economy, and society/politics, as well as weighting profiles to reflect relevant stakeholders’ perspectives. Both criteria and weighting profiles are tailored to digital applications in the energy sector. The assessment of the criteria is performed within the LCA and the expert interviews. A five-step approach for the application of the framework is defined.

## 4.3 Research question 3

RQ3: Is the framework suitable for evaluating digital applications in the energy sector, and how does the evaluation of individual applications turn out, are there implementation risks or bottlenecks, what solution options exist?

The suitability of the framework is assessed in article 3 based on the approach and the criteria described in Section 2.3. The description in Section 3.3.2 extends the assessment in article 3 by including certain aspects of the framework's application in article 2. This allows for a broader, more profound assessment basis and, thus, a more robust answer to RQ 3. In this section, only a short synthesis is provided.

The conclusiveness of the result is found to be high based on the correctness, assessed via a comparison with other scientific studies and the standard deviation of received expert answers, and the actions and measures derived from the detailed insights. The feasibility of use is found to be medium, mainly affected by the high effort and required level of expertise for the LCA, which decreases the otherwise very good feasibility of use. Finally, the adaptability of the framework is found to be high, i.e., the farmwork can be applied to very different digital applications and can cope with varying levels of data availability. Considering the above, it is concluded that the evaluation framework is very well suited for its purpose.

The second part of RQ 3 addresses the evaluation results obtained in article 2 and 3. The individual results of the two evaluations are described in Sections 3.2 and 3.3 and in full length in the respective articles. Therefore, in this subsection, only high-level results are discussed with a focus on implementation risks, bottlenecks, and solution options.

In the case of the "smart meter", a variety of studies already existed prior to the publication of article 2, including CBAs and LCAs, highlighting various details but lacking a holistic perspective. Hence, here, the relevance of the performed evaluation is mainly the extension of results to a holistic overview, including the representation of different stakeholders' perspectives. The overall evaluation result is positive for all perspectives, i.e., weighting profiles. Thus, the benefits of the smart meter roll-out outweigh the downsides, mainly due to positive ecological effects as well as improved generation and grid controllability. However, the result from the energy utilities' perspective is close to neutral, indicating that this stakeholder will most likely not have an intrinsic motivation to drive the roll-out of smart meters. As a solution, the technical and regulatory implementational effort could be reduced to increase the utilities' motivation. At the same time, the integrity of the critical infrastructure, the data security as well as the user's privacy cannot be compromised to not further decrease social acceptance. Based on the LCA, the potential for energy savings as well as the devices' own energy consumption are identified as key drivers of the environmental performance and areas where further research and measures are required. Although the smart meter roll-out is already underway, the results obtained in this study can be used to speed up the roll-out process and ensure positive impacts are achieved.

In the case of the "ADLS", few studies are available, covering only social acceptance and aviation risk aspects. Thus here, not only the holistic overview but also the evaluation details present a relevant novelty. The overall evaluation result is positive for all stakeholder perspectives, i.e., the benefits outweigh the downsides, mainly due to the very positive effect on the social acceptance as well as (socio-)economic upsides for the supplier and along the entire value chain. The upsides could even further increase due to high growth and innovation potentials. Yet the result from the wind farm operators' perspective, i.e., the stakeholders who implement the technology, is close to neutral, potentially causing a slow roll-out. Therefore, solutions need to be found to decrease the technical and regulatory implementation effort, improve the profitability for wind park operators and ensure the availability of required hardware, such as semiconductors, and skilled technicians. Improvements regarding these issues would increase the overall evaluation result, in particular, from the wind farm operators' perspective, and thus likely accelerate the roll-out. To ensure a timely yet feasible roll-out amidst the identified bottlenecks, a prolonged roll-out period is recommended, which, in fact, has since the submission of article 3 been put into legislation by the regulator. Since the roll-out is in its initial phase, the suggested actions can still be applied. Article 3 has already been mentioned in public discussions on ADLS, highlighting the practical and societal relevance of the holistic evaluation result.

# 5 Conclusion

Digitalization causes increasingly profound impacts across society and industry, including the energy sector. A holistic understanding of the potential impacts early on in the development and implementation of new digital applications is important to avoid risks and bottlenecks while taking advantage of the benefits. The review of available literature revealed a content and methodological gap regarding the holistic evaluation of digital applications in the energy sector. Therefore, the goal of this thesis was to develop an evaluation framework to close the identified gap. Based on this goal, three objectives and three corresponding research questions were defined and addressed in three peer-reviewed articles. In the first article, a literature review was carried out in order to identify and categorize digital applications in the energy sector as well as associated benefits, risks, and affected stakeholders. In the second article, the available evaluation and assessment methods were discussed, and a framework for the holistic evaluation of digital applications in the energy sector was developed as well as tested by evaluating the digital application "smart meter". The third article presented an improved version of the framework as well as an evaluation of the application "ADLS (Aircraft Detection Lighting Systems)" for wind turbines and closed with an assessment of the suitability of the developed framework.

In line with the research questions, the results obtained in this thesis consist of three parts. From each result, conclusions can be drawn.

The first result is the categorization of identified digital applications in the energy sector, presented in article 1. The novelty of article 1 consists of the comprehensiveness of the list of applications as well as the categorization structure based on impact areas. This categorization of digital applications is quite relevant as it can be and has been used as a basis to structure further research both for this thesis as well as for fellow researchers active in the field of digital applications.

The second result, the developed evaluation framework presented in articles 2 and 3, is the central novelty of this thesis. The framework, based on a combination of MCA, LCA, and expert interviews, closes the methodological gap identified for the holistic evaluation of digital applications. In both articles, the feasibility of the framework is demonstrated based on the evaluation of two very distinct digital applications. In article 3, it is concluded that the framework has a high suitability after conducting a suitability assessment based on the conclusiveness of results, the feasibility of use, and the framework's adaptability. The holistic evaluation of digital applications and, therefore, the developed framework is highly relevant to facilitate discussions about the role of digitalization as a transformative process as well as application-specific opportunities and threats. It can be used by researchers, companies, and governmental and non-governmental institutions to identify potential risks, develop solutions and, thereby, ensure a sustainable implementation of digital applications. Therefore, besides the scientific novelty in the area of technology evaluation methodology and systems science, the framework provides a benefit to society by supporting the societal discourse about digital applications.

The third result consists of the two individual evaluation results of the digital applications “smart meter” and “ADLS” in articles 2 and 3. The evaluations are the first and second applications of the developed framework. Thus, the achieved results are the first holistic evaluation results of each of the two digital applications. For each application, results at three different levels of detail were obtained. The most aggregated level, i.e., aggregation to one single indicator, revealed that overall the advantages outweigh the disadvantages for both analyzed digital applications. This level of detail is used for high-level comparisons. The second aggregation level, consisting of the four categories “Technology”, “Ecology”, “Economy”, and “Society & politics”, revealed the differences between stakeholder views and therefore serves as a basis for broader sociopolitical discussions. The most granular level, based on the individual criteria, in combination with the very detailed insights drawn from qualitative interview comments and the life cycle assessment, was used to identify risks and improvement potentials as well as to derive required actions. These details are relevant for all actively involved stakeholders. Overall, the obtained results provided both a high-level and easy-to-grasp overview suitable for broader communication as well as detailed insights into benefits, risks, bottlenecks, and necessary actions. It is concluded that the results are relevant for policymakers, NGOs, equipment manufacturers, users, and other affected stakeholders. Regarding the timing of the evaluation, it is concluded that while an evaluation prior to a roll-out would be ideal to act on the findings, later evaluations do still contribute valuable results. Besides that, evaluations at a later stage may profit from better availability of data.

Considering all the above, it is concluded that the three main results close the identified gaps and present distinct novelties and scientific advancements. They are not only of high relevance to the various stakeholders involved but also contribute added value to society. Hence, the three peer-reviewed articles providing these results exhaustively answer the three research questions and, thus, collectively constitute the cumulative dissertation thesis.

# 6 Outlook

In future advancements of the framework, two methodological additions could be beneficial. A fuzzy logic could be applied to the MCA evaluation scale, which would allow the integration of fuzzy verbal expert interview answers, i.e., intermediate marks within the ordinal scale such as "almost 2". This could increase the accuracy of the answers, improve the framework's handling of uncertainties, and thereby improve the comparability of results. However, these improvements come at the cost of increased complexity. Although the applied MCA method, simple additive weighting, which is relatively simple and transparent, can be combined with fuzzy logic, the addition would increase the methodological complexity and hence increase the required expertise and reduce the transparency of the result calculation process. Moreover, similarly to the application of the life cycle assessment (LCA) for ecological criteria, economic and social criteria could be assessed in life cycle costing (LCC) and social life cycle assessment (SLCA), respectively. The addition of LCC and SLCA could improve the objectivity of the result, however, it would also significantly increase the required effort and expertise of the practitioner. Furthermore, clearer guidelines on how to define the reference in step 1 of the framework could prove to be necessary to decrease the potential effect of the practitioners' decision in this step on the final result. Yet this would decrease the flexibility of the framework.

Besides the suggested methodological advancements, the framework's field and mode of application can be further evolved. A prospective future direction of the research could be for the framework to be applied to numerous different digital applications in the energy sector by different practitioners. The frequent use itself may reveal further improvement potential. Besides that, further improvements may be identified by retrospectively analyzing previous evaluations regarding the accuracy of results and conclusions. The framework could also be adapted for the evaluation of digital applications in other sectors, thereby enlarging the scope of the framework. For each additional sector, the list of criteria as well as the weighting profiles would need to be adapted. Theoretically, other non-digital applications could also be evaluated using the framework. However, depending on the characteristics of these applications, other methods may be more suitable. Prospectively, with increasing numbers of performed evaluations, the results can not only be used for the discussion of opportunities and risks of individual applications but increasingly as a basis for a transparent, fact-based discourse between policymakers, businesses, and consumers about general targets and guidelines of the digitalization as a transformative process. As laid out in the introduction, it is this discourse that enables the realization of the greatest possible benefits of the digitalization of the energy sector while avoiding adverse effects.

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## References 3: Regulations

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|---|---|
| BGBl. I 2016 S. 2034 §29 | 39 |
| BGBl. I 2022 S. 1237 §9 | 48 |

# Annex

## Weighting profiles

**Table 2: Proposed weighting profiles for four common stakeholders (source: adapted from articles 2 and 3)**

| | Weighting profiles<br>Categories and criteria | *Energy utility* | *Consumer (Prosumer)* | *Environmental NGO* | *National economy* |
|---|---|---|---|---|---|
| **Technology** | Aggregated technology category | 27,7 | 20,0 | 18,0 | 23,6 |
| | Generation and consumption controllability | 4,8 | 1,0 | 3,2 | 2,7 |
| | Network controllability | 3,5 | 1,0 | 1,6 | 2,2 |
| | Resilience of critical infrastructure | 4,3 | 4,8 | 2,6 | 2,7 |
| | Security of private & company data | 2,2 | 4,3 | 1,6 | 2,2 |
| | Technical development, production, implementation, operational, and end-of-life effort | 2,6 | 1,9 | 1,1 | 3,0 |
| | Availability of materials and know-how | 2,6 | 2,4 | 2,1 | 2,7 |
| | Innovation potential with/without retrofit possibility | 3,0 | 2,9 | 2,6 | 2,1 |
| | Interdependencies (synergies/competitions) | 2,2 | 1,0 | 1,1 | 3,8 |
| | Potential technical impact of failure | 2,6 | 1,0 | 2,1 | 2,2 |
| **Ecology** | Aggregated ecology category | 26,4 | 24,0 | 39,7 | 29,4 |
| | Cumulative energy demand | 4,1 | 2,7 | 2,9 | 3,4 |
| | Global warming potential | 5,0 | 3,6 | 6,9 | 4,4 |
| | Adiabatic resource depletion | 3,5 | 2,2 | 4,9 | 2,4 |
| | Human toxicity | 3,0 | 4,4 | 4,4 | 2,7 |
| | Ecotoxicity | 2,2 | 2,2 | 4,4 | 2,7 |
| | Wildlife protection | 1,9 | 3,6 | 5,9 | 4,8 |
| | Enabling integration of renewable energies | 5,2 | 4,4 | 6,4 | 6,4 |
| | Potential ecological impact of failure | 1,5 | 0,9 | 3,9 | 2,6 |
| **Econo** | Aggregated economy category | 22,6 | 21,3 | 15,5 | 19,9 |
| | Profitability for suppliers | 4,5 | 2,3 | 2,1 | 4,4 |

| | | | | | |
|---|---|---|---|---|---|
| | Growth potential | 2,8 | 1,7 | 1,0 | 4,9 |
| | Economic barriers to market entry | 2,8 | 1,2 | 1,6 | 2,1 |
| | Profitability for users | 4,5 | 5,8 | 2,1 | 2,6 |
| | Convenience | 1,1 | 2,3 | 1,6 | 0,5 |
| | Usability | 1,7 | 2,9 | 1,6 | 1,1 |
| | Transparency and controllability | 1,1 | 1,7 | 1,6 | 0,5 |
| | Privacy | 1,1 | 2,3 | 2,1 | 0,5 |
| | Potential economic impact of failure | 2,8 | 1,2 | 2,1 | 3,3 |
| **Society & politics** | Aggregated society & politics category | 23,2 | 34,7 | 26,8 | 27,1 |
| | Social acceptance/rejection | 3,7 | 10,4 | 6,8 | 6,9 |
| | Participation in the energy sector | 3,7 | 4,1 | 2,0 | 2,8 |
| | National value creation steps | 1,3 | 3,1 | 2,9 | 3,4 |
| | Jobs | 3,3 | 5,7 | 2,0 | 3,3 |
| | Working conditions | 2,3 | 5,2 | 3,4 | 2,0 |
| | Dependence on other nations | 1,7 | 1,0 | 2,0 | 1,0 |
| | Regulatory implementation effort | 3,3 | 1,0 | 2,0 | 2,9 |
| | Government support | 1,7 | 1,0 | 2,9 | 2,0 |
| | Potential societal impact of failure | 2,3 | 3,1 | 2,9 | 2,9 |
| **SUM** | | **100** | **100** | **100** | **100** |

**Peer-reviewed article 1**

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applied sciences

MDPI

Review

# Review and Categorization of Digital Applications in the Energy Sector

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**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

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## 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.

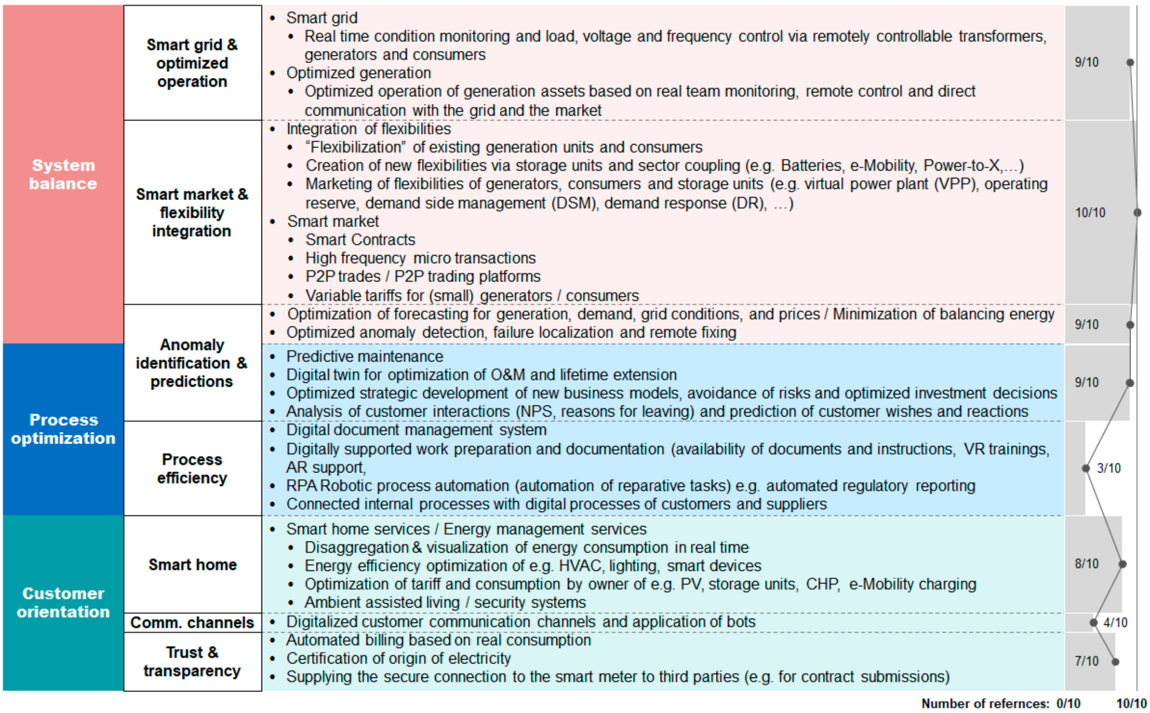
As a first step, transparency on which digital applications can be expected in the electricity sector and why they will/might be implemented needs to be created. Therefore, this article presents the results of a literature review of ten publications with the following three objectives:

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<br>  • Real time condition monitoring and load, voltage and frequency control via remotely controllable transformers, generators and consumers<br>• Optimized generation<br>  • 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<br>  • "Flexibilization" of existing generation units and consumers<br>  • Creation of new flexibilities via storage units and sector coupling (e.g. Batteries, e-Mobility, Power-to-X,…)<br>  • Marketing of flexibilities of generators, consumers and storage units (e.g. virtual power plant (VPP), operating reserve, demand side management (DSM), demand response (DR), …)<br>• Smart market<br>  • Smart Contracts<br>  • High frequency micro transactions<br>  • P2P trades / P2P trading platforms<br>  • 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<br>• Optimized anomaly detection, failure localization and remote fixing | 9/10 |
| **Process optimization** | | • Predictive maintenance<br>• Digital twin for optimization of O&M and lifetime extension<br>• Optimized strategic development of new business models, avoidance of risks and optimized investment decisions<br>• Analysis of customer interactions (NPS, reasons for leaving) and prediction of customer wishes and reactions | 9/10 |
| | **Process efficiency** | • Digital document management system<br>• Digitally supported work preparation and documentation (availability of documents and instructions, VR trainings, AR support,<br>• RPA Robotic process automation (automation of reparative tasks) e.g. automated regulatory reporting<br>• Connected internal processes with digital processes of customers and suppliers | 3/10 |
| **Customer orientation** | **Smart home** | • Smart home services / Energy management services<br>  • Disaggregation & visualization of energy consumption in real time<br>  • Energy efficiency optimization of e.g. HVAC, lighting, smart devices<br>  • Optimization of tariff and consumption by owner of e.g. PV, storage units, CHP, e-Mobility charging<br>  • 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<br>• Certification of origin of electricity<br>• 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.

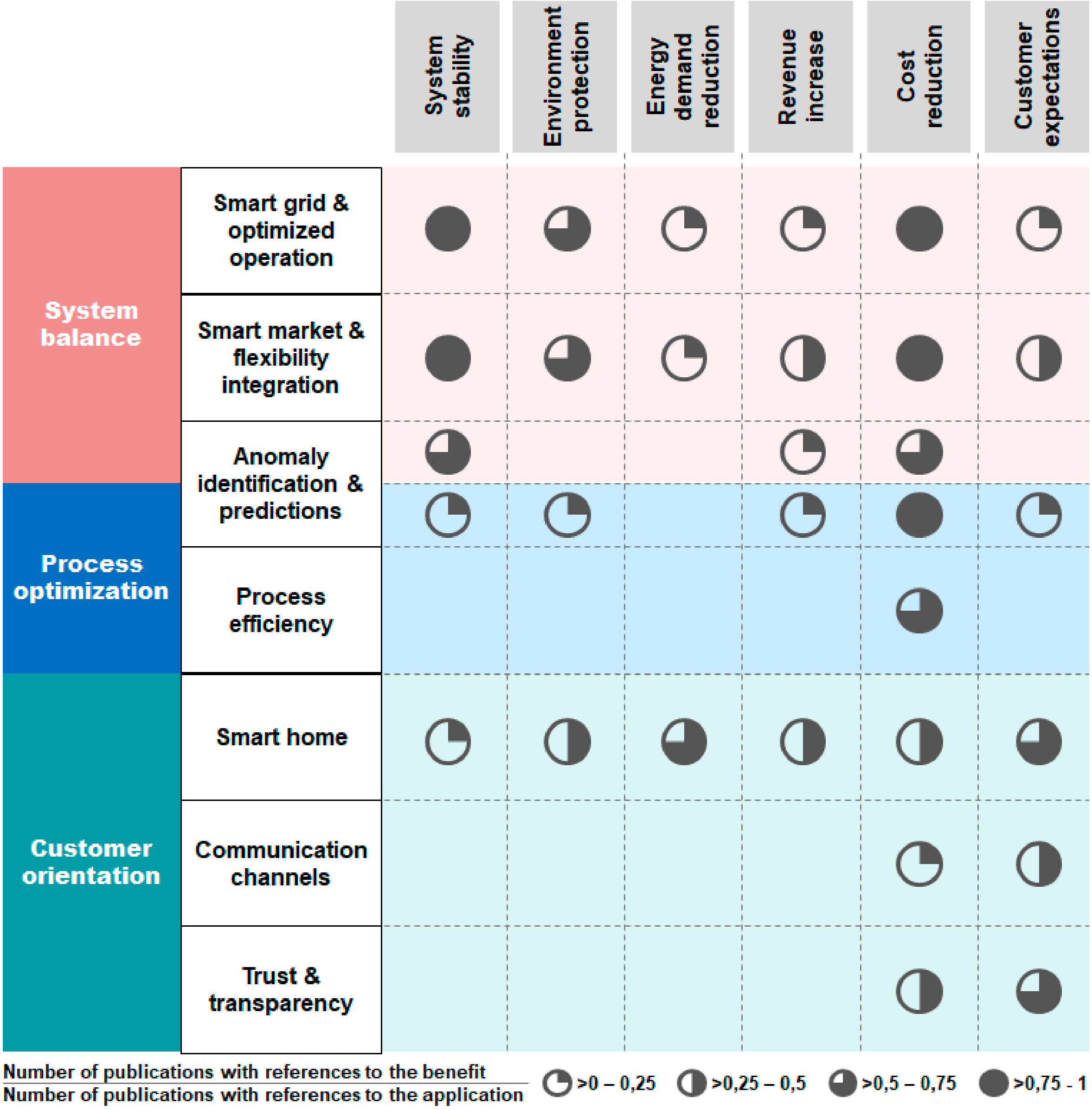
## 3. Objective and Approach of the Literature Review

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 | ● | ◕ | ◔ | ◔ | ● | ◔ |
| System balance | Smart market & flexibility integration | ● | ◕ | ◔ | ◑ | ● | ◑ |
| System balance | Anomaly identification & predictions | ◕ | | | ◔ | ◕ | |
| Process optimization | Anomaly identification & predictions | ◔ | ◔ | | ◔ | ● | ◔ |
| Process optimization | Process efficiency | | | | | ◕ | |
| Customer orientation | Smart home | ◔ | ◑ | ◕ | ◑ | ◑ | ◕ |
| Customer orientation | Communication channels | | | | | ◔ | ◑ |
| Customer orientation | Trust & transparency | | | | | ◑ | ◕ |

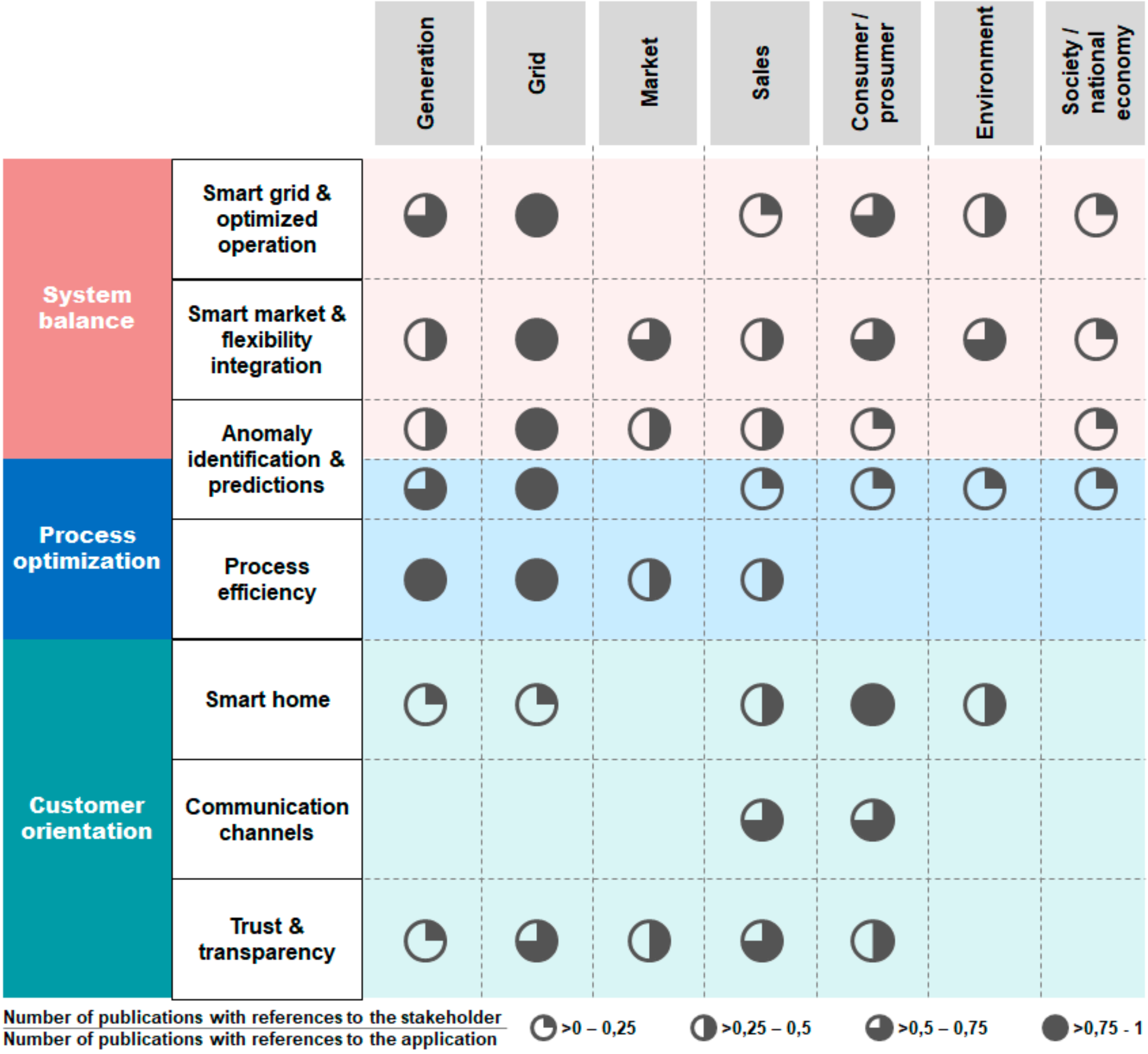
Number of publications with references to the benefit / Number of publications with references to the application

◔ >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.

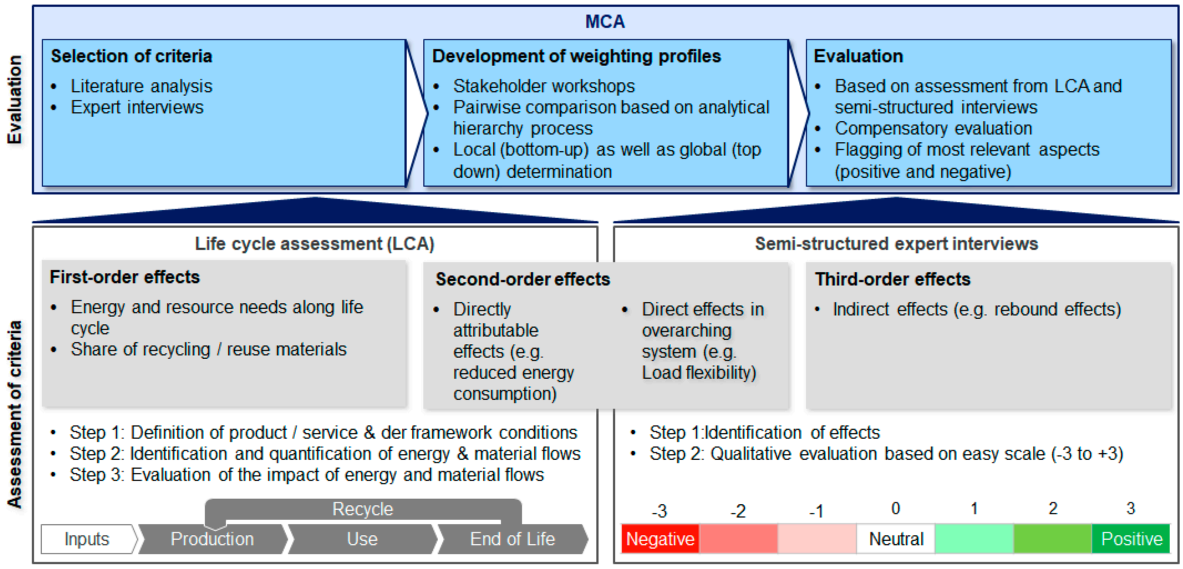


**Figure 4.** Suggested combination of methodologies for holistic assessment and evaluation of digital applications.

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.

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**Peer-reviewed article 2**

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sustainability

MDPI

*Article*

# Holistic Evaluation of Digital Applications in the Energy Sector—Evaluation Framework Development and Application to the Use Case Smart Meter Roll-Out

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**Abstract:** The development of digital technologies is accelerating, enabling increasingly profound changes in increasingly short time periods. The changes affect almost all areas of the economy as well as society. The energy sector has already seen some effects of digitalization, but more drastic changes are expected in the next decades. Besides the very positive impacts on costs, system stability, and environmental effects, potential obstacles and risks need to be addressed to ensure that advantages can be exploited while adverse effects are avoided. A good understanding of available and future digital applications from different stakeholders' perspectives is necessary. This study proposes a framework for the holistic evaluation of digital applications in the energy sector. The framework consists of a combination of well-established methods, namely the multi-criteria analysis (MCA), the life cycle assessment (LCA), and expert interviews. The objective is to create transparency on benefits, obstacles, and risks as a basis for societal and political discussions and to supply the necessary information for the sustainable development and implementation of digital applications. The novelty of the proposed framework is the specific combination of the three methods and its setup to enable sound applicability to the wide variety of digital applications in the energy sector. The framework is tested subsequently on the example of the German smart meter roll-out. The results reveal that, on the one hand, the smart meter roll-out clearly offers the potential to increase the system stability and decrease the carbon emission intensity of the energy system. Therefore, the overall evaluation from an environmental perspective is positive. However, on the other hand, close attention needs to be paid to the required implementation and operational effort, the IT (information technology) and data security, the added value for the user, the social acceptance, and the realization of energy savings. Therefore, the energy utility perspective in particular results in an overall negative evaluation. Several areas with a need for action are identified. Overall, the proposed framework proves to be suitable for the holistic evaluation of this digital application.

**Keywords:** digitalization; digital applications; cyber–physical systems; energy sector; sustainability; holistic evaluation; framework; multi-criteria analysis; life cycle assessment; expert interviews; smart meter

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## 1. Introduction

Digitalization is often seen as a megatrend of our time. However, this trend began several decades ago with the use of the first industrial computers. Nevertheless, due to the exponentially accelerating developments of digital technology and its transformative speed and impact, digitalization is now one of the main drivers for change in our industry and society. The technological developments are often mutually reinforcing; thus, the trend is expected to continue to accelerate. This fundamental socio-economic transformation is envisioned in [1] and described from an economic perspective in [2]. Some areas of economy and society, such as commerce, banking, and communication, have already undergone significant changes and are today the digital leaders, while others remain mostly unchanged as identified in a survey among German companies [3]. In fact, the energy sector was a pioneer of digitalization in using early digital monitoring and control systems in power plants and the transmission network, as explained in the educational publication on power supply systems [4], decades before the term digitalization became widely used. Today, many digital solutions have already been implemented on all energy value stream steps, yet the value stream itself remains mostly unchanged. Looking forward, a wide variety of future potential digital applications can already be identified. An overview of applications is presented in [5]. Numerous publications describe specific applications, e.g., a concept of universal smart machines for the energy sector consisting of electric protection equipment, and electricity quality measuring and monitoring devices is recently presented in [6]. These applications offer enormous potential to positively impact all three aspects of the energy sector "target triangle" (cost, system stability, environmental impact) and might even affect the value stream itself. Whether or not the energy value stream fundamentally changes, digitalization will likely play an essential role in the changes of the energy sector within the next decades [7].

For companies, regulators, and non-governmental stakeholders, a good understanding of the developments, the digital applications available now and in the future, and their associated impacts, benefits, and risks is essential. On the one hand, this transparency is needed for broad societal and political discussions about the targets and pathways of the digitalization. On the other hand, it is an essential piece of information for companies to develop and sustainably implement digital applications.

Therefore, a framework suitable for the evaluation of digital applications in the energy system is required. Digital applications in the energy sector can be extremely diverse (see definition in Appendix A) and a large number of stakeholders are potentially involved. A broad range of potential technical, economic, ecological, and social impacts can be caused [5]. In particular, ecological impacts can be quite substantial and often require a lifecycle perspective for full coverage. Furthermore, the development of new applications can be rapid. Due to the described nature of digital applications, an evaluation framework needs to be highly flexible, on the one hand, yet provide sufficient guidance to make alternatives comparable on the other. It needs to cover the wide range of potential impacts and be able to cope with qualitative as well as quantitative evaluation criteria. The integration of a life cycle perspective must be possible, at least for parts of the evaluation. Furthermore, the perspectives of different stakeholders need to be integrated. Besides that, the level of detail of the assessment needs to be flexible to cope with the varying availability of data and data of varying quality. The flexibility on the level of detail is also important to allow the user to decide if an initial "Quick Check" is desired or rather a "Deep Analysis".

A variety of methods are applied in the assessment and evaluation of technologies, for example, the technology assessment (TA), the cost benefit analysis (CBA), the multi criteria analysis (MCA), and the life cycle assessment (LCA). In the following paragraphs, we analyze whether and how these methods could be used for the intended purpose.

The technological assessment (TA) is a tool to systematically study unintended, indirect, or delayed impacts of technological developments on society [8]. In general, the TA is open to different ways of assessing the content matter; however, it provides guidelines regarding the overall process. Several types of TA are discussed in the edited volume [9]. The advantage of the TA is its very flexible approach, which can be applied to any technology and can cover all impacts. The disadvantage is that no specific methods for assessments are given such that the result heavily depends on the skill and experience of the person/organization conducting the TA, e.g., ref. [10] states that one success factor is to ensure dedicated academic capacity. Although the method gained high popularity already in the 1970s when the U.S. Office of Technology Assessment was established, it is still frequently applied today in the context of supporting public and parliament discourses, and continues to be refined for this purpose as, for example, in [11]. It is also applied in the field of digital technologies and in the energy sector. An application of the method for theich isture of t of the digitalizationsocialheate than the expert interviews.ange the tendency of the rsult.e aspects of grid and assessment of "clean energy" is, for example, presented by the International Energy Agency (IEA) in [12]. In [13], the method was recently used to assess the future of industry 4.0, which is a key part of the digitalization, and in [14], TA is used to identify and evaluate digitalization measures for battery cell production. Due to the open nature of the approach, however, TA does not give sufficient guidance on which assessment tools to use and which criteria to consider for the intended purpose of a digital application evaluation framework.

The cost benefit analysis (CBA) is based on the monetary value of efforts and impacts and makes the monetary implications of different alternatives comparable. Non-quantifiable effects can only be included informatively. Although, in theory, a holistic approach is possible, in some assessment areas, such as social acceptance or human safety, it is more difficult to calculate the monetary value as the authors explain in [15]. CBA guidelines for specific applications, including digitalization topics, are provided by the European Commission and are publicly accessible. For example, ref. [16] gives guidance on performing a CBA for smart meters, ref. [17] for smart grids, and [18] for investment projects. Examples of the use of CBAs in the energy industry are numerous. In the context of this study especially, the CBAs focusing on smart meters are relevant. Reference [19] presents a CBA for the German smart meter roll-out, ref. [20,21] provide CBAs for the roll-out in Great Britain, and [22] is a review study of the different CBAs performed of smart meter roll-outs in Europe. Of course, the CBA method can also be applied to other topics in the energy sector, such as energy planning [23] and, more recently, the evaluation of digital condition monitoring for remote maintenance systems in power plants [24]. Due to the limitation to impacts, which can be quantified as monetary values, however, the CBA is not suitable for holistically evaluating digital applications.

The multi criteria analysis (MCA) method consists of a range of different impact methods, which all use multiple criteria to evaluate alternatives and support the decision-making process, among them being multi attribute utility and value theories (MAUT and MAVT), simple additive weighting (SAW), and the analytical hierarchy process (AHP), as well as outranking methods. A short and concise overview including the advantages and disadvantages per method is presented in [25]. MCA methods are especially suitable for complex subject matters with multiple objectives and multiple stakeholders with different perspectives. It is possible to integrate qualitative as well as quantitative criteria and take the entire life cycle into account [26]. The MCA method has been used in the energy sector for several decades and has become even more popular in recent years [27]. An extensive literature review regarding MCA methods, the area of application, the stepwise approach, strengths and weaknesses as well as used criteria is performed in [28]. The context of the presented literature review is the sustainability assessment of renewable energy development. The authors conclude that no single impact method can be identified as the best or worst and that hybrid methods, therefore, are becoming increasingly applied. A recent practical example of the use of MCA methods in the energy sector is [29]. Here, multi-actor adoption of the MCA is used to evaluate different energy options for a German village. Multi-actor adoption allows for the determination of stakeholder-specific criteria, besides stakeholder-specific weights. A recent non-energy-related example of an MCA application is performed in [30]. Here, a multiple criteria approach is used to assess investment projects, including risk factors where different risk components are included as criteria. Furthermore, the MCA is also already applied to assess specific topics of the digitalization in the energy sector. In [31], the AHP is used to assess digital energy services regarding energy efficiency. In [32], an MCA approach is used to identify the most beneficial robotics technology for the power industry. Due to its well-proven use for energy and digital topics and the possibility to include perspectives of various stakeholders and qualitative as well as quantitative data, the MCA is found to provide a suitable basis for the intended digital application evaluation framework.

The life cycle assessment (LCA) follows a cradle-to-grave approach with a focus on identifying and quantifying environmental impacts [33]. Depending on the quality of the input information, it can provide precise information as to where along the life cycle environmental impacts occur. The LCA is defined by the standards in [34,35]. Guidelines for the application of the method are given in [36,37]. In a broader sense, the life cycle approach can be used for a life cycle sustainability assessment (LCSA) as a combination of LCA, life cycle costing (LCC), and social life cycle assessment (S-LCA) [38]. Two LCA approaches can be distinguished: attributional and consequential LCA. While the attributional LCA looks at impacts directly attributed to a product/service, the consequential LCA also takes into account the consequence (marginal effects) in the wider system caused by the product/service (e.g., change of use patterns) as stated in [33]. Tools and databases are publicly and commercially available and make the LCA easily applicable. However, the skill and experience of the practitioner has a direct effect on the modeling as stated by [39]; therefore, in-depth knowledge about the assessed life cycle as well as the analysis methods are required to yield meaningful results. Applications of LCA methods in the energy sector are very common. The energy sector is the main contributor to environmental effects, such as the emission of GHG [40]; therefore, a detailed understanding of the impacts along the life cycle in the energy sector is of outstanding importance. A literature review of LCA studies regarding electricity generation technologies is published in [41]. An assessment of LCA applications to assess GHG removal technologies is recently discussed in [42]. The LCA of the deployment of smart meters in the Californian energy system, presented in [43], is frequently referenced in this paper. LCA methods have already been applied to a variety of digital topics. An assessment of different home energy management applications is presented in [44]. In [45], a LCA concept for assessing new industry 4.0 applications is proposed, which uses ICT to automatically gather and monitor relevant mass and energy flows. Overall, the LCA is a well-established method for assessments with a life-cycle perspective of energy and digital topics and enables the inclusion of effects along the entire life cycle. Therefore, it is found to be a suitable assessment tool to be used in the context of the proposed framework.

Some of the methods described above can be combined. A recent example of the combination of MCA and LCA is [46], wherein a surface treatment process is evaluated. Eight criteria in the categories of economy, ecology, and technology are assessed in an LCA. The results are aggregated, using three different MCA methods. All criteria are quantitative. The authors conclude that the combination of MCA and LCA has a high potential while not finding any significant differences in the outcome between the three MCA methods. The prosuite project, documented in [47,48], aimed at developing a new methodology for the sustainability impact assessment of new technologies. A combination of LCA and MCA is proposed. The authors suggest a new hierarchical structure of impact categories, criteria, and so-called contributors. A LCA is used to assess the criteria. All criteria are quantitative. For the aggregation, the MCA methods of weighted sum and outranking are used. The project shows how LCA and MCA can be combined as a powerful assessment and evaluation tool. In the energy sector, a combination of the LCA and MCA methods is used by [49] to assess and evaluate 11 energy mix scenarios for Mexico until 2050, along 17 criteria in the categories of environment, economy, and society. The combination of MCA and LCA is well established. However, without further assessment methods, the combination lacks the possibility to cope with non-quantifiable data and is, therefore, not suitable for the intended purpose.

Furthermore, the MCA is also commonly combined with stakeholder/expert interactions. A recent example in the energy sector is [50], where a participatory MCA is conducted (and combined with system modeling) to assess linkages between water resources and energy technologies in Morocco and evaluate water-saving measures. Digitalization topics have also already been evaluated based on a combination of MCA and stakeholder/expert interactions. In [51], most recently, the authors use an MCA method as well as expert interactions to identify the relevance for the sustainability of different enablers of the industry 4.0 development. An approach to assess countries' industry 4.0 readiness level based on MCA methods and expert interactions is recently presented in [52]. The assessment via expert interactions is suitable for qualitative information; however, results may have higher uncertainty. In the context of the evaluation of digital applications in the energy sector, the long-term environmental impacts, in particular, require a more thorough life-cycle assessment.

In [53], the authors conduct an MCA to compare electricity generation technologies combining the MCA with both LCAs (for qualitative data) and expert judgment (for qualitative data). For each criterion, a specific assessment method, i.e., LCA or expert judgment, is determined. This approach offers many of the characteristics required for the intended purpose of the study presented here. However, the clear allocation of assessment methods to criteria does not provide sufficient flexibility for the purpose of evaluating the wide variety of digital applications with different availabilities of data.

As revealed by the discussed literature, the application of evaluation methods in the energy sector is frequently used and well-proven, especially the combination of MCA and LCA. Besides that, first applications of the discussed evaluation methods for specific digital topics are identified. None of the discussed methods or combinations of methods, however, are directly suitable as an evaluation framework for the variety of digital applications in the energy sector. Although the approach presented in [53] already shows several important characteristics, it does not meet the required specifications described above. Furthermore, the promising combination of MCA, LCA, and expert interactions has not yet been applied to digital applications. Therefore, the aim of this paper is to provide an evaluation framework for digital applications with the required properties and to demonstrate it on a selected example.

The remainder of the article is organized as follows: the proposed evaluation framework and its adaption are described in Section 2. In Section 3, the application to a German smart meter roll-out is evaluated as a first test of the framework's suitability. Finally, the results of the evaluation are discussed in Section 4, whilst a critical reflection of the suitability of the proposed framework is performed and potential adaptions are suggested in Section 5.

## 2. Proposed Evaluation Framework

Overall, the discussed literature offers a sound basis for the development of the proposed evaluation framework to close the identified gap. Going beyond the existing approaches discussed above, this paper develops an approach providing novelties on three levels:

(1) A framework is proposed based on three well-established methods, namely the multi-criteria analysis, the life-cycle assessment (consequential LCA in this case) and expert interviews. The methods can be combined in a flexible way depending on the desired level of detail and the availability of data.
(2) Since the evaluation of digital applications in the energy sector is the focus of the framework, it is adapted to the special characteristics of these applications. This is mainly done by providing a set of criteria and weighting profiles.
(3) In order to validate the theoretical concept, the framework is applied to the use case of the German smart meter roll-out.

The objective of the proposed framework is to provide a structured and transparent basis for the holistic evaluation of digital applications in the energy sector. The result of the holistic evaluation can facilitate broader societal and political discussion and support companies and other stakeholders to identify risks and critical aspects as well as potential solutions. The intended user of this evaluation framework are fellow researchers, companies of the energy sector, and governmental and non-governmental organizations.

### *2.1. Framework Development by Combination of Three Methods*

As depicted in Figure 1, the main evaluation methodology of the framework is a MCA, providing the overall evaluation structure. The assessment of the different criteria defined in the MCA, i.e., gathering and assessing the information, is conducted either within the LCA for quantitative aspects or via the expert interviews (EI) for (mostly) qualitative aspects. This combination of the LCA and EI offers flexibility to the user to choose the desired level of detail. Either a qualitative "Quick Check", encompassing the four assessment dimensions but based only on expert interviews, or a "Deep Analysis" based on detailed LCA results besides the expert interviews can be performed. Due to the high impact of the energy sector on the environment, it is of outstanding importance to understand the full environmental impacts of changes caused by digital applications. To cover all environmental impacts, a life-cycle perspective is necessary. Therefore, the deep analysis, based on an LCA, is applied for the assessment of the ecological criteria.

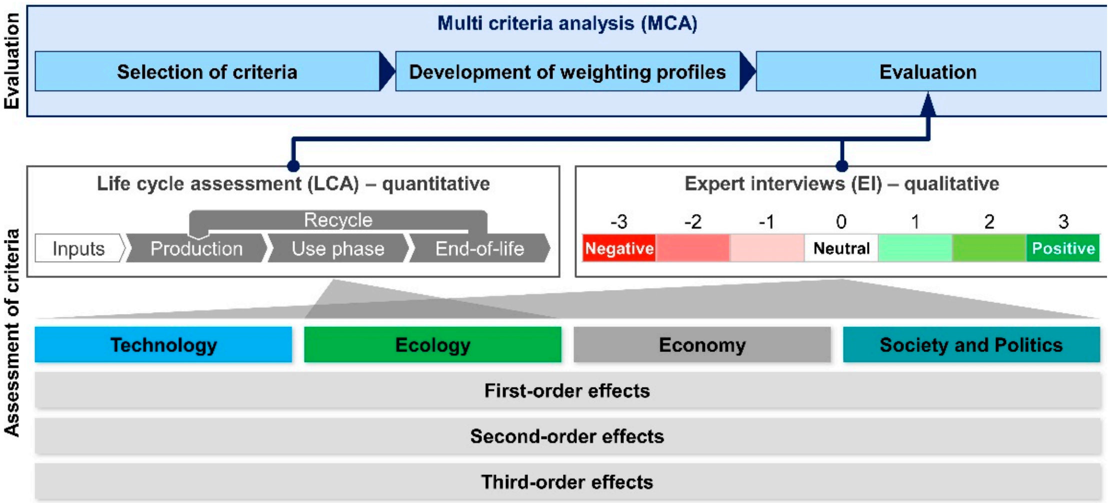

**Figure 1.** Framework for holistic assessment and evaluation of digital applications based on [5].

The MCA offers the possibility to aggregate the results on different levels, enabling a strong reduction of complexity on the one hand and providing relevant detailed information for in-depth discussions on the other. Based on the intended receiver of the result (e.g., scientific researcher, employee, or politician), an adequate level of detail can be chosen.

#### 2.1.1. Multi-Criteria Analysis (MCA)

The general MCA approach [54] is slightly modified. The following steps are performed:

1. Definition of the evaluation subject(s).
2. Identification of the relevant evaluation criteria.
3. Determination of the weighting of the criteria.
4. Assessment and evaluation of the criteria.
5. Aggregation of results and comparison of the alternatives.

As the proposed framework is intended to be suitable for all digital applications in the energy sector, step 1, the definition of the evaluation subject(s) is performed once to collectively define digital applications and derive necessary evaluation characteristics, and subsequently for each individual digital application under evaluation.

In order to achieve a holistic perspective, the evaluation criteria identified in step 2 belong to four categories—technology, ecology, economy, and society/politics (Section 2.2). These criteria cover most possible impact areas. Therefore, the framework is suitable for diverse kinds of existing digital applications as well as potential new applications. In the case that an impact is not reflected, the approach can be adapted by adding the respective criteria.

Step 3 includes the definition of weighting factors per criteria based on expert interviews. The perspectives of multiple stakeholders can be integrated via different weighting profiles (Section 2.3). The proposed weighting profiles are seen as a proposal and can be adapted as needed by the user of the framework.

The assessment of the criteria is conducted via the LCA and/or EI. The evaluation range is defined to be −3 to +3, with −3 being a very negative impact and +3 being a very positive impact. The evaluation range is depicted in Figure 2.

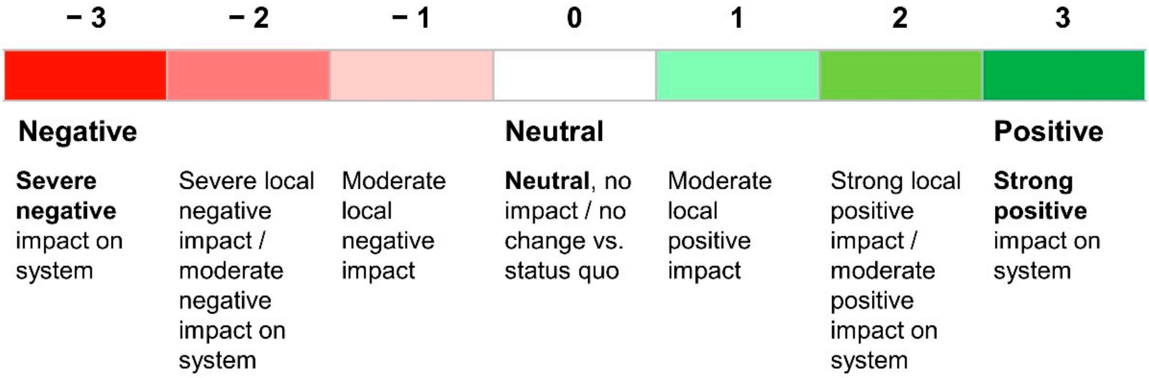

**Figure 2.** Evaluation range for MCA criteria in the case of expert interviews.

After the assessment of the criteria, the results are aggregated (Section 2.4). The compensatory system allows for the aggregation of the results of individual criteria into overall scores. Full aggregation (i.e., compensation) is possible, yet the user may decide to display the results on different aggregation levels, thus providing more detail.

### 2.1.2. Life Cycle Assessment (LCA)

According to [34], the LCA generally consists of the following four steps, which can be performed iteratively:

1. Goal and scope definition.
2. Inventory analysis.
3. Impact assessment.
4. Interpretation of the result.

The definition of the goal, scope, and functional unit in step 1 needs to be in line with the overall definition of the evaluation subject of the MCA, as the methods are combined in the framework. In particular, it needs to be considered whether an isolated application (attributional LCA) or the application, including system-wide effects (consequential LCA), is assessed. In the context of the proposed framework, in most cases, the consequential LCA is more appropriate since not only the application of one single product itself, but the impacts caused by a nationwide application are of interest. Steps 2 and 3 follow the general LCA approach. Step 4, the interpretation of results, is subsequently performed in the MCA as part of the overall framework.

### 2.1.3. Expert Interviews (EI)

The EI is a method used to quickly gather high-density information if a mostly qualitative and subjective result is acceptable.

For this study, semi-standardized systemizing interviews, as described in the educational edited volumes ([55], p. 33) and ([56], p. 465), are conducted, using the list of criteria as a structure. This offers a good compromise between comparability between the information gathered in different interviews and ensuring that the relevant aspects are identified and covered. To minimize the interviewer’s influence on the outcome, an approach of minimal interventions is used, meaning that after an initial introduction and explanation, no input from the interviewer is given throughout the central part of the interview as long as the interview partner does not raise any questions or the interviewer identifies any misunderstandings. The interviews can include quantifiable and non-quantifiable first-, second-, and third-order effects, thus all criteria can be assessed. However, it needs to be noted that EIs, unless conducted in a fully standardized way with a high number of experts, cannot be representative. However, as the expert is seen as a representative for a larger group, reasonable results can be expected.

### *2.2. Criteria Selection*

The selection of criteria is of particular importance, as it defines the range of effects considered in the analysis. The criteria need to be MECE (Mutually Exclusive and Collectively Exhaustive: No Overlap/Duplication, Fully Comprehensive) as well as relevant for the evaluated alternatives. In particular, it must be ensured that all stakeholders' perspectives are reflected.

The suggested list of evaluation criteria is based on an analysis of the existing literature, the corresponding author's own professional experience in the energy sector and expert interviews. In the first step, a long list of criteria is gathered based on the existing literature. MCA review papers, as well as articles on specific MCA applications, are analyzed. The primary focus is on MCAs in the energy sector. In particular, the publications [28,57–60] are considered. The broadest overview of used criteria, based itself on a very comprehensive literature review, is presented in [59]. The publications reviewed in [59] include a variety of different technologies as well as different analysis objectives. Therefore, the identified "typical" evaluation criteria are relatively high level and holistically cover the areas of technology, economy, ecology, and society. A similar structure of criteria categories is also found in several publications reviewed in [28]. Two specific MCA applications used to develop the criteria list are [58,60]. In [58], the case of regional use of bioenergy in Germany is used to demonstrate the decision-making process based on the MCA. Although the criteria are not structured into the four previously mentioned categories, collectively, they do cover these categories. The publication [60] adds the category legislation to the four categories for the MCA of bioenergy options in Tanzania.

The resulting long list of criteria is subsequently extended and structured based on the corresponding author's own professional experience of several years in the energy industry and with digitalization endeavors. Lastly, the criteria are refined and validated in expert interviews. Several interviews are conducted with a variety of experts, including one expert for IT security, two university professors in the field of power engineering, one representative of an energy distribution network company, one management consultancy executive with a specialization in the energy sector, one member of the energy department of the German consumer protection organization and one researcher in the field of energy technologies and life-cycle assessment. Overall, the technical, ecological, economic as well as societal perspectives are covered via the selection of experts. The interviews are conducted sequentially and on the basis of the long list of the previously identified criteria. In some cases, changes made in a later interview have to be reiterated with experts of previous interviews. Although a correlation or an overlap between criteria should be avoided, this is not possible in all cases. In particular, some technical criteria also have an impact on ecologic, economic, and societal aspects. However, these overlaps are minimized.

Overall, this approach resulted in the list of criteria displayed in Table 1. The list is structured into 4 + 1 categories, including the technology, ecology, economy and society/politics categories as well as a cross-functional risk category. The cross-functional risk of failure category consists of one criterion regarding the probability of failure and four criteria covering the impacts of failure per each of the four other categories. For each application, a failure scenario needs to be defined.

**Table 1.** List of MCA criteria.

| **Technology (hard and software)** | | **Economy** | |
|---|---|---|---|
| Generation controllability | resulting effect | Profitability for supplier | resulting effect |
| Operating reserve | resulting effect | CAPEX for supplier | effort |
| Ramp-up/down speed | resulting effect | OPEX for supplier | effort |
| Plannability of generation/consumption | resulting effect | Revenue for supplier | resulting effect |
| Black start ability | resulting effect | Amortization period | effort |
| Network controllability | resulting effect | Strategic advantages/disadvantages for supplier | resulting effect |
| Power flow optimization (high voltage) | resulting effect | Accessing new customer segments | resulting effect |
| Regional/local balancing (medium/low voltage) | resulting effect | Global growth potential | resulting effect |
| Energy savings/demand | resulting effect | First mover advantage/ disadvantage | resulting effect |
| Power demand | resulting effect | Further economic effects | resulting effect |
| Gas / heat demand (only if relevant) | resulting effect | Competitive situation | effort |
| Vulnerability of critical infrastructure | resulting effect | Market entry barriers | effort |
| Dangers of cyber attacks | resulting effect | Profitability for users | resulting effect |
| Dependence on IT systems | resulting effect | CAPEX for users (only if provider $\neq$ user) | effort |
| Security of private and company data | resulting effect | OPEX for users (only if provider $\neq$ user) | effort |
| Confidentiality of private and company data | resulting effect | Revenue for users (only if provider $\neq$ user) | resulting effect |
| Integrity of private and company data | resulting effect | Amortization period | effort |
| Availability of private and company data | resulting effect | Non-monetary benefits for users | resulting effect |
| Technological marketability (market readiness) | effort | Comfort (Convenience) | resulting effect |
| Technical implementation effort | effort | Usability | resulting effect |
| Hardware and constructions | effort | Transparency and controllability | resulting effect |
| Software | effort | Economic security and independence | resulting effect |
| Technical operating effort | effort | **Society and Politics** | |
| Technical disposal / recycling effort | effort | Social acceptance / rejection | effort |
| Availabilities of materials, know-how and capacities | effort | National added value | resulting effect |

**Table 1.** *Cont.*

| | | | |
|---|---|---|---|
| Availability of raw materials | effort | National value creation steps | resulting effect |
| Availability of know-how and capacity for production | effort | Jobs | resulting effect |
| Availability of know-how and capacity for inst. / O&M | effort | Working conditions | resulting effect |
| Availability of know-how and capacity for recycling/disposal | effort | Privacy | resulting effect |
| Innovation potential with/without retrofit possibility | resulting effect | Participation in the energy sector | resulting effect |
| Interdependencies (synergies/competition) | resulting effect | Generational justice | resulting effect |
| Interdependencies with applications in the energy sector | resulting effect | Dependence on other nations | resulting effect |
| Interdependencies with applications in other industries | resulting effect | Regulatory implementation effort | effort |
| **Ecology** | | Governmental support | effort |
| Environmental effects | resulting effect | **Probability and impact of failure** | |
| Energy balance | resulting effect | Probability of failure | risk |
| Greenhouse gas emissions | resulting effect | Technical impact | risk |
| Resource depletion | resulting effect | Ecological impact | risk |
| Human toxicity | resulting effect | Economic impact | risk |
| Enabling integration of renewable energies | resulting effect | Societal impact | risk |

### *2.3. Criteria Weighting*

The weighting of the criteria is necessary to reflect differences in the importance of different criteria. Weighting becomes especially important when the multi criteria analysis includes the perspectives of different stakeholders. Either one weighting profile, which covers all stakeholders' perspectives, can be defined, or the stakeholders' different views can be represented in different weighting profiles.

An extensive range of methods is available to determine weighting factors, each with inherent advantages and disadvantages. The method of criteria weighing might have a stronger effect on the overall result than the method of the MCA as suggested by [61]. A comprehensive overview of weighting methods is given in ([62], pp. 46–58), as the authors extend the previously prepared review by [63]. The authors conclude that there is not one method that proves to be superior but the method rather needs to be chosen individually based on the MCA method used, the type of criteria, the available information, and the knowledge and skill of the person determining the weighs. Overall methods can be classified into direct vs. indirect, objective vs. subjective [62,64], and compensatory vs. non-compensatory [65]. Well-known and broadly used weighting methods include ranking, rating (including point allocation), and pairwise comparison (including the analytical hierarchy process).

In the context of this study, point allocation, a direct, subjective, and non-compensatory rating method, is used. This method bears the inherent advantage of its simplicity and is found to be well working in the experimental comparison of weighting approaches in [66]. It is chosen to use 100 allocation points. The 100 points represent 100% importance, a concept that is understood by experts and decision makers without further explanation. Once all points are allocated, in order to increase the weight of one criterion, the point allocator needs to reduce the weight of another. This forces the point allocator to thoroughly question previously determined weights. In this case, after the allocation of all points, a sense check is encouraged by comparing selected pairs of criteria in an iterative process to ensure that both the weighting order and the weighting distances between them reflect the allocator's preference. This sense check is necessary, due to the large number of criteria. As the approach starts with weighting the high-level criteria categories, the number of criteria within each category does not influence the overall weight of the category. The risk of non-matching criteria units is encountered by choosing matching units and communicating those to the point allocators.

The weighting itself, meaning the allocation of points, is performed by experts in expert interviews. Overall, seven interviews are conducted with experts, including two representatives of a regional energy utility company, one representative of an energy distribution network company, one management consultancy executive with a specialization in the energy sector, one representative of an NGO with an environmental focus, one member of the energy department of the German consumer protection organization and one representative of the German Trade Union Confederation. Based on the weightings defined in the interviews, several weighting profiles representing different perspectives are defined. In the context of this work, four profiles are defined, namely, energy utility, consumer (prosumer), environment NGO, and national economy. The differences on the category level are depicted in Figure 3.

These profiles are calculated by averaging the weightings over the relevant interview results. The energy utility weighting profile is based on the results of the two interviews with regional energy utilities and the distribution network operator. The consumer (prosumer) perspective is based on the interview results of the representatives of the consumer protection organization and the trade union. The environmental perspective is based on the interview with the environmental NGO. Finally, the national economy perspective is calculated as an average of all interview results with two exceptions. Firstly, the weighting results of the two participating regional utilities are averaged and counted as one result so that the utility perspective is not overrepresented in the national economy view. Secondly, the result of the consultancy executive is counted twice, as he has the broadest overview of the energy sector. It is important to notice that results based on seven interviews cannot be statistically representative and, therefore, the weighting profiles need to be understood as a subjective but well-educated estimate.

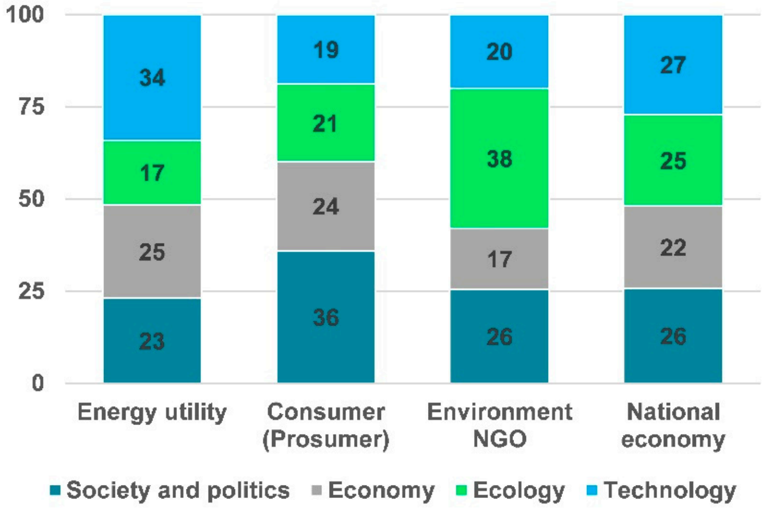

**Figure 3.** Weighting profiles.

### 2.4. Normalization and Aggregation of Results

Using the weights previously defined, the results can be aggregated. The aggregation is performed sequentially from sub-criteria to criteria, to category, to overall application level. Here, the simple additive weighting (SAW) method is used as described in [57] due to its simplicity. The aggregated result is calculated as the weighted sum of the (sub)criteria results by the following:

$$\overline{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i-1}^{n} w_i} \tag{1}$$

with $\overline{x}$ being the arithmetic mean, i.e., the result calculated based on the weight $w_i$ and the (sub)criteria evaluation $x_i$ with $i$ being the number of (sub)criteria.

In the case of the quantitative LCA results, these need to be translated into the qualitative MCA evaluation range before aggregation, referred to as normalization. Normalization is conducted using a reference value. The reference can be external (e.g., national $CO_2$ reduction target) or internal ($CO_2$ eq. reduction of a presented scenario). External referencing is preferred to internal references, as it offers increased objectivity [67]. However, the reference needs to be defined for each evaluation and each criterion based on the availability of information and objectives of the evaluation, external references may not always be available.

## 3. Test of the Proposed Framework

After the development of the evaluation framework and its adaption to digital applications in the energy sector described in Section 0, a digital application is evaluated as a first test of the framework's suitability. The evaluated digital application is the smart meter roll-out in Germany. This application is well defined by a German federal law [68]. As it is one of the main topics of the digitalization of the energy sector, it offers reasonably good availability of data.

### 3.1. Analysis of Boundaries and Assumptions

In the following section, the smart meter roll-out, the analysis boundaries, and key assumptions are described.

The subject of the evaluation is the smart meter in comparison to the conventional meter. The comparison is conducted in the context of the German national smart-meter roll-out over a time period of 20 years. Operational roll-out effects (e.g., replacing still-functional conventional meters, system effects which require a minimum number of smart meters to become effective) are not considered, but rather a steady-state of using smart meters vs. using conventional meters.

The basic functionalities of the smart meter and its components (§21) as well as the smart meter roll-out (§29) in Germany are defined by the federal law for "digitalization of the energy transition" [68]. According to §21, a smart meter needs to have the functionality to measure the electricity used or produced and relevant grid parameters to store and manage the data, to provide an option to visualize energy-related data, to establish secure connections to transmit energy-related data, to connect further devices and to provide an option to implement different types of tariffs. The smart meter herein is called the intelligent measuring system (iMSys) and consists of the modern measuring device (mMe) and the gateway (GW), which is the communication unit. At this point in time (26 November 2020), there are four producers of smart meters offer devices, which meet the above criteria and are certified as defined by the German federal office for information security, while five others are still awaiting certification. The smart meter configuration modeled in this study is based on the information provided by two manufacturers exclusively to this research project.

The list of assumptions on aspects of the smart and conventional meters, such as the electricity consumption per device, lifetime, and the recycling share, is displayed in Table A1 (Appendix B). As no reliable information could be obtained on the maintenance need, the maintenance processes are not included in the LCA model. Several assumptions are taken regarding the as-is and future development of key aspects of the energy sector, including the number of metering points, the electricity demand, and the electricity GHG intensity.

The above-mentioned federal law also describes the roll-out plan. Energy consumers of more than 6000 kWh/year are required to receive an iMSys, while all smaller consumers receive only the mMe without the communication device. Energy producers with a bigger capacity than 7 kW are also required to install an iMSys. However, a revision of the German law for renewable energies [69], which is currently debated, envisions a roll-out of iMSys to generation assets of above 1 kW. The present study assumes a roll-out as described in the "Rollout Scenario Plus" of [19]. Based on this scenario, there will be installed 16.2 Mio iMSys and 35.4 Mio mMe, thus a total of 51.6 million meters in Germany. One difference between the used scenario and the currently planned roll-out exists. In the "Rollout Scenario Plus", it is assumed that all generation assets with >0.2 kW receive an iMSys instead of the currently planned limit of >1 kW. However, the difference in terms of number of smart meters as well as in terms of system impact is believed to be small enough to be disregarded. According to data of the German registry for electricity generators available at [70] in 2020, there are only ~29 thousand generation assets that fall into the described range versus a total of 1.52 million assets under the definition of [69].

The electricity demand in Germany is modeled based on the "Energy market prognosis" [71] of the German Federal Ministry for Economic Affairs and Energy. On the one hand, efficiency increases have reduced the demand in recent years and further efficiency increases can be expected during the next decades. On the other hand, a strong electrification trend is expected, e.g., electric cars, electric heating, which would increase electricity demand. Therefore, overall demand is expected to remain constant over the next 20 years.

The development of the GHG intensity of the German electricity mix is estimated based on historic emission and energy consumption data from the European GHG Inventory [72] and yearly report of the specific $CO_2$ emissions of the German energy mix published by the German Environment Agency [73] as well as the reference prognosis and trend scenario for future energy generation in [71] adopted for the 2019 developed coal exit path described in the final report of the German "Coal Commission" [74]. In contrast to the referenced climate reports, in this LCA, the GHG intensity is calculated as the global warming potential over 100 years (GWP100—calculated according to the "AR5" dataset given in [75]). The GWP100 also includes effects of upstream value stream steps, e.g., the proportionate use of the electricity grid. Thus, the GHG intensity values calculated based on the GWP100 are higher than those ones of the referenced data. The GWP100 is measured in kg $CO_2$ eq. emissions (kg $CO_2$ eq.), which means that also GHG emissions other than $CO_2$, e.g., methane, are included, normalized to the effect of $CO_2$. Hence, in the following, if $CO_2$ eq. emissions are mentioned, the underlying calculation is the GWP100. This approach leads to an GWP100 of the German electricity mix of 0.460 (2020), 0.330 (2030) and 0.257 kg $CO_2$ eq./kWh (2040) as stated in Table A1. For all production process steps, the energy mix of 2020 is used; for the use-phase steps, the energy mix of 2030 is used; and for the end-of-life phase, the energy mix of 2040 is used.

In order to include the impacts of the smart meter on the energy system, a consequential LCA is performed. The question of how smart meters impact the energy system is discussed widely and several studies have come to different conclusions. In this study, two technical impacts on the energy system are considered: a reduction of the energy demand and a reduction of the required grid reinforcements. These are described as the most relevant technical impacts in the German smart meter cost–benefit analysis [19]. The reduction in energy demand is believed to be due to increased transparency on energy consumption of different appliances, leading to a behavioral change. The magnitude of behavioral change seems to depend on the level of feedback that a user gets from the smart meter, i.e., feedback via in-house displays or online platforms accessible via mobile devices result in more energy savings compared to feedback via the integrated display of the meter, which is usually located in a non-living area of the building. A good overview of different evaluations of the expected energy savings is given in ([20], p. 19 Part II). The authors cite 57 different studies indicating energy savings between 0 and 19.5%, with the most reliable studies ranging between 1 and 4%. The authors conclude to use 2.8% for the British cost–benefit analysis. For Germany, the authors of [19] conclude to take a more conservative approach due to the high level of uncertainty and assume an average energy saving of 1.8%. This study follows this overall conclusion. However, several aspects that may influence the overall energy savings are not modeled separately, such as different types of user feedback, the difference in savings between mMes and iMSys and the size (in kWh) and location of the smart meter user. Since the uncertainty of this assumption is high, especially because it is unclear whether the energy savings are time persistent, a sensitivity analysis with a focus on the energy savings assumption is conducted.

Besides the potential energy savings, the smart meters could also reduce the necessity for grid reinforcements. Grid reinforcements could be avoided due to improved planning based on more data points from the smart meters, due to reduced peak loads based on remotely controllable, small-scale distributed generation assets, and due to the reduction in energy demand. In [19], the authors quantify the reduction based on these three effects as 1% in the high voltage transmission grid and 30% in the low and medium voltage distribution grid. The reduction potential in the distribution grid is much greater, as the controllable small-scale generation assets are usually connected to the low voltage grid. This study follows the conclusion on grid reinforcement reduction taken by the authors of [19].

Although a variety of other impacts are likely to materialize, they are not included in the LCA as they are difficult to quantify, and no consistent values are found in the literature. Among these impacts is the increased integration of renewable energies, which could lead to a $CO_2$ eq. emission reduction and the effects of improved load shifting, which could further increase the reduction of the required grid reinforcements. Instead, these effects are reflected in the qualitative expert interview evaluations.

### *3.2. Life Cycle Assessment*

A consequential life-cycle assessment is performed for the smart meter roll-out. For this purpose, first, the life cycle of one individual smart meter and one conventional meter (as a comparison) is analyzed. In a second step, these findings are put into the context of the German electricity system over an analysis period of 20 years, which roughly resembles the lifetime of electricity meters. In a last and final step, the effects (consequences) that the smart meters cause in the energy system regarding energy demand and the need for grid reinforcements are included. A schematic overview is depicted in Figure 4.

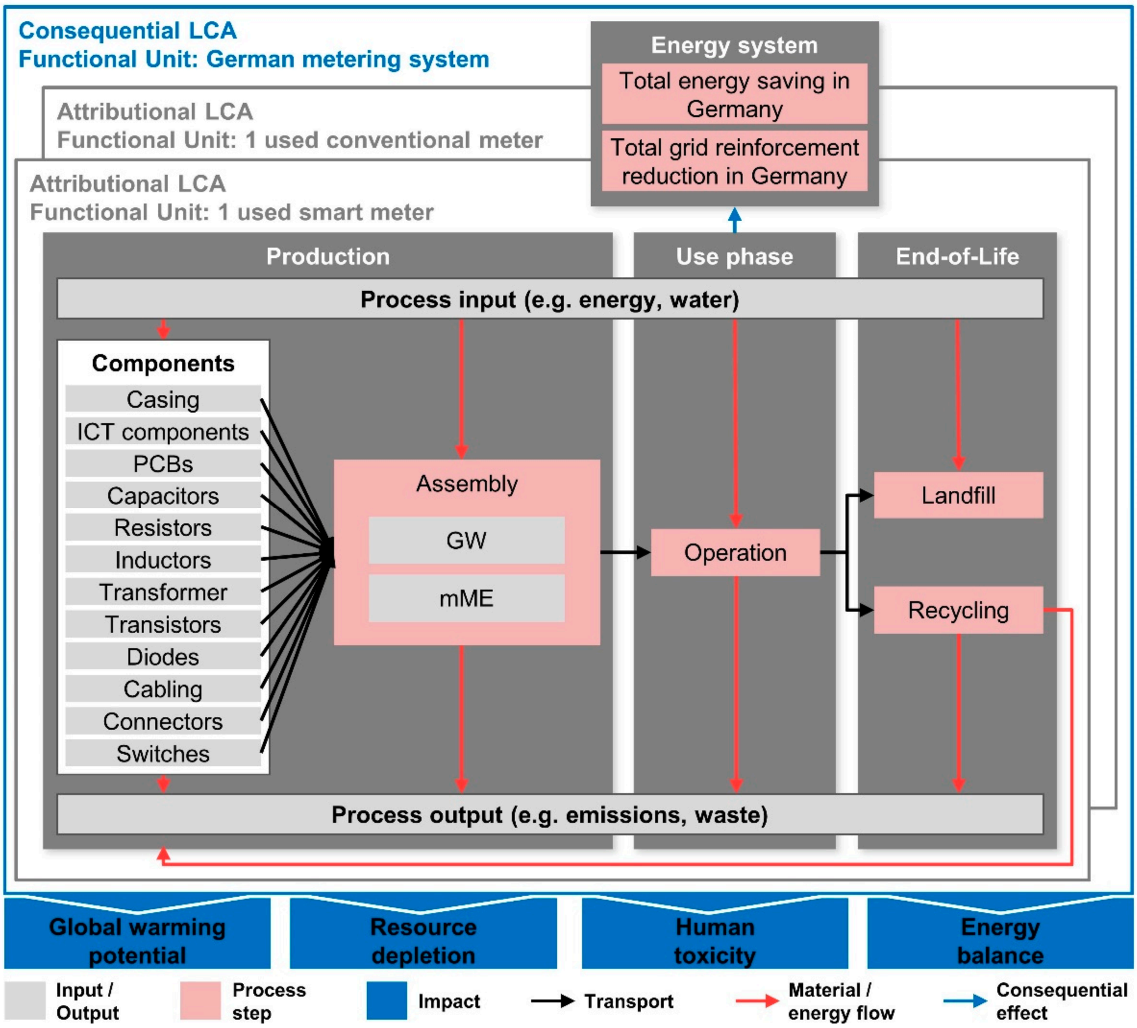

**Figure 4.** Schematic overview of smart meter LCA.

The life-cycle analysis of an individual smart meter (consisting of a mMe and a GW) is conducted in cooperation with two smart meter manufacturers. While one shared rather high-level results of the previous internal life-cycle analysis, the second one provided full transparency on the list of components assembled in the devices and their geographic origin (data supplied in several iterations between January 2019 and December 2020). All standard components, such as resistors, capacitors, and transistors (see Figure 4), are detailed based on the specific components' datasheets. All custom components, such as the device case, are detailed by the smart meter manufacturer.

The entire list of components and their origins is modeled in OpenLCA (1.10.1), using the ecoinvent (3.3-cut-off) database and a slightly modified version of the CML 2001 impact assessment method. The standard settings for production of the identified components are mostly used; however, the geographic location is adapted and the required transport is added. For some components, no standard settings are available; here, new settings based on literature and web research about the components' production process are implemented.

The main impact category discussed in the following section is the global warming potential over 100 years (GWP100). Further analyzed parameters are the energy balance, human toxicity (HTP100), and the depletion of resources as the most relevant expected ecological impacts caused by digital applications in the energy sector.

The life cycle analysis results reveal that 75% of the GWP100 of the smart meter's production is caused by the gateway, with the biggest contributor for both devices, GW and mMe being the ICT components. The total production-related GWP of one smart meter is found to be 82 kg $CO_2$ eq. When the use phase as well as the recycling/landfilling are added to the LCA, the total smart meter lifetime GWP is calculated to be 558 kg $CO_2$ eq. Similarly, to the smart meter, the conventional meter is modeled. However here, data of incorporated materials from [43] are used for the life-cycle assessment. The overall production GHG footprint of a conventional meter is found to be 11 kg $CO_2$ eq., and therefore much smaller than the footprint of the smart meter. The total conventional meter lifetime GWP is 211 kg $CO_2$ eq.

In order to directly compare the smart meter and the conventional meter, their lifetime needs to be proportionally considered, i.e., 20/18 = 1.11 smart meters and 20/30 = 0.67 conventional meters are required during the 20-year analysis period. The result shows that the use of a smart meter causes an increased GWP100 impact of about 489 kg $CO_2$ eq., more than the use of a conventional meter over 20 years. However, not all consumers will receive fully-fledged smart meters; some, depending on their consumption, will only receive a mMe without the GW. Therefore, the roll-out assumption about the number of mMes and full smart meters (iMSys) described in Section 0 need to be considered. Approximately 35.4 million mMes and 16.2 million smart meters (iMSys), instead of a total of 51.6 million conventional meters, are assumed to be in use during the analysis period of 2020–2040. The life cycle impact (including production, use-phase, and end-of-life) of the smart meter roll-out, compared to using conventional meters, is an increase in the GWP100 of $8.2 \times 10^9$ kg $CO_2$ eq., i.e., 8.2 Mio t $CO_2$ eq. over 20 years.

However, the use of smart meters also causes effects within the energy system, which need to be included in the consequential LCA. As discussed in Section 0, the two system effects of electricity savings and reduction of grid reinforcements are modeled. Taking into account the life cycle impact of smart and conventional meters and the positive system effects of smart meters, overall, a GWP100 reduction of 23.9 Mio t $CO_2$ eq. over the analysis period of 20 years is identified.

The GWP100 results of the LCA of the live cycle comparison between smart and conventional meters are depicted in Figure 5. GWP100 impacts of the conventional meter are regarded as negative, as they are seen as avoided impacts.

Besides the GWP100, two further LCA impact categories, human toxicity, and resource depletion, as well as the LCA energy balance, are analyzed. Under the above-described assumptions (base scenario), all parameters show a significantly positive impact of the smart meter roll-out (see Figure 6).

The sensitivity of the results to different assumptions is discussed in Section 3.4 (see Figures 9 and 10).

### 3.3. Expert Interviews and MCA Evaluation

The expert interviews to evaluate the smart meter roll-out in Germany are conducted with the same seven experts already consulted to develop the weighting profiles (see Section 0). In some cases, weighting and evaluation are performed within one session. For every criterion, the experts could decide whether they want to provide any evaluation at all and, if so, if they want to evaluate on the criteria level or, in case they feel sufficiently knowledgeable, on the sub-criteria level. This approach ensures that experts can evaluate criteria in-depth in their area of expertise, while avoiding evaluating criteria where they lack the required expertise.

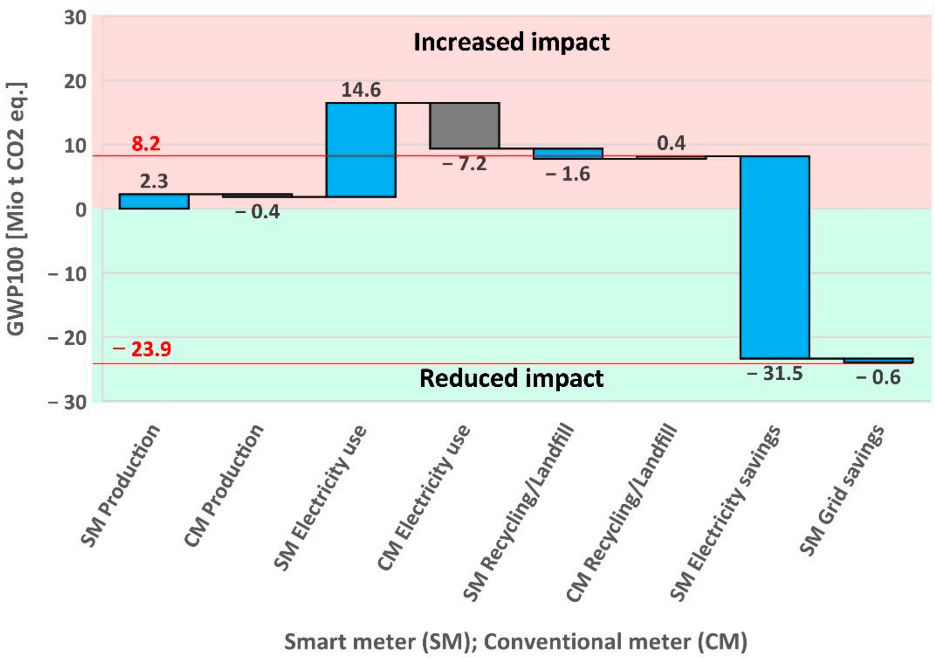

**Figure 5.** GWP100 result of LCA comparison of smart and conventional meters over 20 years.

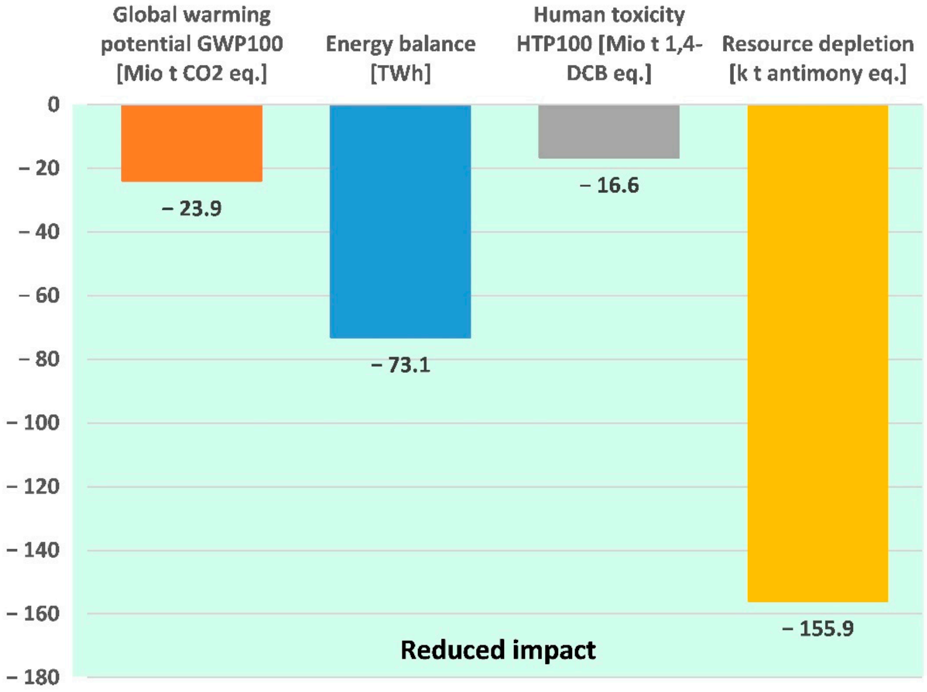

**Figure 6.** LCA impact categories for comparison of smart and conventional meters over 20 years.

For the aggregation of results, the SAW method is applied (see Section 2.4), using the weights of the defined weighting profiles (see Figure 3).

As one of the goals of the presented evaluation framework is to combine the views of different stakeholders, the overall evaluation is calculated based on the arithmetic average of each sub-criterion, criterion, and category across all experts. One adaption, however, is made. Since two of the experts are representatives of a regional energy utility, their results are averaged first such that they only contribute as one expert to the overall result (same procedure as conducted for calculating the weighting average).

For LCA criteria, i.e., energy balance, GWP100, resource depletion, and human toxicity, only the normalized LCA results are used for the MCA evaluation. The quantitative LCA results need to be translated into the qualitative MCA evaluation scale from −3 to +3. As described in Section 2.4, the reference for this normalization needs to be determined for each criterion and for each assessment of a digital application. In this case, the results are translated against an internal value, the results of the "2.25% electricity savings" scenario, which reflects a very positive scenario. The scale is set to be +3 for the results of the "2.25% electricity savings" scenario and 0 for zero effect on the impact category. For the base scenario, this translates into MCA evaluations of +2.3 for the energy balance, the GWP100, and the resource depletion and a +2.5 for human toxicity.

Overall, the above approach leads to the results depicted in Figures 7 and 8. While Figure 8 provides a better overview of aggregated results, Figure 7 is particularly important to understand which benefits are generated by the application and where risks of negative impacts appear. This knowledge can start a solution-finding process to resolve the causes of negative evaluations.

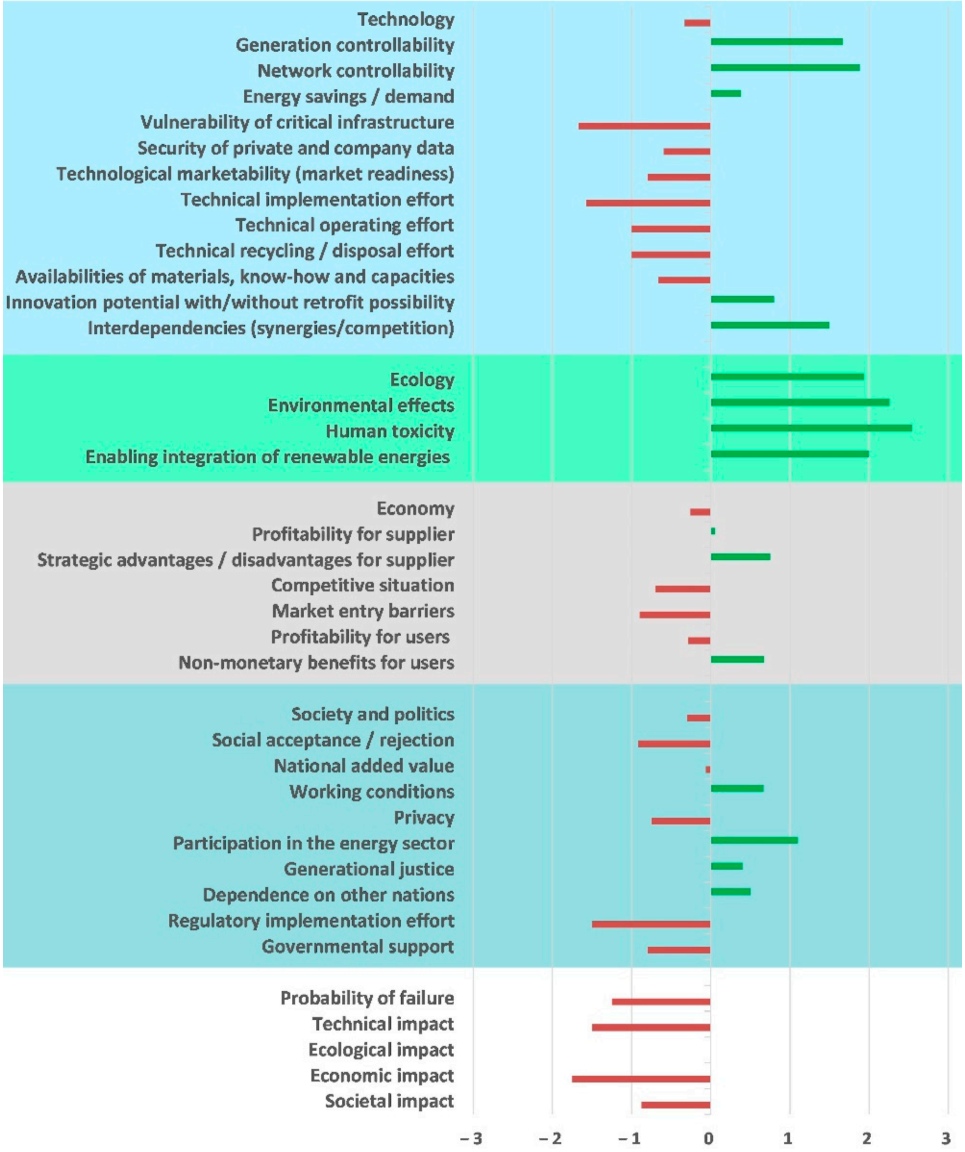

**Figure 7.** MCA result per criterion for national economy weighting profile.

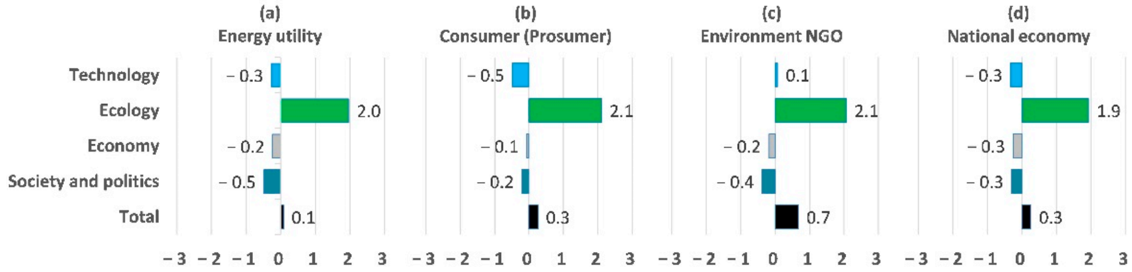

**Figure 8.** MCA result per category for four weighting profiles.

The results per criterion for the national economy weighting profile are depicted in Figure 7. The categories technology, economy, and society and politics show an overall negative evaluation while ecology overall is evaluated positively.

In particular, the category technology reveals a negative result. The main negatively evaluated criteria are the impact on the vulnerability of the critical infrastructure and the technical implementation effort. On the side of positively evaluated criteria, the effects on the controllability of the generation and the grid are among the most positive. Further positively evaluated criteria are the innovation potential and interdependencies.

The ecology result is significantly positive across all criteria and sub-criteria.

The economy category is evaluated as slightly negative, mainly due to high market entry barriers and expected future increased competition. The most positive criteria of this category are the non-monetary benefits for the supplier and the user. For the supplier, the potential to reach new customer segments and for the user an increase in convenience are the most positive non-monetary benefits. The monetary profitability for the supplier is very slightly positive. On the other side, the profitability for the user is negative.

In the category of society and politics, the experts see a significant need for regulatory implementation effort and the need for governmental support. Furthermore, it is expected that the smart meters will be met with rejection rather than with acceptance. The main positive criterion of this category is the increase in participation of formerly passive consumers in the energy sector.

For the evaluation of the probability and impact of potential failures, the worst technical malfunction is considered. For the smart meter roll-out, this worst case is assumed to be a widespread malfunction of the meters, delivering no or wrong consumption, generation, and grid data. The case of an intentional attack on smart meters is already covered in the criterion vulnerability of the critical infrastructure. The biggest negative impacts are believed to be of an economic and technical nature, while the societal impact is only slightly negative, and no ecological impact is expected. As risk is a cross-functional category, no category score is calculated, but the evaluations are allocated to the respective category where the impact occurs.

As discussed in Section 2.3, different weighting profiles are derived from the weighting expert interviews (see Figure 3). These weighting profiles influence the overall MCA results, as they represent the perspectives of different stakeholders. The different results are depicted in Figure 8. Figure 8d, “National economy”, shows the same weighting profile used for the results in Figure 7. The energy utility perspective (a) is notably similar to the national economy perspective. The main difference is in the evaluation of the category society and politics. Here, the energy utilities give more weight to the regulatory implementation effort, which causes a more negative overall result. The consumer perspective (b) reveals a more negative result in the technology category. This is mainly due to the higher weighting of the IT and data security criteria. The environmental NGO perspective (c) is the only one with a positive result in the technology category, due to the much lower weighting of the technological effort criteria (e.g., implementation effort, operation, and maintenance effort); this gives more relative weight to the positively evaluated generation and grid controllability. The positive technology evaluation and more weight on the ecological category cause the more positive evaluation of this weighting profile.

Overall, the total result is slightly positive for all weighting profiles. The environmental impact category is evaluated positively for all weighting profiles, while the economy and society and politics categories are evaluated negatively for all weighting profiles. The technology category is only positive when evaluated with the environmental NGO weighting profile.

The different weighting profiles could be seen as a sensitivity analysis regarding the impact of weighting. However, in the proposed framework, the use of different weighting profiles is an integral part, thus these weighting profiles and their effects are seen as part of the results rather than a sensitivity analysis.

### *3.4. Sensitivity Analysis*

First, the sensitivity of the LCA results to two central assumptions (potential contribution to energy savings, decarbonization paths of the German energy mix) is analyzed, and subsequently, the impact of different LCA results on the overall MCA evaluation is assessed.

Although the LCA is based on a detailed technical analysis of the components of a mMe and a GW, several assumptions need to be made when the findings of these devices are put into the context of a nationwide roll-out with effects on the broader energy system. The main assumptions are discussed in Section 3.1. An overview of all explicit assumptions is presented in Table A1.

Figure 9 depicts the sensitivity of the LCA result regarding the assumption on the smart meters' potential to cause energy savings. The reasons why a special focus is put on this assumption are that, on the one hand, it is subject to high uncertainty, and, on the other hand, it has a very strong effect on the LCA outcome. The base scenario assumes a saving of 1.8% of the electricity used by the users of the smart meters. In this scenario, all evaluated LCA impact categories are positively impacted (meaning a reduction of the impact is achieved). Therefore, the sensitivity analysis focuses primarily on identifying the tipping point where LCA results turn out negative (meaning an increase of the impact). Within the analyzed range of energy savings, all four impact factors have a linear correlation with the energy-saving assumption. The GWP100 break-even energy saving rate is found to be 0.43%. If smart meters generate more energy savings, their overall impact on the GWP100 is positive (GWP reduction). The energy balance and the resource depletion break-even point is very close to the GWP100 break-even point, indicating the close connection of the impact factors. Regarding the impact on human toxicity, a decrease is identified across all energy saving scenarios, even for the no electricity savings scenario. This is due to the modeled grid reinforcement reduction, which reduces the use of copper and its effects on human toxicity.

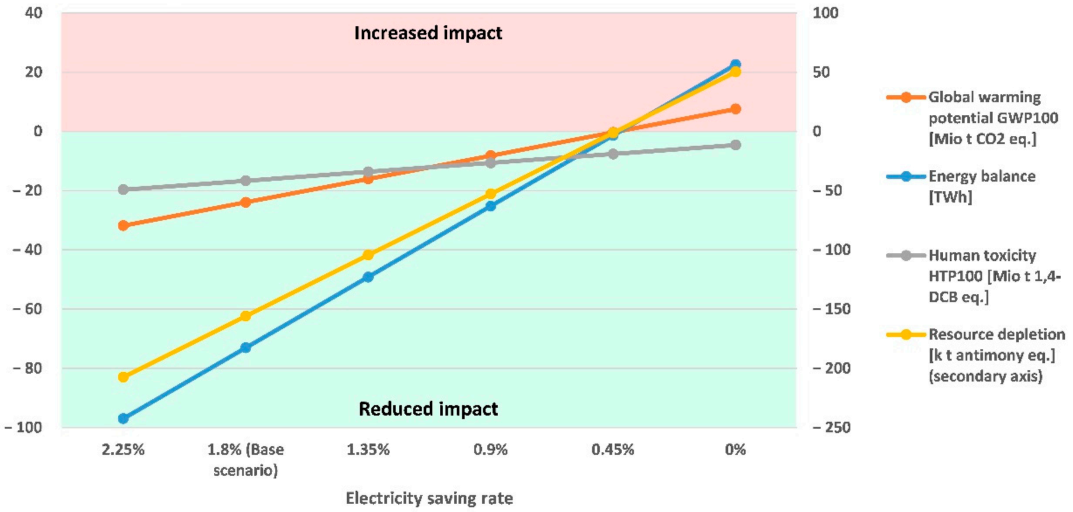

**Figure 9.** Sensitivity of LCA result regarding energy saving assumption.

Since the electricity savings determine whether an overall GWP reduction can be achieved, an analysis of the different decarbonization paths of the German energy mix is necessary. If the decarbonization is achieved faster than expected, i.e., GWP intensity is only half of the estimates for 2030 and 2040, a GWP reduction would still be achieved. However, with only 12.02 Mio t $CO_2$ eq. over 20 years compared to 23.9 Mio t $CO_2$ eq. in the base scenario, the reduction is significantly smaller. If the GWP intensity does not decrease but rather stays constant over the next 20 years, the potential emission reduction increases to 33.5 Mio t $CO_2$ eq., respectively.

Comparing the influence of the energy saving on the LCA outcome in Figure 9 to the further impact factors in Figure 10, it can be seen that the very dominant effect on the impact categories is created by the energy savings. The "no grid reinforcement savings" scenario slightly reduces the savings in resource depletion due to the use of copper wire for grid reinforcements. This, in turn, also reduces the positive impact on human toxicity. However, the GWP saving remains almost unchanged. The "no recycling of smart meters" scenario tests the impact if smart meters cannot be recycled. Overall, the impact of this scenario is rather low, mainly due to the low production impact and long lifetime of the devices. If the smart meters have an own electricity consumption twice as high as assumed, a stronger effect on the energy balance, the resource depletion, and the GWP can be noted. An even higher own electricity demand is very unlikely, according to the manufacturers and utility experts. Yet, this effect does not come close to eliminating the overall savings. In the case of no positive system effect, i.e., no electricity savings and no grid reinforcement savings, all LCA impact categories increase and consequently, no positive impact is generated by the smart meters. The negative impact seen in this scenario is the production and operation impact of smart meters as electronic devices with a higher own electricity consumption and a shorter lifetime, compared to the analog conventional meters.

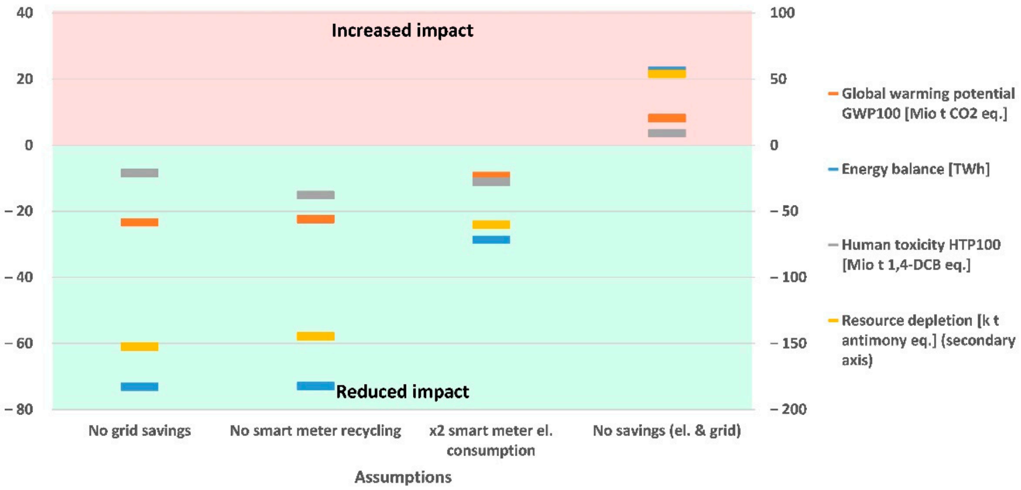

**Figure 10.** Influence of general assumptions on LCA result.

In a second step, the effect of the LCA result on the overall MCA evaluation is assessed. As described in Section 0, the LCA results are translated against an internal value, the results of the "2.25% electricity savings" scenario. While for the base scenario, this translates into MCA evaluations of +2.3 for the energy balance, the GWP100, and the resource depletion and a +2.5 for human toxicity, for the worst-case "no savings" scenario (no electricity savings and no reduction of grid reinforcements) this translates into an MCA evaluation of −0.7 for energy balance, −0.8 for GWP100 and resource depletion and −0.6 for human toxicity. Based on this translation, the difference between the base scenario and the "no savings" scenario affects the MCA result regarding the ecology category, which changes from an overall score of positive 1.9 to a neutral 0 for the national economy perspective. This, in turn, changes the overall MCA outcome from a positive 0.26 to a negative −0.23.

## 4. Discussion

Following the structure of the former section, the discussion is structured in three parts: LCA, MCA, and sensitivity analysis.

### *4.1. LCA*

Smart meters are relatively similar to other ICT hardware with regards to the type of components and materials used and the manufacturing process; therefore, the total production GWP impact and the main contributors are similar. A smartphone has a production GWP of approximately 48 kg $CO_2$ eq. [76]. Considering that a smartphone is significantly smaller and lighter but has a more potent CPU and a bigger display, the obtained smart meter GWP result of 82 kg $CO_2$ eq. is plausible. Besides that, similar to the smartphone, the main source of GWP impact is identified as the ICT components, such as integrated circuits. In contrast to a smartphone, the electricity meters have a long lifetime; therefore, the share of the GWP impact of the production, compared to the use phase, is found to be rather small. With an expected lifetime of 18 years, the GWP100 of the smart meter use phase is by a factor of seven greater than the GWP100 of the production of the device. This finding is roughly confirmed by the high-level life cycle analysis data supplied to the research project by a second smart meter manufacturer. Thus, own electricity consumption is the factor with the biggest impact on the GHG emissions caused by the electricity meters and, therefore, offers the most significant leverage for improvements.

Comparing the life-cycle impact of using smart meters over 20 years to using conventional meters reveals an increase in the GWP100 of 8.2 Mio t $CO_2$ eq. This shows that if the smart meters do not generate benefits, they merely increase the GWP100 of the metering system. However, the additional 8.2 Mio t $CO_2$ eq. emissions over 20 years are small compared to the yearly ~111 Mio t $CO_2$ eq. emissions (calculated for 2020 based on assumptions in Table A1, 104 Mio t $CO_2$ eq. based on [71]) of the electricity consumed by the smart meter users (households and small businesses). Therefore, it is apparent that already, a very small impact on the energy demand can neutralize the additional GWP100 emissions of the smart meters.

The consequential LCA looks beyond the direct life-cycle impact of the device and takes system impacts into consideration. In this case, the two system impacts energy savings and grid reinforcement reductions are assessed. When including both of them, the overall effect of using smart meters instead of conventional meters is positive, meaning a GWP reduction of 23.9 Mio t $CO_2$ over 20 years. Here, the overwhelming effect is the reduction of the energy demand. However, comparing the GHG reduction achieved over 20 years to the yearly $CO_2$ eq. emissions of the smart meter users (111 Mio t $CO_2$ eq., see above) reveals that the smart meter, including the modeled system effects, does not drastically change the $CO_2$ eq. intensity of the energy mix. In order to play an important role in the energy transition, the smart meters need to enable further system effects, such as enabling the integration of more renewable energies.

Besides the GWP, three additional impacts are assessed. Under the base scenario assumptions, all parameters show a significantly positive impact of the smart meter roll-out. The reduction of 73.1 TWh of the electricity demand is driven by the modeled energy savings of 1.8%. The reduced human toxicity is due to the modeled energy savings (~2/3) and the modeled grid reinforcement reduction (~1/3). The reduced resource depletion is mainly driven by the reduced energy demand and the subsequently reduced depletion of fossil fuels. The different hardware of smart and conventional meters does not have a significant impact on the overall resource depletion.

Although the results of the LCA of smart meters vs. conventional meters in California [43] partly include different effects and therefore indicate different GWP levels, qualitatively, they are in line with the results of this study, e.g., proportions of GWP contribution of production, use-phase, and end-of-life, offset of higher GWP of smart meters production and use-phase via energy savings.

### *4.2. MCA*

The MCA discussion is structured along the four criteria categories. The results are based on the expert interviews as well as the LCA results.

The category technology is evaluated negatively, thus it is necessary to identify which aspects cause this negative evaluation and identify potential solutions. The results show that the experts mainly see a high technical implementation effort and a negative effect on the vulnerability of the critical infrastructure. These points indicate areas where a special focus needs to be applied when defining the smart meter roll-out. Furthermore, some steps are seen as still necessary to reach marketability of the smart meters. This includes the technical ability to allow remote control, the interoperability between devices of different manufacturers and a process to recalibrate existing meters. On the other hand, also positive impacts can be identified. The main positively evaluated technological criteria are the controllability of the electricity generation and the grid. However, experts consistently noted that one requirement for these positive impacts to materialize is an extended possibility for distributed generation assets and consumers to be remotely controlled. This involves establishing the regulative basis (currently not given for consumers and smaller generators) and the certification of communication gateways with the required technical ability. On the one hand, the remote controllability is the basis for several other intended positive impacts of the smart meter, such as the integration of renewable energies, energy savings, improved profitability for users due to flexible tariffs and, in a broader sense, increased participation of users in the energy sector. On the other hand, however, the requirement to equip also smaller generation assets with smart meter gateways could reduce their profitability and cause fewer small-scale renewable assets to be connected to the grid. These effects on grid and generation controllability are the main technological reason for the smart meter implementation and as such, their influence on the evaluation of the technology category might be underrepresented. Experts consistently were surprised by the negative (or only very slightly positive) outcome of the technology category based on their own weighting and evaluation. A higher number of effort criteria, which are generally evaluated negatively, potentially causes this apparent weighting imbalance. Thus, a better balance between effort and impact criteria might be needed. Many experts see the smart meter as an enabler for future developments, such as smart home applications. Therefore, the innovation potential is evaluated positively. Nevertheless, the experts expressed the concern that the first-generation smart meters already need to be upgradeable/updateable to fulfill the full range of future applications and thus do not need to be replaced before the end of their lifetime.

Due to the positive LCA results and the positive effect on the integration of renewable energies, the overall ecological result is positive. The improved integration of renewables likely correlates with the technical criteria of generation and grid controllability and is one of the main reasons for the implementation of smart meters. The expert interview results for LCA criteria, although not part of the evaluation, can be used to crosscheck the LCA results. The experts evaluate the LCA criteria as less positive, compared to the outcome of the LCA. The biggest difference occurs for the sub-criterion resource depletion. Here, it is possible that the experts considered a practical roll-out, which involves replacing still-functional conventional meters with new smart meters, which influences resource depletion negatively. In the LCA, this practical roll-out effect is not considered.

The monetary profitability for the supplier is slightly positive. Considering that the prices for smart meters are regulated and set as low as possible while still allowing the supplier to benefit, this evaluation is plausible. The profitability for users, on the other hand, is evaluated slightly negatively. The experts do not expect that the users’ reduction in the electricity bill (or increase in revenues from a small generation asset) will outweigh the monthly cost of the smart meter. However, many experts note that the profitability as well as the users’ non-monetary benefits could be improved/increased if further applications are built on the basis of the smart meter, such as smart home systems. A key requirement for this is the right to use the user data, potentially by third parties, to offer these products and services. For consumers with a small consumption who only have the mMe without the communication gateway, it is required to establish a connection to the mMe via, for example, the user's own router. Here, the regulatory framework needs to be established. However, as these measures could affect the users' privacy and the integrity of the user data, caution is required, and a compromise needs to be made. The negative profitability for the user in combination with concerns about data security and privacy could be the reasons for the experts' opinion that the smart meters will rather be rejected than accepted. Here, specific research into the reasons why users may reject the smart meter are recommended in order to develop measures to increase the acceptance.

Besides the results of the national economy perspective discussed in depth above, three additional stakeholder perspectives are defined as weighting profiles. In this case, all weighting profiles yield the same overall result tendency. However, the environmental NGO perspective reveals two differences. The overall result is more positive compared to the other weighting profiles and the technological category is positive instead of negative. This indicates that the biggest advantages are in areas important for these stakeholders, such as grid and generation controllability, integration of renewables, and life cycle performance. The most negative result in the technology category occurs in the consumer perspective (b) due to a higher weighting of the IT and data security criteria. This indicates that this is a point of concern for users and, as such, needs to be addressed by energy utilities as well as the regulator.

### *4.3. Sensitivity Analysis*

In the sensitivity analysis, the energy saving parameter is identified as the most influential on the LCA result. The GWP100 break-even energy saving of 0.43%, above which an overall GWP reduction is achieved by the application of smart meters, is roughly confirmed by [43], where it is found to be 0.25%. Within the scope and range of the sensitivity analysis, no other factor changes the tendency of the result. In a second step, the influence of the LCA sensitivity on the MCA outcome is analyzed. In the case of the "no savings" scenario, both the ecology category and the overall result turn out negative. This result underlines the importance of ensuring that these benefits are, in fact, achieved during the roll-out.

## **5. Conclusions and Outlook**

A framework consisting of an MCA combined with an LCA and expert interviews for the holistic evaluation of digital applications in the energy sector is proposed and tested on the use case of the smart meter roll-out. The framework provides a result, which is reduced in complexity to enable broader discussions, reflects the perspectives of different stakeholders and provides detailed insights on critical aspects of the application.

Criteria for the MCA are developed based on the review of literature and refined in expert interviews. Weighting profiles for perspectives of different stakeholders are developed, also based on expert interviews. The LCA is performed using detailed information on the technical setup of smart and conventional meters and a set of assumptions. The outcome of the LCA is the assessment of several criteria in the ecology category. LCA results are subsequently integrated into the MCA evaluation. All MCA criteria are evaluated in expert interviews. Results are aggregated using the SAW method.

The evaluation of the smart meter roll-out is the first test of the proposed evaluation framework.

The LCA reveals that the smart meter as an electronic device has a higher environmental impact compared to conventional meters, mainly due to the high consumption of electricity, which is the biggest impact factor on the smart meter's life cycle greenhouse gas emissions. However, if the smart meter roll-out results in an electricity saving of >0.43%, the overall environmental impact, mainly the GWP, would be reduced. The electricity saving potential has the most significant influence on the overall LCA result.

The overall MCA result, including evaluation of criteria in expert interviews and the LCA results, reveals a slightly positive overall score for most stakeholder perspectives. While the core reasons for the smart meter roll-out, generation and grid controllability, and further integration of renewable energies are all evaluated very positively, negative evaluations in the area of IT and data security, implementation and operational effort, social acceptance, and profitability overall offset the result into the negative range. These negative aspects need to be addressed and solved in order to take full advantage of the positive impacts of the smart meter. Critical aspects of the smart meter roll-out are identified, and key insights on required actions are gathered during the expert interviews.

Overall, the first test of the framework results in a largely consistent evaluation of the smart-meter roll-out, in line with the relevant discussed existing studies on smart meters for most aspects. Therefore, the overall goal of the proposed framework is met, and it is concluded that the framework is suitable for evaluating this digital application in the energy sector. Yet another test with a different application is recommended to prove the versatile applicability of the framework for digital applications.

Although the first test is considered successful, several areas for further improvements of the framework are identified. Most notably, some modifications need to be made on the criteria. It would be beneficial to reduce the number of overall criteria to improve the practical usability of the framework, although, due to the complexity and diversity of digital applications, no drastic reduction is possible. In the technology category, it seems to be necessary to rebalance the number of effort and impact criteria to obtain results that are more realistic. This could be done by summarizing several effort criteria into one. Furthermore, although the intention while defining the criteria was to avoid overlaps and, therefore, double counting as far as possible, some cases of double counting were identified and need to be resolved. The most prominent example is the technical impact on energy consumption and the ecological criteria energy balance. Lastly, the hierarchy level of some criteria and sub-criteria needs to be reconsidered, e.g., human toxicity and global warming potential should be on the same hierarchy level.

The point allocation weighting method based on the distribution of 100 points was easily understood. However, in practical use, many experts faced the difficulty of leveling the weights between (sub)criteria of different categories. To reduce this problem, some pairs of criteria were randomly picked for direct comparison. Sometimes the two criteria could meaningfully be compared; sometimes, the direct comparison did not seem suitable. It is possible to define a standard set of suitable (sub)criteria pairs for direct comparison, ensuring that general leveling of weightings is achieved.

The evaluation range set from −3 to +3 was easily understood and, for the most part, intuitively used. No need for adaption was seen here.

Currently, the results are presented on the criteria level and summarized to the category level, following the hierarchical structure of the criteria. However, it could be of significant interest to derive a medium layer of result aggregation, which does not follow the hierarchical structure but is based on cross-functional result categories. These result categories could summarize different efforts, such as implementation and operational effort as well as different impacts, such as effects on the system stability, the environment, or the IT security. Based on these result categories, a weighting sensitivity analysis could be performed (e.g., sensitivity if system stability is weighted more).

Currently, neither the uncertainty of the input nor the number of evaluation points (how many experts evaluated a specific criterion) is considered. Therefore, the robustness of the results can only be ensured through the sensitivity analysis. An indication of the robustness could make transparent where a sensitivity analysis is required and increase confidence in the result.

Furthermore, a check of the usage of materials versus a list of critical materials, such as [77], issued by the European commission could be performed. This is already partly covered in the LCA impact category depletion of resources. However, only a more in-depth knowledge of the exact material can lead to mitigation actions, such as finding substitutes.

Lastly, the weighting profiles should become adaptive not only to the stakeholder's perspective but also to the type of application under evaluation such that non-relevant criteria do not need to be evaluated.

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

## Appendix A

### *Appendix A.1. Definitions of Digitalization Terminology*

The term digitalization as well as connected terms, such as digital transformation, digital applications, or the term "smart", have gained popularity during the last decade. Monthly online searches for the term digitalization have increased by a factor of 8 between 2010 and 2020 [78]. However, there is still no common definition of the key terms. Therefore, these are defined for the context of this study. The definition is based on the previous publication [5] and is very similarly used in [79].

### *Appendix A.2. Digital Technology*

Digital technologies can be based on software or a combination of hardware and software, so-called cyber–physical systems. Pure ICT (Information and Communication Technology) hardware thus only becomes a digital technology in combination with the corresponding software. Software for which no specific hardware is required can be defined as a software-based digital technology, but of course, some kind of hardware is also required for its execution. Even given this definition, different authors see different digital technologies. Overviews of digital technologies are presented in [79] (which reflects the authors' view based on a survey among European utilities), a survey among German medium-size utilities ([80], p. 22), an extensive book on digital transformation ([81], p. 31 ff) and a global survey among companies of the energy sector ([82], p. 9).

### *Appendix A.3. Digitalization*

The term digitalization includes both the increasing implementation of digital technology in more and more areas of business and private life as well as the resulting socio-economic effects in the economy as well as the society.

### *Appendix A.4. Digitization*

Digitization is the process of changing from analog to digital, e.g., converting paper documents into pdf (or other formats) or creating digital data tables from paper-based data. Therefore, digitization can be seen as one of the initial steps of digitalization.

### *Appendix A.5. Digital Transformation*

The digital transformation describes the socio-economic part of the process of implementing the digitalization within companies or other groups. In particular, this includes the creation of digital strategies, the adaptation of new working methods and structures, and, in a broader sense, cultural and organizational changes.

### *Appendix A.6. Digital Application*

Digital applications must be based on digital technologies and are usually the goal of digital transformations. The distinction between technology and application is made by the question of whether there is a direct benefit. An application must generate a benefit in itself, while a technology forms the basis for applications but does not have an inherent benefit. Of course, some applications and technologies can be argued to be either one.

### *Appendix A.7. Smart*

The term smart, although very frequently used, still lacks a common definition. For the context of this article, the authors assume the following characteristics for the adjective smart as defined in [5]: (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).

## Appendix B

**Table A1.** List of LCA assumptions.

| | Unit | Production (Value in 2020) | Use-Phase (Value in 2030) | End of Life (Value in 2040) | Source |
|---|---|---|---|---|---|
| **Assumptions German electricity system** | | | | | |
| GWP100 German electricity mix p.a. | kg $CO_2$ eq./kWh | 0.460 | 0.330 | 0.257 | See Section 0 |
| Electricity use households & small businesses p.a. | TWh | 265.7 | constant | | [83] * |
| Grid reinforcement low voltage p.a. | km | 690 | constant | | [84] ** |
| Grid reinforcement medium voltage p.a. | km | 2920 | constant | | [84] |
| Grid reinforcement high voltage p.a. | km | 490 | constant | | [84] |
| Number of mMes | | 35,400,000 | constant | | [19] |
| Number of iMSys | | 16,200,000 | constant | | [19] |
| Number of conventional meters | | 51,600,000 | constant | | [19] |
| **Assumptions smart meter devices** | | | | | |
| Analysis period | years | 20 | - | | - |
| Lifetime of mMe | years | 18 | constant | | Grid operator |
| Lifetime of GW | years | 18 | constant | | Grid operator |
| Lifetime of conventional meter | years | 30 | constant | | Grid operator |
| Effective power mMe | W | 2.4 | constant | | Manufacturer |
| Effective power GW | W | 8 | constant | | Manufacturer |
| Effective power conventional meter | W | 2.4 | constant | | Grid operator |
| Energy use of production mMe | kWh | 1 | constant | | Manufacturer |
| Energy use of production GW | kWh | 1 | constant | | Manufacturer |
| Energy use of production conventional meter | kWh | 1.6 | constant | | [43] |
| Energy use of disassembly mMe | kWh | 3.3 | constant | | Ecoinvent |
| Energy use of disassembly GW | kWh | 2.2 | constant | | Ecoinvent |
| Energy use of disassembly conventional meter | kWh | 10.9 | constant | | Ecoinvent |
| Weight mMe | g | 495 | constant | | Manufacturer |
| Weight GW | g | 339 | constant | | Manufacturer |
| Weight conventional meter | g | 1650 | constant | | [43] |
| Recycling rate SM | % | 80% | constant | | Manufacturer |
| Recycling rate conventional meter | % | 80% | constant | | Estimate |

**Table A1.** *Cont.*

| | Unit | Production (Value in 2020) | Use-Phase (Value in 2030) | End of Life (Value in 2040) | Source |
|---|---|---|---|---|---|
| **Assumptions effects of smart meter** | | | | | |
| Electricity demand savings | % | 1.8% | constant | | [19] |
| Electricity demand savings p.a. | TWh | 4.782 | constant | | calculated |
| Grid reinforcement reduction low voltage | % | 30% | constant | | [19] |
| Grid reinforcement reduction medium voltage | % | 30% | constant | | [19] |
| Grid reinforcement reduction high voltage | % | 2% | constant | | [19] |
| Grid reinforcement reduction low voltage p.a. | km | 207 | constant | | calculated |
| Grid reinforcement reduction medium voltage p.a. | km | 876 | constant | | calculated |
| Grid reinforcement reduction high voltage p.a. | km | 9.8 | constant | | calculated |

* Data on net electricity consumption by consumer groups provided by the German Association of Energy and Water Industries; ** study on the innovation requirements in the German electricity distribution network by the German Energy Agency.

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# Holistic evaluation of aircraft detection lighting systems for wind turbines in Germany using a multi-method evaluation framework

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Transponder-based Aircraft Detection Lighting Systems (ADLS) are increasingly used in wind turbines to limit beacon operation times, reduce light emissions, and increase wind energy acceptance. The systems use digital technologies such as receivers of digital transponder signals, LTE/5G, and other information and communication technology. The use of ADLS will be mandatory in Germany both for new and existing wind turbines with a height of >100 m from 2023 (onshore) and 2024 (offshore), so a nationwide rollout is expected to start during 2022. To fully realize the benefits while avoiding risks and bottlenecks, a thorough and holistic understanding of the efforts required and the impacts caused along the life cycle of an ADLS is essential. Therefore, this study presents the first multi-aspect holistic evaluation of an ADLS. A framework for evaluating digital applications in the energy sector, previously developed by the authors, is refined and applied. The framework is based on multi-criteria analysis (MCA), life cycle assessment (LCA), and expert interviews. On an aggregated level, the MCA results show an overall positive impact from all stakeholders' perspectives. Most positive impacts are found in the society and politics category, while most negative impacts are of technical nature. The LCA of the ADLS reveals a slightly negative impact, but this impact is negligible when compared to the total life cycle impact of the wind turbines of which the ADLS is a part. Besides the aggregated evaluation, detailed information on potential implementation risks, bottlenecks, and levers for life cycle improvement are presented. In particular, the worldwide scarcity of the required semiconductors, in combination with the general lack of technicians in Germany, lead to the authors' recommendation for a limited prolongation of the planned rollout period. This period should be used by decision-makers to ensure the availability of technical components and installation capacities. A pooling of ADLS installations in larger regions could improve plannability for manufacturers and installers. Furthermore, an ADLS implementation in other countries could be supported by an early holistic evaluation using the presented framework.

KEYWORDS

digitalization, cyber-physical systems, wind energy, sustainability, holistic evaluation, multi-criteria analysis, life cycle assessment, aircraft detection lighting systems

## 1 Introduction

Wind turbines (WTs) are potential obstructions to air traffic and must therefore be equipped with obstruction lights (flashing red beacons) if their total height exceeds 100 m (outside of urban areas), as defined by the International Civil Aviation Organization (ICAO, 2018) and specified for Germany in the "General Administrative Regulation on the Marking of Aviation Obstructions" (BMDV, 2020). Obstruction lights can cause annoyance and thus reduce the acceptance of wind energy (Pohl et al., 2021). As modern turbines become taller and more turbines are installed, more people may be affected, leading to an increasing acceptance problem. Social acceptance of wind energy projects, however, is of great importance to avoid local opposition. Such opposition can delay or impede the construction of new WTs and even slow down the overall transition to renewable energies (Ellis and Ferraro, 2016).

In order to reduce the light emissions caused by the flashing red beacons and thereby increase the social acceptance of WTs, the German regulatory authority has specified in the Renewable Energy Act (German Federal Ministry for Economic Affairs and Energy, 2021) the obligation to equip WTs with Aircraft Detection Lighting Systems (ADLS). ADLS allow WTs' beacons to remain off during nighttime hours when no aircraft is detected in the vicinity. Under the aforementioned law, ADLS are mandatory for all onshore WTs that require aviation obstruction lighting and all offshore WTs located near the coast and in certain offshore areas. The obligation will take effect on 1 January 2023 for onshore and 1 January 2024 for offshore turbines. It is estimated that approximately 17,500 onshore turbines (Roscher, 2019) and all of the 1,500 offshore turbines (Deutsche WindGuard GmbH, 2021) will need to be retrofitted by the start of the obligation. However, due to a technological dispute that was not resolved until 2019, only a minority of turbines have already been equipped. Therefore, a large rollout is expected during the year 2022.

Given this nationwide rollout, a thorough understanding of its impacts is necessary for all stakeholders involved to be able to weigh positive and negative impacts against each other and to avoid otherwise unforeseen potential negative impacts or implementation bottlenecks. Several studies analyzed the impact of ADLS on WT acceptance. An early study (Hübner and Pohl, 2010; Pohl et al., 2012), funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety, and Consumer Protection, found that nighttime obstruction lighting is less of a cause for annoyance compared to changes in the landscape and emitted noise, but is perceived as similarly annoying compared to shadow flicker. The authors recommend the use of ADLS as a measure to improve acceptance. Further, in (Rudolph et al., 2017), the authors confirmed previous studies and identified a perceived annoyance associated with obstruction lights from WTs. A comparison of annoyance between Europe and the United States (Hübner et al., 2019) shows that obstruction lights cause slightly higher annoyance among Europeans, but overall annoyance levels are relatively low. A more recent study found that annoyance from obstruction lighting is generally low but on average higher than noise annoyance and more geographically widespread. The authors again recommend the use of ADLS (Pohl et al., 2021). Overall, evidence suggests that ADLS will indeed have a positive impact on the social acceptance of wind turbines. In addition, a technical risk assessment focusing on aviation was conducted for the transponder-based technological options in comparison to radar-based options (Behrend, 2019). The author concludes that the risk of a system failure with consequences for aviation safety is very low and the same for all technological options.

According to the authors' knowledge, societal impacts beyond acceptance, non-aviation-risk-related technical impacts, and environmental as well as economic impacts have not yet been analyzed. In particular, neither a life cycle assessment nor an environmental study, or a holistic assessment incorporating multiple perspectives, involving relevant stakeholders, and considering all relevant impact areas has been conducted so far. In order to close this gap, in this paper, a multi-method framework for evaluating digital applications in the energy sector, previously developed by the authors (Weigel et al., 2021), is refined and applied to conduct a holistic evaluation of ADLS. The main novelty of the study is that it presents the first holistic evaluation of ADLS, in contrast to existing publications, which focus on single evaluation aspects. A secondary minor novelty is the refinement of the evaluation framework and its application.

The remainder of the article is organized as follows: the refinement of the evaluation framework and its adaption to ADLS is described in Section 2. While Section 3 shortly describes the ADLS technology and the chosen assumptions, Section 4 shows the results of the holistic evaluation. After discussing the results in Section 5, the conclusions and an outlook are given in Section 6.

## 2 Methodology

There are a variety of sustainability and multi-criteria evaluation methods and combinations of methods, many of which have recently been used for high-level assessments at

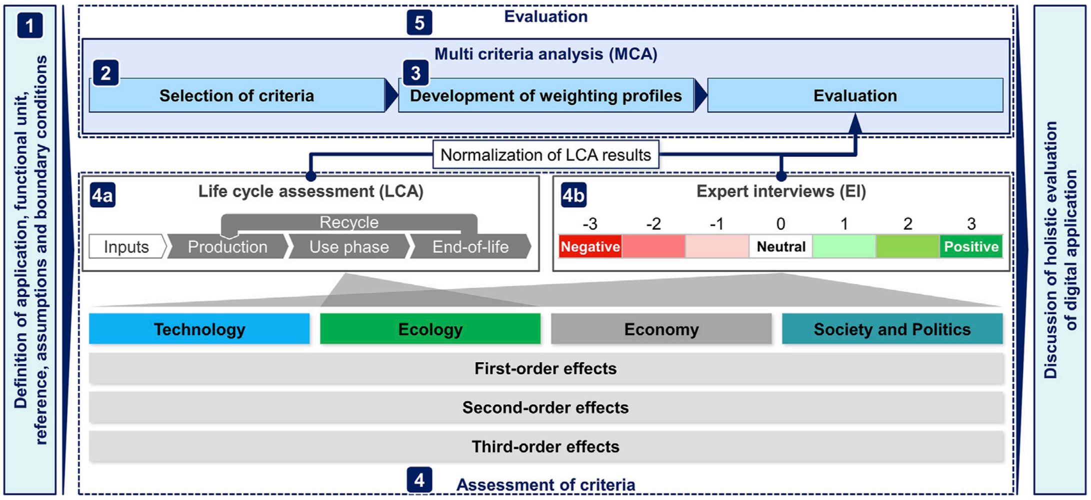

FIGURE 1
Modified multi-method framework for evaluating digital applications in the energy sector, based on (Weigel et al., 2021).

the country level, e.g. (Sun et al., 2022), (D'Adamo et al., 2022), for more specific assessments in the energy sector, e.g., (Kluczek and Gladysz, 2022), (Naegler et al., 2021), and for assessments of digital topics, e.g., (Gährs et al., 2021), (Zhang et al., 2021). A review of methods applied in the energy sector (energy planning) and each method's appropriateness in the decision problem's context is provided in (Cajot et al., 2017). In (Weigel et al., 2021) the authors thoroughly discuss a variety of current evaluation and assessment methods and identify a gap regarding an approach to transparently and holistically evaluate digital applications in the energy sector. To fill this gap, a combination of three well-established methods is suggested, and its use is demonstrated. The novelty of the framework consists of the specific combination of methods and its adaption to digital applications in the energy sector.

The objective of the framework is to provide a structured basis for the holistic evaluation of digital applications. To achieve this holistic view, multiple criteria covering the impact areas technology, ecology, economy and society and politics are evaluated in a multi-criteria analysis (MCA), and the perspectives of relevant stakeholders are considered in the form of weighting profiles. While most ecological criteria are assessed by performing a life cycle assessment (LCA), all other criteria are assessed by conducting expert interviews (EI) with relevant stakeholder representatives. Furthermore, due to the dynamic development of digital applications, a flexible approach is applied that can be adapted to the practitioner, the application, and the availability of information. In this way, a wide range of digital applications, including future developments, can be evaluated. Last but not least, the applied approach provides detailed insights as well as aggregated results with a high level of transparency on each step of the evaluation.

The framework applied in this study is a refined version of the framework originally presented by the authors in (Weigel et al., 2021) and consists of the following steps (Figure 1):

1) Definition of application, functional unit, reference, assumptions, and boundary conditions
2) Selection of criteria
3) Development of weighting profiles
4) Assessment of the criteria
    a) Environmental criteria based on LCA
    b) All other criteria based on EIs
5) Evaluation of application based on criteria assessments and weighting profiles within MCA

Generally, the first step is the definition of the application under investigation, the functional unit, the reference for the evaluation, and key assumptions. This step ensures a consistent and efficient assessment and evaluation process.

The selection of criteria (step 2) can be moved up and down in the sequence within certain limits. In this study, it is performed beforehand based on the general requirements for digital applications in the energy sector, following a thorough literature review and discussions with experts.

In step 3, weighting profiles are developed. To some extent, this could also be done beforehand, based on general requirements for digital applications. However, case-specific adaptations are likely to be required, as different applications may involve different stakeholder roles. The study-specific stakeholder profiles are derived from expert opinions following the expert interviews in step 4b. The point allocation method is applied. Experts are asked to assign 100 points sequentially to categories and then to criteria. The

100 points represent 100% importance, a concept that is intuitively understood by the interviewees.

The LCA approach (step 4a) is based on the standard defined in (ISO/TC 207/SC 5, 2006). It is carried out using the software openLCA (v1.10.1), the ecoinvent (v3.3) database, and the CML2001 impact calculation method, from which the environmental impact criteria global warming potential 100a (GWP), adiabatic resource depletion (ARD), human toxicity 100a (HT), and ecotoxicity 100a (ET—as the average of different ecotoxicity aspects) are selected, extended by the cumulative energy demand (CED). The LCA results are normalized to the MCA evaluation scale by comparison with a reference value. This reference value is a quantification of the reference defined in step 1.

The expert interviews (step 4b) are semi-standardized, which ensures comparable results across different EIs while providing the flexibility to capture additional detailed information. The list of criteria is used as the interview structure.

The MCA (step 5) uses a direct ordinal rating scale ranging from -3 (strongly negative impact) via 0 (no/neutral impact) to +3 (strongly positive impact). The scale is intuitive for experts, and the evaluation can be broken down into two questions: 1. Is the impact positive, negative or neutral (+ or—range); 2. how positive or negative is the impact (±1, 2, or 3). The simple additive weighting (SAW) method, also known as the weighted sum method (WSM) is used to aggregate the criteria evaluations into category and total results. The SAW method is commonly applied due to its popularity and simplicity (Cajot et al., 2017). It provides a high level of transparency on how results are aggregated from detailed criteria evaluations.

Compared to the originally provided version of the framework (Weigel et al., 2021), three main improvements to the method are made in this paper:

1) The list of criteria is modified in order to reduce the complexity and eliminate overlaps between criteria. In particular, the number of responses per criterion, the weighting of each criterion, as well as direct expert feedback were evaluated to identify required adaptions. Based on the findings, the former sub-criteria level is eliminated, the total number of criteria is reduced, and the number of criteria is more evenly distributed among the categories. Some sub-criteria are upgraded to criteria, and a few new criteria are added. The updated criteria used in this study can be found in the presentation of the results in Section 4.4.
2) In addition, the expert interview approach is adjusted. The weighting (formerly being the first part of each expert interview) is done independently by the experts after the interview. The adapted approach meets the experts' expectations to talk directly about the application itself, shortens the interview, and reduces the interviewer's influence on the weighting. However, a good explanation of how to perform the weighting is necessary, and not all experts provide (useful) weighting results on their own.
3) Last but not least, an indication of the uncertainty and data robustness of the expert interview results is assessed using the standard deviation and the number of received evaluations. The standard deviation $s$ is calculated for the sample of each criterion as given in Formula 1

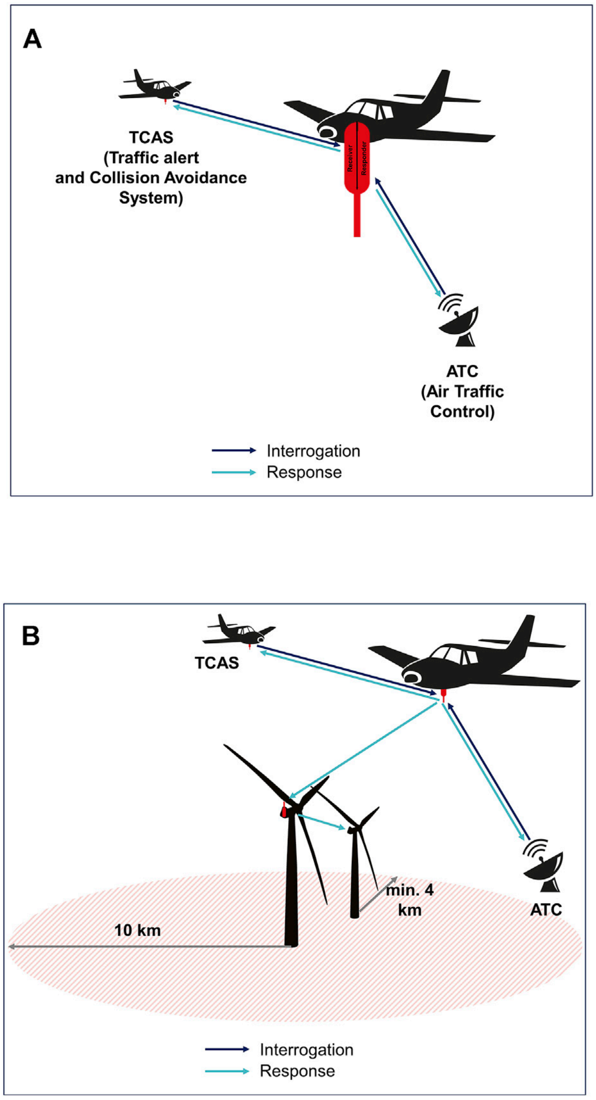

FIGURE 2
Illustrative functionality of **(A)** a transponder in aviation; **(B)** a transponder-based ADLS.

$$s = \sqrt{\frac{\sum_{i=1}^{n} [x_i - \bar{x}]}{n-1}} \tag{1}$$

where $n$ is the number of evaluations per criterion provided by the experts in the expert interviews, $x_i$ are the evaluations (between -3 and +3) per expert, and $\bar{x}$ is the average of the given evaluations. A margin of error for a specific confidence interval is not used because the data points do not necessarily follow a normal distribution shape. Furthermore, it should be noted that the deviation of the answers given in the expert interview is only one of many possible sources of error.

# 3 ADLS technology, system boundaries, and assumptions

## 3.1 Description of the technology

Different technologies to equip WTs with an ADLS are permitted. Three technological approaches can be distinguished based on active radar, passive radar, and transponders (secondary radar). Each technology may have its own use case due to its inherent advantages and disadvantages. There is evidence, however, that transponder-based ADLS technology will be predominantly deployed. Most of the consulted experts expected this trend, and two organizations are already in the process of covering two entire German states with this technology—North Rhine-Westphalia (Bode and Klümper, 2021) and Saarland (BNK, 2022). Therefore, this publication focuses on transponder-based ADLS.

Transponders have been widely used in commercial aviation for several decades. They are considered part of secondary surveillance radar (SSR). The term transponder is a hybrid of transmitter and responder. After receiving a signal from a secondary radar antenna on 1,030 MHz, the transponder actively sends a response signal on 1,090 MHz. The response signal contains a four-digit identity code as a minimum (Mode A) or a unique 24-bit aircraft identity number, altitude, speed, and flight path, as well as GPS coordinates for ADS-B (Automatic Dependent Surveillance - Broadcast) as a maximum (Mode S enhanced). Transponder responses are triggered by air traffic control (ATC) and other aircraft's traffic alert and collision avoidance systems (TCAS), see Figure 2A.

If airborne transponders are not triggered, they broadcast one signal per second by default (Mode S only, not Mode A). All aircraft flying at night within or outside of air traffic-controlled areas must use a Mode S transponder (BMDV, 2018). Some exceptions exist for military, police, and rescue aircrafts. The signals sent out by the aircrafts' transponders are used by the transponder-based ADLS. The ADLS passively receive the transponder signals without sending any interrogation signal themselves. The minimum information received is the aircraft identity code (from Mode A transponders). In this case, the distance is calculated based on the signal intensity. In most cases, more information such as altitude, speed, flight path, and GPS coordinates are received (Mode S and ADS-B), and the exact position can be determined. An ADLS receiver covers a minimum radius of 10 km. Based on the defined impact area of a horizontal 4 km radius around each WT (BMDV, 2020), all WTs within a 6 km radius can be covered by one ADLS, see Figure 2B. In practice, the ADLS receives transponder signals of well beyond 10 km, however, this does not change the evaluation since the technical setup (how many turbines are covered by one ADLS) is defined by the 10 km minimum radius.

## 3.2 Functional unit and system boundaries

The functional unit of the evaluation is one single transponder-based ADLS. The reference system used to evaluate the magnitude of the impact is the wind turbines covered by the ADLS. The selection of the reference is therefore aligned with the subjective perception of the relevance of ADLS's impact on the system they are part of. Since the number of covered turbines and the technical configuration of the ADLS may vary, a base case is defined, and sensitivity analysis for different setups are conducted. Theoretically, for modern wind farms, there is no limit to how many WTs can be covered by one single ADLS. In practice, however, there are technical, topological, and ownership structure limitations. In this paper, a setup with eight turbines is chosen as the base case based on the average number of turbines covered per ADLS in the German State of North Rhine-Westphalia (Bode and Klümper, 2021). If all covered turbines have a single central communication unit, which is usually the case for modern wind farms, the central ADLS can directly operate the obstruction lights of all turbines, as depicted in Figure 2B. However, if a central communication interface is not available, additional communication modules must be installed. For this study, the case of only one communication unit is chosen due to a lack of information on a realistic average number of communication units per ADLS. Therefore, the base case is defined as one ADLS with one signal receiver and one communication unit covering eight WTs.

## 3.3 Life cycle assessment key assumptions

For the life cycle inventory (LCI), the material and energy flows of one single ADLS are modeled. One analyzed base case ADLS consists of the following hardware components: one signal receiver, one communication module, mounting, cabling, antennas, and additional infrared (IR) beacons required per each of the eight turbines. As depicted in Figure 3, the model covers the production, the use, and the end-of-life phases. In addition to the directly attributable effects on the mass and energy flow, two effects caused by the reduced operating time of the beacons are additionally allocated to the LCI. Based on real-world data from a test site supplied by an ADLS supplier, it is assumed that the beacons remain off during 98% of the nighttime. Besides a reduced beacon electricity consumption, the reduced operating hours lead to an increased lifetime of the

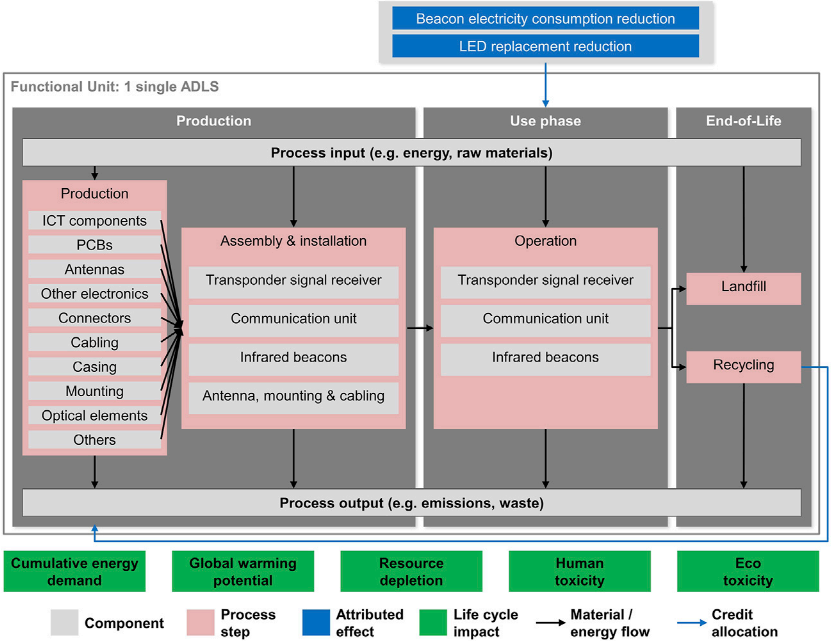

FIGURE 3
LCI model of ADLS.

beacons' LEDs and thus to a reduced need for replacement. A reduction in LED replacement of 1.29 units per beacon over the analysis period is calculated based on an expected LED operating life of 50,000 h and a correction factor based on manufacturers' knowledge of the probability of failure modes leading to replacement. It is assumed that the ADLS hardware has a technical lifetime of more than 25 years, but the hardware is decommissioned together with the turbine so that the effective ADLS lifetime depends on the lifetime of the turbine. Here, a turbine and ADLS lifetime of 20 years is assumed. Therefore, the analysis period is also set at 20 years.

Since the electricity consumption of digital applications with a long expected lifetime tends to have a great effect on the life cycle impact, special consideration is given to the electricity mix. Three different electricity mixes are defined for this study based on the expected development of greenhouse gas (GHG) intensity of the German electricity mix over time (measured in $CO_2$ equivalents, $CO_2$ eq.). The three mixes are defined as described in (Weigel et al., 2021), based on historical $CO_2$ emissions and energy consumption, reference prognosis, and trend scenarios for future energy generation and the 2019 developed coal exit path. Different shares of electricity generation technologies are modeled for each mix, however, the underlying unit processes for these technologies in the LCA database remain unchanged as no prospective datasets are available. The 2022 mix is used for the production phase, the expected 2032 mix for the use phase, and the expected 2042 mix for the end-of-life phase. The ADLS's energy self-consumption during the use phase is covered to 19% by electricity from the German electricity mix and to 81% by electricity from the wind turbine itself. The life cycle impact of the electricity generated by the wind turbine is based on a 3.25 MW turbine currently in operation. Effects that are not considered in the LCI are the need for maintenance and spare parts (no data available and the impact is likely to be very small), the server operation and data transmission (there is no data available), and the transport of materials for production, installation, and end-of-life steps (the impact is likely to be very small as most steps take place within Germany). Relevant assumptions and sources are listed in Appendix Table 2 in the Annex.

## 3.4 Expert interviews assumptions

The aim for the selection of experts is to cover all stakeholder roles and identify experts with a high level of expertise. In a first step governmental, scientific, business and journalistic publications were analyzed to identify relevant stakeholder roles and experts. Following the initial identification, further experts were identified by asking each expert at the end of the interview to identify further stakeholder roles and name experts.

The group of twelve interviewed experts includes: four representatives of wind farm operators or operator associations in charge of implementing ADLS, two

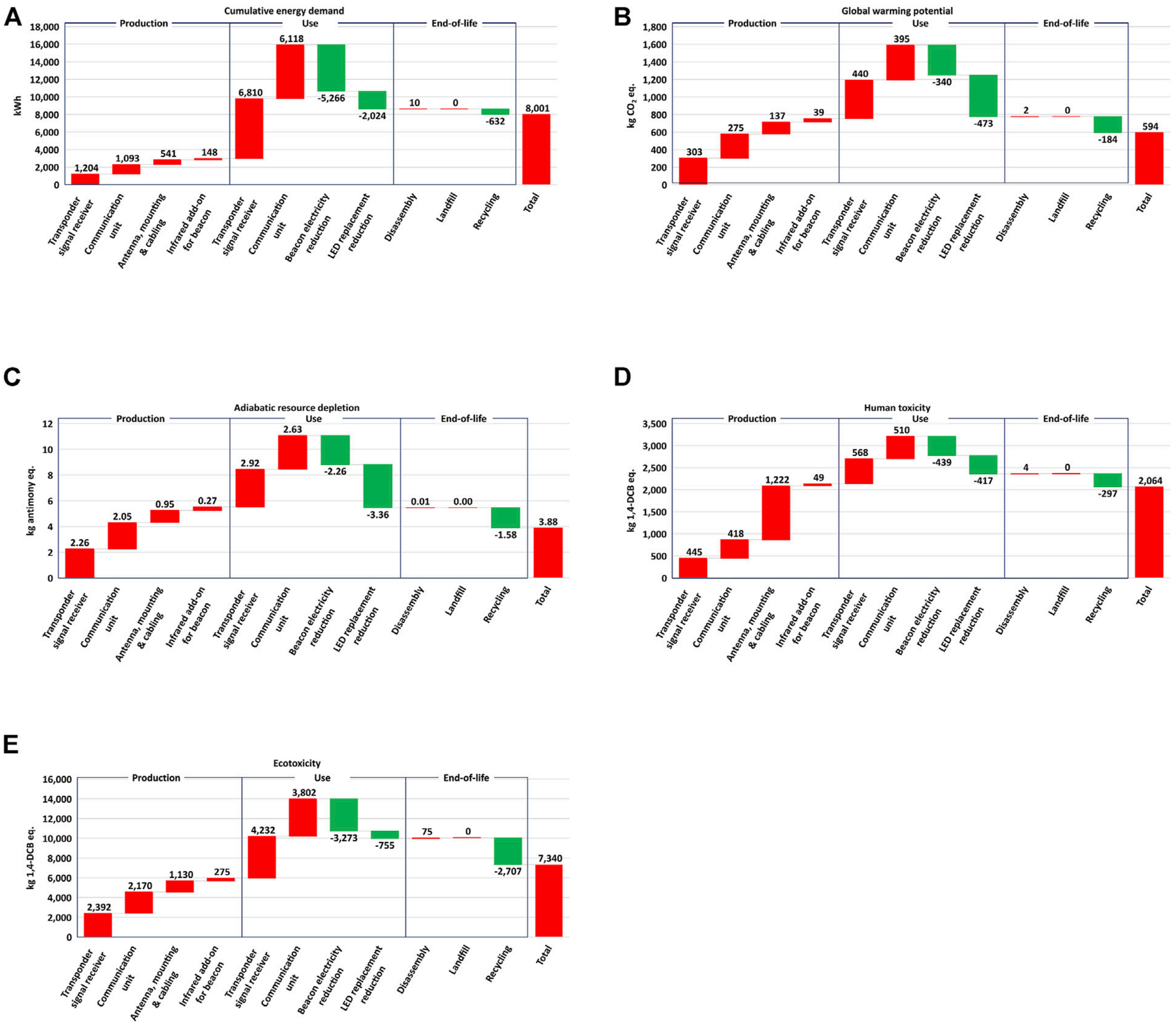

FIGURE 4
Life cycle impact assessment for the base case. Functional unit: one ADLS in the base case. **(A)** Cumulative energy demand; **(B)** Global warming potential; **(C)** Adiabatic resource depletion; **(D)** Human toxicity; **(E)** Ecotoxicity.

environmental NGO experts for wind energy, two ADLS-specific policy advisors to the involved German Federal Ministries, one employee of a wind turbine manufacturer tasked with equipping future turbines with ADLS, one ADLS manufacturer (from the same company that supplied the data for the LCA), and two scientists with expertise in social acceptance of WTs, including lighting induced stress. No affected neighbors of WTs were directly interviewed for this study, but rather the two mentioned scientists researching social acceptance were interviewed to present their insights of the perspective of this group. All experts are based in Germany and are native German speakers. Age and sex were not documented as deemed not relevant.

The individual online expert interviews were conducted between September 2021 and January 2022 and each took about 90 min. No material was sent out beforehand, the interviews were not recorded or transcribed, and the results were captured as the evaluation per criterion, including qualitative remarks. Furthermore, following the expert interviews, the experts were asked to assign weights to the criteria and to submit the weighting within 2 weeks. Based on the responses of nine experts (one wind farm operator, the turbine manufacturer, and the ADLS manufacturer did not submit weighting), five (non-representative) weighting profiles reflecting key stakeholders' perspectives were derived.

# 4 Results

In this section, the results of the LCA are presented first, followed by the results of the MCA, which integrates LCA and expert interviews. The LCA results are presented separately from the MCA results because detailed conclusions about life cycle impacts can be drawn.

## 4.1 LCA results

### 4.1.1 Impacts of the base case

In Figure 4, the breakdown of the calculated life cycle impacts over 20 years for the base case is depicted. In total, all five impacts increase with the application of an ADLS. The shares of the three life cycle phases on the total impact, however, are very different. Each step of the production phase leads to an increase in all five impacts. In the use phase, the energy consumption of the ADLS components leads to an increase, while the beacon electricity savings and the LED replacement reduction cause an impact decrease. Relative to the production and the use phase, the end-of-life phase causes a small impact decrease. The effort for disassembly and landfilling is more than compensated by credits given due to recycling.

The cumulative energy demand (CED) is depicted in Figure 4A. The ADLS use phase's energy consumption is 4.3 times higher than the production's energy consumption. The decisive impact on the CED during the 20-years use phase is caused in particular by the electricity consumption of the ADLS hardware (approx. 13,000 kWh) and the saved electricity consumption of the beacons (approx. -5,200 kWh).

Figure 4B shows the breakdown of the global warming potential (GWP). The ADLS operation's energy consumption emissions (835 kg $CO_2$ eq.) over 20 years are about 10% higher than the production-related emissions (754 kg $CO_2$ eq.). Similar to the CED, the GWP is mainly caused by the ADLS's electricity consumption. Since 81% of the consumed electricity is assumed to be generated by the turbine itself (with a low impact on GWP), the GWP is mainly driven by the remaining 19% taken from the grid (although an increasingly decarbonized future German electricity mix is assumed). During the production phase, the signal receiver is the largest GWP contributor with 303 kg $CO_2$ eq., followed by the communication unit with 275 kg $CO_2$ eq. The mounting, cabling, and antenna (137 kg $CO_2$ eq.) and the required infrared beacons (39 kg $CO_2$ eq.) cause a relatively small GWP. For these hardware units, the components with the highest GWP are the printed circuit boards, including the electronic components mounted on them such as integrated circuits, resistors and capacitors, other electronic components such as power supplies, heaters, surge suppressors, and circuit breakers, and the mounting material (mainly steel). The savings of -814 kg $CO_2$ eq. (caused by lower beacon energy consumption and reduced replacement of LEDs) offset 97% of the ADLS's electricity consumption emissions. The reduction in LED replacement causes a larger GWP effect (-473 kg $CO_2$ eq.) than the reduced beacon electricity consumption (-340 kg $CO_2$ eq.). The main driver for the LED replacement reduction's GWP effect is the saved energy consumption of the avoided production of diodes and PCBs. Again, the beacon energy consumption reduction's GWP effect is driven by the 19% $CO_2$ intensive electricity taken from the German energy mix. The end-of-life steps, especially disassembly and landfilling of the non-recyclable parts, do not cause significant GWP impacts. Recycling, however, can avoid emissions of -184 kg $CO_2$ eq.

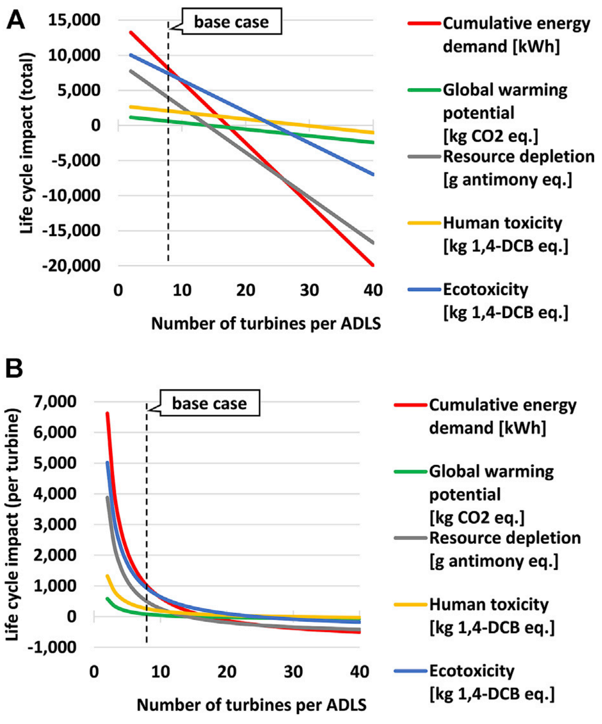

FIGURE 5
Life cycle impact of one ADLS for different numbers of covered WTs. Functional unit: one ADLS in the base case with varying numbers of WT. **(A)** per ADLS; **(B)** per turbine.

The breakdown of adiabatic resource depletion (ARD) impacts given in Figure 4C shows a high correlation with the GWP. The main driver in both cases is the use of fossil fuels for energy (electricity and heat) generation during production, use, and end-of-life. However, compared to GWP, production and recycling have a slightly higher proportional impact on ARD, as physical production materials contribute directly to ARD, while only their $CO_2$ eq. footprint contributes to GWP.

The main difference in the breakdown of human toxicity (HT) impacts in Figure 4D compared to GWP and ARD is the high impact of the antenna, mounting, and cabling component production. With 1,222 kg 1,4-DCB eq., these parts cause more than half of the total HT production impact, compared to only

17–18% of the production impact for GWP and ARD. This high impact is driven by the exploration of copper, which is mainly used for cabling. The HT production impact is significantly higher than the impact caused by the ADLS's electricity consumption during the use phase. Furthermore, it is evident that both savings in the use phase have a similar impact on the HT, while for GWP and ARD, the saving due to the reduction of LED replacement is larger.

The ecotoxicity (ET) impact in Figure 4E shows a relatively high impact of the ADLS energy consumption compared to the production. Moreover, the saved electricity consumption of the beacons causes a much higher ET impact than the reduction of the LED replacement. It is evident that ET is also driven by energy consumption. However, unlike GWP and ARD, it is not driven by the use of fossil fuels but rather by the production of the required power infrastructure such as power plants, wind turbines, and grids. Therefore, the advantage of using wind energy over fossil fuel energy is smaller for ET than for GWP/ARD. During production, ET is driven by the use of gold, brass, silver, and other precious metals.

In the following, the sensitivity of the results regarding the most relevant factors is presented. These factors are, in particular, the number of turbines covered by one ADLS, the required number of communication units, and the achieved beacon operation reduction rate.

### 4.1.2 Variation in the number of wind turbines

Figure 5A depicts the life cycle impact depending on the number of WTs covered by the ADLS. The technical setup of the base case is applied, i.e., the ADLS contains one signal receiver and one communication unit independently of the number of covered turbines. On the one hand, the required efforts for the production and operation of the ADLS hardware remain the same regardless of the number of turbines. In theory, there is no limit to how many turbines can be covered by one ADLS as long as they are within the defined spatial range of the system. On the other hand, the savings, i.e., the reduction of the beacon energy consumption and the LED replacements, occur per turbine. Therefore, the life cycle impacts decrease linearly the more turbines are covered by one ADLS. Depending on the impact criteria, the break-even point (BEP), i.e., the number of turbines, for which the savings outweigh the impacts of ADLS production and operation, is different. While for less than 15 turbines, all indicators show an increased impact (as also analyzed above for the base case with 8 WT), they all decrease if more than 30 turbines are covered. The BEP for both the GWP and the ARD, appears at about 15 WTs. In the case of CED, ET, and HT, it occurs only at larger numbers of turbines of about 18, 27, and 30, respectively. The setup of one single turbine covered by one ADLS is not displayed in Figure 5 since, in this case, the ADLS hardware can be reduced, making this a special case with a non-linear effect, which, however, in reality, is rather rare.

If the results are normalized to one turbine, the impact per turbine decreases and follows a hyperbola (Figure 5B). The family of curves can be described by

$$f_{a,b}(x, i) = a_i + \frac{b_i}{x} \tag{2}$$

where $x$ describes the number of WTs, $a$ the horizontal asymptote, $b$ the shape of the hyperbola and i denotes the five different impact criteria. The factor $b$ depends on the life cycle impact of the central parts of the ADLS, i.e., the signal receiver, communication units, and antenna, mounting and cabling. In this study, the impact of these parts is always a positive value (increased impact) since no saving effects are generated. The horizontal asymptote $a$ depends on the life cycle impact of all turbine-dependent parts and effects, i.e., infrared beacons, reduced beacon operation, and reduced LED replacement. In this study, the impact of these parts and effects is a negative value (decreased impact) because for each additional turbine, the credited saving effects outweigh the impact of the additional infrared beacon. Therefore, for a large number of turbines, the impact curves converge to the horizontal asymptote $\lim_{x \longrightarrow \infty} a_i$. The curves cross the zero line at the break-even points $\text{BEP}_\text{i}$ (see Figure 5A) when the sum of the savings per turbine outweighs the increased impact.

In order to understand the different BEP per impact criteria, the findings of Figure 5 and Figure 4 need to be combined. GWP and ARD are both driven by the use of fossil fuels. Both savings, beacon electricity consumption reduction and LED replacement reduction, increase directly with the number of turbines and have a proportionally large effect on fossil fuel use and thus on GWP and ARD, causing a BEP at already 15 turbines. The CED is directly driven by energy demand, regardless of its source. Therefore, while the reduction in LED replacement has a proportionally large impact (compared to the energy consumption of the ADLS and the saved energy consumption of the beacons) on GWP and ARD, it does not have a strong impact on CED. Consequently, the CED savings achieved per turbine are proportionally smaller than for GWP and ARD, so more turbines are required to achieve a net-zero balance. The HT has the same proportional reduction impact per turbine as the GWP (the lines are close to parallel), but because of the higher production effect, mainly driven by the use of copper, more turbines are needed to balance the production impact, i.e., the BEP shifts to the right. The ET has a rather similar BEP as the HT. However, the main reason why more turbines are needed to offset the ET impact of the production is that the reduction in LED replacement has a proportionally small impact on ET since, for the given quantity of LEDs, neither the total energy consumption for production nor the demand for precious metals is exceptionally high.

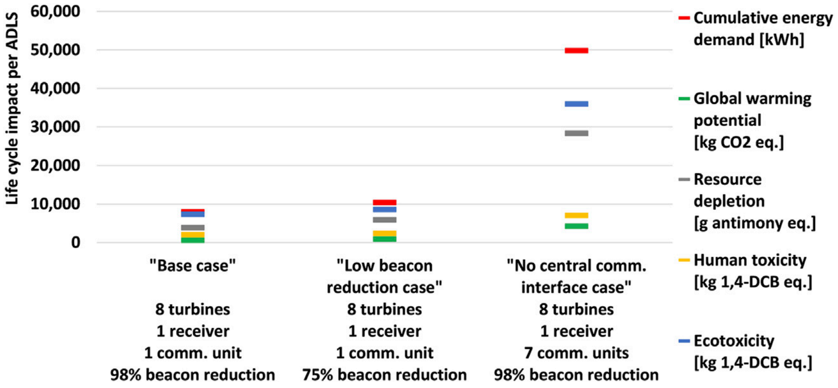

FIGURE 6
LCIA for different ADLS cases. Functional unit: one ADLS.

### 4.1.3 Variation of the required number of communication units

The base case contains one communication unit. Depending on the technical and legal setup of the wind farm, however, between one communication unit for all turbines and one unit for each turbine may be necessary. The additional communication units cause impacts both through their production and their energy consumption during the use phase. The results for different numbers of communication units are depicted in Figure 6: One unit as the base case (all turbines are part of the same wind farm with one central communication infrastructure) and seven units as the worst case (each turbine is a single wind farm, and/or no central communication infrastructure exists). It is evident that the requirement to install more than one communication unit could drastically increase all analyzed life cycle impacts. Between the best and the worst case, the identified impacts increase by a factor of about 3–7, depending on the impact criterion. The highest increase is observed for ARD, GWP, and CED.

### 4.1.4 Variation of the beacon operation reduction rate

Furthermore, the life cycle impact depends on the beacon operation reduction rate, i.e., the percentage of nighttime that the lights remain off. The beacons are assumed to remain off during 98% of the nighttime in the base case. The reduction rate could realistically be as low as 75% near airports with more nighttime air traffic. Figure 6 shows the impact of a low reduction rate, leading to a smaller reduction in beacon power consumption as well as a smaller reduction in LED replacement. The impact on the outcome compared to the base case is an increase of 50% on GWP and ARD, 30% on CED, and approximately 15% on human and ecotoxicity.

## 4.2 LCA result normalization

Since the MCA evaluation scale ranges from -3 to +3, the LCA results must be normalized to this scale in order to include them in the MCA. The reference chosen in Section 3.2 for this study are the WTs, which are covered by the ADLS, thus, the reference value is the life cycle impact of these WTs. By comparing the ADLS's impact to the reference value, the normalized evaluation $E_i$ can be calculated for each impact criterion $i$. If the ADLS has the same life cycle impact as the group of turbines, i.e., the total impact is doubled, this is considered strongly negative (-3). If the life cycle impact of the ADLS is zero, i.e., total impact does not change, this is considered neutral (0). If the ADLS reduces the life cycle impact by the absolute value that the turbines increase it, i.e., the total impact is neutralized to zero, this is considered strongly positive (+3). Within this range, the evaluation $E_i$ for each criteria can be calculated using

$$E_i = \frac{I_{ADLSi}}{I_{WTs\,i}} \times E_{max} \tag{3}$$

based on the ratio between the assessed ADLS's and WTs' life cycle impact, $I_{ADLSi}$ and $I_{WTs\,i}$ respectively and the maximum evaluation $E_{max}$, i.e. -3 or +3. If $I_{WTs\,i}$ is an increased impact $E_{max}$, i.e., -3 is used and vice versa. This approach leads to the evaluation calculated in Table 1.

It can be seen that all criteria are evaluated very close to zero, i.e., with a negligible or neutral impact. In the context of the life cycle impact of the WTs covered by the ADLS, the ADLS life cycle impact is less than 0.006% and thus negligible. This finding also holds true for the technical scenarios with the highest increase in life cycle impact (two turbines, one receiver, one communication unit) and the highest (realistic) decrease in life cycle impact (40 turbines, one receiver, one communication

TABLE 1 Normalization of LCA results to MCA evaluation scale.

| Life cycle impacts | 1 ADLS | 8 WTs | 1 ADLS/8 WTs (%) | Evaluation |
|---|---|---|---|---|
| Cumulative energy demand | 8,001 [kWh] | 1,299,030,015 [kWh] | 0.0006 | - 0.00002 |
| Global warming potential | 594 [kg $CO_2$ eq.] | 20,039,960 [kg $CO_2$ eq.] | 0.0030 | - 0.00009 |
| Resource depletion | 4 [kg antimony eq.] | 132,273 [kg antimony eq.] | 0.0029 | - 0.00009 |
| Human toxicity | 2,064 [kg 1,4-DCB eq.] | 60,690,800 [kg 1,4-DCB eq.] | 0.0034 | - 0.00010 |
| Ecotoxicity | 7,340 [kg 1,4-DCB eq.] | 383,844,537 [kg 1,4-DCB eq.] | 0.0019 | - 0.00006 |

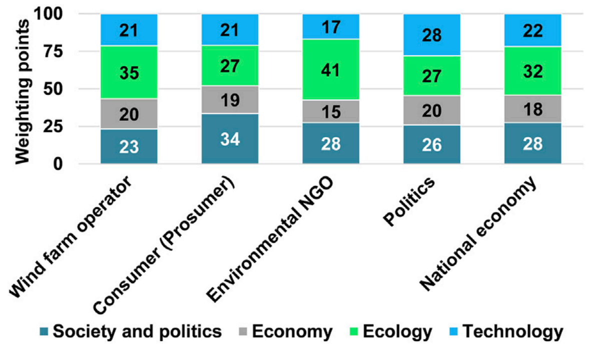

FIGURE 7
MCA weighting profiles.

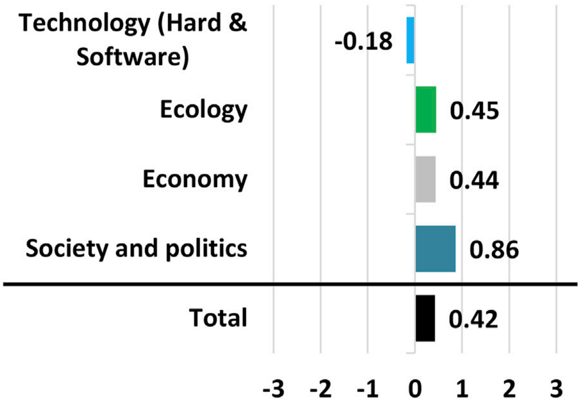

FIGURE 8
Aggregated MCA result from a national economy perspective.

unit). It can be concluded that environmental life cycle impacts do not play a significant role in the holistic evaluation of the application in this case.

## 4.3 MCA weighting profiles

Before combining the LCA and the EI assessment results in the MCA, weighting profiles for the criteria must be defined. As described earlier, the responses of nine experts are used to derive five weighting profiles, as depicted in Figure 7. The wind farm operator perspective is based on the three wind farm operator representatives, the consumer perspective on the two scientists with wind energy acceptance expertise, the environmental NGO perspective on the two NGO members, and the political perspective on the two political advisors. The national economy perspective is calculated as the average of the preceding weighting profiles.

For wind farm operators, i.e., the users of ADLS, the ecological impact is the most important impact, followed by societal, technical, and economic aspects, all of which are about equally important. From the consumers' point of view, technical and economic aspects have low relevance, while aspects concerning society and politics have the highest importance. From the environmental NGO's perspective, ecological aspects are by far the most important ones. The political perspective is the most balanced weighting profile, and the national economy represents the average view across all interviewed experts. Overall, ecological aspects are considered as most important, while the economic aspects are considered the least relevant.

## 4.4 MCA results integrating LCA and EIs

Subsequently, the normalized LCA and the EI results are combined in the MCA and aggregated based on the weighting profiles. First, the results calculated based on the "national economy" weighting profile are presented (Figure 8 and highlighted lines in Figure 9), followed by an overview of the results based on the different weighting profiles (Figure 10).

Figure 8 illustrates the aggregated results at the MCA category level. The overall evaluation is slightly positive. The largest positive impacts are in the society and politics category. The technology category is evaluated slightly negatively. The ecology and economy categories are both slightly positive.

The next level of detail, i.e., the results per criterion, is depicted in Figure 9. Together with each result, the standard deviation of the EI responses and the number of responses

FIGURE 9
Criteria level MCA results from a national economy perspective, including standard deviation and number of data points.

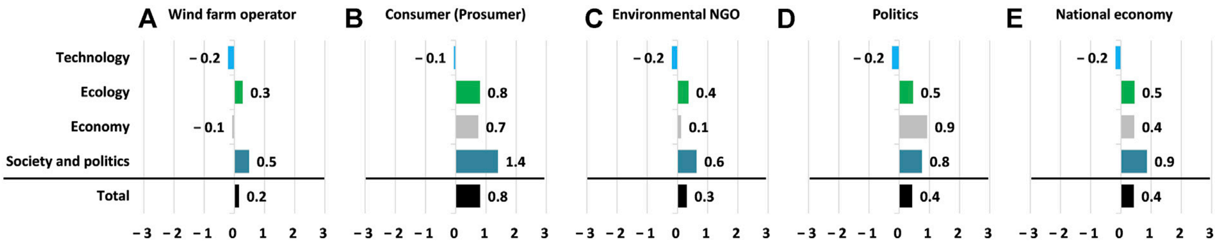

FIGURE 10
Aggregated MCA results from different stakeholders' perspectives: **(A)** Wind farm operator; **(B)** Consumer (Prosumer); **(C)** Environmental NGO; **(D)** Politics; **(E)** National economy.

received are given as an indication of the reliability of the data per criterion. Since the values of the five LCA-based criteria are derived from the normalization in Section 4.2, no standard deviation is provided. Further sources of uncertainty are qualitatively discussed in Section 5.3.

Within the slightly negatively evaluated technology category, the main negative drivers are the required technical effort and the availability of materials and know-how. The greatest technical effort is required for development and implementation, while operation does not cause any relevant additional effort. In particular, the implementation effort for existing turbines is high, especially for old turbines without appropriate communication infrastructure. For newly built turbines, the additional implementation effort will be low. Regarding the availability of materials and know-how, a major bottleneck for the rollout is identified. In particular, the production bottleneck is a shortage of ICT equipment on the world market, especially semiconductor-based integrated circuits. A bottleneck for the implementation is a shortage of technicians with the necessary know-how due to a general shortage of technicians in Germany. Although these shortages are generally expected to persist for several years, they are most likely no long-term barrier to further ADLS deployment after the initial rollout due to the small quantities needed in comparison to the total capacities of semiconductors and trained technicians. Minor negative effects are expected on the resilience of the critical infrastructure and data security, as there are additional potential points of attack, especially for systems with internet access. However, since the information processed is not critical, the risk of cyberattacks is low. Nevertheless, there is an additional dependency on the availability of correct data. The main positive factors are seen in the potential for innovation, such as improved accuracy of aviation data, integration of other data sources, improved monitoring of beacons, and synergies with other applications. These synergies could include, for example, more effective management of increasing air traffic and control of, for example, unmanned aerial vehicles (UAVs) based on detailed traffic data over lower airspace. Others are the identification of noise sources by matching air traffic data with sound pressure levels and the application of ADLS to other obstacles such as buildings. No impacts on generation, consumption, and grid controllability are identified.

Although the five normalized LCA results do not show significant impacts on the ecology category, the overall category reveals a positive result due to the anticipated positive impacts on enabling more renewable energies and protecting wildlife. The integration of more renewable energies could be positively influenced as approval processes could proceed more quickly due to a reduced number of arguments of lawsuits against new WTs, and neighbors could accept more turbines in their vicinity because they are perceived as less stressful. Although a positive impact on wildlife protection is expected by most experts, the standard deviation of responses is very high. On the one hand, the impact on wildlife could be reduced as nighttime light emissions are reduced. On the other hand, IR light could have a new impact, possibly on other species. Plants will most likely not be affected.

In the economy category, high profits and growth potential are seen for ADLS providers. After an initial spike during the rollout, long-term demand to equip new turbines and offer operational services is likely. Since Germany is the first country to introduce a nationwide ADLS obligation that also allows the use of transponder technology, there could be significant export potential, giving German providers a first-mover advantage. In addition, as mentioned, further growth potential exists through the application of the technology to other obstacles such as buildings, bridges, chimneys, etc. However, the standard deviation of responses regarding growth potential is high, indicating significantly divergent views. Furthermore, market entry barriers are estimated to be relatively high. The main obstacles for new suppliers are patents and the complex type examination certification procedure. For the user's side, the profitability is evaluated slightly negatively, with a high standard deviation in responses. No significant impact on non-monetary user benefits, such as transparency, controllability, usability, etc., is found. Monitoring and control of beacons could be slightly improved, which would lead to more transparency.

The most positively evaluated category, society and politics, is primarily driven by the very strong positive evaluation of the impact of ADLS on social acceptance. Reduced lighting reduces lighting-related stress and thus increases acceptability. The acceptance evaluation shows a very low standard deviation and a maximum number of responses, indicating low uncertainty. In addition, positive effects on the value creation steps in Germany and on the number of jobs are also expected. New value creation steps for the production, installation, and opertion of ADLS will be implemented, creating some jobs in the medium to high qualification range. No significant impacts are seen on participation in the energy sector, labor conditions, dependence on other nations, or need for government support. However, the regulatory implementation effort is evaluated relatively strongly negatively. The effort required to create the necessary regulatory framework in advance of the ADLS obligation was quite high, several laws and regulations had to be amended. Some final procedural clarifications are still needed, in particular, a definition of who is authorized to test and certify the proper installation and operation of ADLS.

The potential impact of a failure is a cross-category set of criteria. These criteria are therefore analyzed jointly. The impact of a failure is a combination of its probability and its potential magnitude. The overall potential impact of a failure is found to be low. The probability of a failure, such as a collision between an aircraft and a turbine, is judged to be virtually zero. Systems must be designed with an engineered fallback option to ensure that beacons remain on if the system fails to operate properly. In addition, always-on IR lights will be added for pilots conducting low-level night flights without transponders, e.g., military and police. The technical and social/political impacts if a failure (collision) actually occurs are somewhat higher compared to the environmental and economic impacts. The technical impact of such a failure could, in the worst case, be the loss of the aircraft, the turbine, and even loss of life. Socially/politically, such a failure could lead to a reduction in the acceptance of wind energy in general.

While the weighting profile "national economy" was analyzed above, the MCA results can also be analyzed with weighting profiles representing the perspectives of the different stakeholders. The aggregated results for different weighting profiles are displayed in Figure 10. The evaluations with all weighting profiles show a positive total result. Overall, the result of the consumer perspective (B) is the most positive, which is mainly due to the high weighting of the society and politics category and in particular the social acceptance criterion. Wind farm operators (A), on the other hand, evaluate the application almost neutrally overall, which is mainly due to the high weighting of profitability for the user. The technology category is evaluated slightly negatively and very similarly across all weighting profiles. The ecology category is evaluated the most positively from the consumer perspective (B), even more positively than from the environmental NGO perspective (C). This is due to the high importance consumers place on enabling renewable energies, while environmental NGOs distribute the weighting more evenly across all ecology criteria. The evaluations for the economics category range from very slightly negative for wind farm operators (A) to positive from a political perspective (D). This evaluation range is based on the different prioritization of economic impacts on the provider side compared to the user side. All weighting profiles lead to a positive evaluation of the category society and politics. From a political perspective (D), not only positive impacts in the society and politics category but also economic benefits are expected. However, from a national economy perspective (E), these are less relevant.

# 5 Discussion

Following the structure of the result section, the LCA results are discussed first, followed by the MCA results, which integrate LCA and EI results. The section concludes with a discussion of the possible sources of error.

## 5.1 LCA result discussion

Based on the LCA results given in Figure 4, it is evident that the five considered impact criteria increase by the use of ADLS in the base case. The analysis of the breakdown of each of the impact criteria reveals the impact drivers and thus aspects with potentially high improvement levers. ADLS hardware energy consumption emerges as one of the most important impact drivers for CED, GWP, ARD, and ET. This underscores the importance of paying attention to energy-efficient design in engineering development. The impact of GWP and ARD can be further reduced by decreasing the $CO_2$ intensity of the energy mix used for production. To reduce the HT and ET impact, the design of the hardware needs to be analyzed regarding the presence and possible substitution of certain materials such as copper, gold, silver, brass, and other precious metals. The finding that GWP and ARD are driven by the $CO_2$ intensity of the energy mix, while HT and ET are driven by the underlying infrastructure, is consistent with other LCAs on energy systems, e.g., (Baumgärtner et al., 2021). Recycling, as modeled in the presented study, results in only a small reduction in all impact criteria (compared to the production impacts). However, an improved recycling process could improve the overall result.

Given the results shown in Figure 5 and Figure 6, it is evident that the ADLS life cycle impacts depend heavily on the number of turbines covered by one ADLS and the number of communication units required per ADLS. Although it may be difficult to influence the layout for existing wind farms, both of these issues can be considered for newly built WTs. Based on the experience from the ADLS planning in North Rhine-Westphalia, the realistic range of onshore turbines covered by one ADLS is between 1 and 33. Therefore, in some cases, the ADLS may lead to an impact reduction of some or all of the analyzed ecological criteria, at least if only one communication unit is required. Since offshore wind farms typically consist of significantly more turbines (currently 12–80 turbines per operational German offshore wind farm) with a central communication unit and are less likely to be located in high air traffic zones, a decreased life cycle impact of using ADLS can be expected here.

## 5.2 MCA result discussion

The MCA provides a holistic overview of all relevant criteria from relevant stakeholders' perspectives. The main objective of the ADLS obligation, to increase social acceptance of wind energy, is likely to be achieved. The evaluation from the consumers' point of view is the most positive, with the highest evaluation in the society and politics category. No fundamental opposition to the obligation needs to be expected, as all stakeholders come to an overall positive evaluation. The stakeholders most affected by the obligation, the wind farm operators, are the ones with the least positive evaluation. Compensation, i.e., a lower regulatory burden, could improve their perception of the application. From a political perspective, not only the positive impact on the society but also on the economy is relevant. Furthermore, it is evident that due to the identified bottlenecks for the rollout (global scarcity of semiconductors and lack of technicians in Germany) and the regulatory process clarifications still needed, the feasibility of a full rollout by the end of 2022 is questionable. The authors recommend a limited extension of the rollout period until these challenges are likely to be mitigated to an acceptable degree. With a very similar argumentation, the German authorities intend to postpone the deadline by 1 year, according to the first draft of a future version of the German Renewable Energy Law (BMWK, 2022).

Such a limited extension of the rollout period would also allow for analyzing the pre- and post-implementation situation of two important aspects, which still require investigation:

1) No studies have yet been conducted on the effects of ADLS on wildlife. Therefore, the uncertainty of expert responses for this criterion is very high (reflected in the high standard deviation shown in Figure 9). Further studies are recommended, e.g., by monitoring finds of dead birds in the area.
2) Several studies demonstrate the relevance of WT lighting on stress and acceptance. Even though lighting is a less relevant cause of stress than noise and shadows flicker, it is visible in a larger surrounding and thus affects more people (Rudolph et al., 2017). However, no study has been conducted that directly measured the change in acceptance in the vicinity of a wind farm before and after the implementation of an ADLS. Therefore, such a study is recommended.

## 5.3 Validity of the results

The evaluation shown here is valid for currently installed ADLS. It is assumed that changing conditions within a short time frame of a few years will not significantly change the evaluation, but changes occurring after more than a decade might do so. Although LCA results, particularly the GWP and ARD impact, might become more positive due to reductions in GHG intensity of the energy used and advances in recycling, the LCA impact as part of the MCA will still be insignificant. However, as the size and number of WTs increase, more people might be affected by lighting-related stress without ADLS. Therefore, it is likely that more and more countries will approve the application of transponder-based ADLS, which will increase the market size and growth potential. At the same time, this will lead to more international competition, which will likely reduce profitability for the first movers.

Furthermore, a critical look at potential sources of error and uncertainty is needed. Some sources of error are inherent to the design and methodology of the framework, while others depend on the evaluation practitioner, the availability of data, and the functionality of the application being evaluated. The most important source of error in MCA is the selection of evaluation criteria. If the criteria do not cover the relevant impacts, the evaluation cannot produce a meaningful result. Therefore, considerable effort has been put into the development of the criteria, which have been updated for this study based on a previous study (Weigel et al., 2021). Furthermore, the MCA and weighting methods may have an impact on the result. The simple additive weighting method (SAW, also known as the weighted sum method), which is commonly applied due to its popularity and simplicity (Cajot et al., 2017), makes it intuitive for decision makers and thereby reduces the probability of user error. Furthermore, the aggregation method allows for a high level of transparency on how aggregated results are derived from criteria evaluations (Wilkens, 2012). The downside of the simplicity is that the compensatory aggregation might reduce the clarity of specific effects for complex problems (Marler and Arora, 2010), (Chu et al., 2007). This disadvantage is mitigated in this study by discussing results on aggregated levels as well as on the detailed criteria level. In (Terrapon-Pfaff, 2014) and (Daugavietis et al., 2022) the authors compare results obtained with different methods, including SAW, and conclude that results using the SAW method do not differ significantly from the results obtained with more complex methods. Furthermore, the SAW method is suitable to be applied with fuzzy numbers for uncertain input data such as subjective expert evaluations. The use of fuzzy sets is described in (Greco et al., 2016, 637), and an application is presented, for example, in (Ziemba, 2021). The integration of fuzzy SAW presents a future improvement possibility for the evaluation framework.

Further uncertainties may arise from the criteria assessment in the LCA and the EIs. The accuracy of the LCA result depends largely on the life cycle model created, including system boundaries, assumptions, input data, databases used, and the inclusion or exclusion of effects. A structured approach to assessing LCA data quality is the pedigree matrix (Weidema, 1998). Since the quality of the data used in this study varies significantly by data point, an overall evaluation of data quality according to the pedigree matrix does not appear feasible. Therefore, rather than assessing the quality of the input information, the effect of uncertainties on the results is estimated using sensitivity analysis. In this study, the sensitivity of the results is shown regarding several parameters, namely the number of turbines per ADLS, the number of communication units per ADLS, and the beacon reduction rate. No other parameters are identified as having a significant impact on the ADLS result. It should be noted that some ADLS use cloud data management, but the required data transfer and server operation are not included in the LCA due to a lack of information (Malmodin et al., 2014). find that the end-user applications cause a significantly higher GHG impact than the data transfer and servers. Therefore, it is unlikely that including both aspects would drastically change the outcome. Yet, a more accurate assessment could increase certainty. Furthermore, the LCA impact method used may have an influence on the results. Within the limited options of methods which include the required impact criteria (CML2001 and ReCiPe) the (midpoint) methods provide largely consistent results for the analyzed impacts (Bueno et al., 2016).

The choice of the reference for normalizing the LCA might have the greatest impact on how the LCA result affects the MCA result. In this study, the life cycle impact of the WTs, which are covered by the ADLS, is used as the reference. The WTs' life cycle impacts assessed with the Ecoinvent database (data source from 2001) result in a GHG intensity of 17.6 g $CO_2$ eq./kWh, while (Hengstler et al., 2021) finds a lower intensity of 10.6 g $CO_2$ eq./kWh for modern onshore low wind turbines. However, even a very large deviation of ±50% from the reference values would not significantly change the impact of the LCA on the MCA outcome.

The EIs are mainly influenced by the selection of experts, i.e., the number of experts, the area and level of their expertise, and their self-perception of knowledgeability to evaluate criteria. Unless a large number of interviews are conducted, which would require a great effort, the interview results cannot be considered representative. Nevertheless, expert knowledge can provide very valuable insights into the subject. Therefore, even a smaller number of experts is acceptable as long as their expertise covers the perspectives of the relevant stakeholders. A practical approach used in this study to ensure that the relevant stakeholder representatives are included is to ask each expert to identify relevant stakeholders. It is highly unlikely that a relevant stakeholder role would not be identified by any of the 12 experts interviewed, so good coverage of the relevant perspectives can be expected. However, as mentioned, no affected neighbors of WTs are directly included in the EIs of this study, but the insights of the two scientists researching the social acceptance of WTs is seen as a good proxy for the perspective of this group. The level of expertise of the experts can be difficult to assess for a non-expert, but information about professional positions, publications, or involvements in reputable organizations can be used as quality control. In addition, each expert is explicitly advised to evaluate only criteria regarding which he or she feels sufficiently knowledgeable. Thus, it can be expected that most answers are based on sound expertise and that different answers are mainly an indication of uncertainty due to the range of possible impacts. As an improvement of the framework in this study, the standard deviation of the EI results is used in combination with the number of responses as an indicator of uncertainty, which revealed high uncertainties in particular for the criteria innovation potential, growth potential, economic barriers, availability of materials and know-how and regulatory implementation effort. Last but not least, the EI result may also be influenced by the interviewer during the interview. Here, a minimal intervention approach was applied, i.e., besides an initial introduction and some necessary criteria clarifications, the interviewer only passively documented the experts' evaluation.

## 5.4 Suitability of the framework

Since, in this study, an adapted version of the previously developed framework is applied, the adapted version's suitability is reviewed. The intended characteristics of the framework are that meaningful and useful results can be obtained, that it is easily usable for researchers and representatives of companies and organizations, and that it can be applied to the variety of current and future digital applications. Therefore, the suitability should be evaluated based on the conclusiveness of results, the feasibility of use, and the adaptability of the framework. The conclusiveness of the results includes both correctness and potential for deriving action. Feasibility of use is based on the effort required for each evaluation as well as the inherent complexity and thus the level of expertise required by the practitioner. Adaptability of the framework is required regarding different types of digital applications, the level of data availability, and practitioners' preferences. These suitability criteria are specific to the evaluation of this framework and can only be evaluated qualitatively.

The correctness of the results is difficult to assess due to the lack of other studies on ADLS. However, based on the possible comparisons of specific aspects with other publications and the relatively high consistency of expert opinions, the results are likely to be very realistic. Sources for uncertainties are identified and, where possible, analyzed via sensitivity analysis or statistical means. Furthermore, the potential to derive actions is high as direct measures and recommendations for further studies, life cycle improvement initiatives, as well as regulatory adjustments are identified. The overall conclusiveness of the result is therefore considered to be high.

The effort required to collect the necessary data for the LCA and to conduct the twelve expert interviews is relatively high. However, the framework improvement implemented in this study to let experts independently conduct the weighting after the interview decreased the interview effort and time requirement for the research team significantly. Due to the methods chosen, the complexity of the MCA and the EIs is rather low, such that this part of the framework can also be carried out by practitioners without a deep theoretical understanding of the methodology. The LCA, however, requires in-depth expertise. Therefore, the feasibility of use is evaluated as medium. This drawback could be mitigated if existing life cycle results could be integrated instead of conducting a separate LCA. In addition, the effort could be further reduced by decreasing the number of expert interviews. However, this could affect the correctness of the result.

The adaptability of the framework regarding different types of applications can be assessed by looking at the difference between the application evaluated in this study and the smart meter rollout evaluated in (Weigel et al., 2021). The two applications differ greatly in terms of the energy value stream step in which they are deployed, their function, and their effects. Furthermore, in this study, a single application is evaluated, while in (Weigel et al., 2021), a nationwide rollout of an application is evaluated. The adaptability regarding the type of application is therefore considered to be very high. The availability of information differs considerably between criteria, e.g., there are several studies on the social acceptance of ADLS, but none on the impact on wildlife. Nevertheless, all criteria can be evaluated in the expert interviews and discussed, including the standard deviation and the number of responses as a measure of the robustness of the result. This demonstrates the very high adaptability of the framework to different levels of data availability. Finally, the adaptability to practitioners' preferences can only be evaluated once the framework has been applied by different practitioners, which is not the case at this stage. Therefore, the overall adaptability is considered to be very high, but the unevaluated adaptability to practitioners' preferences has to be taken into account.

Considering the high conclusiveness of the results, the medium feasibility of use, and the very high adaptability, it is concluded that the evaluation framework is well suited for its purpose.

## 6 Conclusion and outlook

In this study, an updated version of a holistic evaluation framework previously developed by the authors was applied to evaluate the application of aircraft detection lighting systems for wind turbines. The framework is specifically designed for the holistic evaluation of digital applications in the energy sector. To achieve a holistic view, multiple criteria covering all relevant impact areas were evaluated, relevant stakeholders' perspectives were considered as weighting profiles, and representatives of relevant stakeholders were involved in the process. A life cycle assessment was performed to assess several environmental criteria. The required data and information were provided by both an ADLS and a beacon manufacturer. Furthermore, twelve expert interviews were conducted to assess all other criteria that were not part of the LCA. The experts also weighted the criteria, and five weighting profiles were created. The study presents the first holistic evaluation of ADLS, in contrast to previous studies, which focus on single evaluation aspects such as aviation risks or social acceptance as well as a refined version of the evaluation framework.

The results of the LCA show a likely increase in the life cycle impact of all analyzed criteria if a realistic design of the system is assumed. The magnitude of the increase depends mainly on the number of WTs covered per ADLS and the need to install additional communication units. Due to the size of offshore wind farms, the ADLS could lead to a reduction in life cycle impacts here. The LCA results of this study can be used by ADLS manufacturers as a starting point for life cycle improvement activities. However, in the context of the life cycle impacts of the turbines covered by the ADLS, the impact of the ADLS is negligible, whether it is increased or decreased. The MCA based on LCA and EI results shows an overall slightly positive evaluation from all stakeholders' perspectives. Therefore, a rollout is expected to be beneficial. The most significant benefits are seen in the increased social acceptance of wind turbines as well as the economic (international) growth potential for the providers of the technology and the resulting impact on the national economy. Two further studies are recommended with respect to 1) wildlife impacts to ensure that potential adverse impacts are identified and addressed and 2) social acceptance impacts to validate and measure wind energy acceptance before and after installing ADLS. Three main bottlenecks for the rollout were identified: the shortage of global semiconductor supply needed for production, the lack of trained technicians for installation, and remaining regulatory uncertainties regarding the approval process. Given these bottlenecks, an extension of the rollout period is recommended. The remaining time until the obligation becomes effective should be used by decision-makers to address the identified bottlenecks. Political decision-makers should drive the administrative process to eliminate the regulatory uncertainties. The issues of global semiconductor scarcity and lack of technicians in Germany go well beyond affecting only ADLS but hinder major developments, such as the transition towards renewable energies, and therefore, need to be counteracted on a broader economic-political level by, e.g., researching material substitutions, investing in new production capacities and supporting continuing professional development. However, smaller measures to mitigate the impact of these bottlenecks on the ADLS rollout can be taken by business decision-makers. For example, the pooling of ADLS installations for an entire region, as done by the association for renewable energies in the state of North Rhine-Westphalia, could improve the plannability for both ADLS manufacturers and installers. Furthermore, the implementation of ADLS in other countries could benefit from an early holistic evaluation using the presented framework.

Potential sources of uncertainty were identified, and, where possible, sensitivity analyses were performed. Given the limitations and uncertainties, the study provides a robust evaluation result with an aggregated overview and valuable insights into bottlenecks and potential for improvements at the criteria level.

The suitability of the updated framework was assessed based on three criteria: conclusiveness of results, feasibility of use, and adaptability of the framework. Overall, the framework was found to be highly suitable for its purpose. Two measures are suggested to further improve the feasibility of use. In addition, the possibility of applying fuzzy sets for the SAW aggregation method was pointed out to improve the handling of uncertainties.

A prospective future direction of the research might be for the framework to be applied to different digital applications in the energy sector by different practitioners. Additionally, the framework could be adapted for the evaluation of digital applications in other sectors. With increasing numbers of performed evaluations, the comparability of results becomes increasingly interesting and should be analyzed. The proposed integration of fuzzy logic may improve the comparability of applications with varying uncertainties. Another interesting future aspect could be the retrospective analysis of previous evaluations regarding the accuracy of results and conclusions.

## Data availability statement

The datasets presented in this article are not readily available because due to confidentiality restrictions of the information supplying company, data on the technical setup of the application can only be shared on an aggregated level upon request to the corresponding author. Raw and anonymized expert interview results can be shared upon request. Requests to access the datasets should be directed to pweigel@uni-osnabrueck.de.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the (patients/participants OR patients/participants legal guardian/next of kin) was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

All authors contributed to the conception and design of the study. PW gathered and analyzed the data and conducted the assessments. The manuscript was prepared by PW, with frequent input and revisions from PV. All authors carefully read and approved the submitted manuscript.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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# Appendix: Relevant assumptions for the LCA of the ADLS

| Assumption | Value | Unit | Source |
|---|---|---|---|
| Turbine lifetime | 20 | Years | Industry standard |
| ADLS lifetime | 20 | Years | ADLS manufacturer |
| Analysis period | 20 | Years | Turbine lifetime |
| Reduction of beacon operational hours during night | 98 | % | ADLS manufacturer |
| Reduction of LED replacements | 1.29 | Replacements/ 20 years | Beacon manufacturer |
| ADLS receiver electric capacity | 31 | W (average per day) | ADLS manufacturer |
| ADLS communication electric capacity | 28 | W (average per day) | ADLS manufacturer |
| Infrared (IR) beacon electric capacity | 1.3 | W (during operation) | Beacon manufacturer |
| Beacon W red electric capacity | 5 | W (during operation) | Beacon manufacturer |
| Beacon W red + IR electric capacity | 6 | W (during operation) | Beacon manufacturer |
| Share of on-site electricity of consumption | 81 | % | ADLS manufacturer |
| GWP 100 of German electricity mix in 2022/ 32/42 | 460/330/257 | kg $CO_2$ eq./kWh | Weigel et al. (2021) |
| Location (Erfurt Germany) | 51°13′55 N<br>6°48′42 O | GPS coordinates | |
| Yearly average night hours | 10.48 | h/d | BMDV (2022) |
| Yearly average twilight hours | 1.25 | h/d | BMDV (2022) |
| Recycling shares | | % | |
| Aluminum | 90[1] | | |
| Cables | 84[2] | | |
| Electronics | 84[1] | | 1) (German Corporation for International Cooperation GmbH (GIZ), 2022) |
| PCBs | 84[2] | | 2) assumed to be same as electronics |
| Plastics | 47[1] | | |
| Steel | 95[1] | | |
| Component weights | Kg | | |
| Receiver | 21.5 | | ADLS manufacturer |
| Communication module | 22.1 | | ADLS manufacturer |
| Mounting/Antenna/Cabling | 43.2 | | ADLS manufacturer |
| Infrared beacon components | 0.16 | | Beacon manufacturer |
| LED beacon components | 0.57 | | Beacon manufacturer |
| LED Lifetime | 50,000 | h | Beacon manufacturer |