A Meta-Review on the Use of Artificial Intelligence in the Context of Electrical Power Grid Operators

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Abstract: With the growing energy hunger of today's society and the ongoing transition from fossil fuels to renewable energies, the demands on the electrical power grids are growing. Consequently, grid operators are seeking for ways to improve their performance, flexibility, and reliability. One of these avenues is the use of artificial intelligence. However, while there are already promising endeavors, this research stream is still far from being mature. For this reason, in the publication at hand, a meta-review is presented that outlines important themes, trends, and challenges to provide scientists interested in the domain with a starting point for new projects.

1 INTRODUCTION

The transition from fossil fuels to renewable energies is one of the major topics of today's time (Neacsa et al. 2022) and it can be expected that its importance will only be increasing in the future (Holechek et al. 2022). While oil and gas are (at least currently) crucial for the creation of certain products (Allison and Mandler 2018), in many cases at least the demand for energy could be satisfied with electrical power created from renewables. However, just producing the electricity is not sufficient. Since renewable energy sources are less consistent in their output and a widespread power supply failure can result in massive negative consequences (Busby et al. 2021), it is also important to have the appropriate infrastructure to reliably store and distribute it to its consumers (Hossain et al. 2016; Kalair et al. 2021). Hence, electrical grid operators play an important role regarding the success of the transition. To facilitate their mission and match the supply with the demand, technological advances such as smart meters, digital twins, and artificial intelligence play an important role (Altenburg et al. 2023b; Bose 2017; Sifat et al. 2023). Therefore, making improvements in these areas is an important part in propelling the transition to renewables. However, to be able to bring about improvements, it is at first important to understand respective the domain. For this reason, this study aims to explore the use of artificial intelligence in the context of electrical power grid operators. The main goal is to provide a general understanding of important themes, trends, and challenges, to equip scientists interested in the field with a starting point and help steer upcoming research endeavors towards a meaningful direction. For this reason, in the publication at hand, a meta-review is conducted that aims to answer the following research question (RQ):

RQ: What are current themes, trends, and challenges regarding the use of artificial intelligence in the context of electrical power grid operators?

To answer the RQ, the paper is structured as follows. After this introduction, the conducted review itself is described. This is followed by a discussion of the findings. Finally, a conclusion is given that also highlights the limitations of the current study as well as avenues for future research.

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2 THE REVIEW

To provide the desired overview of the domain, a meta-review was conducted, which means that instead of primary works, relevant literature reviews were gathered and analysed. This way, a high-level picture emerges, which can be used to identify important streams and themes and to steer future research endeavors. For this purpose, in the following, the applied review protocol is outlined in detail as recommended by (Vom Brocke et al. 2009). The protocol itself was developed based on (Levy and J. Ellis 2006; Okoli 2015; Vom Brocke et al. 2009) as well as this study's particular needs.

The description of the review process is succeeded by a brief overview of the identified papers. Subsequently, the corresponding findings are discussed.

2.1 Review Protocol

To find the relevant literature that provides an overview over the use of artificial intelligence in the context of electrical power grids, several scientific search engines and databases have been utilized. Namely, these are Scopus, IEEE Xplore (IEEE), ACM Digital Library (ACM), and AIS electronic Library (AISeL). These were chosen for the following reasons. Scopus is arguably the biggest abstract and citation database for scientific literature. IEEE and ACM are highly relevant for the computer science domain. Finally, AISeL hosts the proceedings of some of the most important conferences in the field of computer science and business informatics. Therefore, by choosing this set of sources, a comprehensive overview of the relevant literature is assured. However, to narrow down the deluge of available publications and to assure a certain relevancy of those that will be further considered in the course of the review process, suitable search terms need to be found, which should, further, be as consistent as possible between the different databases.

Because the paper's regarded domain are electrical power grids, at least one of the terms *power grid*, *energy grid*, *electricity grid*, or *electrical grid* is expected to appear in the title of relevant contributions. Further, since the paper aims to explore the use of artificial intelligence in this context, the term *artificial intelligence*, its abbreviation *AI*, *machine learning* as a commonly used and referred to subdisciplice of , or its abbreviation *ML* are required to be mentioned in title/abstract/keywords (Scopus), the metadata (ACM), respectively anywhere (ACM), depending on the specifics and possibilities of the search engines.

Finally, to accord for the meta-review aspect of this study, the title also needed to contain *review*, *survey*, *overview*, *study*, *state of the art*, or *situation* to cover a wide variety of terms that might be used to denote the sought after type of work. However, the latter two parts of the search term were only used for Scopus, IEEE, and ACM. In AISeL, the options to finetune the search are limited. Though, the number of search results is also manageable. Therefore, in contrast to the other engines, here, only the first part of the search term was applied. The used search terms are shown in Table 1.

Table 1: The search terms.

Search Engine	Search Term
Scopus	(TITLE ("power grid" OR "energy grid" OR "electricity grid" OR "electrical grid") AND TITLE-ABS-KEY ("machine learning" OR "ML" OR "artificial intelligence" OR "AI") AND TITLE (review OR survey OR overview OR study OR "state of the art" OR situation)) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar"))
IEEE Xplore	("Document Title":"power grid" OR "Document Title":"energy grid" OR "Document Title":"electricity grid" OR "Document Title":"electrical grid") AND ("Document Title":review OR "Document Title":survey OR "Document Title":overview OR "Document Title":study OR "Document Title":"state of the art" OR "Document Title":situation) AND ("All Metadata":"machine learning" OR "All Metadata":"ML" OR "All Metadata":"artificial intelligence" OR "All Metadata":"AI")
ACM Digital Library	[[Title: "power grid"] OR [Title: "energy grid"] OR [Title: "electricity grid"] OR [Title: "electrical grid"]] AND [[Title: review] OR [Title: survey] OR [Title: overview] OR [Title: study] OR [Title: "state of the art"] OR [Title: situation]] AND [[All: "machine learning"] OR [All: "ml"] OR [All: "artificial intelligence"] OR [All: "ai"]]
AIS electronic Library	title:("power grid" OR "energy grid" OR "electricity grid" OR "electrical grid")

By applying the search terms to the databases, a total of 18 journal articles and 44 conference papers was identified. The distribution across the sources as well as the overall course of the search can be seen in Figure 1.

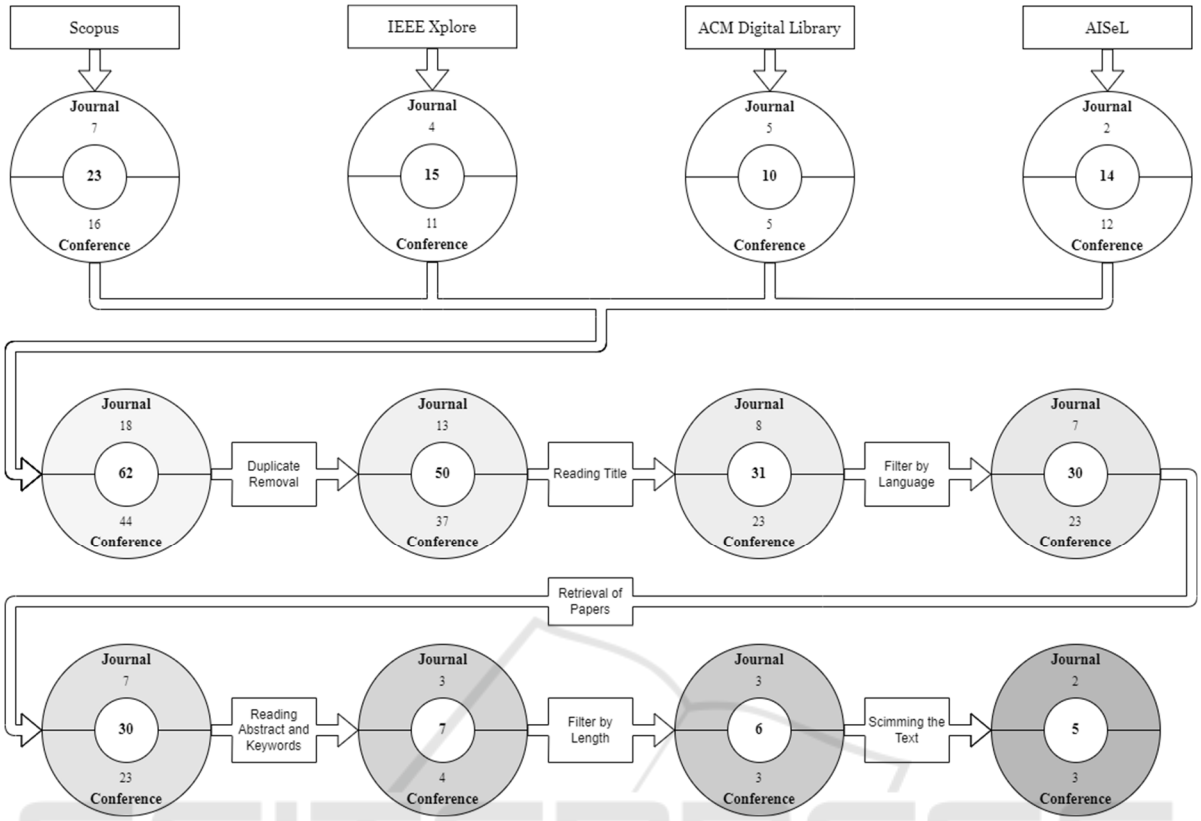

Figure 1: The review protocol.

In a first filter step, duplicate papers were removed. There were eleven papers that had duplicates, with one even appearing across three databases. Hence, this step led to a reduction by twelve entries, leaving 13 and 37 contributions for journal articles respectively conference papers.

For the purpose of further narrowing down the set of acquired literature, some inclusion and exclusion criteria have been defined. While the former have to be completely fulfilled for a paper to be considered, none of the latter must apply or a paper is rejected.

To ensure a certain quality, only peer-reviewed conference papers and journal articles are used. Moreover, due to the design of this study as a meta-review, the considered contributions have to be either a literature review or shall at least comprise a review of the literature that constitutes an important part of the work. Finally, a paper needs to relevantly contribute to answering the RQ to justify its inclusion.

As a basic condition to allow the understanding of the content, the papers have to be written in English. Hence, papers written in other languages are excluded. This also applies to papers whose comprehensibility is insufficient to be deemed beneficial. Additionally, short papers are also excluded, with the minimum requirement being defined as a length of at least six pages. Further, if an updated or extended version of a paper is found, the older one is discarded.

An overview of the formulated inclusion and exclusion criteria is given in Table 2.

Table 2: The inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Paper is a conference paper or journal article	Paper is not written in English
Paper is either a literature-review or contains a literature review as an important part of the work	Paper is not comprehensible enough to be beneficial
Paper provides valuable input to answer the RQ	Paper has a length of less than six pages
	Paper has an updated version that is part of the literature set

Using these criteria, the identified candidate papers were filtered by title. However, this was handled not that strictly, meaning that whenever there was doubt, the paper was carried over to the next phase. In doing so, a total of 31 papers was kept.

However, one of them was written in chinese and was, for this reason, removed. By now, this process was carried out, using the data exported from the databases, without a need to actually use the actual papers. When trying to retrieve them, this was successful for all of them. Hence, none needed to be excluded for availability reasons.

Now, abstract and keywords were read to determine the suitability for answering the RQ. This left seven papers, with one being afterwards excluded due to its length of only four pages. Further, one paper had six pages with the last one not being entirely filled. However, since it was deemed relevant after reading the abstract, it was not removed, since the criterion was slightly vague in that regard and the more generous interpretation was chosen. As a result, at this point, the set of literature comprised three journal articles and three conference papers.

In a final step, these publications were scimmed over to determine their suitability and one, namely „Mobile Apps Meet the Smart Energy Grid: A Survey on Consumer Engagement and Machine Learning Applications“ (Chadoulos et al. 2020), was excluded. While it appeared to be relevant, it was determined that the exploration of the use of machine learning referred to the mobile apps and was, therefore, a bit too far from the topical focus of this review. An additional step to account for updated versions of papers was not necessary, since there were none left at this phase, even though, at an earlier point, at least one of these pairs was noticed. However, both entries were already removed during the title screening.

Thus, the final set comprises two journal articles and three conference papers that will be further described in the following sub-section. While this number is generally rather low, the positioning of this study as a meta-review and the comprehensive nature of the identified publications still allows to get a meaningful overview of the domain and, thereby, answer the RQ.

2.2 The Identified Papers

As a result of the described search and filter process, a final set of five publications emerged that each contain reviews of the literature relevant to understand the current themes, trends, and challenges regarding the use of artificial intelligence in the context of electrical power grid operators.

A list of these papers is given in Table 3. They focus on aspects such as, inter alia, fault diagnosis, risk mitigation, the handling of uncertainty, and the harnessing of digital twins, thereby covering a rather broad spectrum within the regarded domain. Further, it is noticeable that they are all rather recent, with the oldest one being from 2019.

In (Chai et al. 2019), an overview of AI approaches for fault diagnosis of power grids is given. The authors identified nine different methods and describe them as well as their advantages and disadvantages. While the paper is a review of the literature and is, therefore, included, it is not described how the used papers were identified. Further, the work remains rather high level and does not go into deep detail. However, the study provides a starting point for researchers interested in the domain, who can then further look into the referred to literature. Moreover, the authors describe several research trends they expect to gain traction in the future.

The topic of ML-based contingency analysis to prevent blackouts is focused in (Yang et al. 2020). While the paper proposes an artifact to address the issue and is, therefore, not a classical literature review, it also contains a part that gives a comprehensive overview of relevant publications in the domain. For this reason, the respective inclusion criterion was deemed fulfilled and the paper included. However, due to its focus, future trends or similar aspects are not discussed.

Supporting the integration of photovoltaic (PV) systems with the use of AI is targeted in (Feng et al. 2021). For this purpose, supported by text mining techniques, the authors conducted an extensive

Table 3: The final set of literature.

No.	Reference	Year	Title	Type	Source
1	(Chai et al. 2019)	2019	Artificial intelligence approaches to fault diagnosis in power grids: A review	Conference Paper	Scopus
2	(Yang et al. 2020)	2020	Power grid contingency analysis with machine learning: A brief survey and prospects	Conference Paper	Scopus, IEEE
3	(Feng et al. 2021)	2021	A taxonomical review on recent artificial intelligence applications to PV integration into power grids	Journal Article	Scopus
4	(Cioara et al. 2022)	2022	An Overview of Digital Twins Application in Smart Energy Grids	Conference Paper	Scopus
5	(Rahim and Siano 2022)	2022	A Survey and Comparison of Leading-Edge Uncertainty Handling Methods for Power Grid Modernization	Journal Article	ACM

literature review that also contains a bibliometric analysis. The study primarily discusses four main application types, namely *forecasting*, the *detection of PV arrays as well as faults in PV systems*, the *optimizitaion of PV systems' designs*, and the *optimization of the control of PV systems*, but also dedicates a section to other (related) topics. Further, potential avenues for future research are outlined.

The application of digital twins in the context of smart energy grids is regarded in (Cioara et al. 2022). While this does not necessarily fit the scope of the study at hand at first glance, there is also a strong focus on the use of ML in the given context. Therefore, this publication was deemed suitable for inclusion. The application domains of digital twins are identified as the *modeling of energy assets*, the *diagnosis of faults and security*, the *operation and control of grids*, as well as *ways to develop and facilitate business models*.

Finally, (Rahim and Siano 2022) focusses the handling of uncertainty in the context of power grids. For this purpose, they created a comprehensive literature review on the corresponding state-of-the art to determine which methods exist. Subsequently, these were discussed and comparatively analysed. In addition, they give separate comprehensive overviews regarding economic operations, bidding strategies, system expansion, electric transport, and microgrids. Thus, they provide insights as well as compiled lists of relevant literature for multiple facets of the domain, and cover several aspects of the field. Further, they also outline research gaps and give future recommendations, thereby providing researchers interested in the domain with a wealth of potential avenues to start off their own research.

2.3 Findings

While the acquired papers all differ regarding their focus and style, together they not only provide a comprehensive overview of the regarded domain but there are also certain themes that are somewhat recurring. For instance, fault diagnosis (Chai et al. 2019; Cioara et al. 2022; Feng et al. 2021) as well as contingency diagnosis (Rahim and Siano 2022; Yang et al. 2020) are referred to in multiple papers. This highlights their importance and is also in accordance with other works (Altenburg et al. 2023a; Busby et al. 2021) that highlight the potential severity of disorders of the energy supply. Moreover, the diversity and vastness of the topic become clearly visible when considering the high number of different methods and techniques that are mentioned in the analyzed papers. While this is attributable to the diversity on artificial intelligence approaches in general and not to the specific application domain, it still stands out compared to many other research streams. Another topic that is mentioned even more, emphasizing its relevance, are time series data, their preservation, analysis, simulation, and forecasting (Cioara et al. 2022; Feng et al. 2021; Rahim and Siano 2022). Also, forecasting in general is prominently positioned, appearing in all of the considered papers (Chai et al. 2019; Cioara et al. 2022; Feng et al. 2021; Rahim and Siano 2022; Yang et al. 2020) in some capacity, yet there is still much room for improvement.

Other directions for future research that are identified include the creation of forecasts based on images, the use of more sophisticated AI approaches, and the management of uncertainties, for instance, by providing probabilistic forecasts (Chai et al. 2019; Feng et al. 2021; Rahim and Siano 2022). Moreover, the combination of multiple AI technologies as well as the fusion of multiple data sources to increase the quality of the outputs has been suggested (Chai et al. 2019). Further, while there are already some papers dealing with the topic of digital twins for facilitating power grid operations, this research stream is still in its infancy and there is much room for advances (Cioara et al. 2022).

Another important topic is the AI support for the planning of sizing and siting of facilities that generate renewable energies (Feng et al. 2021). Due to the general inconsistency of the production with its dependence on a multitude of factors (e.g., specifics of the respective region and its weather), sophisticated tools can provide invaluable help to maximize the effective output and contribution to the reliability of the overall energy supply under consideration of all the relevant factors and constraints.

Finally, the practical application of the developed theories and methods was highlighted as an important part of the overall process that is currently somewhat lacking (Chai et al. 2019). While there are many theoretical works, these also need to prove their effectiveness in real-world-scenarios, which needs to be facilitated in the future.

3 DISCUSSION

As the contributions that were identified through the conducted review show, there are many different directions within the general research stream regarding the use of AI in the context of electrical power grid operators.

Moreover, by analysing the found literature, it became apparent that the domain is not yet matured

and many challenges still need to be addressed. Examples that especially stood out for their prevalence and importance were fault diagnosis and contingency analysis, the handling of time series data, the fusion of varying input data, and the improvement of AI algorithms as well as their combination. The notion regarding the maturity gets further substantiated by the fact that the oldest contribution from the identified set of literature is from 2019 and, thus, rather recent. Since literature reviews are oftentimes used to consolidate the findings of many scattered studies when a field otherwise gets too incomprehensible, their emergence could also be interpreted as a sign of growing maturity of a field (Kraus et al. 2020).

While, despite the best efforts to achieve comprehensiveness, the rather low number of identified review papers might also be caused by the choice of consulted databases, it also highlights the necessity for the creation of more literature reviews to further capture the domain in breadth as well as in depth (Kraus et al. 2020).

Further, while the acquired publications already give a broad overview of the domain, there are also many additional aspects that can be found in the topical literature that heavily impact the operations of grid operators despite not necessarily always being directly controlled by them. Examples of this are, for instance, the use of (AI supported) apps to influence the behavior of energy consumers (Chadoulos et al. 2020), the detection of electricity theft (Yadav and Kumar 2021), the advancement of domain-specific explainable AI (Machlev et al. 2022), or the advanced automation of buildings to improve energy efficiency (Roselyn et al. 2019). Therefore, a tighter integration of grid operators, energy producers, and energy consumers appears reasonable to harness synergies, which should also be reflected in the literature.

Finally, to reiterate a point from the previous sub-section, the exploration of real-world case studies as well as their collection and amalgamation to gain actionable insights should be highly prioritized.

4 CONCLUSION

While the reliable operation of energy grids was already a demanding task before, due to the challenges that come with the transition from fossil fuels to renewable energies, this issue has been further exacerbated. Consequently, adequate means to support this cause are highly sought after. One of the opportunities that come with the emerging technological possibilities is the utilization of AI to facilitate the corresponding operations. However, this research streams still offers a lot of room for advancements, which also implies numerous opportunities for future research. Yet, to meaningfully contribute, it is important to at first get an overview of the domain to purposefully steer one's endeavors. For this purpose, oftentimes literature reviews constitute a suitable starting point. However, due to the vastness of the regarded domain, these can also only capture certain of its aspects. Therefore, to get a wider (though admittedly less deep) overall picture, in the publication at hand, instead, a review of topical literature reviews, hence a meta-review, was conducted. In doing so, five contributions were identified that each provide an overview of pertinent literature and which together provide a meaningful picture of current themes, trends, and challenges in relation to the corresponding research. These findings were then analysed and discussed, and promising avenues for future research were outlined.

However, one limitation of this study certainly is the rather low number of identified reviews. While the results still provide valuable insights, a higher number of relevant papers would have still improved the significance and possibly uncovered additional insights. Therefore, further expanding the scope by including more databases or by adding to the search terms could be valid approaches for the future. Moreover, conducting a very comprehensive literature review instead of a meta-review could also be a promising step. However, due to the very high number of topical publications, the scope of this might be too large to be feasible. Besides that, repeating the current study in several years, when there might be more relevant reviews also appears like a worthwhile endeavor. Besides focusing on expansions and modifications to this study, adding to the field by creating new literature reviews to capture additional aspects of the domain can also advance the corresponding research.

Finally, directly addressing the issues and opportunities highlighted in this paper should, of course, also be emphasized as a promising avenue for researchers who want to comtribute to the domain. This especially holds true when it comes to conducting studies in real-world settings, which have been identified as crucial but too sparse.

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