Energy for Sustainable Development 84 (2025) 101596

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

Digitalization opportunities to enable local power system transition to net-zero

Elnaz Azizi [a,*], Weiqi Hua [a], Bruce Stephen [b], David C.H. Wallom [a], Malcolm McCulloch [a]

[a] *Department of Engineering Science, University of Oxford, Oxford OX2 0ES, UK*

[b] *Institute for Energy and Environment, Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G1 1RD, UK*

ARTICLE INFO

Keywords:
Data analytics
Distribution network
Machine learning
Operation
Planning
Power system reliability
Smart grid
Sustainability transition

ABSTRACT

The energy sector is pivotal in driving the transition towards a sustainable net-zero future, with the adoption of digital technologies playing a key role in this evolution. While much of the existing research has centered on sustainability through centralized energy generation and large-scale transmission systems, this paper addresses a notable gap by focusing on how data-driven decisions in local power systems, supported by digitalization, can enhance efficiency, reliability, and sustainability. The framework of this paper is derived from a survey from eight organizations of power sector, covering transmission and distribution, aiming to answer the question: "Which decisions within local power systems need to be informed by data?". Through inductive coding of survey responses, we identified key themes fall into two main categories: requirements of local energy systems and opportunities provided by digitalization to meet these requirements. Mapping responses to each of these categories underscore the equal significance stakeholders place on the role of digitalization in both planning and operation. Also, with this mapping, we uncovered four key opportunities of digitalization, with predictability and interoperability being the most crucial, followed by responsiveness and automation. Aligned with the identified codes, academic research, industrial implementations and ongoing projects are reviewed to showcase the current practical applications of digitalization. Finally, we identify potential research areas that could further benefit local energy systems through effective use of digitalization. This paper provides insights into the digitalization opportunities in local power systems, offering a comprehensive overview for the data science and power engineering communities.

Contents

* Corresponding author.
E-mail addresses: elnaz.azizi@eng.ox.ac.uk (E. Azizi), weiqi.hua@eng.ox.ac.uk (W. Hua), bruce.stephen@strath.ac.uk (B. Stephen), david.wallom@oerc.ox.ac.uk (D.C.H. Wallom), malcolm.mcculloch@eng.ox.ac.uk (M. McCulloch).

https://doi.org/10.1016/j.esd.2024.101596
Received 20 August 2024; Received in revised form 5 November 2024; Accepted 5 November 2024
Available online 29 November 2024

Introduction

This paper addresses the question: How can digitalization contribute to tackling challenges arising from decarbonization in local power systems? In recent years, due to the increasing demand and the high uptake of low-carbon technologies (e.g., renewable resources), local power systems have faced new challenges such as unmet power demand; curtailed generation; inverse power flow; and varying frequency and voltage (Hoang, Nguyen, et al., 2021; Liu, Zheng, Hu, & Yu, 2023). Effectively addressing these challenges requires a comprehensive understanding of the essential requirements of these systems from practical perspective and proposing efficient solutions. In this context, digitalization emerges as a powerful solution enabler, offering advanced data and computational capabilities, such as automation at scale, for stakeholders, including distribution network operators (DNOs) and consumers (Dranka & Ferreira, 2020). Therefore, it becomes imperative, to unlock the full potential of digitalization in these systems to support stakeholders and to ensure efficient operation and accurate planning. This paper aims to explore these opportunities by identifying how digitalization can address the requirements of local power systems. This exploration is framed based on the inductive coding of survey responses of eight stakeholders within power sector, aligning these with a review of academic papers, industrial implementations, and projects in the field.

Following the latest scientific evidence on climate change and global warming, countries are aiming to bring greenhouse gas emissions to net zero by 2050, with a tight decarbonization goal regarding the electricity generation sector for 2035 (Ahmed, Assadi, Ahmed, & Banihabib, 2023; Binyet & Hsu, 2024). This target has led to an increasing number of low-carbon technologies in power systems. In this context, DNOs are requested to improve the utilization of locally generated renewable energy by transitioning towards a more decentralized model to coordinate generation and demand in electric power systems (Couraud et al., 2023). Local power systems are promising models for adopting new technical solutions and smart strategies for managing and planning electricity distribution networks, taking into account operations under both normal and emergency conditions in both developed and developing countries (Deb et al., 2023; Knox, Hannon, Stewart, & Ford, 2022). Therefore, local power systems are gaining attention among policy makers and practitioners (Ford, Maidment, Vigurs, Fell, & Morris, 2021). These systems play essential role in bridging the gap between international targets and local ambition, whilst maintaining network resilience (Irshaid, Mochizuki, & Schinko, 2021; Wu, Zhou, & Gan, 2023).

While low-carbon technologies bring many benefits to local power systems, they also introduce challenges. These challenges manifest in several ways: firstly, due to the dependence of these resources on the weather, the pattern of demand and generation undergoes significant changes (Ang et al., 2022). This results in increased uncertainty within the system, thereby impacting control and management strategies. Secondly, there is often a need for reinforcement within the system to ensure its resilience and stability. Additionally, existing capacity may prove insufficient to meet demand in certain instances, leading to instances of generation curtailment (Alkhalidi, Alqarra, Abdelkareem, & Olabi, 2022; Jenkins & Kockar, 2020). Furthermore, the growing generation from renewable resources contributes to inverse power flow, further complicating system dynamics (Yuan, Low, Ardakanian, & Tomlin, 2022). Moreover, localized meteorology, lack of load diversity, and small load aggregations create greater volatility in these systems compared to national or regional levels (Crozier, Morstyn, & McCulloch, 2020). To ensure the reliability of these systems, it is imperative to address and overcome these challenges effectively.

In parallel with the uptake of low-carbon technologies in local power systems, there has been a drive towards digitalization. This has been facilitated by the deployment of smart meters and sensors that has led to exponential growth in the scale and diversity of data available within these systems (Ford et al., 2021; Jafari, Kavousi-Fard, Chen, & Karimi, 2023). However, the availability of data alone is insufficient for identifying the requirements of the grid and addressing them. In other words, effectively translating data into actionable information requires integrating it with sophisticated analytics such as machine learning algorithms, optimization methods, visualization techniques, etc (Olu-Ajayi, Alaka, Sulaimon, Sunmola, & Ajayi, 2022). This emphasizes the importance of identifying the requirements of local power systems and leveraging digitalization to meet these needs, thereby enhancing system operational management and decision-making.

In this regard, there has been a growing body of literature focusing on the computational capabilities that digitalization provides to power systems. As an example, Ibrahim et al. in Ibrahim, Dong, and Yang (2020) investigate the application of machine learning to address smart grid challenges. They also focused on techniques across the entire grid, discussing the limitations of various techniques as well as possible solutions for future practice. Similarly, Ullah, Zaib, et al. in Ullah, Al-Turjman, Mostarda, and Gagliardi (2020) conducted a thorough review on the role of machine learning in evaluating smart cities. They present an overview of its current state, identifying significant research gaps and suggesting future directions for study. Zhao, Yang, et al. in Zhao, Zhang, Zhang, Wang, and Li (2020) focused specifically on two machine learning methods, supervised and unsupervised learning, in a building level. They provided a comprehensive discussion on the strengths and limitations of these approaches, evaluating their effectiveness and identifying areas where they excel or fall short. Hernandez-Matheus, Alejandro, et al. in Hernandez-Matheus, Löschenbrand, Berg, Fuchs, Aragüés-Peñalba, Bullich-Massagué, and Sumper (2022) focused on the applications of data-driven methods within local energy communities. Moreover, they suggested future directions considering uncertainty in these systems. Hernandez-Matheus, Alejandro, et al. in Hernandez-Matheus et al. (2022) review applications of machine learning algorithms in local energy communities discussing strengths of each algorithm.

Another category of studies has focused on the implementation of digitalization in the energy sector. The definition of digitalization as a megatrend in energy sector was examined in Heymann, Milojevic, Covatariu, and Verma (2023) while proposing policy options to maximize its potential and address risks to decarbonization and consumers. Authors in Trahan and Hess (2021) focused on the role of digitalization in driving sociotechnical changes within local power organizations. Kazmi, Hussain, et al. in Kazmi, Munné-Collado, Mehmood, Syed, and Driesen (2021) conduct a thorough review of open-source datasets, models, and tools that are facilitated by digitization in the energy sector. Veskioja, Kaija, et al. in Veskioja, Soe, and Kisel (2022) focused on the challenges and opportunities of digitalizing the energy sector considering social and technical viewpoints. Moreover, they review how to create a supportive environment for more digitalization opportunities. Di Silvestre, Maria Luisa, et al. review the effect of implementing digitalization on the evolution of transmission and distribution power systems (Di Silvestre, Favuzza, Sanseverino, & Zizzo, 2018). Authors in Baidya, Potdar, Ray, and Nandi (2021) investigate how digitalization in enery system can improve existing smart grid ecosystem towards facilitation of better monitoring services. Song, Jie, et al. in Song, He, Wang, and Zhang (2022) present a comprehensive review of digital technologies and their potential applications in energy and transportation systems. This paper also identifies corresponding challenges and future research directions. Similarly, Ferdaus, Dam, Anavatti, and Das (2024) provides a comprehensive review of over 2,000 studies on the role of digitalization transforming the energy sector for a sustainable net-zero future. Matanov, Nikolay, et al. in Matanov and Nankinsky (2021) review the contribution of digitalization in addressing challenges of increasing integration of low-carbon technologies. Lin, B. and Huang, C review applications of digitalization in moderating the effects of the up-take of low-carbon technologies in 33 countries (Lin & Huang, 2023). Ma, Jinjin, et al. explore the opportunities of digitalization to carbon neutrality process in energy systems (Ma et al., 2024).

In short, the existing research has the following gaps. Majority of previous reviews in this field primarily focus on the national or customer level, failing to adequately explore the opportunities digitalization presents for local power systems. Although numerous surveys address the concept of smart grids, they often neglect specific implications and considerations at the local power level (LV distribution networks). These reviews tend to be solution-centric, concentrating on the implementation of various digitalization-based (data-driven) solutions without providing clear application benefits or well-defined use cases from a power system perspective. Furthermore, they overlook industrial viewpoints and fail to review relevant projects in this domain. The future directions are from data scientists viewpoints and not from power system communities.

To address the gaps identified in the literature, this paper introduces a novel framework specifically designed to explore the digitalization needs and opportunities for local power systems from stakeholders' viewpoints. Given the intricate and multifaceted nature of decarbonization within these systems, stakeholder perspectives are essential for framing how digitalization can effectively tackle emerging challenges (Gunnarsdóttir, Davíðsdóttir, Worrell, & Sigurgeirsdottir, 2021; Toivanen et al., 2017; Wang & Mansouri, 2020). By incorporating insights from those directly involved in shaping, implementing, and experiencing these systems, this study underscores the importance of harnessing the full potential of digitalization in local power systems. Our framework is built on a comprehensive review of previous research, industrial implementations, and relevant projects, enriched by insights gathered through targeted surveys with power system stakeholders. This approach not only identifies the unique requirements of local power systems but also uncovers actionable digitalization opportunities to meet these needs, offering a holistic view that bridges academic research with real-world applications. The specific contributions of this paper are summarized below.

- This paper uniquely focuses on reviewing digitalization opportunities in meeting the requirements of local power systems, rather than on national-level or individual building-level systems.
- Beyond theoretical viewpoints, the paper includes practical insights derived from a survey that captures the requirements of local power systems from various stakeholders' perspectives.
- The survey responses are inductively coded based on the identified needs of local energy systems, resulting in three primary codes: planning, operation, and stakeholder engagement. Similarly, the survey responses are also coded to identify digitalization opportunities, uncovering four main codes: predictability, interoperability, responsiveness, and automation. By mapping responses to both sets of codes, we created a framework that demonstrates how digitalization meets specific needs within local power systems.
- Above brief review of academic research in this field, it aims to provide a thorough examination of industrial implementations of digitalization in place-based energy systems. Additionally, it reviews projects related to the application of digitalization in local power systems.
- Finally, it identifies the current gaps and challenges in the field of application of digitalization in local power systems and provides recommendations for future research.

Through this paper, we aim to highlight the potential insights and benefits of adopting digitalization strategies within local power systems. Our intention is to draw attention from the DNO research community to the exploration and exploitation of digitalization as a superior solution for enhancing the resilience and efficiency of power systems. At the same time, it offers researchers an overview of the most relevant research trends in the application of digitalization to local energy systems. The total framework of this paper is shown in Fig. 1. This paper is framed based on a structured approach derived from interviews with key stakeholders. The insights gained from these interviews allowed us to identify the requirements of the grid as well as the opportunities that digitalization offers in local energy systems which will be discussed in Section "Digitalization-based solutions for local energy systems requirements". Building on this foundation, a comprehensive review of relevant academic literature, industrial implementations, and ongoing projects is provided in Section "Field review: research, industry, and projects". In Section "Challenges and future work", the current challenges and future directions are outlined, synthesizing insights from the previous sections to provide a comprehensive view of the topic. Finally, Section"Conclusion" concludes the paper.

To ensure the study's integrity, a risk and ethics assessment following the Medical Sciences Interdivisional Research Ethics Committee (IDREC) at the University of Oxford in accordance with the procedures laid down by the University for Ethical Approval for all research involving human participants was completed and approved with Reference: R83244/RE001. All names were removed from data records to preserve anonymity.

Digitalization-based solutions for local energy systems' requirements

The challenges posed by low-carbon technologies in local power systems are fundamentally power system problems. While additional sensing deployment and data analytics provide valuable insights, they represent only part of the solution. Addressing these challenges effectively requires a comprehensive approach that includes assessing network constraints, potentially through power system modeling, and progressing towards decision support or automation. Decision support, in particular, is a human interface issue. The individuals involved in these processes are typically not data scientists; hence, the communication and tools used must be framed in the language of the power system domain. This ensures that the solutions are accessible and actionable for the practitioners in the field.

In essence, digitalization and data analytics are instrumental tools utilized by the power system community to tackle the challenges associated with integrating low-carbon technologies. However, their effective application depends on seamless integration with traditional power system methodologies and clear communication tailored to the expertise of the power system professionals. Therefore, this review paper is framed based on the various stakeholders' views gathered from survey to investigate how digitalization can meet the requirements of local power systems. This section will provide details of the survey. Following that, the survey responses will be inductively coded. Then, the digitalization capabilities for addressing these responses will be

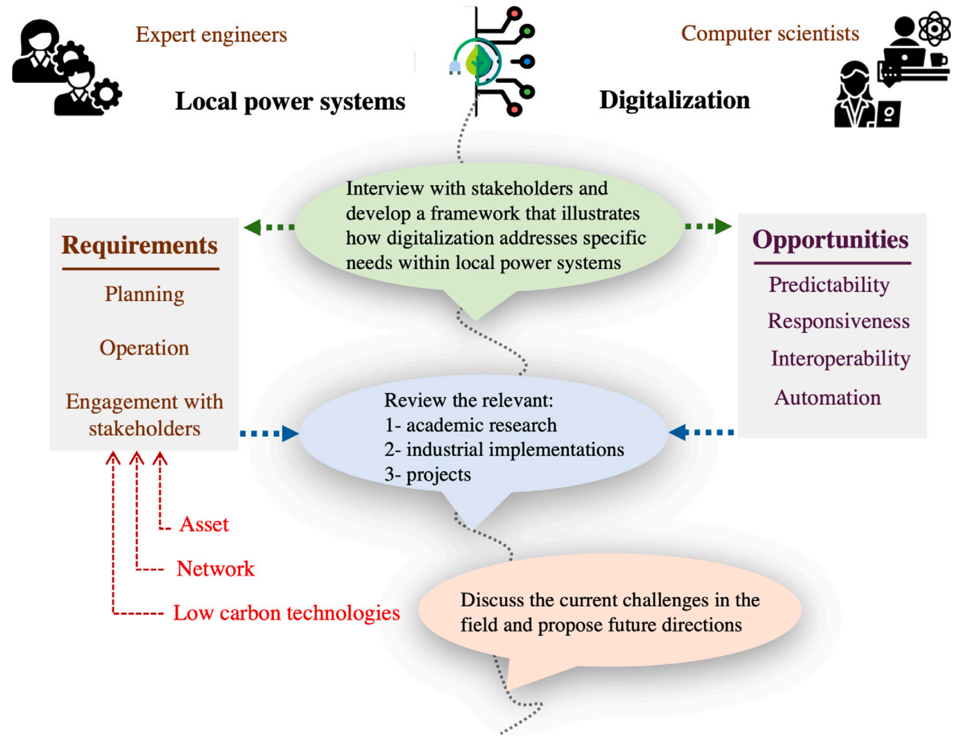

Fig. 1. Methodology used to capture stakeholder value perspectives in local power systems and align these with digitalization solutions.

discussed. Finally, a framework illustrating the relationship between digitalization opportunities and local power system requirements will be presented.

Survey data collection

The survey was conducted in a data workshop in June 2023 for the project of International Community for Local Smart Grids (ICLSG) organized by University of Oxford. This project is a knowledge-sharing partnership founded to accelerate a fair, resilient and local transition to net zero (Gunnarsdóttir et al., 2021). Their geographical areas for this task include UK, Australia, and Asia. The list of organizations is shown in Table 1. The interviews were conducted during an online data workshop via Microsoft Teams, where the sessions were recorded with the participants' consent. The stakeholders participating in the workshop were partners of ICLSG, representing various sectors such as grid planning, operation, and low-carbon technologies. A total of 14 individuals from both academia and industry participated in the interviews. Of these, 13 had direct industry experience, while 1 was exclusively from an academic background. Notably, 7 of the 13 industry participants also had at least one year of academic experience. The interviewees held senior positions, with industry experience ranging from 5 to 17 years. Interviewees had job titles in system operations, planning, research, flexible solutions, innovation projects, connections, business relations, business development, asset strategy, distributed energy resources, operations, and smart energy systems. This diverse composition ensured a wide range of perspectives on the challenges and opportunities within local energy systems. Fig. 2 shows the demographics and professional background of your survey participants.

The workshop was moderated by two facilitators – one from academia and the other from industry – who guided the discussion and provided space for follow-up questions to delve deeper into emerging themes. The focus of this survey was to understand the current requirements of local power systems that can be solved by data and digitalization. The primary question presented to participants was: *Which decisions within the local power systems need to be informed by data?*. After stating the question, one of the moderators framed a central question to the group for clarification: We want to figure out what it is that you are using data for, especially considering the challenges in local energy systems. To facilitate responses and foster collaboration, participants used the Miro platform, allowing them to visually share their thoughts and ideas in real-time, enhancing the collective understanding of the issues being discussed. The list of the responses to the posed question is shown in Table 2.

The next step was analyzing the qualitative data using thematic analysis. An inductive coding framework was developed to categorize and organize the data into key themes. These themes were directly related to the topics discussed during the workshop, such as grid planning, operational challenges, and the integration of low-carbon technologies. Validation of the findings involved cross-checking the interview insights with other sources of data, such as literature reviews and industry reports, to confirm consistency in the identified themes (presented in Section "Field review: research, industry, and projects"). Additionally, we conducted member checking, where the synthesized findings were shared with two participants of the workshop. This allowed them to verify whether the interpretations accurately reflected participants' views and contributions, ensuring that the data had been understood and represented correctly.

What are the requirements of local power system from the perspective of stakeholders in the survey?

Responses of the interview are categorized into a hierarchical structure. The structure consists of three main categories, planning, operation, and engagement with stakeholders and four sub-categories which are discussed in details below.

Planning

With the huge amount of distributed energy sources connecting to low-voltage distribution networks and with the high amount of aging infrastructure in distribution networks, owners of distribution

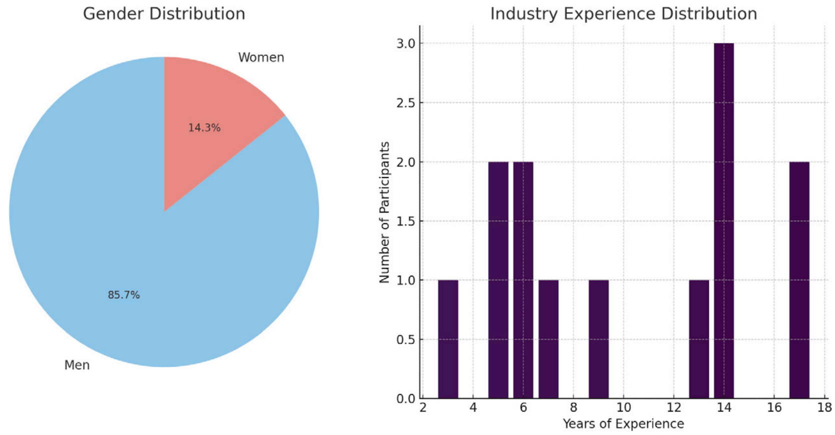

Fig. 2. Gender distribution and industry experience of survey participants.

Table 1
Name, description of organizations, and number of attendees from each organization in the ICLSG data workshop.

Organization name	Organization description	#	Logo
Scottish and Southern Electricity Networks (SSEN)	SSEN is a DNO, responsible for delivering power across central southern England and the north of Scotland.	1	
Ausgrid	Ausgrid is a distributor of electricity on Australia's east coast.	2	Ausgrid
Citizens Own Renewable Energy Network Australia Incorporated (Corena)	It is an Australian nonprofit organization that relies on voluntary contributions from the public to fund practical renewable energy projects.	2	CORENA
Tokyo Electric Power Company (TEPCO)	TEPCO is a Japanese electric utility holding company servicing Japan by generating and supplying power.	2	TEPCO
Electricity Supply Board (ESB)	ESB is a state owned electricity company operating in the Republic of Ireland.	2	ESB
Welnetworks	It is an electricity distribution company, serving the northern and central Waikato region of New Zealand.	2	WEL Networks
Israel Electric Company (IEC)	It is the largest supplier of electrical power in Israel and the Palestinian territories.	2	

networks, and owners of distributed energy sources need to strategically make informed investment decisions in network infrastructures (Mahdavi, Javadi, & Catalão, 2023). These decisions include maintenance, replacement, and upgrades of infrastructure, invest on upgrades (such as substation (primary/secondary) upgrade) and forecasting (such as network capacity, demand, and generation) (Bhusal, Abdelmalak, Kamruzzaman, & Benidris, 2020). These decisions aim to ensure the security of supply, maximize the utilization of local resources, minimize the overall investment costs, and achieve net-zero emission targets, based on accurate long-term predictions and strategies.

Operation

The increasing number of physical assets, such as solar panels, heat pumps, and smart meters, along with the associated issues of missing data and variable data quality, poses significant challenges to network operators (Xu et al., 2020). Additionally, the rise in data associated with non-physical assets, such as load profiles and contracts, further complicates the management of local power systems. These increase the requirement of asset/resource management in these systems (Li et al., 2020). Active responses to system faults, controlling and management in the local power system and observing the current state of the system are essential for timely decision-making and problem resolution. These operational strategies aim to enhance system efficiency, minimize downtime, and optimize resource utilization, ultimately contributing to the overall reliability and resilience of the distribution network.

Engagement with stakeholders

Efficient communication with low latency and collaborative efforts with stakeholders (including consumers, system operators, local authorities, and emergency response agencies), are also crucial in developing coordinated response plans and sharing critical information during crisis situations and improving stakeholders' experience (Bhatt & Singh, 2020; Cao, Chen, Qiu, & Hou, 2021).

What does digitalization provide to the local power system from the perspective of stakeholders in the survey?

The digitalization of local power systems has emerged as a transformative force, offering a multitude of benefits to the stakeholders in the field including predictability, responsiveness, interoperability, and automation. All these capabilities will be discussed below.

Predictability

Predictability refers to the ability to reliably anticipate future system states and resulting operational consequences. According to Anderson and Fouad (2008), predictability is essential for effective power system planning and operation. Digitalization enhances predictability by providing advanced data analytics and modeling techniques that allow DNOs to forecast electricity demand and generation patterns, load variations, and potential equipment failures with high accuracy (Morales, Conejo, Madsen, Pinson, & Zugno, 2014). This predictive capability empowers DNOs to plan their activities well in

Table 2
The list of responses to the posed question: which decisions within the local power systems need to be informed by data?

#	Response	#	Response
1	Distribution Future Energy Scenarios (DFES)	19	Ensuring safe installation of smart meters
2	Where is the highest penetration of Low Carbon Technology (EVs and HPs) and where is it growing?	20	Environmental risk management (e.g. Bushfire, Vegetation management)
3	Forecasting PV output (weather data)	21	Predictive activates for maintenance and network refurbishment
4	Comparing weather data to asset load data	22	Asset replacement
5	Network capacity forecasting	23	Asset Management (network assets)
6	Network Planning, model validation, forecasting	24	Organize maintenance activates
7	Analyze loads and generation behavior	25	What is the health of our transmission and distribution assets and how can this inform maintenance policy?
8	Network upgrade requirements	26	Improve customer experience
9	Forecasting customer demand	27	Where are customers experiencing power quality issues and how can they be resolved?
10	Asset Investment Planning	28	power quality issues
11	Justifying investment decisions,	29	Analyze network performance
12	Optimize capex and opex	30	Solar hosting limitations
13	Plan investments	31	Inform our stakeholders (inc local authorities)
14	Where should we invest in the distribution network to accommodate electrification of heat and transport?	32	Identifying opportunities for flexible solutions
15	Online monitoring of assets	33	Billing
16	Live/Real-time network status	34	Establishing DER database
17	Online asset monitoring	35	How can we make best use of Smart Meter data?
18	Safe network operation		

advance, enabling informed decisions about the installation, maintenance, and upgrades of power infrastructure. By understanding future requirements, DNOs can allocate resources more efficiently, optimize investments, and ensure a resilient distribution network adaptable to changing energy landscapes.

Responsiveness

Responsiveness is defined as the ability to select and implement the appropriate response to forthcoming operational events in the power network (Wood, Wollenberg, & Sheblé, 2013). Digitalization equips DNOs with enhanced situational awareness and the capability for active response. Real-time monitoring of the distribution grid through sensors and smart meters provides continuous data streams about grid conditions, power quality, and equipment health (Amin & Wollenberg, 2005). This real-time information allows DNOs to promptly detect anomalies, such as voltage fluctuations or overloads. With heightened awareness, DNOs can take immediate actions to mitigate potential issues, such as re-routing power flows or dispatching maintenance teams to address emerging problems. By swiftly responding to grid disturbances, DNOs can prevent outages, reduce downtime, and maintain a reliable power supply for consumers (Reddy et al., 2021).

Interoperability

Interoperability is a key aspect of digitalization that fosters machine to machine interface and seamless communication and coordination among various devices, systems, and stakeholders within the power ecosystem (Sebilleau, Farre, & Genest, 2023). DNOs benefit from interoperable solutions by being able to integrate data and insights from diverse sources, such as renewable energy sources, energy storage systems, and demand response programs. This integration facilitates comprehensive decision-making and facilitates the optimal utilization of distributed energy resources. Interoperability also enables DNOs to collaborate effectively with other entities, such as transmission system operators and neighboring distribution networks. Through this collaborative approach, DNOs can manage network challenges more efficiently, ensure grid stability, and enable the efficient sharing of resources (Basso & DeBlasio, 2012). Interoperability allows different components of local energy systems, e.g., distributed energy generators, storage systems, loads, and distribution networks, to exchange information and coordinate their activities seamlessly. Advanced information and communication infrastructures are citric in enhancing the interoperability and supporting the digitalization for local energy systems.

Automation

Automation in power systems refers to the use of control systems and information technologies to reduce the need for human intervention in the production and distribution of electricity (Glover, Sarma, & Overbye, 2012). Digitalization enables the automation of control and monitoring processes, revolutionizing how DNOs manage the distribution grid. Automated control systems can swiftly respond to changing grid conditions by adjusting parameters like voltage, frequency, and power flows (Song & Johns, 1999). This automated control improves grid stability and reduces the need for manual interventions. Additionally, automation plays a pivotal role in seamlessly integrating renewable energy sources and electric vehicle charging infrastructure into the grid by managing congestion through voltage control and limiting thermal stresses (Momoh, 2012). By leveraging automation, DNOs enhance operational efficiency, reduce operational costs, and create a more adaptable and resilient distribution network for the future.

Findings

The responses, as detailed in Table 3, indicate that stakeholders place nearly equal importance on planning and operation, with 41% of responses affirming the critical role of both in ensuring the reliability and sustainability of local power systems. Within the planning category, a notable 27% of stakeholders emphasized low-carbon technologies, underscoring the recognition of their vital role in achieving Net-Zero targets. In the operation category, a significant portion of responses (20.6%) highlights the importance of asset management, indicating that stakeholders are highly focused on the efficient utilization of existing resources. This suggests that while planning for future infrastructure is

Table 3
Inductively coding of responses based on the requirements of the local power systems (all numbers are based on Table 2).

		Sub-codes of requirements			
		Low-carbon technologies	Network	Asset	Others
Main codes of requirements	Planning	1-2-3-4-7-14-30-32-34	5-6-8	10-21-23-24	9-13-20-27
	Operation	2-3-4-7	5-16-18-29	12-15-17-22-23-25	20-28-32-33-34-35
	Engagement with stakeholders	–	–	–	11-13-14-26-27-31-33-35

Table 4
Inductively coding of responses based on digitalization opportunities (all numbers are based on Table 2).

		Responses
Main codes of capabilities of digitalization	Predictability	1-2-3-4-5-6-7-9-10-11-13-14-20-21-22-25-28-30-32
	Responsiveness	2-7-8-16-17-18-23-26-27-29-32-34
	Interoperability	1-6-13-14-21-31
	Automation	12-15-16-17-18-19-20-22-23-24-25-28-29-33-35

crucial, stakeholders also view the optimization of current assets as a key factor in maintaining system resilience during the energy transition. Additionally, while engagement with stakeholders accounts for 16.7% of the responses, this reflects a growing recognition that collaborative efforts across sectors will be required to address both technical and non-technical challenges, ensuring that all voices in the energy ecosystem are considered.

In mapping digitalization opportunities, Table 4 shows that predictability was the most frequently cited digitalization capability (36.5% of responses). This reflects that stakeholders recognize the need for advanced data-driven solutions that enable better decision-making in real-time and over long-term horizons, especially in the face of increasing volatility due to the integration of renewable energy sources. Responsiveness and automation, which account for 23.0% and 28.5% of responses, respectively, are also identified as critical capabilities. Stakeholders emphasized that digitalization can improve the system's ability to respond rapidly to fluctuations in energy supply and demand, thus enabling greater operational flexibility. Automation, particularly in grid operation, is viewed as an enabler of this flexibility, ensuring that local power systems can swiftly adapt to the increasing complexity of managing diverse energy inputs and outputs.

The Sankey diagram in Fig. 3 illustrates the framework connecting digitalization opportunities with the requirements of local power systems, based on the identified inductive codes. This visual representation reinforces how digitalization can facilitate a seamless transition towards Net-Zero, offering strategic pathways for stakeholders to explore and implement in their respective domains. For instance, predictability directly supports both planning and operational functions, facilitating the integration of low-carbon technologies and enabling more efficient resource management. Similarly, responsiveness and automation help enhance system flexibility, allowing stakeholders to navigate uncertainties related to renewable energy variability and demand-side management in local power systems.

Field review: research, industry, and projects

In this section, we will briefly review the analytical research on the application of digitalization in meeting the requirements of local power systems. Subsequently, we will discuss the industrial implementations and ongoing projects in this field.

Review of academic papers

As Shown in Fig. 4 sourced from Scopus (Elsevier, 2024), Digitalization in energy planning (10.6%) utilizes big data and artificial intelligence to optimize resource allocation and system design. Digitalization in energy operations (20.9%) involves real-time monitoring and management of energy distribution through smart grids and automation systems. The application of blockchain and smart contracts in the energy market (15.9%) brings transparent and efficient decentralized trading platforms. Smart demand management (20.9%) optimizes energy usage through dynamic pricing and user behavior analysis. Digitalization of energy storage (10.6%) improves storage efficiency through smart battery management and energy management software. Integration of renewable energy (5.2%) relies on forecasting and hybrid systems optimization to achieve reliable grid operation. Privacy protection and security in energy systems (15.%) ensure system and data security through intrusion detection and data encryption.

Stakeholders in local power systems, i.e., energy suppliers, storage owners, consumers, and distribution network operators, can benefit from the data analytic opportunities offered by digitalization to achieve accurate predictions, optimal dispatch, demand response, and predictive maintenance. The distribution of research directions in digitalization, as shown in Fig. 4, highlights key focus areas over the past five years.

1. Digitalization in energy operations (21%): A significant portion of studies in this category, including those by Junior et al. (2024), Zhang, Zhang, et al. (2023), explore load and generation forecasting, which are critical for both planning and operational purposes. Allee, Williams, Davis, and Jaramillo (2021), Gaboitaolelwe et al. (2023) focus on how low-carbon technologies – such as electric vehicles, heat pumps, and solar panels – affect load and generation. These studies emphasize the need for accurate forecasting and operational planning in digitalized local power systems.
2. Smart demand management (21%): This area includes research by Saeedi, Sadanandan, Srivastava, Davies, and Gebremedhin (2021), which focuses on non-intrusive load monitoring (NILM). NILM disaggregates load without requiring additional costly sensing and communication infrastructure, enabling more effective demand management. These studies examine the influence of temperature and consumer behavior on the performance of low-carbon technologies, emphasizing smart demand strategies.
3. Privacy protection and security in energy systems (16%): Digitalization also raises important security concerns. For instance, (Zhang, Zhang, et al., 2023) examine the risks related to data protection and security in digitalized local power systems. These studies propose approaches to safeguard sensitive data while maximizing the benefits of digitalization.

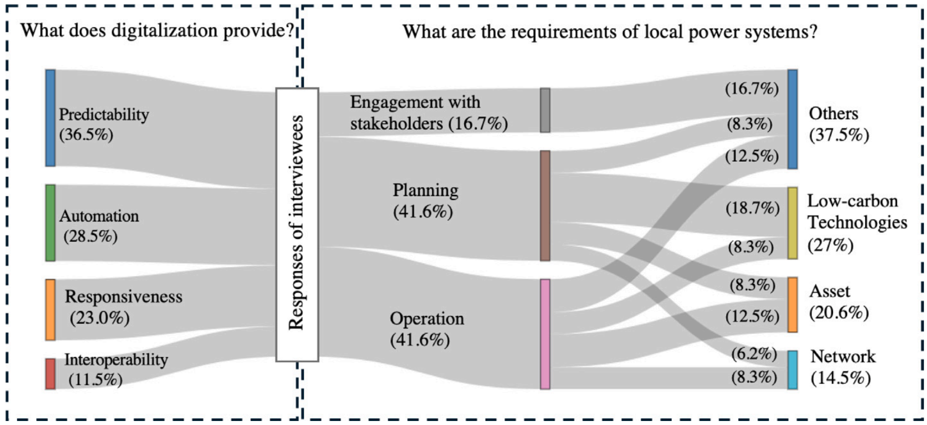

Fig. 3. Sankey diagram of digitalization capabilities for meeting local power system requirements based on the survey responses.

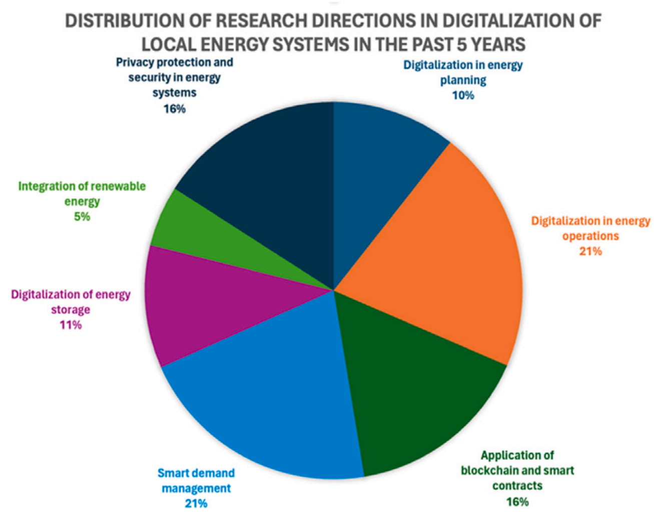

Fig. 4. Statistical summary for digitalization of local energy system sourced from Scopus (Elsevier, 2024).

4. Application of blockchain and smart contracts (16%): The work by (Bayer & Pruckner, 2023) explores the role of blockchain and smart contracts in improving the security and interoperability of digital energy systems. This research highlights the potential of blockchain to enhance trust and automation within the digital infrastructure.
5. Digitalization in energy planning (10%): (Chen, Liu, & Li, 2020) and (Ismeil, Alfouly, Hussein, & Hamdan, 2023) contribute to this category by examining the impacts of digitalization on energy planning, particularly concerning the integration of renewable energy sources and the infrastructure requirements needed to support them. These studies analyze the grid's capacity to host low-carbon technologies and propose strategies for re-infrastructuring.
6. Digitalization of energy storage (11%): The findings from studies like (Zhang, Gao, & Zhou, 2023) are instrumental in improving decision-making related to energy storage asset sizing. By integrating data from planning, operation, and weather forecasting, these studies provide insights into optimizing storage systems in digitalized local power systems.
7. Integration of renewable energy (5%): (Pelz, 2020) focus on the integration of renewable energy into local power systems. Their work, along with other studies, addresses the challenge of monitoring renewable energy generation and managing its intermittent nature through digital solutions.

The research directions highlighted in the figure reflect the broad scope of digitalization efforts in local power systems. The increasing use of digital twins, as discussed by Yassin, Shrestha, and Rabie (2023), promises to enhance system observability, predictability, and security by creating virtual replicas of physical assets, thereby promoting risk-free evaluations of operational scenarios.

Review of industrial implementations

For asset planning and management, Wärtsilä (*Wärtsilä Smart Power Generation*, 2023) offers GEMS energy management system to monitor, control and optimize energy assets on both site and portfolio levels. AVEVA (*AVEVA*, 2023) offers the Unified Operations Center platform to optimize the performance of power plants and other energy systems. Hitachi (*Hitachi Lumada Digital Solutions*, 2023) has developed its Lumada platform for digital solutions of the high-voltage direct current (HVDC) and power quality solutions. For the operation, Siemens (*Siemens Digital Twin Solutions for Energy Systems*, 2023) offers a range of digital twin solutions for energy systems, including its Microgrid Management System (MGMS) which is designed to optimize the use of renewable energy sources and storage systems in microgrids. ABB (*ABB Ability Digital Twin Technology*, 2023) has developed digital twin products which can be applied to local energy systems to improve efficiency, reliability, and sustainability. Eaton (*Eaton Intelligent Power Manager*, 2023) has developed the Intelligent Power Manager (IPM) software which uses digital twin technology to optimize the use of power systems and energy storage in data centers and other facilities. Honeywell (*Forge Energy Optimization*, 2023) provides Forge Energy Optimization platform uses digital twin technology to optimize energy use in buildings and other facilities. The platform uses real-time data to optimize energy consumption and reduce costs. Schneider Digital (*Schneider Digital*, 2023) offers a digital twin for distribution networks to optimize the use of renewable energy sources and storage systems in local energy systems. Johnson Controls (*Johnson Controls*, 2023) designed the Openblack platform based on a digital twin for buildings and other facilities to optimize energy consumption and improve building performances. Mitsubishi Electric (*e-F@ctory for Energy*, 2023) has developed e-F@ctory as a digital solution for energy management which is designed to optimize the use of energy in factories and other industrial facilities. For stakeholder engagement, Schneider Electric (*EcoStruxure Energy Management*, 2023) offers the EcoStruxure Machine Expert Twin which includes a digital twin for energy systems. The platform is designed to help businesses and organizations optimize their energy use and reduce costs. For responsiveness and automation, General Electric (GE) (*GE Digital*, 2023) offers digital solutions for energy management, including its Network Digital Twin which helps system operators optimize performance, efficiency, and maintenance.

Facing extreme weather in Scotland due to climate change, project NIMBUS (Association, 2024f) aims to utilize high-resolution weather data to predict climate change impacts on assets, enhancing resilience and reducing costs by prolonging asset life and minimizing unnecessary interventions. These insights can benefit other national infrastructure providers, contributing to better preparedness for future extreme weather events. Analogously, the Predict4Resilience project (Association, 2024g) aims to develop extended (two-week) forecasts of extreme weather events and potential network faults, leveraging advanced weather data analysis to improve power grid reliability, minimize network outages and ensure supply security. The EN-twine project (Association, 2024d), scoped viable use cases of Digital Twins for Transmission/Distribution networks, focusing on articulating flexibility at the boundaries between the 2., aligning with the growing role of distribution networks in transmission system balancing. This project will explore the feasibility and development of this system, aiming to improve visibility, control, and consumer participation in the energy market to build a demonstrable digital twin and a roadmap for network-wide benefits. In order to achieve net zero emissions by 2050, the UK needs to rapidly decarbonize its homes. The CEV project (Association, 2024a) explores the role of smart home technologies in energy management, identifying factors and potential barriers to adoption, with the aim of accelerating widespread implementation towards a greener future. For better decision-making and ensuring a sustainable future, a Virtual Energy System (ESO, 2024) is being created - a digital replica of Britain's entire energy system for accurate forecasting, intelligence investment, and overall management decisions. The Digi-GIFT project (Association, 2024c) aims to address data fragmentation in network management by establishing a common standard for interoperable data sharing, enabling enhanced customer interaction, network control, and secure service development in our digitized network. Through this platform, opportunities for predictive maintenance and improved control will be unlocked, while prioritizing safety through data-driven cybersecurity techniques. The Fast Flex project (Association, 2024e) explores leveraging demand electrification to create regional-scale energy buffers, addressing stability challenges in the British power system caused by decarbonization-induced inertia reduction. Through discovery, it assesses technical needs and cost benefits, ensuring net zero without compromising the security of supply. The Crowdflex: Discovery (Association, 2024b) project aims to leverage domestic flexibility in grid operations through three main methods: analyzing consumer behavior, assessing market design rules, and addressing regulatory barriers, which aims to increase renewable power usage, lower grid balancing costs, and reduce consumer bills.

Challenges and future work

The aim of this section is twofold. First, we will briefly discuss the challenges of the current approaches from the perspectives of both data scientists and power system professionals. Second, we will suggest future directions for tackling these challenges and improving the contribution of digitalization in meeting the requirements of local power systems.

What are the challenges related to data?

One of the most significant challenges in integrating digitalization and data analytics into local power systems is data quality and resolution. The majority of data used in power systems comes from different sources, often with varying spatial and temporal resolutions. This inconsistency complicates obtaining a consistent and accurate overview necessary for efficient operation and effective decision-making. For example, datasets with differing resolutions can obscure critical phenomena; low voltage (LV) loads may go undetected at a 5-min resolution, while power quality (PQ) events require sub-second monitoring for accurate detection. The discrepancies in data resolution affect the ability to perform comprehensive analyses and draw meaningful conclusions.

Data accessibility and synchronization present another set of challenges. Often, data samples are not recorded simultaneously due to the lack of clock synchronization or irregular tracking of events, such as faults. This misalignment complicates the integration and comparison of data from different sources. Additionally, anomalies in data from periods like the COVID-19 pandemic years (2019–2020) pose validation challenges that further hinder reliable analysis.

A critical challenge is the inaccessibility or non-existence of data of the power network topologies in a usable form. Detailed network information is essential for accurately assessing and modeling network constraints. Without this information, it becomes challenging to understand and optimize the power system's operation. Furthermore, the lack of observability in LV distribution networks is particularly pronounced due to the vast number of components and their geographical spread, making comprehensive monitoring difficult.

Future work

Digitalization and data analytics are utilized by the power system community to tackle the challenges associated with integrating low-carbon technologies. However, their effective application depends on seamless integration with traditional power system methodologies and clear communication tailored to the expertise of the power system professionals. To advance the field of digitalization in meeting the requirements of local power systems, several key areas require further investigation:

1. **Incorporate domain-knowledge:** While data mining techniques have been utilized in various energy analysis applications, the incorporation of domain knowledge remains limited. Future methods should embrace the features of expert systems and cognitive computing systems to leverage domain knowledge effectively. As an example, in flexibility provision for the grid, we do not need to know the topology of the feeder, but a data-driven method can be benefited by it.
2. **Data protocols and data management:** Another important research direction involves the evaluation of data quality and the establishment of standardized methods for data collection and cleaning. Robust evaluation techniques need to be developed to assess the quality of data, considering factors such as accuracy, completeness, and consistency. Additionally, standardized protocols for data collection and cleaning should be established to streamline the process and facilitate data interoperability across different platforms and systems. This standardization effort will contribute to more reliable and comparable results in energy analysis studies. Moreover, the establishment of protocols for data transfer between stakeholders is vital. As digitalization involves multiple entities, including energy providers, policymakers, and consumers, it is crucial to define protocols that facilitate secure and seamless data exchange. These protocols should consider data privacy, security, and interoperability to ensure smooth collaboration and information sharing.
3. **Visualization:** The role of visualization as an intermediary between data and application deserves attention. Proposing effective visualization techniques can help stakeholders comprehend complex energy data and make informed decisions. Research efforts should focus on developing innovative visualization methods that cater to the specific needs of local energy systems. By presenting data in a visually intuitive and interactive manner, stakeholders can gain valuable insights and effectively communicate energy-related information. DNOs should be able to monitor the system's health and identify any potential issues or anomalies promptly. This requires visually representing data and metrics such as energy consumption, generation, and network conditions. This enables them to make informed decisions, take proactive actions to optimize system operation and mitigate risks and evaluate the effectiveness of implemented measures.

4. **Scalability:** Scalability is another crucial aspect to consider in future research. While digitalization has shown promise at the local level, extending its applications to a larger scale, such as city-wide or country-wide implementations, poses significant challenges. Developing scalable approaches that can accommodate the complexity and volume of data at broader scales is essential. Such approaches should address the computational efficiency, data storage requirements, and analytics capabilities necessary to handle large-scale energy systems.
5. **Consumers' participation:** There is a need to address the missing role of consumer facilitation in the context of local power systems. While digitalization offers opportunities for consumers to actively participate and manage their energy consumption, current frameworks often overlook the consumer's role. Future research should focus on developing mechanisms and tools that empower consumers, enabling them to actively engage with local power systems, access real-time information, and make informed choices regarding their energy usage.

In summary, advancing research in incorporating domain knowledge, data protocols, visualization, scalability, and consumer participation will be essential to harnessing the full potential of digitalization in local power systems, ensuring efficient, reliable, and consumer-centric solutions for a sustainable energy future.

Conclusion

This paper reviews the requirements of local power systems that can be addressed by digitalization. The structure of the paper is derived from a survey conducted with eight stakeholders in the power sector to answer the question: "Which decisions within local power systems need to be informed by data?" The responses were inductively coded based on the requirements of these systems and digitalization opportunities.

Mapping the responses to both identified categories of codes underscores the equal significance that stakeholders place on the roles of digitalization in both planning and operation, with a predominant focus on predictability and interoperability. These insights reflect the critical need for predictive analytics and advanced forecasting tools to enhance operational efficiency and reliability. The emphasis on interoperability highlights the necessity for seamless communication and integration across various components and systems within the power infrastructure.

This paper also reviews recent academic research on the requirements mentioned in the survey. Moreover, it reviews projects related to the application of digitalization in local power systems and industrial implementations of digitalization in the field. By showcasing these practical applications, we seek to inspire further investigation and encourage the integration of digitalization as a fundamental component of local power system protection and advancement.

Additionally, the challenges from the perspectives of both power system communities and data scientists have been discussed, including data resolution, validation concerns, and the absence of network topology information. To address these challenges, future research directions were proposed, which include the integration of domain expertise into data-driven methodologies, the establishment of standardized data protocols and management techniques, the enhancement of visualization methods, ensuring scalability, and encouraging consumer involvement. These advancements will contribute to more efficient and sustainable energy management practices, enhance decision-making processes, and ultimately drive the transition towards a smarter and more resilient energy future.

CRediT authorship contribution statement

Elnaz Azizi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Weiqi Hua:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Bruce Stephen:** Writing – review & editing, Supervision, Methodology, Conceptualization. **David C.H. Wallom:** Writing – review & editing, Supervision, Methodology. **Malcolm McCulloch:** Writing – review & editing, Supervision, Data curation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to grammar check. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This project is supported by the Eric and Wendy Schmidt AI in Science Postdoctoral Fellowship, a Schmidt Futures program. Thanks to the International Community for Local Smart Grids (ICLSG) for sharing the data.

References

ABB ability™ digital twin technology. (2023). URL https://new.abb.com/industrial-software/features/model-predictive-control-mpc/digital-twin-applications. (Accessed 29 April 2023).
Ahmed, N., Assadi, M., Ahmed, A. A., & Banihabib, R. (2023). Optimal design, operational controls, and data-driven machine learning in sustainable borehole heat exchanger coupled heat pumps: Key implementation challenges and advancement opportunities. *Energy for Sustainable Development*, *74*, 231–257.
Alkhalidi, A., Alqarra, K., Abdelkareem, M. A., & Olabi, A. (2022). Renewable energy curtailment practices in Jordan and proposed solutions. *International Journal of Thermofluids*, *16*, Article 100196.
Allee, A., Williams, N. J., Davis, A., & Jaramillo, P. (2021). Predicting initial electricity demand in off-grid Tanzanian communities using customer survey data and machine learning models. *Energy for Sustainable Development*, *62*, 56–66.
Amin, M., & Wollenberg, B. F. (2005). Toward a smart grid: power delivery for the 21st century. *IEEE Power and Energy Magazine*, *3*(5), 34–41.
Anderson, P. M., & Fouad, A. A. (2008). *Power system control and stability*. John Wiley & Sons.
Ang, T.-Z., Salem, M., Kamarol, M., Das, H. S., Nazari, M. A., & Prabaharan, N. (2022). A comprehensive study of renewable energy sources: Classifications, challenges and suggestions. *Energy Strategy Reviews*, *43*, Article 100939.
Association, E. N. (2024a). CEV: Critical factors for the adoption of smart homes for energy efficiency and implications for consumers and providers. URL https://smarter.energynetworks.org/projects/10027307/. (Accessed 18 May 2024).
Association, E. N. (2024b). CrowdFlex: Discovery. URL https://smarter.energynetworks.org/projects/10027180/. (Accessed 18 May 2024).
Association, E. N. (2024c). Digi-GIFT. URL https://smarter.energynetworks.org/projects/10025639/. (Accessed 18 May 2024).
Association, E. N. (2024d). EN-twin-e. URL https://smarter.energynetworks.org/projects/10025651/. (Accessed 18 May 2024).
Association, E. N. (2024e). Fast flex. URL https://smarter.energynetworks.org/projects/10025660/. (Accessed 18 May 2024).
Association, E. N. (2024f). NIMBUS - network innovation and meteorology to build for sustainability. URL https://smarter.energynetworks.org/projects/10020514/. (Accessed 18 May 2024).
Association, E. N. (2024g). Predict4Resilience. URL https://smarter.energynetworks.org/projects/10025656/. (Accessed 18 May 2024).
AVEVA. (2023). URL https://www.aveva.com/en/solutions/operations/unified-operations-center/. (Accessed 29 April 2023).
Baidya, S., Potdar, V., Ray, P. P., & Nandi, C. (2021). Reviewing the opportunities, challenges, and future directions for the digitalization of energy. *Energy Research & Social Science*, *81*, Article 102243.
Basso, T., & DeBlasio, R. (2012). *IEEE smart grid series of standards IEEE 2030 (interoperability) and IEEE 1547 (interconnection) status*: *Tech. rep.*, National Renewable Energy Lab.(NREL), Golden, CO (United States).

Bayer, D., & Pruckner, M. (2023). A digital twin of a local energy system based on real smart meter data. *Energy Informatics*, *6*(1), 8.

Bhatt, B., & Singh, A. (2020). Stakeholders' role in distribution loss reduction technology adoption in the Indian electricity sector: An actor-oriented approach. *Energy Policy*, *137*, Article 111064.

Bhusal, N., Abdelmalak, M., Kamruzzaman, M., & Benidris, M. (2020). Power system resilience: Current practices, challenges, and future directions. *IEEE Access*, *8*, 18064–18086.

Binyet, E., & Hsu, H.-W. (2024). Decarbonization strategies and achieving net-zero by 2050 in Taiwan: A study of independent power grid region. *Technological Forecasting and Social Change*, *204*, Article 123439.

Cao, J., Chen, X., Qiu, R., & Hou, S. (2021). Electric vehicle industry sustainable development with a stakeholder engagement system. *Technology in Society*, *67*, Article 101771.

Chen, S., Liu, P., & Li, Z. (2020). Low carbon transition pathway of power sector with high penetration of renewable energy. *Renewable and Sustainable Energy Reviews*, *130*, Article 109985.

Couraud, B., Andoni, M., Robu, V., Norbu, S., Chen, S., & Flynn, D. (2023). Responsive flexibility: A smart local energy system. *Renewable and Sustainable Energy Reviews*, *182*, Article 113343.

Crozier, C., Morstyn, T., & McCulloch, M. (2020). The opportunity for smart charging to mitigate the impact of electric vehicles on transmission and distribution systems. *Applied Energy*, *268*, Article 114973.

Deb, S., Li, D., Sinha, S., Malik, P., Raina, G., & Wang, J. (2023). Local energy system: A comprehensive review of modelling, tools and pilot projects. In *2023 international conference on power electronics and energy* (pp. 1–6). IEEE.

Di Silvestre, M. L., Favuzza, S., Sanseverino, E. R., & Zizzo, G. (2018). How decarbonization, digitalization and decentralization are changing key power infrastructures. *Renewable and Sustainable Energy Reviews*, *93*, 483–498.

Dranka, G. G., & Ferreira, P. (2020). Towards a smart grid power system in Brazil: Challenges and opportunities. *Energy Policy*, *136*, Article 111033.

e-F@ctory for Energy. (2023). URL https://www.mitsubishielectric.com/fa/solutions/efactory/index.html. (Accessed 29 April 2023).

Eaton intelligent power manager. (2023). URL https://www.eaton.com/gb/en-gb/catalog/backup-power-ups-surge-it-power-distribution/eaton-intelligent-power-manager-.html. (Accessed 29 April 2023).

EcoStruxure™ energy management. (2023). URL https://www.se.com/ww/en/product-range/97196554-ecostruxure-machine-expert-twin/?N=3346888123. (Accessed 29 April 2023).

Elsevier (2024). Scopus. URL https://www.scopus.com/home.uri. (Accessed 07 June 2024).

ESO, N. G. (2024). Virtual energy system. URL https://www.nationalgrideso.com/future-energy/virtual-energy-system. (Accessed 18 May 2024).

Ferdaus, M. M., Dam, T., Anavatti, S., & Das, S. (2024). Digital technologies for a net-zero energy future: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *202*, Article 114681.

Ford, R., Maidment, C., Vigurs, C., Fell, M. J., & Morris, M. (2021). Smart Local Energy Systems (SLES): A framework for exploring transition, context, and impacts. *Technological Forecasting and Social Change*, *166*, Article 120612.

Forge energy optimization. (2023). URL https://www.honeywellforge.ai/us/en/products/cre/energy-optimization. (Accessed 29 April 2023).

Gaboitaolelwe, J., Zungeru, A. M., Yahya, A., Lebekwe, C. K., Vinod, D. N., & Salau, A. O. (2023). Machine learning based solar photovoltaic power forecasting: A review and comparison. *IEEE Access*, *11*, 40820–40845.

GE digital. (2023). URL https://www.ge.com/digital/blog/what-digital-twin. (Accessed 29 April 2023).

Glover, J. D., Sarma, M. S., & Overbye, T. J. (2012). *Power system analysis and design*. Cengage Learning.

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., & Sigurgeirsdottir, S. (2021). It is best to ask: Designing a stakeholder-centric approach to selecting sustainable energy development indicators. *Energy Research & Social Science*, *74*, Article 101968.

Hernandez-Matheus, A., Löschenbrand, M., Berg, K., Fuchs, I., Aragüés-Peñalba, M., Bullich-Massagué, E., et al. (2022). A systematic review of machine learning techniques related to local energy communities. *Renewable and Sustainable Energy Reviews*, *170*, Article 112651.

Heymann, F., Milojevic, T., Covatariu, A., & Verma, P. (2023). Digitalization in decarbonizing electricity systems–Phenomena, regional aspects, stakeholders, use cases, challenges and policy options. *Energy*, *262*, Article 125521.

Hitachi Lumada Digital Solutions. (2023). URL https://www.hitachienergy.com/uk-ie/en/news/press-releases/2021/11/hitachi-energy-launches-identiqtm-digital-twin-for-sustainable-flexible-and-secure-power-grids. (Accessed 29 April 2023).

Hoang, A. T., Nguyen, X. P., et al. (2021). Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process. *Journal of Cleaner Production*, *305*, Article 127161.

Ibrahim, M. S., Dong, W., & Yang, Q. (2020). Machine learning driven smart electric power systems: Current trends and new perspectives. *Applied Energy*, *272*, Article 115237.

Irshaid, J., Mochizuki, J., & Schinko, T. (2021). Challenges to local innovation and implementation of low-carbon energy-transition measures: A tale of two Austrian regions. *Energy Policy*, *156*, Article 112432.

Ismeil, M. A., Alfouly, A., Hussein, H. S., & Hamdan, I. (2023). Improved inverter control techniques in terms of hosting capacity for solar photovoltaic energy with battery energy storage system. *IEEE Access*.

Jafari, M., Kavousi-Fard, A., Chen, T., & Karimi, M. (2023). A review on digital twin technology in smart grid, transportation system and smart city: Challenges and future. *IEEE Access*, *11*, 17471–17484.

Jenkins, M., & Kockar, I. (2020). Impact of P2P trading on distributed generation curtailment in constrained distribution networks. *Electric Power Systems Research*, *189*, Article 106666.

Johnson controls. (2023). https://www.johnsoncontrols.co.uk/openblue-ppc?utm_source=google&utm_medium=cpc&utm_campaign=connected-buildings&utm_term=openblue-platform&gclid=CjwKCAjw-IWkBhBTEiwA2exyO027UruCvGCHYBtCyYkp0N68AW96Zp1TplpvyWPsbubID4IlcNCnWhoCo_UQAvD_BwE. (Accessed 29 April 2023).

Junior, M. Y., Freire, R. Z., Seman, L. O., Stefenon, S. F., Mariani, V. C., & dos Santos Coelho, L. (2024). Optimized hybrid ensemble learning approaches applied to very short-term load forecasting. *International Journal of Electrical Power & Energy Systems*, *155*, Article 109579.

Kazmi, H., Munné-Collado, Í., Mehmood, F., Syed, T. A., & Driesen, J. (2021). Towards data-driven energy communities: A review of open-source datasets, models and tools. *Renewable and Sustainable Energy Reviews*, *148*, Article 111290.

Knox, S., Hannon, M., Stewart, F., & Ford, R. (2022). The (in) justices of smart local energy systems: A systematic review, integrated framework, and future research agenda. *Energy Research & Social Science*, *83*, Article 102333.

Li, Y., Wang, C., Li, G., Wang, J., Zhao, D., & Chen, C. (2020). Improving operational flexibility of integrated energy system with uncertain renewable generations considering thermal inertia of buildings. *Energy Conversion and Management*, *207*, Article 112526.

Lin, B., & Huang, C. (2023). Promoting variable renewable energy integration: the moderating effect of digitalization. *Applied Energy*, *337*, Article 120891.

Liu, J., Zheng, Y., Hu, X., & Yu, S. (2023). Assessing renewable energy efficiency to identify improvement strategies: A network data envelopment analysis approach. *Energy for Sustainable Development*, *76*, Article 101308.

Ma, J., Yang, L., Wang, D., Li, Y., Xie, Z., Lv, H., et al. (2024). Digitalization in response to carbon neutrality: Mechanisms, effects and prospects. *Renewable and Sustainable Energy Reviews*, *191*, Article 114138.

Mahdavi, M., Javadi, M. S., & Catalão, J. P. (2023). Integrated generation-transmission expansion planning considering power system reliability and optimal maintenance activities. *International Journal of Electrical Power & Energy Systems*, *145*, Article 108688.

Matanov, N., & Nankinsky, P. (2021). Modern aspects of the digitalization in distribution systems. In *2021 13th electrical engineering faculty conference* (pp. 1–7). IEEE.

Momoh, J. A. (2012). *Smart grid: fundamentals of design and analysis*. John Wiley & Sons.

Morales, J. M., Conejo, A. J., Madsen, H., Pinson, P., & Zugno, M. (2014). *Integrating renewables in electricity markets: operational problems*. Springer.

Olu-Ajayi, R., Alaka, H., Sulaimon, I., Sunmola, F., & Ajayi, S. (2022). Machine learning for energy performance prediction at the design stage of buildings. *Energy for Sustainable Development*, *66*, 12–25.

Pelz, S. (2020). Disaggregated household energy supply measurement to support equitable municipal energy planning in rural Nepal. *Energy for Sustainable Development*, *59*, 8–21.

Reddy, C. R., Prasad, A. G., Sekhar, D. C., Goud, B. S., Kumari, K., & Kumar, M. D. (2021). Voltage sag and swell compensation in integrated system using advanced UPQC. In *2021 international conference on decision aid sciences and application* (pp. 419–423). IEEE.

Saeedi, R., Sadanandan, S. K., Srivastava, A. K., Davies, K. L., & Gebremedhin, A. H. (2021). An adaptive machine learning framework for behind-the-meter load/PV disaggregation. *IEEE Transactions on Industrial Informatics*, *17*(10), 7060–7069.

Schneider digital. (2023). URL https://www.se.com/uk/en/work/services/field-services/digital-services.jsp. (Accessed 29 April 2023).

Sebilleau, D., Farre, M., & Genest, O. (2023). *How to ensure interoperability in demand response systems: the examples of the European projects H2020 GIFT and MAESHA*. IET.

Siemens digital twin solutions for energy systems. (2023). URL https://www.siemens.com/global/en/products/energy/grid-software/operation/grid-control/spectrum-power-mgms.html. (Accessed 29 April 2023).

Song, J., He, G., Wang, J., & Zhang, P. (2022). Shaping future low-carbon energy and transportation systems: Digital technologies and applications. *IEnergy*, *1*(3), 285–305.

Song, Y. H., & Johns, A. T. (1999). *Flexible AC transmission systems (FACTS)*. Institution of Engineering and Technology.

Toivanen, P., Lehtonen, P., Aalto, P., Björkqvist, T., Järventausta, P., Kilpeläinen, S., et al. (2017). Finland's energy system for 2030 as envisaged by expert stakeholders. *Energy Strategy Reviews*, *18*, 150–156.

Trahan, R. T., & Hess, D. J. (2021). Who controls electricity transitions? Digitization, decarbonization, and local power organizations. *Energy Research & Social Science*, *80*, Article 102219.

Ullah, Z., Al-Turjman, F., Mostarda, L., & Gagliardi, R. (2020). Applications of artificial intelligence and machine learning in smart cities. *Computer Communications*, *154*, 313–323.

Veskioja, K., Soe, R.-M., & Kisel, E. (2022). Implications of digitalization in facilitating socio-technical energy transitions in Europe. *Energy Research & Social Science*, *91*, Article 102720.

Wang, B., & Mansouri, M. (2020). Understanding the stakeholders' interaction in complex energy system: A systems viewpoint. In *2020 IEEE international systems conference* (pp. 1–7). http://dx.doi.org/10.1109/SysCon47679.2020.9275883.

Wärtsilä smart power generation. (2023). URL https://www.wartsila.com/insights/article/it-s-easy-to-tell-these-twins-apart. (Accessed 29 April 2023).

Wood, A. J., Wollenberg, B. F., & Sheblé, G. B. (2013). *Power generation, operation, and control*. John Wiley & Sons.

Wu, J., Zhou, Y., & Gan, W. (2023). Smart local energy systems towards net zero: Practice and implications from the UK. *CSEE Journal of Power and Energy Systems*.

Xu, Y., Yan, C., Liu, H., Wang, J., Yang, Z., & Jiang, Y. (2020). Smart energy systems: A critical review on design and operation optimization. *Sustainable Cities and Society*, *62*, Article 102369.

Yassin, M. A., Shrestha, A., & Rabie, S. (2023). Digital twin in power system research and development: principle, scope, and challenges. *Energy Reviews*, Article 100039.

Yuan, Y., Low, S. H., Ardakanian, O., & Tomlin, C. J. (2022). Inverse power flow problem. *IEEE Transactions on Control of Network Systems*, *10*(1), 261–273.

Zhang, H., Gao, S., & Zhou, P. (2023). Role of digitalization in energy storage technological innovation: Evidence from China. *Renewable and Sustainable Energy Reviews*, *171*, Article 113014.

Zhang, T., Zhang, X., Chau, T. K., Chow, Y., Fernando, T., Iu, H. H.-C., et al. (2023). Highly accurate peak and valley prediction short-term net load forecasting approach based on decomposition for power systems with high pv penetration. *Applied Energy*, *333*, Article 120641.

Zhao, Y., Zhang, C., Zhang, Y., Wang, Z., & Li, J. (2020). A review of data mining technologies in building energy systems: Load prediction, pattern identification, fault detection and diagnosis. *Energy and Built Environment*, *1*(2), 149–164.