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IoT implementation for energy system sustainability: The role of actors and related challenges

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1. Introduction

The proliferation of IoT (Internet of Things) technology has attracted the interest of practitioners and scholars alike. Over the past few years, IoT has exhibited remarkable growth, transitioning from a mere 5 billion devices in 2015 to a projected 75 billion devices by 2025, representing an extraordinary year-on-year development (Forster et al., 2021). This increase in the dispersion can be attributed to the manifold opportunities it presents to various actors (Anagnostopoulos et al., 2017; Chen et al., 2014; Nižetić et al., 2020) across different areas of application (Jayachandran et al., 2022; Palaniyappan et al., 2023), as well as its vast potential to contribute to sustainable development (Bibri, 2018; Mastos et al., 2020; Sodhro et al., 2019).

Thereby, the term "Internet of Things" (IoT) refers to networks of interconnected devices linked to the internet, enabling data sharing among them (Clark, 2016). IoT is an integral component of "Big Data," providing the data foundation for artificial intelligence applications essential for automation and enhanced intelligence (Rhodes, 2020). The World Economic Forum (2018) has identified IoT technologies as a catalyst for sustainability, particularly in advancing sustainable development goals such as creating sustainable cities and communities and fostering affordable and clean energy solutions (World Economic Forum, 2018). Artificial intelligence, underpinned by IoT technologies, plays a pivotal role in the evolution of "smart cities" (Vinuesa et al., 2020) and "smart homes" (Stojkoska and Trivodaliev, 2017), relying on seamless device interconnectivity.

Within households, IoT technologies enable the establishment of "energy-aware environments" by facilitating the coordination of devices with smart metering systems, allowing homeowners to manage their energy consumption more effectively (Ahmadi et al., 2022; Stojkoska and Trivodaliev, 2017). This process includes optimizing energy consumption by household appliances, which can be scheduled to operate during periods of lower energy costs, typically during night-time hours (Al-Ali et al., 2017).

In the broader context of the energy sector, digitalisation plays a pivotal role in decentralisation and decarbonization efforts. It offers enhanced visibility into the energy system and its assets, aiding in better planning for demand response and the integration of variable renewable energy sources (Lin and Xie, 2023; Rhodes, 2020). The IoT's influence on these domains of the energy landscape is a noteworthy aspect of contemporary technological transitions. Hence, it becomes evident that IoT technologies play a pivotal role in facilitating the synchronization of the supply and demand aspects within the energy system (Palaniyappan et al., 2023). Furthermore, IoT gives rise to opportunities for integrating and managing electric vehicles, inspecting and managing the electricity generation units, and the power grid, in addition to "smarter tariffs" and incentivising more efficient consumer behaviour (Darby, 2018). The decarbonization of the energy system involves greater decentralisation of energy production, storage and usage (Jie et al., 2023), and in enabling this decentralisation, IoT can have a substantial impact on sustainability (Alanne and Saari, 2006; Ponce-Jara et al., 2017). For the EU, the digitalisation of the energy system is a policy priority, and this digitalisation will rely on technologies including smart IoT devices and meters, 5G and 6G, in addition to further innovations involving a pan-EU energy data space and digital twins (European Commission, 2023). A greater focus on the coordination of energy assets, consumers and producers at a local level is a core part of the EU's strategy, and this explains the need for enhanced digitalisation (European Commission, 2023).

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Thus, IoT in the context of the energy system and smart grid is considered to enable "energy-based analytics data provided from the user to utility [that] could potentially significantly enhance the efficiency and reduce congestions in the smart grid, thus contributing to the improvement of power supply reliability in the future 100% renewable energy scenario" (Reka and Dragicevic, 2018, p. 90). In this context, we consider system efficiency to be improved when the peak load is reduced and system reliability is improved (Khalil et al., 2021).

Thus, despite the vast potential benefits of IoT technologies in energy systems (Bedi et al., 2018), many barriers are preventing IoT from realizing this potential (Čolaković and Hadžialić, 2018). Generally, there are ethical considerations concerning, e.g., the effect on employment (Kumar et al., 2021) and security and privacy concerns when sensitive data is exchanged (Righetti et al., 2018). An increasing number of scholarly publications address said concerns (Darby, 2018; Haarstad and Wathne, 2019; e.g. Jayashankar et al., 2018; Kummitha and Crutzen, 2017) and, at the grid level, IoT security around authorization, privacy, trust, and authentication are considered significant implementation barriers (Khatua et al., 2020).

In addition, organisational challenges include how firms pursue market opportunities and construct successful business models out of IoT technologies (Abbate et al., 2019). There is also a general need for cultural change in organisations to embrace digitalisation, appreciate the value of data generated, and develop new data-related competencies (Sandys et al., 2019). Smaller organisations face particular difficulties in bearing the cost of deploying IoT-related IT infrastructure (Liu et al., 2019). In terms of barriers to consumer adoption, the cost of replacing appliances before the end of their useful life plays a crucial role (Sniderman and Raynor, 2015) besides a lack of technological readiness on the part of households leading to resistance to the adoption of IoT (Caputo et al., 2018). However, besides the potential benefits of adoption regarding the sustainability potential (Shrouf and Miragliotta, 2015), there may be valid actor-specific reasons for non-adoption. Constraints inherent to IoT technologies include issues around interoperability (Noura et al., 2019), namely the capacity of multiple devices being able to interact with one another despite the specific hardware and software (Čolaković and Hadžialić, 2018); this interoperability is crucial to the development and growth of IoT solutions (Bedi et al., 2018). Moreover, IoT technologies give rise to security and data privacy issues for consumers (Rhodes, 2020). These challenges underlie the unfulfilled potential of IoT technologies and need to be addressed by governmental actors to foster the adoption of IoT (Abrishambaf et al., 2019; O'Dwyer et al., 2019).

Hence, to understand how technologies disperse within specific domains and get adopted across actors (Markard and Truffer, 2008), we draw on technological innovation systems theory (TIS) (Carlsson et al., 2002; Nevzorova and Karakaya, 2020). TIS, defined as a "dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology" (Carlsson and Stankiewicz, 1991, p. 111), has proven to be a beneficial perspective not only within the domain of innovation management but for understanding the spread of ecological innovation at the systems' level too (Kanda et al., 2019). In this vein, research on sustainability has employed a TIS perspective. For example, Sharma et al. (2020) study the adoption and implementation issues of waste management in a smart city context and reveal that a lack of an institutional-level framework and infrastructure are the major hurdles. However, extant literature accentuates the role of the different actors in TIS as decisive for the overall outcome and suggests addressing this under-researched area (Markard et al., 2020; Verkade and Höffken, 2018). To address this research gap, we focus on the role of actors within the domain of energy systems and disentangle the very actor-specific preferences to understand the implementation of IoT. Our overall research aim is to explore the role of multiple actors in the diffusion of IoT within the specific context of the energy sector through the theoretical prism of TIS. There are two overarching research objectives, namely.

a) To apply TIS theory (discussed above) as a framework for the diffusion of IoT in the energy system to gain deeper theoretical insights into the drivers and barriers.
b) To combine TIS theory with a MAMCA approach to assess the motivations of each actor in this system concerning the adoption of IoT.

These objectives lead to the following research questions.

(i) What are the actor-specific preferences in terms of the extent of implementation of IoT in the energy sector?
(ii) Which factors facilitate and prevent the diffusion of IoT within the energy sector for multiple actors?

To implement this, we conduct a Multi-Actor-Multi-Criteria Analysis (Ball et al., 2021; Karbasioun et al., 2023; Palm et al., 2023; Turcksin et al., 2011) to understand the preferences of a variety of actors within the energy system (Pohekar and Ramachandran, 2004). Our approach is informed by literature on actors in the energy sector (e.g. Ding et al., 2023) and IoT. Thus, we address the deployment of IoT in the energy sector and contribute to the extant literature in several ways. First, we identify actors in the energy sector based on extant literature and detect underlying adoption criteria and dimensions, which play a crucial role in IoT implementation. Second, we contribute to the literature on technology innovation systems for actors (Mignon and Bergek, 2016) by addressing adoption hurdles at the actor level. Third, we apply a multi-actor, multi-criteria approach (MAMCA) and, thus, adapt a valuable yet novel methodological approach from decision sciences to examine adoption issues at the actor level. Fourth, we outline policy recommendations to overcome adoption obstacles. The paper outlines the literature on innovation systems and actors, discusses the different preferences and decision criteria, and concludes with identified hurdles that inform policy implications.

2. Theoretical background

Innovation management is a multifaceted field encompassing technological development and implementation dynamics. Scholars in this domain draw on diverse theoretical perspectives to explore how innovations emerge, disperse, and eventually influence industries (Adams et al., 2006). As such, technological innovation research is broad and embraces many different theoretical perspectives and foci (Tidd, 2001). For example, research on innovation within firms assumes the firm as a conceptual boundary. Thus, a multitude of analytical levels has been put into the spotlight, ranging from individuals and leadership styles (Howell and Higgins, 1990) to firm resources (Teece, 1996) and innovation practices (Anzola-Román et al., 2018), communication patterns (Rothwell and Robertson, 1973) and firm reputation (Höflinger et al., 2018). Subsequently, innovation within firms is often used to explain organisational performance variations (Azar and Ciabuschi, 2017) and is widely considered a driver of firm survival (Lin et al., 2013).

Innovation does not only happen within organizational frontiers but often results from intricate interactions between organisations and their broader external environments. This interaction is influenced by factors ranging from competitive pressures to regulatory frameworks (Garcia and Calantone, 2002; Guo et al., 2017; Utterback, 1971). Recognizing the environmental and systemic nature of innovation, researchers have expanded their focus to include examining whole systems within which innovation activities are embedded (Cancino et al., 2018; Tidd, 2001; Vargo et al., 2020).

2.1. *Innovation within systems*

The systemic nature of technological innovation has led to the development of frameworks that conceptualize how technologies are developed, adopted, and diffused across entire systems (Markard and Truffer, 2008). As a promising theoretical perspective, technological innovation systems theory (TIS) explains the diffusion of innovation within defined boundaries or across systems and has become a prevalent analytical angle to investigate technological innovation at the systems level. In that vein, TIS is considered an interaction network between agents within a specific area and in a given institutional environment that is part of generation, diffusion, and utilization of technology (Carlsson and Stankiewicz, 1991; Frank et al., 2018).

In the context of TIS, innovations are seen not just as outcomes but as processes that involve multiple actors - from policymakers to businesses and consumers - each playing specialized roles. These roles include the creation of knowledge, the formation of markets, the direction of search efforts, the management of resources, and the development of legitimacy for new technologies (Granstrand and Holgersson, 2020). It is important to note that TIS emphasizes that innovations emerge from the combined efforts of various actors whose activities are coordinated to support the entire system's growth and sustainability (Carlsson et al., 2002; Vargo et al., 2020).

Uncertainty is usually high in a newly established TIS, and several competing technological categories can co-exist (Berg et al., 2019). Consequently, scholarly efforts focus on the necessary foundations and evolving dynamics of technological innovation systems. Resources are developed within organisations and systems by combined financial, human, and other resources (Markard and Worch, 2009; Suurs and Hekkert, 2009). Other intangible resources at the system level, such as governance structures and trust, emerge dynamically at the formal network and system levels (Musiolik et al., 2012). As a result, many scholars put system-level properties of closed geographical spheres in the spotlight of their research (Hekkert et al., 2007; Liu and White, 2001; Raven and Walrave, 2020; Walrave and Raven, 2016).

Additionally, within the subdomain of sustainability innovations, scholars acknowledge that the diffusion of technology for sustainability is unpredictable and depends on its economic potential and the development of said technology (Kemp and Volpi, 2008). Therefore, sustainability innovations are often considered from a transition perspective (Kivimaa, 2014). However, one factor crucial for the dispersion of sustainable technologies is the extensive interplay of institutions, regulatory systems, and policies (Foxon and Pearson, 2008) at the systems level, thus how they collaborate to overcome barriers and foster the adoption of new technologies (Nevzorova and Karakaya, 2020).

Nevertheless, a relevant and often overlooked aspect in extant TIS research is the actors' role within innovation systems (Coenen, 2015). Accordingly, TIS studies first require boundary clarification and actor identification within the set system (Markard et al., 2015). Actors within a system can either "contribute to the success or failure of the TIS" (Skoczkowski et al., 2020, p. 7) generally, but their role is yet to be "explored in greater depth" (Köhler et al., 2020, p. 1). For example, by analysing publications and patents, Kushnir et al. (2020) systematically identify actors that adopt hydrogen direct reduction in the Swedish steel industry. This way, they classify a range of corporate, academic, institutional, and other actors whose activities interplay within the innovation system and crucially shape how the steel industry transitions. In a similar vein, with a focus on the contestation of competing ethanol production technologies in Brazil, Furtado et al. (2020) suggest that the role of actors and their interactions are crucial for adopting technology.

Despite some focus on actors in technological innovation systems literature, scholars argue in favour of taking a closer look at the specific roles of actors within TIS (Binz et al., 2014). On the one hand, a wide range of actors are highly interconnected and depend on each other's actions and decisions for technology implementation and dispersion, while, on the other hand, the multitude of actors makes it difficult to understand adoption issues and facilitators, which are highly actor-specific. TIS has been applied to understanding smart-grid innovation, with Norouzi et al. (2023) using this approach to explore the success and failure drivers behind smart-grid innovation in the Netherlands, highlighting its usefulness in analyzing energy system innovation.

2.2. Energy systems, actors, and adoption barriers

Overall, many areas could benefit from the sustainability potential that originates from IoT implementation. Nevertheless, the spread of novel technologies can be relatively slow. Overall, the potential for sustainability benefits through the implementation of IoT in energy systems, such as Smart Grids, is significant (European Commission, 2024). However, the diffusion of these technologies encounters numerous barriers. Effective implementation requires technological innovation and changes in consumer behavior, supportive regulatory frameworks, and robust infrastructure development (Agyekum et al., 2021; Markard et al., 2020; Scherrer et al., 2020). Understanding the preferences, motivations, and constraints of various actors involved in the energy sector can provide valuable insights into the mechanisms of technology adoption and diffusion.

Some scholars have, for example, explored various actor-related aspects regarding IoT and smart grids. A study by Cambini et al. (2016) discusses how to encourage investment in smart grids by Distribution Network Operators (DSOs), with DSOs expected to shoulder the largest share of the investment costs in SGs. Another recent study explored the motivation of utilities as smart-grid actors in Switzerland, where they are not exposed to energy savings obligations. Fouiteh and colleagues found that some utilities are more enthusiastic about energy efficiency, while others are less engaged and more tentative (Fouiteh et al., 2023).

Darby (2020) focussed on smart grid implementation and emphasised the importance of middle actors in the dispersion of smart thermal storage to allow for the shift in demand response systems. Such middle actors are installers, project coordinators, housing managers, and electricity supply center staff, who are decisive in shaping the outcome and ultimate implementation (Darby, 2020).

Consequently, a system-wide focus on actors to explain technological innovation through TIS is considered beneficial (Bhatt and Singh, 2020; Tricoire, 2015) yet absent in sustainability research (Wang et al., 2019). Hence, we seek to investigate system-wide actor preferences and explain IoT implementation for smart grids. We conducted a comprehensive literature search in indexed databases (EBSCO, WEB OF SCIENCE), reviewed papers from the energy sector and IoT, and identified areas of IoT application and actors based on the extant literature. An overview of

Table 1
Application areas of IoT.

	Smart Grid	Smart City
Application:	Efficient use of existing energy infrastructure, matching electricity supply & demand in real time, enabling dynamic electricity tariffs, automatic sensing of faults. A major contribution is enabling the integration of variable renewable energy sources into the electricity system.	Smart buildings, urban mobility, intelligent waste management, smart urban planning. Goal is to optimize running of the city to lead to economic, social and environmental benefits.
Facilitating factors	- Flattening peak-load of energy grid. - Increase stability of system.	- Improved air quality. - Sustainable transportation. - Resource usage of buildings.
Implementation obstacles	- Investment problems - Technology specific issues like interoperability and security - Organizational factors - Interoperability - Digital skills	- Interoperability - Energy consumption

smart grids and smart cities is provided in Table 1. Subsequently, we identify relevant actors and evaluate various actor-specific ‘adoption hurdles’ in the different areas of application, which we discuss in more detail in the following sections.

3. Methodology

This study examines the case study of smart grids in which IoT technologies are central. IoT technologies underpin the rollout of smart grids and involve significant investment and adaptation, making smart grids an interesting case study for adopting IoT technologies. Within Europe, smart grids are a centerpiece of sustainability transitions. Hence, we decided to focus on exploring this specific case of energy systems within Europe because it entails various actors and allows the application of decision science methodology. This section outlines an overview of MAMCA, the approach taken within MAMCA, and the actors involved and their preferences (Keseru et al., 2021).

We evaluate adoption hurdles across the identified actors in the

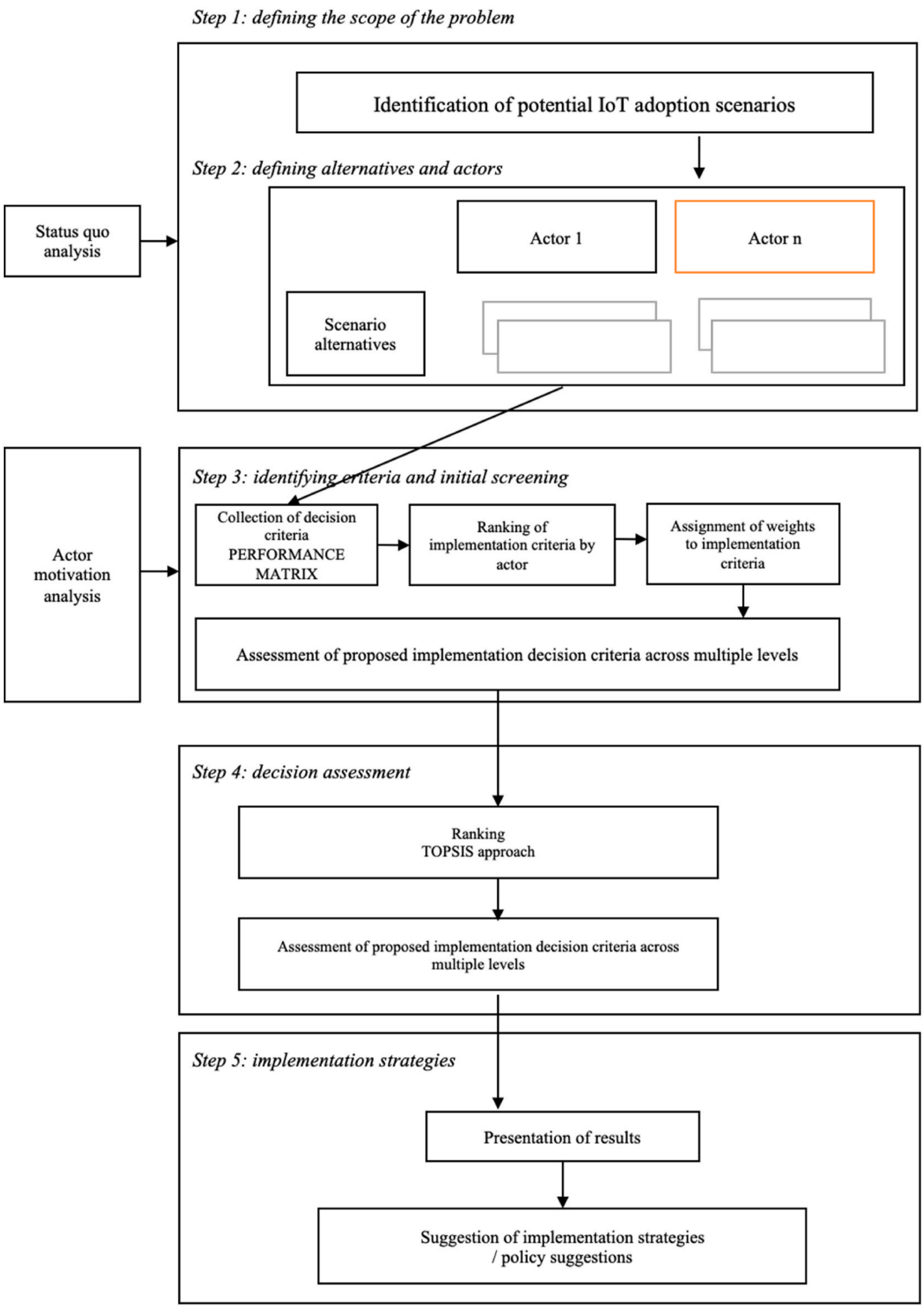

Fig. 1. Overview of analytical approach.

literature review by evaluating their respective decision preferences. To assess actor preferences, we draw on the extant multi-actor-multi-criteria evaluation methodology (Buldeo Rai et al., 2018; Macharis et al., 2012; Mokarram et al., 2020; Zanghelini et al., 2018) and adapt it to fit the context of IoT adoption in the energy sector. We aim to identify the drivers of adopting more ambitious deployment scenarios for IoT and the hurdles for actors. The identified actors and motivations are outlined in the following sections, and an overview of the MAMCA approach can be seen in Fig. 1.

The MAMCA method yields the preference of each actor for an IoT deployment scenario. MAMCA encompasses a variety of different approaches, each with advantages and disadvantages. We apply the well-known TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) approach. TOPSIS involves generating two ideal-type solutions, a positive ideal and a negative ideal, and calculating the distance of each alternative from these ideal solutions, with proximity to the positive and distance from the negative ideal indicating better performance. The results were calculated using Python software, which adapted a scikit-criteria template created by Cabral et al. (2016) .

A set of variables characterises the performance of each scenario, i.e. “Incremental”, “In-between” and “Embedded”. Each scenario involves a different level of adoption of IoT technologies and a different performance on each variable. Variables such as % gains in efficiency and the value of IoT to consumers annually perform better under scenarios with greater adoption, namely the “In-between” and “Embedded” scenarios, whereas variables like investment costs and cybersecurity will perform better under the “Incremental” scenario, involving a less intensive adoption of IoT technologies. Certain variables are easier to operationalise, as they are more quantifiable, such as % gains in energy efficiency, value of IoT to different actors annually, investment costs to different actors and costs of integration. Other areas, such as cultural adaptation, cybersecurity, and data privacy, are more difficult to operationalise as they cannot be quantified. The performance of each scenario on these variables must be assessed on a scale from 1 to 5. Future work could consider how to operationalise these variables better. The way variables have been operationalised is outlined in the explanatory notes of the performance matrix, a full version of which is provided in the supplementary material.

3.1. Smart grids: a case study of IoT implementation

The specific context of this study is the diffusion of smart grids, in which IoT technologies are central; we regard smart grids as a case study representing IoT technologies in a sustainability context. The UK Government has set up an Energy Data Taskforce to examine the possibilities for data to enable a low-carbon and decentralised energy system (Sandys et al., 2019). This task force has outlined the potential obstacles to realizing the full potential of data in the British energy system. It is important to note that there are different degrees of realisation of smart grids, extending far beyond only the rollout of smart meters. “Smart grid” is a rather abstract term used to refer to different scenarios relating to the future evolution of the electricity system (Mallett et al., 2018). Smart grids are described by Drtil (2024) as “*electricity networks that use digital technologies, sensors, and software to better match the supply and demand of electricity in real-time while minimizing the costs and maintaining the stability and reliability of the grid*” (Drtil, 2024)

There are different degrees of fulfillment of smart grids, from the rollout of smart meters to more sophisticated arrangements. Barriers exist in terms of the more sophisticated forms of smart grid adoption. The UK’s Energy Data Taskforce has highlighted the need for common standards in terms of data collection to facilitate cooperation among actors in the energy system (Sandys et al., 2019). Moreover, Rhodes (2020) argues that concerns over cybersecurity and data privacy could hamper consumer engagement in more sophisticated scenarios and that there could be data skills gaps on the part of companies, such as electric utilities. Regarding the Chinese experience with smart grids, Mah et al. (2017) have criticised the lack of adoption of data visualisation tools to facilitate communication between utilities and consumers, the absence of dynamic pricing, crucial for demand response, and limited progress in developing new products, services, and markets from smart grids. Likewise, in an investigation into smart grids in the Netherlands, ten Heuvelhof and Weijnen (2013) outline different degrees of adoption from less ambitious scenarios, focused on the grid and grid operators implementing IoT technologies, to more extensive scenarios in which utilities and consumers adopt IoT technologies. Each scenario implies a flow of advantages and disadvantages for each actor, and, depending on their priorities, they will prefer a more ambitious or less ambitious scenario. Kataray et al. (2023) stress the need for better regulation and demand-side management in integrating renewable energy with smart grids.

Our conception of smart grid deployment scenarios outlines three possible outcomes based substantially on the system boundaries for smart grids suggested by ten Heuvelhof and Weijnen (2013). First, the smart grid deployment is restricted to grid operators with the rollout of smart meters and other technologies such as predictive maintenance (Civerchia et al., 2017; Mahmoud et al., 2021) in an “incremental scenario”. Second, the “In-Between Scenario” includes electricity generators in the smart grid, and this could involve adopting new software and business models, as suggested by Mah and colleagues above (2017). The third scenario is the “Embedded scenario,” in which the interface between consumers and utilities is very advanced, allowing consumers to transmit the power they generate onto the grid (Hui et al., 2020). These scenarios have different performance characteristics and are interpreted differently by each actor.

3.2. Actors and motivations in IoT deployment in the energy system

In this section, the performance of each of the three scenarios based on the six overarching criteria will be outlined, in addition to the priorities of each selected actor. In Table 2, the performance matrix is presented, displaying the performance of the three scenarios. In the supplementary material, the Excel file offers explanatory information on the performance matrix. The performance matrix details the performance of each implementation scenario on a set of variables relevant to the actors. Data on performance was taken from our literature review, government documents, and industry reports. Where no data was available, we had to estimate performance based on our knowledge of the topic, and, especially for more abstract variables, such as cybersecurity, we used *Likert* scales. With sustainability, smart grids hold potential for improved system efficiency and the integration of variable renewable power sources, but IoT technologies are also associated with rebound effects, as they also depend on materials and consume power, as referred to by Ku (2018). Smart grid technologies lead to economic opportunities and new business models but require investment at the system and household levels, including replacing obsolete equipment and end-use devices. Security concerns relate to the danger of cyber-attacks and data privacy, which increase as smart grids become increasingly sophisticated. Ease-of-adoption encompasses the challenges that smart grids entail in terms of the need for companies to adapt to new skills and the hassle factor involved for consumers in full participation. Cooperation involves the extent of standardisation and interoperability in each scenario, enabling the collaboration of different actors. Each of these overarching categories consists of sub-variables reflecting the dimensions of the category.

3.3. Factors underlying preferences of actors

We identify ten key actors involved in implementing the smart grid concept. There are governmental actors, namely government and regulators, responsible for infrastructure, ICT network operators, and electricity grid operators. There are electric utilities that generate and sell the power. Electricity consumers are households, public

Table 2
Full performance matrix[a].

Sub_categories	Scenarios		
	Incremental	Inbetween	Embedded
Estimated system efficiency improvement (%)[b]	24.4%	32.5%	60%
Integration of Green Tech (Mio €)[c]	179.5	359.5	719
Rebound effect	4	3.5	3
Value of IoT (Private firms) (Billion $)	0	9	18
Value of IoT in 2023 (Utilities) (Billion $)	2	3	5
Value of IoT annually (consumers EU) (billion €)	1.2	3.6	6
Investment costs_Households (% original_construction_costs)	1	4	7
Smart_Grid_Investment_Costs (Annual through to ~2030 billion $)	266	533	800
Investment_Costs_Network_Operators (billion £ annually)	1.5	2	2.5
Obsolescence of existing devices	4	4	3.5
Cybersecurity	5	3	2
Data privacy	5	3	2
Need_Solutions for all customers	4	3.5	3
Skills adaptation	4	3.5	3
Cultural adaptation	4	3.5	3
Interoperability	2	3	5
Open data	2	3	5
Participation of new entrants	1	3	5
Need_Supportive regulation	4	3	2

[a] Variables are explained in the explanatory notes within the performance matrix in the supplementary information.
[b] Energy efficiency improvements in % terms at the EU-wide level – the greater adoption of digital technologies allows residential and industrial consumers to be more self-sufficient which leads to greater energy efficiency.
[c] Under Embedded scenario, the costs of integrating variable renewable energy technologies fall – hence greater savings (719 Mio. €) are available compared to the Incremental and Inbetween scenarios.

organisations, and progressive and traditional private firms. Progressive private firms have a culture that embraces new technologies, including firms founded more recently and operating in higher value-added and service sectors of the economy. Traditional private firms may be less accepting of change and may include, for example, firms that are longer established and operate in lower value-added areas of the economy. Public organisations could include bodies like universities and local authorities. The different actors and their roles in the diffusion of smart grids are given in Table 3.

Weightings correspond to each variable in the performance matrix's importance for each actor. Due to the large number of actors, it was

Table 3
Actors in smart grid diffusion.

Actor	Role in Smart Grid Diffusion
Energy Operators	Provide electricity tariffs suitable for smart grids Develop new business models around smart energy
Government	Sets the overall framework – e.g. policy around smart grids, security & data privacy
Regulators	Enforce the rules around smart grids, e.g. how consumers engage with grid, Vehicle2Grid services
Grid Operators	Roll out smart meters & other grid-based IoT technologies
Network Operators (ICT)	Build the 5G infrastructure on which the IoT technology depends
Households	Consumers: participate in smart grid
Public Organisations	Consumers: participate in smart grid
Private Organisations (progressive)	Consumers: participate in smart grid
Private Organisations (traditional)	Consumers: participate in smart grid
Other Energy-related actors	E-mobility providers, energy storage operators, aggregators, installers of decentralised energy technologies, building managers

impossible to derive these weights empirically, e.g. via focus groups or surveys, and it was necessary to use our estimations based on our reading and knowledge of IoT and smart grids. The performance of each IoT deployment scenario on each criterion is multiplied by the weighting attached to that criterion by each actor, and this leads, via the TOPSIS approach, to the preferences for each actor for each scenario, as seen in Table 4.

4. Results

This section discusses the actors' preferences regarding the three IoT deployment scenarios. Smart grids serve as a specific application of IoT technologies. Our study aims to showcase how adopting IoT systems can promote sustainability. The choice of smart grids as our focus is notable since it exemplifies the common incentives and disincentives linked with adopting sustainable IoT. As depicted in Fig. 2, the actors are evenly divided into two groups: (i) those favoring the incremental deployment scenario and (ii) those leaning toward the embedded scenario. Notably, no actor showed a preference for the In-Between scenario. This finding suggests a clear divide between actors eager for a more aggressive IoT deployment and those more cautious, with minimal interest in a middle-of-the-road approach.

The embedded scenario has the highest score for the government and other energy actors. For the government, this can be attributed to the high weighting given to sustainability, with the more ambitious IoT deployment scenario holding more benefits for the integration of demand-side management, renewable energy resources, and other technologies in the energy transition, including e-mobility (Le Ray and Pinson, 2020; Reka and Dragicevic, 2018). Gains to energy efficiency result at the actor and system levels, with IoT technologies enabling greater self-sufficiency for residential and household consumers and better supply and demand management; gains are measured in overall % terms. The sustainability priority overrides concerns relating to cybersecurity.

Other energy-related actors rely on a more ambitious deployment scenario, i.e., the Embedded Scenario, for their activities to flourish. For instance, e-mobility providers need to integrate electric vehicles with utilities so that vehicles can automatically charge when electricity prices are low (Wang et al., 2011). Grid operators, public organisations, and progressive private firms also favour the embedded scenario, albeit to a lesser extent. IoT-enabled smart grids allow grid operators to assimilate an increasing share of VRE (variable renewable energy technologies) to their grids, as IoT technologies allow better matching of electricity generation and consumption (Bansal and Singh, 2016). Through dynamic pricing, whereby electricity prices fluctuate according to the power supply on the electricity market, determined by weather conditions, consumers adjust their usage, and this can lower congestion and decrease the need to resort to peak power plants (Faruqui et al., 2010). Better matching supply and demand has economic benefits for grid operators. For example, in 2019, German grid operators had to pay out €719 million to generators to curtail their production due to an oversupply of electricity (Bundesnetzagentur, 2019); broader diffusion of smart grids could help reduce the need for this compensation. The advantages of integrating VREs alongside possible financial savings outweigh the costs of the more ambitious IoT deployment scenario, although these are considerable for utilities through 2040. For instance, the Electric Power Research Institute (2011) , referring to the US context, estimates annual investment costs associated with smart grids of between 17 and 24 billion dollars through 2040.

On the consumption side, progressive private firms and public organisations see opportunities to enhance their sustainability performance through engaging in the smart grid. For instance, industrial actors can offer system services through demand response, adjusting their consumption to meet the power grid's needs. The flexibility reduces the need for other options like peaking power plants or storage technologies and is useful for the electricity system (Shoreh et al., 2016).

Table 4
Weightings for actors[a].

CATEGORIES / ACTORS	Energy Operators	Grid Operators	Network Operators (ICT)	Government	Households	Public Organisations	Private Organisations (Progressive)	Private Organisations (traditional)	Other Energy-Related Actors	Regulators
Estimated system efficiency improvement (%)	4	5	2	5	3	5	3	3	2	0
Integration of Green Tech (Mio €)	4	5	2	5	2	5	4	2	5	0
Rebound Effect	0	0	3	5	2	2	3	2	2	0
Value of IoT (Private Firms)	0	0	0	3	0	0	5	3	5	0
Value of IoT (Utilities)	5	0	0	3	0	0	0	0	0	0
Value of IoT (Consumers)	0	0	0	3	5	0	0	0	0	0
Investment Costs (Households) %	0	0	0	2	5	5	5	5	5	0
Smart Grid Investment Costs	5	5	0	2	0	0	0	0	0	0
Investment Costs (Network Operators)	0	0	5	2	0	0	0	0	0	0
Obsolescence of existing devices	0	0	0	0	4	4	3	4	1	0
Cybersecurity	5	5	4	5	2	4	5	3	2	5
Data Privacy	5	0	4	5	4	4	4	3	2	5
Need_Solutions_All_Customers	0	0	4	0	1	0	3	2	3	0
Skills Adaptation	5	0	0	3	1	2	1	2	1	0
Cultural Adaptation	4	0	0	2	3	3	1	3	4	0
Interoperability	3	0	4	1	3	4	4	2	4	3
Open Data	2	0	2	4	1	3	5	2	3	3
Participation of New Entrants	0	0	2	3	1	2	0	1	1	4
Need_Supportive_Regulation	4	5	5	3	1	2	4	2	5	0

[a] This table represents the importance attached to each of the variables by each of the ten actors on a scale from 1 to 5.

The other five actors opt for the incremental scenario, although it is very marginal for the regulators. Reluctance regarding more ambitious deployment scenarios can be attributed to (i) a lack of clarity over the economic benefits, (ii) concerns with the ease of adoption, and (iii) security concerns. Energy operators must bear the investment costs in IoT technology in the more ambitious adoption scenarios by upgrading power equipment and software necessary to engage in the embedded scenario. However, it remains unclear how utilities can create new business models around smart technologies, as discussed earlier by Ma and colleagues (2017), and this contrasts with the investment costs they have to bear. Moreover, if prosumers are engaged in the electricity market, utilities need to form a new relationship with these customers and even become accustomed to new actors, such as aggregators, representing these consumers (Le Ray and Pinson, 2020).

Utilities face barriers to do with data skills shortages and organizational culture (Rhodes, 2020). ICT network operators are responsible for installing the 5G technology, which underpins the rollout of IoT technologies. The greater the geographical coverage of this network, as implied by the Embedded Scenario, the higher the costs for the network operators; the costs increase sharply depending on the speed of deployment and the breadth of the population covered by 5G (Oughton and Frias, 2018). The politics surrounding 5G can lead to uncertainty for these operators (O'Donnell, 2019), while there have been indications of hesitancy on the part of operators in bidding for the 5G spectrum, partly due to the heavily indebted position of operators in the current climate.

In contrast to progressive private firms, traditional private firms are less likely to embrace opportunities offered by smart grids and are more likely to be concerned about the investment costs and security issues involved in a more ambitious deployment. It is assumed that households are interested in the private benefits of installing IoT technologies, so they are focused on the possible savings on energy bills from smart meters. While the Embedded Scenario offers potentially greater savings through households being able to produce their power and act as prosumers (Parag and Sovacool, 2016), where they both consume electricity and sell electricity back to the power grid, the higher investment costs, in addition to the concerns about data privacy and security (Tu et al., 2017) deter them from preferring this option. Regulators have responsibility for overseeing the system, and their reluctance to embrace the embedded scenario has to do with concerns about security and the ease of adoption of such technologies. The regulator is responsible for the framework of the electricity system, how it is structured, and how the market functions (Xenias et al., 2015) and must consider these risks in assessing the implementation options for smart grids.

Norouzi et al. (2023) discuss three main failure points for smart grid innovation, and these are all soft factors, namely knowledge diffusion, the inability to create legitimacy, and the absence of institutions for experimentation purposes and market formation. These factors appear to be reflected in the findings above in that there is a hard core of enthusiastic adopters combined with more reluctant actors due to a lack of understanding of the advantages of adoption and uncertainty, which has not been targeted by regulation. Moreover, Norouzi et al. (2023) criticise the limited attention paid to end-users, which is also consistent with our findings about the challenges consumers face in adoption.

5. Discussion

Smart energy offers a good case study for analysing the diffusion of IoT technologies, as, in this sector, such technologies further a public good in the form of a more sustainable electricity system. However, this sector is also complex, given the various actors involved in the energy system, its capital-intensive nature, and the high-security concerns. The existence of high-tech actors enthusiastic about the possibilities of IoT technologies alongside other actors, including more risk-averse households and more traditional energy companies, highlights the challenge of achieving the full potential dissemination of IoT in this sector.

Moving from the current Incremental Scenario, based around smart

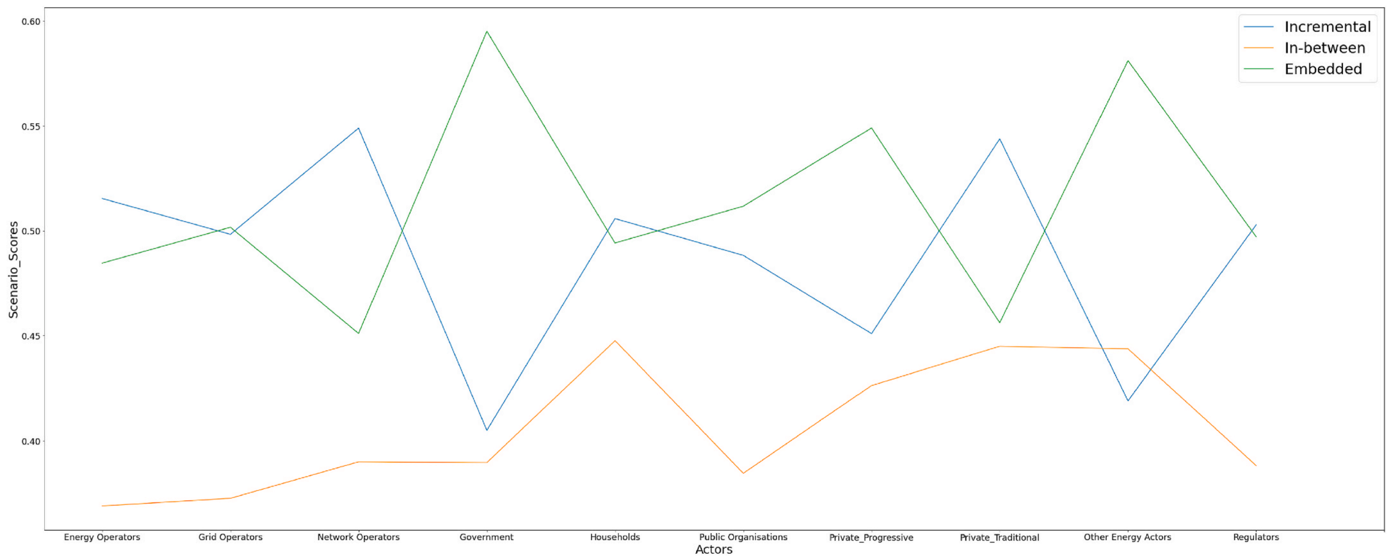

Fig. 2. Results from TOPSIS

grids, to a scenario resembling the Embedded Scenario, reflecting a far greater systemic change orientated around a digitalized energy system, would represent a major achievement for sustainability policies and make the system more economically efficient (Chadwick and Raver, 2012). Fulfilling such a goal means overcoming the resistance of the remaining actors identified in this study, which could be accomplished in several ways.

Initially, greater incentives for electric utilities and network operators to invest in IoT technologies are needed. It is currently unclear how these actors can monetize the further implementation of IoT and the new business models that could emerge from investing in upgrading their equipment, purchasing new software, and expanding the geographical coverage of the 5G network. Under the Embedded Scenario, electric utilities may need to switch roles from electricity producers to service providers, e.g., installing, maintaining, and operating smart home technologies. For network operators, governments may need to offer inducements or subsidies to encourage the rollout of 5G, which is necessary for the full adoption of IoT technologies across all geographical areas, in the form of subsidies.

A possibility for overcoming cybersecurity concerns is to invest more in cyber-security skills (Motlagh et al., 2020) to ensure more protection against hacking. There could be greater cooperation between energy companies, grid operators, and high-tech start-ups to identify and counteract cybersecurity dangers. In terms of data privacy, there needs to be a common set of standards and the establishment of industry norms. Adopting a smart home must be easy for households, and this involves ensuring interoperability by ensuring that all IoT devices can use one central platform (Sniderman and Raynor, 2015), meaning that there is standardisation; this can already be observed at the European level (European Commission, 2024). Households need to be sure that their data privacy will be respected, and this goes back to the setting of industry standards and norms.

6. Conclusions & implications

This study stimulates debate and discussion about adopting IoT in the energy sector by different actors. We distinguish between more limited scenarios of adoption, which are limited to grid operators, and more advanced adoption scenarios, in which all the actors engage fully in the smart grid via IoT technologies.

Some challenges affect the deployment of IoT more generally, and these challenges often transfer to the smart grid context. A major barrier in the EU is the rollout of the infrastructure undertaken by ICT network operators. The European Commission warned that network operators would only invest if there were clear indications of strong demand for 5G-based products and favourable regulatory conditions. In their report, the European Commission also highlighted that poor coordination of the rollout of 5G in the EU would lead to different levels of spectrum availability, harm service continuity across borders and the setting of common standards (P.3), and, ultimately, recommended a deadline of the end of 2020 for the introduction of large-scale commercial 5G and that provisional spectrum bands be made available by 2019. To date, this goal has not been achieved, with, as of 2020, there having been only a limited development of infrastructure and a small commercial rollout. In the more advanced "Embedded Scenario", a higher deployment speed and breadth is necessary, implying higher investment costs for the network operators.

6.1. *Implications for policy*

The Green Deal introduced by the European Union in 2020 sets the agenda for a stark transformation of existing domains, one of which is the energy system (European Commission, 2024). If the EU wants to achieve the desired kind of smart grid scenario, it will have to emphasise the coordination of deployment strategies across member states and ensure more certainty for operators regarding the demand and supportive regulation for 5G. Regarding standards and norms, the EU's Data Strategy (European Commission, 2023) aims to enable data-sharing while creating clear rules on access to data and reinforcing user rights; this will help with interoperability and open data and targeting security and privacy concerns.

The benefits of a more radical adoption scenario are misaligned with the inherent costs and risks for electric utilities, private firms, and households. The investment cost side could be targeted through low-interest loans for implementing smart homes or installing smart devices on business premises. In the Embedded Scenario, with full engagement of consumers and organisations in smart grids, the concerns about cybersecurity and data privacy will be stronger than in the other scenarios. This approach necessitates continued collaboration between the energy sector, IT companies, and government to ensure preparation for these risks if more reluctant actors are to be persuaded to opt for the embedded scenario. For utilities to develop new business models around information sharing and different relationships with customers and other actors, such as e-mobility service providers, regulators need to support flexibility in the experimentation with new services and ways of operating. Interoperability and standardisation, enabling data sharing among devices, and using common platforms are crucial to the Embedded Scenario and should be a priority at the EU level. Creating a culture of awareness around cybersecurity and data appears to be a necessary precondition for reaching the Embedded Scenario. The challenges outlined above are common to every IoT deployment scenario. However, these challenges become amplified with the more ambitious scenarios and require greater policy attention. Consequently, our call renews the urge by extant literature for a high-level policy agenda for accelerated implementation of the Embedded scenario (Haarstad and Wathne, 2019).

6.2. Implications for theory

Technological innovation systems research explores the adoption of technologies across specific systems (Kanda et al., 2019; Markard and Truffer, 2008; Walrave and Raven, 2016). The focus is on various contextual factors and interactions within such systems (e.g. Bergek et al., 2015). Despite some attempts to investigate micro-foundations of TIS (Markard and Worch, 2009), one underexplored domain in TIS research has been the diversity of actor preferences (Coenen and Díaz López, 2010), which regularly diverge considerably. Thus, one theoretical implication is the need to break down systems in which innovations occur into activities and actors, including those involved in adopting a particular technology and what they do in the system. This perspective shift contributes to the micro-foundations of TIS research, which has vastly focussed on system properties and related questions. Without such an actor perspective, it remains challenging to understand the drivers and barriers to the system-wide adoption of innovation of a particular technology. In addition, we enrich TIS with a rarely applied methodology to explain implementation hurdles at the actor level. By leaning on the multi-actor- multi-criteria methodology widely used in decision sciences (Baudry et al., 2018; Hamadneh et al., 2022; Mecca, 2023) and applying it to a TIS actor perspective, we address divergence across actors and within the entire system.

Moreover, concerning theories around energy systems (Eleftheriadis and Anagnostopoulou, 2015), this paper shows the necessity of understanding the intersection between energy technologies and regulatory and policy issues around Big Data.

6.3. Limitations & future research directions

This research, as any, does not come without limitations. On the one hand, it is limited by the quality of the data available on actors' preferences; these have been estimated from secondary data sources and by the authors' prior knowledge of the context of the energy system. The data can, therefore, be affected by authors' biases, which is a key limitation of this method. Thus, the qualitative interpretation of the case could be considered less robust than quantitative approaches (Keseru et al., 2021; Kowalski et al., 2009). In addition, the simplification of the natural complexity within innovation systems, and, more specifically, our multi-actor-multi-criteria-analysis, is another limitation that needs to be considered. However, we acknowledge that this is a general shortcoming of the underlying methodology, specifically as we rely on secondary data to extract actor preferences.

Consequently, this paper cannot outline a fine-grained representation of actors and their preferences; instead, it aims to take a deliberate systems perspective. Nevertheless, we seek to stimulate discussion about the role of actors in this innovation system, namely their different motivations and behaviours towards deploying IoT in the context of the energy system for smart grids. Future research can explore the role of specific actors related to smart grids. There is great potential in applying TIS to understand actor motivation. Our framework case can be used as a basis for empirical research in which an actor or multiple actors could be surveyed about their preferences. Thus, subsequent quantitative and qualitative approaches could contribute to our understanding of actors' preferences in greater detail. Moreover, there is scope to analyse the potential negative implications of IoT adoption and ethical issues associated with IoT technologies. Our analysis argues that greater IoT adoption is desirable and instrumental for reaching greater sustainability levels.

CRediT authorship contribution statement

Christopher Stephen Ball: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Daniel Degischer:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jup.2024.101769.

References

Abbate, T., Cesaroni, F., Cinici, M.C., Villari, M., 2019. Business models for developing smart cities. A fuzzy set qualitative comparative analysis of an IoT platform. Technol. Forecast. Soc. Change. https://doi.org/10.1016/j.techfore.2018.07.031.

Abrishambaf, O., Lezama, F., Faria, P., Vale, Z., 2019. Towards transactive energy systems: an analysis on current trends. Energy Strategy Rev. 26, 100418 https://doi.org/10.1016/j.esr.2019.100418.

Adams, R., Bessant, J., Phelps, R., 2006. Innovation management measurement: a review. Int. J. Manag. Rev. 8, 21–47. https://doi.org/10.1111/j.1468-2370.2006.00119.x.

Agyekum, E.B., Amjad, F., Mohsin, M., Ansah, M.N.S., 2021. A bird's eye view of Ghana's renewable energy sector environment: a Multi-Criteria Decision-Making approach. Util. Pol. 70, 101219 https://doi.org/10.1016/j.jup.2021.101219.

Ahmadi, S., Khorasani, A.H.F., Vakili, A., Saboohi, Y., Tsatsaronis, G., 2022. Developing an innovating optimization framework for enhancing the long-term energy system resilience against climate change disruptive events. Energy Strategy Rev. 40, 100820 https://doi.org/10.1016/j.esr.2022.100820.

Al-Ali, A.R., Zualkernan, I.A., Rashid, M., Gupta, R., Alikarar, M., 2017. A smart home energy management system using IoT and big data analytics approach. IEEE Trans. Consum. Electron. 63, 426–434. https://doi.org/10.1109/TCE.2017.015014.

Alanne, K., Saari, A., 2006. Distributed energy generation and sustainable development. Renew. Sustain. Energy Rev. 10, 539–558. https://doi.org/10.1016/j.rser.2004.11.004.

Anagnostopoulos, T., Zaslavsky, A., Kolomvatsos, K., Medvedev, A., Amirian, P., Morley, J., Hadjieftymiades, S., 2017. Challenges and opportunities of waste management in IoT-enabled smart cities: a survey. IEEE Trans. Sustain. Comput. 2, 275–289. https://doi.org/10.1109/TSUSC.2017.2691049.

Anzola-Román, P., Bayona-Sáez, C., García-Marco, T., 2018. Organizational innovation, internal R& D and externally sourced innovation practices: effects on technological innovation outcomes. J. Bus. Res. 91, 233–247. https://doi.org/10.1016/j.jbusres.2018.06.014.

Azar, G., Ciabuschi, F., 2017. Organizational innovation, technological innovation, and export performance: the effects of innovation radicalness and extensiveness. Int. Bus. Rev. 26, 324–336. https://doi.org/10.1016/j.ibusrev.2016.09.002.

Ball, C.S., Vögele, S., Grajewski, M., Kuckshinrichs, W., 2021. E-mobility from a multi-actor point of view: uncertainties and their impacts. Technol. Forecast. Soc. Change 170, 120925. https://doi.org/10.1016/j.techfore.2021.120925.

Bansal, P., Singh, A., 2016. Smart metering in smart grid framework: a review. In: 2016 Fourth International Conference on Parallel, Distributed and Grid Computing (PDGC). IEEE, pp. 174–176. https://doi.org/10.1109/PDGC.2016.7913139.

Baudry, G., Macharis, C., Vallée, T., 2018. Range-based Multi-Actor Multi-Criteria Analysis: a combined method of Multi-Actor Multi-Criteria Analysis and Monte Carlo simulation to support participatory decision making under uncertainty. Eur. J. Oper. Res. 264, 257–269. https://doi.org/10.1016/j.ejor.2017.06.036.

Bedi, G., Venayagamoorthy, G.K., Singh, R., Brooks, R.R., Wang, K.C., 2018. Review of internet of things (IoT) in electric power and energy systems. IEEE Internet Things J. https://doi.org/10.1109/JIOT.2018.2802704.

Berg, S., Wustmans, M., Bröring, S., 2019. Identifying first signals of emerging dominance in a technological innovation system: a novel approach based on patents.

Technol. Forecast. Soc. Change 146, 706–722. https://doi.org/10.1016/j.techfore.2018.07.046.
Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Transit. 16, 51–64. https://doi.org/10.1016/j.eist.2015.07.003.
Bhatt, B., Singh, A., 2020. Stakeholders' role in distribution loss reduction technology adoption in the Indian electricity sector: an actor-oriented approach. Energy Pol. 137, 111064 https://doi.org/10.1016/j.enpol.2019.111064.
Bibri, S.E., 2018. The IoT for smart sustainable cities of the future: an analytical framework for sensor-based big data applications for environmental sustainability. Sustain. Cities Soc. 38, 230–253. https://doi.org/10.1016/j.scs.2017.12.034.
Binz, C., Truffer, B., Coenen, L., 2014. Why space matters in technological innovation systems—mapping global knowledge dynamics of membrane bioreactor technology. Res. Pol. 43, 138–155. https://doi.org/10.1016/j.respol.2013.07.002.
Buldeo Rai, H., Verlinde, S., Macharis, C., 2018. Shipping outside the box. Environmental impact and stakeholder analysis of a crowd logistics platform in Belgium. J. Clean. Prod. 202, 806–816. https://doi.org/10.1016/j.jclepro.2018.08.210.
Bundesnetzagentur, 2019. Monitoring Report 2019.Bundesnetzagentur: Bonn.
Cabral, J., Luczywo, N.A., Zanazzi, J.L., 2016. Scikit-Criteria: Coleccion de metodos deanalisis multi-criterio integrado al stack cientifico de Python. In: SIO 2016, 14º Simposio. Argentino de Investigación Operativa 59–66. URL: https://scikit-criteria.quatrope.org/en/latest/.
Cambini, C., Meletiou, A., Bompard, E., Masera, M., 2016. Market and regulatory factors influencing smart-grid investment in Europe: evidence from pilot projects and implications for reform. Util. Pol. 40, 36–47. https://doi.org/10.1016/j.jup.2016.03.003.
Cancino, C.A., La Paz, A.I., Ramaprasad, A., Syn, T., 2018. Technological innovation for sustainable growth: an ontological perspective. J. Clean. Prod. 179, 31–41. https://doi.org/10.1016/j.jclepro.2018.01.059.
Caputo, F., Scuotto, V., Carayannis, E., Cillo, V., 2018. Intertwining the internet of things and consumers' behaviour science: future promises for businesses. Technol. Forecast. Soc. Change 136, 277–284. https://doi.org/10.1016/j.techfore.2018.03.019.
Carlsson, B., Jacobsson, S., Holmén, M., Rickne, A., 2002. Innovation systems: analytical and methodological issues. Res. Pol. 31, 233–245. https://doi.org/10.1016/S0048-7333(01)00138-X.
Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. J. Evol. Econ. 1, 93–118. https://doi.org/10.1007/BF01224915.
Chadwick, I.C., Raver, J.L., 2012. Motivating organizations to learn: goal orientation and its influence on organizational learning. J. Manag. 41, 957–986. https://doi.org/10.1177/0149206312443558.
Chen, S., Xu, H., Liu, D., Hu, B., Wang, H., 2014. A vision of IoT: applications, challenges, and opportunities with China perspective. IEEE Internet Things J. 1, 349–359. https://doi.org/10.1109/JIOT.2014.2337336.
Civerchia, F., Bocchino, S., Salvadori, C., Rossi, E., Maggiani, L., Petracca, M., 2017. Industrial Internet of Things monitoring solution for advanced predictive maintenance applications. J. Ind. Inf. Integr. 7, 4–12. https://doi.org/10.1016/j.jii.2017.02.003.
Clark, J., 2016. What Is the Internet of Things (IoT)? IBM Blog. https://www.ibm.com/blogs/internet-of-things/what-is-the-iot/.
Coenen, L., 2015. Engaging with changing spatial realities in TIS research. Environ. Innov. Soc. Transit. 16, 70–72. https://doi.org/10.1016/j.eist.2015.07.008.
Coenen, L., Díaz López, F.J., 2010. Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. J. Clean. Prod. 18, 1149–1160. https://doi.org/10.1016/j.jclepro.2010.04.003.
Čolaković, A., Hadžialić, M., 2018. Internet of Things (IoT): a review of enabling technologies, challenges, and open research issues. Comput. Network. 144, 17–39. https://doi.org/10.1016/j.comnet.2018.07.017.
Darby, S.J., 2020. Demand response and smart technology in theory and practice: customer experiences and system actors. Energy Pol. 143, 111573 https://doi.org/10.1016/j.enpol.2020.111573.
Darby, S.J., 2018. Smart technology in the home: time for more clarity. Build. Res. Inf. 46, 140–147. https://doi.org/10.1080/09613218.2017.1301707.
Ding, L., Zhang, Z., Dai, Q., Zhu, Y., Shi, Y., 2023. Alternative operational modes for Chinese PV poverty alleviation power stations: economic impacts on stakeholders. Util. Pol. 82, 101524 https://doi.org/10.1016/j.jup.2023.101524.
Drtil, M., 2024. Smart grids. Int. Energy Agency. https://www.iea.org/energy-system/electricity/smart-grids.
Electric Power Research Institute, 2011. Estimating the Costs and Benefits of the Smart Grid: A Preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Fully Functioning Smart Grid. EPRI, Palo Alto. https://smartgrid.gov/files/documents/Estimating_Costs_Benefits_Smart_Grid_Preliminary_Estimate_In_201103.pdf.
Eleftheriadis, I.M., Anagnostopoulou, E.G., 2015. Identifying barriers in the diffusion of renewable energy sources. Energy Pol. 80, 153–164. https://doi.org/10.1016/j.enpol.2015.01.039.
European Commission, 2023. Digitalisation of the European Energy System. European Commission, Brussels. https://energy.ec.europa.eu/topics/energy-systems-integration/digitalisation-energy-system_en.
European Commission, 2024. The next generation Internet of Things. European Commission, Brussels. https://digital-strategy.ec.europa.eu/en/policies/next-generation-internet-things.
Faruqui, A., Harris, D., Hledik, R., 2010. Unlocking the €53 billion savings from smart meters in the EU: how increasing the adoption of dynamic tariffs could make or break the EU's smart grid investment. Energy Pol. 38, 6222–6231. https://doi.org/10.1016/j.enpol.2010.06.010.
Forster, M., Groß, J., Kamping, A.K., Katilmis, S., Reichel, M., Sandner, P., Schröder, P., Whitepaper, I., 2021. Der Zahlungsverkehr der Zukunft: Programmierbare Zahlungen im Bereich IoT Whitepaper. https://www.ppi.de/no_cache/payments/next-generation-payments/whitepaper-zahlungsverkehr-der-zukunft/?tx_powermail_pi1%5Baction%5D=create&tx_powermail_pi1%5Bcontroller%5D=Form.
Fouiteh, I., Cabrera Santelices, J.D., Patel, M.K., 2023. How committed are swiss utilities to energy saving without being obligated to do so? Util. Pol. 82, 101582 https://doi.org/10.1016/j.jup.2023.101582.
Foxon, T., Pearson, P., 2008. Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime. J. Clean. Prod. 16, S148–S161. https://doi.org/10.1016/j.jclepro.2007.10.011.
Frank, A.G., Gerstlberger, W., Paslauski, C.A., Lerman, L.V., Ayala, N.F., 2018. The contribution of innovation policy criteria to the development of local renewable energy systems. Energy Pol. 115, 353–365. https://doi.org/10.1016/j.enpol.2018.01.036.
Furtado, A.T., Hekkert, M.P., Negro, S.O., 2020. Of actors, functions, and fuels: exploring a second generation ethanol transition from a technological innovation systems perspective in Brazil. Energy Res. Social Sci. 70, 101706 https://doi.org/10.1016/j.erss.2020.101706.
Garcia, R., Calantone, R., 2002. A critical look at technological innovation typology and innovativeness terminology: a literature review. J. Prod. Innovat. Manag. 19, 110–132. https://doi.org/10.1111/1540-5885.1920110.
Granstrand, O., Holgersson, M., 2020. Innovation ecosystems: a conceptual review and a new definition. Technovation 90–91, 102098. https://doi.org/10.1016/j.technovation.2019.102098.
Guo, L. ling, Qu, Y., Tseng, M.-L., 2017. The interaction effects of environmental regulation and technological innovation on regional green growth performance. J. Clean. Prod. 162, 894–902. https://doi.org/10.1016/j.jclepro.2017.05.210.
Haarstad, H., Wathne, M.W., 2019. Are smart city projects catalyzing urban energy sustainability? Energy Pol. 129, 918–925. https://doi.org/10.1016/j.enpol.2019.03.001.
Hamadneh, J., Duleba, S., Esztergár-Kiss, D., 2022. Stakeholder viewpoints analysis of the autonomous vehicle industry by using multi-actors multi-criteria analysis. Transport Pol. 126, 65–84. https://doi.org/10.1016/j.tranpol.2022.07.005.
Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Change 74, 413–432. https://doi.org/10.1016/j.techfore.2006.03.002.
Höflinger, P.J., Nagel, C., Sandner, P., 2018. Reputation for technological innovation: does it actually cohere with innovative activity? J. Innov. Knowl. 3, 26–39. https://doi.org/10.1016/j.jik.2017.08.002.
Howell, J.M., Higgins, C.A., 1990. Champions of technological innovation. Adm. Sci. Q. 35, 317. https://doi.org/10.2307/2393393.
Hui, H., Ding, Y., Shi, Q., Li, F., Song, Y., Yan, J., 2020. 5G network-based Internet of Things for demand response in smart grid: a survey on application potential. Appl. Energy 257, 113972. https://doi.org/10.1016/j.apenergy.2019.113972.
Jayachandran, M., Rao, K.P., Gatla, R.K., Kalaivani, C., Kalaiarasy, C., Logasabarirajan, C., 2022. Operational concerns and solutions in smart electricity distribution systems. Util. Pol. 74, 101329 https://doi.org/10.1016/j.jup.2021.101329.
Jayashankar, P., Nilakanta, S., Johnston, W.J., Gill, P., Burres, R., 2018. IoT adoption in agriculture: the role of trust, perceived value and risk. J. Bus. Ind. Market. https://doi.org/10.1108/JBIM-01-2018-0023.
Jie, H., Khan, I., Alharthi, M., Zafar, M.W., Saeed, A., 2023. Sustainable energy policy, socio-economic development, and ecological footprint: the economic significance of natural resources, population growth, and industrial development. Util. Pol. 81, 101490 https://doi.org/10.1016/j.jup.2023.101490.
Kanda, W., Río, P. del, Hjelm, O., Bienkowska, D., 2019. A technological innovation systems approach to analyse the roles of intermediaries in eco-innovation. J. Clean. Prod. 227, 1136–1148. https://doi.org/10.1016/j.jclepro.2019.04.230.
Karbasioun, M., Gholamalipour, A., Safaie, N., Shirazizadeh, R., Amidpour, M., 2023. Developing sustainable power systems by evaluating techno-economic, environmental, and social indicators from a system dynamics approach. Util. Pol. 82, 101566 https://doi.org/10.1016/j.jup.2023.101566.
Kataray, T., Nitesh, B., Yarram, B., Sinha, S., Cuce, E., Shaik, S., Vigneshwaran, P., Roy, A., 2023. Integration of smart grid with renewable energy sources: opportunities and challenges – a comprehensive review. Sustain. Energy Technol. Assessments 58, 103363. https://doi.org/10.1016/j.seta.2023.103363.
Kemp, R., Volpi, M., 2008. The diffusion of clean technologies: a review with suggestions for future diffusion analysis. J. Clean. Prod. 16, S14–S21. https://doi.org/10.1016/j.jclepro.2007.10.019.
Keseru, I., Coosemans, T., Macharis, C., 2021. Stakeholders' preferences for the future of transport in Europe: participatory evaluation of scenarios combining scenario planning and the multi-actor multi-criteria analysis. Futures 127, 102690. https://doi.org/10.1016/j.futures.2020.102690.
Khalil, M.I., Jhanjhi, N.Z., Humayun, M., Sivanesan, S.K., Masud, M., Hossain, M.S., 2021. Hybrid smart grid with sustainable energy efficient resources for smart cities. Sustain. Energy Technol. Assessments 46, 101211. https://doi.org/10.1016/j.seta.2021.101211.
Khatua, P.K., Ramachandaramurthy, V.K., Kasinathan, P., Yong, J.Y., Pasupuleti, J., Rajagopalan, A., 2020. Application and assessment of internet of things toward the sustainability of energy systems: challenges and issues. Sustain. Cities Soc. 53, 101957 https://doi.org/10.1016/j.scs.2019.101957.

Kivimaa, P., 2014. Government-affiliated intermediary organisations as actors in system-level transitions. Res. Pol. 43, 1370–1380. https://doi.org/10.1016/j.respol.2014.02.007.
Köhler, J., Raven, R., Walrave, B., 2020. Advancing the analysis of technological innovation systems dynamics: introduction to the special issue. Technol. Forecast. Soc. Change 158, 120040. https://doi.org/10.1016/j.techfore.2020.120040.
Kowalski, K., Stagl, S., Madlener, R., Omann, I., 2009. Sustainable energy futures: methodological challenges in combining scenarios and participatory multi-criteria analysis. Eur. J. Oper. Res. 197, 1063–1074. https://doi.org/10.1016/j.ejor.2007.12.049.
Ku, A.Y., 2018. Anticipating critical materials implications from the Internet of Things (IOT): potential stress on future supply chains from emerging data storage technologies. Sustain. Mater. Technol. 15, 27–32. https://doi.org/10.1016/j.susmat.2017.10.001.
Kumar, L., Wang, Y., Agbotiname, P., Imoize, L., 2021. Internet of Things, Artificial Intelligence and Blockchain Technology. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-74150-1.
Kummitha, R.K.R., Crutzen, N., 2017. How do we understand smart cities? An evolutionary perspective. Cities 67, 43–52. https://doi.org/10.1016/j.cities.2017.04.010.
Kushnir, D., Hansen, T., Vogl, V., Åhman, M., 2020. Adopting hydrogen direct reduction for the Swedish steel industry: a technological innovation system (TIS) study. J. Clean. Prod. 242, 118185 https://doi.org/10.1016/j.jclepro.2019.118185.
Le Ray, G., Pinson, P., 2020. The ethical smart grid: enabling a fruitful and long-lasting relationship between utilities and customers. Energy Pol. 140, 111258 https://doi.org/10.1016/j.enpol.2020.111258.
Lin, B., Xie, Y., 2023. Does digital transformation improve the operational efficiency of Chinese power enterprises? Util. Pol. 82, 101542 https://doi.org/10.1016/j.jup.2023.101542.
Lin, R.-J., Tan, K.-H., Geng, Y., 2013. Market demand, green product innovation, and firm performance: evidence from Vietnam motorcycle industry. J. Clean. Prod. 40, 101–107. https://doi.org/10.1016/j.jclepro.2012.01.001.
Liu, S., Zhang, Y., Liu, Y., Wang, L., Wang, X.V., 2019. An 'Internet of Things' enabled dynamic optimization method for smart vehicles and logistics tasks. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.12.254.
Liu, X., White, S., 2001. Comparing innovation systems: a framework and application to China's transitional context. Res. Pol. 30, 1091–1114. https://doi.org/10.1016/S0048-7333(00)00132-3.
Macharis, C., Turcksin, L., Lebeau, K., 2012. Multi actor multi criteria analysis (MAMCA) as a tool to support sustainable decisions: state of use. Decis. Support Syst. 54, 610–620. https://doi.org/10.1016/j.dss.2012.08.008.
Mah, D.N., Wu, Y.-Y., Ronald Hills, P., 2017. Explaining the role of incumbent utilities in sustainable energy transitions: a case study of the smart grid development in China. Energy Pol. 109, 794–806. https://doi.org/10.1016/j.enpol.2017.06.059.
Mahmoud, M.A., Md Nasir, N.R., Gurunathan, M., Raj, P., Mostafa, S.A., 2021. The current state of the art in research on predictive maintenance in smart grid distribution network: fault's types, causes, and prediction methods—a systematic review. Energies 14, 5078. https://doi.org/10.3390/en14165078.
Mallett, A., Stephens, J.C., Wilson, E.J., Langheim, R., Reiber, R., Peterson, T.R., 2018. Electric (dis) connections: comparative review of smart grid news coverage in the United States and Canada. Renew. Sustain. Energy Rev. 82, 1913–1921. https://doi.org/10.1016/j.rser.2017.06.017.
Markard, J., Bento, N., Kittner, N., Nuñez-Jimenez, A., 2020. Destined for decline? Examining nuclear energy from a technological innovation systems perspective. Energy Res. Social Sci. 67, 101512 https://doi.org/10.1016/j.erss.2020.101512.
Markard, J., Hekkert, M., Jacobsson, S., 2015. The technological innovation systems framework: response to six criticisms. Environ. Innov. Soc. Transit. 16, 76–86. https://doi.org/10.1016/j.eist.2015.07.006.
Markard, J., Truffer, B., 2008. Technological innovation systems and the multi-level perspective: towards an integrated framework. Res. Pol. 37, 596–615. https://doi.org/10.1016/j.respol.2008.01.004.
Markard, J., Worch, H., 2009. In: Technological innovation systems and the resource based view - Resources at the firm, network and system. Industrial Dynamics and Entrepreneurship, Utrecht.
Mastos, T.D., Nizamis, A., Vafeiadis, T., Alexopoulos, N., Ntinas, C., Gkortzis, D., Papadopoulos, A., Ioannidis, D., Tzovaras, D., 2020. Industry 4.0 sustainable supply chains: an application of an IoT enabled scrap metal management solution. J. Clean. Prod. 269, 122377 https://doi.org/10.1016/j.jclepro.2020.122377.
Mecca, B., 2023. Assessing the sustainable development: a review of multi-criteria decision analysis for urban and architectural sustainability. J. Multi-Criteria Decis. Anal. https://doi.org/10.1002/mcda.1818.
Mignon, I., Bergek, A., 2016. System- and actor-level challenges for diffusion of renewable electricity technologies: an international comparison. J. Clean. Prod. 128, 105–115. https://doi.org/10.1016/j.jclepro.2015.09.048.
Mokarram, M., Mokarram, M.J., Gitizadeh, M., Niknam, T., Aghaei, J., 2020. A novel optimal placing of solar farms utilizing multi-criteria decision-making (MCDA) and feature selection. J. Clean. Prod. 261, 121098 https://doi.org/10.1016/j.jclepro.2020.121098.
Motlagh, H.N., Mohammadrezaei, M., Hunt, J., Zakeri, B., 2020. Internet of things (IoT) and the energy sector. Energies 13, 494. https://doi.org/10.3390/en13020494.
Musiolik, J., Markard, J., Hekkert, M., 2012. Networks and network resources in technological innovation systems: towards a conceptual framework for system building. Technol. Forecast. Soc. Change 79, 1032–1048. https://doi.org/10.1016/j.techfore.2012.01.003.
Nevzorova, T., Karakaya, E., 2020. Explaining the drivers of technological innovation systems: the case of biogas technologies in mature markets. J. Clean. Prod. 259, 120819 https://doi.org/10.1016/j.jclepro.2020.120819.
Nižetić, S., Šolić, P., López-de-Ipiña González-de-Artaza, D., Patrono, L., 2020. Internet of Things (IoT): opportunities, issues and challenges towards a smart and sustainable future. J. Clean. Prod. 274, 122877 https://doi.org/10.1016/j.jclepro.2020.122877.
Norouzi, F., Hoppe, T., Kamp, L.M., Manktelow, C., Bauer, P., 2023. Diagnosis of the implementation of smart grid innovation in The Netherlands and corrective actions. Renew. Sustain. Energy Rev. 175, 113185 https://doi.org/10.1016/j.rser.2023.113185.
Noura, M., Atiquzzaman, M., Gaedke, M., 2019. Interoperability in internet of things: taxonomies and open challenges. Mobile Network. Appl. 24, 796–809. https://doi.org/10.1007/s11036-018-1089-9.
O'Donnell, B., 2019. The 5G landscape, Part 2: spectrum and devices. Forbes Inc, New Jersey. https://www.forbes.com/sites/bobodonnell/2019/10/24/the-5g-landscape-part-2-spectrum-and-devices/.
O'Dwyer, E., Pan, I., Acha, S., Shah, N., 2019. Smart energy systems for sustainable smart cities: current developments, trends and future directions. Appl. Energy 237, 581–597. https://doi.org/10.1016/j.apenergy.2019.01.024.
Oughton, E.J., Frias, Z., 2018. The cost, coverage and rollout implications of 5G infrastructure in Britain. Telecommun. Pol. 42, 636–652. https://doi.org/10.1016/j.telpol.2017.07.009.
Palaniyappan, B., T, V., Chandrasekaran, G., 2023. Solving electric power distribution uncertainty using deep learning and incentive-based demand response. Util. Pol. 82, 101579 https://doi.org/10.1016/j.jup.2023.101579.
Palm, J., Kojonsaari, A.-R., Öhrlund, I., Fowler, N., Bartusch, C., 2023. Drivers and barriers to participation in Sweden's local flexibility markets for electricity. Util. Pol. 82, 101580 https://doi.org/10.1016/j.jup.2023.101580.
Parag, Y., Sovacool, B.K., 2016. Electricity market design for the prosumer era. Nat. Energy 1, 16032. https://doi.org/10.1038/nenergy.2016.32.
Pohekar, S.D., Ramachandran, M., 2004. Application of multi-criteria decision making to sustainable energy planning—a review. Renew. Sustain. Energy Rev. 8, 365–381. https://doi.org/10.1016/j.rser.2003.12.007.
Ponce-Jara, M.A., Ruiz, E., Gil, R., Sancristóbal, E., Pérez-Molina, C., Castro, M., 2017. Smart Grid: assessment of the past and present in developed and developing countries. Energy Strategy Rev. 18, 38–52. https://doi.org/10.1016/j.esr.2017.09.011.
Raven, R., Walrave, B., 2020. Overcoming transformational failures through policy mixes in the dynamics of technological innovation systems. Technol. Forecast. Soc. Change 153, 119297. https://doi.org/10.1016/j.techfore.2018.05.008.
Reka, S.S., Dragicevic, T., 2018. Future effectual role of energy delivery: a comprehensive review of Internet of Things and smart grid. Renew. Sustain. Energy Rev. 91, 90–108. https://doi.org/10.1016/j.rser.2018.03.089.
Rhodes, A., 2020. Digitalisation of Energy: an Energy Futures Lab Briefling Paper. Imp. Coll, London. https://spiral.imperial.ac.uk/handle/10044/1/78885.
Righetti, F., Vallati, C., Anastasi, G., 2018. IoT applications in smart cities: a perspective into social and ethical issues. In: 2018 IEEE International Conference on Smart Computing (SMARTCOMP). IEEE, pp. 387–392. https://doi.org/10.1109/SMARTCOMP.2018.00034.
Rothwell, R., Robertson, A.B., 1973. The role of communications in technological innovation. Res. Pol. 2, 204–225. https://doi.org/10.1016/0048-7333(73)90003-6.
Sandys, L., Dobson, R., Brown, E., Graham, G., Lane, R., Verma, J., 2019. Energy data Taskforce: a strategy for a modern digitalised energy system - energy systems catapult. Energy Data Taskforce Rep. https://es.catapult.org.uk/report/energy-data-taskforce-report/.
Scherrer, A., Plötz, P., Van Laerhoven, F., 2020. Power from above? Assessing actor-related barriers to the implementation of trolley truck technology in Germany. Environ. Innov. Soc. Transit. 34, 221–236. https://doi.org/10.1016/j.eist.2020.01.005.
Sharma, M., Joshi, S., Kannan, D., Govindan, K., Singh, R., Purohit, H.C., 2020. Internet of Things (IoT) adoption barriers of smart cities' waste management: an Indian context. J. Clean. Prod. 270, 122047 https://doi.org/10.1016/j.jclepro.2020.122047.
Shoreh, M.H., Siano, P., Shafie-khah, M., Loia, V., Catalão, J.P.S., 2016. A survey of industrial applications of Demand Response. Elec. Power Syst. Res. 141, 31–49. https://doi.org/10.1016/j.epsr.2016.07.008.
Shrouf, F., Miragliotta, G., 2015. Energy management based on Internet of Things: practices and framework for adoption in production management. J. Clean. Prod 100, 235–246. https://doi.org/10.1016/j.jclepro.2015.03.055.
Skoczkowski, T., Verdolini, E., Bielecki, S., Kochański, M., Korczak, K., Węglarz, A., 2020. Technology innovation system analysis of decarbonisation options in the EU steel industry. Energy 212, 118688. https://doi.org/10.1016/j.energy.2020.118688.
Sniderman, B., Raynor, M.E., 2015. Power struggle: customers, companies, and the internet of things. Deloitte Rev 83–99.https://www2.deloitte.com/content/dam/insights/us/articles/internet-of-things-customers-companies/DUP1202_DR17_PowerStruggle.pdf.
Sodhro, A.H., Pirbhulal, S., Luo, Z., de Albuquerque, V.H.C., 2019. Towards an optimal resource management for IoT based Green and sustainable smart cities. J. Clean. Prod. 220, 1167–1179. https://doi.org/10.1016/j.jclepro.2019.01.188.
Stojkoska, B.L.R., Trivodaliev, K.V., 2017. A review of Internet of Things for smart home: challenges and solutions. J. Clean. Prod. 140, 1454–1464. https://doi.org/10.1016/j.jclepro.2016.10.006.
Suurs, R.A.A., Hekkert, M.P., 2009. Competition between first and second generation technologies: lessons from the formation of a biofuels innovation system in The Netherlands. Energy 34, 669–679. https://doi.org/10.1016/j.energy.2008.09.002.

Teece, D.J., 1996. Firm organization, industrial structure, and technological innovation. J. Econ. Behav. Organ. 31, 193–224. https://doi.org/10.1016/S0167-2681(96)00895-5.

ten Heuvelhof, E., Weijnen, M., 2013. Investing in smart grids within the market paradigm: the case of The Netherlands and its relevance for China. Polic. Soc. 32, 163–174. https://doi.org/10.1016/j.polsoc.2013.05.002.

Tidd, J., 2001. Innovation management in context: environment, organization and performance. Int. J. Manag. Rev. 3, 169–183. https://doi.org/10.1111/1468-2370.00062.

Tricoire, A., 2015. Uncertainty, vision, and the vitality of the emerging smart grid. Energy Res. Social Sci. 9, 21–34. https://doi.org/10.1016/j.erss.2015.08.028.

Tu, C., He, X., Shuai, Z., Jiang, F., 2017. Big data issues in smart grid – a review. Renew. Sustain. Energy Rev. 79, 1099–1107. https://doi.org/10.1016/j.rser.2017.05.134.

Turcksin, L., Macharis, C., Lebeau, K., Boureima, F., Van Mierlo, J., Bram, S., De Ruyck, J., Mertens, L., Jossart, J.-M., Gorissen, L., Pelkmans, L., 2011. A multi-actor multi-criteria framework to assess the stakeholder support for different biofuel options: the case of Belgium. Energy Pol. 39, 200–214. https://doi.org/10.1016/j.enpol.2010.09.033.

Utterback, J.M., 1971. The process of technological innovation within the firm. Acad. Manag. J. 14, 75–88. https://doi.org/10.5465/254712.

Vargo, S.L., Akaka, M.A., Wieland, H., 2020. Rethinking the process of diffusion in innovation: a service-ecosystems and institutional perspective. J. Bus. Res. 116, 526–534. https://doi.org/10.1016/j.jbusres.2020.01.038.

Verkade, N., Höffken, J., 2018. The design and development of domestic smart grid interventions: insights from The Netherlands. J. Clean. Prod. 202, 799–805. https://doi.org/10.1016/j.jclepro.2018.08.185.

Vinuesa, R., Azizpour, H., Leite, I., Balaam, M., Dignum, V., Domisch, S., Felländer, A., Langhans, S.D., Tegmark, M., Fuso Nerini, F., 2020. The role of artificial intelligence in achieving the Sustainable Development Goals. Nat. Commun. https://doi.org/10.1038/s41467-019-14108-y.

Walrave, B., Raven, R., 2016. Modelling the dynamics of technological innovation systems. Res. Pol. 45, 1833–1844. https://doi.org/10.1016/j.respol.2016.05.011.

Wang, Q., Hauge, J.B., Meijer, S., 2019. Adopting an actor analysis framework to a complex technology innovation project: a case study of an electric road system. Sustainability 12, 313. https://doi.org/10.3390/su12010313.

Wang, X., Tian, W., He, J., Huang, M., Jiang, J., Han, H., 2011. The application of electric vehicles as mobile distributed energy storage units in smart grid. In: 2011 Asia-Pacific Power and Energy Engineering Conference. IEEE, pp. 1–5. https://doi.org/10.1109/APPEEC.2011.5748400.

World Economic Forum, 2018. The effect of the Internet of Things on Sustainability. World Economic Forum, Geneva. https://www.weforum.org/agenda/2018/01/effect-technology-sustainability-sdgs-internet-things-iot/.

Xenias, D., Axon, C.J., Whitmarsh, L., Connor, P.M., Balta-Ozkan, N., Spence, A., 2015. UK smart grid development: an expert assessment of the benefits, pitfalls and functions. Renew. Energy 81, 89–102. https://doi.org/10.1016/j.renene.2015.03.016.

Zanghelini, G.M., Cherubini, E., Soares, S.R., 2018. How multi-criteria decision analysis (MCDA) is aiding life cycle assessment (LCA) in results interpretation. J. Clean. Prod. 172, 609–622. https://doi.org/10.1016/j.jclepro.2017.10.230.