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Energy Management Systems in Smart Cities: A Review from the Perspective of Complex Networks Design

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Smart cities are a very promising concept for achieving the sustainability of urban settlements. This is especially true for sustainability related to general aspects of energy management, e.g., generation, transformation, distribution, and storage. Despite their considerable potential, smart cities are complex systems in nature, as numerous individuals and subsystems participate in their performance. Because of this complexity, numerous challenges are presented for the conception of this type of system, i.e., during its design stage. The contribution provides a brief literature review that focuses on energy management in smart cities. Initially, an overview of the field is provided by analyzing the co-occurrence of keywords in the literature available in the SCOPUS database. Subsequently, strategies for energy management in smart cities, modeling approaches, and challenges and opportunities are discussed. For this, the work refers to earlier literature reviews that describe in detail relevant subjects from the perspective of networks design and optimization. The review aims at helping interested readers recognize the systematic tools available for the design of energy systems as well as the challenges offered in this rapidly evolving area, thereby contributing to the advancement of sustainable and efficient energy solutions within the context of urban environments.

1. Introduction

Modern society faces a major challenge concerning the improvement of people's quality of life while preserving the environment and biodiversity. The Sustainable Development Goals (SDGs) defined by the United Nations (UN) are robust evidence of this conundrum. The 17 objectives defined in 2015 (United Nations, 2015a) set objectives addressing social challenges, such as the elimination of poverty and other deprivations, but also trace objectives for climate action and resource preservation. However, the constant population growth as well as the elevated resource-depletion rate of high-quality life make guaranteeing social wellbeing expensive in terms of resources. Because of this challenge, sustainability has emerged as a recurrent term in various disciplines, as it refers to the fulfillment of humankind's needs without jeopardizing the capability of future generations to meet their own needs.

The objective "sustainable cities and communities" is one of the SDGs that better represents this challenge. Such a goal aims at making cities more resilient and sustainable in terms of poverty elimination, pollution reduction, access to quality transport, etc. (United Nations, 2015b). Consequently, research on sustainable urban development has gained attention by addressing topics such as urban planning, transport systems, waste management, access to information, and energy management. Such ideas are especially relevant considering that by 2050, it is expected that two-thirds of the world's population will be living in urban areas (United Nations, 2015b). These ideas have resulted in the concept of smart cities as an alternative that seizes innovative technology to enhance the inhabitants' quality of life in a sustainable way. One of the first definitions of a smart city dates back to the end of the 20th century. In this context, smart cities are described as urban centers that prioritize safety, security, environmental sustainability, and efficiency by deploying advanced materials, sensors, and networks in the design, construction, and maintenance of all city infrastructure (Hall et al., 2000).

This concept of a smart city has gained popularity in the last decade thanks to recent technological advances such as increased rates of data transfer, larger connectivity capabilities, and enhanced general development of Information and Communication Technologies (ICT). Moreover, these technologies have transformed the vision

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of smart cities, and new definitions have appeared. The International Telecommunication Union (ITU), for instance, has defined smart city as an innovative city that employs ICT tools to improve the quality of life, the efficiency of the city, and that is sustainable in economic, environmental, social, and cultural aspects (ITU, 2015). Regarding this, Bajdor and Starostka-Patyk (2021) carried out a bibliometric analysis, finding more than 1,300 contributions published between 2000 and 2020. However, despite the substantial number of contributions published in recent years, the authors concluded that this is not a fully exploited area and still offers numerous future opportunities. Moreover, their bibliometric analysis allowed them to conclude that, as expected, sustainable development has been strongly associated to smart cities research.

A deepest revision on the area of sustainable development reveals that energy management has received noticeable attention among scholars, being at the core of the research related to smart cities. In this regard, Sukhwani et al. (2020) performed a bibliometric analysis of the water-energy-food nexus in smart cities, finding that energy efficiency, utilization, and conservation are key areas in smart cities, especially when associated with ICT as smart solutions. The progress in this area has also been documented in previous reviews. For instance, Alotaibi et al. (2020) presented a comprehensive review of the advances and research in smart grids, with a special focus on topics such as data management, cybersecurity, and renewable energy integration.

Moreover, a recent bibliometric analysis surveyed contributions between 2017 and 2022, classified them into 5 clusters, and discussed technological gaps for adequate implementation of smart grids (ur Rehman et al., 2023). As the population continues to grow, it is expected that the relevance of energy systems in sustainable urban development will keep increasing. The integration of ICT into urban infrastructure will depend on the capability of scientists and engineers to achieve high functionality and sustainability for the smart energy systems. Therefore, it becomes of utmost importance to recognize the techniques and resources available for the design and optimization of complex energy networks.

Despite the utility of prior review papers in discovering recent developments, they frequently offer limited guidance for discerning contributions addressing challenges and tools for design of this type of complex systems. This work presents a literature review of energy management in smart cities from the perspective of the design of complex networks. The contribution discusses distinct strategies related to energy management and saving in smart cities, and provides the reader with an insightful overview concerning the modeling and optimization of problems related to this type of system. Herein, a review of relevant literature is performed with a focus on energy management networks, especially in previous reviews available in the literature that deal with topics of interest for networks' design and optimization. This overview aims at guiding the reader interested in design and optimization through the myriad of papers available and providing an analysis of the challenges and opportunities in this area.

2. Methodology

This contribution focuses on reviewing papers concerning energy management in smart cities. For this, a search was performed in the SCOPUS database for contributions published in scientific journals containing "smart city" and "energy management" in the title, keywords, or abstract. The search and retrieval of the data were conducted utilizing the search string '(TITLE-ABS-KEY (smart city) AND TITLE-ABS-KEY (energy AND management))' in the database's advanced search. The results of this search were retrieved via Python's library "Pybliometrics," which permits accessing relevant metadata concerning the contributions, such as title, author names and affiliations, citation count, and keywords.

To provide an overview of the current status of the field, an analysis of co-occurrence was performed, looking for terms related to energy management and sustainability in keywords provided by the authors. For this, the documents' metadata was exported into a RIS file, where duplicate contributions were removed from the results. The keyword co-occurrence analysis was performed in the software VOS viewer (Universitet Leiden, 2023). In this analysis, words whose relationship with the selected topic is not evident were excluded, such as cybersecurity and block chain. Thereafter, the contributions to be reviewed were selected by considering their relevance in terms of their number of citations and looking for previous reviews that addressed one or more of the topics that are significant for the design of complex energy systems.

3. Design of energy networks in smart cities

Initially, the search yielded close to 3,700 documents for the string specified, ranging from 2005 to 2023. The duplicate entries were removed from the initial set of documents. Hence, a total of 1,496 were categorized as journal contributions whose publication dates can be traced back to 2008. The database of journal contributions was used to perform a co-occurrence analysis in the keywords, with a specific focus on terms related to energy management. Naturally, the term "smart city" was the one appearing the most frequently with 511 counts, followed by other relevant terms used for the search, i.e., "smart grid" (138), and "energy management (87).

Following closely behind were other significant terms, including "energy efficiency" (85), "sustainability" (67), and "renewable energy" (62), denoting their crucial role in the context of energy management discussions. Moreover, terms that reflect the current trends of the field were also identified, such as "wireless energy sensors" (76), "electric vehicles (55), "demand-side management" (39), optimization (34), energy storage (22), and circular economy (13). Figure 1 shows a map of co-occurrence for the terms identified in the author's keywords. In this figure, the size of the frames and labels is proportional to the number of occurrences, whereas the color of the frame denotes the average year of publication for the contributions where the term appears.

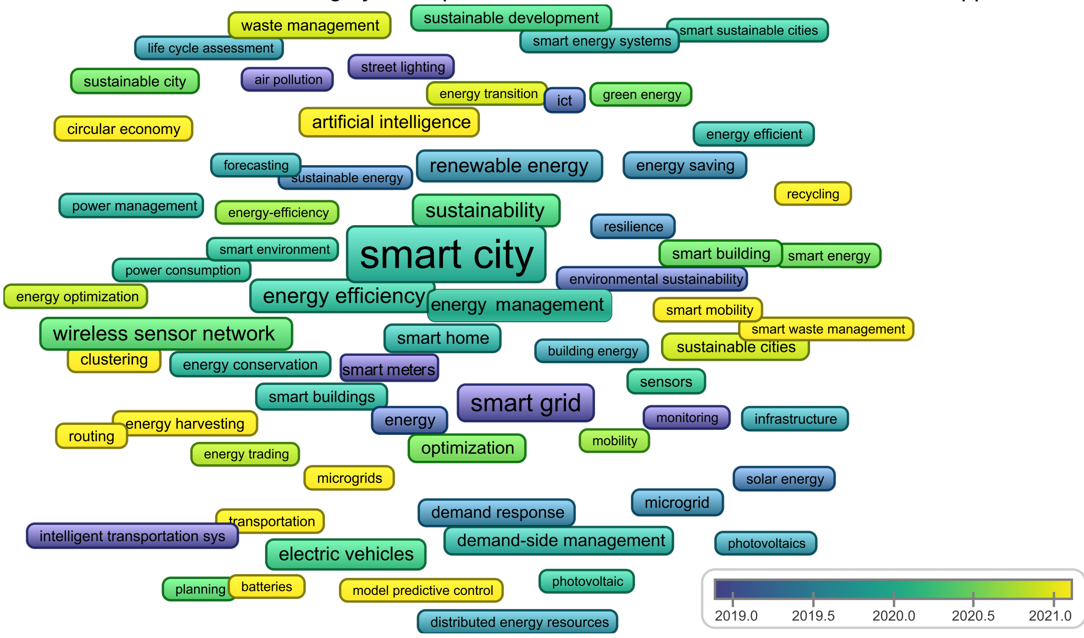

Figure 1: Map of occurrence of energy-management-related terms in keywords for journal contributions retrieved during the search

The map shows that terms related to strategies for energy saving and optimization, with a focus on sustainability, have been significant for research before 2020 (green and blue). Furthermore, it is shown that the most recent literature is distinguished by the use of cutting-edge concepts like artificial intelligence and the circular economy. Terms such as energy saving, efficiency, and conservation highlight the role smart cities are expected to have in sustainable development as an integral part of renewable, green, and efficient energy networks. The section's remainder discusses some contributions that examine relevant energy management strategies, modeling techniques, and opportunities and challenges for the design of energy management systems in smart cities.

3.1 Strategies for energy management in smart cities

The review of the literature reveals a wide range of strategies for improving energy management, from the use of cutting-edge technology, such as smart metering and demand-side management in public lighting systems, to the replacement of conventional generation by renewable sources. Table 1 summarizes some of the most significant strategies, accompanied by references to relevant contributions that provide details concerning their applications and impacts. These strategies are expected to be used simultaneously in smart cities and smart grids to enhance the sustainability of the network. For a detailed description, and a general overview of their state of the art, the reader may refer to the work of Calvillo et al. (2016) who present a comprehensive discussion on key elements in energy management for cities, such as alternatives for generation and storage, as well as proposals for improving the energy infrastructure and transport sector.

3.2 Modelling approaches and solution strategies

Numerous models are available to deal with the task of modeling complex energy networks. These models are usually employed for determining the configuration of new networks, i.e., the design of the network, or for optimizing the operation parameters of already existing systems, i.e., analysis and optimization. Consequently, these models typically represent the systems by resorting to two types of variables related to the system's components, i.e., discrete variables that represent their inclusion in the network and variables that relate the energy loads for each of them. Various models available are based on the idea of representing multiple energy carriers as networks of different *energy hubs* connected to each other. These hubs represent elements in the network that exchange energy with the surrounding systems, primary energy sources, and consumer ports (Geidl and Andersson, 2007). In addition to the contributions listed before, the reader is referred to the contribution of Seferlis et al. (2021), who reviewed the theory of energy generation and distribution in multiple scenarios.

Table 1: Summary of strategies for energy management and efficiency in smart cities

Strategy	Description	Referred contributions
Renewable energy sources	Partial or total replacement of conventional non-renewable energy generation methods, such as fossil fuels, by renewable alternatives, e.g., wind or solar power.	- Description of roles of renewables in smart cities (Hoang et al., 2021). - Review of renewables sources of energy in smart grids (Alotaibi et al., 2020).
Improvement of energy efficiency in industrial facilities	Enhancing how industrial and productive systems generate, supply, and use distinct types of energy, so that productive systems can be integrated into smart cities in closed loops, e.g., waste produced biogas supplied to consumers in the city.	- Comprehensive review of design, integration, and operation strategies in productive systems (Seferlis et al., 2021). - Graph-theoretic approach for optimization of energy link between cities and industry (Sandor et al., 2010).
Distributed generation systems	Transitioning from centralized energy generation (where most of the load is produced in a single facility) to production in smaller plants to reduce costs and lower carbon emissions.	- Role of distributed generation and description of tools (Mehigan et al., 2018).
Demand-side management	Set of strategies where the demand loads requirements are modified via techniques such as dynamic pricing.	- Description of strategies of demand side management (Alotaibi et al., 2020). - Framework of demand-side management in smart cities (Mentzingen et al., 2020).
Smart grid control and metering	Precise metering and monitoring of the systems to improve their efficiency according to the data collected. An interesting example is the smart control of traffic and street lighting.	- Examination of benefits and disadvantages of smart metering systems (McHenry, 2013). - Smart control of street lighting (Kovács et al., 2016).
Energy storage	Inclusion of energy storage to mitigate uncertainty of renewable energy sources, fluctuating prices and demands. This strategy adds stability and increases reliability via various technologies, such as batteries, hydrogen, or phase change materials, e.g., excess energy produced at low-demand periods can be stored and utilized to alleviate the system in periods of high demand	- Review of common electric storage technologies (Calvillo et al., 2016). - Description of phase-change materials for thermal storage (Sharma et al., 2021). - Power planning for renewable energy and storage considering environmental footprints (Varbanov et al., 2022).
Electric vehicles in the grid	The incorporation of electric vehicles in the city infrastructure is one of the most relevant strategies. This requires additional infrastructure for battery charging.	- Review of smart charging strategies for electric vehicles (García-Villalobos et al., 2014). - Socio-technical paradigm for charging based on demand response (Pournaras et al., 2019).

Moreover, the contribution of Mancarella et al. (2014), who categorized models of multiple-energy systems according to the aggregation level used to represent the system's elements into four distinct perspectives: (i) according to a spatial perspective (e.g., buildings, generation plants, cities, or countries); (ii) according to the type of services generated (e.g., heating, electricity, and cooling); (iii) according to the distinct types of fuel deployed; and (iv) models that accurately represent the interconnection of the system's elements and their network nature of multi-energy systems.

It is worth noting that the last group of models allows for a rigorous depiction of the system's interactions, making it the most suitable for design tasks. Moreover, these models confer on the designer the capacity to consider different alternatives for energy storage, represent the geographical distance between the network's elements, and model parameter variations for various time periods. Models of this kind have been deployed in approaches for the systematic design of networks (Voll et al., 2012). However, the mixture of discrete and continuous variables, in addition to the complex models of transmission and technologies, renders these models difficult to solve for larger systems. The implementation of these models is made more practical by means of simplifications, such as linearizing cost and efficiency relationships. Numerous solution approaches for this type of problem have been summarized by Sami et al. (2021).

3.3 Opportunities and challenges

Smart cities are expected to constitute a step towards urban development, particularly when it comes to energy management. As a result, finding the best energy distribution that maximizes societal, environmental, and economic benefits must be the guiding premise for designing smart energy systems. On the one hand, a primary challenge is the complex composition of practical networks which involves multiple stakeholders such as companies, governments, and users. Effective decision-making in the various sustainability dimensions requires understanding interactions among these agents and their roles, often necessitating agent-based modeling and game theory to align their interests. On the other hand, smart grid design needs to be tackled from a multi-objective optimization perspective that does not consider solely economical aspects but also includes environmental and social criteria. The latter may constitute an additional challenge itself, as multiple indicators may be required to capture the environmental and social impact of an entire city. Naturally, the inclusion of various objectives and additional criteria is expected to hinder the problem solution; hence, multicriteria-decision analysis and the generation of multiple solutions might be appreciated (Voll et al., 2015).

Moreover, these systems must contemplate the reduction of carbon emissions through the replacement of traditional fossil fuels with cleaner alternatives. Renewable energy sources have a crucial role in this transformation; however, uncertainties like biomass composition and unpredictable weather patterns pose an additional challenge to this goal. Because of this intrinsic variability, the energy infrastructure must be designed so that it is robust and flexible enough to manage variations in these external factors. As a result, it can be difficult to analyze stochastic parameters and variables while also considering how they might vary over time. The addition of these components requires larger models in terms of variables and equations, which necessitate novel solution approaches.

Furthermore, it is expected that smart energy systems will be resilient to disturbances, i.e., that they will have an adequate response to failures and changes in demand patterns. Hence, it will be necessary to thoroughly determine the smart system's resilience and reliability, this may require consideration of further steps and examination during the design stage (Orosz et al., 2018). In terms of improving these properties, energy storage offers multiple alternatives for adding resilience to the system; therefore, their inclusion and operation should also be considered during the design step. This involves determining the best storage alternatives as well as relevant parameters such as its plausible location (Varbanov et al., 2022). In addition to the energy storage, the network's capacity to adapt to dynamic conditions can be increased by integration with cutting-edge technologies such as artificial intelligence (AI), machine learning, and sophisticated control strategies. Thus, the design phase must consider the operation of ICT to remain effective in a technological environment that is always changing.

In this regard, the inclusion of dynamics, multiple equations that represent the behavior of storage systems, allocation decisions, and the design of control and data interfaces pose a challenge in terms of modeling and solution techniques. This challenge is increased as there are no two identical cases, and the conditions of every system must be independently considered. Hence, it is expected that the complexity of the network will increase as more rigorous models and considerations are included.

4. Conclusions

Smart cities are regarded as the future of human urban settlement. The completion of this vision entails that smart cities are designed via systematic methods that guarantee adequate decision-making in the interests of society. This contribution provides a brief literature review on smart energy system design. The review guides readers toward pertinent contributions that provide in-depth information about strategies and models addressing optimization of these complex networks. The need for more research is highlighted by describing the opportunities and challenges in the research field, especially when it comes to solving the difficulty of designing increasingly complex energy systems.

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