Transformation to Sustainable Energy System for Smart Cities

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Transformation is a deliberate, carefully planned, complete reconstruction, the effects of which will be used in the long term. It usually concerns economic infrastructure, and its implementation requires a multifaceted approach for the solutions created. The term smart city is associated with the words livable, green, intelligent, low carbon, sustainable, digital, information, knowledge, resilient, eco, and ubiquitous. Targeting sustainable energy systems is now an integral element of smart-city operation.

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1. Introduction

Transformation is a deliberate, carefully planned, complete reconstruction, the effects of which will be used in the long term. It usually concerns economic infrastructure, and its implementation requires a multifaceted approach for the solutions created. Nadler's concept of an ideal system, developed in the 1960s, assumed that an ideal model would be created which should be verified by existing conditions in reality, which would enable the preparation of a holistic improvement of the system's functionality that can be realized in practice [1]. The integrating element of the system is the function (mission, goal, task), the realization of which requires technical systems (fixed assets), as well as a group of competent contractors (executing the project), all of which should be selected deliberately, in the context of the technologies necessary to support the processes. Such a system requires sources of supply (input elements) and distribution of products (including undesirable ones—waste) at the output. The whole function is in the environment, hence the system's interaction with the environment and reciprocally—the environment with the system.

The one-size-fits-all view of the system described here also applies to energy systems, which in the past were analyzed primarily from the perspective of economic efficiency. Today, significant changes are evident due to different priorities. In 1987, the Gro Harlem Brundtland Our Common Future report [2] presented the concept of sustainable development in its broadest sense, in which development was defined as meeting the needs of both present and future generations, determining to a large extent the quality of life (the social aspect) by appropriately and consciously shaping the relationship between economic growth (the economic aspect) and respect for the environment (the environmental aspect). In the late 1980s, the concept of the creative city (creative city) emerged [3], and a practical implication of the application of the idea of sustainable development is the concept of the compact city or city of short distances [4]. The main thrust of this concept is to strive to reduce energy consumption, including reducing vehicular transportation, shortening the routes and transmission networks of various utilities, and solving the problem of so-called urban sprawl [5].

2. The Concept and Scope of Smart Cities

The importance of smart cities in enhancing sustainability is widely recognized in the literature and practice. However, it's crucial to acknowledge that the actual implementation and impact of smart-city initiatives can vary significantly from one city to another. The success of smart-city projects depends on various factors, including governance, technology adoption, and community engagement.

Smart cities represent an innovative concept aimed at enhancing the sustainability and quality of life for urban populations [6]. Furthermore, initiatives focused on digitization and the development of smart cities are essential to bolster ecological and economic sustainability. Nevertheless, a more direct way to articulate this added value is by initially deducting the benefits from the efforts [7]. The notion of a smart city is relatively recent, emerging as a product of an evolutionary process [8]. It is important to highlight that the concept of a smart city gradually took shape from various perspectives as a means of characterizing technological transformations within urban environments. The earliest reference to such a concept can be traced back to 1997, when it was introduced as a virtual city, denoting local ICT network initiatives facilitating the emergence of local cybernetic (virtual) communities [9]. These virtual cities were dependent on the World Wide Web (WWW) and functioned as digital counterparts to tangible urban spaces [8]. Subsequently, the term 'digital city' emerged, signifying the presence of infrastructure conducive to the formation of virtual communities [10].

In the year 2000, the smart-city concept was formally defined as a city that systematically oversees and integrates the state of its entire critical infrastructure, encompassing elements such as roads, bridges, tunnels, railways, subways, airports, seaports, communication networks, sanitation systems, energy resources, and even buildings. This comprehensive approach aimed at optimizing resource utilization, planning preventive maintenance operations, and ensuring safety while maximizing the quality of services for its residents [11]. A decade later, it was emphasized that a smart city is one that harmoniously blends physical infrastructure, information technology infrastructure, social infrastructure, and business infrastructure to harness the collective intelligence of the city's inhabitants [12]. In essence, the concept of a smart city revolves around the idea of viewing it as a collection of initiatives designed to enhance the efficiency of urban centers through the utilization of data, information, and information technologies (IT). This, in turn, leads to the provision of more efficient services for citizens, as well as the monitoring and optimization of city functions, fostering collaboration among various economic entities, and encouraging the adoption of innovative business models within both the private and public sectors [13].

As a matter of fact, we observe a progression starting from the inception of the virtual city, with the establishment of ICT networks, a concept that gained prominence in the literature after the 1990s [14]. This evolution continued with the widespread adoption of ICT throughout the entire urban infrastructure, facilitating intelligent management of energy consumption, transportation, and building systems [15]. Subsequently, the notion of a 'smart city footprint' emerged, quantified through indicators reflecting the city's capacity across various dimensions, including society, economy, mobility, and governance. This phase involved large-scale experimentation, effectively treating the city as a dynamic living laboratory [8]. In the most recent approaches, the primary focus has shifted towards enhancing the everyday quality of life for residents, promoting sustainable development, prioritizing environmental concerns, optimizing mobility, and expanding green spaces and smart energy systems [16][17].

The historical evolution of the smart-city concept reflects the changing technological landscape and the growing recognition of the need for integrated urban planning. However, it's important to note that the definition and understanding of smart cities can vary among scholars, practitioners, and policymakers. This can lead to challenges in implementation and measurement. Metropolitan regions are responsible for approximately 70% of worldwide CO_2 emissions and account for two-thirds of global energy consumption. In this respect, governments worldwide have pledged to cooperate in addressing global energy, climate, and environmental challenges [6]. Therefore, the role and importance of energy systems and the transformation towards their sustainability should be emphasized. From the point of view of the "green transformation" of urban areas, this is a key aspect driving these changes.

3. Sustainable Energy Systems for Smart Cities

Energy-generation systems are engineered to transform primary energy sources like heat, electricity, and cooling into alternative secondary energy forms. Common methods for generating renewable energy include the use of wind turbines, hydroelectric dams, and multi-generational power plants. In a typical smart energy system, renewable energy takes precedence over fossil fuels. However, to ensure year-round system reliability, fossil fuels may be used as an additional energy source [18].

Management systems play a multifaceted role in fostering effective interaction between household residents and the management framework. They include functions such as monitoring and logging, along with the use of various predefined risk alerts to enhance home security through a management system. Homeowners have the flexibility to control household appliances based on their preferences using Smart Home Energy Management Systems (SHEMS), mobile applications, or manual methods [19].

As indicated in the reference [20], numerous studies have demonstrated that the Internet of Things (IoT) offers significant advantages compared to other communication networks. The IoT is gaining popularity due to its user-friendliness and compatibility with diverse communication protocols [21]. Building Energy Management Systems (BEMS) find applications across a range of building types, including residential, industrial, administrative, and commercial structures. Moreover, the integration of intermittent renewable energy sources with an appropriate energy-storage system within the building is essential to ensure the reliability and efficiency of BEMS, addressing a critical requirement [20].

Consequently, the assessment of a specific area within a building is ascertained through the deployment of sensors. The definition of a 'zone' can vary based on architectural considerations and the manner in which sensors are incorporated into the building; it could encompass a single room, an entire floor, or even the entire structure.

These sensors play a pivotal role in monitoring indoor-comfort parameters, including occupancy, CO_2 levels, temperature, and humidity. Additionally, sensors are capable of detecting critical situations such as fire hazards, flooding, or unauthorized intrusion [22].

Many authors and organizations have introduced and put into practice the concept of the ‘smart city,’ which remains relatively new [23]. Smart cities are specifically designed to tackle or mitigate the challenges posed by rapid urbanization and population growth. These challenges encompass various aspects such as energy provision, waste management, and transportation, all with the aim of maximizing efficiency and resource utilization. The existing energy classification categorizes areas of intervention within smart cities in diverse ways. However, a limitation of these classifications is their exclusive focus on the smart grid when addressing energy concerns, overlooking essential elements like transportation and infrastructure [24].

Cities’ energy demands are both intricate and multifaceted. Consequently, contemporary cities should harness the synergies among different energy solutions to improve their existing systems and implement new ones using a cohesive and optimized approach. Challenges such as volatile energy supply-and-demand, the imperative of more energy-efficient transportation, and various other energy-related issues necessitate collective solutions rather than isolated approaches [25].

In a city that prioritizes the well-being of its residents and is mindful of environmental concerns, the foremost consideration is meeting the needs of its inhabitants. Sustainable development is centered on the city’s holistic advancement, promoting fairness and conservation. In contrast to the focus of smart cities, it involves integrating green spaces and eco-friendly practices into the urban landscape to mitigate pollution, reducing carbon emissions, and safeguarding natural resources [26]. By leveraging advanced technologies like ICT and other cutting-edge methods, a city can enhance the quality of life for its residents, optimize operational efficiency, and bolster competitiveness, while also addressing the present and future generations’ needs. Cities must evolve to become more intelligent and environmentally sustainable to reduce CO_2 emissions. Key benefits encompass advancements in renewable energy, efficient waste management, and improved traffic conditions. Many smart-city initiatives revolve around the implementation of efficient grid- and watershed-management systems [27].

A system for ensuring human safety and monitoring energy consumption can be established through the utilization of water-level-monitoring devices. Initiatives and activities aimed at conserving resources are regarded as sustainable practices. Sustainable development is built upon five core pillars: ecological preservation, social progress, cultural conservation, and economic growth [28]. These encompass various aspects, such as intelligent streets, smart lighting, efficient parking facilities, and intelligent traffic signals, which collectively enhance navigation efficiency and expedite transfers. By utilizing these environmentally friendly technologies, individuals can reduce their carbon footprint and enhance their social capital [28]. In addition to improving public services, infrastructure, and sustainability, smart cities strive to create a more advanced social environment for their residents [29]. These concerns and the reinvigoration of cities as pivotal economic hubs, both nationally and globally, have emerged in response to urbanization and global economic shifts [30].

In smart cities, both new and existing structures are designed to be more energy-efficient and operationally effective. The optimization of power generation, which encompasses various energy sources and has distributed generation, relies on a detailed analysis of energy-consumption patterns [31]. Precise metering is an essential component of effective energy management. Managing energy resources within these urban areas poses significant challenges due to their intricate nature and critical importance. To enhance corporate social responsibility and mitigate greenhouse-gas emissions, it becomes essential to closely monitor operational costs and prepare accurate budgets based on utility bills. Reducing dependency on unreliable supply chains is a key objective. The approach outlined below facilitates discussions on energy utilization and, consequently, contributes to the economic development of a sustainable smart city [32].

As an alternative, there is the option of an urban-construction group. This small, intelligent community can utilize an Internet of Things (IoT) platform comprehensively, allowing its members to collaborate effectively in enhancing their energy-generation capacity with the goal of reducing the city's CO_2 emissions. In line with our proposed energy-management system's approach, buildings equipped with Renewable Energy Sources in Society (RESS) can be synchronized to reduce their reliance on the primary distribution grid [33]. This strategy, centered on renewable-energy adoption, contributes to a reduction or elimination of greenhouse-gas emissions. Wind and solar energy sources are currently recognized as the most cost-effective, based on global research. Our objective is to pioneer a novel method for assessing the optimal capabilities of RESS, which takes into account building usage patterns, seasonal variations, energy expenses, and carbon-emission taxes [34].

4. Conclusion

Based on the literature review, it can be indicated that issues related to energy systems—in the context of the implementation or functioning of smart-city assumptions—are extremely complex. Production, distribution, and effective energy management at the building or city level constitute a significant challenge. Additionally, new solutions, technologies, innovations, and systems are systematically created to streamline or improve the functioning of energy systems. This is fundamental from the point of view of reducing greenhouse-gas emissions or implementing the concept of sustainable development. This also shows the importance of scientometric analyses for the analyzed issues.

Recognizing the role of energy systems in urban sustainability is crucial. However, achieving sustainable energy systems in cities requires comprehensive planning, investment in renewable energy sources, and policy support. It's also essential to consider the broader implications of energy transformation on economic and social aspects. In conclusion, the provided literature excerpts offer valuable insights into the evolution and importance of sustainable energy systems for smart cities. While the concept holds promise for addressing various urban challenges, its successful implementation requires careful consideration of technological, social, economic, and environmental factors, as well as ongoing evaluation and adaptation to local contexts.

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