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A systematic review of the smart energy conservation system: From smart homes to sustainable smart cities

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ABSTRACT

In recent years, smart cities have emerged with energy conservation systems for managing energy in cities as well as buildings. Although many studies on energy conservation systems of smart homes have already been conducted, energy management at the city level is still a challenge due to the various building types and complex infrastructure. Therefore, this paper investigated the research themes on smart homes and cities through a quantitative review and identified barriers to the progression of smart homes to sustainable smart cities through a qualitative review. Based on the results of the holistic framework of each domain (smart home and city) and the techno-functional barriers, this study suggests that the following innovative solutions be suitably applied to advanced energy conservation systems in sustainable smart cities: (i) construction of infrastructure for advanced energy conservation systems, and (ii) adoption of a new strategy for energy trading in distributed energy systems. Especially, to reflect consumer behavior and energy in sustainable smart cities, the following responses to future research challenges according to the "bottom-up approach (smart home level to smart city level)" are proposed: (i) development of real-time energy monitoring, diagnostics and controlling technologies; (ii) application of intelligent energy management technologies; and (iii) implementation of integrated energy network technologies at the city level. This paper is expected to play a leading role as a knowledge-based systematic guide for future research on the implementation of energy conservation systems in sustainable smart cities.

1. Introduction

Due to the rapidly progressing urbanization and population growth throughout the 20th century, the urban resident population has soared (55% of the total population worldwide as of 2018) [1]. Since major cities, which occupy only 5% of the earth's land, account for 75% of the world's fossil fuel usage, the rapid urbanization and explosive increases in energy demand in cities are of concern [2]. Moreover, as it is expected that by 2050, the world's urban population will reach 68.4% of the world's total population, measures are required to address not only the increase in the consumption of fossil fuel in cities, but also the excessive load of local power plants due to the imbalance in energy consumption [3]. In particular, buildings and infrastructure account for about 40% of global energy consumption, of which the residential sector takes up about 7%. Thus, the development of new technologies to save energy effectively in single-family or multi-family housing is of much interest [4].

Meanwhile, due to the "global lockdown" (a situation in which people are not allowed to do outside economic and social activities freely) and "contactless" (non-face-to-face services such as teleworking and e-learning) caused by the Coronavirus Disease-19 (COVID-19) pandemic, the role of urban housing is changing [5]. With the emergence of the era of the New Normal wherein flexible workplaces, online learning, remote medical services, and other types of living patterns for social distancing become natural, residential spaces, which used to be the opposite of workspaces, now require an environment in which various social activities such as education, work, and meetings can take place [5–7]. In addition to those, despite the 17% decrease in the daily global CO_2 emissions from fossil fuels this year, the time that city dwellers spend in their living space has increased, and accordingly, the daily global CO_2 emissions from fossil fuels in the residential sector have increased by 2.8% [8]. Therefore, smart technologies and strategies to effectively control energy in the residential sector are becoming more important.

Smart homes are the new trend in the residential sector [9,10]. Lutolf (1992) defined smart homes as "homes where different services are

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integrated through the use of a common communication system". Many scholars and scientists have suggested ways to improve energy efficiency in the residential sector by using Industry 4.0 technologies such as information and communications technology (ICT), Internet of Things (IoT), and artificial intelligence (AI) [11–13]. They have also called the aforementioned housing facilities "smart homes" and "home automation". The potential for new technologies applied to various smart home products could reduce energy demand in residential sector based on convenience and functionality. According to Ford et al. [14], introducing smart home products (e.g., smart appliances and load monitoring) in traditional housing facilities results in energy savings of about 12%–20%.

Many previous papers have developed and proposed the smart home energy management system (HEMS), as well as various energy conservation systems for smart homes [14–23]. Ghaffarian Hoseini et al. [15] aimed to define the nature and characteristics of smart homes by collecting case models of various smart homes types in the U.S. and analyzing their common features. Beaudin and Zareipour [16], Zhou et al. [17], and Celik et al. [18] reviewed the optimal combination of HEMS components, such as renewable energy, energy storage systems (ESS), and smart meters, using various analysis methodologies (e.g., heuristic algorithm, game theory, and fuzzy programing). Finally, Khan et al. [22], Haider et al. [23], and Makhadmeh et al. [24] reviewed studies on demand response power scheduling that would allow for peak load shaving under HEMS by optimizing the energy demand of domestic appliances and, at the same time, by keeping the output of distributed energy systems at a constant level.

Generally, most papers analyzed the technical characteristics of smart homes by focusing on the technologies in smart homes, and proposed the direction for the energy conservation system of the future smart home by exploring current technical developments. Nevertheless, the scope of the future research recommended in the previous review papers was often limited to the technologies applicable to the inside of smart homes and the maturity of such technologies. In addition, there were few connections between smart homes and smart cities in terms of their physical, digital, and theoretical aspects, despite the rapid changes in technology.

As smart homes are expected to play a key role in the development and expansion of smart cities, being the most basic unit of smart cities [25], various papers have recently been conducted that propose technical infrastructure where the energy conservation systems for smart homes can be implemented in smart cities [17,25–28]. Rathore et al. [29] argued that smart cities can be established by converging smart systems (e.g., smart homes and smart parking) and IoT devices (e.g., monitoring sensors, actuators, and smartphones). In addition, they proposed an integrated system that could process a large amount of urban-related big data in order to collect data in real time from many IoT devices. Bhati et al. [30] suggested the application of smart technologies for public services and utilities to smart homes. As such, since the characteristics and technical directions of the energy conservation systems used in smart homes and smart cities differ, their differences first need to be comprehended. Smart homes and smart cities have different concepts of share utility, scheduling, property, and energy-saving benefits, and such conceptual differences can be huge obstacles to the future direction of smart energy conservation systems.

Therefore, this study reviews the level of the current technological development of smart energy conservation systems by conducting quantitative and qualitative reviews (refer to Fig. 1). First, research themes for energy conservation systems in domains of smart home and smart city were defined through systematic quantitative literature review using the strategic diagram. Second, through qualitative reviews of filtered research papers, we explore and present innovative solutions for the barriers that energy conservation systems of smart home must overcome to construct a sustainable smart city. Finally, various future research directions were proposed for the application of such technologies to sustainable smart cities.

2. Review methodology

In this study, systematic quantitative literature review (SQLR),

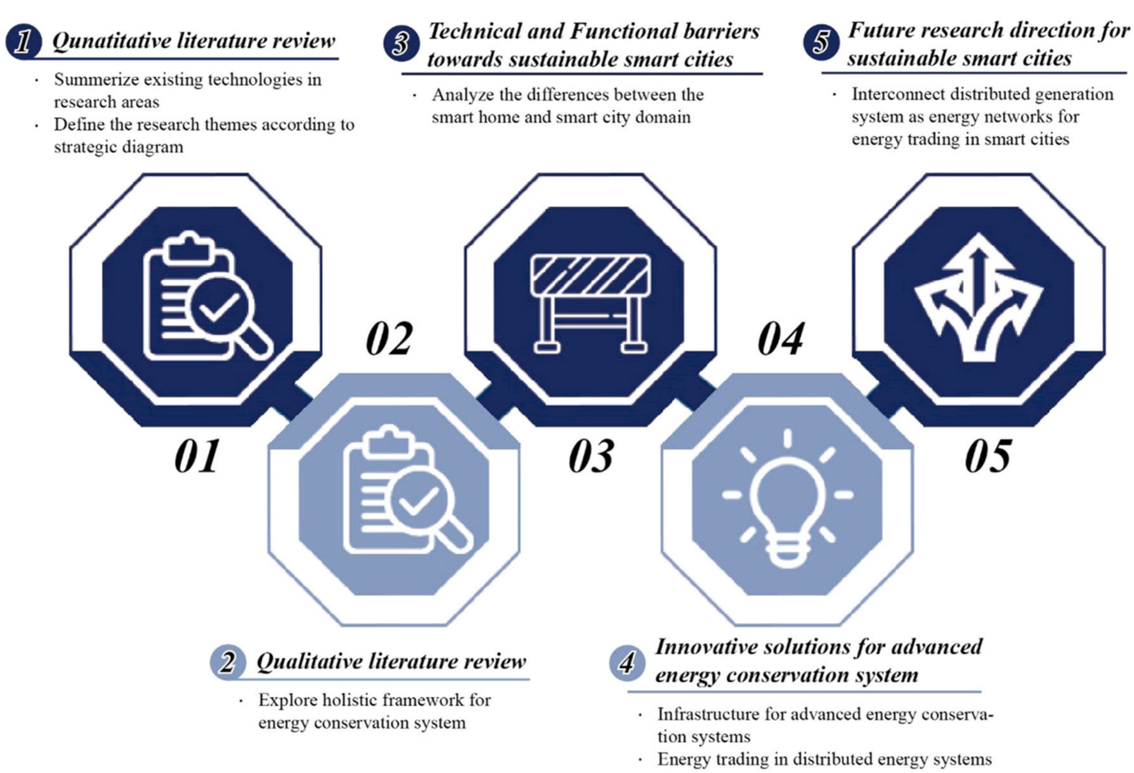

Fig. 1. Research flow diagram.

which summarizes and evaluates existing technologies in certain research areas, was used to define and explore the research area for energy conservation systems that are actively applied to the domains of smart homes and smart cities [31,32]. Previously, there has been several studies using systematic review method or quantitative research method to define the research areas of smart energy conservation system. Marikyan et al. [33] executed systemically review the literatures associated with smart home technology and examined the current state of smart home in user's perspectives following a three-stage approach: planning stage, conducting stage, and reporting stage. Mekuria et al. [34] applied the systemic literature review method targeted at searching a smart home reasoning system by formulating seven research questions.

In general, SQLR systematically and inclusively collects previous research papers by using a research paper search engine, and, at the same time, selects papers based on predefined inclusion/exclusion criteria so as to extract answers to Research Questions (RQs) [35]. Moreover, it is effective in summarizing and understanding the research theme (i.e., the specific question, hypothesis, or problem posed in the research. To conduct SQLR, the following five RQs were set.

- ***RQ1.*** What is the research trend on energy conservation systems in smart homes?
- ***RQ2.*** What is the research trend on energy conservation systems in smart cities?
- ***RQ3.*** What are the technical and functional barriers to the progression of smart homes to smart cities?
- ***RQ4.*** What are the solutions for the advanced energy conservation systems in the future smart city?
- ***RQ5.*** What is the future research direction for sustainable smart cities?

This study conducted SQLR through the following four review stages (refer to Fig. 2): (i) planning stage, (ii) filtering stage, (iii) clustering stage, and (iv) reporting stage.

2.1. Planning stage

The planning stage determined the search options and scope of the previous research papers that were to go through the SQLR process (refer to Table 1). The search was conducted by dividing the papers into the domain of smart homes and that of smart cities. As for the smart home domain, the study used search queries such as *"Smart home" or "Home automation" and "Energy"* to search for scientific research papers. Furthermore, as for the smart city domain, queries such as *"Smart city" and "Energy"* were used. By referring to the period (i.e., 2013) in which new technologies had been established and the research in the concerned area had been systematized, the study limited the search criteria to research papers published between 2013 and 2019 [36]. As a result, the search results based on the aforementioned criteria yielded 17,555

Table 1
Search options in the planning stage.

Search options		Contents
Search algorithm		SCOPUS advanced search engine
Search protocol		Advanced PRISMA protocol
Search in		Title, abstract, author keyword, keyword plus
Search query	Smart home domain	"Smart home" or "Home automation" and "Energy"
	Smart city domain	"Smart city" and "Energy"
Coverage		2013–2019
Document type		Articles, articles in the press, review papers, conference papers
Database source		SCOPUS, IEEE

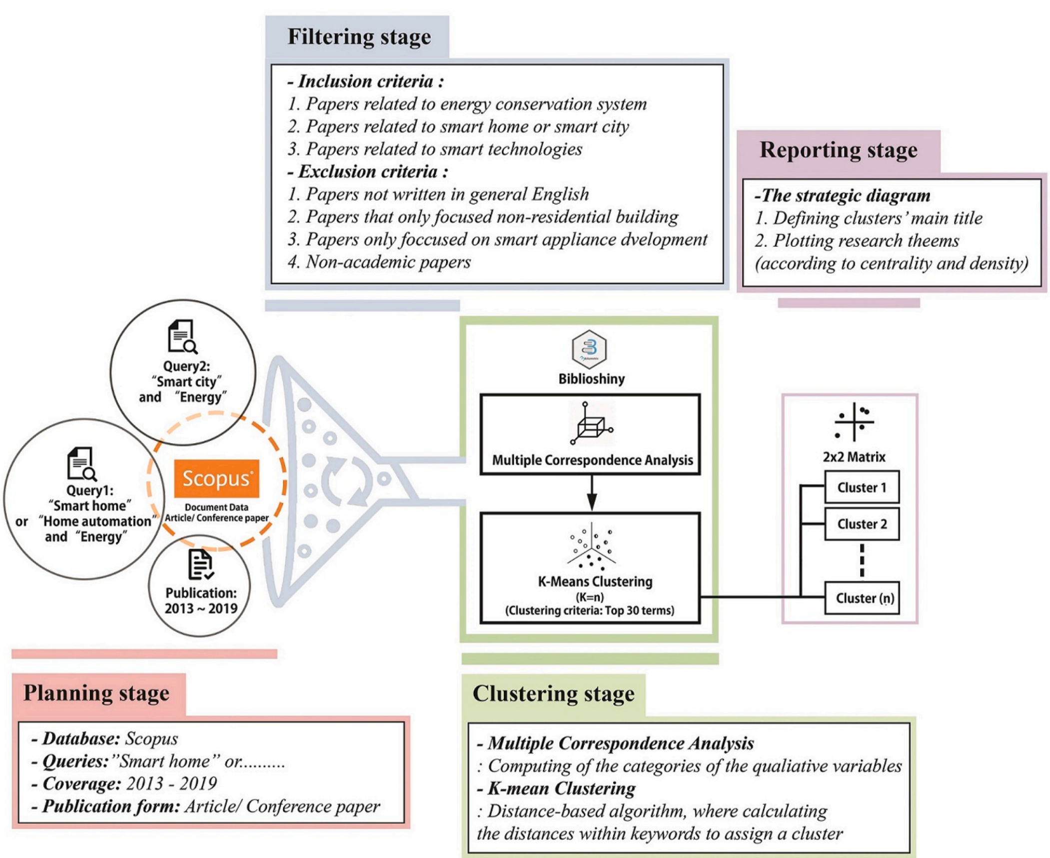

Fig. 2. Four stages of the systematic quantitative literature review.

papers for the smart home domain, and 3539 papers for the smart city domain, from the previous research papers.

2.2. Filtering stage

Based on the suitability of the research papers to the research area, the study made the preliminary selection from the previous research papers in the planning stage by reviewing only the title, keyword, and abstract. The inclusion and exclusion criteria for determining and removing the previous search papers that had a low correlation to the research area are as follows (refer to Table 2). In addition, when it was difficult to select papers according to the inclusion and exclusion criteria because the title/keyword/abstract of the scientific research papers were vague, the selection was made after the full text was skimmed. The study determined a total of 2009 papers in the smart home domain and 769 papers in the smart city domain.

2.3. Clustering stage

In the clustering stage, a co-occurrence analysis was conducted by considering the relation among the keywords of the selected papers, which were selected in the filtering stage. The co-occurrence analysis was conducted and visualized using the *bibliometrix* [35–37]. *Bibliometrix (*Official link*: https://www.bibliometrix.org/)* is an open-source tool programmed in *R package* for carrying out a comprehensive systemic reviews of scientific literature. The following methods were used for the co-occurrence analysis: (i) multiple corresponding analysis and (ii) the k-mean clustering algorithm.

- ***Multiple Corresponding Analysis (MCA)***: MCA is a statistical method that analyzes the co-occurrence of keywords expressed in a nominal scale, and visualizes its results by presenting them on the coordinate plane [38,39]. The closer the distance between the keywords on the coordinate plane is, the higher the frequency of their simultaneous occurrence in research papers is. The origin on the coordinate plane shows the mean average location of all the keywords and the central point of the research area (meaning the common and shared topics).
- ***k-mean clustering algorithm***: k-mean clustering allows for categorization of many keywords into several groups to increase the overall understanding of the target research area and to present various research themes [40,41]. k-mean clustering is an unsupervised learning method by which keywords are bound together into k number of groups with k number of central points.

Table 2
Inclusion and exclusion criteria in the filtering stage.

Inclusion criteria	Exclusion criteria
Papers whose title/abstract/keywords state that they deal with 'smart living environments in smart homes and smart cities'	Papers that are not published in the original English language
Papers whose title/abstract/keywords state that they deal with 'energy issues in smart living environments'	Paper duplicated (only the most complete version is included.)
Papers whose title/abstract/keywords state that they deal with 'smart technologies applied to smart living environments'	Papers that focused only on smart appliance developments, smart robots, smartphones, smart water systems, smart lighting systems, etc.
Papers that focused on smart energy conservation systems, energy load management, distributed energy generation, ESS, wireless telecommunication, etc.	Papers that focused only on non-residential buildings

2.4. Reporting stage

In this stage, the strategic diagrams were used to determine which position (i.e., research theme) each cluster assumed in the research area [42,43]. The strategic diagrams can also be expressed in a 2 × 2 matrix design, consisting of four research themes (refer to Fig. 2). The *x*-axis indicates the level of *centrality*, and the *y*-axis shows the level of *density*. *Centrality* indicates the strength of the interaction between two clusters. Therefore, it can be used as a scale of the importance of the concerned cluster in the whole research area [44]. Since *density* indicates the coherence and internal strength of a cluster, it can be used as a scale of how a cluster has developed into unique research themes [44].

As shown in Fig. 3, the values of the *centrality* and *density* of each cluster determine the relative location of that cluster in the quadrant, which reflects the intellectual progress within the research theme. The strategic diagram in this study consists of the following four research themes.

- ***Core themes (Quadrant I)***: Quadrant I has higher *centrality* and *density*. It is defined as the *core* themes that play the "mainstream" role in the research area. Clusters included in the *core themes* have already been well developed and have reached research maturity. Furthermore, these clusters tend to have closer relations to other clusters.
- ***General and broad themes (Quadrant II)***: Quadrant II shows higher *centrality* but lower *density*. It is defined as the *general and broad themes* that play the role of a "bandwagon" (an idea that has become very popular) in the research area. The clusters in these themes are at the central location for forming the research area, but the research maturity is not yet very high.
- ***Emerging themes (Quadrant III)***: Quadrant III shows lower *centrality* and *density*. It is defined as the *emerging themes* that play the role of "chaos/unstructured topics". Research on these themes is not active, and the research maturity is not yet high.
- ***Developed but isolated themes (Quadrant IV)***: Quadrant IV shows lower *centrality* and higher *density*. It is defined as *developed but isolated themes* that play the role of an "Ivory tower" (an idea of separation from the mainstream and practicalities of the research area) in the research area. The keywords included in these themes are more specialized and localized than those in the other themes, and have low accessibility to general researchers.

3. Current technical phase of smart energy conservation systems

This section presents research themes determined through a quantitative review of energy conservation systems in the smart home domain and the smart city domain. The results from the strategic diagram and the top 30 keywords based on occurrence were used.

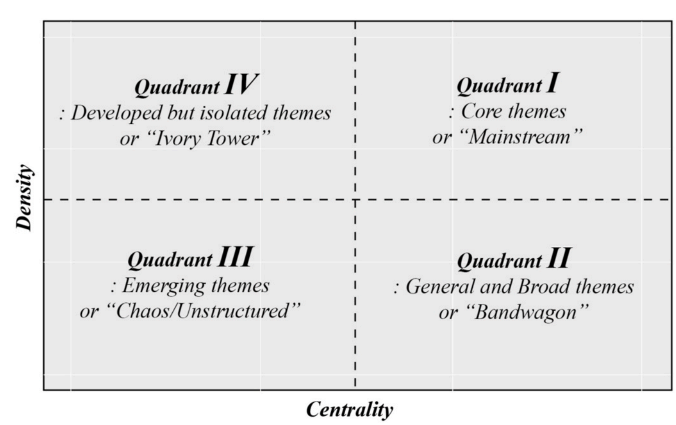

Fig. 3. Strategic diagram.

3.1. Smart home domain

3.1.1. Research themes according to the strategic diagram

Fig. 3 shows the main research themes on energy conservation systems in smart homes. The keywords for the energy conservation systems in smart homes belong to the following four clusters: (i) Cluster 1: energy utilization; (ii) Cluster 2: energy management system; (iii) Cluster 3: air conditioning; and (iv) Cluster 4: forecasting (refer to Table S1 and Fig. 4).

First, the following are the keywords in Cluster 1, which are the *core themes* of the strategic diagram: *energy utilization* (595), *domestic appliances* (392), *Internet of Things* (373), *energy efficiency* (361), *energy conservation* (232), *controller* (166), *electric power utilization* (150), *monitoring* (138), *wireless sensor network* (131), *smart meters* (114), and *information management* (113). Cluster 1 is assumed that active research on smart energy conservation systems has already been conducted for a long time. In other words, the keywords in Cluster 1 perform the main role of defining the technical elements and technologies essential to the smart home architecture. Cluster 1 has played the backbone role in the research area, along with ICT. As such, the research themes in Cluster 1 have shown to offer research foundations based on which various energy conservation systems for smart homes can be stably introduced to the area.

Second, the following keywords in Cluster 2 refer to the *general and broad themes* in the strategic diagram: *energy management system* (1705), *smart grid* (949), *demand response* (574), *costs* (476), *electric power transmission networks* (444), *scheduling* (440), *energy storage system* (405), *renewable energy resources* (357), *optimization* (299), *housing* (285), *electric utilities* (205), *photovoltaic cells* (196), *integer programing* (108), and *energy resources* (102). The keywords in this cluster can be bandwagon that lead the research trends. However, despite their central role in forming the research area, these research themes still have low research maturity. That is, there is great potential for these themes to develop as *core themes* in the research area through active and continuous research and technical development. As such, the research themes in Cluster 2 concern the smart power scheduling for demand response on the smart grid that allows for the peak load shifting strategy and energy efficiency of smart homes.

Third, the following keywords in Cluster 3 refer to the *emerging themes* in the strategic diagram: *air conditioning* (120), *heating* (125), and *electric load management* (111). The keywords in this cluster have not yet been established as research topics, and have low research maturity. The keywords in Cluster 3 are considered to be related to heating, ventilation and air conditioning (HVAC) systems installed in normal houses. The heating or cooling energy consumption of HVAC systems differs according to the consumer's personal thermal comfort and occupancy time. The ultimate aim of researches on the HVAC system is to improve the thermal satisfaction of the consumer and, at the same time, to optimize the operation schedule so as to reduce energy consumption, peak load demand, and the electricity bill [45]. As opposed to the other research themes Cluster 3 considers the consumer's health and well-being.

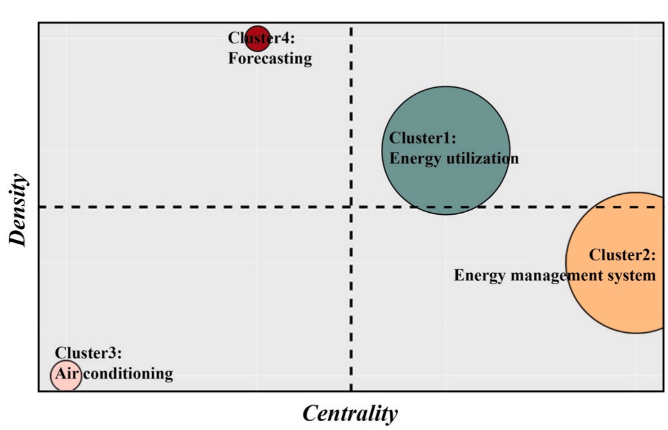

Fig. 4. Main research themes on energy conservation systems in smart homes.

Finally, the following keywords in Cluster 4 refer to the *developed but isolated themes* in the strategic diagram: *forecasting* (321) and *algorithm* (368). The keywords in this cluster play the role of an "Ivory tower" that is far removed from the mainstream research area. That is, these themes are considered very specialized and localized. In particular, the journals on *algorithm* and *forecasting* are in such subject areas as computer science or mathematics, and require a very high level of specialized knowledge for general researchers.

3.1.2. Holistic framework of energy conservation systems in smart homes

Qualitative reviews of energy conservation systems in smart homes have revealed that renewable energy systems should be used as an active strategy for the optimal operation of microgrids and nearly-zero energy buildings (nZEB). Furthermore, ESS should be installed to stably supply power by using a distributed energy system with high uncertainty, depending on the external environment [46]. Due to the appearance of ESS with distributed energy systems and the depreciation of the prices of IoT devices, the concepts of "smartness" and "automation" were added to conventional energy conservation systems, and turned them into smart energy conservation systems. Meanwhile, several studies have argued that smart energy conservation systems should be integrated and controlled by determining the correlation among sub-sectors in smart homes, and should be operated efficiently with minimal costs [47]. Zipperer et al. [48] defined a smart energy conservation system as a connector that allows for smooth power transmission between the central electricity power grid and domestic appliances, and plays the role of a switchboard for data flow in the power system.

Based on the results of qualitative reviews, Fig. 5 shows the conceptual diagram for the following five technical and functional variables of smart energy conservation systems in smart homes: (i) microgrid; (ii) HEMS; (iii) demand response; (iv) consumer behavior; and (v) forecasting.

- ***Microgrid***: A microgrid is a next-generation electricity transmission network that maximizes energy efficiency by exchanging real-time energy information between an electricity supplier and an electricity consumer [49]. In addition, it is considered a sub-concept of a smart grid, and as referring to a relatively smaller-scale power generation system, signifying a local and self-reliant power system centered on a distributed energy system with ESS [50]. Furthermore, a microgrid plays a key role between stakeholders (i.e., suppliers and consumers). For suppliers, microgrids reduce power fluctuation and offer ancillary consumer services (such as voltage and frequency regulation). For consumers, microgrids can maximize the advantages of the distributed energy system installed in a home and secure essential infrastructure with which to trade surplus electricity [50–52].
- ***HEMS***: HEMS is a networked and automated control system for various domestic appliances, which are the main energy consumption sources of homes, with IoT technology [53]. The recent development of IoT technology, changes in the mobile application market, and the technical development of smart appliances and smart meters have further promoted the distribution of HEMS, which consist of a wireless network, smart appliances, smart sensors, and smart meters [53–56]. Furthermore, by monitoring the usage patterns of domestic appliances, reducing the uncertainty in the electricity generation of distributed energy systems and the energy storage capacity of ESS, and increasing energy efficiency by monitoring and controlling energy information under the rapidly changing residential housing environment, HEMS can be considered an essential technical element of smart homes [16,57]. The actual elements of HEMS consist of smart appliances and smart meters. First, smart appliances

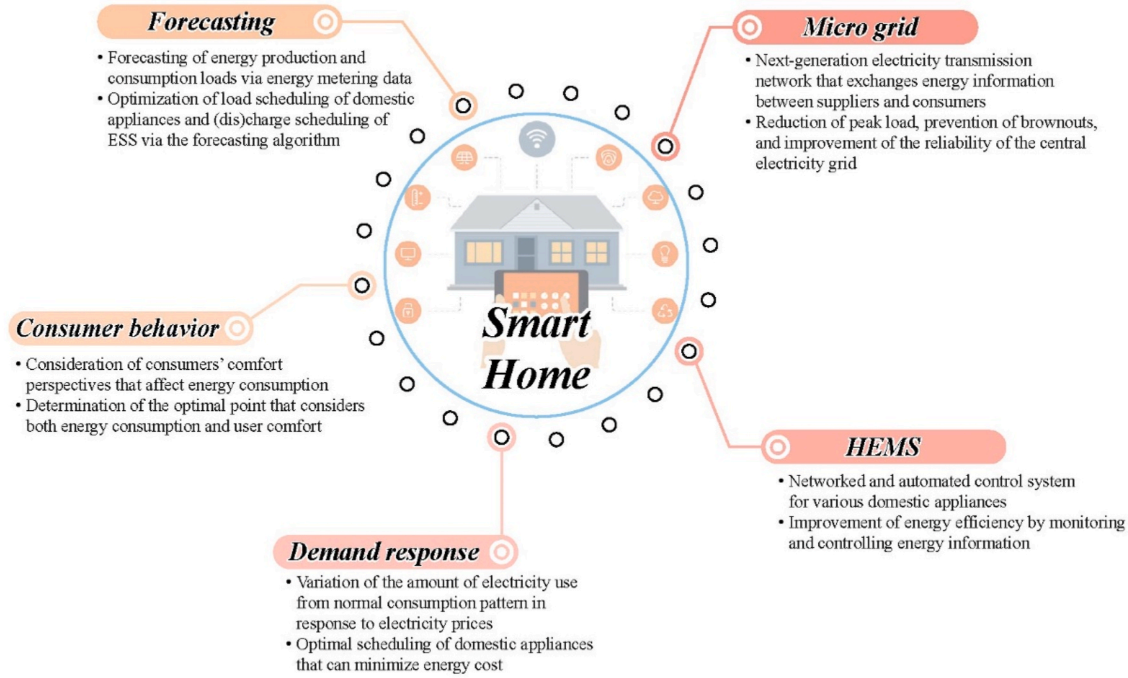

Fig. 5. Conceptual diagram of an energy conservation system in smart homes.

are essential in improving the energy efficiency of smart homes [58]. Yildiz et al. [20] categorized smart appliances by load pattern (i.e., uncontrollable appliances: lighting; uninterruptible appliances: clothes washer, dryer, etc.; controllable appliances: elevator; and regulating appliances: HVAC, water heaters, etc.), and argued that the time of use should be optimally controlled based on the electricity load profile of smart appliances. Second, smart metering is essential in real-time energy load-monitoring of smart homes. It monitors the energy load, energy generation, and various IEQ factors of smart homes, and detects and offers feedback on the changes in energy consumption. Fugate et al. [59] categorized monitoring targets into building performance parameters (e.g., energy and occupants' comfort perception and IEQ. Furthermore, load monitoring allows for real-time detection of the energy consumption and demand of smart appliances [20,58,59].

- ***Demand response***: In recent years, distributed energy systems have been installed in many households. It became necessary to establish plans to efficiently control these systems. If consumers will consider a demand response management program, they would reduce the peak load, avoid time zones with a higher energy cost, and plan for optimal scheduling for each domestic appliance to minimize the total energy cost. Chen et al. [60] defined demand response as "the variation of the amount of energy usage from the normal consumption pattern in response to electricity prices", and identified the main objective of demand response as the improvement of the power system flexibility and peak load shedding by moving on-peak loads to an off-peak hour. The demand response program was divided into the following two categories: (i) incentive-based demand response and (ii) price-based demand response [60–72]. First, under the incentive-based demand response program, the goal of consumers is to reduce the energy load during the promised period to prevent disadvantages. If consumers succeed in energy load reduction, they will receive incentives such as discount rates or rebates according to their participation in the demand response program [67]. Second, under the price-based demand response program, consumers control the energy load by responding to dynamic rates of electricity such as the real-time price or the time of use.
- ***Consumer behavior***: In the past, an energy conservation system was introduced to promote energy efficiency of domestic appliances. Recently, however, there has been an increase in researches not only on energy-saving perspectives, but on consumers' comfort perspectives (e.g., thermal comfort, visual comfort, and air quality comfort). Household energy savings and consumer comfort have a trade-off relationship [73–75]. Thus, it is difficult to satisfy both. There has been active research on energy conservation systems that consider the energy efficiency of smart homes and consumer comfort at the same time [47,76–92].
- ***Forecasting***: To predict the various elements of energy conservation systems, variables such as weather conditions, energy output, and expected load should be collected, and a corresponding database should be established. Using the forecasting algorithm based on the established database, the load scheduling of domestic appliances and the (dis)charge scheduling of ESS can be optimized. In this way, the balancing of energy demand and supply for smart homes can be maintained, and the optimal intersection of energy savings and consumer comfort can be found, which would play a key role in the demand response program. Forecasting for smart homes in various perspectives could now become much easier with the technical development of smart metering and the increase in its usage.

As discussed above, each factor helps achieve one goal: the smooth operation of the smart energy conservation system to attain energy efficiency via mutually organic links and complex structures. The energy system is distributed with ESS in microgrid functions to supply stable electricity so that smart appliances can be operated. Furthermore, HEMS measures the amount of energy generation, the energy storage status of ESS, the energy load, and consumer behavior via smart metering, and transmits the data to the central controller. At the same time, demand response considers real-time electricity rates or incentives, and conducts optimal load scheduling to minimize electricity consumption. Through forecasting based on the currently measured data, the management and scheduling of smart energy conservation systems can be flexibly controlled.

3.2. Smart city domain

3.2.1. Research themes according to the strategic diagram

Fig. 6 shows the main research themes on energy conservation systems in smart cities. The systematic review showed that the keywords for energy conservation systems in smart cities belong to the following five clusters: (i) Cluster 1: smart grid; (ii) Cluster 2: energy conservation; (iii) Cluster 3: energy efficiency; (iv) Cluster 4: commerce; and (v) Cluster 5: artificial intelligence (refer to Table S2 and Fig. 5).

First, the following are the keywords in Cluster 1, which are the core themes in the strategic diagram: *smart grids* (304), *electric power transmission networks* (175), *renewable energy resources* (144), *energy management* (133), *optimization* (49), *energy resources* (45), *energy utilities* (44), *digital storage* (42), *costs* (37), *demand response* (35), and *energy storage* (30). This cluster is essential for energy conservation systems of smart cities and can be understood as the research area that has already been actively studied. The combination of these keywords generally means energy infrastructure and communication in smart cities.

Second, the following keywords in Cluster 2 are the core themes in the strategic diagram: *energy conservation* (66), *sustainable development* (57), and *decision-making* (43). Cluster 2 may not be considered a technical area of smart conservation systems, but the combination of their keywords means governance of smart cities. As such, while having the same research themes as Cluster 1, Cluster 2 has different research characteristics.

Third, the following keywords in Cluster 3 refer to the *general and broad themes* in the strategic diagram: *energy efficiency* (209), *Internet of Things* (264), *energy utilization* (187), *automation* (74), *security* (52), *big data* (50), *green computing* (50), *wireless sensor networks* (48), *information management* (46), *sensor nodes* (41), and *cloud computing* (30). The combination of these keywords explains technologies that perform comprehensive processing of big data collected with IoT in all subsectors of smart cities. In other words, it explains technologies that complement problems, which result from the increase in the applicability of energy conservation systems in the smart city domain.

Fourth, the following keywords in Cluster 4 refer to are the emerging themes in the strategic diagram: *commerce* (73), *blockchain* (37), and *scheduling* (3). The combination of these keywords signifies the economic activities of consumers with surplus electricity generated by the expanded distribution. Since Cluster 4 is an emerging research area in the smart city domain, further research on it is expected to be actively conducted in the future.

Finally, the following keywords in Cluster 5 refer to the emerging themes in the strategic diagram: *artificial intelligence* (30) and *forecasting* (30). The combination of these keywords means that big data are processed by artificial intelligence (AI) and presented by a forecasting model.

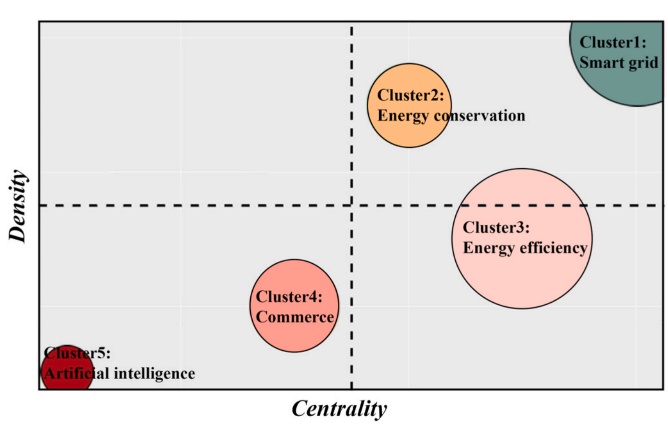

Fig. 6. Main research themes on energy conservation systems in smart cities.

3.2.2. Holistic framework of energy conservation systems in smart cities

The rational and comprehensive application of novel technologies such as ICT or AI have played the role of a springboard for the development of smart cities' energy conservation systems [93,94]. Innovative technologies, networks, policies, and infrastructure established new concepts of energy usage among urban dwellers and promoted their participation in energy conservation [95]. Technologies that can collect and process big data allow for better understanding of urban dwellers' behavior, reduce decision-making risks and uncertainty, and improve the interconnectivity of various city components [96,97]. Fig. 7 shows the conceptual diagram of the following five technical and functional variables of smart energy conservation systems in smart cities: (i) smart grids, (ii) commerce, (iii) big data analysis, (iv) cloud computing, and (v) decision-making.

- ***Smart grids***: In the past, electric power transmission networks generally supplied electricity or thermal energy produced from large-sized local power plants to each household via electric cables or pipes. This had a top-to-bottom unidirectional approach and a centralized characteristic. However, with the development of various renewable energy resources (i.e., solar PV) and the improvement of ESS capacity and performance, power plants have been replaced with collective distributed energy systems in the residential sector. Moreover, with the advancement of ICT, decentralized bidirectional grids have emerged [98]. Since smart grids promote the integration and electrification of distributed energy systems that independently generate electricity within smart cities, they are essential elements of a sustainable energy future [99–102]. Smart grids have not only presented a new paradigm for electricity systems, but have also promoted interaction among all stakeholders and provided new social networks, such as for social welfare and economic values. Smart grids exceed simple electricity transmission and offer economic values and business opportunities [101,102].
- ***Commerce***: As smart grids develop, the increase in energy flexibility via distributed energy systems has made it easy to balance energy supply and demand [103]. Consumers can make economic benefits by trading surplus energy. Thus, the concept of commerce (markets) that can satisfy consumers' desire for economic benefits has emerged throughout smart cities [104]. The energy market controls the amount of transactions that can satisfy each consumer's needs by determining different amounts of consumer supply and demand. In addition, consumers can trade by responding to energy prices in real time, thanks to the development of ICT. The concept of commerce is new and has not yet been considered in the smart home domain, so research is required to establish suitable infrastructure.
- ***Big data***: With the increasing role of ICT in smart cities and the rise in the measurement scope of smart metering, more and more studies are focusing on the big data process and analysis methods. That is, there is a growing number of studies on data analysis methodologies such as AI, machine learning, deep learning, and Q-learning. In recent years, big data analysis has played an important role not just in acquiring information on historic trends but also in formulating a future energy plan for smart cities via forecasting. For instance, the energy response patterns of district heating systems differ by building, so thermal load forecasting that considers such differences is required [105].
- ***Cloud computing***: Smart cities require a large-scale data center that can accommodate and process energy-related big data. However, the increase in the number of physical machines in data centers causes disadvantages in terms of initial installation costs, operating costs, cooling costs, etc. [104–107]. To solve these problems, cloud computing has been proposed. Cloud computing allows for on-demand availability of virtual machines. That is, data processing is performed not by customers' physical computers but by virtual machines linked to a large-scale cloud. Thus, the introduction of cloud computing can reduce costs such as of individual purchases

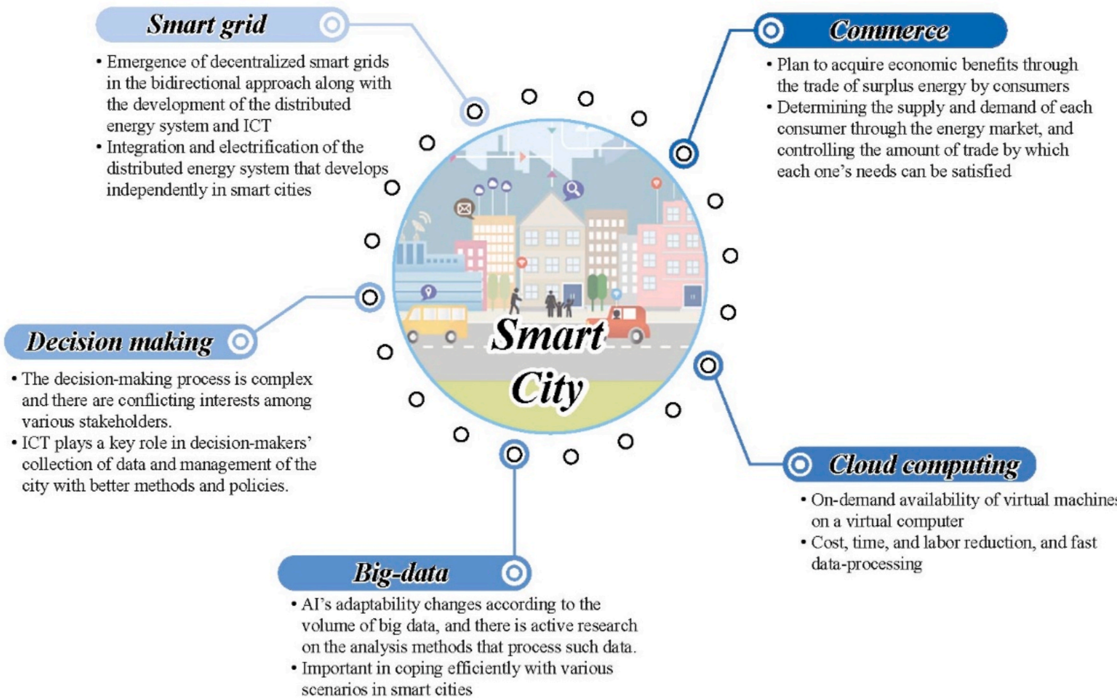

Fig. 7. Conceptual diagram of energy conservation systems in smart cities.

and installation or update costs, as well as time and labor costs. While the existing data storage system is limited in terms of its slow data processing capacity and finite data storage, cloud computing offers fast data-processing capacity and handles big data more smoothly.

- ***Decision-making***: In smart cities, good governance means not only adopting new energy conservation technologies, but also improving transparency in data-sharing and decision-making. ICT helps decision-makers collect data and manage a city with better policies and methods [108]. However, decision-making is complex in principle, and interconnected with various conflicting interests of stakeholders [109]. Such characteristics cause complexity and uncertainty in the decision-making process [110].

Each factor helps smoothen the operations to achieve only one objective, via mutually organic connections and complex structures. Similar to smart homes, in smart cities, electric energy is produced and stored via a distributed energy system with ESS installed in homes. However, unlike smart homes that pursue only energy sufficiency, smart cities have a concept of energy trading that exchanges surplus electricity. All data transmitted from each household via smart metering are stored via cloud computing. Decision-makers in smart cities use such big data to determine future energy policies.

4. Technical and functional barriers of smart homes towards sustainable smart cities

In this section, the differences between the smart home domain and the smart city domain are analyzed via a qualitative review of energy conservation systems. Both smart homes and smart cities are rapidly emerging IoT applications, but some of their features differ (refer to Table 3).

First, in smart homes, the end-users that benefit from technology are usually the homeowners, whereas in smart cities, they are citizens in a community. Second, smart homes consist of separated small devices, whereas smart cities have relatively large-scale connected devices. Third, in terms of the direction of technical development, smart homes

Table 3
Differences between smart homes and smart cities from various perspectives.

Classification	Smart home domain	Smart city domain
End-users	Homeowners (individual)	Citizens
IoT devices	50 or more	10 million or more
Connectivity	Separated	Integrated
Scale	Small	Large
Feature	Functionality	Compatibility
Property	Private property	Public property
Energy-saving benefit	Direct	Indirect
Data storage	On-premise	Cloud computing

pursue functionality, whereas smart cities pursue compatibility. Fourth, smart homes return profits generated by saving and producing energy to homeowners, whereas smart cities return the profits to public communities, and some of those profits are indirectly returned to members of society. Finally, smart homes often use a traditional on-premise method wherein data collected via smart metering are stored in a server owned by individuals, whereas smart cities store data via centralized cloud computing.

4.1. Interoperability

Smart cities aim for compatibility of all IoT devices, and should establish an integrated ICT infrastructure that allows for remote monitoring and data-based decision-making. However, to realize interoperability with smart devices, applications, and platforms made under different manufacturing environments, much time and cost should be invested [111]. Thus, it is essential to acquire interoperability (i.e., scalability) via compatible technologies that can support various types of smart devices.

Interoperability refers to the properties that allow for compatibility and interconnectivity of different hardware and software [112]. In fact, several previous studies related to energy conservation systems in smart homes mentioned technical limitations and stresses related to the need for interoperability. At the same time, they have proposed various solutions such as communication standards integration, open source, and fog computing, among others. Zipperer et al. [48] argued that the electric energy management technology used in smart homes could not be widely distributed because of the lack of related policies and standards on interoperability, and proposed the standardization and development of technologies in each area to solve these issues. Kahrobaee et al. [113] and Ahmad et al. [114] pointed out that most energy metering and environmental monitoring technologies lack interoperability, causing the vender lock-in phenomenon. Ahlgren et al. [115] argued that IoT communication technology would play a key role in establishing smart cities, and that interoperability of devices would be very important as the scope of applications of technologies expands.

4.2. Flexibility

According to the International Energy Agency [116], the flexibility of a power system refers to “the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise”. In other words, flexibility means that the additional energy cost generated by the variability in energy demand can be reduced, and stable electric energy can be supplied. Along with the advancement of smart grids, various types of distributed energy systems have been introduced to residential houses at a large scale, which have caused many problems. With the various types of renewable energy resources for the recently introduced distributed energy systems and the growing variety of weather conditions and building use types at installation locations, it is evident that the existing ESS cannot supply stable electricity output. Therefore, research is required to analyze the optimal sizing, location, and operation strategies of ESS to avoid standardized manufacturing methods and to attain flexibility with respect to all variables [117–120]. Smart cities consist of various sectors (e.g., the transportation sector, industrial sector, and residential sector) [120]. With the advancement of smart grids, each sector can enhance its power system flexibility via electrification. The stability in all sectors of smart cities may differ according to the flexibility of the sectors. The potential for flexibility has not yet been fully realized. Thus, efforts to improve flexibility shall result not only in the stability of smart cities, but also in the public interest of communities, including consumers.

4.3. Decentralization

Centralization is a system whereby one group (e.g., a country or a large company) becomes a central point and exerts authoritative and vertical power over the rest of the components. Here, the other components play the role of consumers or end-users. On the other hand, decentralization is a system whereby component groups in small units are dispersed or distributed and come into operation locally. Here, each component contributes to the same objectives at the same level and takes the same level of responsibility.

In existing smart energy conservation systems, the limitations of centralization are as follows. For instance, cloud computing that collects data with the existing centralized method is vulnerable to more risks than decentralized cloud computing under hacking attacks. In addition, due to the considerable amount of data, data transmission and reception are often delayed, and a very small number of global companies can monopolize data [121]. The centralized electricity market is limited when consumers select an electricity trading company due to the unidirectional electricity transmission, and consumers can only receive limited information on electricity prices. Also, consumers may not cope well with unexpected service interruptions of electricity trading companies, network failures, and other variables due to natural disasters. Furthermore, as the size of the electricity market increases, it becomes more difficult to perform integrated management of energy and select optimal trading methods [122].

A smart city is similar to a conventional city with respect to the implementation of new technologies such as ICT, but differs from a conventional city in city management and the roles of citizens. In a conventional city, the government usually manages the city using a top-down approach, and the citizens are passive and perform only the role of data users or consumers. Conversely, in smart cities, city management is performed using a bottom-up decentralized approach, and citizens play a leading role in supplying and consuming data [123–125]. To transform a conventional city with strong centralization characteristics into a smart city, the concept of decentralization should be strengthened in various aspects that include data computing and energy markets.

5. Innovative solutions for advanced energy conservation systems in future smart cities

To overcome the technical and functional barriers to the progression of smart home technologies to sustainable smart cities, this study proposes innovative solutions for advanced energy conservation systems in future smart cities under the following two categories (refer to Fig. 8): (i) infrastructure for advanced energy conservation systems, and (ii) energy trading in distributed energy systems.

5.1. Construction of infrastructure for advanced energy conservation systems

5.1.1. Integrated platform for energy management in smart cities

The ultimate aim of the IoT energy management platform is to interconnect all current technologies and systems into one network, and to establish an integrated platform [125]. To efficiently implement smart home technologies in smart cities, an integrated smart platform that allows for the interoperability of platforms should be developed. Since existing platforms do not allow for interoperability unless they were produced under the same manufacturing environment and their maintenance and repair are difficult, research is required to consider interoperability and scalability. Towards this end, this study proposed solutions in four aspects.

- ***Standardization***: In smart cities, standardization is essential for the interoperability and scalability of platforms that consist of many hardware devices and software programs. Accordingly, since 2013, the International Organization for Standardization [126], International Electrotechnical Commission (IEC) [127], International Telecommunications Union (ITU) [128], and Institute of Electrical and Electronics Engineers (IEEE) [129] have been developing an international standardization guide for the technologies related to smart cities. Among them, the international standardization institutions such as ITU, IEC, and IEEE are establishing standards related to energy management platforms in each area. ITU-R, which is in charge of the radiocommunications sector, focuses on wireless and mobile communication related to 5G [130]. ITU-T, which is in charge of the telecommunications standardization sector, focuses on big data, IoT, AI, and security [131]. IEC is in charge of standardization in the areas of smart grids, smart homes, intelligent buildings, transportation, and aviation. IEEE is in charge of standardization in the electronic and telecommunications sectors such as in computer engineering, wireless local area networks, and wireless personal area networks [132].
- ***Microservice architecture***: The monolithic architecture, which has long been used, contains all logics in one software [133]. It offers easy development in local environments; and since all logics are in one package, it is easy to distribute. However, as the software needs to be continuously updated, adding one new function requires comprehensive inspection, which necessitates much time and effort. On the contrary, in microservice architecture, one big software is divided into several small software programs (microservices), each of which performs an independent role, and swift and stable updates of large-scale and complex applications is possible. Therefore, developers can freely work together to develop software programs via

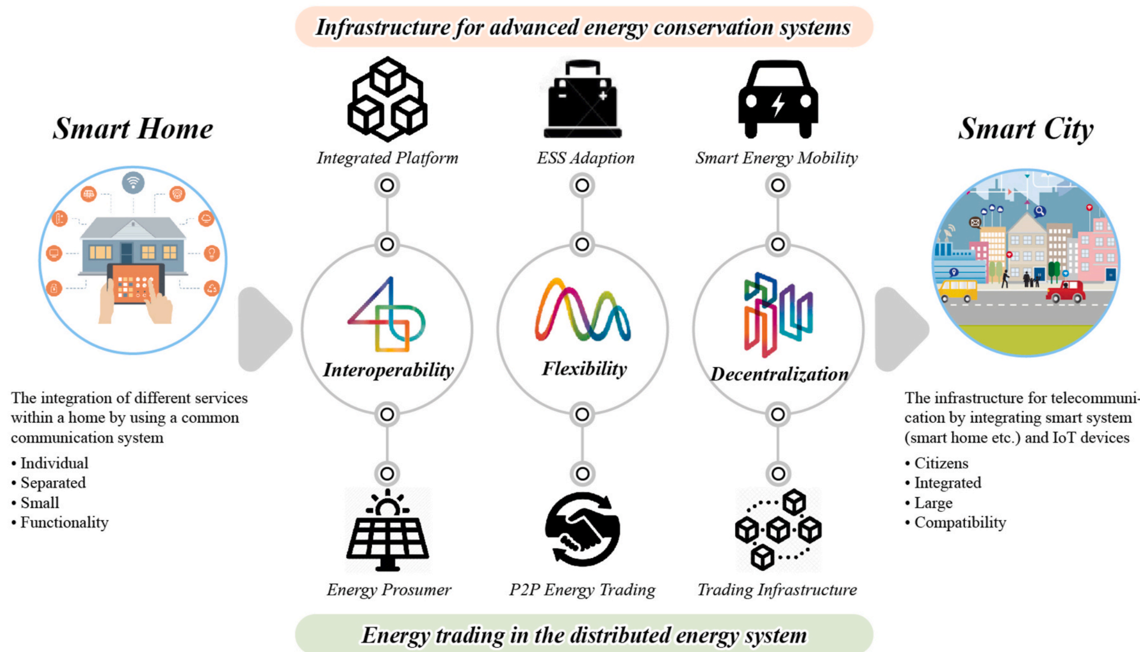

Fig. 8. Innovative solutions for advanced energy conservation systems in future smart cities.

the same cloud, allowing for time and cost savings in the development and maintenance of a platform [134].

- ***Fog computing***: Most smart cities are currently based on cloud computing, which can offer scalability in service and energy-related data. However, centralized process-type cloud computing has delays in data transmission and reception, besides which a small number of global service providers has been known to monopolize data. To solve these issues, a cloud service concept called fog computing has emerged. Fog computing or edge computing [121,135] refers to localized cloud computing in an intuitive sense of being closer to the ground than to a cloud. Fog computing is a technology that processes data in advance as the existing nodes in cloud computing, which manage data transmission and reception, and acquire their own advanced computing capabilities thanks to the advancement of the integrated circuit performance of semiconductors. In this way, excessive traffic in cloud computing could be distributed [121].
- ***Open source***: The innovation of AI, big data, and IoT technologies required for the efficient operation of the energy management platform in smart cities is performed based on open-source software. The biggest advantage of open-source software is that the consumer no longer stays in the role of a buyer but can become an engineer at the same time, who develops the platform directly [136–138].

5.1.2. *Adoption of ESS for smart energy sharing systems*

Unlike conventional fossil-based energy generation, distributed energy systems, which show variations in electricity generation depending on the weather and time, can increase grid instabilities. Therefore, ESS, which can store surplus electric power in batteries and use it when needed, is essential [139,140]. However, ESS is expensive and requires a separate installation space, making it difficult to secure economic feasibility with it in smart homes. Therefore, it is expected that the effective operation of ESS could be achieved by integrating renewable resources and sharing energy within smart cities, and by establishing demand-response schemes [141,142].

- ***Optimal sizing***: ESS can be used as a smart energy-sharing system at the community level by connecting it to small-scale distributed energy systems [143–147]. Towards this end, ESS should offer sufficient capacity to accommodate the amount of electricity generated by the distributed energy system. Therefore, the determination of the optimal size of ESS has become an important issue in the supply of a sufficient amount of electricity energy during the peak load time at the community level [142,148]. However, ESS is still expensive and requires a large installation space [143]. A model for determining the optimal sizing of ESS should be developed that considers the energy generation and energy demand of the grid according to the regional differences and building types.
- ***Operation scheduling strategy***: With the increase in the demand for ESS, there have been various issues in the process of installing, operating, and managing the ESS. It is important to establish an operation scheduling strategy with which to dynamically control the amount of electricity (dis)charge based on the specific energy load pattern resulting from the database on the actual electricity use in smart cities [149,150]. Therefore, in the smart grid, an algorithm or automated system should be developed, which can establish an operation scheduling strategy by considering the energy consumption that changes according to the ESS installation objectives (i.e., economic and environmental benefits) and building use type (i.e., residential buildings, office buildings, educational facilities, etc.). ESS owners can collect the ESS installation cost fast while maintaining the self-consumption of electricity at a certain level, thereby improving the self-sufficiency rate of the distributed energy system with ESS.
- ***Electric power system stabilization***: In buildings and communities where ESS is installed, it is very important to supply electricity by relying on the balance of electricity generation and demand [146]. One of the main functions of ESS is ancillary service, which can solve power quality problems that occurs when electricity generation and demand are imbalanced [147]. The 60Hz frequency of the AC shows an irregular response over time. The ESS continuously performs charging and discharging within a very fast time (about 200 ms) to stabilize the irregular frequency to 60Hz. This function of the ESS that raises and lowers the required frequency is called the primary and secondary power frequency regulation [151]. Since the electricity power generated from distributed energy systems is direct current, the necessity of smart transformer linked to medium voltage grids is increasing [149]. Smart transformers enable bi-directional electricity power transformation between AC and DC, and reduce

efficiency degradation, helping to improve electricity power quality [150].

- ***Power-to-X***: Power-to-X (P2X) is a long-term and large-sized electricity storage method that allows for converting surplus electricity into another type of energy so that it can be used in other areas [152, 153]. Here, according to X, a different type of energy converted from electric power can be applied to ammonia (P2A), chemicals (P2C), fuel (P2F), gas (P2G), liquids (P2L), or hydrogen (P2H), among others. The P2X system can reduce GHG emissions more significantly than the conventional energy storage method, thanks to the combination with low-carbon electricity production and carbon capture technologies [154]. Furthermore, because the current P2X system has significant installation and management costs is difficult to apply to smart homes [155], it has a much bigger potential in smart cities with a larger generation unit [156–158].

5.1.3. Smart energy mobility for efficient energy consumption

Generally, Energy mobility (i.e., e-mobility) refers to an environmentally friendly transportation that utilizes sustainable energy sources (e.g., electricity, green hydrogen, fuel cell) by replacing the traditional transportation equipped with internal combustion engines (e.g., diesel, gasoline) that consume fossil fuels [159]. Representatively, Electric Vehicle (EV) and green hydrogen vehicles are competing as candidates for the next generation of transportation model.

In the case of EVs, an external electricity charging station is used to charge the battery. Conversely, in the case of hydrogen vehicles, the battery can be charged through the hydrogen tank inside the vehicle to generate electricity [160]. This study mainly reviewed electric vehicles that are easy to connect with the smart or micro grid. There has been growing interest in the mobile system as an energy-sharing strategy for efficient energy consumption.

- ***Electric vehicle (EV)***: One of the most well-known examples of energy mobility is vehicle-to-grid (V2G), which connects the battery of an EV to the electricity network and uses EV as mobile ESS. In the future, EV's batteries can be used to stabilize a smart grid. The V2G technology can charge the EV via the electricity network established in a smart city, and transmit the surplus electricity left after driving back to the grid, thus offering the user financial benefits and maintaining a stable electricity supply [161]. For example, EV users can charge their EV at dawn, when electricity prices are relatively lower, and sell the electricity charged in the EV during the energy peak time of office buildings (during the daytime when the EV is parked), allowing for peak load shifting in the entire smart grid. In addition, downtown areas far from a power plant have a relatively higher electricity transmission loss factor. Therefore, many EVs in downtown areas can satisfy energy demand in smart cities at a closer distance, allowing for fast and stable electricity supply [162]. Accordingly, the V2G technology essential in smart cities has a huge potential to expand to vehicle-to-something (V2X), which allows for the energy stored in the EV to be used anytime and anywhere that energy is required in a smart city by using various devices at home or buildings that need electricity, that is, vehicle-to-home (V2H), vehicle-to-building (V2B), and vehicle-to-device (V2D), according to the purposes of the charging and discharging specifications and standards for bidirectional chargers.
- ***Mobility infrastructure***: To establish energy mobility successfully in smart cities, mobile infra-services should be expanded. The establishment of infrastructure (EV charging stations) is essential in determining the technical, economic, and environmental performance of the batteries installed in the EV, as well as in the promotion of V2G and efficient energy consumption and sharing. Furthermore, in keeping with the distribution and expansion of EV and the change of energy mobility in smart cities, new infra-services should be introduced in gas stations, such as energy-sharing, EV rental, and AI signages for traffic, which allows for energy charging and sale at the same time, in addition to filling gas, vehicle maintenance and repair, and car cleaning services, by reinterpreting the space of existing gas stations. On the other hand, sun-to-vehicle (S2V) and other EV charging technologies that directly produce and consume energy via photovoltaic generation and charging stations can be developed to allow for EVs to be charged faster and driven over a longer distance. Finally, there is a research that proposes the optimal placement and area of electric vehicle parking lots by considering the surrounding traffic pattern and energy demand [163–165].

5.2. New strategies for energy trading in distributed energy systems

5.2.1. Prosumers as potential users of energy conservation systems

Energy prosumers are a key concept related to of energy supply and demand in smart cities, along with grids, smart grids, and IoT [93]. First mentioned by US futurologist Alvin Toffler in his book 'The Third Wave', prosumers connote passive consumers who have transformed into active producers during the era of renewable energy technology [166]. In this study, a prosumer is defined as one who produces and consumes renewable energy through distributed generation [167]. The roles of the energy prosumer defined in this study are as follows: (i) energy generation, consumption, and storage through a distributed energy system with ESS; (ii) making of technical, economic, and environmental decisions for energy usage; and (iii) participation in activities that create value for energy services. In performing such roles, the energy prosumer does not always pursue self-sufficiency, but can also affect the value chain of commercial energy suppliers [168].

To create more energy prosumers, renewable energy portfolio standards and feed-in-tariffs are in operation, and various economic incentives are being offered. In the U.S., there are tax incentives for energy prosumers who have installed solar PV panels, although such incentives differ by state or region (i.e., tax reductions by the federal government on the installation cost of solar PV panels [169–173]); and there are cash incentives (i.e., payment of cash by state governments and electric utilities based on the solar capacity of the PV panel and the performance of the energy generation) [169,174].

5.2.2. Peer-to-peer energy trading

Energy trading between energy prosumers is called "peer-to-peer (P2P) energy trading", which is a type of shared economy that can be realized within the same power grid. P2P energy trading can acquire financial profits because it allows the energy prosumer to sell surplus electricity to energy consumers who need energy. In addition, compared to the existing long-distance electricity transmission, P2P energy trading has a shorter transmission distance, so its transmission loss is small, and it can increase the stability of the local electricity supply. In the perspective of energy prosumers, they can sell the surplus electricity after self-consumption to another energy consumer and so acquire profits. Here, the energy prosumer who sells surplus electricity can extract the levelized cost of energy and the production cost per unit electricity, as well as sell surplus electricity at a higher price and compensate for the cost invested on the installation of the distributed energy system. On the other hand, the energy consumer who purchased the surplus electricity can acquire profits when he or she purchases the surplus electricity at a price lower than that from the centralized power plant. That is, both the energy prosumer and the energy consumer can acquire economic profits via P2P energy trading within the price range [167]. In the perspective of the social community, renewable energy is considered an alternative technology for electricity generation for those who use existing fossil fuels (i.e., coal, oil, and natural gas). Indeed, not all renewable energy sources are 100% eco-friendly, but the effect on natural environments can be minimized if the use of fossil fuels is minimized, and if they are replaced with renewable energies. In such circumstances, the introduction of additional P2P energy trading can offer much more flexibility in the use of the produced renewable energy and can reduce the energy load so as to reduce the environmental load due to power generation [175].

5.2.3. Business model for data-based P2P energy trading

P2P energy trading business model can largely be divided into three models: (i) the auction-based model, (ii) the bilateral-contract-based model, and (iii) the blockchain-based model.

- *Auction-based model* [176–180]*:* The auction-based model is an effective method of determining the price of items whose market value has not been clearly determined. Basically, potential users bid for an item that they wish to purchase, and the seller sells the item to the highest bidder. The auction-based model can be changed to forward auction, reverse auction, double auction, or English auction, among others, depending on the number of sellers or purchasers, the limit in the bidding price, the limit in the bidding time, and whether or not the bidding prices are to be made public.
- *Bilateral-contract model* [181–183]: In the design of a market with a multiple-to-multiple structure, the bilateral-contract model is based on a contract for mutual profits among energy prosumers. Key considerations in this model are the setting of a contract amount that all the energy prosumers wish to abide by, and the strategy for that amount [181]. The energy prosumer and the potential purchaser can trade renewable energy at a fixed price during the contract period based on a bilateral contract. This is a useful model for managing financial risk with renewable energy, with an uncertain output [184].
- *Blockchain-based model* [185,186]: Blockchain technology is an emerging information technology that offers a new opportunity in the P2P energy trading market in that energy consumers can verify information on the producer of the renewable energy that they wish to purchase and on the renewable energy sources, etc., and can participate directly in the decision-making process [187–189]. In addition, the blockchain-based model can guarantee the reliability of the subjects in traction without a centralized management organization, and can prevent the increase in the corresponding operational costs or the degradation of information security [190].

Supportive policies and regulations from the local governments were essential for the P2P business models to be well applied to the local electricity market and to improve economic performance [191]. A policy that is friendly to prosumers provided an access to capital for them to encourage the decentralization of existing grid infrastructure through voluntarily installing distributed energy system and ESS required for energy production [192]. This policy provided an opportunity to actively participate in the P2P energy trading market. In addition, regulation restrictions were the most important key factor to the success of the energy market. In detail, innovation testbeds and regulatory sandbox allowed platform developers to freely verify their pilot programs within the P2P energy trading market [193].

5.2.4. P2P energy trading market

P2P energy trading market can largely be divided into two trading model: (i) Day-ahead trading and (ii) Intraday trading.

- *Day-ahead trading*: With Day-ahead energy market, prosumers contract to buy or sell wholesale electricity one day before the operating day to avoid electricity price volatility [194]. Hourly contracts are basically submitted by the prosumers in terms of a multi-volume price pair that indicates the willingness of the prosumers to sell/-buy a certain amount of energy at a price above or below their respective specified price [195]. Both suppliers and buyers were able to submit hourly bulk price offers and bids on P2P energy market. In addition, Day-ahead trading also allows prosumers to trade in block product where they specify fixed volume, fixed price, and a continuous time slot.
- *Intraday trading*: Apart from day-ahead trading, Intraday trading allows prosumers to continuously trade wholesale electricity during the operating day [196]. Prosumers were able to negotiate a contract up to an hour before the actual delivery. Intraday trading is particularly useful for prosumers in adjusting unexpected volatilities caused by imbalance between an amount of power generation and power consumption [197]. One major difference to day-ahead trading is the pricing on the intraday trading. Unlike uniform price in day-ahead trading where the last accepted bids set the price of all transaction, intraday trading were set in a pay-as-bid. In other words, for each completed transaction, the price was evaluated in a continuous transaction.

6. Future research direction for sustainable smart cities

For the advanced energy conservation system in the future, new energy infrastructure should be developed, and new strategies for energy trading at the city level should be realized. Therefore, it is important to interact with each factor of energy generation as well as energy consumption, and to interconnect distributed generation systems as energy networks for energy trading in smart cities.

Fig. 9 shows a new proposal for the sustainable smart city, combining and balancing the IoT-based integrated energy platform and the big data-based intelligent energy trading system. Especially, to reflect the complicated and subdivided characteristics of consumers as well as buildings, a *"Bottom-up approach (smart home level → smart city level)"*, which can take into account both consumer behavior and energy, should be used in a sustainable smart city.

Future research challenges for sustainable smart cities can be divided into the following three levels according to the bottom-up approach: (i) development of real-time energy monitoring, diagnostics, and controlling technologies at the room level; (ii) application of intelligent energy management technologies at the building level; and (iii) implementation of integrated energy network technologies at the city level.

First, real-time energy monitoring, diagnostics, and controlling technologies at the room level, which consider the consumer behavior, should be developed. To monitor the energy performance, information on the energy consumption and other behavior of each consumer of the room of the building should be collected from various sensors in real time. Based on the database established through the spatial and temporal integration of the collected real-time data, an intelligent and automatic energy performance analysis (i.e., energy usage pattern analysis, energy benchmark, etc.) should be conducted using AI technology. Then to improve the energy performance of the room, control solutions for electrical products (i.e., appliances and facilities) that consider the consumer's bio-reaction should be proposed based on the results of the experiment through the virtual reality, halogens, and environmental chamber. As a result, a potential user can monitor, diagnose, and control the energy performance at the room level using an IoT-based sensor network.

Second, intelligent energy management technologies at the building level should be applied. To effectively manage the energy performance of buildings, big-data analytics technologies (i.e., energy demand forecasting using historical data, and anomaly detection and automatic alarm using real-time empirical data) can be developed. Also, the information on the energy generation of the renewable energy system and the building energy consumption should be collected in real time to reduce the peak load. Moreover, the optimal operation algorithm of the building energy can be developed using various decision-making tools such as agent-based modeling. Through the integration of these energy management technologies, various solutions (i.e., adoption of the renewable energy system with ESS, building energy efficiency management, etc.) can be proposed for improving the energy performance of buildings.

Third, integrated energy networks at the city level should be implemented by using smart energy management technologies. With the

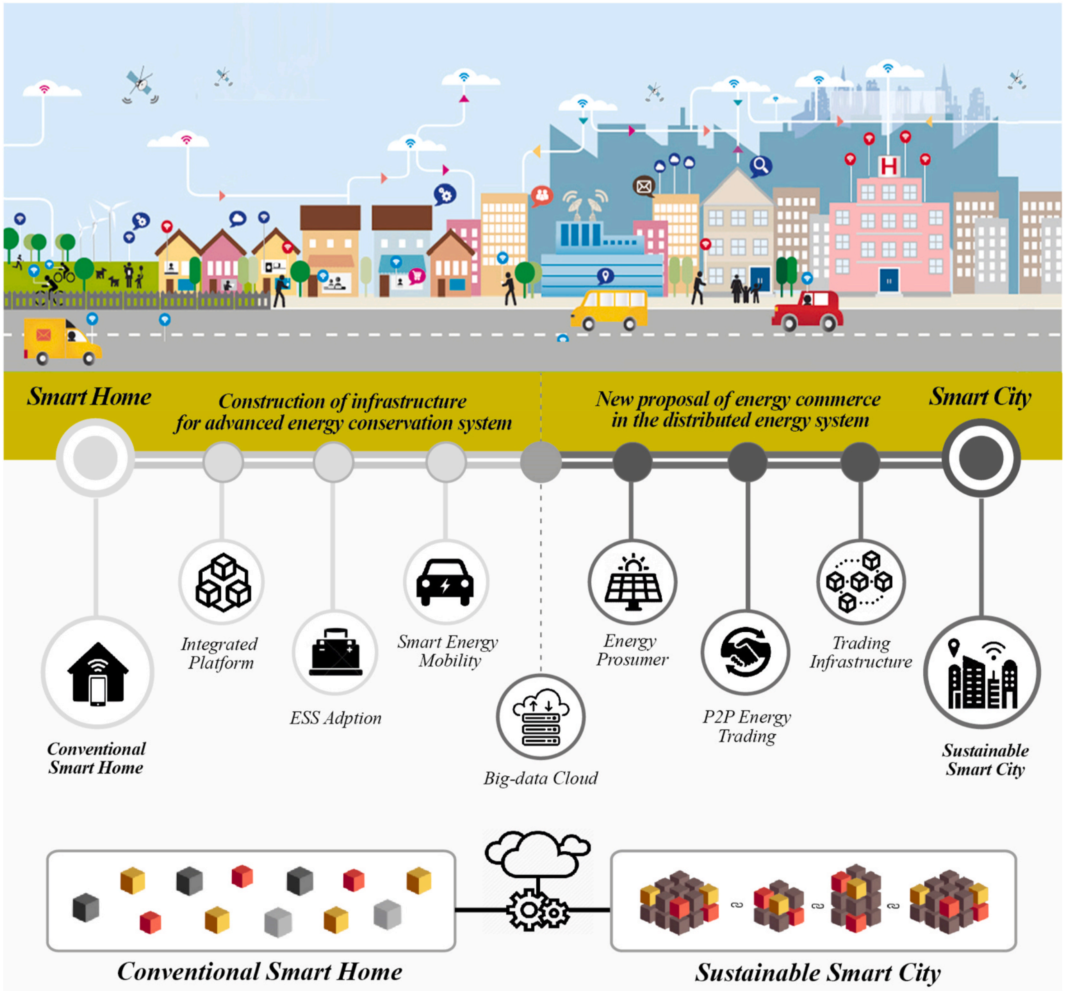

Fig. 9. New paradigm of the sustainable smart city.

development of new technologies, the 'Internet of Energy (IoE)" concept, which upgrades and automates energy infrastructure through the mixed use of energy conservation systems and IoT technologies, is becoming a hot topic. Besides, from a city perspective for IoT technology and energy infrastructure, the energy network is essential for flexible energy trading between the distributed energy generation systems and for efficient management of the energy peak load based on the demand response. Therefore, using the internet based-integrated energy network system, various emerging technologies for the effective operation of the advanced energy conservation system can be applied to sustainable smart cities. Furthermore, if the usability and feasibility of the integrated energy network system with various infrastructure is verified, it can be used anywhere in the world to implement a sustainable smart city in the future.

7. Conclusion

With the recent trend towards smart cities with energy conservation systems, this study conducted a systematic review to propose insights for future research on a sustainable smart city. As a result of the systematic review of 21,094 relevant literatures, the holistic framework of, as well as research themes on smart homes and cities were identified. Qualitative reviews of sequentially filtered relevant literatures have identified technical and regulatory barriers to the current stage of smart homes and cities. Three overarching barriers toward smart cities were as follows: (i) Interoperability, (ii) Flexibility, and (iii) Decentralization. To overcome these barriers of the progression of smart homes to sustainable smart cities, this study proposed innovative technical and regulatory solutions (i.e., construction of infrastructure for advanced energy conservation systems and new strategy for energy trading in distributed energy systems) for the suitable application of the advanced energy conservation system in the sustainable smart city. Finally, future research challenges from using the bottom-up approach were proposed that considered the occupants' behavior and energy in a sustainable smart city.

Despite the novel systematic review method, this study has several insurmountable limitations. This study has conducted the systematic reviews on general energy issues of smart homes and cities, regardless of regional/cultural differences of each country. In future research, we plan to present an advanced solution considering regional/cultural differences that is more detail and highly feasible. Additionally, this study overlooks specific proposals for the economic feasibility of smart energy conservation systems. In fact, there is an increasing research trend that deals with price competitiveness (such as design cost, installation cost, and operation costs) of smart devices used in smart homes and smart cities. In future research, we plan to present an economic proposal for the energy efficiency of smart conservation system through the life cycle perspective. Furthermore, we plan to discuss the practical implications of this systematic reviews in more detail.

Although this study had limitations due to the review method that was employed using the limited database based on the keywords within the research scope, this study can play a leading role as a knowledge-based systematic guide for future research on energy conservation systems of sustainable smart cities. Moreover, unlike this study that only focused on the energy issue, if future research is conducted considering the occupants' health, transportation, security, blockchain, and energy, the conclusion of this study will be taken a step further by suggesting a new strategy and innovative solutions for sustainable smart cities.

Declaration of competing interest

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

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Nomenclature

Abbreviations

ICT	Information and Communications Technology
IoT	Internet of Things
AI	Artificial Intelligence
HEMS	Home Energy Management System
ESS	Energy Storage System
SQLR	Systematic Quantitative Literature Review
RQs	Research Questions
MCA	Multiple Corresponding Analysis
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
ITU	International Telecommunications Union
IEEE	Institute of Electrical and Electronics Engineers
P2X	Power-to-X
EV	Electric Vehicle
V2G	Vehicle-to-Grid
P2P	Peer-to-Peer

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.110755.

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