buildings

*Review*

# A Sustainability Evaluation of Buildings: A Review on Sustainability Factors to Move towards a Greener City Environment

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**Abstract:** Energy-efficient and sustainable building management has always been a key concern surrounding buildings. The rise of environmental and social concern in today's world has brought more attention to the issue of sustainable and smart building management. This paper aims to review the state-of-the-art research and performance on building management that aims to make more sustainable and energy-efficient decisions. This paper classifies building management based on technologies utilized for management and different aspects of management that should be considered when regarding the larger picture of "sustainability". Additionally, while keeping in mind that long-term sustainability cannot be achieved through energy management alone, this research investigates previous works that also mention diverse aspects that must be taken into consideration when creating a truly successful smart building environment: costs, occupant comfort, and security. Of course, each field deserves an extensive analysis, but the purpose of this review paper is to deliver current research that has brought attention to the rapidly shifting and developing field of smart buildings to provide a macro-level holistic viewpoint on how smart buildings and homes should be approached from a sustainability viewpoint.

**Keywords:** sustainability; smart buildings; data analysis; reinforcement learning; big data; internet of things; building management; smart building security; security; ESG



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## 1. Introduction

With rising interest in global warming and sustainability, the topic of energy is becoming ever more crucial in every field of industry and society in today's world. This is also applied to the field of buildings and architecture. Most people spend almost 85 percent of their lives in buildings, and the fact that buildings contribute 30 to 40 percent of the overall amount of carbon emissions is a clear indicator as to why controlling the emission rates of smart buildings will have a lasting impact on the sustainability of society and the environment.

The issue of sustainability is, however, not merely about reducing carbon emissions and thereby improving the environment. Of course, controlling energy consumption and emission rates leads to environmental and societal sustainability by creating a "green" society. Thus, much research is being conducted on the topics of reducing carbon emissions, managing control systems to achieve an efficient usage of energy, predicting energy usage to cut excess emissions and costs, etc. While previous works recognize the need to understand energy conservation, there is also continuous research surrounding smart building security and, in turn, security for energy conservation systems in smart buildings.

Controlling carbon emission rates and energy consumption rates in smart buildings or green buildings is nothing new. There have been plenty of previous research and active attempts to reduce carbon emission rates, lower energy consumption levels, control the amount of waste produced in buildings, etc., as methods towards making the building environment “greener”.

However, sustainability incorporates a wider definition than energy conservation and maintaining a sustainable energy environment. The generally accepted definition of sustainability incorporates the concept of having the ability to maintain a specific ratio or level continuously; in the business world, it means to maintain or improve profitability without causing adverse environmental impacts. The dictionary definition of sustainability according to the Cambridge Dictionary is “the quality to be able to continue over a period of time” or “the quality of causing little or no damage to the environment and therefore able to continue for a long time”, providing either a very broad or narrow perspective of what sustainability incorporates. From a more multifaceted and holistic viewpoint, sustainability can only truly occur when the “sustainability” of all aspects of society is achieved.

Toli et al. provide a comprehensive overview of what dimensions sustainability originates from and presents different definitions of what sustainability can potentially incorporate and represent. Their research first notes that sustainability can be achieved environmentally, economically, or socially, and that sustainability may be defined in different variations depending on the field. Environmental sustainability covers ecological aspects and is intended to conserve the natural environment and natural resources. Achieving environmental sustainability is also achieved through the energy production-based economy. Social sustainability includes citizen well-being, equity, community autonomy, and the overall gratification of human needs. Economic sustainability aims for diversity in urban areas and economic vitality [1].

Although the presented areas are slightly different, they are not so far from what sustainability aims to achieve in today’s era, where the topic of ESG (environment, social, governance) is brought to intense attention. As such, sustainability covers a wider range as to which topics and issues should be considered to make a sustainable society and community. However, sustainability fundamentally shares a common goal and flow regardless of the dimension it is applied in. In almost every dimension, sustainability indicates a society and infrastructure that further enhances the quality of life of individuals within a society. A simple example from an ESG point of view is the following: governance that can effectively guide and regulate measures for environmental sustainability will lead to energy conservation and reduced carbon emission rates, which lead to a cleaner environment and healthier ecosystem, thereby extending a comfortable living environment for humans and other species residing on earth.

Given such an understanding of sustainability and the expectations that come from efforts towards achieving sustainability, the next step is to understand how sustainability can be achieved today without having to destroy and rebuild all components that are already rooted as basic infrastructures of society. Rather, the question focuses on how we can obtain sustainability in already existing social and city infrastructures. Simply cutting energy usage levels and lowering carbon emission rates is not the only method used to enhance the sustainability of smart buildings. It is a clear method to obtain sustainability for a single building, but not necessarily for the collective ecosystem of a city and between cities.

This research attempts to understand the key actors that create a truly sustainable city environment and society. Instead of looking at buildings as singular entities, our research understands buildings other members of society, and it understands sustainability from the viewpoints of energy, environment, governance, safety and security, and healthy and wholesome lifestyles. Mainly, this research will attempt to formulate sustainable governance policies that will overall move the city and society towards sustainability by utilizing digital twin technology. The data that will be inputted to the digital twin are collective building energy, environment, and social environment data that were collected and analyzed through big data and AI technology. Once more detailed keywords and key actors for sustainable governance are obtained, this research will ultimately provide indicators and standards that will grade the sustainability levels of individual cities and further provide guidelines towards sustainability.

## 2. Previous Works

Energy conservation is one of the most prevalent and popular topics regarding smart buildings and management systems. The reasons for this are intuitive, as sustainability is most frequently understood from the viewpoint of environmental friendliness.

Energy in smart buildings is also discussed in diverse topics, but the topics often overlap with one another, simply due to the shared interest in obtaining sustainability. Even if the topics do not directly overlap, the topics are closely knit to one another, in that each topic ultimately is a threshold or subsequent step towards reaching a carbon-neutral and environmentally friendly green status.

Broadly speaking, the research topics of related works touched upon energy conservation, cost savings, energy management, and occupant comfort. At a glance, the topics may seem to be specific and independent from one another, but it does not take long to understand that there is a cyclical relationship between the largely grouped topics.

There is no doubt that, from an environmental sustainability standpoint, smart building energy management and carbon emission rates have direct correlations. However, energy conservation also leads to increased sustainability in a smart building. The sustainability of a smart building also indicates that the building itself has a long lifespan, and for a building to have a lasting lifespan, it must be constantly occupied by residents. A building or residential space loses its sustainability when it becomes vacant and abandoned. Controlling energy consumption and carbon emission rates can therefore expand the lifespan of a smart building or home. Energy conservation is bound to lead to long-term cost reduction in the management and maintenance rates of a smart building. The efficient use of energy from lower rates enhances resident satisfaction, consequently leading to the long-term occupancy of the smart building.

There is little disagreement, however, that numerically available datasets are the most convenient to work with and manage when it comes to creating a sustainable building environment. Questions surrounding occupant comfort are intuitive, but they are more difficult to articulate in datasets due to their subjective nature. However, when considering occupant comfort and ideal living environments from a human viewpoint, aspects such as temperature, cost, humidity, security, etc., all play into the larger picture of occupant comfort that leads to sustainable buildings.

From such a perspective, energy management and consumption reduction are probably the most fundamental steps towards creating a sustainable building environment. There is no doubt that efforts towards conserving energy require an effective energy management system and dataset, and successful energy management and consumption reduction in thermal energy, as well as temperature control (both for water and heat), will lead to cost savings. Additionally, accurately and effectively managing energy datasets to nimbly understand and adjust to energy settings that quickly reflect real-time environmental data and settings, as well as ideal user preference, leads to higher occupant satisfaction and can further lead to occupant safety and security management as well.

Keeping in mind that buildings and the energy consumption and emissions of buildings take up a large portion of the primary energy in the world, previous works look at energy and energy management in smart buildings from a sustainability perspective. Vijayan et al. provide a review on automation systems in smart buildings and how automation systems can enhance the sustainability of buildings. The research is not limited to energy and energy management systems, but emphasizes the role automation systems can play in HVAC management, fire management, and furthermore, elderly care. Such research drives the research field closer to what we consider a holistic sustainable building environment [2]. The goal of effective energy management includes a wide range of goals, such as residential comfort, cost management, enhanced energy utilization, etc. However, the main goal is to further improve energy efficiency and utilization while maintaining a comfortable environment not only for residents, but also for the environment.

Due to the relatively tilted interests towards more macro-level topics, such as environmental friendliness, going green, carbon neutrality, net-zero, and sustainability, the very fundamental and important identity of smart buildings and smart homes almost appears to have been forgotten. The goal at the very beginning of smart home development was to customize settings for occupants, thereby achieving optimal comfort and satisfaction for dwellers. Cost management also cannot be overlooked, as both individuals and corporate organizations will only be willing to voluntarily achieve energy-efficient and environmentally friendly smart buildings if there are immediate and tangible benefits such as cost reduction and energy efficiency.

The question then becomes "how can energy and cost efficiency be obtained while creating a comfortable and safe environment for dwellers and residents?" Previous works focusing on energy conservation often adopted methods, such as machine learning and deep learning techniques, to make adequately accurate predictions on how to maintain appropriate energy maintenance cost levels. When making such predictions, the resident comfort factor should also be kept in mind. This is because methods for preserving energy are overtly simple in the realm of sustainability.

As mentioned before, sustainability is not a simple issue that can be obtained by solely making an approach from an energy perspective, and certainly not from merely controlling energy levels within a singular building.

The prediction and estimation of energy consumption/performance is key for energy management in smart buildings, allowing for improved decision making that can lead to decreased energy usage. Additionally, such predictions can aid the construction of smart buildings by estimating the total energy consumption of newly constructed smart buildings. Prediction and estimation techniques can also further lead to the creation of the most comfortable living environment for occupants, which will then increase the likelihood of residents choosing to reside in the designated building for a long period.

Thus, Section 2.1 focuses on introducing previous research that has primarily experimented with diverse artificial intelligence technologies in order to create the most accurate energy management and prediction models. Subsequently, Section 2.2 introduces previous research that focus on another key element in sustainable buildings: security. We have organized the previous works based on the two larger subtopics because both energy management, which leads to efficient energy consumption rates and lowered costs, and security systems in sustainable buildings are accurately measurable topics that have a critical impact on occupant comfort and satisfaction. Additionally, we have an understanding that it is crucial to touch upon the state-of-the-art technologies that have built the cornerstone of sustainable building infrastructures and systems. Based on previous research, we will then further develop and present our thoughts on sustainable buildings and their core aspects in Section 3.

### 2.1. Artificial Intelligence Technology in Sustainable Buildings

Many of the previous works surrounding sustainable buildings primarily focus on utilizing diverse AI technologies to make energy consumption predictions, energy management simulations, etc. Conducting such research is a method to create the most sustainable energy environment in the building and, thus, further cutting down energy consumption levels and carbon emissions and enhancing sustainability and comfort levels within the building. This section introduces previous research that has focused on such topics by utilizing AI technologies, such as deep learning, deep reinforcement learning, machine learning, big data analysis, etc.

The data prove that understanding fundamental energy consumption patterns and thereby effectively managing the energy consumption and emission levels of smart buildings will be the key to achieving a green environment. The importance of achieving environmental sustainability and, furthermore, carbon neutrality is becoming a key global goal in today's world. Therefore, effectively managing energy and moving towards creating sustainable smart buildings will be the key goals, as buildings currently make up around one third to one fourth of the world's overall carbon emissions. Pham et al. take on this sustainable viewpoint of buildings in today's world and study how buildings are affecting the world's energy consumption rates and greenhouse gas emission levels. This research proposes a Random Forest (RF)-based prediction model that will predict the short-term energy consumption in the hourly resolution in various buildings. This research is significant in that it utilizes and proves the effectiveness of machine learning models while also providing guidelines towards enhanced energy efficiency and sustainability in buildings [3].

Yu et al. review deep reinforcement learning technologies used in the field of energy management. While numerous variations in deep learning technologies have been utilized in this field of study, they primarily note that deep learning technology is promising in this field of study because it effectively solves some notable challenges: difficulties in developing an explicit building thermal dynamics model that is efficient and accurate for building control, uncertainties surrounding system parameters, operational constraints due to spatial and temporal issues, building optimization problems that cannot be solved in real time due to large solution spaces, and the low versatility of traditional management methods [4]. Kim et al. understand the need for a more cost effective and flexible method to manage the energy consumed by buildings in the smart grid environment. Their research provides insight towards an energy management system of smart energy buildings connected to an external grid along with other energy resources, such as energy storage systems, a renewable energy source, and a vehicle-to-grid station [5]. A more up-to-date study by Fu et al. also prove the effectiveness of using reinforcement learning in the field of the energy-efficient control of buildings. Reinforcement learning, a machine learning technique, is increasingly used in intelligent building control to improve efficiency and reduce energy consumption. Fu et al. categorize reinforcement learning algorithms and identify the specific control problems that each algorithm is best suited to address in intelligent buildings. Their research reviews the current applications of these methods in building management, discusses challenges and future prospects, and offers guidance for researchers in this field [6].

Additionally, the previous works that this study reviews suggest the goal of energy conservation in the fields of thermal energy and temperature control for both water and heating systems in smart buildings and households. Such topics are viewed with interest not only due to the goal of achieving environmentally friendly carbon emission rates, but also due to interests on a more individual level; these interests include managing energy so that occupants can cut costs and obtain the ideal settings that provide optimal comfort and satisfaction. Gupta et al. suggest the use of a deep reinforcement learning-based energy-efficient heating control system in smart buildings. Their research primarily focuses on improving thermal comfort and reducing energy costs in smart buildings and suggests that decentralized control shows better results than a centralized controller [7].

Generally, predictions or estimations of energy consumption and energy performance were made most frequently and effectively using machine learning techniques. Tsanas et al. researched how statistical machine learning tools can provide an accurate quantitative estimation of energy performance. They created a framework by inputting variables, such as the surface area, wall area, overall height, roof area, relative compactness, orientation, glaring area, and glazing area distribution, on two output variables, namely the cooling load and heating load of residential buildings. Their study notes that the results show the feasibility of utilizing machine leaning tools to estimate building parameters, shedding insight as to how machine learning tools can effectively estimate the energy performance rates in buildings [8]. More recently, Qiao et al. also address the challenge of limited occupational data in predicting building energy consumption by introducing an agent-based machine learning model that generates simulated data, significantly improving the prediction accuracy. Their study also employs Boruta feature selection, further enhancing the performance of hybrid agent-based algorithms [9]. Ding et al. also present a study that demonstrates the use of machine learning algorithms to predict the energy consumption of public buildings by analyzing a feature matrix. Their research primarily focuses on the importance of establishing optimal prediction models for analysis and the importance of datasets to achieve good model performance. Their study contributes to the field by providing a reference for database establishment and by conducting a data analysis of building energy consumption [10].

Olu-Ajayi et al. also researched how deep learning technologies can be utilized to make energy consumption predictions for residential buildings. The paper presents and uses several machine learning technologies, including Artificial Neural Networks (ANNs), Deep Neural Networks (DNNs), Gradient Boosting (GB), Random Forest (RF), K Nearest Neighbor (KNN), Stacking, Support Vector Machines (SVMs), Linear Regression (LR), and Decision Trees (DTs). The research notes that DNN was the most efficient model for energy use prediction and suggests that such models should be used by building designers in order to make more well-informed decisions and management and optimization designs [11]. Brandi et al. also suggested using deep reinforcement learning technologies to optimize indoor temperature control and heating energy consumption rates in buildings. They utilized deep reinforcement learning to control the supply water temperature setpoint to terminal units of the building's heating system, but noted that a dynamic deployment is absolutely necessary in cases where input variables are not selected with caution [12]. Moon et al. conducted research on how artificial-intelligence-based thermal control algorithms can be utilized in double-skin buildings. The research notes that, among several rule-based and AI-based algorithms, an ANN-based algorithm proved to be the most energy-efficient and reliable algorithm. However, the research also differentiated the best algorithms based on interest. For instance, if comfortable thermal conditioning is the primary goal, a fuzzy logic or adaptive neuro-fuzzy inference system algorithm would be the optimal solution, whereas for energy conservation and system operation stability, an ANN-based algorithm would be the ideal option [13]. More recently, Ghenai et al. developed an adaptive neuro-fuzzy inference system (ANFIS) for very short-term and accurate energy consumption forecasting in educational buildings by utilizing data from smart energy meters and weather conditions. The ANFIS model demonstrates high accuracy with correlation coefficients over 0.97 for 30 min to 4 h ahead forecasting, indicating its effectiveness in predicting building energy use. The research is significant for energy planning in microgrid systems, aiding in efficient operations and demand-side management [14].

Amber et al. compared five intelligent system techniques that are anticipated to adequately forecast energy consumption. The five techniques mentioned in this study are Multiple Regression (MR), Genetic Programming (GP), Artificial Neural Network (ANN), Deep Neural Network (DNN), and Support Vector Machine (SVM), and the study provides insights that, among the five techniques, the ANN had the best performance. The study also contributes to the field of study by selecting parameters that help observe and forecast electricity consumption rates, including temperature, solar radiation, humidity, wind speed, and weekday index [15]. Baris et al. go further to present a system engineering approach to address the gap between the predicted and actual energy performance in public buildings by using simulations with limited historical data. It introduces a method combining a principal component analysis, a multi regression analysis, and an artificial neural network to identify key variables and optimize energy savings through genetic algorithms. When tested in a pilot project, this approach achieved a significant 25% reduction in energy use while maintaining occupant comfort [16].

Singh et al. researched machine learning models that can provide quick energy results while drastically reducing computational demand and resources. The study notes that such models for multiple building shapes will be crucial for early-stage energy prediction, and thus, it focuses on collecting new samples that will allow for more generalization. The core goal of this research was to also save the use of costly data collection resources by honing in on a limited number of more substantial samples [11]. Similarly, Olu-Ajayi et al. also recognize the resourcefulness of machine learning techniques and compared nine machine learning classification-based algorithms for energy performance assessment at the design stage of residential buildings [17].

Energy consumption and occupant comfort are, of course, two topics that are correlated, and Mateo et al. also understand the important role of energy prediction when reducing energy consumption in buildings, and aim to enhance energy management via machine learning methods so that energy efficiency and occupant comfort are further maximized [18]. More recent research by Yuan et al. introduces a temporal–sequential (TS) analysis combined with machine learning for accurate occupancy forecasting in buildings, acknowledging the importance of occupancy data for energy management. Utilizing hourly data from 16 buildings, the paper demonstrates that the TS-week-ANN model, which incorporates a 1-week seasonal period, significantly outperforms traditional methods. The research emphasizes the inherent temporal and sequential nature of building occupancy, highlighting its utility in improving energy simulations and operations [19]. Missaoui et al. analyzed the performance of a Global Model-Based Anticipative Building Energy Management System (GMBA-BEMS) in managing household energy, as the given system is able to optimize user comfort and energy costs while also taking into account resident expectations and existing physics constraints such as energy prices and power limitations. The research primarily focuses on how energy management in home appliances, such as washing machines, dishwashers, and heating systems, from a grid point of view, thereby focusing not only on the energy side of smart homes, but also on resident comfort and satisfaction [20]. Dalamagkidis et al. also present research that focuses heavily on obtaining occupant comfort in buildings while minimizing energy consumption rates. The research identifies the importance of thermal comfort and indoor air quality for optimal occupant comfort while also finding a compromise for energy costs [21].

On the other hand, often times there is the question on whether energy is being efficiently used when putting forth occupant comfort as the first priority. Chong et al. used Bayesian calibration to assess how different levels of occupancy data resolution affect energy use predictions in buildings. They found that a building energy model's accuracy improves with detailed occupancy data from Wi-Fi connections, significantly reducing prediction errors. However, occupancy data with a higher spatial resolution can lead to increased prediction errors, highlighting a balance between model complexity and data accuracy [22]. Such research, which correlates user comfort, energy efficiency, and eco-friendliness, is closer to the sustainable building environment that our current society is aiming towards.

Chen et al. note the importance of natural ventilation in the realm of green buildings, as it improves building energy efficiency, air quality, and the indoor thermal environment. Thus, the research goes on to present a reinforcement learning strategy that will aid optimal control decisions for HVAS and window systems, ultimately minimizing both energy consumption and thermal discomfort in the building. The control system takes into account indoor and outdoor environmental aspects, such as humidity, solar radiation, temperature, and wind speed, thereby truly working with natural environmental elements that will enhance the greenness of the building [23]. Fu et al. introduce a multi-agent deep reinforcement learning approach (MA-CWSC) for optimizing HVAC systems, offering a model-free online learning solution. The MA-CWSC uses five agents for parallel learning, improving action space efficiency and speeding up convergence compared to traditional methods. The experimental results reveal that the MA-CWSC achieves significant energy savings, nearly matching model-based methods, and outperforms single-agent deep Q-networks in the learning rate [24].

Elsisi et al. present a study on the effective energy management of smart buildings via deep learning-based Industry 4.0 and IoT. The purpose of utilizing such technologies in this study was to help make more efficient decisions when it comes to energy consumption. The simulation results of the study revealed and stressed that the proposed deep learning-based algorithm aids in the accurate detection of the number of persons in a specified area and the statuses of the air conditioners [25]. Mariano-Hernández et al. provide a review of the existing strategies for building energy management systems. The research provides an overview of energy management systems from a model predictive control standpoint, demand side management standpoint, optimization standpoint, and fault detection and diagnosis standpoint [26].

Other works utilize technologies such as smart grids, microgrids, and blockchain to estimate and predict the energy output and input, thereby attempting to provide an energy management model. Park et al. suggest using a building energy management system based on the smart grid and provide some insights based on the results from the test bed in Jeju Island [27]. Shakeri et al. review demand response programs (DRPs) and how smart technologies, like smart grids and energy management systems, enable consumers to reduce electricity costs. It provides an overview of home energy management systems (HEMSs) and load management techniques, highlighting their role in smart grid functionality. They emphasize the significant impact of storage devices on the efficiency of energy management strategies [28]. Cutsem et al. utilized blockchain for energy management not only in singular buildings, but also in a community of buildings. The paper primarily focuses on understanding the demand response and how cooperative energy management is necessary for the larger community goal of using carbon-free resources or decentralized aggregated grid services. The research provides insights as to how smart building management should go forward to create a carbon-free community [29]. Zhang et al. suggested using a microgrid-based energy consumption and operation management system in a smart building. With the understanding that microgrids are effective in providing energy to buildings with reduced costs and gas emissions, the paper suggests the active utilization of microgrids while reflecting real-time prices for more efficient energy trade and consumption [30].

Cost management is also key in energy management, as lower cost and high energy effectiveness are, of course, the best outcomes for any scenario. Dynamic energy management systems use real-time pricing and local renewable energy generation forecasts. Other technologies utilized were rule sets, building load prediction, model predictive control, demand side management, optimization, and fault detect and diagnosis. Doukas et al. suggested an intelligent decision support model that utilizes rule sets based on a conventional building energy management system. The research primarily focuses on enhancing the living quality in buildings and also managing energy so that costs are saved [31].

Some previous works recognize the importance of policies in the realm of smart buildings and energy conservation. Rocha et al. shed light on the policy aspect of building energy management systems in smart buildings and provides an integrated optimization model that mimics a smart BEMS that combines decisions on cooling and heating system operations. The results from the research prove that using a smart BEMS results in more significant energy consumption reduction compared to reductions from conventional BEMS policies [32]. More recently, Kozlovska et al. analyzed the integration of building energy management systems (BEMSs) with building information modeling (BIM) in construction and building management, highlighting its benefits and feasibility. Through a literature review, bibliometric analysis, and real-world case studies, the study explores the impact and effectiveness of BEMS-BIM integration. It emphasizes the potential of this integration to improve building performance, increase sustainability, and drive efficiency in the industry [33].

### *2.2. Security in Sustainable Buildings*

As mentioned earlier, the issue of security has both direct and indirect impacts on the sustainability of a smart building or smart home. When security is lacking and residents are deprived of the sense of safety, a smart building or home then loses its initial purpose and use. Safety and hazard detection in smart buildings has been a more traditionally researched field, but recent developments in big data technology, artificial intelligence, deep learning, and machine learning have evolved the research to another level. What the relatively new technologies have allowed for is prediction in hazard management. Collective data that are rapidly analyzed in real time allow for this type of hazard detection and prevention in smart buildings and smart homes. Vulnerability analysis using machine learning and hazard material prediction via machine learning are two of the research projects that attempt to provide answers to safety concerns in buildings. Wu et al. present research on how machine learning techniques can be utilized to predict the presence of hazardous materials in a building and suggests that the model can help make better informed decisions regarding risk evaluation [34].

The topic of security is often approached from the perspective of either physical security and safety issues or cyber security issues. Previous works also approach the topic of security and safety in smart buildings from such viewpoints but are not limited to them. In the past, residents and managers of buildings had to rely on surveillance systems and access control systems within and around buildings. Although such systems provided necessary safety, as they managed and tracked down individuals entering and leaving the building, the systems were not data-centered, and thus, they often did not reflect real-time collective data. Additionally, the systems required manual surveillance to provide more real-time safety and security measures. Similarly, hazard systems, such as fire alarm systems, merely performed the job of alerting occupants in times of emergency instead of actively making predictions to counter potential accidents and safety hazards. More recent technologies take into consideration the clear limitations of traditional safety and hazard detection systems, thereby working towards systems that can provide real-time data that can be analyzed and put into use to make predictions about dangerous situations.

Additionally, security leakage can lead to direct energy leakage in situations where energy resources or computational resources are used by external sources that have hacked the system. This type of security issue then leads to inefficient energy usage within a smart building or home, which then, of course, leads to a lack of sustainability from an energy perspective as well. King et al. provide insights as to how the evolution of smart buildings and smart building technologies have brought upon security issues regarding facilities within the buildings. The research notes that, due to the interconnective nature of smart building systems, buildings are subject to threats that involve hijacking building automation systems to damage property, destroy or steal sensitive data, destroy environmentally sensitive products, or carry out blackmail. The research also notes that security solutions must not only take into consideration security systems, but also hazard systems, such as fire systems. The paper stresses the need for constant software and firmware updates and resilience strategies in smart buildings [35]. The rise of smart cities and smart buildings, driven by advancements in information technology and IoT, has led to an increase in data generation and the need for efficient IT systems in these buildings. Sándor et al. highlight the critical importance of cybersecurity in smart building design, given the increased vulnerability to cyberattacks due to the integration of various IoT elements [36]. Mylrea et al. note the danger of cybersecurity attacks in smart autonomous buildings, noting that the most registered attacks targeted systems connected and related to the energy value chain or generation, transmission, and distribution [37]. Modern building automation systems (BASs), which are integral to smart building functionality, face increased cyber security threats due to their growing connectivity and Internet accessibility. Li et al. go further to review vulnerabilities and potential cyber attacks on BASs, along with their impacts, and discuss detection and defense strategies across different system levels. They categorize cyber-resilient control strategies for BASs and highlight the need for further research and development in this area [38]. Rathinavel et al. note that using IoT devices in smart buildings increases the potential risk of vulnerabilities in smart buildings and suggest the deployment of software for the secure deployment of IoT devices across the building [39]. Affia et al. introduce a new security risk management framework that incorporates the IoT architecture to enhance the analysis of security risks in IoT devices. A hackathon learning model is proposed to teach participants how to apply this framework effectively. The framework and learning model were successfully integrated into a cybersecurity course, proving to be effective in guiding students in IoT security risk management and application in real-world scenarios [40].

Stamatescu et al. provide perspectives for smart building automation systems, primarily focusing on presenting cybersecurity threats at the device, system, and communication and interoperability levels [41]. Khatoun et al. further discuss cybersecurity and privacy issues and solutions in smart cities by understanding the role and potential threats that exist in smart building services and cyberspace services. The paper also provides multifaceted insights into what roles the government, healthcare, critical infrastructure sector, smart buildings, and transportation sector play in the smart city, thereby providing directions as to how numerous players are correlated in our future cities [42]. Fabrègue et al. discuss the privacy and security risks associated with vast data collection and sharing in smart cities, highlighting the inadequacy of current legal and practical remedies. They emphasize the importance of data privacy in building successful smart urban communities, drawing insights from technology trends and policies in Italy and Switzerland [43].

The most familiar security issues in buildings are physical or cyber intrusion and attacks from outside and illegal sources, and the more well-known safety issues are building hazards. Physical security is closely related to surveillance and keeping track of visitors to prevent and, in times of emergency, efficiently track and hold accountable parties that have created controversy. Ciholas et al. provide a systematic literature review on the security of smart buildings, noting that security issues in smart buildings are inevitable, especially with the growing nature of automation in smart buildings, but they also note the significant lack of empirical evaluations in the field [44].

Cyber security issues require several fundamental traits, namely confidentiality, transparency, integrity, etc., which is why blockchain and smart contracts are often noted as effective technologies to manage security and privacy-related issues within an organization. Rahman et al. present a distributed blockchain-based SDN-IoT network that can be utilized in smart building management. The proposed network is meant to securely transfer data within the smart building while also being automatic [45]. Rathinavel et al. study security concerns and countermeasures in an IoT-integrated smart building, especially in the context of building automation system (BAS) implementation [39].

Recent research has also utilized technologies such as machine learning to distinguish cyberattacks and faults in smart buildings. Patil et al. understand the current security challenges that exist in smart buildings due to the increasing use of IoT devices and how it further complicates the security issues within a building management system. While smarter technologies and devices allow for more convenience, at the same time, they create a window for more security attacks, and this research focuses on how utilizing machine learning technologies may aid in the process of identifying and managing security threats [46].

However, aside from the one-dimensional viewpoint that security and safety are important, and when risks can potentially lead to excess costs that are worth more than initial installation costs, more current attacks on smart buildings have proven to have a direct effect on the energy sector of buildings as well. Elnour et al. present research on how the security aspect of building management systems has become ever more important in today's age due to the rapidly increasing deployment of IoT in buildings. The research provides a Transient System Simulation Toll model that can assess the cybersecurity aspect of HVAC systems in buildings. The research notably compares the suggested model to pre-existing standard machine learning approaches, noting that the suggested model can effectively detect potential cyber attacks with low computational costs and high reliability [47].

Kharchenko et al. suggest a security and availability model for smart building automation systems, thereby working towards a more secure and automated environment for a smart building [48]. Building Automation and Control Systems (BACSs) have continued to evolve from traditional integrated systems to increasingly adopt IP-connected IoT devices, expanding automation but also exposing buildings to more cyberattacks. Despite its growing importance, the security of BACS has been less structured and more superficial compared to other domains like industrial control systems. Graveto, Vitor et al. survey recent research and industry developments in BACS security, discussing existing threats, known attacks, and future research directions [49]. Lork et al. also present research regarding air conditioning energy management but utilize an uncertainty-aware deep reinforcement learning framework. The results from the study reveal that such uncertainty-aware deep reinforcement learning techniques also show more effective discomfort management [50]. Dai et al. address the issue of inefficient cooling in commercial buildings during morning hours, especially in hot seasons, leading to energy waste. They propose a new iterative learning control strategy using Q-learning to manage cooling distribution and achieve uniform cooling across different building zones. The strategy successfully reduced the precooling time by up to 12.1% and reduced daily energy consumption by 5.1% up to 17.8%, translating to significant weekly energy savings in the test building in Hong Kong [51].

The key takeaways from up-to-date hazard detection research are real-time data analysis utilizing technologies such as machine learning. Surveillance systems have also been enhanced due to recent technological developments, as sensor networks, smart cameras, surveillance, pervasive computing, face recognition, etc., are being utilized to further defend systems within smart buildings. Whereas physical attacks and intrusion still rely on surveillance systems and access control systems, more recent security issues focus on the dangers suggested by cyberattacks. Theoretically, without human surveillance added, physical surveillance systems can also be targets of cyberattacks, and defense systems can be disarmed through cyberattacks. Not only are cyberattacks clear risk factors for existing physical security systems, but they can also have a direct effect on other systems throughout a smart building.

As such, most previous works have noted the potential and very potent security risk of cyberattacks, thereby stressing the need to further implement technologies that can actively and more intricately defend systems from outer attacks. Blockchain technology and smart contracts were initially introduced with the hope of strengthening systems by providing integrity. Belgaum et al. also note the newly but very prevalently rising security challenges in smart cities due to the extensive development of technologies like IoT that provide both a more convenient and vulnerable environment security-wise. The results from the research show that smart buildings are the least influenced factor in the smart city environment; nonetheless, the research provides insights into security challenges that will potentially occur as more smart buildings coalesce to build a smart city [52]. Wendzel et al. recognize the potential benefits that smart buildings can gain from saving costs, maximizing resident comfort and security, conveniently interacting with other smart things in the grid, and being environmentally friendly. However, the paper also recognizes the myths surrounding smart buildings and what potential security risks exist in the compensation of the benefits of smart buildings. The paper notes that residents and researchers must be wary of the following concepts of smart building security: the fact that smart buildings are internet-based communications, the impact attacks will have on the physical environment of the building and its surroundings, the issues of long-term software deployment systems, the need for user-oriented software design, the importance of addressing insecure network stack implementations, and the need to distribute freely accessible standards for reference [53]. Li et al. conduct a comprehensive review of smart building research through bibliometric and content analyses, revealing it as a growing, interdisciplinary field with high international collaboration. The key themes identified include the integration of IoT, WSN, and cloud computing for automation, and the focus on balancing energy efficiency with human comfort using continuous monitoring and machine learning. The study introduces a Human–Cyber–Physical System (HCPS) framework, outlining future research directions in occupant-centered smart buildings, such as adaptive building envelopes and integrated management systems [54].

### 2.3. Key Takeaways and Limitations

Previous research has reviewed and thoroughly studied specific topics in sustainable buildings. Many of the studies have primarily focused on reducing energy consumption rates and costs in the buildings, thereby leading to a greener and cost-efficient building environment. In this process, numerous types of artificial intelligence technologies have been utilized in order to simulate the building environment and deduct optimal environment settings. This is also true when simulating a secure building environment, for AI technologies are no doubt the most effective tools for creating simulations prior to implementation.

However, while reviewing previous works, our researchers noticed that, compared to the wide range of technical papers that aimed for a greener sustainable building environment, there was a comparative lack of research focusing on the social aspects of sustainable buildings. Previous studies have all ultimately aimed towards creating a building environment that is greener and sustainable, which includes the concept of a more comfortable and occupant-friendly environment as well.

There is an understanding for the need to not only incorporate the multifaceted aspects of energy and technology, but also societal and geographical aspects that act as key actors in a sustainable building and society. Moving forward, in Section 3, we will introduce a holistic viewpoint of what actors are involved in creating a smart and sustainable building.

## 3. Key Actors of Sustainability in the Smart Building and Smart City Environment

While previous works primarily look at smart buildings from an energy perspective, still, few studies look at sustainability from a holistic viewpoint. As mentioned in the introduction, sustainability is a goal that needs to be observed from numerous aspects in diverse domains and must be achieved at all levels of society to be truly substantial.

Based on previous works and pre-existing research, our research understands the key components of sustainability to include energy, environment, governance, safety and security, and a healthy and wholesome lifestyle.

Energy and the environment come the most naturally as two of the five main factors of sustainability, as previous research also primarily focuses on these two factors in the realm of sustainability. Additionally, the term "sustainability" also tends to stir up a more intuitive connection towards energy and the environment, since sustainability itself is often understood in the same term as being "green", which is most closely knit to the concepts of protecting the environment and reducing energy/carbon emission rates.

Safety and security, however, also relate to the sustainability of smart buildings and society. When security is lacking and residents are deprived of the sense of safety, a smart building or home then loses its initial purpose and use. Additionally, security leakage can lead to direct energy leakage in situations where energy resources or computational resources are used by external sources that have hacked the system. This type of security issue then leads to inefficient energy usage within the smart building or home, which then, of course, leads to a lack of sustainability from an energy perspective.

We classified healthy and wholesome lifestyles as another aspect of sustainability, because ultimately, the comfort and well-being of residents and social members are keys when discussing the sustainability of a smart building and city. The previous works that we reviewed suggested energy conservation in the fields of thermal energy and temperature control for both water and heating systems in smart buildings and households. Such topics are viewed with interest, not only to achieve environmentally friendly carbon emission rates, but also due to interests on a more individual level; these interests include managing energy so that occupants can cut costs and obtain the ideal settings that provide optimal comfort and satisfaction.

Due to the relatively tilted interests towards more macro-level topics, such as environmental friendliness, going green, carbon neutrality, net-zero, and sustainability, the fundamental and important identity of smart buildings almost appears to have been forgotten. The fundamental goal of residential buildings is to customize settings for occupants, thereby achieving optimal comfort and satisfaction for dwellers. Cost management also cannot be overlooked, as both individuals and corporate organizations will only be willing to voluntarily achieve energy-efficient and environmentally friendly smart buildings if there are immediate and tangible benefits, such as cost reduction and energy efficiency.

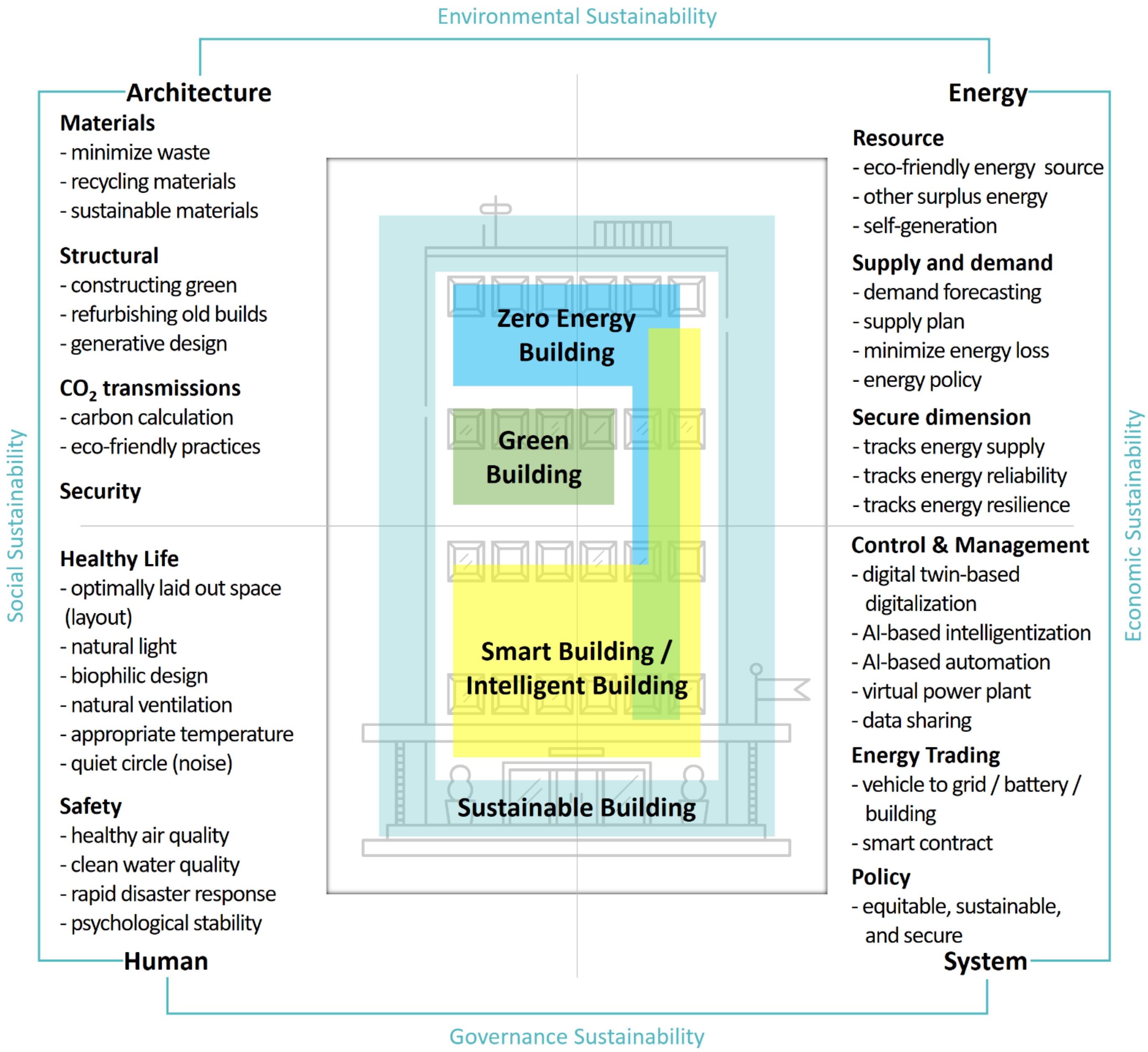
The question that we suggest is "how can creating a comfortable and safe environment for dwellers and residents lead to sustainability?" This question is not just relevant to the topic of energy rates and cost management, but also focuses on creating optimal living environments for building and city dwellers. Dweller-friendly layouts within the building and residential space, lighting that is ergonomically friendly, biophilic designs, ventilation that allows for optimal air conditions throughout the smart building and city, maintaining the most comfortable room temperature for dwellers, blocking out unwanted noise pollution within the building, etc., will be closely related to the overall sustainability levels of the smart building and city as well.

Figure 1 aims to demonstrate our definition of a sustainable building. The various yet slightly different terms that are frequently used interchangeably are introduced, as the other terms collectively lead to the definition of a sustainable building in this research. The terms zero-energy building, green building, and smart/intelligent building may, at a glance, seem to share more similarities, but they focus on different goals and purposes.

We have classified and selected four dimensions as the key actors that characterize and define a sustainable building: architecture, energy, human, and system. The architecture category includes actors such as materials used in the construction of the building, the structure of the building, and the $CO_2$ transmission of the building. The energy category includes the energy resources used in the building and how energy is generated, the supply and demand systems and policies, and the secure dimensions of energy in the building. The human category looks at actors that are more closely related to occupant comfort. The health and safety of occupants are included under the human category. Finally, the system category introduces actors that directly compose the infrastructure and system of the building. Control and management methods and technologies, energy trading technologies and contracts, and policies are included under the system category.

The name zero-energy building suggests that the building's core focus is on reducing the carbon emission rate and excess energy consumption. Omrany et al. provide a bibliometric review of net zero-energy buildings and research on the topic, noting that the concept of net zero-energy buildings is built from the goal to reduce energy consumption and $CO_2$ emissions that occur from buildings' operation. In order to curtail the dependency on fossil fuels, zero-energy buildings urge the production and utilization of renewable energy [55]. Wu et al. even define net zero-energy buildings as buildings that can at least generate just as much energy as the buildings consume, suggesting that net-zero buildings can be achieved through minimizing the energy demand within buildings via improved building designs and occupant habits, or by further increasing the amount of renewable energy generation [56]. Ahmed et al. note that buildings can achieve net-zero energy and reduce carbon emissions drastically through retrofits, integrated building design, and energy conservation [57]. Thus, it can be agreed that zero-energy buildings focus most heavily on energy resource allocation and production, energy trade based on supply and demand within and outside of the buildings, renewable energy resource production and self-sufficiency, and what materials were initially used in the construction of the buildings. As such, zero-energy buildings focus on the environmental sustainability of the buildings but lean less towards the human aspect of the building environment.

A green building may appear to be similar, if not identical, to a zero-energy building, but it is even more limited in its definition and core actors. Green buildings primarily and almost solely focus on how environmentally friendly the buildings are, not in their operation, but simply regarding their architecture and construction processes. Li et al. note that the key characteristics of green buildings is that they are designed to reduce the strain on environmental resources by efficiently utilizing natural resources and reducing garbage. This, in turn, aims to have positive effects on resident health and improve the sustainability of the construction industry [58]. Energy is also an interest in green buildings, especially regarding energy consumption and carbon emission rates, but green buildings focus on a smaller scope compared to the other building types mentioned in this paper.




- Green Building : Architecture and Energy Focus
- Zero Energy Building : Architecture, Energy and System Focus
- Smart Building / Intelligent Building : Energy, System, and Human Focus
- Sustainable Building : Architecture, Energy, System, and Human Focus

**Figure 1.** Various evolved building concepts.

Smart buildings or intelligent buildings aim for environmental sustainability and system management that are necessary for smarter energy usage and trade. Additionally, a smart or intelligent building aims for a more comfortable living environment for occupants. Dakheel et al. note that a smart building utilizes an advanced control system and smart meters along with energy storage and demand-side flexibility. The research also defines a smart building as a space that reacts to occupant and user needs and is also able to diagnose faults that can occur in the building operations [59]. Froufe et al. note that smart buildings' definition evolved over time, stating that the earlier definition of smart buildings emphasized the digital, technological, and innovational aspect of cyber cities and buildings. However, since the 1990s, smart buildings started to focus more on user interaction and social context with the ultimate goal of improving the quality of life [60]. Thus, it can be agreed that smart buildings also work towards the automation of such services that enhance occupant experience and suggest not only more comfortable but also safer building environments and systems for occupants.

Finally, the sustainable building in our research combines all of these actors mentioned in the other buildings and furthermore aims for a long-term sustainable building and city environment by reducing energy usage and carbon emissions by intelligently utilizing and distributing energy resources within and outside of the individual building. Such measures ultimately work towards creating a cleaner, cost-effective, and safer living space for occupants, which will then lead to the extended use of a building for the sustainable city. Therefore, we define a sustainable building to be a building that holistically incorporates the systematic and architectural aspects of a building in order to create a more environmentally and occupant-friendly building environment. Sustainability is not limited to the individual building, but ultimately, the larger society and city environment as well.

Figure 2 notes the values that were considered in this research when selecting the five evaluation indexes of a sustainable building. The following figure was drawn from a marketing perspective, but we derive the core concepts from the figure. In a sustainable building, the first two evaluation indexes mentioned are equivalent to the functional value mentioned in the figure below. However, we found further significance in the figure below due to the emotional value and lifestyle value. We have already reviewed previous works that understand the importance of occupant comfort and eco-friendly building environments, and the emotional value and lifestyle value accurately suggest how such aspects should also be taken into consideration to obtain a sustainable building environment. Of course, not all of the characteristics introduced in the figure directly translate into the necessary sustainability aspects of buildings, but the figure is noteworthy in that it provides insights into what non-technological and non-functional values exist from a consumer or occupant perspective.

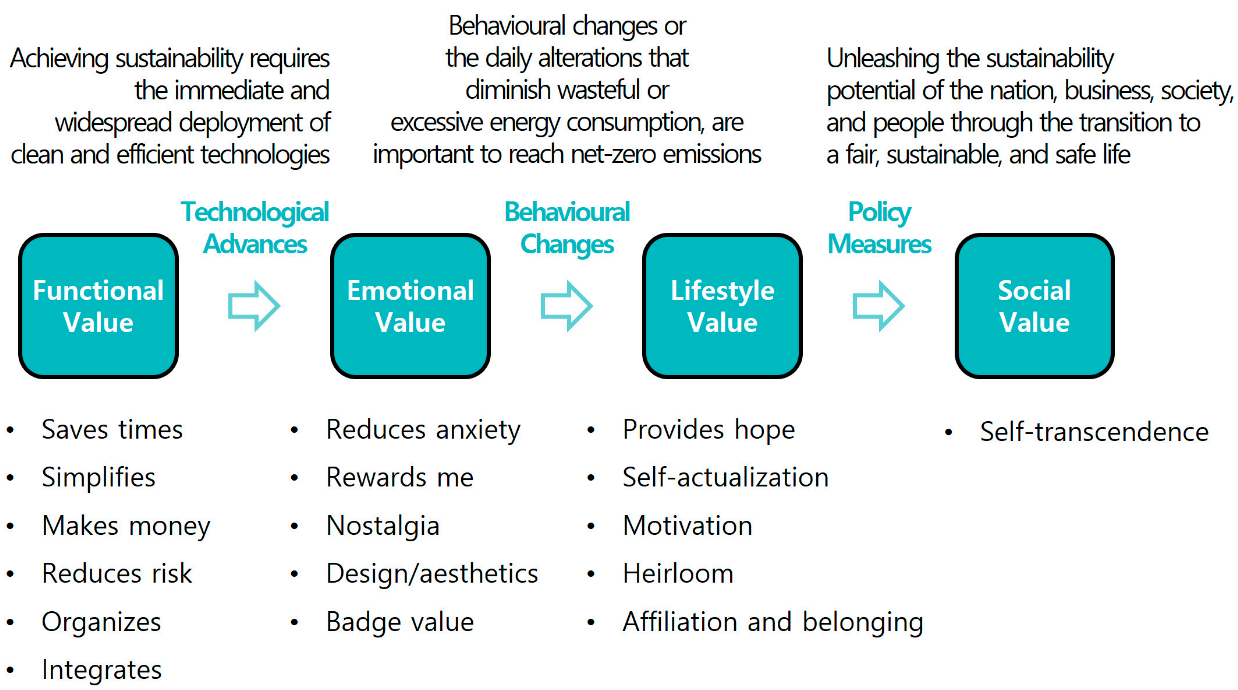



**Figure 2.** Step-by-step change in values for sustainability.

Finally, we include governance as a key factor towards reaching a sustainable living space and society, because governance will provide clear-cut guidelines for individual buildings and cities. Governance, in the realm of obtaining societal sustainability via smart buildings and cities, is an issue that must be viewed from multifaceted viewpoints. That is to say, numerous elements, including environmental, sociological, economical, and technological elements, must be considered and must each have their own governance policies to abide by. However, governance policies also need to be somewhat customized depending on the city or society that they are being applied to.

For instance, a port city like Busan will have different geological elements, demographics, technological availability, and nearby energy resources that can be efficiently utilized compared to those in Seoul. Similarly, a city in Gangwon province will be different from Seoul in that it can most easily utilize wind power as its core energy source, and once again, the demographics, residential patterns, and technological advantages may be different as well.

Our research notes that such differences between cities are fundamentally existent, and thus, we provide a sustainability scoring system that will draw a framework for the sustainability of different cities and societies. To first derive governance policies, our research collects and analyzes data from buildings and society. That is to say, the following section of this paper will analyze big data from buildings, smart buildings, energy usage, and other environmental data along with social environment data, such as pre-existing policies, and collectively analyze what governance policies may be effective for the current and diverse societies. The conclusive governance policy derived will then be applied in the digital twin to review its effectiveness, and from the results, the sustainability scoring system will be derived.

## 4. A Building and Society Approach to Sustainability for Carbon Neutrality

Before providing a sustainability scoring system for cities, our research will first provide a digital twin-based model that collects big data and conducts an AI-based analysis in order to derive more specific guidelines for sustainability. The overview of the model is presented visually in Figure 3.

Utilizing digital twin technologies is not an uncommon research method in this field of research. Previous works have also extensively explored the potential of digital twins in the field of energy research. Xia et al. recognize that combining building information modeling and IoT technology can fulfill the needs of digital twin processing and information management needs at the building and city levels [61]. Digital twin technologies are not just effective for modeling and monitoring energy usage levels in a building or city but have also proves to be resourceful in measuring the levels of comfort in communities. Zaballos et al.'s research aims to obtain digital twin modeling to measure different aspects of comfort in a smart campus. Thermal comfort, acoustic comfort, and visual comfort were the measured and modeled aspects, along with energy efficiency modeling [62].

Given that digital twin modeling has proven to be resourceful when modeling and measuring different indexes that are included in the larger picture of sustainability, our research also suggests a digital twin-based model for a more sustainable building environment. First, we suggest two viewpoints when discussing sustainability: the viewpoint that is primarily concerned with economic benefits and energy efficiency, and the social environment viewpoint, which involves governance and policies surrounding sustainability.

The first viewpoint, which is the building energy and environment data viewpoint, includes aspects such as BIM, BAS, SEMS, microgrids, etc. Concepts and technologies regarding BIM and BAS are the most prevalent and traditional building systems within smart buildings. BEMS and microgrids are more developed building systems that utilize IoT, sensors, and power grids. Such building systems can effectively manage energy but have clear limitations when applied to sustainable buildings.

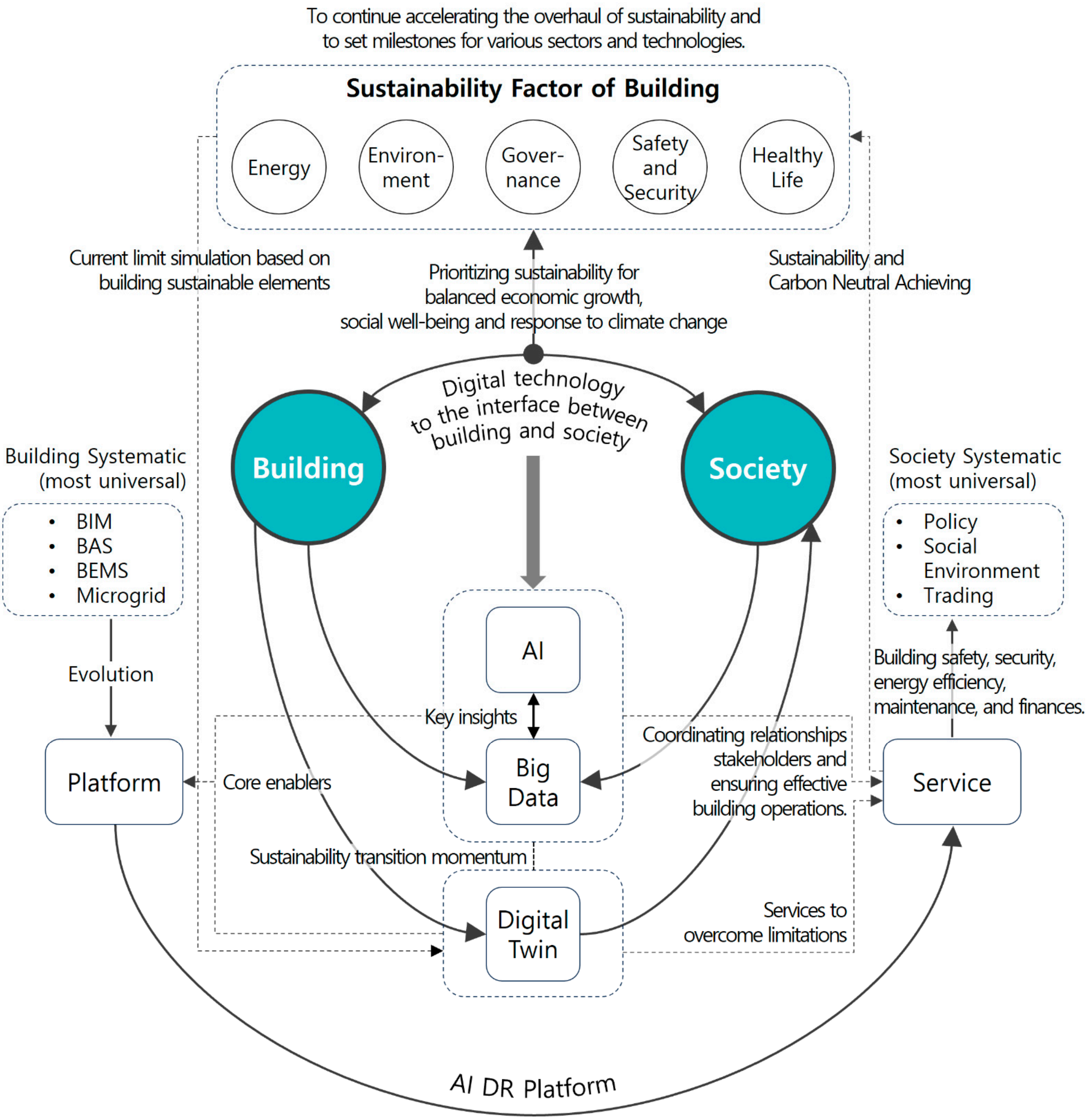



**Figure 3.** Approach to a sustainable building concept.

One of the most prominent limitations would be that each building operates independently, meaning that there is zero connectivity with other buildings. This scalability issue leads to issues with sustainability, as a single building cannot lead to expanded sustainability, as the operation of a single smart building also cannot lead to expansive sustainability due to limitations in energy production. Similarly, the flipside also includes limitations in the supply of energy sources from outer sources, and ultimately hinders the construction of a flexible and elastic supply and demand system.

Also, the lack of correlation between buildings indicates that there is likely a lack of reliable data because data from a single building will lack diversity and quality. To fix such limitations, data access rights, data usage methods, and data security all need to be reviewed and reorganized.

The second viewpoint of social environment data includes social systematic topics, such as policy and governance. There are, of course, preexisting policies and regulations regarding smart buildings, but currently, there are insufficient operating policies tailored to the social environment, such as building characteristics, resident characteristics, and the surrounding environment. Thus, it is important to understand that, to create a sustainable building, there first needs to be sustainable services that are provided within the building and also to the building. In that sense, governance and policies must be tweaked according to social environments.

However, the initial necessary stage would be to first define and categorize elements of social environments. For instance, understanding that surrounding environments play a role in defining the levels of sustainability for a city/building and understanding that the proximity of green energy resources affect the sustainability levels of a city/building will be the first steps to recognizing specific elements for sustainability elements. Thus, creating diverse city environment scenarios that include aspects of energy trade, existing governance, the population density within a city/building, existing grid scalability, etc., will be critical to further understand and set clearer governance guidelines for the sustainability of social environments.

The question of "how we can evolve from existing social systematic policies to sustainability" must be answered first. Our research suggests that digital twin technology may be an efficient technology that can make this process a reliable and efficient one. Customized policies and sustainable services are set, according to the social environment, through digital twins based on sharing between data from a social perspective and data from a building perspective. This is based on the need for policies that promote social and economic development that are sustainable, energy-efficient, and environmentally friendly.

The goal is, of course, ultimately realizing sustainability through the intersection of the two perspectives mentioned above using digital technologies. Through digital technologies, points that can connect the two perspectives are derived, and based on this, the sustainability of smart buildings is realized. The digital technologies that we recognize in this research are AI and AI with Demand Resource (DR), big data, and digital twins with a virtual power plant (VPP).

The first step is the forecasting process through AI. This stage aims to understand and predict efficiency, economics, sustainability, security, and other aspects that will contribute to creating a sustainable building and social environment. A means for precise and efficient prediction is needed, and AI is used to overcome complex value chain problems between the energy supply and demand processes through AI-based intelligence. This stage is an absolute necessity, as for sustainability, the early prediction of volatility due to social/environmental changes is essential, and there are numerous aspects of data that play into making such early-on predictions. Some of those aspects include an increase in energy data, system complexity, changes in operation/management systems, the diversity of energy flows, the transformation of social values, and the emergence of new markets/industries and new strategies in the new economy.

Due to the increase in energy data, the generation of energy big data, stabilization through energy security and security, and improvement in energy efficiency must also be considered. In short, energy must also become digital in line with the evolution of building systematics. Regarding system complexity, the expansion of energy demand and increase in distributed resources, increased connectivity between energy production–delivery–storage–consumption, and changes towards P2P (Platform to Platform) are aspects that must be taken into account, as there is increased focus on system connectivity/scalability. Changes in operation and management systems indicate the need for a sustainable expansion in carbon neutrality from buildings to the city level. Elements such as the digitalization of infrastructure/data and new management measures through digital innovation (integrated management, virtual power plant (VPP), and increase in management scope) will have to be examined as players in reaching sustainability.

The rise of energy trading and prosumers has promoted a shift from centralized, one-way energy supply to a two-way supply–demand situation. Unlike the previous elements mentioned, which were primarily elements in the evolution of building systematics, the concept of diversity in energy flow and trade is a more social systematic evolution. The transformation of social values and the emergence of new markets and industries are also parts of the social systematic evolution. One of the most prominent changes in social values includes ESG-based sustainable management, which, in detail, shows transformation in regulation, investment, evaluation, and customer interests as well. The topics in new markets/industries and new strategies, including energy/system transition, shared economy, carbon-neutral economy, decarbonization, carbon-neutral city, etc., require an expansion in the existing grid and convergence between industries and economies.

The data and elements collected and analyzed through AI are then shared via big data, and sustainability is examined through data from buildings and social sectors. This big data is then utilized to verify sustainability from a building perspective-based social perspective through simulation and optimization using digital twin. Finally, AI with the DR platform provides sustainable services through a sustainable perspective, which umbrellas both the building perspective and social perspective.

## 5. Sustainability Scoring Index

With the understanding that sustainability must be approached from a multifaceted viewpoint that incorporates both the social and energy aspects, we suggest a scoring index. The suggested index includes and further identifies, in detail, the players that create a sustainable building and social environment mentioned in the previous section. However, it must be mentioned that we have selected the indexes based on whether they can be strictly digitized and evaluated objectively.

The five categories are energy, environment, governance, safety and security, and a healthy and wholesome lifestyle. Each large category is then specified into smaller categories, which are listed below.

The energy category is meant to assess how "green" or sustainable the energy being used within the smart building is. Thus, the first smaller category is "the ratio of green energy usage". For this study and classification, we view "green energy" as the equivalent of "renewable energy". Green energy is viewed only strictly as an energy resource in this category, and buildings or organizations are assessed based on how much green energy is used in terms of the overall energy usage. The next smaller category is the "energy independence rate", which indicates how much green energy is included in the overall energy consumption. Both the "ratio of green energy usage" and "energy independence rate" require a range of time to be set in order to make accurate assessments and be ranked accordingly. Finally, an "energy efficiency rating certification system certified by a public certification agency" will be the third evaluation system in the energy category. This public certification is issued by the Korea Energy Agency in Korea and by Energy Superstar in the US. The assessment standard will depend on whether the organization or building has gone through regular evaluations by the public certification agency, and what rating it has received.

The environment category indicates the social environment status and infrastructure of where energy is produced, how it is delivered, and how and where it is consumed. Hence, the first smaller category is "green energy delivery distance". Considering the nature of green energy being consumed during the process of delivery, naturally, a higher rating will be given when the delivery distance is shorter. A shorter delivery distance indicates that more energy will be successfully delivered to the destination, and thus proves to be a more efficient delivery process. The second smaller category is the "ratio between EV distribution rate vs. EV charging station". This is one of the more direct infrastructure indications, and of course, a higher rating will be granted if the EV charging stations are sufficient to the number of EVs distributed. The third smaller category is the "carbon reduction per year/month". The final category is an extended version of the third category, as it is the "carbon reduction compared to a thousand years/month". Both categories are clear indications that actively indicate how carbon-neutral goals are being met, and have thus been selected as smaller categories of the larger social environment and infrastructure category. Table 1 shows the indexes for sustainability building evaluation in energy and environment categories.

**Table 1.** Sustainability building evaluation index in energy and environment category.

| Category | Index | Key Components [1] VP-A [2] | Key Components [1] VP-B [3] | Detailed |
|---|---|---|---|---|
| Energy | Green energy usage | 5, 6, 16 | 26 | The ratio of green energy a building uses. (Green energy rate) = (Amount of green energy used)/(Total energy usage) |
| | Energy independence | 1, 5 | 26 | The ability of a building to generate and sustain the necessary energy independently without relying on external energy sources. (Self-sufficiency rate) = (Amount of energy self-produced)/(Total energy demand) |
| | Public certification for energy | 3 | 20, 32 | Compliance of the building energy performance with government or government-recognized energy certification programs. (The total sum of certification points with applied weights) |
| | Green energy accessibility | 3, 5 | 26, 28 | How easily a building can access and utilize green energy generation sources (GEGSs). (Green energy accessibility) = (Proximity to GEGSs) × (Capacity of GEGSs) × (Number of available green energy sources) |
| | Energy resilience | 5, 6 | 23, 26 | The ability to readily meet the energy demand of a building through the possession of reserve energy. (Energy reserve rate) = (Capacity of reserve energy)/(Total energy demand) (Reserve energy recovery time) = (((Capacity of ESS batteries) × (Capacity of green energy system))/(Total energy demand)) × (Unit time) |
| | Eco-friendly mobilities acceptability | 4, 7, 8 | 29, 30 | The capability to respond to the energy demand of eco-friendly mobilities. (The total of EV demand energy)/(Capacity of EV chargers) |
| Environment | Carbon reduction | 4, 5, 16 | 21 | The extent to which a building reduces its carbon emissions. ($CO_2$ reduction rate) = 1 − ((Current $CO_2$ emissions)/(Baseline $CO_2$ Emissions)) |
| | Climate adaptation | 2, 15 | 31 | The ability of a building to respond to and adapt to changing climate and environmental conditions. (Energy consumption ratio per climate value) = (Amount of energy consumption)/(Difference in internal and external environmental data values) (Energy efficiency ratio (EER) of HVAC system) = (System capacity)/(Power consumption) |
| | Greening | 4, 18 | 19, 27 | Sufficient green space in the building. (Green space ratio) = (Area of green space)/(Total floor area of the building) |

[1] Figure 4. Key components for building sustainability. [2] Viewpoint of building energy and environments. [3] Viewpoint of social systematic elements.

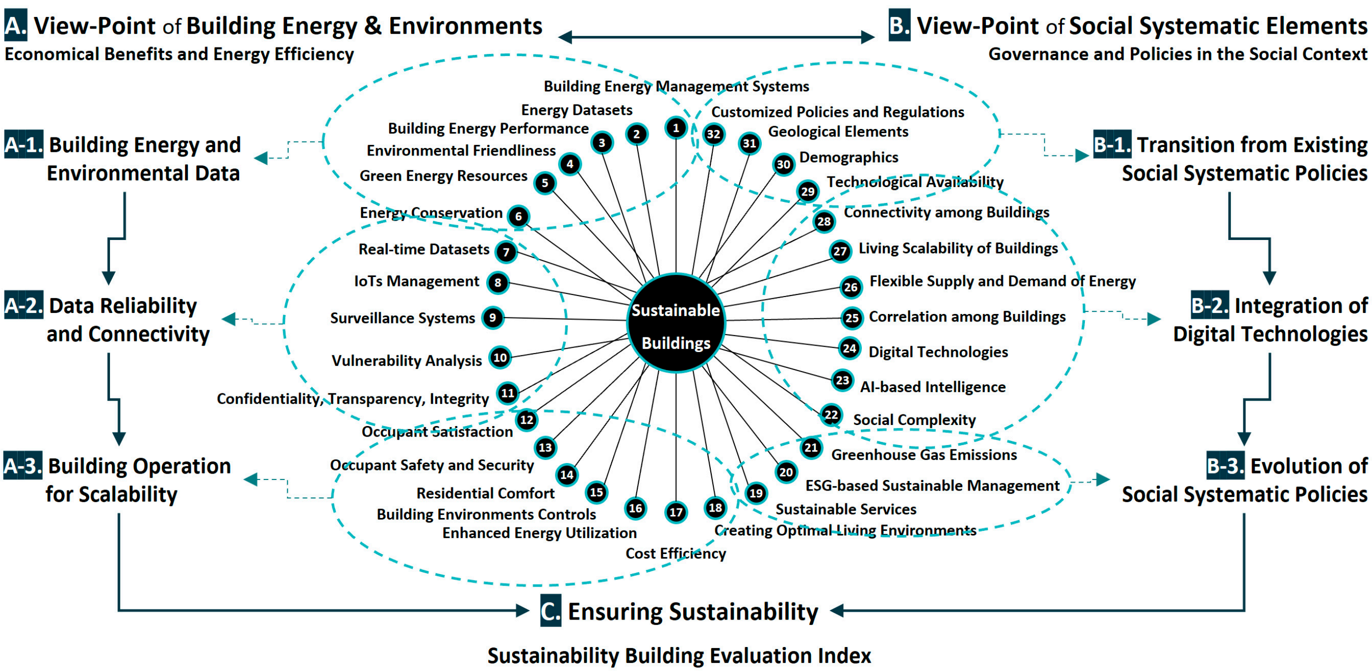



**Figure 4.** Key components for building sustainability.

The third larger category selected is the governance category and is focused on understanding the general flow of energy and people within smaller communities. The first smaller category is the “energy transaction rate” and any consortiums that may exist between buildings and communities to further enact the energy transaction process effectively. The second smaller category selected is the “population density within the community”, and the third smaller category is the “building density within the community”. The two smaller categories share some commonalities and are also reflective of one another in that communities with lower population densities but high building densities may lead to unused building spaces, which, in turn, lead to the direct unsustainability of buildings. Vice versa, communities with high population densities but comparatively low building densities also require more building infrastructure, leading to further policies, technology systems, etc., to maintain a sustainable building and city environment. All smaller categories in the governance category will be graded based on the policy implementation rate and degree of implementation compared to the targeted goals.

The fourth category is safety and security. The first smaller category is security from a data security perspective and is classified as “how much data security programs are implemented within the building”. This category is judged based on the number of cyber security attacks the building has undergone annually, and whether necessary security programs or measures were equipped and applied. The second smaller category then goes into the topic of security from a physical standpoint and is classified as “data management methods”, “physical barriers”, and “physical equipment such as cords connecting within and outside of the building”. Data management methods include how surveillance systems and the data from these systems are managed, and how management systems are regularly updated. Physical barriers include the management and effectiveness of both surveillance equipment within and outside the building, and any other physical barriers that may prevent trespassing or external threats towards residents of the building. Finally, the management and protection of cords that deliver or receive energy from outside of the building are included as the final subcategory of security, as the damage of such physical equipment leads to energy leakage and lower energy efficiency rates.

For the smaller categories of safety, the primary goal is to assess how well the building is prepared for any potential hazards. The smaller categories include “how equipped the building is in case of any fire, flood, earthquake or natural hazards”, “how efficiently emergency and shut down systems are managed", and "how hazard reports or feedback from residents are being managed". Since most buildings undergo regular hazard check-ups by law, this category focuses more on the aspects that are necessary for residents to feel safe and stable within the building. Depending on the region or country, the categories for hazards may also focus more heavily on human hazards, such as gun attacks, or focus less heavily on certain natural disaster hazards. This category also relates to the psychological stability of residents, which will be further discussed in the following and final category.

Finally, the final larger category is the health and well-being of residents. This category, of all categories, was more difficult to classify due to its somewhat subjective nature of assessment. This also means that, most of the time, the well-being and satisfaction of building dwellers are often overlooked in the building environment, which makes this category all the more important because the healthy lifestyles of building dwellers will lead to more satisfied residents and thus prevent abandoned or empty buildings in the long run, leading to a more sustainable building and community environment. Keeping this in mind, the first smaller category is "energy control in relation to resident comfort". This category includes aspects of ventilation, room temperature management, and noise levels within the building/public spaces and individual rooms. Each aspect is measured to create a total score for the subcategory. The second smaller category is "resident friendly design", which includes aspects of the use of natural lighting and biotechnical designs. This subcategory focuses more on the psychological comfort of residents, whereas the previous subcategory focuses on the physical comfort of residents. Of course, both subcategories are closely interrelated, but for the purpose of assessment, the two were divided as separate scoring indexes. The third smaller category is "resident healthy technology", which includes whether the building adequately includes and distributes technology, such as IoT and health management systems, or emergency health aid within the building. Other aspects that were considered under this category included the usage of human-friendly building materials during construction and the existence of natural building spaces such as garden space rations within the building, but the two aspects were more difficult to implement after the construction of the building, and hence, were not included in our scoring index.

## 6. Scenario of How the Scoring Index Can Be Applied in Different Regions

Since we have provided a scoring index in the previous section, this section is dedicated to providing a simple scenario of how the scoring index can be applied in different regions, and what regional or societal conditions will affect the scoring process.

For the purpose of this study and for easy understanding of how the scoring indexes can be applied, we chose two cities in South Korea: Seoul and Jeju Island. Additionally, since specific buildings were not selected for this scenario, building surroundings, regional characteristics, and the green energy impact will be primarily discussed in this scenario.

It is first essential to understand the two regional and social differences between Seoul and Jeju Island. Seoul is first an inland area, and as it is the capital city of South Korea, the population density and building density are very high. Although some of the working population resides and tend to move to the outskirts of Seoul or satellite cities surrounding Seoul during non-office hours, the city is still generally densely populated throughout all times of the day and year. Additionally, there are many high-rise buildings in Seoul, which means it is an unsuitable environment to collect naturally sourced green energy, such as solar energy and wind power energy. In regions with a high building density, such as Seoul, there is a lack of a separate installation space. Table 2 notes detailed geographical differences between the two cities.

When applied to existing buildings, the area and location where the system can be installed are very limited. The reconstruction of buildings for green energy production is also very limited. Wind energy also has constraints on land and wind speed. In inland regions, such as Seoul, the efficiency of urban small-scale wind power generation is significantly low due to low wind speeds. Additionally, onshore wind power generation does not currently exist in Seoul, and efficiency is low due to the long distance from nearby onshore and offshore wind power farms. Hence, Seoul is, all in all, a city that is unsuitable for generating green energy, but will primarily act as a heavy energy-consuming city. Solar energy has land and building constraints.

**Table 2.** Regional characteristics of Seoul and Jeju.

| 2021~2022 | Region | Seoul | Jeju |
|---|---|---|---|
| Land | Land area ($km^2$) | 605.2 | 10,850.2 |
| Human | Population status (thousands) | 9411 | 676 |
| | Population density ($people/km^2$) [1] | 15,551 | 365 |
| Building | Building status (building) | 560,460 | 184,921 |
| | Construction compressibility (%) [2] | 114.26 | 4.97 |
| | Building complexity (%) [3] | 19.2 | 1.95 |
| | Building energy consumption (TOE) in 2021 | 7,650,243 | 311,447 |
| Green energy—solar | Opening of solar power plant (opening) | 548 | 1680 |
| | Solar power plant capacity (MW) | 49 | 546 |
| | Solar power generation in 2021 (MWh) | 244,804 (Business + Personal) | 676,330 (Business + Personal) |
| | 2021 solar energy production (TOE) | 55,298 (Business + Personal) | 145,474 (Business + Personal) |
| Green energy—wind | Onshore/offshore wind power plants (units) | 0 | 24 (127) |
| | Onshore/offshore wind power plant capacity (MW) | 0 | 298.7 |
| | Wind energy generation in 2021 (MWh) | 198 (Only Personal) | 529,363 (Business + Personal) |
| | 2021 wind energy production (TOE) | 45 (Only Personal) | 112,780 (Business + Personal) |
| | Average wind speed (m/s) | 2.4 | 3.7 |
| | Maximum wind speed (m/s) | 7.7 | 12.4 |
| EV | Electric vehicle chargers by 2022 (units) | 34,602 | 5872 |
| | Number of electric vehicle registrations in 2022 (units) | 59,327 | 32,976 |
| | Electric vehicle/charger ratio (car charging ratio) [4] | 1.7 | 5.6 |

[1] Population density: number of people per 1 $km^2$; formula: number of residents divided by area. [2] Compression: proportion of total floor area per unit area (volume ratio); formula: total floor area of buildings in Seoul/Jeju grid divided by grid area (0.25 $km^2$) $\times$ 100% average, grid: 500 m $\times$ 500 m. [3] Complexity: an indicator of how diversely an area is being utilized for various purposes. Formula: ratio of more than 12 different types of building uses out of the entire grid. Grid: number of uses within 500 m $\times$ 500 m. [4] Charging ratio: number of electric vehicles per charger.

Jeju Island shows stark differences from Seoul, as it is first, of course, an island. Heavy winds allow for the easy collection of wind power, and since the island does not have many high-rise buildings, it is also easier to collect solar power. Such geological characteristics allow for high distribution ratios of eco-friendly/green energy, and Jeju Island has a high distribution rate of electric vehicle charging infrastructure. This indicates that Jeju Island is, by itself, both an efficient and energy-friendly provider and consumer of green energy.

Going back to the scoring index mentioned in the previous section, we will briefly cross-examine how the two cities would score in the two categories of energy and environment. The purpose of this examination is to provide an overall understanding of how the scoring index can be implemented for communities and buildings and does not go into extreme detail.

The first smaller category of the energy category is "energy ratio of green energy usage". In the case of Seoul, green energy generation is more difficult than it is in Jeju, and the operation of green energy power generation complexes is highly difficult, so unless Seoul city constantly receives green energy from other cities, the intuitive scoring to this category would be "low". Compared to Seoul, however, Jeju Island has geological environments that allow for the easier collection of green energy, and it is generally a green energy self-sufficient city, so the intuitive score for this category would be "high". Similarly, the scoring for the subindex "energy independency rate" would also show nearly the same scores for each city for the previously mentioned reasons. Seoul is generally a non-self-sufficient city when it comes to green energy generation, and Jeju is a highly self-sufficient city in green energy collection, generation, and consumption.

The first smaller category of the environment category is "green energy delivery distance". Green energy is easily generated and distributed within Jeju Island, making the island a green energy self-sufficient region. This indicates that the delivery distance will be very short, and thus, Jeju Island would score "high" in this subcategory. However, Seoul is a non-self-sufficient city when it comes to green energy generation and consumption, and thus would have to receive green energy from other regions across the country. In this case, the green energy delivery distance inevitably becomes longer, which means the amount of green energy being delivered will be canceled out with the energy being used during the delivery process. Thus, Seoul would also score lower in this category compared to Jeju Island.

The second subcategory is the "ratio between EV distribution rate vs. EV charging station". As mentioned before, Seoul is a very densely populated city, meaning that there are more vehicles and more EV vehicles than most cities in South Korea. However, EV charging systems are somewhat lacking compared to the EV distribution rates, especially with recent abrupt changes to implement more EVs, even for public transportation, to reach the carbon-neutral goal. The continued expansion of electric vehicle charging infrastructure will improve the accessibility of charging stations and increase operational efficiency. With increased charging infrastructure and number of electric vehicles, the demand for more electric energy is a natural phenomenon. However, in the short term, it is highly likely that the energy source supplied according to the immediately increased energy demand will be supplied based on existing chemical energy sources. This is another obstacle to going carbon neutral. In line with the increased energy demand due to the expansion in the electric vehicle supply, the production/supply of green energy must also increase accordingly. Now, as the impact of electric vehicles on the sustainability of buildings gradually expands, buildings, electric vehicles, and charging infrastructure will be integrated into one infrastructure, replacing existing general parking lots. In other words, we must now review the sustainability of not only the eco-friendliness of buildings and connected urban elements and infrastructure, but also the energy sources needed to operate and drive them and the methods of producing those energy sources.

Although we have not touched upon all of the scoring index categories, the purpose of the scenario was to provide an overall understanding of how the scoring index will be put into action for different cities and different buildings within the city as well.

The purpose of the scoring index is to understand certain blind spots within the city or building environment that create excess energy consumption, non-eco-friendly energy generation, discomfort for city and building dwellers, and a lack of active policies to fix such issues. Such problems within the city or building environment will easily lead to energy generation and consumption that is far from green, will not help to cut down on carbon emission rates, and drive residents out of certain regions or buildings, leading to an overall unsustainable building and city environment. Thus, it is important to understand such problematic blind spots and be able to specifically assess which areas must be further worked on to create a sustainable building and city environment.

## 7. Conclusions and Future Works

In this paper, we focused on identifying the active players that will help reach a sustainable and carbon-free society today. For this study, we dissected players within the building and community levels with the understanding of how green energy and the generation, distribution, and consumption of it will play major roles in reaching a more sustainable building and city environment. Not only that, but we also understand that energy is not the one and only player in reaching the societal goal towards carbon neutrality, and thus, we identified players within the social environment as well.

The scoring index suggested in this identifies specific aspects that can objectively assess such players, and goes on to link aspects such as governance, safety and security, and healthy lifestyles for dwellers within the building and city—these are all important but often overlooked players in the conversation of reaching energy and social sustainability.

For future research, we will aim to further expand and specify the scoring index by actively testing and simulating the green energy generation rates a city can realistically reach during specific timeframes and determine the most energy-efficient energy trading route between cities. Additionally, future works will aim to simulate the smart building in the digital twin to gain optimal energy consumption choices that will lead to reduced energy consumption and costs.

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