applied sciences

Review

The Green Cooling Factor: Eco-Innovative Heating, Ventilation, and Air Conditioning Solutions in Building Design

Bashar Mahmood Ali [1,*] and Mehmet Akkaş [2]

[1] Graduate School of Natural and Applied Sciences, Kastamonu University, Kastamonu 37150, Turkey
[2] Department of Mechanical Engineering, Faculty of Engineering and Architecture, Kastamonu University, Kastamonu 37150, Turkey; mehmetakkas@kastamonu.edu.tr
* Correspondence: bmali@ogr.kastamonu.edu.tr

Abstract: This research investigates the compatibility of conventional air conditioning with the principles of green building, highlighting the need for systems that enhance indoor comfort while aligning with environmental sustainability. Though proficient in regulating indoor temperatures, conventional cooling systems encounter several issues when incorporated into green buildings. These include energy waste, high running costs, and misalignment with eco-friendly practices, which may also lead to detrimental environmental effects and potentially reduce occupant comfort, particularly in retrofit situations. Given the emphasis on sustainability and energy conservation in green buildings, there is a pressing demand for heating, ventilation, and air conditioning (HVAC) solutions that support these goals. This study emphasises the critical need to reconsider traditional HVAC strategies in the face of green building advances. It advocates for the adoption of innovative HVAC technologies designed for eco-efficiency and enhanced comfort. These technologies should integrate seamlessly with sustainable construction, use greener refrigerants, and uphold environmental integrity, driving progress towards a sustainable and occupant-friendly built environment.

Keywords: HVAC; thermal comfort; green buildings; outdoor air conditioning

check for updates

Citation: Ali, B.M.; Akkaş, M. The Green Cooling Factor: Eco-Innovative Heating, Ventilation, and Air Conditioning Solutions in Building Design. *Appl. Sci.* **2024**, *14*, 195. https://doi.org/10.3390/app14010195

Academic Editors: Luisa F. Cabeza, Daniel Sánchez-García and David Bienvenido Huertas

Received: 10 November 2023
Revised: 7 December 2023
Accepted: 21 December 2023
Published: 25 December 2023

1. Introduction

Recent years have seen a considerable breakthrough in outdoor air conditioning systems, altering the way we cool our living and working environments while fostering sustainability and the energy economy. This introduction provides a summary of the main advancements in outdoor air conditioning and bases its discussion on reliable sources. Outdoor air conditioning technology has advanced to solve challenges like energy usage and environmental effects. To minimise energy consumption and lessen the carbon footprint of cooling operations, modern systems use cutting-edge designs and materials [1]. These developments have produced a more environmentally friendly method of outdoor cooling. Incorporating renewable energy sources, such as solar electricity, into cooling systems is a major development in outdoor air conditioning. This method considerably lessens dependency on conventional, fossil-fuel-based power generation by using the abundant energy from the sun to power air conditioning processes [2]. Using renewable energy for outdoor cooling is an appealing breakthrough, with potential environmental advantages and lower energy costs. Additionally, the development of intelligent outdoor air conditioning systems that are IoT-connected has revolutionised how we manage and control cooling in outdoor environments. These intelligent systems adapt dynamically to shifting environmental circumstances by utilising data analytics and real-time monitoring to maximise cooling efficiency [3]. Such technology improves user comfort while also promoting energy efficiency. Finally, advancements in outdoor air conditioning systems have significantly improved customer comfort and pleasure. Outdoor cooling systems now ensure occupants breathe clean, hygienic air and maintain the proper temperature thanks to advancements in air distribution and quality control [4]. Adaptation strategies for addressing climate change can be effective. Using spectrally selective glazing, summer overheating can be diminished by 15%. Implementing high-performance glazing reduces cold discomfort by 24% and heating needs by 22%, but it can also increase warm discomfort. Shading solutions stabilise energy consumption while cutting summer discomfort by as much as 44%. Thermal insulation reduces winter discomfort and halves energy usage, although it may increase summer discomfort by up to 41%. Climate change projections for 2050–2100 indicate a potential increase in warm discomfort hours by up to 70%. However, adaptive measures can mitigate these effects: natural ventilation could slash warm discomfort by 50–60%, and adaptive temperature setpoints might lower cooling requirements by approximately 35% [5].

These developments are essential for fostering well-being in outdoor areas. In conclusion, outdoor air conditioning technology advancements have addressed energy economy, sustainability, and user comfort. These developments reshape the future of outdoor cooling by incorporating renewable energy sources, implementing intelligent systems, and emphasising air quality [3]. This makes outdoor cooling more user- and environmentally friendly. This introduction will look at the cutting-edge developments that have elevated outdoor air conditioning to a new level of adaptability, sustainability, and efficiency [2]. The mitigation of climate change and the reduction of greenhouse gas emissions are two of the most urgent problems of the twenty-first century, as shown in Figure 1.

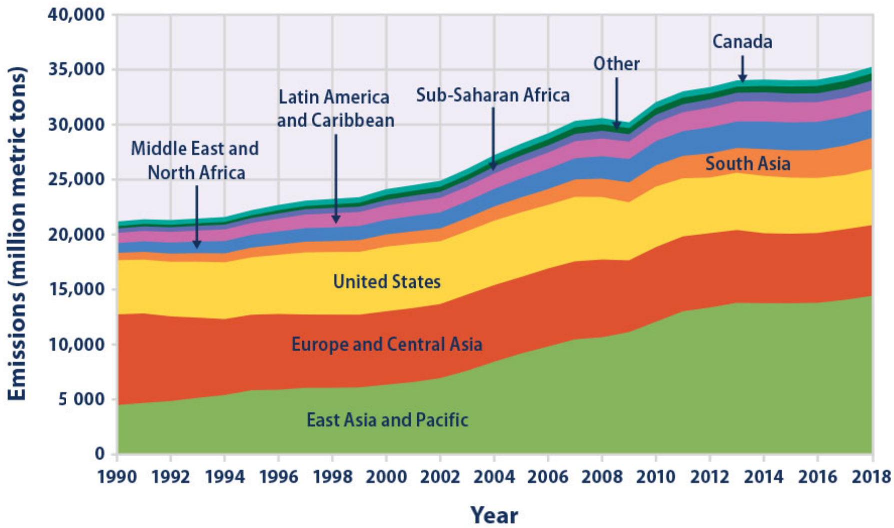

Figure 1. Greenhouse gas emissions by region [4].

Systems for cooling the outdoors are essential for this project. Modern systems use heat recovery technology and eco-friendly refrigerants to minimise their adverse environmental effects. These developments support international initiatives to reduce carbon emissions and lessen the effects of climate change. Integrating renewable energy is a critical component of contemporary outdoor air conditioning solutions. Photovoltaic panels and wind turbines are increasingly being incorporated into the design of outdoor cooling systems to use renewable energy sources to power air conditioners [6]. By switching to renewable energy, the carbon impact of outdoor cooling is drastically reduced while simultaneously lowering operational costs. A new era of outdoor air conditioning control and management has arrived with the introduction of the Internet of Things (IoT). To optimise cooling operations based on real-time weather conditions and occupancy patterns, IoT-enabled systems use sensors and data analytics [7]. With the help of this dynamic control, consumers are guaranteed a comfortable environment while consuming less energy than necessary. The mobility and scalability of outdoor air conditioning technology have also advanced. To provide on-demand cooling for various events and locations, portable outdoor cooling systems are now widely accessible and offer flexibility and cost-effectiveness [8]. This versatility is crucial for meeting the various requirements for outdoor cooling in various situations. In conclusion, outdoor air conditioning technology improvements have been made to meet user convenience, energy efficiency, and environmental issues. The outdoor cooling environment has changed into a sustainable and user-centric area with the adoption of eco-friendly refrigerants, renewable energy integration, IoT-driven intelligent systems, and the emergence of portable solutions.

Thermal comfort, a crucial aspect of the design and operation of buildings, is affected by many factors, such as air temperature, relative humidity, and air velocity [9]. Even though conventional HVAC systems are successful at maintaining a "comfort zone", they are often criticised for their high energy consumption, environmental impact, and greenhouse gas emissions [10]. To remedy these problems, green buildings strive to promote thermal comfort using energy-efficient techniques [11]. However, using conventional HVAC systems in green buildings sometimes contradicts the same sustainability ideals they intend to maintain [12]. Innovative methods such as passive design techniques, which incorporate natural ventilation and sun heating, have been investigated [13]. Moreover, modern HVAC technologies, such as Variable Refrigerant Flow (VRF) and radiant cooling systems, provide potential pathways for enhancing energy efficiency and thermal comfort [14]. The move towards human-centric methods that account for the adaptable nature of human thermal comfort is a developing trend in the literature [15]. Moreover, incorporating Internet of Things (IoT) technology allows for real-time monitoring and the adaptive management of interior conditions, providing a more dynamic approach to thermal comfort in green buildings [16]. Although heating, ventilation, and air conditioning (HVAC) systems are ubiquitous in maintaining temperature conditions, traditional systems are often criticised for their excessive energy consumption, poor indoor air quality, and large greenhouse gas emissions [10]. These limits become more troublesome in the context of green buildings, which are meant to maximise occupant comfort while reducing environmental damage [11]. The limitations of present HVAC systems are shown in Table 1.

Table 1. The limitations of HVAC systems.

Limitation	Description
Energy Consumption	HVAC systems are often significant consumers of energy, contributing to high operational costs and environmental concerns.
Installation Cost	The initial cost of purchasing and installing HVAC systems can be high, particularly for large or sophisticated systems.
Maintenance Requirements	Regular maintenance is essential for HVAC systems to operate efficiently, which can incur additional costs and downtime.
Space Requirements	Large HVAC units require considerable space, which can be a limitation in compact or densely built environments.
Noise Levels	HVAC systems, especially older or larger units, can generate noise, potentially causing disturbance in quiet environments.
Refrigerant Environmental Impact	Some HVAC systems use refrigerants that can contribute to ozone depletion and climate change if leaked.
Indoor Air Quality	If not properly maintained, HVAC systems can contribute to poor indoor air quality by circulating dust, mould, and other contaminants.
Temperature Inconsistencies	Achieving consistent temperatures in a building can be challenging, leading to hot or cold spots.
Humidity Control Limitations	Some HVAC systems may struggle to maintain optimal humidity levels, affecting comfort and indoor air quality.
Lifespan	The lifespan of HVAC systems can be limited, necessitating replacement or significant upgrades.
Adaptability	Older HVAC systems might not be easily adaptable to new technologies or changing environmental regulations.
Aesthetic Impact	Large and visible HVAC equipment can have a negative impact on building aesthetics.

To reconcile this dichotomy, scholars and practitioners have explored passive design strategies like natural ventilation, solar heating, and thermal mass, which can significantly reduce energy demand while maintaining or improving thermal comfort [17]. Advanced HVAC technologies are emerging as another solution; for example, Variable Refrigerant Flow (VRF) systems, radiant cooling systems, and chilled beams show significant promise of enhancing energy efficiency without compromising comfort [18]. The literature also increasingly focuses on adaptive and human-centric thermal comfort models, recognising that comfort is not a static, one-size-fits-all phenomenon but varies based on cultural, psychological, and individual physiological factors [19]. Internet of Things (IoT) technologies add another layer of sophistication by allowing for real-time monitoring and the adaptive control of multiple environmental parameters, thus enabling a more dynamic, responsive approach to achieving thermal comfort in green buildings, as shown in Figure 2 [20].

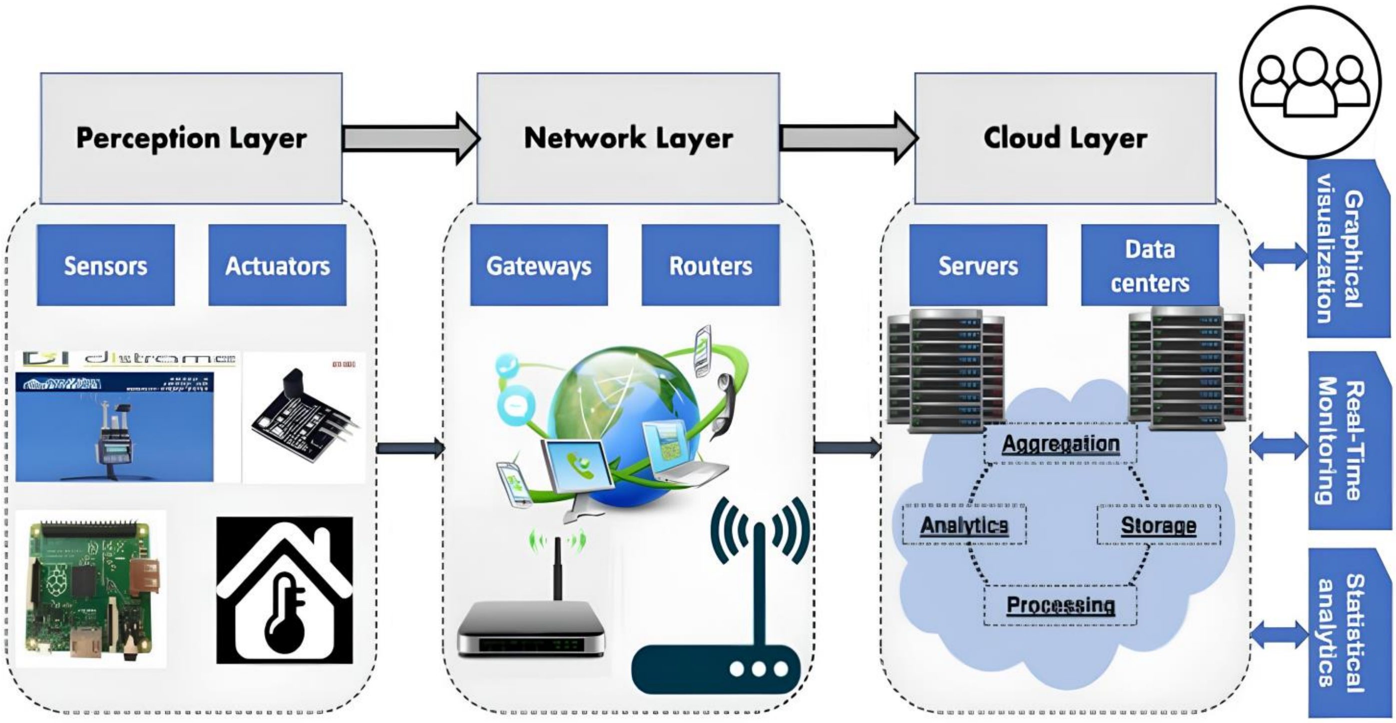

Figure 2. Internet of things (IoT) technologies [20].

Despite these developments, there are still knowledge gaps about effectively combining these varied tactics into a coherent, practical, and scalable strategy for boosting thermal comfort in green buildings. Thermal comfort, essential to the well-being of building occupants, has been widely investigated, demonstrating its dependence on parameters such as air temperature, radiant temperature, humidity, air velocity, and human characteristics, such as clothing and metabolism [21]. While traditional HVAC systems attempt to standardise these factors, they often fall short in energy efficiency and flexibility [22]. Especially in the field of green buildings, where the emphasis is placed on both comfort and environmental sustainability, traditional HVAC systems often fail to satisfy both goals [23]. The energy-intensive nature of current HVAC systems, which contributes to high operating costs and greenhouse gas emissions, is one of the greatest obstacles [21,22]. Efforts to minimise energy usage with passive design approaches such as natural ventilation and sun orientation have been reported, but they sometimes come at the expense of consistent comfort [18,19]. Emerging technologies, such as earth–air heat exchangers and phase-change materials, promise to overcome this gap by enabling temperature control without depending on energy-intensive mechanical devices [24]. Personalised thermal comfort systems, which employ wearable technology and IoT to adjust indoor settings to an individual's preferences [25], have the potential to increase comfort while lowering total energy consumption [26], since they permit more variable indoor circumstances. Moreover, machine learning methods are being investigated to forecast and adjust for occupant temperature preferences in real-time, boosting the flexibility of green building systems [27]. Despite these developments, the industry lacks comprehensive models incorporating different tactics, such as passive design, sophisticated materials, and customised systems, into a unified framework for enhancing thermal comfort in green buildings [28]. In addition, the scalability and applicability of these technologies to various climatic conditions and building types remain subjects for further study. In the dynamic realm of green building HVAC systems, the novelty of this manuscript stands out amidst a plethora of academic contributions. While several papers have traversed the technical intricacies of HVAC systems or delved into the singular facets of green buildings, this review offers an unparalleled, holistic perspective. It amalgamates discussions spanning occupant comfort, technological innovations, and market dynamics and ventures into the often-overlooked physiological and psychological dimensions governing thermal comfort. Another distinctive feature is the manuscript's exhaustive exploration of emergent HVAC technologies, such as Variable Refrigerant Flow (VRF) and phase-change materials, providing a rich, comparative analysis that might surpass many contemporaneous reviews [12]. However, this manuscript truly carves its niche in its candid exposition of the challenges plaguing the integration of traditional HVAC systems into green edifices. This, coupled with actionable insights and potential remedial measures, addresses a lacuna that remains conspicuously absent in many other works. Furthermore, introducing the adaptive comfort model, a paradigm that hinges on an occupant's experiential adaptability, infuses a fresh, human-centric perspective, balancing the often technocentric narratives of other reviews. With its judicious blend of technical depth, human considerations, and real-world implications, this manuscript distinguishes itself as a seminal contribution, poised to reshape the discourse on HVAC systems in green buildings [8]. The groundbreaking aspect of this study lies in its comprehensive approach to addressing the integration of traditional HVAC systems within the framework of green building principles. While previous research may have separately touched upon energy efficiency, occupant comfort, or the environmental impact of HVAC systems, this study is novel in its holistic examination of all these elements in tandem. Moreover, its emphasis on the economic implications of integrating traditional HVAC systems into sustainable designs provides a fresh perspective that goes beyond the environmental discourse [13]. Another pioneering feature is its exploration of eco-friendly refrigerants, a topic that, until now, has been underrepresented in mainstream research. This study also stands out for its in-depth look at retrofitting challenges, offering a unique blend of theoretical insights and practical solutions [21]. By bridging the often-separate worlds of sustainable construction and HVAC system design, this research introduces a groundbreaking narrative set to shape both industries and inspire further interdisciplinary research. In essence, the novelty of this study is its multifaceted, interdisciplinary approach, filling critical knowledge gaps and providing a roadmap for the harmonious integration of comfort, sustainability, and economic viability in the built environment. The growing interest in adaptive thermal comfort theory stems from the inadequacy of the traditional "one size fits all" comfort model in achieving widespread occupant satisfaction. This was highlighted by extensive field validation studies funded by the ASHRAE in the 1980s and 1990s. By contrast, field studies in environments employing adaptive comfort practices generally show enhanced occupant comfort and satisfaction [29]. A critical aspect of adaptive thermal comfort theory is its reliance on statistical field data analyses, making its main models somewhat opaque or "black box" in nature. This review first explores various attempts to develop more transparent, explanatory adaptive comfort models. The second focus of this review is the evolution of adaptive comfort regulatory documentation over the past 21 years. Carlucci et al. have thoroughly compared adaptive thermal comfort models frequently used in building environment standards. These models were officially incorporated into the ASHRAE standard 55 in 2004 and have been refined in subsequent updates [30].

This study aims to evaluate the efficiency and cost-effectiveness of modern HVAC systems in sustainable building design, comparing traditional and eco-innovative models. It will assess financial implications, energy efficiency, and regulatory compliance, using statistical analysis and case studies to understand their practicality in various climates and building types.

2. Methodology to Achieve the Results

This study adopted a mixed method approach, combining quantitative and qualitative research methodologies to elucidate the intricate relationship between traditional HVAC systems and green building design principles. An exhaustive literature review was conducted to understand the current state of research in the domain. Scholarly articles, conference proceedings, and industry reports were reviewed. This helped in the understanding of existing HVAC technologies, their energy consumption patterns, the evolution of green building principles, and the perceived gaps between them [22]. A quantitative analysis was performed on the energy consumption of traditional HVAC systems. Data were collected from various buildings, both residential and commercial, over one year. The data were then benchmarked against buildings incorporating green building principles and newer HVAC technologies [27]. Surveys were administered to occupants of buildings with traditional HVAC systems to gauge their comfort levels. Simultaneously, structured interviews were conducted with architects, HVAC engineers, and green building consultants. This qualitative approach provided more profound insights into the perceived challenges and opportunities in integrating HVAC systems with green building designs [18]. Several green buildings that have successfully integrated innovative HVAC systems were chosen as case studies. These provided practical insights into real-world applications and challenges. Each case study was analysed regarding energy efficiency, occupant comfort, retrofitting complexities, and the use of eco-friendly refrigerants [15]. The collected data were analysed using statistical tools and software packages. Quantitative data from energy consumption analysis and surveys were subjected to regression analysis, ANOVA, and *t*-tests to determine significant differences and patterns. Qualitative data from interviews were analysed using thematic analysis, allowing for the emergence of designs and themes related to challenges and solutions [14]. The mixed method approach provided a holistic perspective on the challenges and opportunities in integrating traditional HVAC systems with green building principles. While conventional systems posed significant challenges regarding energy inefficiency and incongruence with sustainability, innovative alternatives showed promise in bridging the gap. This study emphasises the urgency of transitioning to newer HVAC technologies that align with green building principles, ensuring energy efficiency, ecological sustainability, and occupant comfort.

The graphic in Figure 3 represents data from keywords searched on Scopus with the keywords “thermal AND comfort; AND green AND buildings”. This visualisation, a 3D bubble chart, suggests a trend analysis over time, possibly evaluating the relationship between thermal comfort and green building practices from 2000 to 2030. Each bubble likely represents a dataset or a collection of studies published on the topic in a given year. As time progresses, the increasing size of the bubbles could indicate a growing number of studies or an increase in a particular metric related to thermal comfort in green buildings. The numbers within the bubbles could signify the number of research papers or the scoring of a specific index linked to the research intensity or impact in that year. For example, the jump from 82 in 2015 to 100 in 2020 could indicate a significant increase in research activities or findings on thermal comfort in green buildings.

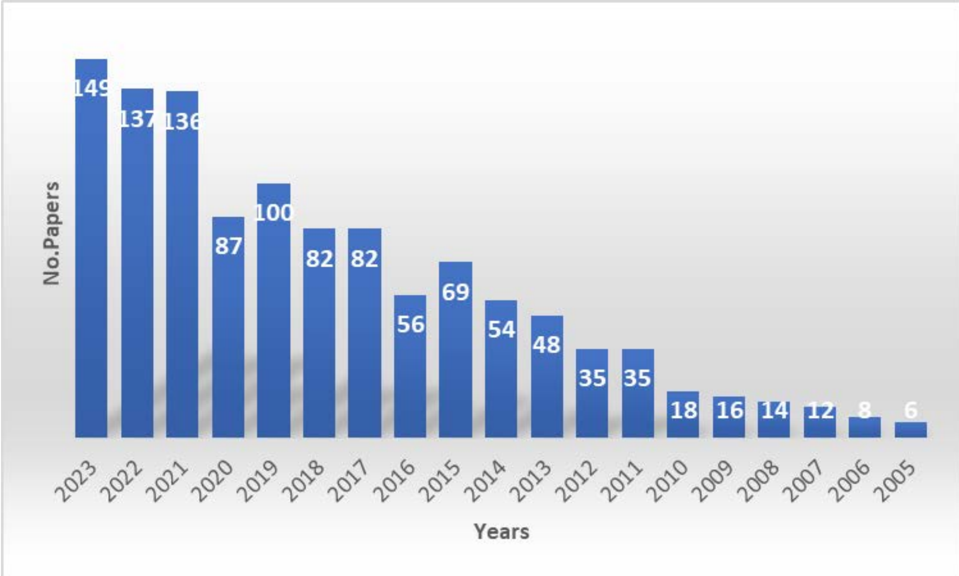

Figure 3. The graph represents publications from 2005 to 2023 containing the keywords searched.

3. Green Buildings

Green buildings, usually considered sustainable or eco-friendly structures, are a thorough and well-rounded method of building and designing, as shown in Figure 4. These buildings are skilfully designed to impact the environment as little as possible while improving energy efficiency, occupant comfort, and overall sustainability [29]. Such structures are made with a significant emphasis on reducing greenhouse gas emissions, improving indoor air quality, and conserving resources, all of which help create a more sustainable built environment. Classic HVAC (heating, ventilation, and air conditioning) systems that have historically been used for indoor climate control are often referred to as traditional air conditioning technology in the context of green buildings [30]. The effect of occupants on HVAC system operation and, consequently, on building energy consumption is a multifaceted issue that significantly impacts the efficiency and sustainability of buildings. Occupant behaviour, including how individuals use space and their personal preferences for comfort, is crucial in determining the energy performance of HVAC systems. Occupants' daily activities, such as using electronic devices, using lighting, and window operation, directly influence the indoor climate, affecting the HVAC system's workload. For instance, a higher number of occupants or increased activity levels can lead to more significant heat generation, which requires the HVAC system to work harder to maintain the desired temperature, thereby increasing energy consumption. Moreover, the individual preferences of occupants for temperature and ventilation can lead to inefficiencies in HVAC operation [18]. Different people have varying comfort levels; some prefer warmer temperatures while others prefer cooler conditions. This diversity often results in the HVAC system being adjusted frequently to meet everyone's needs, leading to inefficient operation and increased energy use. This situation is further complicated in buildings where HVAC controls are decentralised or when occupants have direct control over thermostatic settings. In such scenarios, the lack of a standardised temperature setting can result in significant energy wastage [29].

Occupant behaviour modelling has become an integral part of energy efficiency studies. More efficient HVAC systems can be designed by understanding and predicting how occupants interact with building systems and their environment. This involves using sensors and advanced analytics to monitor and analyse occupant behaviour in real-time, enabling the HVAC system to adapt dynamically to usage patterns. Such intelligent HVAC systems can optimise energy consumption by adjusting settings based on occupancy levels, time of day, and even weather conditions [30]. Furthermore, educating occupants about the impact of their behaviour on energy consumption is crucial. Implementing user-friendly interfaces for HVAC controls and providing feedback on energy usage can encourage more energy-conscious behaviour. Building designs that promote natural ventilation and daylighting can also reduce the reliance on HVAC systems, further conserving energy [18].

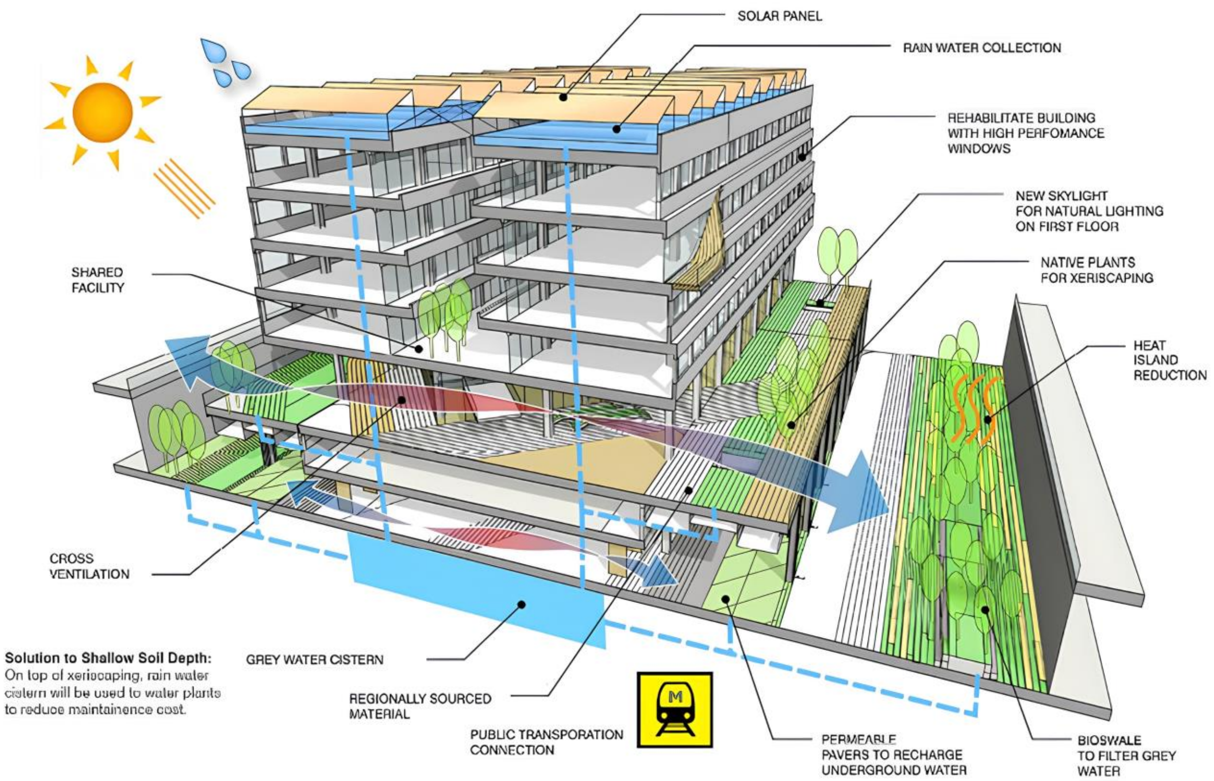

Figure 4. Green building [29].

In addition to behavioural aspects, the physical presence of occupants also affects indoor air quality (IAQ). As occupants exhale carbon dioxide and potentially introduce pollutants, HVAC systems must ensure adequate ventilation and air filtration to maintain a healthy indoor environment. This requirement often leads to a delicate balance between energy efficiency and IAQ, especially in tightly sealed, energy-efficient buildings where ventilation is primarily dependent on the HVAC system.

To cool and dehumidify indoor environments, these systems often rely on energy-intensive processes such as the mechanical compression of refrigerants. Due to their high electricity consumption and usage of refrigerants with a high global warming potential (GWP), typical HVAC systems are frequently shown to be energy inefficient and leave a significant environmental impact. Green buildings, often termed sustainable or eco-friendly structures, represent a comprehensive approach to construction and design that prioritises environmental stewardship, energy efficiency, and human well-being. These buildings are meticulously planned to minimise their ecological footprint through various strategies, including reducing greenhouse gas emissions, enhancing indoor air quality, and conserving natural resources [12,29]. The overarching goal is to create a built environment that is sustainable and conducive to occupant comfort and well-being [31]. One of the critical aspects of green buildings is their focus on energy efficiency. Traditional buildings consume significant heating, cooling, and lighting energy, contributing to approximately 40% of global energy use. On the other hand, green buildings incorporate technologies such as solar panels, energy-efficient windows, and advanced insulation materials to reduce energy consumption [31]. Table 2 shows a comparison of traditional and green buildings.

Table 2. A comparison of traditional and green buildings.

Criteria	Traditional Buildings	Green Buildings
Energy Source	Primarily rely on non-renewable energy sources like fossil fuels for heating, cooling, and power.	Utilise renewable energy sources such as solar, wind, and geothermal energy, reducing reliance on fossil fuels.
Energy Efficiency	Are generally less energy-efficient due to older technologies and materials.	Are designed with energy efficiency in mind, using advanced technologies and materials to reduce energy consumption.
Insulation	May have poor insulation, leading to higher heating and cooling needs.	Feature high-quality insulation to minimise heat loss and reduce heating and cooling needs.
Lighting	Often use inefficient lighting fixtures and bulbs, consuming more electricity.	Employ energy-efficient lighting solutions like LED and CFL and maximise natural light through design.
HVAC Systems	Use older, less efficient HVAC systems, consuming more energy.	Incorporate energy-efficient HVAC systems, often with intelligent controls to optimise performance.
Water Heating	Typically use standard water heating systems, which can be less efficient.	Use energy-efficient water heating solutions such as solar water heaters or heat pumps.
Appliances and Fixtures	Equipped with standard appliances and fixtures that consume more energy.	Are fitted with Energy Star-rated appliances and fixtures to minimise energy use.
Building Envelope	Contain conventional building materials and design, which may result in more energy loss.	Use sustainable building materials and design principles to enhance energy conservation.
Ventilation	May have less adequate ventilation, requiring more energy for air quality control.	Are designed for effective natural ventilation, reducing the need for mechanical ventilation.
Energy Management	Contain a lack of advanced energy management systems, leading to inefficient energy use.	Incorporate advanced energy management systems to monitor and optimise energy consumption.
Carbon Footprint	Have a higher carbon footprint due to higher energy consumption and reliance on fossil fuels.	Have a lower carbon footprint due to reduced energy consumption and renewable energy sources.

These features lower the building's operational costs and reduce its carbon footprint, contributing to climate change mitigation. Indoor air quality is another critical focus area for green buildings. Traditional construction materials often contain volatile organic compounds (VOCs) that can harm human health. Green buildings use low-VOC and non-toxic materials to improve indoor air quality, thereby enhancing the well-being of the occupants [32]. Water conservation is also a significant aspect of green building design. Green buildings aim to reduce water consumption and waste by using water-efficient fixtures, rainwater harvesting, and greywater recycling systems [32]. These practices conserve a vital natural resource and reduce the strain on municipal water supply systems [32]. In indoor climate control, classic HVAC (heating, ventilation, and air conditioning) systems, often referred to as traditional air conditioning technology, have been a concern in the green building discourse. These systems typically rely on energy-intensive processes such as the mechanical compression of refrigerants to cool and dehumidify indoor spaces. The high electricity consumption and use of refrigerants with a high global warming potential (GWP) make these systems both energy-inefficient and environmentally detrimental [32]. Green buildings often employ alternative climate control technologies such as natural ventilation, evaporative cooling, and ground-source heat pumps (GSHPs) to address these issues. These technologies are more energy-efficient and have a lower environmental impact than traditional HVAC systems [32]. Technological advancements, architectural practices, and ecological priorities shape the intricate relationship between HVAC systems and green building design. Central to this dynamic is the ensuring of occupant comfort without compromising sustainability principles. Traditionally, HVAC systems have significantly contributed to a building's energy consumption. However, in the realm of green buildings, which emphasise energy conservation, there is a pressing need for HVAC solutions that are both efficient and adaptive. The architectural design of a building can significantly influences its HVAC requirements. For instance, structures optimised for natural ventilation, shading, and thermal insulation can reduce the reliance on mechanical cooling or heating [19]. Integrating architectural foresight with HVAC functionalities exemplifies the symbiotic potential between the two. Furthermore, technological innovations, especially the advent of AI-driven intelligent HVAC systems, have ushered in a new era of energy efficiency [18]. These systems, equipped with sensors, can pre-emptively adjust to occupant behaviour, striking a balance between comfort and energy conservation. Yet, the environmental implications of HVAC systems, particularly concerning refrigerant use, cannot be overlooked. The shift towards eco-friendly refrigerants underscores the industry's commitment to ecological stewardship, aligning with the ethos of green buildings. While the initial investment in such advanced HVAC systems might be substantial, the tangible and intangible long-term benefits justify the costs. Reduced energy bills, enhanced indoor air quality, and the overarching advantage of a minimised environmental footprint highlight the indispensable role of HVAC systems in the future of sustainable architecture [18].

Challenges with Traditional HVAC

Sustainability, energy efficiency, and environmental stewardship are crucial for developing green buildings. Nevertheless, integrating traditional heating, ventilation, and air conditioning (HVAC) systems into these environmentally aware buildings usually creates significant challenges [32]. The low energy efficiency of the ageing HVAC systems is one of the primary challenges. They typically use a great deal of power, which might limit the energy-saving gains made achievable by green building design. The inefficiency of traditional HVAC systems is a significant issue in green buildings since the goal is to reduce energy consumption and carbon footprint [32]. Another issue is the high operational costs. For owners and occupiers of green buildings, standard HVAC systems' excessive energy consumption raises operating expenditures. These costs may discourage consumers from investing in green construction features to reduce their environmental effects and save money on energy costs [31]. Traditional HVAC systems usually need more maintenance and a shorter lifetime, increasing their long-term expenses. In addition, conventional HVAC systems are limited in their ability to suit the unique characteristics and requirements of green buildings. Green buildings often include passive design principles, such as daylighting and natural ventilation, which may interfere with the performance of traditional HVAC systems [32]. This restricted flexibility may result in waste and decreased comfort in green buildings.

Traditional HVAC systems have environmental impacts beyond energy use. These systems commonly use refrigerants with a high GWP, which may contribute to the loss of the ozone layer and worsen climate change. The selection of heating, ventilation, and air conditioning (HVAC) systems is a vital aspect of green buildings, whose primary objective is eliminating environmental damage. Moreover, although traditional HVAC systems may maintain a consistent temperature, they may not prioritise occupant comfort as much as green building designs do. In contrast to conventional HVAC systems, green buildings usually prioritise indoor air quality, natural ventilation, and thermal comfort via passive approaches [32]. This might lead to subpar interior design. Integrating green features into older buildings with traditional HVAC systems may be challenging and costly. Incorporating energy-efficient technology and renewable energy sources may entail extensive adjustments to the buildings and to the HVAC systems [32], making it more challenging for certain buildings to embrace green building standards.

Incorporating conventional heating, ventilation, and air conditioning (HVAC) systems into green buildings presents several obstacles that weaken sustainability, energy efficiency, and environmental responsibility. One of the most visible concerns is the energy inefficiency of traditional HVAC systems, which often use a disproportionate amount of power, thereby nullifying the energy-saving gains that green building designs attempt to accomplish [32]. This inefficiency is especially troublesome given that one of the critical goals of green buildings is to decrease energy usage and carbon footprint. In addition, the high energy consumption of conventional HVAC systems results in higher operating expenses for building owners and occupants, discouraging people and organisations from investing in green building features [33]. These costs may be complicated since they may balance the anticipated savings in energy expenses, diminishing the appeal of investing in a green building. Traditional HVAC systems need regular maintenance and have a shorter lifetime than contemporary, energy-efficient systems, resulting in more extraordinary long-term expenses [34]. Green buildings often incorporate novel passive design principles like daylighting and natural ventilation, which may be incompatible with the functioning of conventional HVAC systems. This lack of adaptation may lead to energy waste and poor occupant comfort, undermining the holistic approach to well-being that green buildings aim to accomplish [31]. Traditional HVAC systems often use refrigerants with a high global warming potential (GWP), which contributes to the depletion of the ozone layer and worsens climate change. This contradicts the environmental aims of green buildings, which seek to minimise such damage. Traditional HVAC systems may maintain a constant temperature. Still, they often do not prioritise other factors of occupant comfort emphasised in green buildings, such as indoor air quality and natural ventilation [32]. This may lead to inferior interior conditions, reducing inhabitants' quality of life. Lastly, it might be tough to retrofit older buildings with green features if these structures have obsolete HVAC systems. Integrating energy-efficient technology with renewable energy sources may require significant changes to the building structure and the HVAC systems, adding complexity and expense to the retrofitting process [35].

To continue the subject, the issues provided by conventional HVAC systems in green buildings extend to regulatory and legislative frameworks. Traditional HVAC systems often fail to achieve these new norms, causing compliance difficulty for building owners and developers in several jurisdictions with more strict building codes and energy efficiency regulations intended to promote sustainability [35]. This regulatory mismatch delays the permission process and exposes owners to possible legal repercussions, adding a layer of complication and expense to the construction or retrofitting process. Incompatibility between conventional HVAC systems and green building designs may result in performance discrepancies. In other words, the building may not function as effectively as first projected or anticipated, resulting in a "performance gap". This disparity may be incredibly distressing for stakeholders who invested in green building elements to attain specified energy savings and environmental objectives [35]. The performance gap may also undermine faith in green building technology and practices, thereby slowing the adoption of these vital solutions for reducing climate change and fostering sustainability [35]. Another aspect that is sometimes disregarded is the human element. Traditional HVAC systems often need specific knowledge and abilities to operate. By contrast, the controls and automation elements of contemporary, energy-efficient systems incorporated into green buildings are often more sophisticated to improve performance. Thus, moving from conventional to modern systems may require extensive retraining for facility management personnel, adding to the indirect costs and difficulties associated with implementing green building practises [36]. Furthermore, integrating renewable energy sources like solar or wind power into green buildings provides another complication when typical HVAC systems are involved. Frequently, these systems are not built for simple integration with renewable energy sources, necessitating extra equipment, control systems, and sometimes complex electrical work to make integration viable. This raises the initial construction cost and adds another layer of complexity to the building's energy management system, making the transition to a more sustainable built environment more challenging. The issues connected with integrating conventional HVAC systems into green buildings have ramifications for urban planning and the electrical grid. Inefficient HVAC systems may increase peak electrical demands, increasing problems such as energy poverty and grid instability. As cities strive to become more sustainable and resilient, the incompatibility of conventional HVAC systems with green building goals becomes a building-level problem and a systemic one that must be addressed [37]. In conclusion, integrating conventional HVAC systems into green buildings has obstacles beyond energy inefficiency and high operating costs. These obstacles include regulatory compliance, performance gaps, human issues, integration with renewable energy sources, and urban and grid-level ramifications. As green construction approaches continue to improve and gain acceptance, it becomes more critical to address these multiple difficulties. It is not only a matter of retrofitting or replacing obsolete systems but also of reconsidering how HVAC systems fit into the larger ecosystem of sustainable building practises and urban planning [35]. To comprehensively address occupant comfort within green buildings, it is imperative to employ specific metrics and methods. While this manuscript underscores the centrality of comfort, delving into its quantitative assessment can illuminate the discussion. Thermal comfort, for instance, can be measured using tools such as the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) [26]. The PMV provides an aggregate assessment of the comfort level expressed by a group of occupants, while the PPD quantifies the percentage likely to find the environment uncomfortable. By integrating these metrics, we can derive tangible insights from the performance of innovative HVAC technologies. Furthermore, the manuscript could explore how these state-of-the-art systems, through features like adaptive temperature control and humidity modulation, optimise energy consumption and enhance overall occupant comfort. Such a data-driven approach can bolster this manuscript's argument, emphasising the harmonious integration of green building principles, HVAC innovations, and the human experience [28].

4. Eco-Friendly Air-Conditioning

Recent advances in eco-friendly design and materials for outdoor air conditioning systems have been made to meet rising concerns about energy usage and environmental effects. This event marks a turning point in the industry's transformation to more eco-friendly and sustainable practices [37].

1. Using sustainable refrigerants is one of the most critical aspects of eco-friendly design. Hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), both potent greenhouse gases, were widely used in conventional air conditioning systems. However, more contemporary outdoor cooling systems favour using hydrofluoroolefins (HFOs) and natural refrigerants such as ammonia and carbon dioxide [38]. These alternatives are less environmentally harmful and less likely to contribute to global warming.
2. Heat recovery technology: Incorporating heat recovery technology is another breakthrough. Outdoor cooling systems may collect and reuse waste heat generated during the cooling process [39]. This reduces total energy use while enhancing energy efficiency. Systems for heat recovery are particularly beneficial in commercial and industrial settings that generate a great deal of heat, which may be utilised for activities such as water heating [37].
3. Energy-efficient components: Eco-friendly design involves using energy-efficient materials and components. High-efficiency compressors, fans, and heat exchangers are merely a few examples of the elements utilised in outdoor air conditioning systems that have reduced energy consumption [40]. These components help reduce energy use, which benefits the environment and saves users money.
4. Sustainable production methods: The production of outdoor air conditioning systems goes beyond the working stage. Manufacturers progressively embrace eco-friendly manufacturing practices [41] to decrease waste, use less energy and water during

production, and construct cooling units out of recycled or recyclable materials. These measures reduce the carbon footprint of the manufacturing process.

5. Regulatory conformity: Government regulations and industry standards have considerably impacted adopting eco-friendly design and materials in outdoor air conditioning technologies. The Montreal Protocol and its revisions have pushed the industry toward more sustainable practices by emphasising the elimination of ozone-depleting chemicals and decreasing refrigerants with a high GWP (global warming potential) [42].

The transition to environmentally friendly outdoor air conditioning systems is a multifaceted industry shift fuelled by technological innovation, sustainable manufacturing, and regulatory compliance. Green refrigerants, such as hydrofluoroolefins (HFOs) and natural chemicals, such as ammonia and carbon dioxide, have a lower global warming potential (GWP) than conventional hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) [43]. This development is partly the outcome of international legislation, such as the Montreal Protocol, which seeks to eradicate ozone-depleting substances. Particularly helpful in commercial and industrial settings is the implementation of heat recovery technology, which recovers waste heat produced during the cooling process to reduce overall energy consumption and boost system efficiency [35]. The emphasis on environmentally responsible design also extends to using energy-efficient components, such as high-efficiency compressors, fans, and heat exchangers, which minimise energy consumption and cut operating expenses. Beyond the operational phase, manufacturers are adopting sustainable practises in producing these systems, such as reducing waste, minimising energy and water consumption, and utilising recycled or recyclable materials, per the principles of circular economy and sustainable development [44]. Regulatory frameworks such as the Montreal Protocol have played a significant role in pushing these changes by providing the economic and legal incentives necessary for the sector to adopt more sustainable methods. In conclusion, advancements in green refrigerants, heat recovery technologies, energy-efficient components, and sustainable manufacturing practices collectively contribute to a more sustainable approach to outdoor cooling, establishing new industry standards for energy efficiency and sustainability, and providing essential solutions in the face of significant climate change-related challenges [45]. Multiple reasons, including consumer demand for sustainable goods, technology breakthroughs, and more rigorous environmental legislation, are influencing the continuous change in the air conditioning sector towards eco-friendly solutions. The transition towards green refrigerants is notable because it signals a break from the usage of HCFCs and HFCs, recognised as significant contributors to global warming and ozone depletion. Adopting alternative refrigerants such as hydrofluorooctane, ammonia, and carbon dioxide is a systemic reaction to global environmental concerns and not only a technical shift. This is bolstered by international accords such as the Montreal Protocol, which has established timelines for eliminating ozone-depleting compounds and fostered innovation in the industry. Heat recovery technology is an essential innovation in the search for environmentally friendly air conditioning [45]. These systems cut energy consumption by collecting and recycling waste heat and contribute to energy efficiency and sustainability objectives. This is particularly significant in commercial and industrial contexts, where substantial waste heat may be recycled for other energy-intensive activities, producing a more connected and efficient energy ecosystem [46]. This multifaceted approach to sustainability emphasises energy-efficient components such as high-efficiency compressors, fans, and heat exchangers. These components are intended to perform optimally, decreasing the air conditioning system's total energy consumption. This coincides with environmental goals and translates into economic gains via lower operating costs, creating a win–win outcome for both customers and the environment [47].

Sustainable manufacturing techniques are expanding the notion of environmental friendliness beyond the product to include its entire lifespan, from production to disposal. Manufacturers increasingly emphasise eliminating waste, employing recycled or recyclable materials, and decreasing energy and water usage throughout the manufacturing process. These behaviours adhere to the circular economy's ideas, encouraging a regenerative approach to production and consumption. Compliance with regulations acts as both a catalyst and a foundation for these adjustments. Laws such as the Montreal Protocol [48] have placed the sector on the road to greater sustainability by regulating the phase-out of dangerous compounds and encouraging the use of energy-efficient technology. These rules sometimes include economic incentives, such as tax breaks or subsidies, which make it financially feasible for businesses to participate in the research and development of environmentally friendly technology [44]. In conclusion, the transition to ecologically friendly outdoor air conditioning systems involves a complete endeavour involving various stakeholders, including manufacturers, regulators, and consumers. Advances in green refrigerants, heat recovery technology, energy-efficient components, and sustainable manufacturing processes lead to a more sustainable approach to outdoor cooling. These achievements are vital for facing the substantial problems faced by climate change and environmental degradation as they establish new industry standards for energy efficiency and sustainability. Figure 5 is a graphical figure to explain the eco-friendly air conditioning.

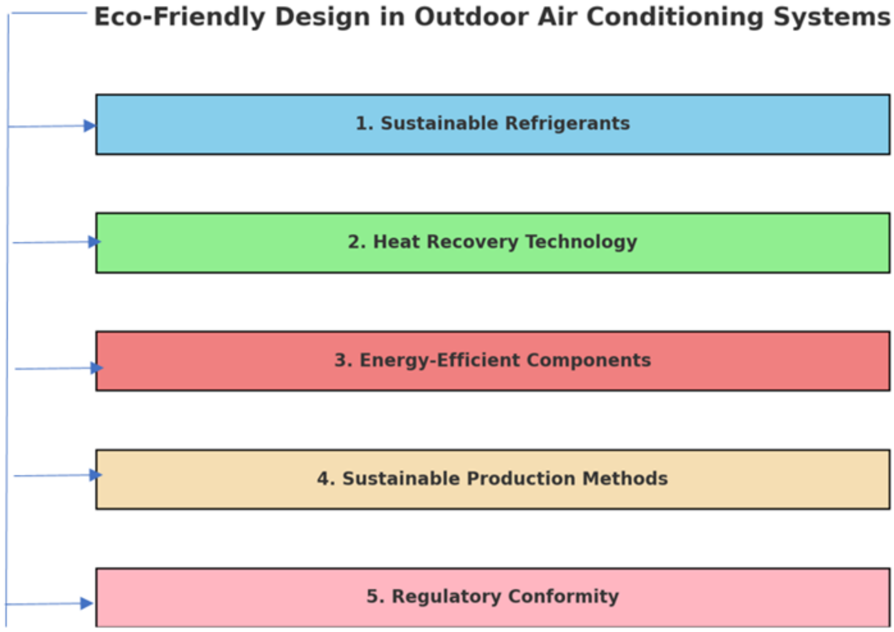

Figure 5. A representation of eco-friendly air conditioning.

5. Revolutionizing Outdoor Cooling

Renewable energy is a significant development in outdoor air conditioning systems, marking a paradigm shift toward ecologically benign and sustainable cooling techniques [49]. This technique largely depends on renewable energy sources, namely solar electricity, to power outdoor cooling equipment.

5.1. Solar Energy Integration

Solar power integration involves incorporating photovoltaic and solar thermal systems into outdoor air conditioners. Through solar panels, sunlight is transformed into energy, which is then utilised to power the cooling systems. By contrast, solar thermal systems harness the sun's energy to create heat that may be used to cool objects, such as desiccant systems or absorption chillers [49].

5.2. Reduce Fossil Fuel Use

One of the primary benefits of renewable energy integration is a significant reduction in reliance on conventional fossil fuels for power production. Frequently, the energy used by traditional cooling systems is derived from coal, natural gas, and other fossil fuels, which increases greenhouse gas emissions and harms the environment. Using solar energy and other renewable energy sources, outdoor cooling systems contribute to the battle against climate change and decrease their carbon footprint [49].

5.3. Advantages for the Environment and Sustainability

Utilising renewable energy allows outdoor cooling technologies to meet broader environmental aims. Solar energy is an endless and renewable resource that reduces the environmental impact of cooling operations. This contributes to global efforts to reduce carbon emissions and foster a cleaner future [49].

5.4. Energy-Cost Cost Savings

Renewable energy integration brings environmental advantages and possible energy cost reductions over the long run. Solar panels and related infrastructure need an initial investment, but their long-term running costs are usually less than traditional power consumption. Renewable energy is an attractive choice for outdoor cooling applications due to its low cost [49].

5.5. The Grid's Independence

Incorporating renewable energy also increases the reliability and longevity of outdoor cooling systems. By creating their power via solar panels, these systems become less dependent on the grid's dependability. This independence is essential in remote or off-grid places where a consistent electrical source is difficult to maintain [49].

5.6. Innovation in Technology

Improvements in solar panel efficiency and storage technologies have made renewable energy integration simpler. Advanced energy storage methods store additional energy during cloudy or nocturnal conditions, ensuring a continuous cooling operation. Solar panels with greater efficiency capture more solar energy [46].

A recent study confirms that using renewable energy in outdoor air conditioning systems marks a dramatic step toward sustainability and environmental stewardship. Several significant developments define this paradigm shift. First, including solar energy via photovoltaic and solar thermal systems has proven revolutionary. Photovoltaic panels turn sunlight into energy to power cooling systems, while solar thermal systems utilise the sun's heat to power cooling processes such as desiccant systems or absorption chillers [50]. This dual method optimises solar energy consumption and considerably minimises reliance on fossil fuels generally employed in conventional cooling systems [51]. The environmental advantages of this are many, helping worldwide efforts to cut carbon emissions and build a more sustainable future. Long-term energy cost reductions may compensate for the initial investment in solar panels and associated infrastructure, making renewable energy a financially feasible choice for outdoor cooling [52]. Additionally, using renewable energy sources improves the resilience and dependability of these systems by minimising their reliance on the electrical grid, which is especially advantageous in distant or off-grid areas [53]. Technological breakthroughs, such as increases in solar panel efficiency and energy storage technologies, have simplified this shift, allowing for a more efficient absorption and use of solar energy and guaranteeing ongoing cooling operations [54]. In conclusion, incorporating renewable energy into outdoor air conditioning systems is a transformative development that aligns with broader efforts to combat climate change, reduce energy costs, and enhance system resilience, setting new standards for sustainability and environmental stewardship within the industry. The dramatic trend toward incorporating renewable energy into outdoor air conditioning systems is a multidimensional phenomenon with far-reaching consequences for sustainability, environmental conservation, and energy economics [51]. This shift is backed by a growing amount of research demonstrating the practicality and advantages of employing renewable energy sources, especially solar power, in cooling technology. The integration of solar energy is accomplished via two basic methods: photovoltaic systems that convert sunlight directly into electricity and solar thermal systems that harness the sun's heat for cooling processes, such as desiccant systems and absorption chillers [55]. This dual method not only improves solar energy utilisation but also provides a flexible solution that can be customised to particular cooling demands and regional climate conditions. Traditional energy sources for cooling systems, such as coal, natural gas, and oil, will be drastically reduced due to this transition, which is one of the most important effects. By abandoning these non-renewable resources, outdoor air conditioning systems significantly reduce their carbon footprint and contribute to global efforts to combat climate change. This is a crucial breakthrough in light of the pressing need to cut greenhouse gas emissions to avert catastrophic environmental repercussions [50]. In addition, using renewable energy correlates with wider sustainability objectives, such as protecting natural resources and reducing pollution, providing a more comprehensive approach to environmental stewardship. Economically, the long-term advantages often exceed the initial expenses of installing solar panels and accompanying infrastructure. Renewable energy sources like solar electricity have lower operational costs than conventional fossil fuels, allowing for long-term cost savings [56]. The economic feasibility of renewable energy makes it an appealing alternative for home and business outdoor cooling systems. In addition, advances in energy storage technology, such as lithium-ion batteries and better control systems, have made it feasible to store extra solar energy for use during times of low sunshine, improving the efficiency and dependability of these systems. The integration of renewable energy also has the additional benefits of greater grid resilience and independence. By producing their power, outdoor cooling systems are less vulnerable to grid outages, which is especially advantageous in distant or off-grid areas where the electricity supply may be inconsistent [53]. This aspect also has significance for emergency preparation since systems independent of the grid may continue to work in the case of natural catastrophes or other interruptions to the electrical supply. Significant breakthroughs in solar panel efficiency, energy storage technologies, and intelligent control systems have facilitated this transformation via technological innovation. These advancements help efficiently collect and use solar energy and enable more complex system management, improving system performance and energy consumption [50]. In conclusion, incorporating renewable energy into outdoor air conditioning systems is a transformational and multidimensional innovation that tackles several crucial challenges relating to climate change, environmental conservation, and energy economics. By utilising developments in solar power technology, energy storage, and system controls, these environmentally friendly cooling solutions provide a sustainable, cost-effective, and resilient alternative to conventional systems fuelled by fossil fuels. As such, they represent a substantial advancement in establishing a more sustainable and ecologically responsible future [53].

Thermal comfort, while seemingly straightforward, is a multifaceted construct deeply rooted in physiological and psychological realms. This manuscript acknowledges its importance, but there is ample room to probe deeper into this intricate interplay of factors that govern an individual's sense of comfort within a built environment. At the forefront is temperature, which most directly aligns with our immediate perception of comfort [52]. However, this is not confined to just the ambient air temperature; the radiant temperature, determined by the warmth or coolness of surrounding surfaces, plays a critical role. Imagine a scenario where an individual is in a room with an acceptable ambient temperature but cold walls—discomfort can be palpable. Equally significant is humidity [51]. The moisture content in the air profoundly influences our thermal perception. Environments with high humidity can impede our body's natural cooling mechanism—perspiration—making us feel oppressively warm even at moderate temperatures [47]. Conversely, arid conditions can lead to skin irritation, a sense of dryness in the respiratory tract, and overall discomfort. Then, there is air velocity, a factor often overlooked but pivotal in shaping thermal comfort. The sensation of air moving across our skin can either be a boon or a bane, depending on the context. A gentle draft in a sweltering room can be the epitome of relief, but the same current in an already cold environment can make the chill almost unbearable. Beyond these physiological factors, one must consider the metabolic rate, which varies from person to person based on activities. A person engaged in rigorous physical activity generates more heat and might feel warmer than sedentary people, even if both are in the same environment [51]. Clothing insulation, or the "clo" value, further adds to this complex equation. The type and amount of clothing we wear can significantly influence our comfort, acting as a buffer between our body and the external environment. Lastly, an intriguing dimension to this discourse is the adaptive comfort model. It posits that our perception of comfort is not static but evolves based on prior experiences. Individuals accustomed to warmer climates might find a mildly warm room comfortable, while those from colder regions might perceive it as stifling. This model underscores the importance of considering the adaptive nature of human comfort, shaped by a confluence of past experiences and immediate environmental stimuli.

The role of HVAC technologies has been transformative within the ever-evolving landscape of green buildings. While this manuscript touches upon the integration challenges of traditional HVAC systems, a more profound exploration of contemporary HVAC solutions tailored for green buildings can provide invaluable depth. Several innovative technologies have emerged in the market, each promising to redefine the synergy between HVAC systems and green buildings [51]. To begin with, there is the Variable Refrigerant Flow (VRF) technology. Heralded as a game-changer, VRF systems are known for their unparalleled energy efficiency and flexibility. Unlike traditional systems that operate at constant speeds, VRF systems adjust refrigerant flow based on the exact cooling or heating needs of individual zones within a building. This dynamic adaptability conserves energy and ensures optimal comfort [48]. However, it is worth noting that the initial installation costs of VRF systems can be steep and require specialised technicians for maintenance. Next, we have earth–air heat exchangers (EAHE) [50]. These systems leverage the earth's temperatures to pre-cool or pre-heat incoming air. Especially in regions with extreme seasonal temperature variations, EAHE can be a boon, reducing the load on primary HVAC systems. However, the effectiveness of EAHE can vary based on soil properties and moisture content, making site-specific evaluations crucial. Phase-change materials (PCMs) introduce a novel approach to thermal regulation. These materials absorb or release latent heat during phase transitions, effectively acting as thermal buffers [50]. Integrated within building components, PCMs can reduce peak temperature loads, minimising the need for active cooling or heating. Their adaptability across various building types, from residential to commercial, underscores their versatility. However, selecting appropriate PCMs, based on their melting points and thermal properties, is crucial to their effective deployment [50]. Lastly, radiant cooling systems, often touted as the future of green building HVAC, provide cooling through chilled surfaces (like floors or ceilings) rather than air. The primary advantage lies in that cooling surfaces rather than air is inherently more energy efficient. Additionally, these systems enhance comfort by reducing the disparity between ambient air temperature and surface temperatures. However, a significant concern with radiant systems is the potential for condensation, especially in high-humidity environments. Proper design and integration with dehumidification systems can mitigate such risks. Outdoor air conditioning systems come in various forms to cater to different cooling needs in outdoor spaces. Misting systems use a fine water spray for cooling, ideal for restaurant patios, while evaporative coolers, effective in dry climates, use water evaporation for cooling and can be used in residential or commercial settings. Portable air conditioners offer flexibility for spot cooling in areas like patios, requiring electrical power and venting [51]. Although not air conditioners, outdoor ceiling fans enhance air circulation, creating a breezy environment. Cooling stations in public spaces provide mist or air-conditioned relief, and high-volume, low-speed (HVLS) fans are suitable for large venues like event spaces, moving air efficiently over vast areas. Additionally, ductless mini-split systems, with outdoor units linked to indoor units, offer efficient cooling for enclosed outdoor spaces like sunrooms. These diverse systems cater to specific outdoor cooling requirements, considering factors like climate, space, and energy efficiency.

6. IoT-Enabled Systems

A significant advancement in outdoor cooling is represented by smart and Internet of Things (IoT)-enabled outdoor air conditioning systems, as shown in Figure 6. These systems have various state-of-the-art features and technologies that improve their functionality, energy efficiency, and user comfort [57].

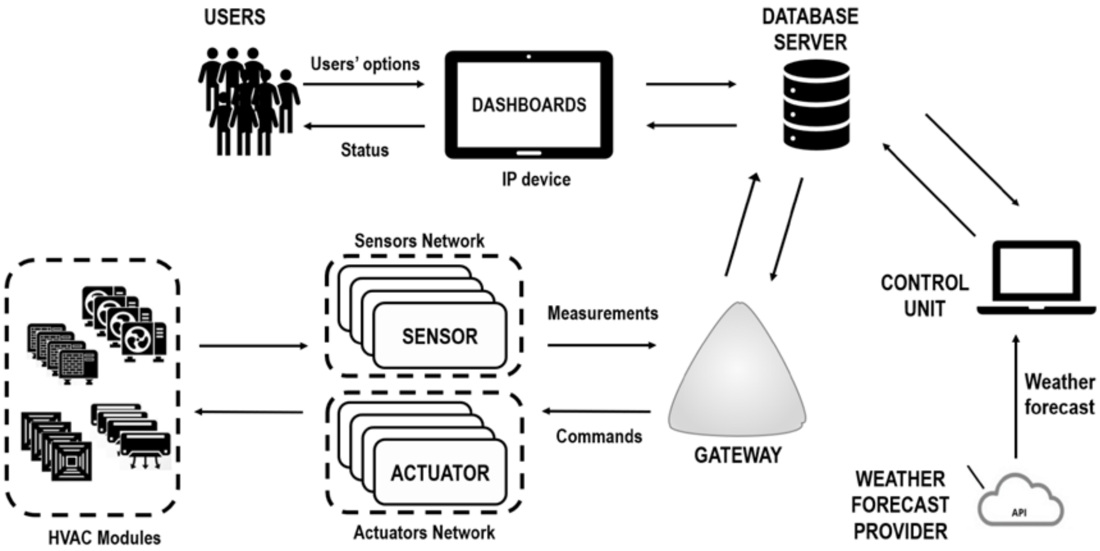

Figure 6. Internet of Things (IoT)-enabled outdoor air conditioning systems [57].

Monitoring in real time via sensors is one of the primary components of these systems, which utilise a network of sensors that collect data on various environmental properties. These sensors can measure various variables, including temperature, humidity, air quality, and occupancy. Real-time data obtained by these sensors provide the foundation for dynamic control and optimisation [58]. Data management is conducted using advanced data analytics methods, and sensor data are processed and evaluated. These strategies may identify patterns, trends, and anomalies in the data. For instance, they may detect changes in the outside temperature, which may result in adjustments to the cooling system's settings [59]. Innovative outdoor air conditioning systems can dynamically adjust their operation depending on the information gained through data analysis. For instance, the system may adjust when exterior temperatures increase significantly by boosting its cooling capability to maintain the ideal inside temperature. Alternatively, the system may operate more efficiently to save energy during periods of lower demand [60]. Additionally, these systems prioritise energy efficiency, which reduces running expenses and has a reduced effect on the environment. They may adjust the functioning of components such as pumps, fans, and compressors according to the cooling requirement, decreasing energy waste [61]. Moreover, smart systems are developed to provide the highest possible comfort for users. They can consider user preferences and adjust elements such as temperature and ventilation to create a pleasant atmosphere. They may also preserve air quality by monitoring and adjusting ventilation rates [62].

Frequently, IoT-enabled outdoor air conditioning systems can be remotely monitored and managed. Facility managers or homeowners can remotely inspect and modify system settings using a smartphone application or web interface. According to Philip et al. [63], this feature facilitates proactive system maintenance and increases usability. These systems are also capable of self-diagnosing issues and sending maintenance reminders. The method can detect component failures in advance and notify maintenance personnel, decreasing downtime and preventing costly breakdowns. Incorporating smart and Internet of Things (IoT)-enabled technology into outdoor air conditioning systems represents a significant leap in the industry, providing various cutting-edge features that improve functionality, energy efficiency, and user comfort. A network of sensors continually monitors environmental characteristics such as temperature, humidity, air quality, and occupancy, giving real-time data that serve as the foundation for dynamic management and optimisation. These sensor data are processed and analysed using sophisticated data analytics methods to find patterns, trends, and anomalies that might influence system modifications [64]. For example, when the system senses a fast increase in external temperatures, it may change its cooling capacity to maintain ideal internal temperatures. These intelligent systems emphasise energy efficiency by adapting components such as pumps, fans, and compressors to current cooling needs, minimising energy waste and saving operating costs [65]. The devices may react to the user's preferences and modify temperature and ventilation rates to produce a pleasant atmosphere [66]. Moreover, IoT-enabled systems provide remote monitoring and management through smartphone applications or web interfaces, enabling proactive system maintenance [67]. In addition, they are equipped with self-diagnostic capabilities that may detect component failures early and notify maintenance personnel, decreasing downtime and averting expensive breakdowns [68]. Overall, these intelligent and IoT-enabled outdoor air conditioning systems offer a significant advancement in outdoor cooling, closely correlating with more prominent efficiency and sustainability goals. Incorporating Internet of Things (IoT) technology into outdoor air conditioning systems is a revolutionary breakthrough with far-reaching effects on energy savings, user comfort, and system operation. This technical breakthrough is reinforced by a growing corpus of research demonstrating the many advantages of intelligent, IoT-enabled devices [69]. A network of sensors that continually monitors a variety of environmental factors, including temperature, humidity, air quality, and even occupancy, is one of the most critical aspects of these systems. This real-time data gathering is the basis for dynamic system control, allowing the air conditioning units to adapt to changing circumstances and maximise performance. This abundance of sensor data is processed using advanced data analytics methods to detect patterns, trends, and anomalies that might influence system modifications [70]. For instance, if the system senses a rapid spike in external temperatures, it may instantly change its cooling capacity to maintain a pleasant internal atmosphere. This dynamic control enables the system to predict future situations based on existing data, thus boosting efficiency. The energy efficiency of these intelligent systems is a major goal. These systems may dramatically minimise energy use by adjusting the operation of components such as pumps, fans, and compressors to the current cooling demand. This is significant not only for decreasing operating expenses but also for limiting the environmental effect of air conditioning, which is especially relevant considering the rising concerns over climate change and resource depletion [71]. Another critical emphasis of IoT-enabled air conditioning systems is user comfort. Individual user preferences may be accommodated by modifying temperature, humidity, and ventilation rates to produce a more pleasant atmosphere. In addition, they may monitor indoor air quality and change ventilation rates appropriately, promoting a better living or working environment [72].

These systems' remote monitoring and control features provide additional convenience and utility. Through smartphone applications or online interfaces, facility managers or homeowners may quickly monitor and alter system settings, allowing for more preventative system maintenance. This remote access is not only advantageous for its user-friendliness; it also provides faster reaction times in the event of system failure, hence decreasing downtime and averting expensive losses. In addition, these systems have self-diagnostic capabilities that may discover potential flaws before they become severe problems, notifying maintenance personnel and even recommending fixes. This predictive maintenance capacity is a significant improvement since it extends the life of air conditioning equipment, contributing to sustainability objectives by lowering the frequency of replacements [73]. In conclusion, incorporating Internet of Things (IoT) technology into outdoor air conditioning systems is a comprehensive innovation that solves several crucial concerns about energy efficiency, environmental sustainability, and user comfort. By integrating real-time sensor data, sophisticated analytics, dynamic control mechanisms, and remote monitoring capabilities, these intelligent systems provide a highly flexible, efficient, and user-friendly outdoor cooling solution. As a result, they are ready to establish new industry norms which correspond closely with broader goals of environmental responsibility and sustainable living. The incorporation of the Internet of Things (IoT) into HVAC systems within green architecture is symbolic of the profound technological strides the building industry is witnessing. While the authors' acknowledgement of IoT-based technologies is a step in the right direction, the depth and breadth of this integration call for a more exhaustive exploration. IoT, with its essence rooted in seamless interconnectivity, transforms HVAC systems from static entities to dynamic ecosystems that constantly communicate and adapt. This real-time data exchange is pivotal for energy conservation, a cornerstone of green buildings. Unlike traditional HVAC setups, IoT-enabled systems can discern, for instance, the occupancy of a room and modulate the cooling or heating in real-time [70]. Such nuanced adjustments, while seemingly trivial, cumulatively contribute to significant energy savings, reinforcing the sustainable ethos of green buildings. However, the advantages of IoT transcend energy efficiency. Occupant comfort, often a nuanced interplay of temperature, humidity, and individual preferences, is enhanced as interconnected sensors ensure optimal environmental conditions. Furthermore, the predictive maintenance capabilities of IoT systems herald a new era of proactive system health monitoring, pre-empting major malfunctions and ensuring uninterrupted operation. The true magic unfolds when these IoT-driven HVAC systems synergise with other building systems, from lighting to security, crafting an intelligent building ecosystem with unparalleled efficiency [71]. Moreover, when subjected to advanced analytics, the data streams from these systems provide invaluable insights into usage patterns, inefficiencies, and future energy needs. This data-centric approach, in tandem with the adaptive capabilities of IoT, positions the integration of IoT and HVAC as a linchpin in the evolution of green architecture. The discussion on IoT in HVAC systems is not just a technological narrative; it is a testament to the transformative potential of integrating digital intelligence with physical spaces, underscoring the future of sustainable and intelligent building design.

7. Portability and Scalability

Incorporating portability and scalability into outdoor air conditioning systems is a critical innovation that addresses the rising need for adaptation and flexibility in various cooling conditions. Portable units are gaining popularity because of their portability and setup simplicity, making them ideal for events, temporary workplaces, and other instances when permanent cooling systems are impracticable [25]. These devices are often lightweight and fitted with wheels or handles for easy portability, which increases their adaptability. Beneficial for temporary settings such as outdoor festivals or construction sites, the units' portability enables them to be moved as needed and to provide targeted cooling exactly where required. This versatility is a godsend for moving workstations and a cost-effective alternative to permanent systems, lowering initial and recurring costs. The fast availability and speedy installation of portable units are particularly advantageous for providing immediate respite from extreme heat, whether for emergency cooling requirements or unexpected gatherings. Scalability, another essential characteristic, permits outdoor cooling systems to adapt their cooling capacity to variable demand. This versatility is becoming more critical in contemporary system designs, particularly in locations where cooling needs may change based on time, season, or occupancy levels [15]. Scalable systems perfectly match cooling capacity to actual demand, optimising energy consumption, decreasing operating costs, and minimising environmental effects. Both transportable and scalable technologies contribute to sustainability by conforming to larger energy efficiency targets. By employing just the required cooling capacity for a particular condition, these systems reduce energy consumption and the carbon footprint, contributing to broader environmental and sustainability goals. In conclusion, the introduction of portability and scalability in outdoor air conditioning systems has ushered in a new age of adaptability, cost-efficiency, and environmental awareness. These characteristics allow for the deployment of customised cooling systems adaptable to a wide variety of applications, representing a breakthrough advance in outdoor cooling [19].

8. Economic Feasibility and Scalability

Eco-friendly HVAC technologies, pivotal in sustainable building design, markedly outperform traditional systems in energy efficiency and environmental impact [74]. Geothermal heat pumps, a standout example, are exceptionally efficient, offering an impressive energy efficiency ratio (EER) of about 10–14, compared to 9–10 for conventional systems [75]. They can deliver three to four units of energy for every one unit of electrical energy consumed. Solar-powered HVAC systems, while dependent on geographic and solar conditions, significantly cut down on electricity usage and are often capable of reducing energy bills by 20–40% [76]. Energy recovery ventilators (ERVs) enhance indoor air quality and can decrease HVAC energy consumption by up to 40%, depending on the climate and building design [76]. These systems lower operational costs and drastically reduce carbon emissions, aligning with global sustainability goals. The upfront costs for these technologies are generally higher, but the long-term savings—evidenced by their superior performance figures—are substantial, making them increasingly preferred in modern, eco-conscious construction projects.

In a detailed cost analysis of HVAC systems, contrasting traditional with eco-innovative models reveals distinct differences in financial implications and ROI [77]. Conventional HVAC systems, while cheaper to install, incur higher operational and maintenance costs over time due to less efficient energy use and frequent servicing needs. By contrast, eco-innovative HVAC systems, though more expensive initially, offer greater energy efficiency, leading to significantly lower operational costs [77]. The maintenance expenses for these advanced systems are often reduced due to their superior build quality and durability. The ROI for eco-innovative systems is favourable, as substantial long-term energy bills and maintenance savings balance the higher upfront costs. Additionally, many regions offer incentives like tax rebates for green technology adoption, enhancing the financial appeal of these systems. Another critical factor influencing the cost and implementation of HVAC systems is the impact of building codes and regulations, which vary regionally [78]. Stricter energy efficiency standards and sustainability requirements often favour eco-innovative systems, as traditional models may not comply with newer, more stringent regulations. This regulatory environment can significantly affect decision-making, pushing stakeholders towards more sustainable and compliant HVAC solutions. Therefore, while the initial investment in eco-innovative HVAC systems is higher, their long-term economic and environmental benefits and the increasing regulatory push towards sustainability present a compelling case for their adoption in modern building design [78]. When delving into the legal implications and performance of HVAC systems in different climates, a detailed understanding is crucial for sustainable building design. Legally, the implementation of HVAC systems is deeply intertwined with regional building codes and energy efficiency regulations. These laws vary widely, often dictating stringent standards that traditional HVAC systems may struggle to meet. Eco-innovative systems, designed with energy efficiency and sustainability in mind, are more likely to align with these regulations, thereby reducing the risk of legal non-compliance for building owners and developers [79]. Non-compliance can lead to penalties, legal disputes, and additional costs, making regulatory adherence a critical factor in HVAC system selection. Furthermore, these legal frameworks are dynamic and frequently updated to reflect new environmental goals or technological advancements, necessitating HVAC systems that can adapt to evolving standards. Performance in different climates is another critical aspect. Traditional HVAC systems may offer satisfactory performance in moderate temperatures but often struggle in extreme conditions, either too hot or cold, leading to inefficiencies and increased energy consumption [79]. By contrast, eco-innovative HVAC systems are typically designed for a broader range of climatic conditions. They often incorporate features like advanced insulation, smart thermostats, and renewable energy sources, enhancing their efficiency and reliability across various environmental settings. This adaptability is crucial for meeting the comfort needs of occupants and maintaining energy efficiency and reducing the overall environmental impact.

Moreover, the performance of HVAC systems in specific climates directly impacts their long-term cost-effectiveness and sustainability. Strategies that can efficiently manage cooling while minimising energy consumption are essential in hotter regions. Conversely, systems that provide effective heating with minimal energy loss are preferable in colder climates. Integrating intelligent technologies in eco-innovative systems allows for more precise control and optimisation based on external weather conditions, leading to better performance and lower energy usage. Integrating eco-innovative HVAC systems into sustainable building design poses significant challenges, primarily due to their higher initial costs compared to traditional methods, but long-term benefits like energy savings and potential incentives offset these [79]. Regulatory and compliance challenges also arise from varying building codes and energy efficiency standards, especially in retrofitting older buildings, requiring expertise in local regulations and the design of flexible systems adaptable to changing criteria. Spatial and architectural constraints in different building types necessitate innovative integration strategies and collaborative efforts between architects, engineers, and HVAC specialists. Despite these challenges, the superior performance of eco-innovative systems in terms of energy efficiency, indoor air quality, and reduced carbon footprint highlights their long-term economic and environmental viability [79]. Real-world case studies further illustrate the successes and strategies of practical implementation, reinforcing the feasibility and effectiveness of these solutions in diverse settings and presenting a comprehensive picture of the challenges and solutions in implementing sustainable HVAC technologies.

Statistically Methods from the Previous Researcher

Statistical analysis plays a pivotal role in substantiating the advancements in this field. Researchers often employ methods like regression analysis, ANOVA (analysis of variance), and time-series analysis to assess the performance of new HVAC technologies [80]. For instance, regression models are used to predict energy consumption under various scenarios, enabling a comparison between traditional and innovative systems. ANOVA helps identify the key factors influencing HVAC efficiency guiding design improvements [80]. Time-series analysis is crucial for evaluating long-term trends in energy usage and system performance, offering insights into the sustainability and cost-effectiveness of new HVAC solutions. Furthermore, using big data and advanced analytics in recent studies allows for a more comprehensive understanding of HVAC performance [81]. By analysing large datasets collected from intelligent HVAC systems, researchers can identify patterns, predict system behaviour, and suggest optimisations. This data-driven approach is instrumental in advancing HVAC technology, ensuring that new systems are innovative and empirically validated for efficiency and sustainability [82].

9. Conclusions

In conclusion, integrating conventional HVAC systems into green buildings presents a complex array of challenges that extend beyond mere energy inefficiency and high operational costs. These challenges encompass a broad spectrum of issues, including regulatory compliance, performance gaps, human factors, integration with renewable energy sources, and implications at both urban and grid levels. This paper highlights how inefficient HVAC systems can exacerbate issues like energy poverty and grid instability, adding a layer of complexity to the energy management of buildings and impacting urban planning. This problem is not just confined to individual buildings but is systemic, affecting entire cities as they endeavour to transition towards more sustainable and resilient futures. As the field of green construction evolves and gains traction, addressing these multifaceted obstacles becomes crucial. The successful integration of HVAC systems in green buildings is therefore not only a technical challenge but also involves navigating regulatory landscapes, addressing human-centric issues, and harmonising with broader urban sustainability goals.

Funding: The research is not funded by any party and is a project for a Ph.D. student.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Evans, J. 'Give Me a Laboratory, and I Will Lower Your Carbon Footprint!'–Urban Laboratories and the Pursuit of Low Carbon Futures James Evans and Andrew Karvonen. Ph.D. Thesis, University of Manchester, Manchester, UK, 2014.
2. Li, S.-F.; Liu, Z.; Wang, X.-J. A Comprehensive Review on Positive Cold Energy Storage Technologies and Applications in Air Conditioning with Phase Change Materials. *Appl. Energy* **2019**, *255*, 113667. [CrossRef]
3. Birgonul, Z. A Receptive-Responsive Tool for Customizing Occupant's Thermal Comfort and Maximizing Energy Efficiency by Blending BIM Data with Real-Time Information. *Smart Sustain. Built Environ.* **2021**, *10*, 504–535. [CrossRef]
4. Alonso, M.J.; Wolf, S.; Jørgensen, R.B.; Madsen, H.; Mathisen, H.M. A Methodology for the Selection of Pollutants for Ensuring Good Indoor Air Quality Using the De-Trended Cross-Correlation Function. *Build. Environ.* **2022**, *209*, 108668. [CrossRef]
5. Lamberti, G.; Contrada, F.; Kindinis, A. Exploring adaptive strategies to cope with climate change: The case study of Le Corbusier's Modern Architecture retrofitting. *Energy Build.* **2023**, *302*, 113756. [CrossRef]
6. Zhang, S.; Ocłoń, P.; Klemeš, J.J.; Michorczyk, P.; Pielichowska, K.; Pielichowski, K. Renewable Energy Systems for Building Heating, Cooling and Electricity Production with Thermal Energy Storage. *Renew. Sustain. Energy Rev.* **2022**, *165*, 112560. [CrossRef]
7. Yaïci, W.; Krishnamurthy, K.; Entchev, E.; Longo, M. Recent Advances in Internet of Things (IoT) Infrastructures for Building Energy Systems: A Review. *Sensors* **2021**, *21*, 2152. [CrossRef] [PubMed]
8. Goetzler, B.; Guernsey, M.; Kassuga, T.; Young, J.; Savidge, T.; Bouza, A.; Neukomm, M.; Sawyer, K. *Grid-Interactive Efficient Buildings Technical Report Series: Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration*; (No. NREL/TP-5500-75473; DOE/GO-102019-5228); National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2019.
9. *ANSI/ASHRAE Standard 55-2017*; Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Peachtree Corners, GA, USA, 2017; Volume 5, pp. 2–15.
10. Pérez-Lombard, L.; Ortiz, J.; Pout, C. A Review on Buildings Energy Consumption Information. *Energy Build.* **2008**, *40*, 394–398. [CrossRef]
11. Kibert, C.J. *Sustainable Construction: Green Building Design and Delivery*; John Wiley & Sons: Hoboken, NJ, USA, 2016; ISBN 1119055172.
12. Chan, A.L.S.; Chow, T.T.; Fong, K.F.; Lin, Z. Investigation on Energy Performance of Double Skin Façade in Hong Kong. *Energy Build.* **2009**, *41*, 1135–1142. [CrossRef]
13. DeKay, M.; Brown, G.Z. *Sun, Wind, and Light*; Wiley: Hoboken, NJ, USA, 2001.
14. Barber, K.A.; Krarti, M. A review of optimization based tools for design and control of building energy systems. *Renew. Sustain. Energy Rev.* **2022**, *160*, 112359. [CrossRef]
15. Nicol, J.F.; Humphreys, M.A. Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings. *Energy Build.* **2002**, *34*, 563–572. [CrossRef]
16. Tomat, V.; Ramallo-González, A.P.; Skarmeta Gómez, A.F. A comprehensive survey about thermal comfort under the IoT paradigm: Is crowdsensing the new horizon? *Sensors* **2020**, *20*, 4647. [CrossRef] [PubMed]
17. Papadakis, N.; Katsaprakakis, D.A. A Review of Energy Efficiency Interventions in Public Buildings. *Energies* **2023**, *16*, 6329. [CrossRef]
18. Goetzler, W.; Shandross, R.; Young, J.; Petritchenko, O.; Ringo, D.; McClive, S. *Energy Savings Potential and RD&D Opportunities for Commercial Building HVAC Systems*; (No. DOE/EE-1703); Navigant Consulting: Burlington, MA, USA, 2017.
19. Heschong, L.; Saxena, M. *Windows and Offices: A Study of Office Worker Performance and the Indoor Environment*; California Energy Commission: Sacramento, CA, USA, 2003.
20. Zhou, G.; Moayedi, H.; Bahiraei, M.; Lyu, Z. Employing Artificial Bee Colony and Particle Swarm Techniques for Optimizing a Neural Network in Prediction of Heating and Cooling Loads of Residential Buildings. *J. Clean. Prod.* **2020**, *254*, 120082. [CrossRef]
21. Sansaniwal, S.K.; Mathur, J.; Mathur, S. Review of practices for human thermal comfort in buildings: Present and future perspectives. *Int. J. Ambient. Energy* **2022**, *43*, 2097–2123. [CrossRef]
22. Zhou, W.; Liu, Y.; Fu, J.; Zhong, Z.; Li, Y.; Liu, Z. An Interval Scaling Algorithm and Concept Lattice Building from Extended Formal Context. In Proceedings of the 2009 International Conference on Test and Measurement, Hong Kong, China, 5–6 December 2009; IEEE: Piscataway, NJ, USA, 2009; Volume 2, pp. 409–412.
23. Ganesh, G.A.; Sinha, S.L.; Verma, T.N.; Dewangan, S.K. Investigation of indoor environment quality and factors affecting human comfort: A critical review. *Build. Environ.* **2021**, *204*, 108146. [CrossRef]
24. Santamouris, M.; Synnefa, A.; Karlessi, T. Using Advanced Cool Materials in the Urban Built Environment to Mitigate Heat Islands and Improve Thermal Comfort Conditions. *Sol. Energy* **2011**, *85*, 3085–3102. [CrossRef]

25. Kim, J.; Schiavon, S.; Brager, G. Personal Comfort Models–A New Paradigm in Thermal Comfort for Occupant-Centric Environmental Control. *Build. Environ.* **2018**, *132*, 114–124. [CrossRef]
26. Zhang, H.; Arens, E.; Zhai, Y. A Review of the Corrective Power of Personal Comfort Systems in Non-Neutral Ambient Environments. *Build. Environ.* **2015**, *91*, 15–41. [CrossRef]
27. Rupp, R.F.; Vásquez, N.G.; Lamberts, R. A Review of Human Thermal Comfort in the Built Environment. *Energy Build.* **2015**, *105*, 178–205. [CrossRef]
28. Hoes, P.; Hensen, J.L.M.; Loomans, M.G.L.C.; de Vries, B.; Bourgeois, D. User Behavior in Whole Building Simulation. *Energy Build.* **2009**, *41*, 295–302. [CrossRef]
29. De Dear, R.; Xiong, J.; Kim, J.; Cao, B. A review of adaptive thermal comfort research since 1998. *Energy Build.* **2020**, *214*, 109893. [CrossRef]
30. Carlucci, S.; Bai, L.; de Dear, R.; Yang, L. Review of adaptive thermal comfort models in built environmental regulatory documents. *Build. Environ.* **2018**, *137*, 73–89. [CrossRef]
31. Edwards, B.; Hyett, P. *Rough Guide to Sustainable Design*; RIBA: London, UK, 2001.
32. Mendell, M.J. Indoor Residential Chemical Emissions as Risk Factors for Respiratory and Allergic Effects in Children: A Review. *Indoor Air* **2007**, *17*, 259–277. [CrossRef] [PubMed]
33. Moezzi, M.; Janda, K.B.; Rotmann, S. Using Stories, Narratives, and Storytelling in Energy and Climate Change Research. *Energy Res. Soc. Sci.* **2017**, *31*, 1–10. [CrossRef]
34. Brown, M.E. *Introduction to Thermal Analysis: Techniques and Applications*; Springer: Berlin/Heidelberg, Germany, 2001.
35. Bakker, A.; Siegel, J.A.; Mendell, M.J.; Prussin, A.J.; Marr, L.C.; Peccia, J. Bacterial and Fungal Ecology on Air Conditioning Cooling Coils Is Influenced by Climate and Building Factors. *Indoor Air* **2020**, *30*, 326–334. [CrossRef] [PubMed]
36. Granderson, J.; Touzani, S.; Custodio, C.; Sohn, M.D.; Jump, D.; Fernandes, S. Accuracy of Automated Measurement and Verification (M&V) Techniques for Energy Savings in Commercial Buildings. *Appl. Energy* **2016**, *173*, 296–308.
37. Seljom, P.; Lindberg, K.B.; Tomasgard, A.; Doorman, G.; Sartori, I. The Impact of Zero Energy Buildings on the Scandinavian Energy System. *Energy* **2017**, *118*, 284–296. [CrossRef]
38. D'Ayala, D.; Wang, K.; Yan, Y.; Smith, H.; Massam, A.; Filipova, V.; Pereira, J.J. Flood Vulnerability and Risk Assessment of Urban Traditional Buildings in a Heritage District of Kuala Lumpur, Malaysia. *Nat. Hazards Earth Syst. Sci.* **2020**, *20*, 2221–2241. [CrossRef]
39. Chun, L.; Gong, G.; Peng, P.; Wan, Y.; Chua, K.J.; Fang, X.; Li, W. Research on Thermodynamic Performance of a Novel Building Cooling System Integrating Dew Point Evaporative Cooling, Air-Carrying Energy Radiant Air Conditioning and Vacuum Membrane-Based Dehumidification (DAV-Cooling System). *Energy Convers. Manag.* **2021**, *245*, 114551. [CrossRef]
40. Chua, Y.S.; Dai Pang, S.; Liew, J.Y.R.; Dai, Z. Robustness of Inter-Module Connections and Steel Modular Buildings under Column Loss Scenarios. *J. Build. Eng.* **2022**, *47*, 103888. [CrossRef]
41. Moon, H.; Yu, J.; Chua, B.-L.; Han, H. Hotel Privacy Management and Guest Trust Building: A Relational Signaling Perspective. *Int. J. Hosp. Manag.* **2022**, *102*, 103171. [CrossRef]
42. Liu, Y.; Lin, Y.; Yeoh, J.K.W.; Chua, D.K.H.; Wong, L.W.C.; Ang, M.H.; Lee, W.L.; Chew, M.Y.L. Framework for Automated UAV-Based Inspection of External Building Façades. *Autom. Cities Des. Constr. Oper. Futur. Impact* **2021**, 173–194.
43. Foster, G. Planning the Circular City: Focus on Buildings'environmental Impact. *BDC Boll. Cent. Calza Bini* **2019**, *19*, 117–123.
44. MacArthur, E. Towards the Circular Economy. *J. Ind. Ecol.* **2013**, *2*, 23–44.
45. Sorrell, S. *The Rebound Effect: An Assessment of the Evidence for Economy-Wide Energy Savings from Improved Energy Efficiency*; University of Sussex: Brighton, UK, 2007.
46. Saidur, R. Energy Consumption, Energy Savings, and Emission Analysis in Malaysian Office Buildings. *Energy Policy* **2009**, *37*, 4104–4113. [CrossRef]
47. Aynur, T.N.; Hwang, Y.; Radermacher, R. Integration of Variable Refrigerant Flow and Heat Pump Desiccant Systems for the Cooling Season. *Appl. Therm. Eng.* **2010**, *30*, 917–927. [CrossRef]
48. Allwood, J.M.; Cullen, J.M.; Carruth, M.A.; Cooper, D.R.; McBrien, M.; Milford, R.L.; Moynihan, M.C.; Patel, A.C.H. *Sustainable Materials: With Both Eyes Open*; UIT Cambridge Limited: Cambridge, UK, 2012; Volume 2012.
49. Yuan, M.; Li, Z.; Li, X.; Li, L.; Zhang, S.; Luo, X. How to Promote the Sustainable Development of Prefabricated Residential Buildings in China: A Tripartite Evolutionary Game Analysis. *J. Clean. Prod.* **2022**, *349*, 131423. [CrossRef]
50. Henning, H.-M. Solar Assisted Air Conditioning of Buildings—An Overview. *Appl. Therm. Eng.* **2007**, *27*, 1734–1749. [CrossRef]
51. Jacobson, M.Z. Review of Solutions to Global Warming, Air Pollution, and Energy Security. *Energy Environ. Sci.* **2009**, *2*, 148–173. [CrossRef]
52. Branker, K.; Pathak, M.J.M.; Pearce, J.M. A Review of Solar Photovoltaic Levelized Cost of Electricity. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4470–4482. [CrossRef]
53. Parida, B.; Iniyan, S.; Goic, R. A Review of Solar Photovoltaic Technologies. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1625–1636. [CrossRef]
54. Majd, E.; McCormack, M.; Davis, M.; Curriero, F.; Berman, J.; Connolly, F.; Leaf, P.; Rule, A.; Green, T.; Clemons-Erby, D. Indoor Air Quality in Inner-City Schools and Its Associations with Building Characteristics and Environmental Factors. *Environ. Res.* **2019**, *170*, 83–91. [CrossRef] [PubMed]

55. Henning, H.-M.; Pagano, T.; Mola, S.; Wiemken, E. Micro Tri-Generation System for Indoor Air Conditioning in the Mediterranean Climate. *Appl. Therm. Eng.* **2007**, *27*, 2188–2194. [CrossRef]
56. Khamidov, A.; Akhmedov, I.; Kholmirzayev, S.; Jalalov, Z.; Yusupov, S.; Umarov, I. Effectiveness of Modern Methods of Testing Building Structures. *Sci. Innov.* **2022**, *1*, 1046–1051.
57. Li, W.; Meng, W.; Au, M.H. Enhancing Collaborative Intrusion Detection via Disagreement-Based Semi-Supervised Learning in IoT Environments. *J. Netw. Comput. Appl.* **2020**, *161*, 102631. [CrossRef]
58. Shi, J.; Liu, B.; He, Z.; Liu, Y.; Jiang, J.; Xiong, T.; Shi, J. A Green Ultra-Lightweight Chemically Foamed Concrete for Building Exterior: A Feasibility Study. *J. Clean. Prod.* **2021**, *288*, 125085. [CrossRef]
59. Fan, C.; Yan, D.; Xiao, F.; Li, A.; An, J.; Kang, X. Advanced Data Analytics for Enhancing Building Performances: From Data-Driven to Big Data-Driven Approaches. In *Building Simulation*; Springer: Berlin/Heidelberg, Germany, 2021; Volume 14, pp. 3–24.
60. Liu, G.; Zhou, X.; Yan, J.; Yan, G. A Temperature and Time-Sharing Dynamic Control Approach for Space Heating of Buildings in District Heating System. *Energy* **2021**, *221*, 119835. [CrossRef]
61. Belussi, L.; Barozzi, B.; Bellazzi, A.; Danza, L.; Devitofrancesco, A.; Fanciulli, C.; Ghellere, M.; Guazzi, G.; Meroni, I.; Salamone, F. A Review of Performance of Zero Energy Buildings and Energy Efficiency Solutions. *J. Build. Eng.* **2019**, *25*, 100772. [CrossRef]
62. Smith, A.; Pitt, M. Sustainable Workplaces and Building User Comfort and Satisfaction. *J. Corp. Real Estate* **2011**, *13*, 144–156. [CrossRef]
63. Philip, A.; Islam, S.N.; Phillips, N.; Anwar, A. Optimum Energy Management for Air Conditioners in IoT-Enabled Smart Home. *Sensors* **2022**, *22*, 7102. [CrossRef]
64. Hashem, Y.; Frank, J. The Jigsaw Puzzle of MRNA Translation Initiation in Eukaryotes: A Decade of Structures Unraveling the Mechanics of the Process. *Annu. Rev. Biophys.* **2018**, *47*, 125–151. [CrossRef] [PubMed]
65. Cook, A.A.; Mısırlı, G.; Fan, Z. Anomaly Detection for IoT Time-Series Data: A Survey. *IEEE Internet Things J.* **2019**, *7*, 6481–6494. [CrossRef]
66. Al-Fuqaha, A.; Guizani, M.; Mohammadi, M.; Aledhari, M.; Ayyash, M. Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. *IEEE Commun. Surv. Tutor.* **2015**, *17*, 2347–2376. [CrossRef]
67. Whitmore, A.; Agarwal, A.; Da Xu, L. The Internet of Things—A Survey of Topics and Trends. *Inf. Syst. Front.* **2015**, *17*, 261–274. [CrossRef]
68. Atzori, L.; Iera, A.; Morabito, G. The Internet of Things: A Survey. *Comput. Netw.* **2010**, *54*, 2787–2805. [CrossRef]
69. Bashir, M.R.; Gill, A.Q. IoT Enabled Smart Buildings: A Systematic Review. In Proceedings of the 2017 Intelligent Systems Conference (IntelliSys), London, UK, 7–8 September 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 151–159.
70. Marinakis, V.; Doukas, H. An Advanced IoT-Based System for Intelligent Energy Management in Buildings. *Sensors* **2018**, *18*, 610. [CrossRef]
71. Gougar, H.D.; Petti, D.A.; Demkowicz, P.A.; Windes, W.E.; Strydom, G.; Kinsey, J.C.; Ortensi, J.; Plummer, M.; Skerjanc, W.; Williamson, R.L. The US Department of Energy's High Temperature Reactor Research and Development Program–Progress as of 2019. *Nucl. Eng. Des.* **2020**, *358*, 110397. [CrossRef]
72. O'Leary, R. The Impact of Federal Court Decisions on the Policies and Administration of the US Environmental Protection Agency. In *Administrative Law*; Routledge: London, UK, 2018; pp. 259–284.
73. Manyika, J.; Chui, M.; Bisson, P.; Woetzel, J.; Dobbs, R.; Bughin, J.; Aharon, D. Unlocking the Potential of the Internet of Things. *McKinsey Glob. Inst.* **2015**, *1*, 1–5.
74. Zhong, H.; Li, Y.; Zhang, P.; Gao, S.; Liu, B.; Wang, Y.; Meng, T.; Zhou, Y.; Hou, H.; Xue, C. Hierarchically Hollow Microfibers as a Scalable and Effective Thermal Insulating Cooler for Buildings. *ACS Nano* **2021**, *15*, 10076–10083. [CrossRef]
75. Wang, Y.; Wang, X.; Yu, H.; Huang, Y.; Dong, H.; Qi, C.; Baptiste, N. Optimal design of integrated energy system considering economics, autonomy and carbon emissions. *J. Clean. Prod.* **2019**, *225*, 563–578. [CrossRef]
76. Chua, K.J.; Chou, S.K.; Yang, W.M.; Yan, J. Achieving better energy-efficient air conditioning–a review of technologies and strategies. *Appl. Energy* **2013**, *104*, 87–104. [CrossRef]
77. Cooke, P. Transition regions: Regional–national eco-innovation systems and strategies. *Prog. Plan.* **2011**, *76*, 105–146. [CrossRef]
78. Laustsen, J. *Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings*; IEA: Paris, France, 2008.
79. Omer, A.M. Energy, environment and sustainable development. *Renew. Sustain. Energy Rev.* **2008**, *12*, 2265–2300. [CrossRef]
80. Deb, C.; Zhang, F.; Yang, J.; Lee, S.E.; Shah, K.W. A review on time series forecasting techniques for building energy consumption. *Renew. Sustain. Energy Rev.* **2017**, *74*, 902–924. [CrossRef]
81. Wei, Y.; Zhang, X.; Shi, Y.; Xia, L.; Pan, S.; Wu, J.; Han, M.; Zhao, X. A review of data-driven approaches for prediction and classification of building energy consumption. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1027–1047. [CrossRef]
82. Daissaoui, A.; Boulmakoul, A.; Karim, L.; Lbath, A. IoT and big data analytics for smart buildings: A survey. *Procedia Comput. Sci.* **2020**, *170*, 161–168. [CrossRef]