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ENERGY-EFFICIENT HVAC SYSTEMS: ENHANCING SUSTAINABILITY IN LOW-INCOME HOUSING

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Abstract: In the recent trend of developing sustainable societies aspiring to net-zero initiatives, the use of energy-efficient HVAC systems has become increasingly popular, specifically in low-income housing schemes. Conventional designs (HVAC) are subjected to high levels of energy consumption exacerbating increased cost of utility and severe environmental damages. This paper aimed to explore innovative and energy-efficient HVAC designs that can significantly contribute to developing sustainable societies with a net-zero future while fostering the environment of social equity. By conducting a comprehensive review of the contextual literature and related studies, the research highlights the significance of energy-efficient HVAC systems in developing sustainable societies and the key challenges preventing the smooth adaptation of modern HVAC systems.

Keywords: Sustainability, Net-zero, Zero-carbon, Low-income housing, Energy-efficient, Greenhouse gases.

I. Introduction

With the increased concern over climatic changes, sustainable eco-system, and global warming, the demand for energy-efficient heating, Ventilation, and Air Conditioning (HVAC) systems has been intensifying continuously within the residential sector specifically, when designed for low-income housing schemes to control the percentage of energy consumption and related climatic changes. The conventional HVAC system designs are based on high energy consumption models, contributing to increased energy utilization and high volume of greenhouse gas emissions, exacerbating the long-term adverse impacts on economic and environmental conditions (U.S. Department of Energy, 2020) [1]. According to recent research, as indicated by Shadmand (2024) [2], the modern designs of HVAC technologies are based on energy-efficient modeling asserting the reduction of energy utilization by 30% to 50%, significantly reducing the cost of energy utilization while enhancing the quality of the environment. The research aimed to explore the modeling and significance of HVAC system designs based on energy-efficient technologies with a specific focus on low-income housing schemes to help assess the socio-economic benefits and identification of significant challenges in implementation. By addressing the aforementioned challenges, this research contributes to the ongoing discourse on sustainability and equitable access to essential technologies.

*A. **Background***

The energy-efficient models of heating, ventilation, and Air Conditioning (HVAC) systems play a critical role in developing eco-friendly and sustainable residential buildings, specifically when focused on low-income housing schemes, where the factor of financial stability often limits accessibility to advanced technology [3]. The energy outcomes of conventional HVAC designs infer compromising results, contributing to excessive levels of energy consumption, which significantly adds to utility costs and environmental depreciation due to greenhouse gas emissions (U.S. Department of Energy, 2020) [2]. However, modern energy-efficient designs are integral to the development of highly sustainable residential buildings with improved overall health outcomes and environmental conditions, promoting economic stability and technological equity [4]. This accounts for the integration of renewable energy sources such as solar energy with advanced technologies to optimize the performance outcomes of HVAC systems and minimize operational costs [5]. This research significantly outlines the current ecosystem of HVAC technologies undermining the need for integration of more advanced and innovative solutions that can significantly address the rising demand for energy-efficient systems, while contributing to the socio-economic development that aligns with the global sustainability goals.

B. Aim and Objectives

In consideration of the aforementioned discussion elaborating the need for more sustainable and eco-friendly systems, the key aim of this research is to explore the critical role of energy-efficient HVAC systems in improvising the factor of sustainability within low-income housing schemes. Thus, the following objectives have been developed to guide the detailed research paradigm.

- To study and analyze the current ecosystem of HVAC technologies and related energy consumption profiles.
- To study and assess the role of energy- efficient HVAC systems on environmental outcomes and utility costs in low-income housing schemes.
- To explore and identify the key challenges that prevent the widespread adoption of energy-efficient HVAC solutions in low- income housing schemes to formulate strategies that can mitigate these impediments.

*C. **Research Questions***

1. *How can innovative HVAC systems contribute to the development of eco-friendly and sustainable infrastructure in low-income housing schemes?*
2. *What are the key challenges that prevent the adoption of sustainable HVAC technologies, and how can they be addressed through policy interventions?*

II. Literature Review

The role of energy is critical in driving the key requisites of the modern world, supplementing multidisciplinary roles and ubiquitous applications in various sectors of life, encompassing key domains such as transportation, telecommunications, and agriculture, as well as the heating, cooling, and lighting within construction and developmental projects [6]. The trends in global energy consumption as reported by the International Energy Agency seemed to be rising at an exponential rate, indicating the projected surge of 53% by the end of 2040; thus, highlighting escalated demand in multiple sectors [7]. Figure -1 depicts the graphical representation of the how energy consumption rate has increased over the years. The increased demand for energy consumption has subsequently amplified the reliance on unsustainable energy resources while heightening the demand for fossil fuels, exacerbating multifaceted challenges that include drastic climatic changes, resource scarcity, environmental, degradation, and social disparities. However, it is subsequent that the contributions made by the construction sector seemed teh most detrimental, escaping the overall rate of global consumption of energy and resources.

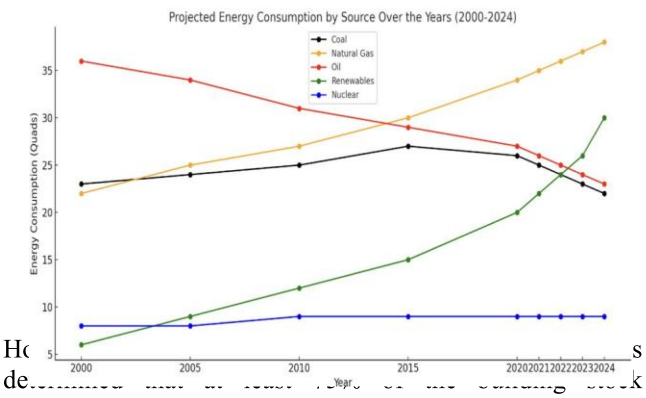

Fig. *1. Energy consumption by source from 2000 to 2024.*

By the latest updation in European energy and environmental protection policies and regulations, the construction sector, specifically the development of high rise buildings is among the top contributors to the global economy and resource flow. Similarly, another survey has indicated that the total energy consumption as reported by the building sector has reached 40% globally while the CO2 emissions were recorded as 38% at the global level [8]. Thus, the International Energy Agency has re-evaluated the key contributors to the energy consumption in the building sector to reach out to the new standards of reducing the level of energy consumption by up to 20%, CO2 emissions by 20%, and integrating a share of renewable energy sources by 20% in total by the end of 2025 [9]. Moreover, global energy organizations are also looking forward to committing to the reduction of GHG (Greenhouse gases) emissions by up to 85-95% by the end of 2050, contributing to the pathway of a competitive low-carbon economy. This calls for the installation of high-profile projects based on energy- efficient models and promoting the use of renewable energy resources in major sectors such as transportation, construction, and manufacturing industries. Another significant goal is to maintain the energy performance of building directives to nearly zero energy, contributing to the net-zero initiative launched by global organizations to decrease teh level of carbon emissions to zero within the next ten years [10]. Thus, the researchers and experts seemed sparingly interested in exploring the new building designs integrated with energy-efficient systems and sustainable technologies to meet the projected targets of reduction in energy consumption levels as indicated by the International Energy Agencies and related global organizations working for the cause [11].

Ho… s de… k (constituting 70-80% of the total residential stock) has already been built and is in the process of building which continues to be present in the next few decades. When explored globally, a large of residential buildings across various countries were developed before the period 1960s, when the concept of energy- efficient buildings and regulations was non-existent or significantly scarce, resulting in inadequate energy infrastructure [12]. This has inferred detrimental impacts on the overall performance of energy, escalating the levels of carbon footprint. An in-depth analysis has been conducted to study the energy consumption rate of older buildings in the selected regions of the UK has indicated that the average consumption of heating oil per square meter is 5 times greater than that of the consumption rate of newer buildings (that are based on energy-efficient designs and innovative system integration) [13]. However, a survey report from Greece indicated that 79% of the total building stock in the territory constitutes a residential sector, consuming almost a quarter of the total units of energy consumption reported by the territory [11]. It further accounted that about 58% of the dwellings had been built before the 1980s when the first thermal regulation was introduced and adopted by the construction industry [9]. Furthermore, the energy consumption rate in Greek housing facilities is found to be much higher than that of other countries where environments are a bit colder such as Germany, Denmark, and the Netherlands.

The continuous rise in demand for energy in the building sector significantly highlights the subsequent need for the adoption of energy-efficient systems to mitigate environmental impacts and the development of sustainable societies. Given the aforementioned discussion, energy-efficient Heating, Ventilation, and Air Conditioning (HVAC) systems have become an emerging research field in the context of mechanical engineering, reshaping the eco-system of modern research, with a specific focus on low-income housing schemes that account for economic vulnerability and poor air quality. According to Simple (2022) [10], the installation of smart HVAC systems that are designed with innovative technology can be the best alternative to conventional building designs, contributing to a substantial energy reduction of up to 50%. In addition to that, the integration of renewable energy sources into HVAC system designs has also proved to be supplemental in further enhancing process outcomes and developing cost-effective infrastructure. However, the prospected challenges aiding multifaceted barriers including, lack of awareness, high cost of installation, and inadequate policy frameworks have significantly impacted the process of adoption of these technologies, more specifically in low-income communities [14].

All things considered, the above literature review signifies the need for a multifaceted approach, integrating technological innovation and policy frameworks with community engagement and social well-being. Thus, subjectifying the use of energy- efficient HVAC systems in low-income housing schemes to reduce energy consumption, enhance overall living conditions, and contribute towards the broader goal of achieving zero-carbon or net-zero communities.

III. **Discussion**

A. How can innovative HVAC systems contribute to the development of eco-friendly and sustainable infrastructure in low-income housing schemes?

Innovative and energy-efficient HVAC systems are integral to the development of eco-friendly and sustainable infrastructure, specifically when focusing on low-income housing schemes [4]. The system is equipped with smart energy models, integrating the latest technologies such as energy recovery ventilation, smart thermostats, and heat pumps that can optimize the level of energy consumption in buildings [15]. Moreover, the use of advanced technology and specific design methodology help them to reduce the levels of GHG emissions; hence contributing to enhanced environmental outcomes as well as reduced reliance on non-renewable energy sources. As highlighted in the above literature review, buildings are contributing around 40% of the total energy consumption globally while constituting a significant portion of GHG emissions. This percentage is even higher when particularly focused on older building designs. Thus, the integration of modern HVAC systems that are based on smart technology and energy-efficient designs, in low-income housing schemes is imperative in decreasing the carbon footprint of the environment. Moreover, it also contributes to the reduction of energy costs for residents, leading to economic stability and the promotion of social equity [16].

In addition to that, the installation of EMS (Energy Management Systems) in HVAC solutions helps in providing real-time data on energy utilization to ensure optimized performance subjected to varying operating conditions [17]. The module is not only helpful in minimizing the levels of GHG emissions but also extends the lifecycle of these systems, leading to lowered cost of maintenance and overall expansion [19]. The literature review above also indicated that the older building designs, constituting around 78% to 80% of the total residential stocks are consuming much higher amounts of energy hence, depicting poor energy infrastructure. Innovation in HVAC systems when aligned with global efforts leads to the development of sustainable and eco-friendly infrastructure.

B. What are the key challenges that prevent the adoption of sustainable HVAC technologies, and how can they be addressed through policy interventions?

Amid the increased social and environmental disparities around the globe, the adoption rate of modern HVAC technologies is far less than that of the benefits being offered by its implementation. There exist a range of challenges preventing the timely adoption of sustainable HVAC technologies, specifically when analyzed within low-income housing schemes. One of the key barriers to its implementation constitutes high upfront cost i.e. the initial cost associated with the implementation of energy-efficient HVAC systems [14]. Moreover, integration of advanced technological modules; for instance, geo-thermal heat pumps, energy recovery ventilators, etc., are subjected to heavy initial investments thus, prohibitive for developers in low- income housing schemes. Additionally, the misinterpreted ideas, misconceptions in policy regulations, and lack of awareness about the multifaceted benefits aiding long-term environmental and economic stability further limit the rate of adoption [16]. Additionally, the imposition of regulatory inconsistencies and insufficient funds and incentives significantly add to the intimidation and challenge. Thus it is of utmost significance to design a robust framework for regulatory and compliance of energy-efficient HVAC systems that can pose strong urges on construction companies to prioritize energy- efficient installations [20]. Moreover, policy interventions, which may include, tax credits, low-interest loans, and government subsidies can lead to faster adoption and encourage contractors for the deployment of energy-efficient HVAC systems by offsetting these initial costs [15].

IV. **Conclusion**

In conclusion, the research has significantly explored the critical role of innovation and technological advances in the design and development of energy- efficient HVAC systems to enhance sustainability and environmental stability with a specific focus on low- income housing schemes. The installment of advanced technology and modern designs in HVAC systems leads to lowered energy consumption, a significant decrease in GHG emissions, and improved overall environmental and social conditions i.e., plays a significant role in addressing global challenges to climate change. However, its widespread adoption is significantly hindered by various challenges including significant regulatory reforms, high cost of installation, and lack of awareness, leading to an unorganized adoption of energy-efficient HVAC systems. Thus it is determined that robust policy interventions, such as regulatory reforms, financial incentives, and initiation of awareness programs will help overcome these challenges. Moreover, the reorganization of older buildings by retrofitting with energy-efficient HVAC systems also helps ensure major cost savings while achieving broader social and environmental goals. Ultimately, the adoption of energy-efficient HVAC systems is imperative for the development of eco-friendly and resilient infrastructure in low-income communities.

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