JOURNAL OF MULTIDISCIPLINARY SCIENCES AND INNOVATIONS

VOLUME 04, ISSUE 10
MOPNTHLY JOURNALS

GERMAN INTERNATIONAL JOURNALS

ISSN NUMBER: 2751-4390
IMPACT FACTOR: 9,08

INTEGRATION OF RENEWABLE ENERGY TECHNOLOGIES IN BUILDINGS FOR ENHANCED ENERGY EFFICIENCY AND REDUCTION OF GREENHOUSE GAS EMISSIONS

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Abstract. This article presents a comprehensive analysis of the integration of renewable energy technologies in the building sector as an effective strategy for improving energy efficiency and reducing greenhouse gas emissions. The study evaluates the performance of solar water heating systems, flat plate collectors, hybrid heating systems, and phase change material (PCM)-based technologies in terms of their technical, economic, and environmental impacts. The results indicate that the application of these systems significantly enhances thermal performance, reduces reliance on fossil fuels, and lowers carbon dioxide emissions while achieving acceptable payback periods. However, the widespread adoption of such technologies remains constrained by financial uncertainty, technical complexity, and limited institutional support. The findings highlight the necessity of a coordinated technological and policy-driven framework to accelerate the transition towards sustainable, low-carbon building energy systems.

Keywords: renewable energy, building sector, energy efficiency, solar water heating, greenhouse gas emissions, hybrid heating systems, phase change materials, sustainable infrastructure, decarbonisation.

Residential households are regarded as one of the most energy-intensive components of the modern economy, contributing nearly 30% to the overall global energy demand [1]. Within this sector, domestic hot water (DHW) production constitutes a substantial portion, accounting for approximately one quarter of the total energy consumption in residential buildings [2]. Although a broad range of technological solutions has been introduced to satisfy DHW requirements, the predominant reliance on fossil fuel-based systems continues to pose serious environmental challenges, particularly due to their significant contribution to greenhouse gas emissions and ecological degradation. In response to these concerns, the incorporation of solar water heating (SWH) systems into conventional thermal frameworks has emerged as an effective and sustainable alternative. This hybrid approach offers considerable potential to decrease fossil fuel dependency, alleviate environmental pollution, and limit greenhouse gas emissions [3]. A comprehensive evaluation conducted by Serban et al. [4] revealed that the adoption of SWH systems in residential applications can lead to annual energy savings of approximately 71%. Furthermore, over the operational lifespan of these systems, a cumulative reduction of around 18.5 tonnes of CO_2 emissions can be achieved, while the discounted payback period is estimated to fall between 6.8 and 8.6 years, underscoring both the environmental and economic sustainability of this technology.

Regions characterized by high population density and rapid demographic growth, particularly the Middle East, exhibit an increasing demand for energy services. This region benefits from exceptionally high solar irradiance levels, with annual average solar intensity ranging between 2000 and 3200 kWh/m², which clearly demonstrates its substantial suitability for the deployment of solar energy technologies [5]. Despite this natural advantage, Middle Eastern countries remain heavily dependent on fossil fuel resources, primarily due to their abundant oil and gas reserves, which continue to dominate the regional energy mix. Statistical evidence indicates that renewable energy sources contributed less than 1% to the total energy consumption of the region in 2018, underscoring the limited integration of sustainable alternatives within the current energy infrastructure [6]. Furthermore, the prevailing arid climate and high ambient temperatures of the Middle East create highly favorable conditions for the large-scale implementation of solar water heating (SWH) systems. In response to these conditions, investment in SWH technologies has demonstrated a noticeable upward trend in recent years. For instance, financial allocation for SWH systems reached approximately 2 million USD in 2016 and is projected to increase by an additional 0.5 million USD by the end of 2024, reflecting growing regional interest in sustainable thermal solutions.

SWH systems demonstrate notable durability, as they are capable of operating for periods exceeding 25 years with minimal requirements for major maintenance, thereby representing a technically reliable and economically sound long-term investment [7]. Owing to their combined economic advantages and positive environmental impacts, the adoption of SWH technologies has experienced considerable growth over the past decade. Among the various configurations, flat plate solar water heating (FPSWH) systems represent the earliest and most conventional form of SWH technology. Their widespread application is primarily attributed to their structural simplicity and relatively low installation costs. Nevertheless, FPSWH systems are characterized by comparatively low thermal efficiency, especially during colder seasons, as a result of elevated heat losses and reduced convective heat transfer coefficients. Empirical observations indicate that their thermal efficiency can decrease significantly from approximately 75% during summer conditions to around 40% in winter operation. Cruz et al. [8] conducted an in-depth assessment of the thermal performance, environmental impact, and economic feasibility of FPSWH systems, revealing that when operated with an auxiliary electric backup, the system achieved a payback period of approximately 4.5 years. Similar investigations by Koroneos and Nanaki [9] evaluated the technical and environmental performance of FPSWH installations and reported a payback period of 5 years, alongside potential lifetime savings of nearly €4,280 in the context of Greece. Furthermore, numerous studies have explored the energy efficiency, economic viability, and environmental consequences associated with FPSWH systems [10, 11]. A comparative theoretical analysis conducted by Nájera-Trejoa et al. [12] examined the economic feasibility of flat plate collectors versus evacuated tube solar collectors. The findings indicated that flat plate systems exhibited a return on investment period of approximately 9 years, whereas evacuated tube systems required around 11 years to achieve financial recovery.

Numerous previous studies have focused on enhancing the thermal efficiency of flat plate solar collectors through various technical modifications and operational strategies. For example, Kizildag et al. [13] evaluated the performance of three flat plate collector prototypes incorporating transparent insulating materials and compared their effectiveness with that of a conventional flat plate collector. Their findings demonstrated that the modified prototypes achieved energy gains approximately 1.4 times higher in spring and 2.5 times higher in winter compared to the standard design. Hashim et al. [14] conducted an experimental investigation into the influence of water flow rate on the outlet temperature and overall effectiveness of flat plate collectors. The results indicated that at flow rates of 5.3 L/min and 6.51 L/min, the maximum outlet temperatures reached 51.4℃ and 49℃, respectively, highlighting the sensitivity of thermal performance to hydraulic operating conditions. In a comparative assessment, Ebaid et al. [15] analyzed the performance of a hemispherical solar collector in relation to a conventional flat plate collector. Their study revealed that the hemispherical configuration achieved a maximum thermal efficiency of 69%, significantly exceeding the 42% efficiency recorded for the flat plate system. Additionally, the integration of a solar reflector to enhance incident radiation was examined by Bhowmik and Amin [16], who reported an approximate 10% improvement in collector efficiency due to increased reflectivity. Shojaeizadeh et al. [17] explored the effect of varying propylene glycol concentrations in a propylene glycol–water mixture on the operational efficiency of flat plate collectors. The experimental outcomes showed that increasing the concentration from 25% to 75% led to improved thermal performance, whereas a further increase from 75% to 100% resulted in a decline of maximum efficiency by approximately 8.3%.

Recent research has increasingly focused on the development and assessment of advanced space heating technologies, with particular emphasis on their energy performance and economic viability. Faraj et al. [18], for example, carried out a comprehensive comparative analysis of an underfloor hydronic heating system by examining the influence of climatic conditions, the integration of phase change materials (PCM), PCM types and properties, as well as the positioning of PCM plates beneath the floor. Their findings indicated that the incorporation of coconut oil-based PCM within the underfloor system resulted in notable performance improvements, achieving an annual cost saving of 169 USD and a payback period of approximately 3.94 years. Similarly, Devaux and Farid [19] performed both theoretical and experimental investigations on the integration of PCM into building structural elements, including walls, ceilings, and underfloor layers, for winter space heating applications. Analysis over a ten-day operational period revealed substantial reductions in both energy consumption and operational costs, amounting to 32% and 42%, respectively. In another study, Arsalan et al. [20] implemented a hybrid solar-based heating system for residential space conditioning, combining evacuated tube collectors, flat plate collectors, and a convective radiator unit. The energy performance evaluation demonstrated a maximum system efficiency of 61%, while the economic assessment reported a benefit–cost ratio ranging from 0.82 to 1.6, alongside a payback period between 7.41 and 8.9 years, confirming the system's technical effectiveness and financial feasibility.

Conclusion. The findings of this study confirm that the integration of renewable energy technologies in buildings plays a critical role in enhancing energy efficiency and mitigating greenhouse gas emissions. Systems such as solar water heating, advanced flat plate collectors, hybrid solar heating configurations, and PCM-enhanced thermal structures demonstrate substantial potential for reducing fossil fuel dependency and improving long-term economic performance. Despite these advantages, the deployment of such technologies is hindered by economic, technical, and institutional barriers. Therefore, achieving a sustainable and low-carbon building energy infrastructure requires a holistic approach that combines technological innovation, supportive energy policies, economic incentives, and capacity-building initiatives. Strengthening these elements will be essential in bridging the gap between climate targets and actual implementation outcomes.

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