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Abstract

Today, building is one of the largest energy-intensive sectors worldwide, contributing substantially to global greenhouse gas emissions and exacerbating the financial burden of escalating energy expenses. To address these issues, there has been a growing interest in adopting sustainable solutions aimed at curbing energy consumption in buildings, particularly those reliant on fossil fuels, and hence mitigate the associated environmental repercussions. Among these solutions, the utilization of sustainable energy systems, encompassing passive strategies, renewable energy technologies and energy storage systems, within buildings is attracting considerable attention. However, selecting the suitable energy systems for a given building is not an easy task since its overall performance depends on many factors. This thesis comprehensively explores the effectiveness of integrating different passive, renewable and storage systems into buildings in numerous locations around the world characterized by distinct climatic conditions, energy accessibility levels, carbon pricing policies, and other economic and environmental contexts. The assessment of these systems is carried out using key software, such as EnergyPlus, OpenStudio and PVsyst, and focuses on three pivotal aspects: energy efficiency, environmental impact, and cost-effectiveness.

The outcomes of this thesis underscore that the energy, economic and environmental effectiveness of passive techniques is significantly influenced by the local climate, energy affordability level and the carbon tax imposed. From an energy perspective, using thermal insulation, shading and green roof methods in hot climates, and thermal insulation and green roof approaches in cold ones reveal the greatest benefits with energy savings of about 34%, 12%, 9%, 61% and 16%, respectively. Conversely, in temperate climates, employing natural ventilation, thermal insulation and shading stands out as the most recommended strategies, boasting impressive energy savings of 60%, 51% and 32%, sequentially. Economically, the cost-effectiveness of passive strategies is closely related to their upfront costs, energy availability level and levied carbon tax. Indeed, the best economic findings are achieved in areas where energy is unaffordable and a high carbon tax is applied. Moreover, it should be noted that passive techniques characterized by high capital investments, such as green roofs and Trombe walls, are generally not cost-effective. On the contrary, all passive methods are environmentally friendly, particularly in regions where no carbon tax is levied. Actually, the environmental viability of these methods could incentivize homeowners to integrate them into their buildings, mainly in countries with abundant energy resources and with no carbon taxation policy.

Concerning renewable energy systems (RESs), photovoltaic (PV) and photovoltaic thermal (PVT) are among the most energy-efficient technologies used in buildings in various climates. Conversely, implementing wind turbines (WTs) and ground source heat pumps (GSHPs) are typically energy-efficient only in windy regions and cold climates, respectively. Environmentally, all RESs are generally eco-friendly since the carbon payback period (CPBP) is found to be in the range of 0.59–0.84 years for PVT, 1.07–1.25 years for PV, 0.67–3.71 years for GSHP and about 0.51 years for WT. From an economic point of view, PV and PVT are the most cost-effective RESs, whilst the WT system is beneficial only in sites characterized by high wind speeds. In contrast, GSHP is a cost-ineffective technology in all climates, owing to its minimal energy production and increased capital and operating costs. Overall, the levelized cost of energy (LCOE) across all climates is in the range of 0.030–0.035, 0.027–0.039, 0.209–1.149 and 0.095–0.725 $/kWh for PV, PVT, GSHP and WT, sequentially.

Regarding energy storage systems, the results of this dissertation highlight that storing excess electricity produced by RESs in batteries rather than as hydrogen is more energy-efficient. Using a tank to store hot water produced by solar collectors also proves to be an energy-efficient storage method, while integrating phase change materials into the building envelope for thermal energy storage shows greater efficiency compared to the Trombe wall design. On the other hand, all the studied energy storage systems are eco-friendly and cost-effective, except for some technologies, such as the Trombe wall design because of its low energy efficiency, elevated embodied carbon and increased initial costs. For all climates, the CPBP/LCOE values vary in the range of 2.21–2.51/0.035–0.039, 0.40–0.67/0.16–0.20, 0.55–0.64/0.039–0.046, 2.80–4.04/0.046–0.067, and 11.24–84.29 years/0.06–0.44 $/kWh for PV with batteries, PV with hydrogen storage, solar collectors with hot water storage, phase change materials, and Trombe wall, respectively.

Finally, it is worth noting that these findings could be reproducible in worldwide regions, which highlight the key role that this dissertation could play in advancing building sustainability research on a global scale. This thesis could also serve as a reference for specialists and policymakers to gain insight into the optimal solutions for building sustainability.

Keywords : *Passive design strategy; Renewable energy; Energy storage; Building sustainability; Hybrid energy system; Comprehensive assessment; Hydrogen production and utilization*