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Comparative Thermal and Techno-Economic Assessment of Residential Building Envelope Systems with Renewable Energy Integration

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Abstract - **The need for enhanced thermal efficiency in residential buildings cannot be overstated, as it plays a critical role in lowering energy consumption, reducing operational costs, and increasing sustainability. Although superior walling systems can help decrease heating and cooling demands, they also tend to be more expensive. The use of renewable energy systems presents a possible alternative for providing cost-effective thermal comfort. This study aims to comparatively assess the thermal and economic efficiency of four different residential walling systems-namely, Cavity Brick (CB), Insulated Cavity Brick (ICB), Insulated Brick Veneer (IBV), and Insulated Reverse Brick Veneer (IRBV)-and to examine the viability of integrating renewable energy systems to improve the performance of building envelopes at a lower cost. Monthly heating and cooling demands were calculated using Autodesk Ecotect Analysis software. Construction material costs were analyzed in PKR, and economic viability was evaluated using Net Present Value (NPV) analysis with a 20-year lifecycle, a 6% discount rate, and a 3% inflation rate. The ICB module demonstrated the highest thermal efficiency but incurred an additional construction cost of PKR 1,504,366 compared to the least expensive IBV module. Although ICB resulted in annual energy savings of PKR 41,937, the NPV of these savings (PKR 629,144) did not offset the additional capital cost. Renewable technologies, particularly a 2 m² solar air heater and a 1 kW PV system, were identified as economical options for space heating, with total 20-year costs below PKR 198,097, making them more viable than the envelope upgrade alone. The findings suggest that integrating renewable technologies with cost-effective building envelopes provides a more favorable thermo-economic approach than relying solely on insulation upgrades.**

Keywords: **Thermal Efficiency, Residential Buildings, Walling Systems, Renewable Energy Systems, Net Present Value (NPV)**

I. INTRODUCTION

Renewable energy technologies have significant potential to enhance building thermal efficiency and promote sustainability, particularly when integrated with advanced materials, notably phase change materials (PCMs) [1]. Various renewable-based solutions can be applied to improve indoor thermal conditions, including photovoltaic systems, evaporative cooling units, wind turbines, and solar thermal heating systems [2]. Solar heating systems involve the use of a solar collector to convert sunlight into heat for warming indoor spaces. Only a small amount of energy is required for the operation of an active solar air heater, primarily to power auxiliary equipment such as air pumps or fans and control devices. Air is the working fluid used in most solar air heaters. The required area of a solar air heater depends on site-specific parameters such as geographic location (latitude and longitude), prevailing wind conditions, available solar radiation, and the heating load necessary to maintain indoor thermal comfort [3].

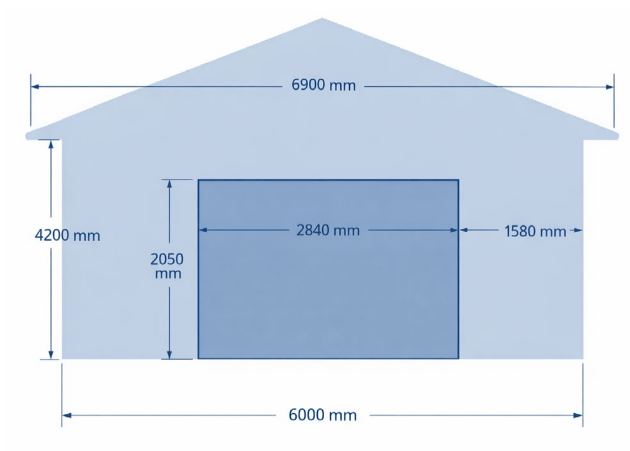
The evaporative cooling system operates on the principle of cooling air by passing it over a wet film or mist formed by water. The system derives its cooling effect from the evaporation of water, which absorbs heat from the indoor air as it changes from liquid to vapor form [4]. The evaporative cooling principle is an energy-saving solution that requires only a cooling fan and pump. Water usage in evaporative cooling systems ranges between 10–30 liters per hour, depending on the system's capacity and the humidity level in the air. From this research, it is observed that buildings can be retrofitted with additional insulation and existing renewable energy (RE) systems, resulting in improved efficiency. The application of an optimum level of insulation can save up to 15% of annual energy use, with an estimated payback period of 11.5 years. The options considered in the research project included the use of solar collectors, wall insulation, window types, and roof insulation. The effectiveness of these options was evaluated based on cost, energy savings, and occupant thermal discomfort. The findings indicated that the use of low-cost solar collectors in combination with wall and roof insulation can lead to measurable savings. However, the use of insulators with higher heat transmittance levels and solar collectors-particularly in higher-altitude locations-results in increased thermal discomfort due to longer hours of exposure. Green roofs contribute to improved thermal performance during winter, thereby reducing the need for both cooling and heating systems during summer [5].

II. METHODOLOGY

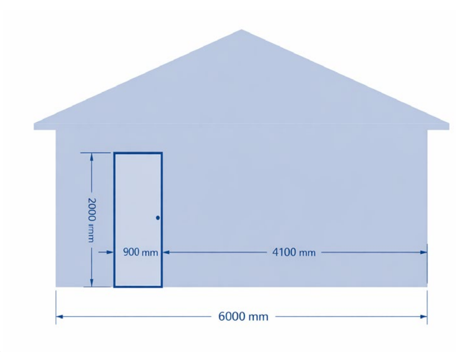
Empirical data were collected from full-scale residential test modules, including outdoor weather conditions and indoor air temperature measurements. These datasets were then used to perform energy simulations in Autodesk Ecotect Analysis software to determine the energy demand required to operate each module under varying environmental conditions. Subsequently, a comprehensive feasibility assessment was conducted to examine and compare the performance efficiency of different housing modules in conjunction with selected renewable energy systems. The objective of this analysis was to identify the most economically viable configuration-specifically, the combination capable of delivering maximum energy savings while minimizing overall implementation and operational costs.

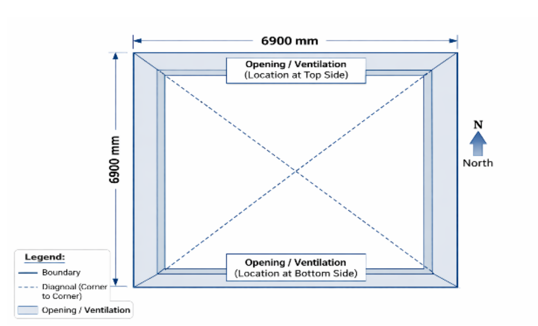
A. Large Scale Test Experimental Modules

A detailed experimental investigation was carried out to analyze the thermal efficiency of residential buildings in Pakistan. For this purpose, four full-scale dwelling prototypes were erected and systematically monitored under different climatic conditions. The selection of these modules was based on construction practices commonly adopted in regions located around Longitude 151.7°E and Latitude 32.9°S [6], ensuring that the study reflected realistic building configurations. All modules were constructed using identical material specifications to maintain consistency in performance comparison. Each unit incorporated a north-facing window fitted with a light-colored aluminum frame and 6.38 mm laminated clear glass. To facilitate access while minimizing unwanted heat transfer, insulated doors were installed on the southern façade. The flooring system consisted of a 100 mm thick reinforced concrete slab extending across the entire floor area. The roof assembly comprised concrete and clay tiles supported by sarking insulation, along with a 10 mm plasterboard ceiling. Additionally, R3.5-rated glass wool batt insulation was placed between the rafters to enhance thermal resistance. To prevent external interference such as wind obstruction or mutual shading, the modules were spaced 7 meters apart. Each structure was designed with a uniform square floor layout measuring 6 m × 6 m, as shown in Figure 1.



(a)





(b) (c)

Fig.1 (a) North; (b) South; (c) Floor Plan for all Modules

Each module is identified according to its respective walling system, as the overall design and construction materials remain identical across all units except for the wall configuration. This distinction allows for clear comparison between modules, as shown in Figure 2 [7].

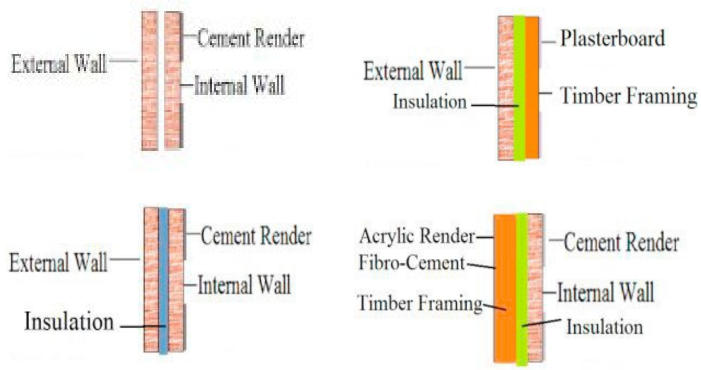


Fig.2 Cavity Brick Module, Insulated Brick Veneer, Insulated Cavity Brick, Insulated Reverse Brick Walling System

It is noted that the cost of building construction varies from one location to another and also depends on the finish type-whether low, medium, or high. The type of construction may be either residential or commercial. This section highlights the costs involved in the modifications described earlier. It is assumed that the implementation does not result in incremental labor costs associated with changing the module components, as these would be part of the original construction costs. The comparisons are based solely on the cost of the materials used.

B. Cost Evaluation of Walling Systems and Windows

Table I shows the average construction and building system costs for the walling systems. It indicates that the cheapest walling system is IBV; therefore, all modules are evaluated against this most cost-effective option, assuming a total wall area of 67.2 m².

TABLE I AVERAGE COSTS OF WALLING SYSTEMS

Walling system	Average cost PKR/m^2	Cost difference compared with IBV in PKR
Cavity Brick	61,630	564,762
Insulated Cavity Brick	67,233	941,270
Insulated Brick Veneer	53,226	0.00
Insulated Reverse Brick Veneer	56,028	188,254

Adopting insulated cavity brick (ICB) walls would increase construction expenditure by approximately PKR 941,270 relative to the most economical configuration, IBV. Although double-glazed windows provide superior thermal resistance compared to single glazing, their market price varies with specifications and manufacturing quality.

Typically, double glazing is at least 25% more costly than single glazing. For new constructions, the additional investment associated with double-glazed windows generally ranges between PKR 840,428 and PKR 1,400,714 when compared with single-glazed alternatives [8]. For the modules considered in this study, upgrading to double glazing would require an incremental cost of about PKR 168,085. From an economic standpoint, this modification is considerably more practical than replacing the entire wall system, as it delivers thermal improvement with a substantially lower capital outlay.

C. Insulation Costs Based on Thermal Resistance

Insulation performance is represented through the use of R-values. A higher R-value indicates greater insulation capability, but typically at a higher cost, as depicted in Table II. Roof insulation was implemented across all modules.

TABLE II AVERAGE COST OF INSULATION ACCORDING TO R-VALUE WITHOUT INSTALLATION

R-Value	Average Cost (PKR/m²)
R1	1,960.98
R2	2,801.40
R3	3,641.82
R4	4,482.24
R5	7,563.78

D. Autodesk Ecotect

The Autodesk Ecotect Analysis program is used for sustainable building design. Sustainability in building design is categorized under building energy analysis [9]. This type of software, which has the capacity to perform functions such as thermal analysis and determination of building thermal loads, has the potential to contribute significantly to energy savings over the building's lifecycle. The most commonly applied method to meet building standard requirements under the ASHRAE standard is the use of the psychrometric chart tool for analyzing climatic factors, a capability supported within the Autodesk Ecotect software [10]. This software is used to model and calculate the monthly space heating and cooling demands for each module. Once the structural dimensions and construction material characteristics are provided, the system carries out the energy performance analysis.

E. Net Present Value

Money in the future has a lower valuation than "today's money," since current funds can be spent or invested immediately. Discounting is the process of converting future monetary amounts into present value. The discount rate refers to the interest rate used to evaluate an investment or project. It represents either the cost of borrowing funds for the project or, if internal funds are used, the return that could have been earned from an alternative investment opportunity.

Net Present Value (NPV) is applied in projects involving multiple cash flows over their operational life [11]. It represents the cumulative present value of all expenditures and returns associated with the project. Annual costs or savings (S) are discounted to their present value-where costs are treated as negative and savings as positive-using an appropriate discount rate and the Present Worth Factor (PWF) [12],

NPV= PWF (i,f,n) x S

$$PWF = \frac{\left[1 - \left(\frac{1+f}{1+i}\right)^n\right]}{\left[\left(\frac{1+i}{1+f}\right) - 1\right]}$$

where:
i : Discount rate
f : Rate of inflation
n : Number of years

III. RESULTS AND DISCUSSION

This portion evaluates the energy demand of each module and identifies the most cost-effective renewable system capable of meeting that demand while potentially supplying surplus energy. Among the configurations, IBV has the lowest construction cost, whereas ICB is the most expensive. Using Autodesk Ecotect in transient simulation mode, the monthly space heating requirements for each unit were calculated. The results indicate that heating requirements during winter are significantly higher, while only minimal energy input is needed during summer to maintain indoor thermal comfort [13]. Additionally, using the ICB module instead of the IBV module would allow for energy savings of PKR 41,937/year. This value is calculated based on the difference in energy consumption between the IBV and ICB modules. The difference is 748.6 kWh/year for heating energy, and the energy price is 56 PKR/kWh. Based on the assumption that the lifespan of a module is approximately 20 years, the current cost (in terms of present value) associated with achieving the necessary energy to maintain comfortable indoor temperature conditions over the entire lifespan of the building can be assessed and compared with alternative sustainable approaches for attaining thermal comfort. Assuming an interest rate of 6%, an inflation rate of 3%, and a 20-year lifespan, the PWF is approximately 15, and the NPV is around PKR 629,144.

It should be noted that the cost of building construction varies depending on location, finish level (low, medium, high), and construction type (residential or commercial, e.g., houses, units, townhouses, etc.). The cost to upgrade from IBV to ICB would be approximately PKR 1,504,366, yielding an energy cost saving of PKR 629,144. New methods for improving the thermal performance of the modules at minimum cost-such as integrating renewable energy systems-will be explored in the subsequent stage [14]. This assumption is based on the premise that no additional labor costs are incurred when changing module components, as these would be integral to the original construction.

Several sustainable technologies can enhance indoor thermal comfort without substantially increasing capital cost. These include solar-based heating systems, evaporative cooling units, and hybrid heating–cooling solutions such as photovoltaic (PV) systems and small wind turbines. System selection must be aligned with local climatic conditions and the availability of solar radiation or wind resources. In hot and dry regions, evaporative cooling performs efficiently, whereas in humid climates, ventilation-based strategies are more appropriate. For colder conditions, solar thermal heating is generally the most suitable option. PV arrays and wind turbines may be deployed in different settings depending on renewable resource availability to meet building heating and cooling demands.

For the ICB module, the annual heating demand is 235.7 kWh, corresponding to an energy cost of PKR 13,205 per year. Using a 6% discount rate, 3% inflation, a 20-year service life, and a present worth factor (PWF) of 15, the total lifecycle heating cost is approximately PKR 198,097. The peak monthly heating requirement is about 73.9 kWh, indicating that a renewable system should deliver nearly 70 kWh per month while remaining below this lifecycle cost to be economically feasible. Although wind speeds between 5–15 m/s are generally adequate for turbine operation, high installation costs and practical constraints limit their suitability. A solar air heater operating at an assumed efficiency of 70% (maximum 75%) with an area of 2 m² can meet most heating requirements except during peak winter months. A 1 kW PV system can sufficiently supply winter heating and summer cooling loads, with surplus summer generation available for household appliances. Based on economic evaluation, solar air heaters and PV systems are financially viable for the CB module, whereas wind systems remain cost-prohibitive under the given conditions.

IV. CONCLUSION

Concerns related to climate change, mitigation of greenhouse gas (GHG) emissions, energy security, and the growing global energy demand are key drivers behind the development of cost-effective and energy-efficient buildings. These designs must account for prevailing climatic conditions to optimize performance and reduce environmental impact. In general, even the best building design using the most suitable materials cannot ensure 100% energy self-sufficiency; therefore, an external energy source is required to provide the heating and/or cooling necessary to maintain acceptable levels of thermal comfort for occupants. The study demonstrates that the lower-cost IBV module, when compared with the other configurations, can achieve substantial thermal improvement through targeted modifications. Specifically, replacing the existing windows with double-glazed units and integrating a 2 m² solar air heater significantly enhances thermal performance and reduces overall energy demand. Furthermore, if grid connectivity is available and surplus electricity can be exported or imported as needed, a photovoltaic (PV) system becomes a more practical and attractive option due to its greater operational flexibility and long-term energy benefits.

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