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RESEARCH ARTICLE

The impact of the wall insulation material and variable refrigerant flow system on building energy consumption and cost

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ABSTRACT - The use of VRF system and insulation in building envelope are both considered as promising option to reduce energy consumption of a building. This study analysis energy saving potential of VRF system and building insulation using modelling and simulation of a typical office building. The model office building is simulated with the weather of Hyderabad, Sindh, Pakistan using EnergyPlus building simulation software. The simulation cases include conventional and VRF air conditioning systems with and without insulation to evaluate and compare the annual cooling and energy savings and payback period. Results showed that by replacing conventional air conditioner with VRF AC electrical power can be reduced by 42-45%. It is also noted that Cellulose, expanded polystyrene, extruded polystyrene and polyurethane insulations can save around 49.5, 51.4, 51.6, and 54.54% of electricity, respectively. In the case VRF air conditioner used with Cellulose, expanded polystyrene, extruded polystyrene and polyurethane insulation may reduce electricity consumption by 66.5, 67.4, 67.5 and 68.9 %, respectively. The payback period varies from 7 to 15 months. However, cellulose with VRF air conditioner has the least payback period of around 7 months. The longest payback period of around 15 months was noted for the un-insulated office building with VRF air conditioner. Despite having longer payback period, the combination of polyurethane insulation with VRF air conditioning system is the most efficient combination.

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1.0 INTRODUCTION

Energy consumption in buildings is increasing day by day due to rapid increase in population and urbanization. It is reported that 30-40% of total primary energy of the world is utilized in buildings [1,2]. Therefore, to invest for energy reduction, building sector is highly attractive [3,4]. However, Heating, Ventilation and Air conditioning System is being considered as an integral part of the building due to increased comfort necessities. It is reported that 37 – 60 % of total electricity use in buildings is required by air conditioning system [5,6]. With the recent drive towards net zero energy buildings, numerous technologies are encouraged with emphasis on their energy efficiency. Two most effective ways of energy conservation in buildings is through insulation of building envelope and using a Variable Refrigerant Flow system. The use of building insulation is considered as a modest, energy efficient way that is pragmatic to industrial, commercial, and residential sectors. Thermal insulator exhibits the capability to cut the heat flow rate with high thermal resistance materials [7]. Building insulation as a result reduces heat flux and retains the heat or cool within the building [8].

Kumar D. [9] introduced novel optimization structure for selecting optimal insulation material which included four optimization criteria i.e., thermal comfort, functioning energy and carbon, embodied energy and carbon and life cycle cost. L. Aditya [10] the purpose of this article is to compile the latest development in building thermal insulations, as well as to address life-cycle analyses and potential emissions reductions using appropriate insulation materials. Yunyi Sun [11] Provided a comprehensive review of transparent insulation materials (TIMs) for saving energy in buildings. Key varieties of TIMs and their characterization in terms of both thermal and optical behaviour are discussed in this review, as well as the benefits that can be realized by using them in buildings. Shiyu Wan [12] developed a methodology for sustainable analysis to direct stakeholders in choosing the best technical mix of energy-efficient retrofit options for major office buildings. This may be consulted as a guide for the other sorts of buildings in the future. Erebor E [13] classified 29 energy-efficient design methods that apply to office buildings into the pre-construction (model and development), construction, and post-construction stages of building projects, and then conducted a review that highlighted the main areas of concentration in these strategies. Junghun Lee [14] investigated the influence of amalgamation the exterior insulation proportion on the energy consumption for cooling as well as heating with several interior heat gains. Pablo Lopez Hurtado [15] summarized the study on cellulose fibre insulation, including its fabrication, installation, and performance. The research focuses on the physical features of cellulose insulation, environmental factors that influence these qualities, and future innovation possibilities. Dong, Y [16] in his study seeks to evaluate the merits, and demerits of

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various exterior wall insulation techniques and offer suggestions for how to use different exterior wall insulation types in various climates.

The cooling capacity of an VRF air conditioner is varied by changing compressor speed in relation to cooling loads. As a result, in long-term operation, the used power is minimized, and the room set point temperature may be maintained at a more stable state than with a constant-speed air-conditioner. Roba Saab [17] investigated under various conditions the performance of Variable Refrigerant Flow (VRF) system also carried out parametric analysis on the VRF cycle model. Waleed Mohamad Elzanati [18] included a detailed description of the proposed regulations as well as a study and comparison of two solutions in terms of peak load reduction and cost-effectiveness. The analysis advised that Bahrain utilize a DC inverter air conditioning system because it is the most cost-effective option. M. Berker Yurtseven [19] performed a field test to compare the energy consumption of constant speed air conditioners (non-inverter AC) and variable speed air conditioners (inverter AC) in two similar public office rooms in terms of user comfort conditions. Hanlong Wan [20] examined VRF system architecture, modelling, experimentation, control approaches, fault detection, diagnostics, and defrost. Concluded that the knowledge-based technique is simple to use but complex to teach, according to the researchers and future research could focus on a combined VRF and energy storage system, or on a novel algorithm that combines the benefits of both data-driven and traditional component-based techniques to provide greater flexibility. Aynur [21] concluded that VRF system uses less energy than conventional air conditioner. The VRF system's biggest disadvantage is its high investment cost. Due to the VRF system's energy-saving potential, the expected payback period might be around 1.5 years. Georges Atallah [22] Lifecycle cost analysis was presented to assess the economic viability of CRF (constant refrigerant flow) and VRF (variable refrigerant flow) air conditioning systems. The findings demonstrated that although while the VRF system's initial cost was 23% more than the CRF system's initial cost, the VRF system's present worth cost at the end of its lifetime was significantly lower than the CRF system's due to lower operating costs. The use of VRF against CRF results in a large energy savings of 27% as well.

From the literature review it has been observed that previous work was focused on the impact of building insulation and VRF AC on electricity consumption separately. Previous studies have not evaluated the comparative or combined effect of applying insulation and VRF AC on energy consumption. In this research, a comparative study between building insulation and variable refrigerant flow air conditioner is conducted. The energy saving potential of building insulation and variable refrigerant flow air conditioner is evaluated and compared for the weather of Hyderabad, Pakistan and also cost benefit analysis is carried out to compute the payback of different combinations.

2.0 METHODS AND MATERIAL

To assess the impact of the different building insulation materials and VRF air conditioner on the cooling energy savings, the following methodology is adopted.

1) The study begins by creating a 3D model of a reference office building using SketchUp software, which is then imported into EnergyPlus.
2) The modeled building is simulated in EnergyPlus without any cooling system, in two different cases, one with insulation and one without insulation.
3) The modeled building is then simulated in EnergyPlus with different cooling systems, including a conventional air-conditioner and a VRF-based air conditioner, for both cases, with and without insulation.
4) The energy and cost savings of each case are evaluated by comparing its monthly energy consumption and energy cost with that of the base case, which is a conventional air-conditioner with no insulation.
5) Lastly, the payback period is used to compare the cost-effectiveness of the different cases and aid in determining the best cooling system option for the building.

To simulate the energy use and costs of an entire structure, a programme called EnergyPlus is used. It is utilised in this study because it is capable of simulating the energy efficiency of a building in a hot, dry environment while accounting for variables like temperature, humidity, solar radiation, and air movement. In order to ensure that all energy flows are balanced, EnergyPlus is able to perform a thorough heat balance calculation on all surfaces inside the building. This is done by solving a set of energy balance equations for zone air as well as the interior and exterior surfaces of walls, roofs, and floors. EnergyPlus is a suitable tool for assessing and contrasting the energy performance of various cooling systems in an office building because it can model a broad spectrum of construction components and systems, including various kinds of cooling systems.

2.1 Reference Building

A model office building located in Hyderabad; Pakistan is the reference building of the study. 2D wire frame view of the reference office building is shown in Figure 1. Table 1 shows the specification of the reference building.

Table 1. Building information and simulation condition of reference building

Building information	Location Building type Building height Floor area Construction and material Window to Wall Ratio	Hyderabad, Pakistan Large office building 3 m 50 m^2 -Wall: 2.61 W/m^2 K (No insulation) -Window: 6.424 W/m^2 K, 0.252 (SHGC), 0.72 m^2 (glass area) -Roof: 5.08 W/m^2 K (No insulation) -Floor: 2.94 W/m^2 K 0.8 %
Simulation Condition	Indoor Set Point Temperature Weather Data Internal thermal Loads	Cooling: 25 ^{O}C Hyderabad, PK People: 0.056 person/m^2 Lighting: 10.65 W/m^2 Equipment: 7.4 W/m^2 Schedule: Large office activity
System	Cooling System	Types: Unitary Single speed air conditioner, VRF air conditioner

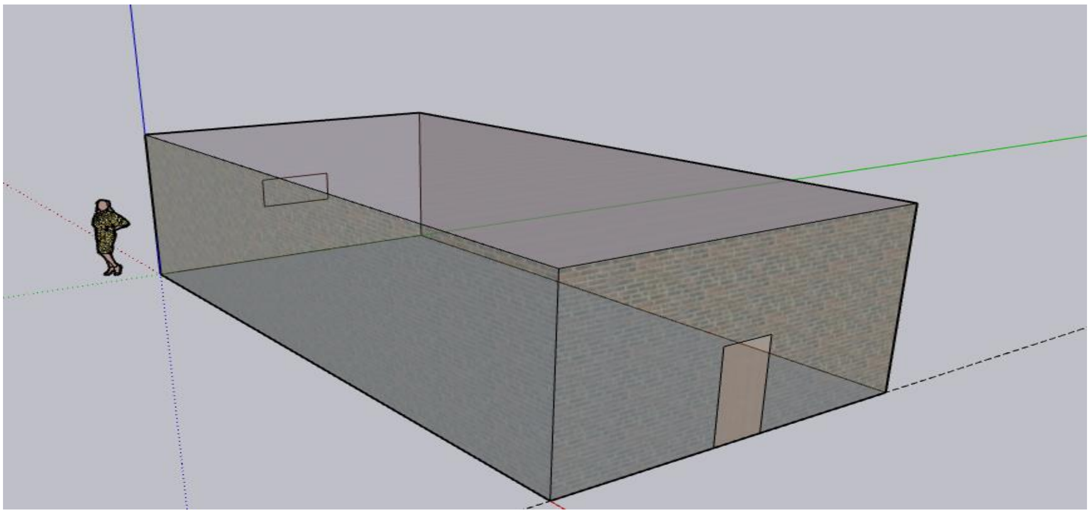

Figure 1. 3D wire frame view of reference office building

2.2 Description of Selected Insulation Materials

The insulation materials used in this study is chosen based on their suitability for hot climates [9] and their availability in the local market. A survey of Pakistan's local market is conducted to determine the cost of the selected materials, which are appropriate for Hyderabad's climate. The survey involved contacting various stores and businesses by phone. The study used polyurethane, extruded polystyrene, and expanded polystyrene insulations, which are suitable for Pakistan's hot climate. Cellulose, which is also a good insulation material for hot weather, was not available in the local market, so pricing information was obtained from the international market. The thickness of the insulation materials used in the study ranged from 1 inch to 1.5 inches. Table 2 shows the thermal and mechanical characteristics of the insulating materials.

Table 2. Properties of building insulation material

Insulation Type	Density (kg/m^3)	Thermal conductivity (mW/mK)	Specific heat capacity (J/kg ^{O}C)	Cost $\left(\frac{\mathbf{Rs}}{\mathbf{ft^2}}\right)$
EPS	34	35.0	1250	50
XPS	36	34.5	1575	70
Polyurethane	95	29.0	1375	120
Cellulose	55	40.0	1450	43

2.3 Weather Profile

The weather profile discussed in this section was generated using meteonorm software. Figure 2 shows the monthly maximum and minimum ambient temperatures curves for the area. It is clear that May, June, and July are very hot where maximum temperatures went above 40 ^{O}C. The global and diffuse radiation for the month of June is recorded as approximately 210 and 110 kWh/m^2, respectively. On the other hand, the global and diffuse radiation for the month of December is approximately 110 and 50 kWh/m^2, respectively.

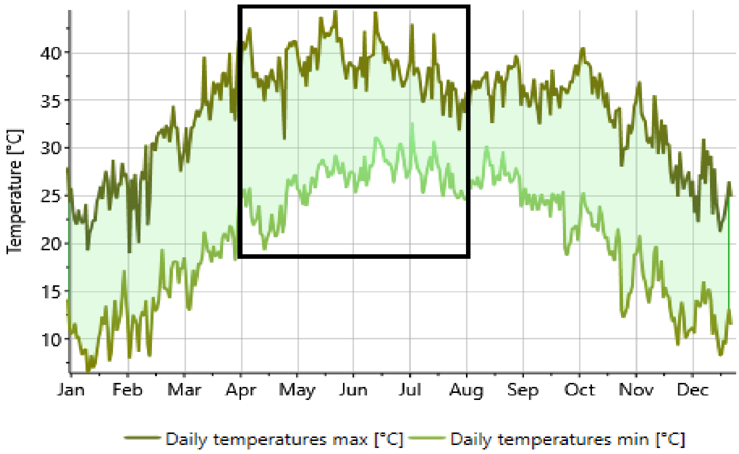

Figure 2. Daily maximum and minimum ambient temperature for Hyderabad

3.0 RESULTS AND DISCUSSION

Whole summer season from March until October is simulated. Because trial/experimental data from a real system was not available for direct confirmation of results. The simulation findings are compared with the trends of a few of the generated outcomes with the results that had already been published. Georges Atallah [22] estimated the economic feasibility of VRF cooling system and Huang H. et al. [23] evaluated the energy saving potential of different insulation materials both found similar trends of energy saving, cost saving and payback periods.

3.1 Peak Zone Air Temperature and Mean Heat Flux

Annual peak zone temperatures are shown in Figure 3 both with and without insulation. The case with no insulation recorded the greatest zone air temperature, reaching 48.6 °C, while the case of polyurethane insulation recorded the lowest zone air temperature, measuring roughly 34.8 °C.

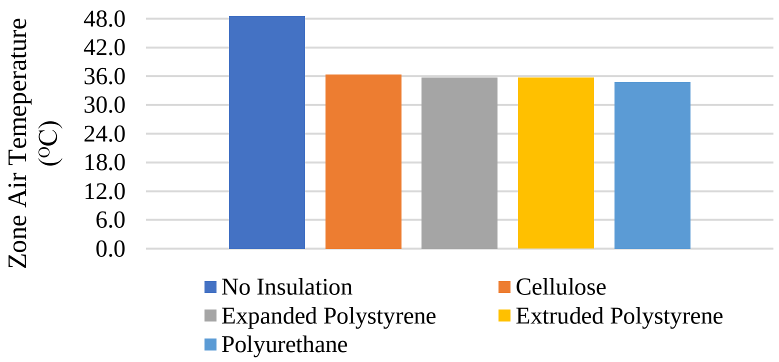

Figure 3. A comparison of peak zone air temperature with and without insulation

Figure 4 displays the modelled office building's typical monthly rate of heat flux (W/m^2). Results indicated that the largest and lowest mean heat flow rates were recorded in the months of May and August, respectively. The building without insulation experiences the highest mean monthly heat flux, which is 38.97 W/m^2. However, the mean monthly heat flux with the insulations of cellulose, EPS, XPS, and PU is 15.4, 14.7, 14.6 and 13.61 W/m^2, respectively.

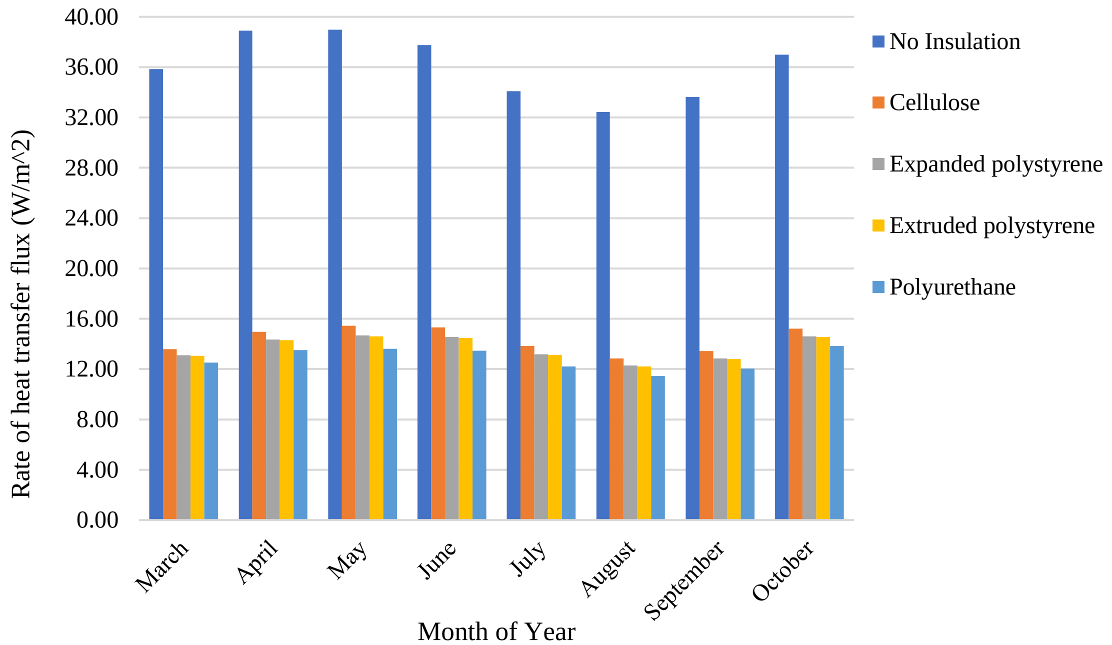

Figure 4. Mean monthly heat flux

3.2 Cooling Load

Figure 5 depicts the cooling load for the building on the design day with and without the use of insulation. Results reveal that cooling load reaches 8.5 kW without insulation while cooling load approaches 2.8, 2.6, 2.6, and 2.3 kW, respectively, with insulation of cellulose, EPS, EXP, and PU. In contrast, Figure 6 displays the cooling load trends for the building on the design day. The graphic makes it evident that the cooling demand rises and peaks at 14:50:00 without insulating the office building. The cooling load increases once insulation is applied and lasts until 15:20:00.

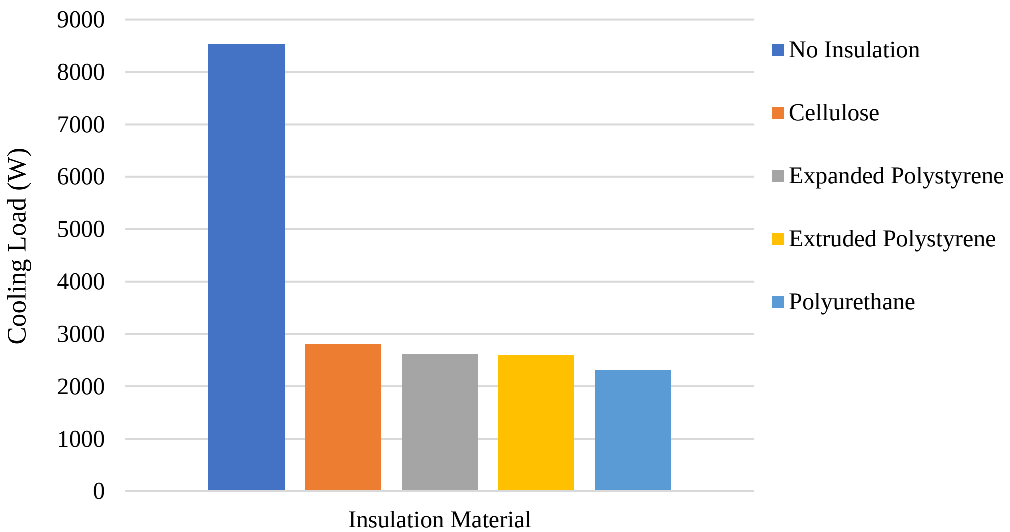

Figure 5. Calculated cooling load

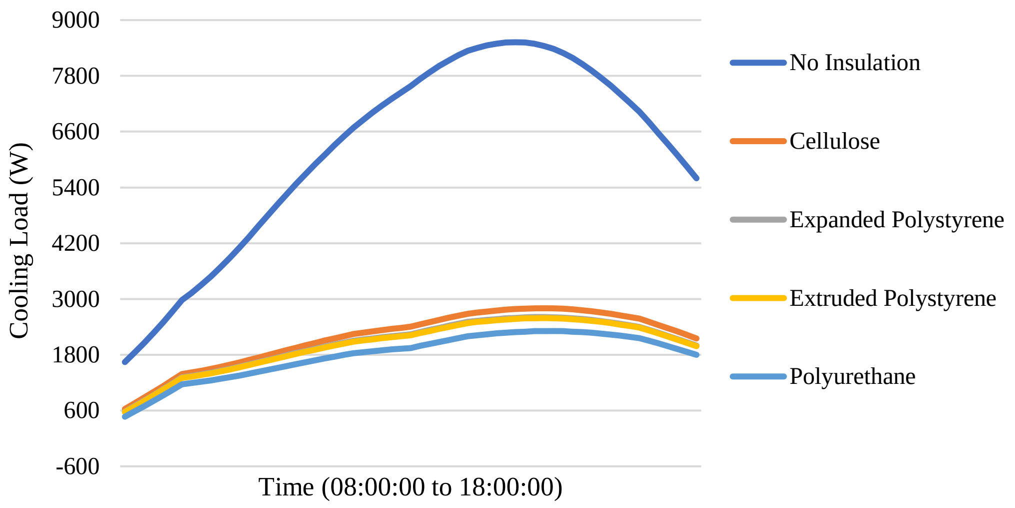

Figure 6. Design day cooling load variation

3.3 Energy Consumption and Energy Savings

Figure 7 displays the monthly electricity usage of a conventional air conditioner. The aforementioned graph makes it very evident that the office building without insulation results in very high energy use. The month of March has the lowest energy use, while the month of May has the most. Energy use for uninsulated buildings in May is 2087 kWh, compared to 1041, 998, 993, and 929 kWh for cellulose, EPS, XPS, and PU, respectively. On the other hand, for the month of March, the energy consumption for uninsulated buildings is 1400 kWh, while the energy consumption for buildings that have cellulose, EPS, XPS, and PU insulation is 672, 646, 642, and 603 kWh, respectively.

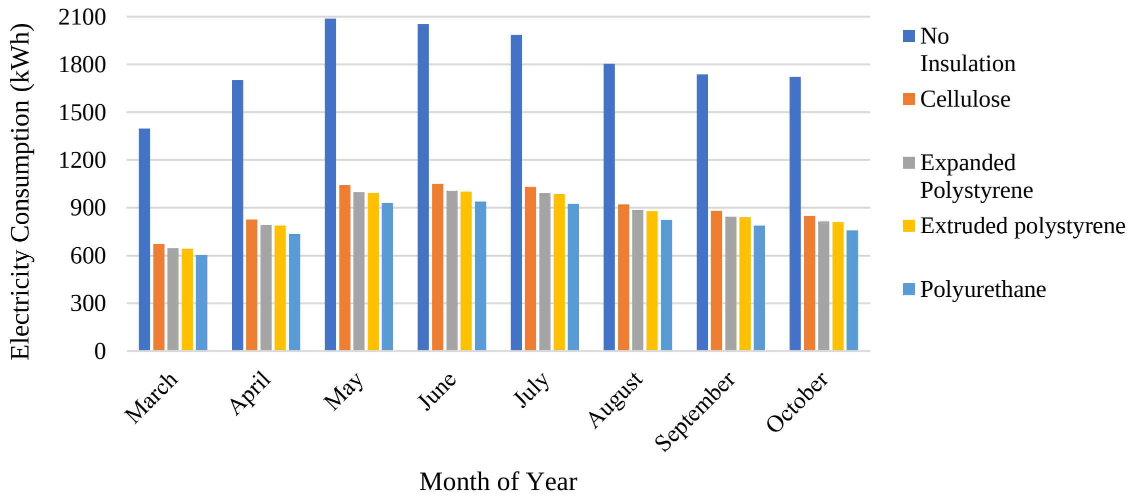

Figure 7. Monthly electricity consumption by conventional AC

VRF air conditioner's monthly electricity use is depicted in Figure 8. VRF type air conditioners use a lot less energy than traditional air conditioners. The most energy is consumed in the month of May, while the least is consumed in the month of March. May's energy usage for uninsulated buildings is 1232 kWh, compared to 688, 665, 663, and 630 kWh for buildings with cellulose, EPS, XPS, and PU insulation, respectively. For the month of March, an uninsulated building uses 780 kWh of energy, whereas cellulose, EPS, XPS, and PU use 453, 441, 439, and 419 kWh of energy, respectively.

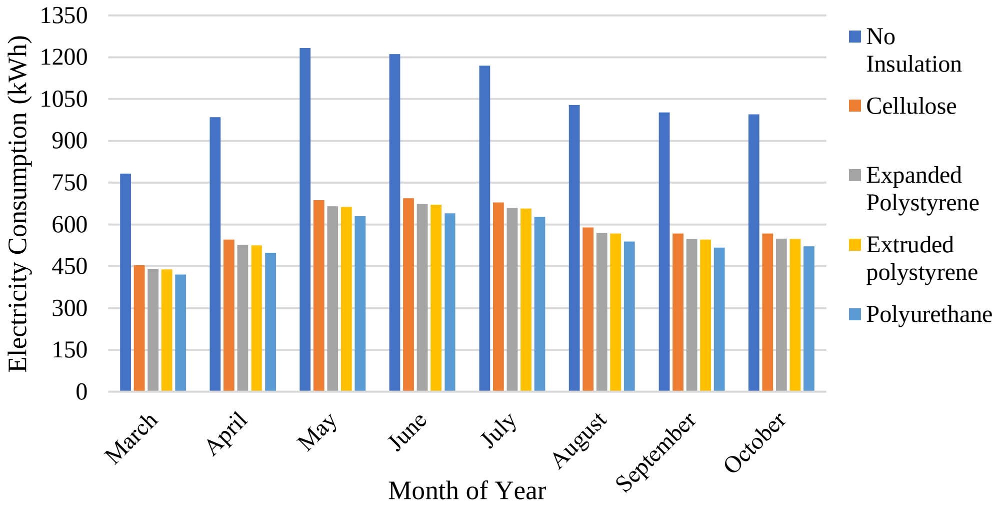

Figure 8. Monthly electricity consumption by VRF AC system

Figure 9 displays the monthly energy savings from various types of insulation. In comparison to other months of the year, May, June, and July have the largest energy savings because they are the warmest months of the year in Hyderabad. Cellulose, EPS, XPS, and PU each save 1046, 1090, 1094, and 1158 kWh of energy for the entire month of May. 1004 kWh, 1045 kWh, 1050 kWh, and 1113 kWh of energy are saved by cellulose, EPS, XPS, and PU during the month of June. Cellulose, EPS, XPS, and PU save 954, 994, 999, and 1059 kWh of energy during the month of July. The electrical energy saved by cellulose, EPS, XPS, and PU for the month of March is 726, 753, 757, and 796 kWh. With conventional air conditioner Extruded polystyrene, expanded polystyrene, polyurethane, and cellulose insulation can each reduce power use by 49.5, 51.4, 51.6, and 54.5%, respectively.

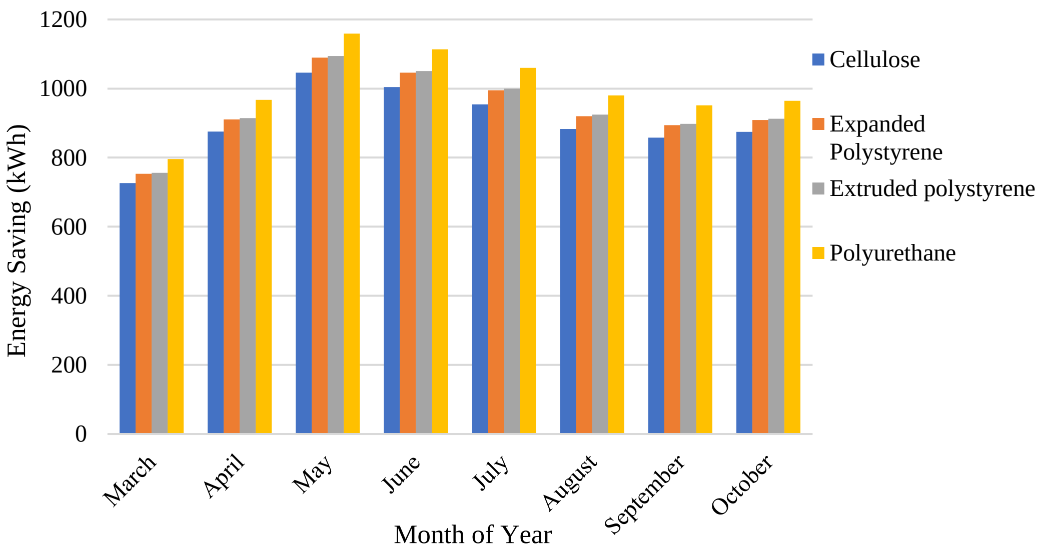

Figure 9. Monthly energy saving by different insulation material

Figure 10 illustrates the VRF AC's monthly energy savings. When compared to other months of the year, May, June, and July have the largest power savings. For the months of May, June, and July, the VRF air conditioning system saved 855, 842, and 815kWh of energy for the uninsulated office building. For the month of May, cellulose, EPS, XPS, and PU with VRF AC saved 1400, 1422, 1425, and 1458 kWh of energy. In June, cellulose, EPS, XPS, and PU with VRF AC saved 1360, 1380, 1382, and 1413 kWh of energy. Cellulose, EPS, XPS, and PU with VRF AC save 1306, 1326, 1330, and 1359 kWh of energy for the month of July. Extruded polystyrene, expanded polystyrene, and polyurethane insulation can all lower electricity consumption for VRF air conditioners by 66.5, 67.3, 67.5, and 69%, respectively.

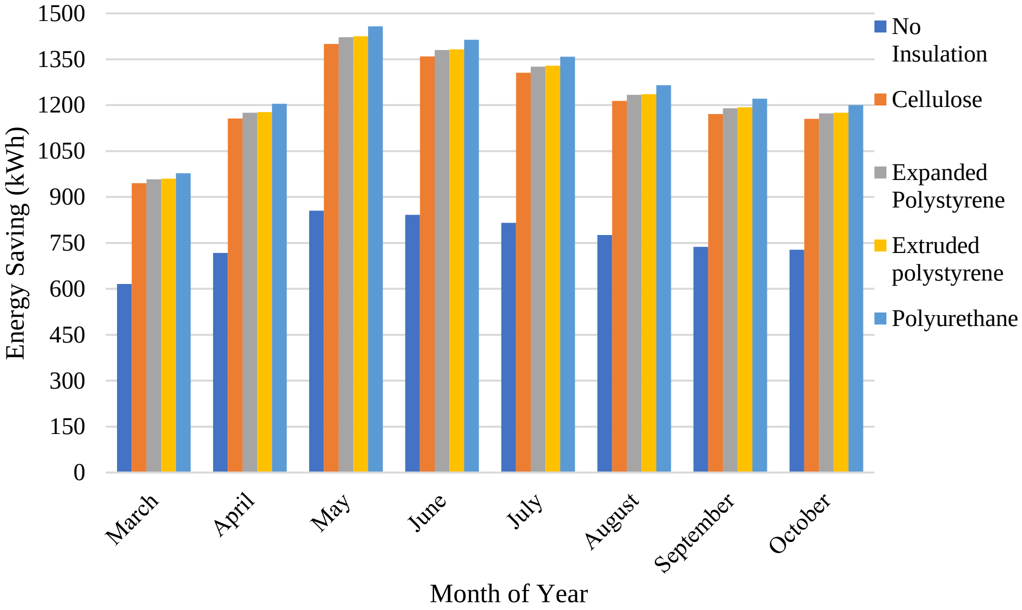

Figure 10. Monthly energy saving by VRF AC with and without different insulation material

3.4 Energy Cost and Cost Savings

The energy cost and cost saving can be found out by using Eqs. (1) and (2), respectively.

$$\text{Energy cost} = \text{Energy consumed in (kWh)*cost of per unit energy in (Rs/kWh)} \tag{1}$$

$$\text{Cost Saving (\%)} = \frac{\text{Cost of energy consumed by (Base Case)} - \text{Cost of energy Consumed by case (x)}}{\text{Cost of energy consumed by (Base Case)}} \text{ x } 100 \tag{2}$$

Figure 11 displays the monthly cost of electricity for traditional air conditioner. Compared to other months of the year, May, June, and July have the greatest energy costs. With a standard air conditioner and an uninsulated office building, the cost of energy for the month of May will be Rs. 45134; however, with cellulose, EPS, XPS, and PU, the costs will be Rs. 22515, 21588, 21480, and 20086 respectively. With a traditional air conditioner, the cost of energy for an uninsulated office building in June will be Rs. 44383, whereas the costs for cellulose, EPS, XPS, and PU will be Rs. 22677, Rs. 21671, and Rs. 20315 respectively.

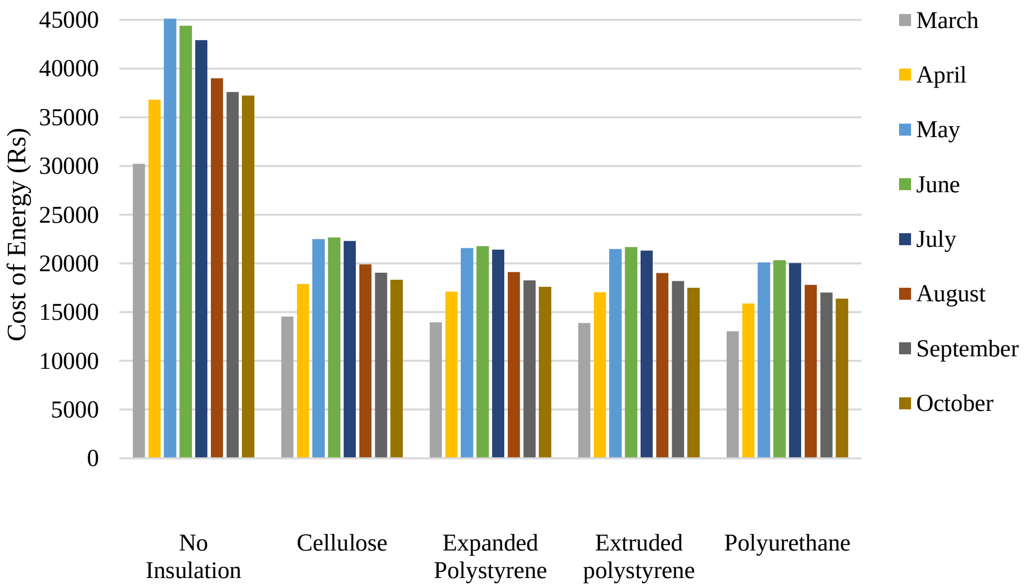

Figure 11. Monthly cost of energy with conventional AC with and without insulation material

The cost of electricity per month using VRF AC is shown in Figure 12. Compared to other months of the year, May, June, and July have the greatest energy costs. With VRF air conditioner, the cost of energy for an uninsulated office building in May will be Rs. 26646, whereas the costs for cellulose, EPS, XPS, and PU will be Rs. 14861, 14387, 14331, and 13614, respectively. When using a VRF air conditioner in an uninsulated office building, the cost of energy for the month of June will be Rs 26180; however, when using cellulose, EPS, XPS, and PU, the costs would be Rs 15000, 14600, 14500, and 13800, respectively. For the month of July, the cost of energy for uninsulated office building with VRF air conditioner will be Rs 25298 while with cellulose, EPS, XPS and PU cost of energy for the month of July will be Rs 14700, 14300, 14200, and 13550 respectively.

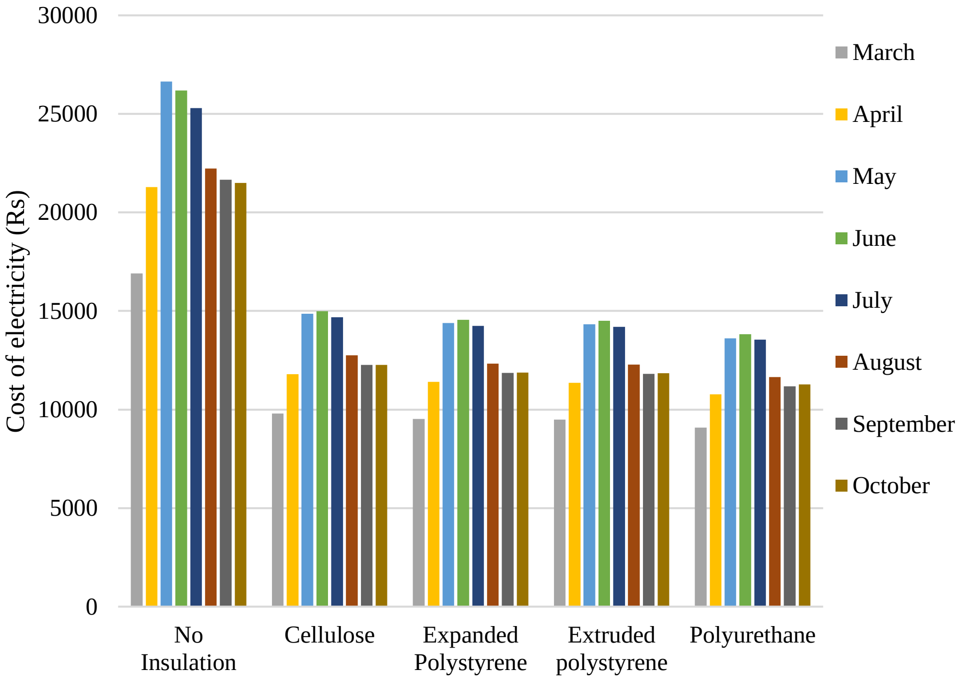

Figure 12. Monthly cost of energy with VRF AC with and without insulation

Figure 13 displays the monthly cost reductions for various types of insulation. In comparison to other months of the year, May, June, and July offer the greatest cost reductions because they are the hottest months of the year in Hyderabad. Cellulose, EPS, XPS, and PU save Rs 22619, 23547, 23654, and 25048 in energy costs for the month of May. Cellulose, EPS, XPS, and PU save Rs. 21706, 22607, 22711, and 24068 in energy costs for the month of June. Cellulose, EPS, XPS, and PU save Rs 20637, 21502, 21602, and 22906 in energy costs during the month of July.

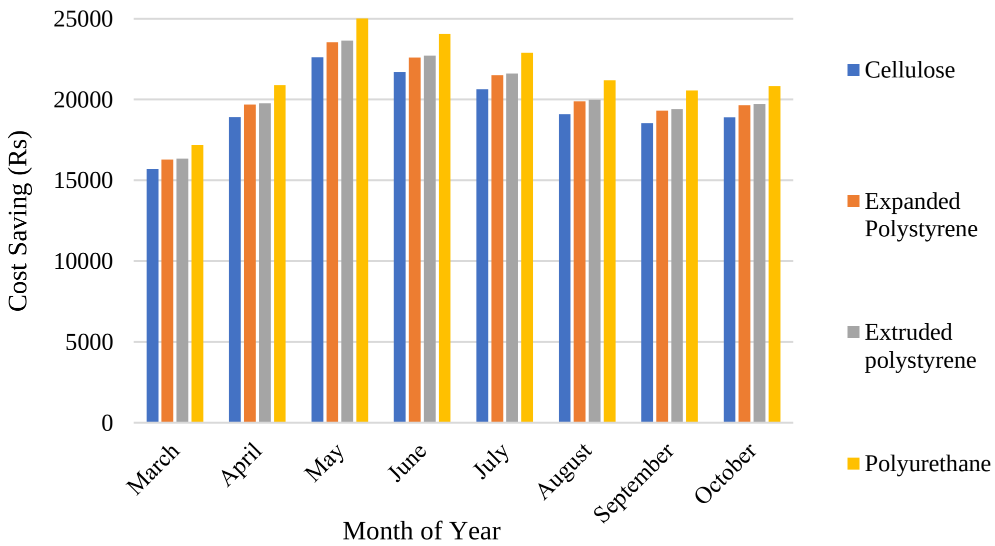

Figure 13. Monthly cost saving by different insulation materials

The monthly cost savings from VRF AC with and without various insulation materials are shown in Figure 14. When compared to other months of the year, May, June, and July show the greatest reductions in energy costs. The VRF air conditioning system for an uninsulated office building saved Rs. 18488, Rs. 18204, and Rs. 17627 in energy costs for the months of May, June, and July. For the month of May, cellulose, EPS, XPS, and PU with VRF AC saved Rs. 30273, 30747, 30803, and 31519 in energy costs. By using cellulose, EPS, XPS, and PU with VRF AC, energy costs for the month of June were reduced by Rs. 29388, 29832, 29884, and 30553. Cellulose, EPS, XPS, and PU with VRF AC save Rs. 28243, 28675, 28726, and 29376 in energy costs for the month of July.

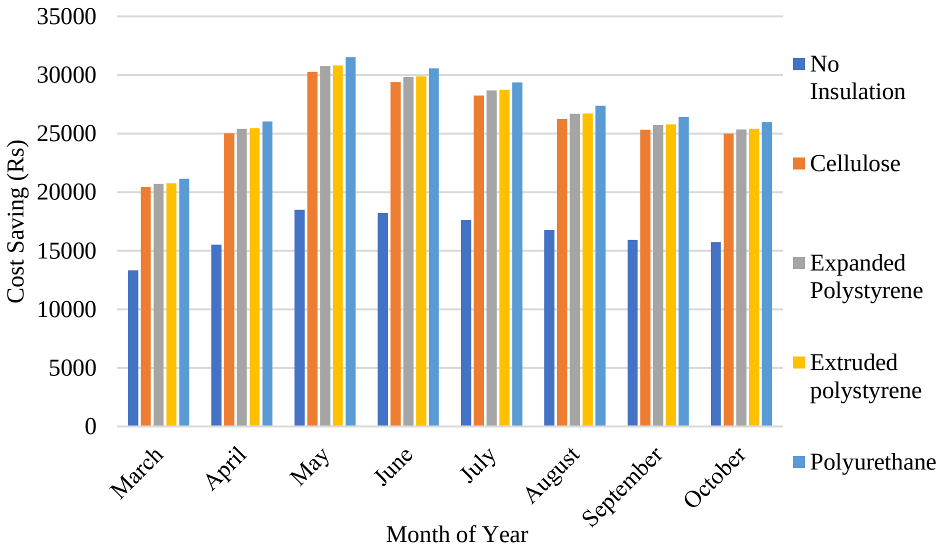

Figure 14. Monthly cost saving by VRF AC with and without insulation materials

3.5 Payback Period

The simple PBP can be calculated by using Eq. (4) as follow:

$$\text{PBP} = \frac{\text{Investment Cost}}{\text{Annual Saving}} \tag{3}$$

$$\text{PBP} = \frac{\text{Cost of AC + Installation Cost +Cost of applying insulation}}{\text{Annual cost saving by case (x)}} \tag{4}$$

Figure 15 illustrates the payback period (in months) with VRF and conventional air conditioning system for various insulation materials. The time frame for repayment varies from 7 to 15 months. The payback period for cellulose insulation with a VRF air conditioner is the shortest at 7 months. The longest payback period, which is roughly 15 months, is for an uninsulated office building with a VRF air conditioner. For cellulose, EPS, XPS, and PU, the payback periods for traditional AC are 7 months, 8 months, 9 months, and 13 months, respectively. The payback periods for EPS, XPS, and PU with VRF AC are, respectively, 7.3 months, 8.6 months, and 12 months.

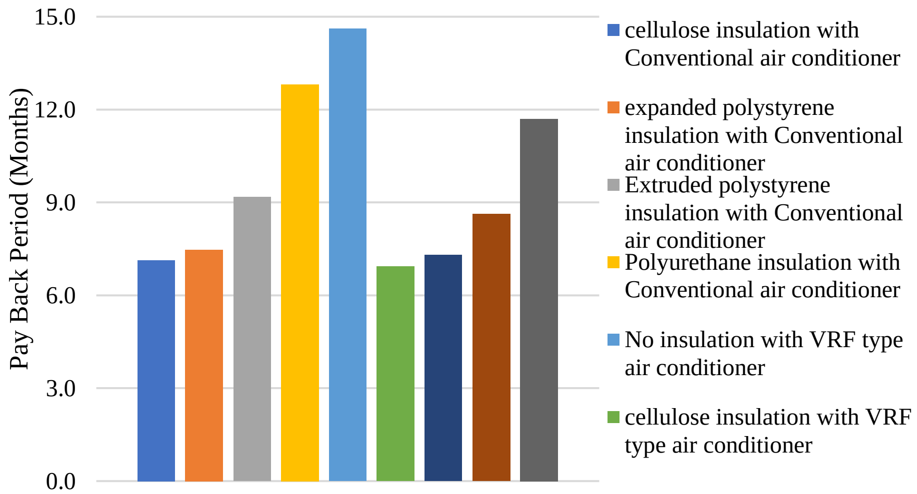

Figure 15. Payback period

4.0 CONCLUSION

The core objective of this study was to compare the benefits of applying insulation material with conventional air-conditioner or using VRF based air conditioner in Hyderabad, Pakistan. From the simulation results, it was concluded that applying the insulation material on the external surface have profound impact on the zone temperature and cooling load. By using polyurethane insulation zone temperature and cooling load can be reduced by 28.4 and 73%, respectively. Similarly, replacing conventional air conditioner with VRF type air conditioner have significant effect on the electricity consumption of the office building. It is noted that VRF type air conditioner can reduce up to 43.6% of electricity. However, Polyurethane insulated building with VRF based air conditioner proved to be the most efficient combination with a saving potential of about 69%. On the basis of this study, it is highly recommended to install VRF type air conditioners in place of conventional air conditioners for better energy efficiency and more cost saving.

5.0 ACKNOWLEDGEMENT

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