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ENERGY PERFORMANCE COMPARATIVE STUDY OF WOOD WOOL SLAB AND A POPULARLY USED BUILDING MATERIAL IN BHUTAN

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***Abstract*—** This work presents a comparative energy performance analysis of building wall materials, namely, hollow concrete brick and wood wool slab (WWS). Based on the functioning of a real-time residential building apartment, the geometry of an apartment is designed in SketchUp and modeled using the OpenStudio plug-in software tool. The net energy performance scenario of hollow concrete brick and wood wool slab are discussed in detail for three principal climatic regions of Bhutan videlicet hot and humid subtropical regions (Phuntsholing), the cooler temperate (Thimphu) of central mountain regions, and the alpine tundra regions (Gasa). The considerable amount of net site energy, net source energy, and annual energy use intensity (EUI) was reduced in wood wool slab walled apartments compared to the hollow concrete brick construction material. The net site energy was reduced by 122.2 kWh, net source energy by 444.4 kWh, and the energy use intensity was decreased by 1.7 kWh/m². Notably, the HVAC energy consumption of wood wool slab apartments is less in all three climatic zones than that of hollow concrete brick apartments. The overall reductions are 453.95 kWh, 122.86 kWh, and 1255.57 kWh for alpine, temperate, and subtropical zones respectively. It is mainly due to the lower thermal transmittance and low thermal conductivity of the wall materials. From this study, it is observed that wood wool slab houses can provide a better indoor environment with less amount of annual energy demand. Therefore, the wood wool slab can be the best alternative low-energy building material in the Bhutanese construction industry.

Keywords—wood wool slab, thermal transmittance value, site energy, source energy.

I. INTRODUCTION

The most disastrous issue over the last decade is global warming. The interest in this topic comes from the need to reduce energy consumption in building sectors and reduce pollutant emissions. Among multiple sectors, energy consumption and carbon emission in the building sector are considerably high. The U.S. Energy Administration states that residential and commercial building accounts for 22 % and 18 % [1] of energy consumption in a combined 40 % of global energy demand is from the building, consequently emitting nearly 30 % of carbon emissions [2]. Therefore, in recent years, the scientific community has started focusing on building energy performance and measures to minimize energy consumption, particularly in residential buildings. Making our home comfortable and energy-efficient through proper early design and construction or by the proper retrofitting with green building materials has become a crucial step.

The traditional buildings are constructed using locally available materials and methods such as soil blocks, timber, clay, and other masonry elements. Similarly, contemporary buildings are constructed from bricks and other concrete materials. However, these houses are neither energy-efficient nor comfortable to live in. Eventually, these houses demand excessive energy to maintain a comfortable indoor temperature. There are no direct negative impacts when constructing dwellings with traditional building materials. However, the consumption of firewood to heat the buildings will be high, which poses a potential threat to the environment. When striving to find alternative solutions to build more energy-efficient and comfortable buildings, it is vital to maintain a low degree of environmental impact while remaining true to the Bhutanese cultural values, accomplishing one of the objectives of the National Housing Policy [3].

Bhutan is still an un-graduated country among the least developed countries. It is obvious to expect the issues associated with the Bhutanese buildings and the materials used in construction. The building materials used in the construction are of high thermal conductivity, and no insulating materials are adopted which leads to the poor energy performance of the buildings. In this type of building, the energy demand to make the indoor environment comfortable is comparatively high which contributes to the emission of carbon.

On the other hand, exposures and health risks in the indoor environment are significant as most of the time people are likely to spend inside the dwellings, consequently exposed to health hazards related to the building's indoor environment [4]. In this regard, maintaining indoor air quality and favorable temperature plays a vital role in minimizing health risks. In Bhutan’s temperate and alpine climatic zones, electric room heaters and firewood are often used for space heating. Electric heaters hold a significant percentage of energy demand in a building up to 30 % to 35 % [5]. Besides, firewood is also used in urban and rural settlements in an average of 5 tonnes and 2.5 tonnes per year respectively [5]. The domestic sector weighs 90 % [6] of firewood consumption which is a big challenge for Bhutan's Commitment to remain under the carbon sequestration capacity of the country's forest. It is high time for Bhutan to focus on proper implementation and monitoring of the national policies and plans such as the Economic Development Policy and National Energy Efficiency and Conservation policy. These policy measures may help to promote the traditional architectural styles and environmental conservation for future generations [7] and also may help to reduce the energy intensity, evade GHG production, and lead to higher revenue earning due to the surplus trade of electricity [8].

Therefore, wood wool slab which is a bio-based building material as a low-energy alternative building material is used to analyze the building energy performance in this research.

1.4 Wood Wool slab

1.1.1 Wood Wool

The suitable wood species used in the production of wood wool slabs come from conifers, namely pine species, and firs. Any other species of trees can also be used if it qualifies the requirement of density and quality of wood wool slabs [9]. The wood is seasoned to remove the inhibitory substance and shredded into wood wool.

1.1.2 Ordinary Portland Cement

An inorganic binding material known as ordinary Portland cement is mixed with seasoned shredded wood wool and then compressed to produce wood wool cement panels or slabs.

1.2 Software Tools

There are many user-friendly designs, layouts, energy simulation, and modeling software tools and engines available for free as well as for commercial purposes. In this study, Trimble SketchUp (version 2021 Pro), EnergyPlus (Version 9.5), Legacy OpenStudio Plugin, and OpenStudio were used.

The design of the building model is done in Trimble SketchUp along with Legacy OpenStudio Plugin. This plugin is vital as it allows users to build 3-D geometries in EnergyPlus format. Then, the 3-D model needs to be imported to OpenStudio to input all the necessary building information and data such as lighting loads, equipment loads, occupancy level, any mechanical system for heating and cooling control, proper schedules, and the design of the building constructions set, etc. The model can be exported in the EnergyPlus format i.e .idf to simulate EnergyPlus. One can also directly simulate within the OpenStudio and view the results in the form of OpenStudio results as well as EnergyPlus results from the ‘result summary’.

1.3 Building Model Scenario

The field study was conducted in an identified three-storey building in Thimphu, Bhutan as shown in Fig. 1. It has five conditioned thermal zones (Living room, Altar room, Bedroom, Kitchen, and Toilet). An apartment of a three-storey building adopted in the study has the dimensions 8.65 m x 8.64 m x 3 m as shown in Fig. 2. To evaluate the effectiveness and suitability of the wood wool slab and the hollow concrete bricks at three distinct climatic zones of Bhutan, OpenStudio-plugin-SketchUp is used to do energy performance simulation. The geometry and the thermal zones are designed in SketchUp 3D modeling software.

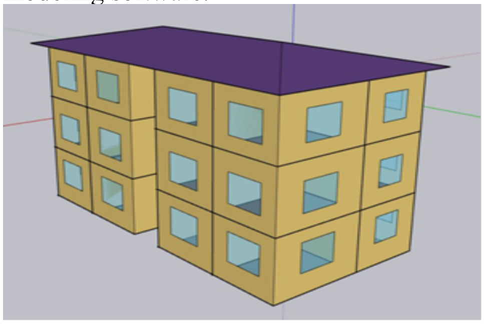


Fig. 1. Real building model

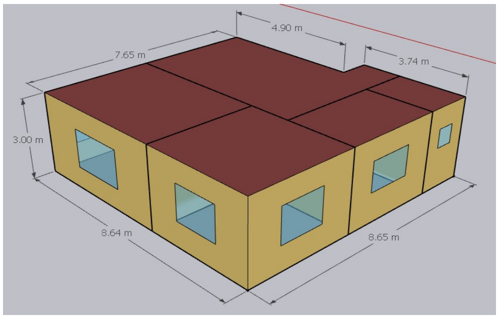


Fig. 2. The geometry of an apartment selected for the study

II. METHODOLOGY

The main focus of the study is the energy consumption of the hollow concrete brick house and the wood wool slab house. It was emphasized mainly on the wall material covering most building areas, keeping other building elements, lighting definition, people definition, and equipment definitions the same throughout the simulation. The same building topology with these two building materials is also being simulated in different climatic zones of Bhutan to examine the energy performance at various locations. A quick and the easiest technique to estimate the energy consumption of the building is by using a specific software tool but the results obtained are not a true representation of the actual building energy consumption [10]. Fig. 3 shows the flow chart of the research approach.

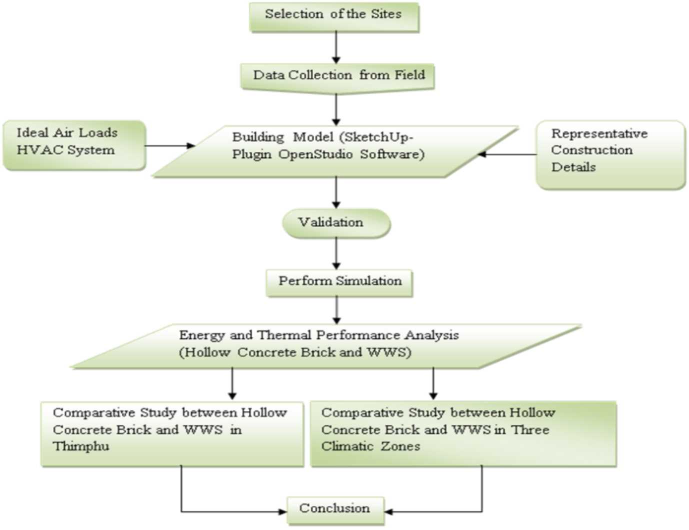


Fig. II. Flow chart of Research Methodology

2.1 Site Selection

The selection of the study site is done based on the various types of building constructions with different materials, weather conditions, and the location and suitability for field research.

Fig. 4. Pictorial view of a selected building

2.2 Data Collection

Data collected from the field is essential for workplace or laboratory research. Through these collected data, we can estimate the annual electricity demand, the comfort of the house, the number of equipment operations, etc, which will help to do energy analysis using computer simulation software. Essential data collected from the field are such as infiltration rate, in-situ thermal transmittance value, utility energy consumption, details of electrical appliances in operation, location, shape, and orientation of a building, and local weather data.

2.3 Building Energy Modelling and Simulation

The geometry of a building selected for study is drawn using SketchUp 3D modemodellingtware and, the energy modeling and simulation were carried out in OpenStudio-plugin-SketchUp.

2.4 Building Model Validation

Simulation model validation is an essential part of the study. It is the method to verify the level of accuracy of the simulation model and input data to be agreed upon as a representation of the actual model. It is sufficient to answer the question "Have we built the right model?" [11]. It compares the performance of the simulation model with the calculated or measured data and determines if the differences are acceptable given the intended use of the model. If the comparison is not up to the agreeable range, the model will be adjusted to get closer to an agreement with the calculated or measured data. There are several ways to validate the simulation models. The widely used approaches are namely, the comparison to other models, face validity, historical data validation, parameter variability-sensitivity analysis, and predictive validation [12]. Among the approaches, the one adopted in this study fall under face validity (i.e., expert view) which can be used when the data-driven model validation is not doable.

III. RESULT AND DISCUSSION

All the essential results related to this research are shown and discussed. In the first phase, the energy performance of the chosen building located in Thimphu with the same design, construction, light, equipment, and heating loads is discussed. In the second phase, the energy performance of first-phase building construction is compared to another building construction that incorporates a wood wool slab in wall construction as an alternative to the existing wall material. In the third phase, the energy performance of hollow concrete brick and WWS is studied in Alpine, Temperate, and Subtropical zones with the same building construction and topology.

3.1 Energy Performance of Existing Building Apartment with Hollow Concrete Brick Wall Material

Site energy is purely meant for the utility bill that accounts for heat and electricity consumption bills in the building. On the other hand, source energy accounts for the total energy used in the building inclusive of the amount of energy lost during the production, transmission, and delivery of that energy to that building [13].

TABLE 1. Site and Source Energy of an apartment

	Total Energy (kWh)	Energy Per Total Building Area (kWh/m²)	Energy Per Conditioned Building Area (kWh/m²)
Total Site Energy	3136.1	44.9	44.9
Net Site Energy	3136.1	44.9	44.9
Total Source Energy	10197.2	146.0	146.0
Net Source Energy	10197.2	146.0	146.0

In the existing building, the net site energy consumed is 3,136.1 kWh, as shown in TABLE 1. All the area of an apartment is conditioned by an ideal air load (without any HVAC system). Therefore, the energy consumed per total building/apartment area is 44.9 kWh/m².

3.2 Energy Performance of Existing Building Apartment with Wood Wool Slab Wall Material

The wood wool slab is adopted as a suitable substitute for hollow concrete brick. Its energy performance results are displayed in table 2:

TABLE 2. Site and Source Energy of an apartment

	Total Energy (kWh)	Energy Per Total Building Area (kWh/m²)	Energy Per Conditioned Building Area (kWh/m²)
Total Site Energy	3013.9	43.2	43.2
Net Site Energy	3013.9	43.2	43.2
Total Source Energy	9752.8	139.6	139.6
Net Source Energy	9752.8	139.6	139.6

The change in the wall material of an existing building has a total site energy consumption of 3,013.9 kWh. All the area of an apartment is conditioned by an ideal air load (without any HVAC system). The energy consumed per total building/apartment area is 43.2 kWh/m². Total source energy was also estimated at 9,752.8 kWh and accounted for 139.6 kWh/m².

3.3 Result Comparison and Discussion in Three Different Climatic Regions of Bhutan

The geographical location and the topography of Bhutan experience a wide range of climatic zones but they are categorized into three dominant climatic zones viz. alpine, temperate (mid-Montana), and subtropical zones [14]. The subtropical zone is hot and humid in summer with an altitude up to 1,800 m above sea level. The elevation ranges between 1,800 m – 3,500 m and is called a temperate zone with cold winter and moderate summer. The short and cool summer and cold winter with snowfall above 3,500 m are known as an alpine zone in Bhutan.

The model and construction sets used for the comparison of two building materials namely hollow concrete brick and WWS in Thimphu were used as a pilot model for three different climatic zones of Bhutan. This was carried out to understand the suitability of the two mentioned building materials in other climatic zones too. The result will provide an overview of the energy performance of these two building materials in their respective zones.

TABLE 3. Energy end-use summary modelled apartment

Bhutan Climatic Zones (Town)	Building Envelope Construction Material			
	Total Site Energy (kWh/year)		Total Site EUI (kWh/m²)	
	HCB	WWS	HCB	WWS
Alpine Region (Gasa) – A	4300	3847.2	61.6	55.1
Temperate (Thimphu) – B	3136.1	3013.9	44.9	43.2
Subtropical (Phuntsholing) – C	5605.6	4350.0	80.3	62.3

Table 3 above provides the simulated energy use overview of hollow concrete bricks HCB and WWS obtained from the OpenStudio model for three different climatic regions of Bhutan. The total amount of energy used in an apartment annually i.e. the total site energy for all three regions is resulted lower in WWS apartment construction compared to the HCB construction. The percentage reductions of the total site energy for alpine, temperate, and subtropical climatic regions are 10.53 %, 3.89 %, and 22.39 % successively. It is because of the low thermal transmittance of the WWS wall construction. The WWS in place of hollow concrete brick has a significant impact on net energy saving. As shown in TABLE 3 above, annual savings in net site energy for alpine, temperate, and subtropical climatic zones are 452.8 kWh/year, 122.2 kWh/year, and 1,255.6 kWh/year respectively. The unwanted heat from the outdoor atmosphere is hindered by its resistive nature and useful heat is not being transmitted out through the wall easily due to the low transmittance properties of the WWS.

Consequently, there is also a reduction in the total site energy use intensity (EUI) which refers to the total apartment's energy use per square meter to the whole apartment's floor area [15]. Annual energy savings per unit area by WWS as a wall material for alpine, temperate, and subtropical climatic zones are 6.5 kWh/m², 1.7 kWh/m², and 18 kWh/m² accordingly. That energy saving is purely due to the low thermal transmittance of a WWS wall material. Fig.5 below shows the graphical comparison of net energy consumption.

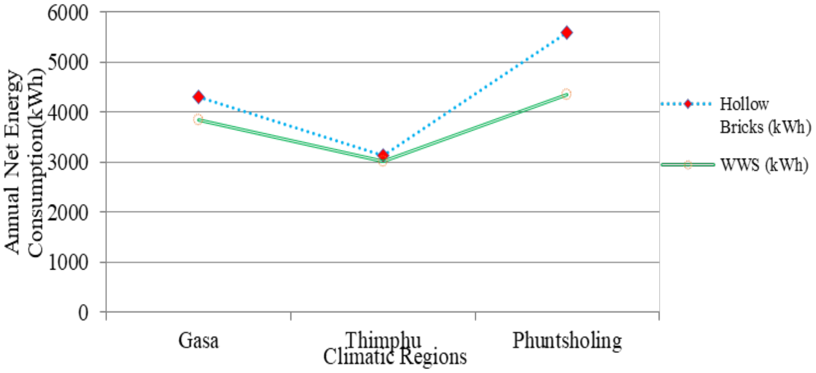
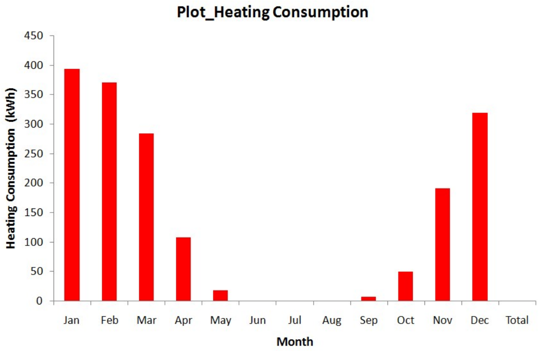
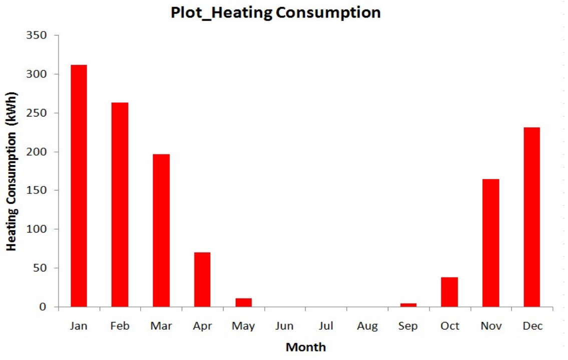


Fig. 5. Annual net energy consumption in three climatic zones

From the above figure 5, you can conclude that the energy consumption in both materials is less in the temperate zone (Thimphu) because the place experiences moderate climatic conditions compared to the other two zones that experience extreme cold and hot weather. However, the energy performance of the wood wool slab is shown better in all three zones. This can be explained with the help of the following tables where a vivid comparison is done in all three zones. The comparison results show that wood wool slab walls perform better in all three climatic zones. The performance of WWS is seen as better even in extreme weather conditions because it has better thermal transmittance and thermal conductivity values that help prevent heat loss through conduction and easy ingress of outdoor heat or cold. From this pilot research, it can be concluded that WWS can be better in all weather conditions including extreme cold and hot as well.

Further, the comparison between WWS and HCB can be understood from the following figure 6 and figure 7. The climatic regions are assigned as sections A, B, and C for Alpine, Temperate, and subtropical zones sequentially.

<table>
<tr><td colspan="2">Building Construction Materials</td></tr>
<tr><td>Hollow Concrete Brick</td><td>Wood Wool Slab</td></tr>
<tr><td colspan="2">Electricity Consumption by Heating and Cooling</td></tr>
<tr><td>A

</td><td>
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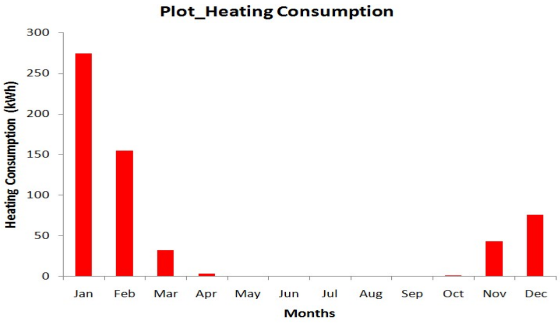
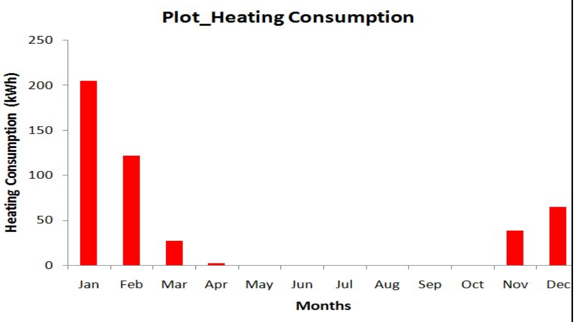
<tr><td>B

</td><td>
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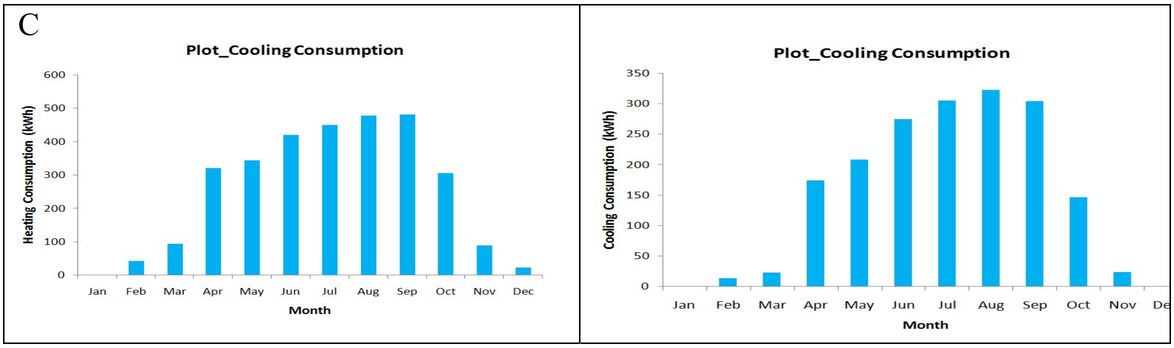
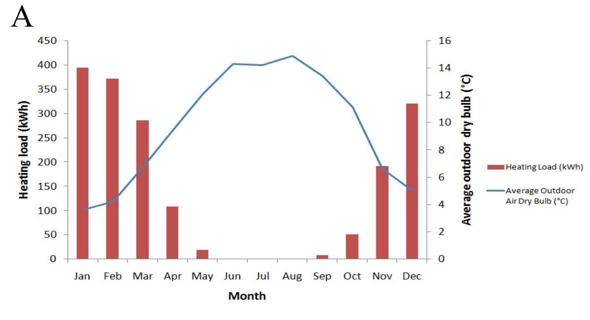
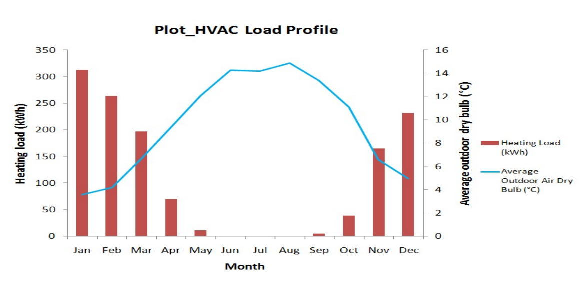
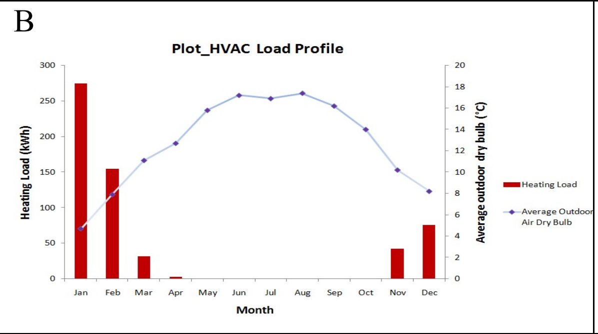
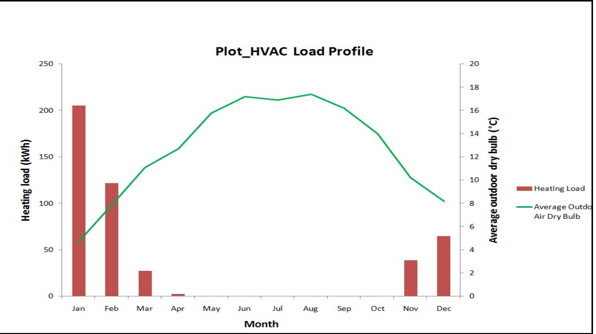


Fig. 6. Monthly heating and cooling load of an apartment

The comparison graph in figure 6 represents the monthly heating and cooling consumption by hollow concrete brick and WWS at three different climatic zones. The simulation result shows that the energy consumption is more in the hollow concrete brick house but it can be reduced with the help of WWS as a building wall material because it has better thermal properties. In general, the energy consumption in the temperate climatic zone is lowest with the outside ambient temperature range from (-8 - 32) °C than that of alpine and subtropical zones. The heating energy consumption in the alpine zone (Gasa) is high due to a higher drop in ambient temperature in colder regions. On the other hand, subtropical regions (Phuntsholing) located in the southern belt consume energy for cooling where space cooling is necessary for the comfort of the occupant in hotter months. Usually, the cooling load arises from April until the end of October as shown in the Section C graph. Nevertheless, the overall heating/cooling energy consumption in the WWS house is better because it hinders heat and cold from moving to/from the building envelope.

<table>
<tr><th colspan="2">Building Construction Materials</th></tr>
<tr><th>Hollow Concrete Brick</th><th>Wood Wool Slab</th></tr>
<tr><th colspan="2">Monthly HVAC Load Profile</th></tr>
<tr><td> </td><td> </td></tr>
<tr><td> </td><td> </td></tr>
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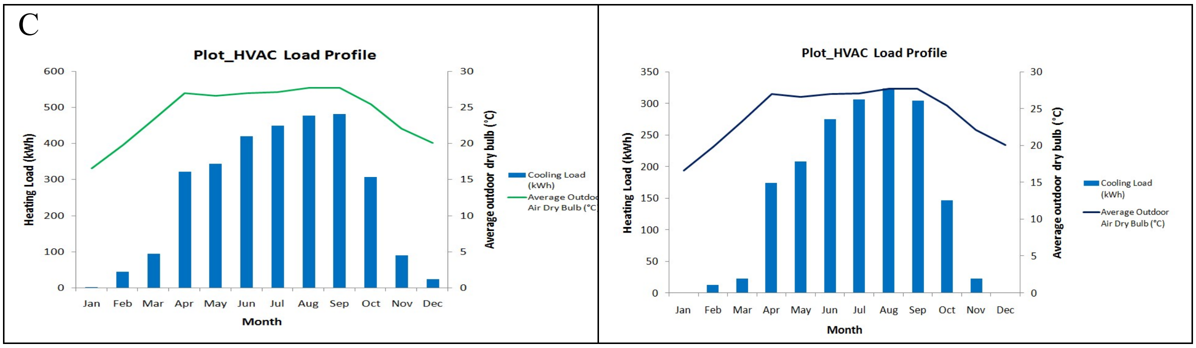

Fig. 7. HVAC Load Profile of an Apartment per Annum

Figure 7 provides the monthly HVAC load profile concerning the outdoor dry bulb temperature for a year. The simulation shows that the HVAC load for all three climatic zones has been reduced appreciably in WWS. The overall reductions are 453.95 kWh, 122.86 kWh, and 1,255.57 kWh for section A (Alpine), section B (temperate), and section C (subtropical) regions, respectively. The importance of thermal transmittance property is observed when a good amount of energy demand is reduced by WWS in buildings. It is also due to the large thermal lag encountered by WWS [16]. The usage of the HVAC component becomes less because the thermal energy on an external surface of WWS gets dissipated before its transfer to the interior space of the building [15]. Figure 7 shows the relationship between heating/cooling and average outdoor dry bulb temperature. In colder places, heating energy consumption keeps on increasing with a decrease in outdoor dry bulb temperature. Conversely, the cooling energy consumption is proportional to the average outdoor dry bulb temperature.

IV. CONCLUSION

An annual energy consumption assessment of an apartment was conducted using the OpenStudio modeling and simulation software tool for popularly used conventional hollow concrete brick and wood wool slab building wall materials. A real-time west-facing residential conventional hollow concrete brick building in Thimphu, Bhutan, was modeled using SketchUp geometry imported to OpenStudio version 3.2.0. Evaluations of energy consumption that include the lighting, electrical equipment, and HVAC load are carried out to check the potential of WWS to reduce the energy demand of an apartment and maintain the thermal comfort of an apartment. Hollow concrete brick that dominates any other building material in the construction industry of Bhutan and potential bio-based low-cost energy building material known as wood wool slab has been chosen to do a computer simulation-based study in three climatic zones of Bhutan namely alpine, temperate, and subtropical climatic zones. The result analysis shows that annual net site energy and annual energy intensity were reduced drastically by substituting hollow concrete brick with WWS. The efficient energy performance of the WWS wall was due to its lower thermal transmittance value (0.334 W/m²K) compared to the hollow concrete brick wall transmittance value (1.803 W/m²K). The thermal transmittance values are retrieved from the OpenStudio simulation results. The space heating loads in the Alpine (Gasa) and temperate (Thimphu) region, and the cooling load in the subtropical area (Phuntsholing) have a substantial percentage of energy reduction with the use of WWS. Overall, the energy performance of WWS is significant and beneficial in reducing the monthly energy consumption and the annual energy demand of a building. The total energy consumption reduction with the help of WWS wall material is 452.8 kWh/year, 122.2 kWh/year, and 1,255.6 kWh/year for alpine, temperate, and subtropical zones respectively. With this evidence, it can be concluded that the WWS can improve the energy performance and thermal performance of a building as well. Owing to its lightweight, easy-to-saw, nail, and drill, it has high potential to be a future building construction solution to offer a better indoor environment to the occupants across diverse weather conditions of Bhutan.

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