Eco-friendly Cooling System Design for a Hostel Building

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Abstract

In order to provide thermal comfort in a tropical country like India, the use of conventional window air-conditioners is very much electricity intensive, which may lead to a further increase in the greenhouse gas (GHG) emissions. A significant economic and environmental advantage can be achieved by adopting modified air cooling systems. This paper presents a case study for proposing a design of an energy-efficient and affordable cooling system for a hostel building located at the Motilal Nehru National Institute of Technology, Allahabad located at Prayagraj (UP), India. The design consists of a solar electricity-based centralized chilled water air conditioning system and an earth air heat exchanger (EAHE) as a passive cooling solution. The EAHE takes advantage of the fact that at a depth of 4 meters, the earth's temperature remains constant throughout the year. An earth air tunnel can provide year round thermal comfort i.e. both heating and cooling depending on inlet air temperature. Simulation showed that, when air is blown at 6.2 m/s velocity through a 70 meter long EAHE with 0.5 meter diameter, the temperature changes from 45°C to 26°C in summers and from 4°C to 16°C in winters. The chilled water AC system is designed for operation with a smart solar grid electricity connection. Results obtained for the solar driven AC system showed that, for a building with 328 TR cooling load, only 65 tCO_2 emission are produced annually, which would have been 928 tCO_2 if connected through grid electricity. This reflects 93% potential reduction in GHG emissions.

Keywords: Sustainable Systems, Energy Efficient Design, Earth Air Heat Exchanger, Thermal Comfort, Renewable System.

1. Introduction

Global warming and urban heat island increase the demand of thermal comfort inside the built envelope. The most common solution is to use mechanical air-conditioning (AC) systems. But for the large cooling requirement (such as in hostels, hospitals, theatres etc.), this solution proves to be very energy intensive.

For large buildings or campuses with multiple building use, water chiller plants for air conditioning are preferred, as compared to window air-conditioners. It normally consists of chillers, cooling towers, pumps and chilled water storage tanks. More than 40% electricity in building is consumed to maintain thermal comfort (Perez-Lombard et al. 2008). Several studies have been reported in the literature for effective management of chiller plants required to save energy and reduce its environment impact. Xiupeng et al. (2014) provided data-driven approach, which was employed to optimize the operation of a chiller plant having multiple chillers. The optimal sequencing of these chillers can improve the plant performance. Chang et al. (2005) proposed branch and bound (B&B) method to solve the optimal chiller sequencing (OCS) problem and to eliminate the deficiencies of conventional methods. They used Lagrangian method that determines the optimal chiller loading (OCL) in each feasible state. Since air conditioning systems consume large amount of electricity in residential, commercial and industrial buildings, hence the search for energy-optimized systems is an urgent need worldwide. This can be done either by producing systems that consume less energy or to use energy from renewable sources. Husnain and Alabbadi, (2000) reported that that the thermal energy storage will reduce the peak cooling-load demand by approximately 30-40% and the peak electrical demand by approximately 10-20%.Leite et al. (2019) presented a technical and economic analysis of air conditioning systems connected to the grid electricity integrated with solar photovoltaic, as a complementary energy source. They analysed two different systems (variable refrigerant flow and water chillers) for two cities in Brazil i.e. Recife and São Paulo, with varying levels of solar radiation and temperature. The authors also applied a mathematical model to evaluate the economic benefits of the integrated use of these systems. They showed that this implementation of air conditioning systems with solar photovoltaic energy could assure high internal rate of return for both cities, with average values around 28% for Recife and 22% for São Paulo,.

Several researchers have studied the use of ground as heat source and sink. Bisoniya et al. (2015) carried out a study to evaluate annual thermal performance of earth air heat exchanger (EAHE) system for hot and dry climatic conditions of Bhopal (Central India). The maximum heating potential and cooling potential of EAHE obtained in the months of January and May, respectively, were calculated as 191.06 kWh and 247.25 kWh. The CO_2 emission mitigation potential was calculated as 101.30 tonnes considering its life span as 50 years. Bansal et al. (2013) studied the underground temperature characteristics of the soil surrounding the EAHE pipe and the effect of duration of operation of EAHE on its thermal performance. Maximum air temperature drop of 15.6, 17.0 and 17.3 K were observed for soil thermal conductivities of 0.52, 2 and 4 W/m.K, respectively. Mahmoud & Nabil (2019) proposed air pre-cooling by inducing ambient air to earth air heat exchanger instead of directly supplying it to thermal systems. Results of the study show that on an average daily basis, a significant induced air temperature drop of 23.5 °C was achieved at the soil moisture content of 30%. Al-Ajmi et al. (2006) developed a theoretical model of an earth air heat exchanger (EAHE) for predicting the outlet air temperature and cooling potential of these devices in a hot, arid climate. Simulation results showed that the EAHE could provide a reduction of 1700W in the peak cooling load, with an indoor temperature reduction of 2.8 °C during summer peak hours (middle of July). The EAHE was shown to have the potential for reducing cooling energy demand in a typical house by 30% over the peak summer season. Jakhar et al. (2015) found that the heating capacity of EAHE system increased by 1217–1280 kWh when it was coupled with solar air heating duct with a substantial increase in room temperature by 1.1 - 3.5 °C.

The objective of the study presented in this paper is to examine sustainable cooling options for a student hostel building on the campus of an engineering institute located in the tropical city of Prayagraj, UP, India. The sustainable options considered are centralized chilled water solar driven AC system and an EAHE system for providing year round thermal comfort.

2. Methodology

This case study was carried out for the SV Patel Hostel, located at MNNIT Allahabad campus in Teliarganj, Prayagraj (25.49° N, 81.86° E), India. It is a two floor building with total 333 rooms and covers 31857 square ft area (287 x 111 sq. ft). It is has eight wings and each wing consists of 15 rooms. Each room area is 82 sq. ft (8.2x10 sq. ft) and has a window opening (3x5 sq. ft), and a door (3x6.7 sq. ft). The CAD model of the building under consideration is shown in Figure 1.

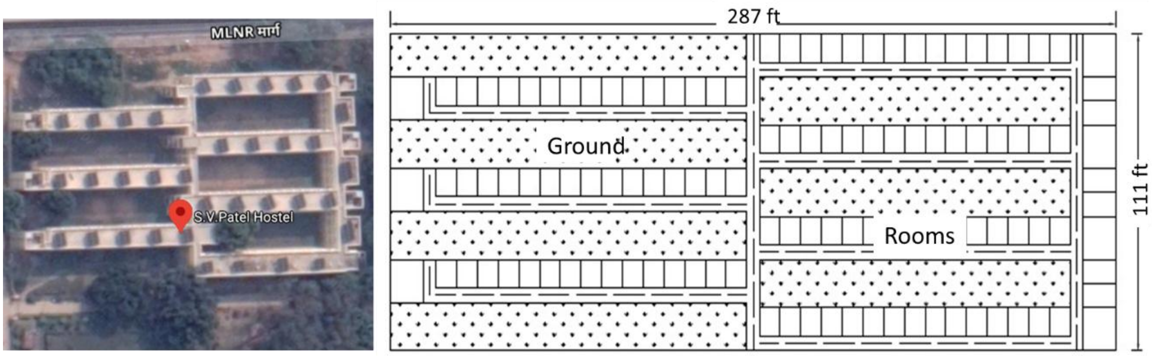

Figure 1 Google satellite image of study site and is top view drawn in AUTOCAD 2018

2.1 Cooling Load Calculation

For cooling load calculation, Quick Energy Simulation Tool (eQUEST) software was used. It allows users with limited simulation experience to develop 3-dimensional simulation models of a particular building design. These simulations incorporate building location, orientation, wall/roof construction, window properties, as well as HVAC systems, day-lighting and various control strategies, along with the ability to evaluate design options for any single or combination of energy conservation measure(s). Such a model for building under consideration is shown in Figure 2.

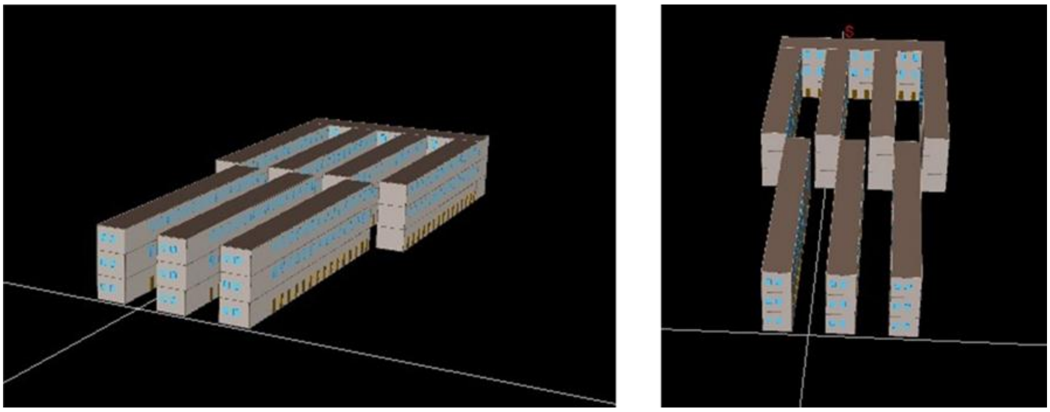

Figure 2 3-D model of building under consideration developed on eQUEST

The software parameter settings also incorporate building envelope model, common brick walls used for building wall construction, concrete roof construction, with glass window and wooden door. Other than these, it also considers daily occupancy for load calculation.

2.2 Earth air heat exchanger

The simplest EAHE can be a pipe of an appropriate dimension buried at a certain depth (generally 4 m) through which air flows (Singh et al. 2018). For winter and summer season, schematic diagram of EAHEs is shown in Figures 3 (a, b). During the summer season, the hot ambient air transfers its heat to the buried pipe and gets cooled (Figure 3a), while in the winter season, the cold ambient air gets heated in the buried pipe (Figure 3b). Due to the complex mechanisms occurring around the earth tube, several simplifying assumptions were made:

- The soil surrounding the pipe is isotropic, with homogenous thermal conductivity in all ground strata (Barakat et al. 2016).
- The thermal resistance of the pipe material is negligible (thickness of the pipe is very small) (Al-Ajmi et al. 2006).
- The pipe is of uniform circular cross-section.
- The temperature profile in the pipe vicinity is not affected by the presence of the pipe. As a result, the pipe surface temperature is uniform in the axial direction (Lee & Strand, 2008).

- The soil surrounding the pipe is homogeneous and has a constant thermal conductivity (Lee & Strand, 2008).

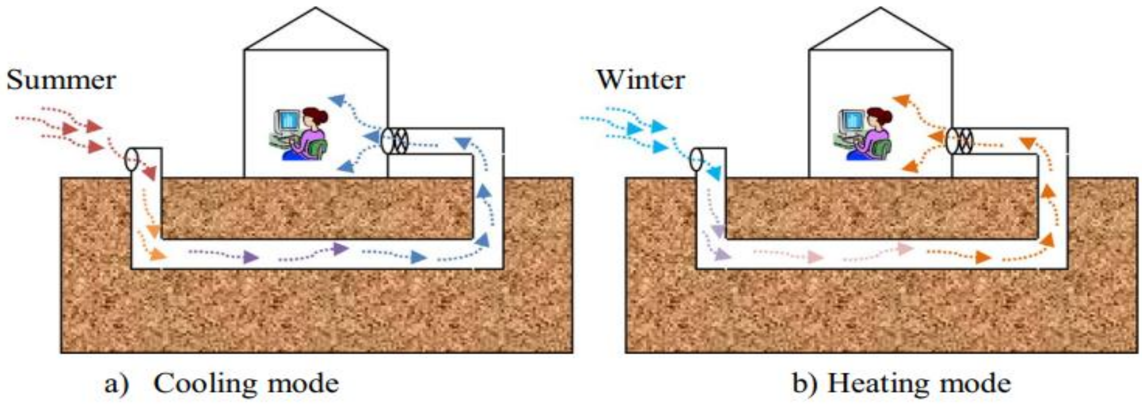

Figure 3 Conceptual view of (a) cooling and (b) heating modes of EAHE (Singh et al. 2018)

Fluid flow in a duct with constant wall temperature is considered for analysis of an EAHE. The flow in this duct is usually in the turbulent range and accordingly the Nusselt number is given by Equation 1 (Cengel & Ghajar, 2017):

$$\mathrm{Nu} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \qquad [1]$$

(Prandtl number $\mathrm{Pr} = \frac{\mu * C}{k}$, Nusselt number $\mathrm{Nu} = \frac{h * d}{k}$, Reynolds number $\mathrm{Re} = \frac{\rho V d}{\mu}$)

Where d stands for diameter of duct, V for velocity of flow, μ for dynamic viscosity of air ($1.8*10^{-5}$ Pa-s), C for specific heat of air ((1.005+1.88ω) kW/kg-K), k for thermal conductivity of air (0.026 W/m-K), ρ for density of air (1.15 kg/m^3), and h for heat transfer coefficient.

On solving for air, the simplified relation for heat transfer coefficient is as given in Equation 2 (Cengel & Ghajar, 2017):

$$h = 3.61\frac{V^{0.8}}{d^{0.2}} \qquad [2]$$

From the heat balance analysis the outlet temperature of the fluid can be calculated for given inlet temperature and flow rate for EAHE. It is given in Equation 3 (Cengel & Ghajar, 2017):

$$\mathrm{Ti} = \mathrm{Ts} + (\mathrm{To} - \mathrm{Ts})e^{\left(-\frac{h\pi DL}{\dot{m}C}\right)} \qquad [3]$$

Where, $\dot{m}$ is mass flow rate of air,T_i is outlet temperature of air after passing through EAHE, To is inlet temperature of air, T_s is temperature of soil, and L is length of EAHE pipe.

For verification of the results simulation was performed using ANSYS Fluent. A standard k-ε turbulence model with enhanced wall treatment was chosen for this analysis.

2.3 Chilled water AC system

The chilled water distribution system consists of chillers, pumps, piping, cooling coils, controls and other components on the evaporator side of the chillers. The chiller unit works on vapour compression cycle. This case study demonstrates chilled water plant designed to circulate constant volume of chilled water through the chiller(s) to the building. Such systems are called constant flow chilled water system. The constant-flow systems can be used in the following configurations:

- Single chiller serving a single cooling load
- Single chiller with multiple cooling loads
- Multiple parallel chillers with multiple cooling loads
- Multiple series chillers with multiple loads

This case study demonstrated the multiple parallel chillers with multiple cooling loads configuration. This is due to safety and better maintenance, which can be achieved in this configuration. Also due to parallel chiller configuration, this system may further be extended to more cooling capacity by just adding chillers to the main header.

Chilled water plant is proposed to be powered by solar PV. Since solar energy can only traced in day time, it requires another energy source for cooling during night time. But this is an energy expensive approach. Hence to provide night cooling, a thermal energy storage tank is proposed for the hostel building under consideration. The chilled water from the chiller is taken in a thermally insulated tank before taking it to the building. During night time, the compressor is shut down and the chilled water stored in the tank is used for the cooling of building. For this the tank must have sufficient chilled water so that it can balance the night cooling load.

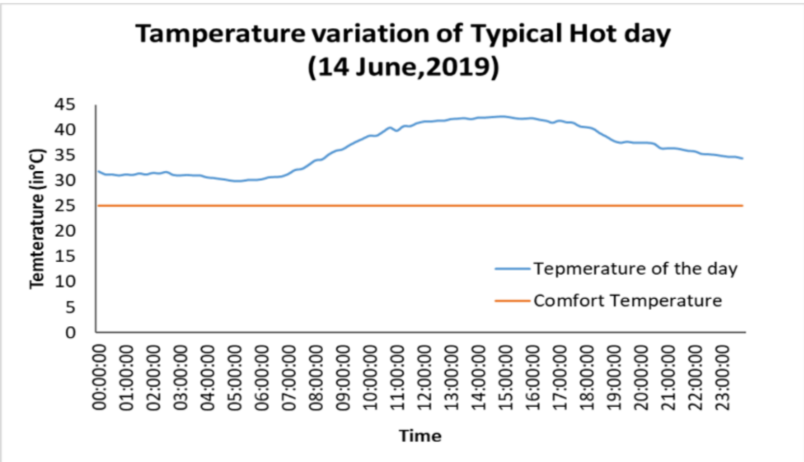

Figure 4: Temperature variation of typical hot day of Prayagraj city

Following consideration are taken for designing of chilled water storage tank, taking in view of the temperature profile shown in Figure 4.

- It is assumed that solar energy is sufficiently available from 8:00 am to 6:00 pm and hence can be used for chilled water production.
- Chilled water is needed to be stored for providing cooling in night time when compressor is in off mode. This period is considered to be of 14 hr (from 6:00 pm to 8:00 am).
- During day hours the ambient temperature is about 16°C -20°C more than the comfort temperature i.e. 25 °C (as shown in the Figure 4).
- While in night time ambient temperature is about 8°C -10°C more than the comfort temperature reduction. Hence cooling load during night can be taken about half of the cooling load in day time.
- Chilled water produced at 6°C will provide effective cooling till it reaches up to 16°C.

So, considering all above mentioned points, the chilled water storage tank is designed for half of maximum cooling load and 14 hours of daily operation.

2.4 Grid connected solar PV system

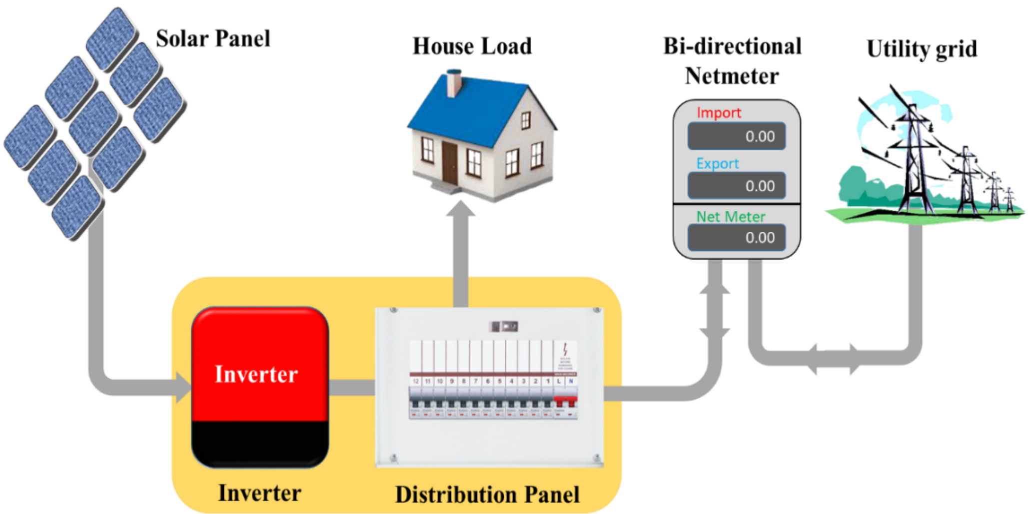

Figure 5: Schematic of grid-connected solar system

As shown in Figure 5, a grid-connected solar system uses solar panels and other components to turn sunlight into electricity for use, while the load remains hooked up to the local utility. An array of solar panels is installed and may be connected to the electrical loads. The additional electricity is transferred to the grid through utility meter (bidirectional net meter). For design of solar PV plant, RETScreen Expert software was used and the data taken into consideration for this design are listed in Table 1.

Table 1: Characteristic data for Solar PV plant design

Location	Prayagraj (Allahabad)
Electricity rate	Rs 6500 per MWh
Slope	25.5° (latitude angle of Allahabad)
Azimuth	0°
Description of Solar PV:	
Type	Poly Si
Manufacturer	Trina Solar
Model	poly-Si - TSM - PC05 / 235 W
Miscellaneous losses	3%
Capital cost	Rs 65,000/kW
Operation & Maintenance cost	Rs 10,000/-
Scrap Value	Rs 1,00,000/-
Plant life	25 years

2.5 Environmental impact analysis

Environmental impact analysis is performed through RETScreen Expert software. The utility grid energy generally produced via thermal power plant, leads to lot of carbon emissions. As in grid connected solar system, a fraction of electricity is used from the utility grid. So, this case study is a demonstration of potential reduction in GHG emissions as compared to base case i.e. when whole chilled water AC plant runs via utility grid electricity.

3. Results and discussion

3.1 Load calculation

In the building under consideration, there are 333 rooms and each room is allotted to two students hence maximum 666 students reside in the building. Under normal operation of building it is assumed to be 90% occupied but from 9:00 am to 5:00 pm due to ongoing classes it is assumed that 70% students are attending the classes and hence low occupancy in the hostel leading to less cooling requirement. This was about the daily occupancy but for the yearly analysis the calendar is divided in three parts as:

1. March to May and August to October, are the month when cooling will be required.
2. November to February being winter season, hence no cooling is required.
3. June and July being summer vacation months, hostel remains closed hence no cooling is required.

In the hostel it is assumed that each room is equipped with 12 W LED bulb and 70 W fan. Along with this each floor has three water coolers as the major load that runs continuously and each water cooler is of 800 W. Based on this data, annual electricity consumption was calculated using eQUEST software and results are shown in Figure 6. The electric energy consumption in space cooling is further analysed on monthly basis and hence cooling load was calculated by taking into consideration 16 hr daily operation time and COP of cooling system as 2.5. The results for cooling load are tabulated in Table 2. Based on above results the centralised chilled water AC plant is to be designed for 328 TR.

Annual Energy Consumption	
Heads	**Electricity kWh x 1000**
Space Cooling	784.4
Vent. Fan	68.6
Misc. Equipment	131.7
Area light	20.5
Total	**1005.2**

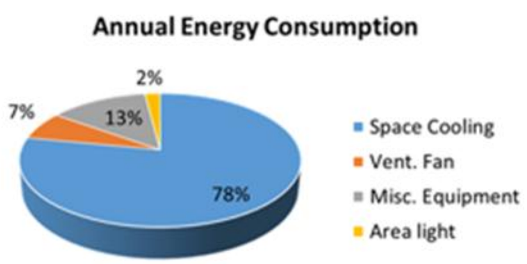

Figure 6: Annual energy consumption due to different loads

Table 2: Monthly cooling load in TR

Month	Cooling Energy consumption in kWh x 1000	Cooling load in kW*	Cooling load in TR
Jan	-	-	-
Feb	-	-	-
Mar	55.3	329.17	93.60
Apr	126.6	753.57	214.28
May	194.2	1155.95	328.70
Jun	-	-	-
Jul	-	-	-
Aug	172	1023.81	291.13
Sep	147.1	875.60	248.98
Oct	88.8	528.57	150.30
Nov	-	-	-
Dec	-	-	-

3.2 Earth air heat exchanger

The EAHE is designed such that it provides the final room temperature of 28 - 30℃, which is good enough for the thermal comfort at an economic cost. This case study demonstrates the design of EAHE for single wing (having cooling load of about 30 kW) and similar design can be reciprocated to the other wings also. At the given site, the soil temperature (~ 4m deep) is observed as 20℃, and earth air tunnel of 0.5 m diameter is taken. The room is supposed to be maintained at 30℃ and the air supplied to the room is at 25℃ (after passing through EAHE). Hence the required air flow rate for removing 30 kW heat is 5.6 kg/s. However, the velocity of air entering the room must be in the range of 5-8 m/s for comfort conditions. Using equations 2 and 3, the outlet temperature from EAHE is theoretically calculated for different velocities at different length of pipe and the results are shown in Figure 7.

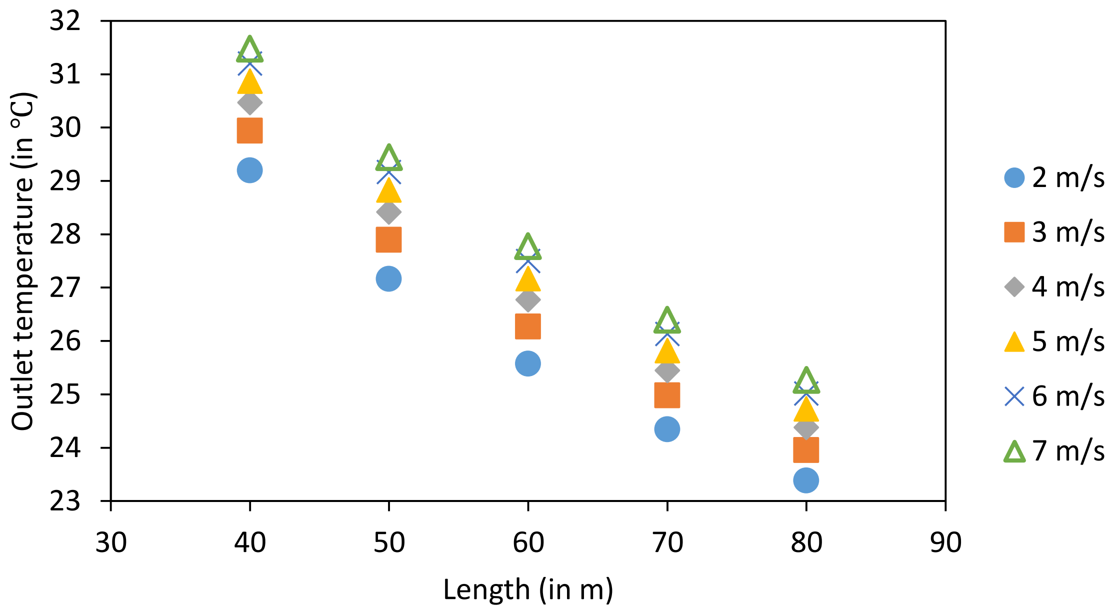

Figure 7: Outlet temperature (for 45 ℃ outlet temperature and 20 ℃ soil temperature)

For cooling load of 30kW, the number of EAHE tubes required are calculated corresponding to each velocity and the results are shown in Table 3. From Figure 7 and Table 3, the optimal number of tubes and its length is selected. For this case study 4 EAHE tubes, each of length 70 m, are selected. To achieve 25℃ outlet temperature, from equation 3, the velocity of air was found to be 6.2 m/s.

The theoretical results are verified against the ANSYS Fluent results for heat transfer through a constant wall temperature tube of length 70 m and 0.5 m in diameter. For the simulation, air velocity is taken as 6.2 m/s and inlet temperature as peak temperature of the month (maximum in case of summer and minimum in case of winter month). Since the flow is in turbulence region, hence standard k-ε turbulence model with enhanced wall treatment was chosen for this analysis. The flow domain was made of 148964 tetrahedral meshing elements with 157168 nodes. Results obtained for each month are shown in Figure 8.

Table 3: Number of tubes requires for cooling load of 30 kW

Velocity (m/s)	Mass flow rate (kg/s)	Heat transfer coefficient (W/m^2K)	Mass flow rate required for 30 kW load (in kg/s)	Number of tubes required
2	0.45	7.22	5.60	13
3	0.68	9.99	5.60	9
4	0.90	12.57	5.60	7
5	1.13	15.03	5.60	5
6	1.35	17.39	5.60	5
7	1.58	19.67	5.60	4

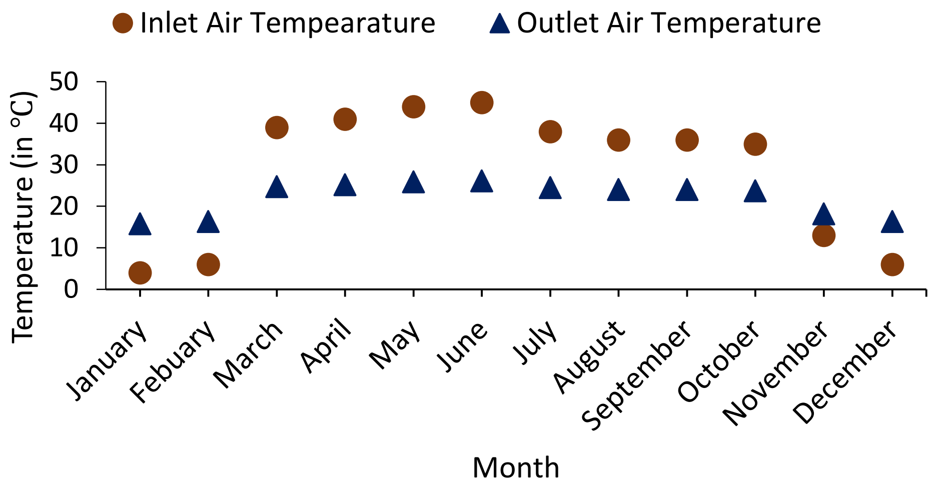

Figure 8: Monthly inlet and outlet temperature for EAHE (ANSYS results)

Results obtained indicate that EAHE can provide year round thermal comfort i.e. cooling in summers and heating in winters.

3.3 Chilled water AC system

The whole plant capacity is 350 TR. For this, two 175 TR chiller units are proposed to be installed for safety and better maintenance. Operating specifications of these chillers are listed in Table 4.

Chilled water will leave the evaporator at 6°C and is brought back as slightly warm water at about 12°C. The proposed design of chilled water plant with duct is shown in Figure 9. In the main header of chilled water, constant flow rate of 2.52 gpm/TR (1 US gallon per minute or 1 gpm = 3.78 litres per minute) is maintained. Pipe size and the flow rate in different pipes are represented in the Figure 9. The main heat exchange process takes place in the room. For this purpose, a fan coil unit is proposed to be installed in each room. The fan blows the air over the coils and as a result of heat exchange the air become cool and dehumidified, whereas the temperature of chilled water rises. This slightly warm water is then flown back to the chillers as shown in Figure 10.

Table 4: Operating specifications of chillers

Property	Value
Refrigerant	R134a
Evaporator refrigerant saturation temperature	4.2°C
Evaporator refrigerant saturation pressure	3.4 bar
Evaporator approach temperature	1.8°C
Compressor refrigerant discharge temperature	46.5°C
Discharge superheat	13°C
Condenser refrigerant saturation temperature	33.5°C
Condenser refrigerant saturation pressure	8.53 bar
Refrigerant flow rate	3.99 Kg/s

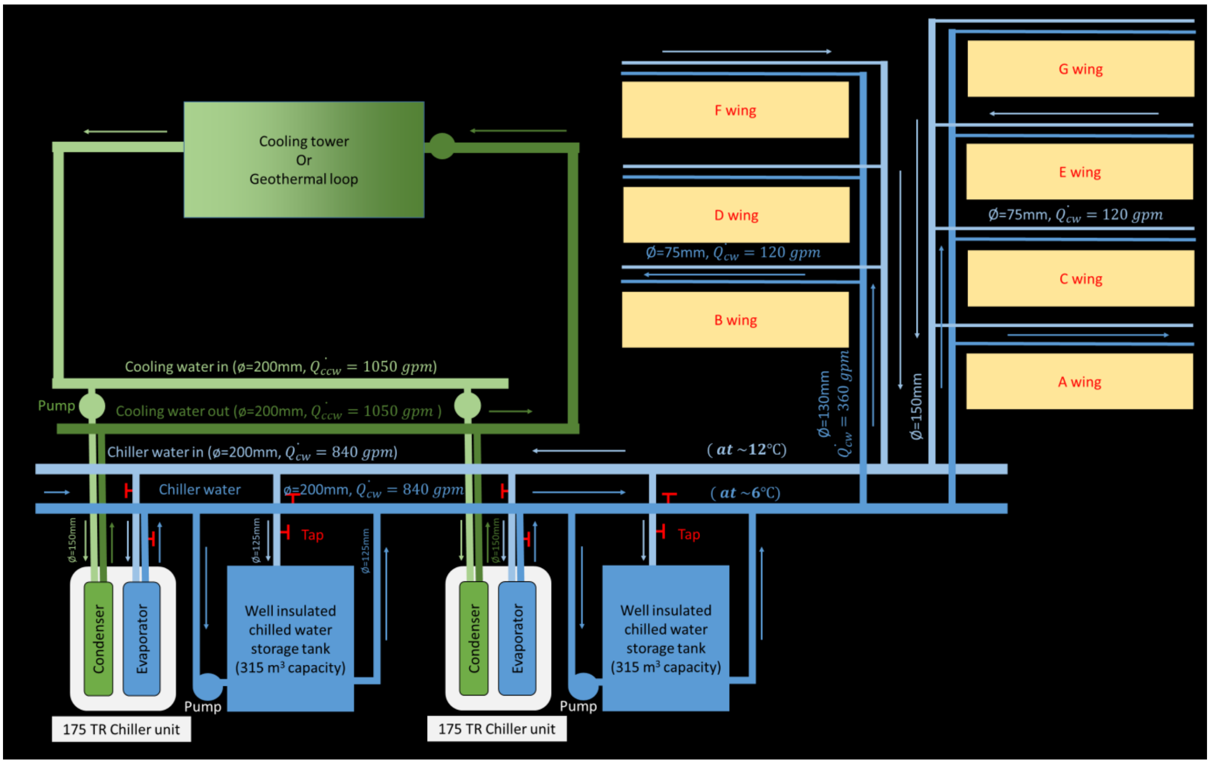

Figure 9 Proposed air-conditioning system design for the hostel building

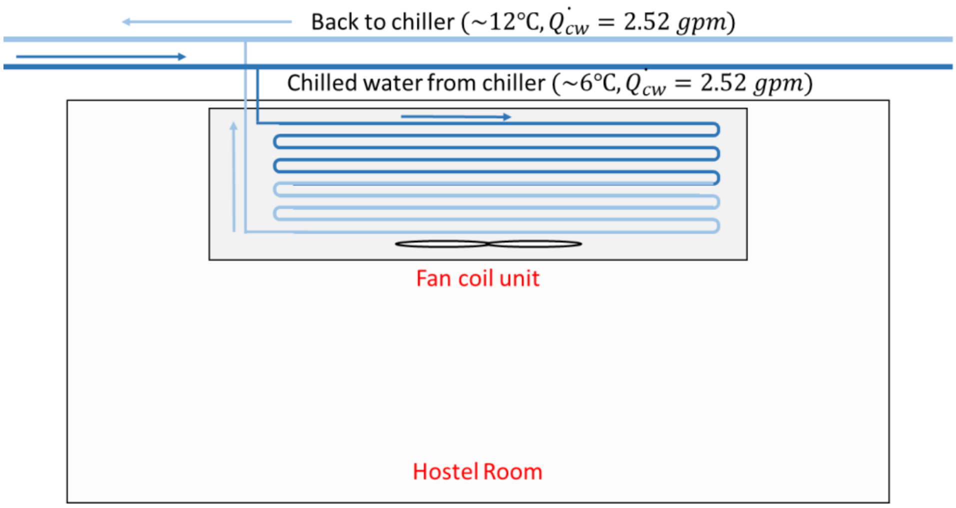

Figure 10 Chilled water flow in room

The chilled water storage tank is designed for 150 TR cooling capacity and 14 hours of daily operation (explained in section 2.3). From heat balancing, the total capacity of the chilled water storage tank was calculated as 630 m^3. Considering the safety and the proper maintenance, instead of single large tank, two small tanks each of 315 m^3 capacity are proposed.

3.4 Grid connected Solar PV system

From Table 2, the maximum electric power requirement is 1156 kW, corresponding to maximum cooling load of 328 TR in the peak summer month of May. If the solar PV plant is designed for the peak load, then it would require excessively large number of solar panels. Hence the solar PV plant is designed for providing the annual average electricity consumption of 784 MWh, through grid connected solar system (shown in Figure 5). In this manner the net grid electricity use is zero. For the data in Table 1, the solar PV plant is designed using RETScreen Expert software and the results obtained are listed as follows:

- To get the annual energy demand of 784 MWh, total 1720 panels will be required.
- The overall plant capacity will be about 404 kW.

For the initial cost of 26.2 million rupees, this system showed payback period of 5.2 years with annual life cycle savings of 4.03 million rupees.

3.5 Environmental Analysis

The results obtained for GHG assessment are provided in Table 5. It shows that the proposed system reduces gross annual GHG emissions by 93%, from 928 tCO_2 emissions in base case to 65 tCO_2 emissions in the proposed case (i.e. 863.8 tCO_2 emission reduction).

Table 5: GHG emissions in base case and proposed case

Annual GHG emissions (tCO_{2e})	
Base case (utility grid electricity)	928.8
Proposed case	65.0
Gross annual GHG emission reduction	863.8

4. Conclusions

Greater use of air conditioning will demand more electricity leading to increased GHG emissions. This case study demonstrated energy efficient and environment friendly technologies for providing thermal comfort for a hostel building. The EAHE would be used for heating in winters and cooling in summers at approximately equal effectiveness at very low cost unlike AC system which costs much more. Central chilled water AC plant is much more effective as compared to individual window ACs, particularly when deigned to run on solar energy. As shown in this study grid connected solar system for the central chilled water AC plant reduced the GHG emission levels by 93%. The detailed economic comparison of the two options presented in this case study needs to be carried out. However, the EAHE option will definitely be much more economical with additional advantage of providing heating in winters.

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