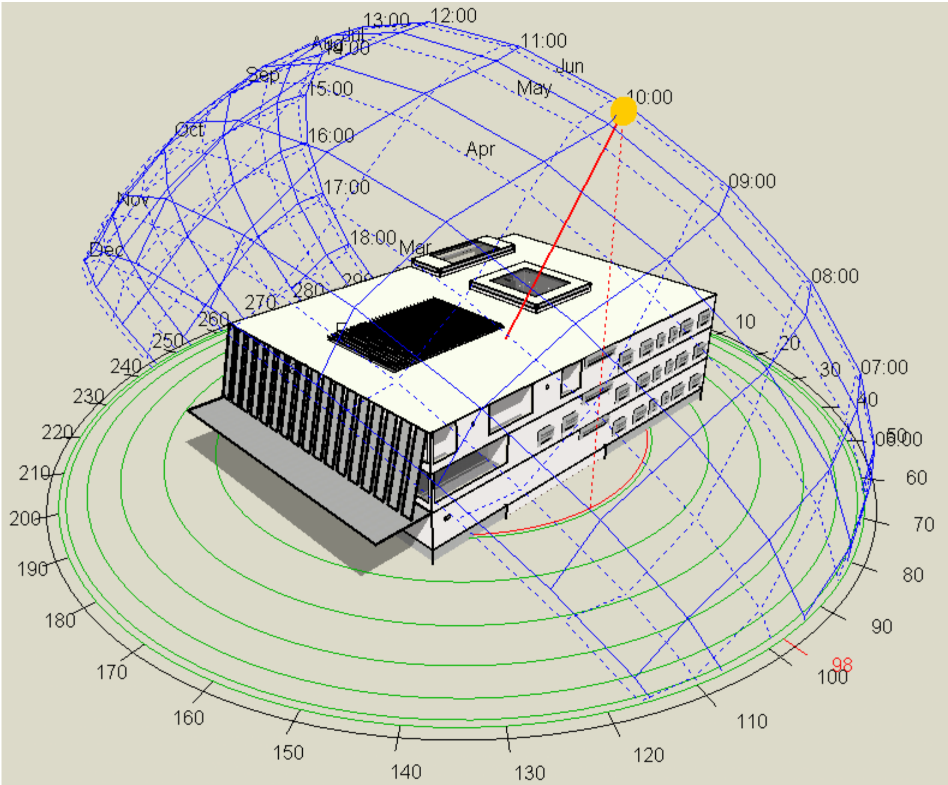
Net Zero Building Design: Using Waste Heat and Industrial By-Products from Rice Processing Plants



Project Details

Objective: Design a net-zero energy office building utilising waste heat from rice processing plants and their by-products as construction materials.

Building: A 3-storey, 3,600 m² office complex combined with residential guest rooms.

Location: Karnal, Haryana, India.

Climate: Composite climate with typical maximum temperatures of 37.4°C in June and minimum temperatures of 7.5°C in January. The annual rainfall is 828 mm and highest relative humidity in August (81.51 %).

Background

Stubble burning of crop residues in India generates nearly 150 million tons of CO_2, > 9 million tons of carbon monoxide (CO), 0.25 million tons of sulphur oxides (SO_X), a million tons of particulate matter and > 0.5 million tons of black carbon. These contribute directly to environmental pollution and to the haze in the surrounding areas and beyond.

In the rice processing plants, which have a significant footprint in Northern India, a multistage process is followed. Rice processing generates rice husk, some of which is reused in the biomass plants to generate electricity to run the plant, generating rice husk ash. The reminder of the rice husk and paddy straws is discarded as waste. However, these waste by-products can be utilised. For example, the ash can be used for making Rice Husk Ash Insulation where the paddy straws and fuel ash are combined to form insulated building blocks. Additionally, the waste heat from the biomass plant can potentially be used for space conditioning.

In this study we incorporate these by-products in the construction of a sustainable net zero office building. The intent is to lower the building's EPI (Energy Performance Index), use the waste material and, as a result, reduce the impact of stubble burning on the environment.

Building Design Details

On a 25-acre rice processing plant in the Karnal district of Haryana, India, a 3,600 m² new office building is planned to be built. This was taken as the case study and submitted as the competition entry for Solar Decathlon India 2021.

The proposed office has open plan and cellular workspaces, a cafeteria, a library, a gym, and guest rooms. The building is primarily mechanically ventilated and conditioned, however some parts of the open plan workspace are naturally ventilated. As the building lies in a rice processing facility, the air quality is poor which restricts the occupants from the opening windows to the outside. Therefore, for the naturally ventilated area, openings are provided in the internal courtyard which has a more controlled microclimate.

An atrium is provided with vents on top to let the hot air escape thus improving natural ventilation by creating a stack effect. To reduce heat gain in the highly occupied open plan office areas due to low angle sun, the atrium and the core is planned to be located on the West of the building and the less heavily occupied office cabins on the East. Figure 2 shows the zoning of the building.

Figure 1: Façade of the proposed design for office

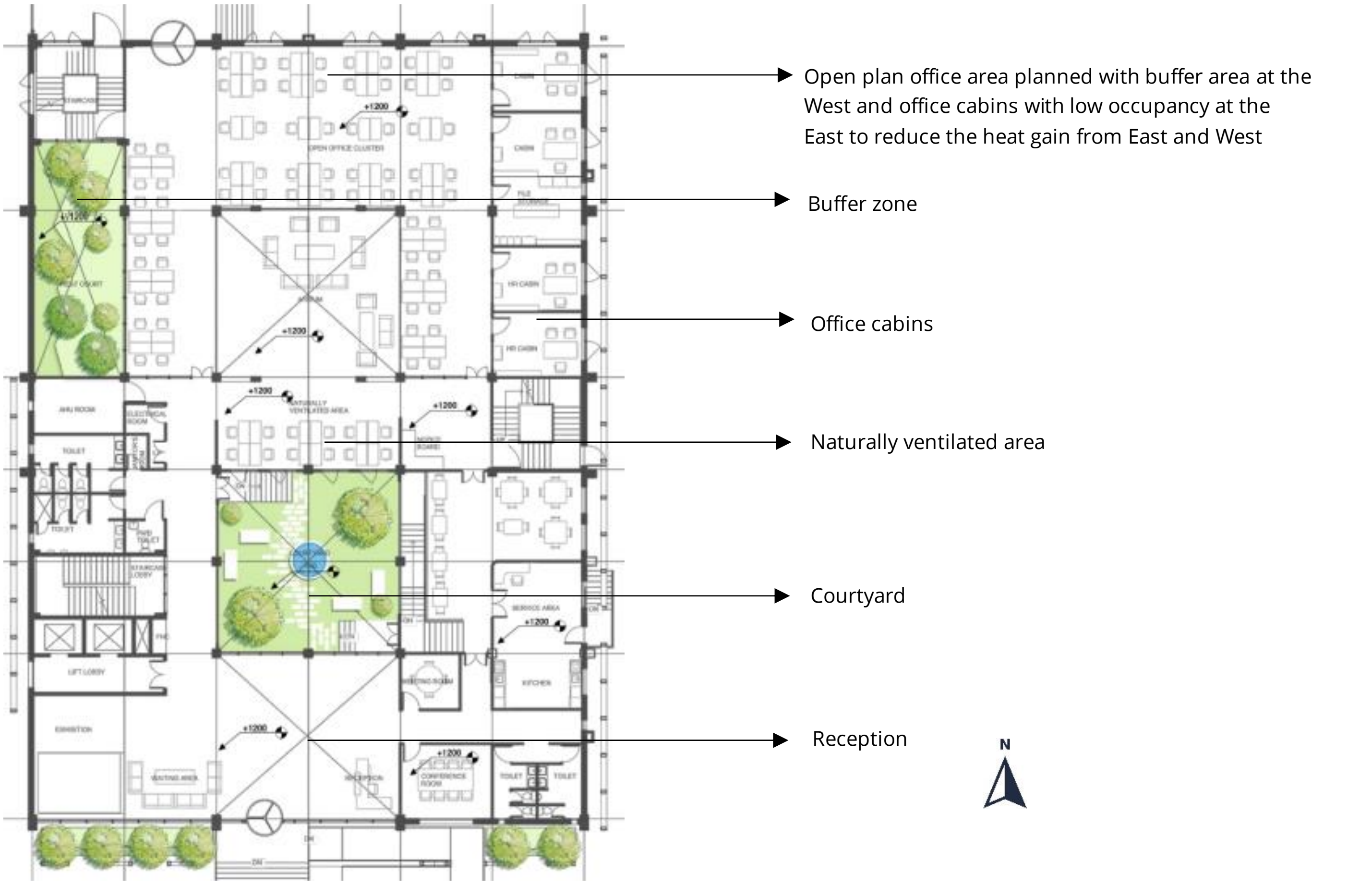


Figure 2: Office ground floor plan

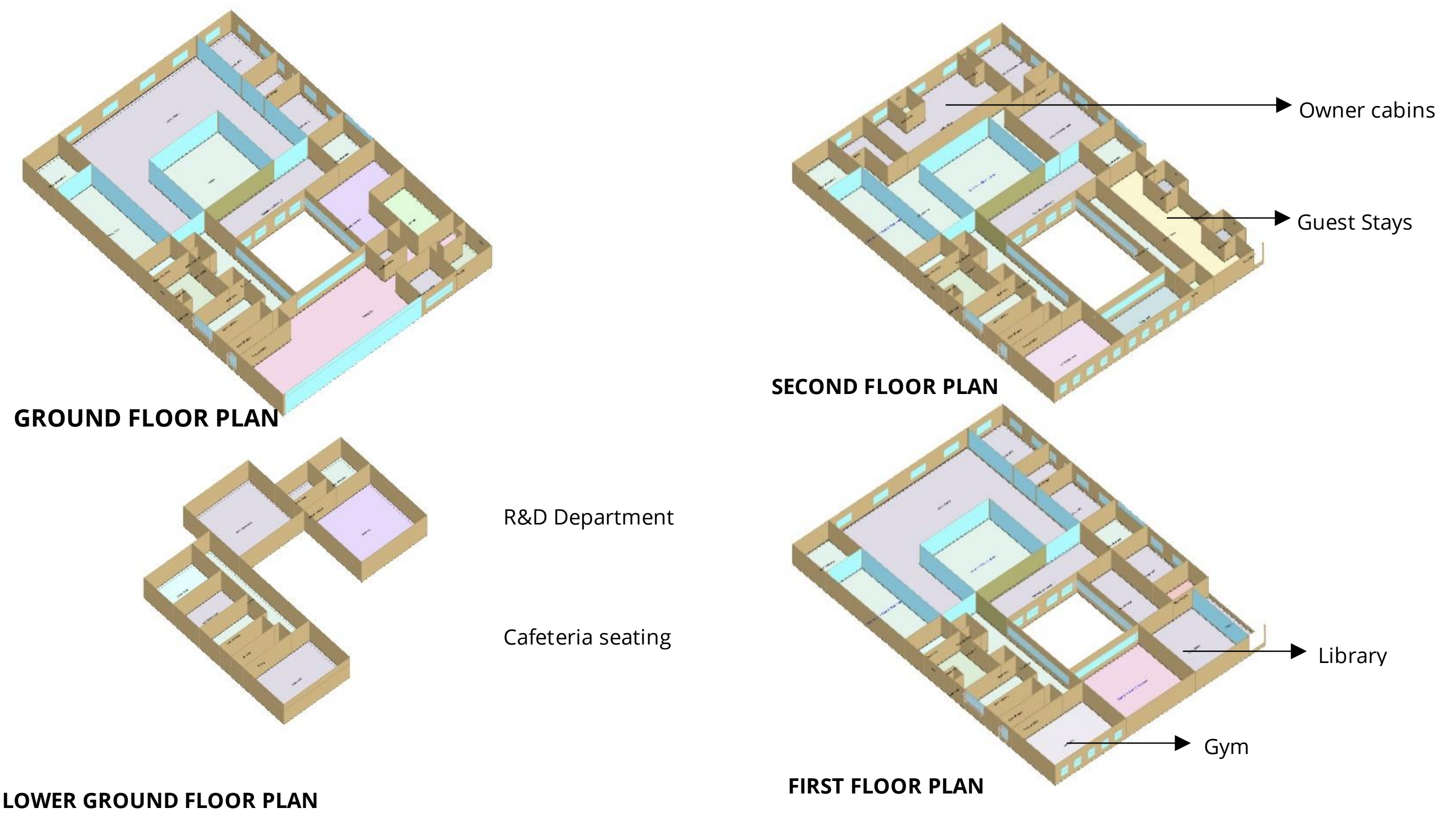


Figure 3: Office floors modelled as separate blocks

Building Occupancy and Operation

The building operates 6 days a week and 8 hours a day from 7:00 to 19:00 with diverse usage patterns. There are 270 full-time occupants. The occupancy, equipment, and lighting schedules follow the same typical profile. The HVAC system is set to maintain the cooling setback temperature of 28°C from 6:00 to 9:00 to reduce the start-up cooling load. On Sundays and holidays HVAC, equipment, and lighting are turned off.

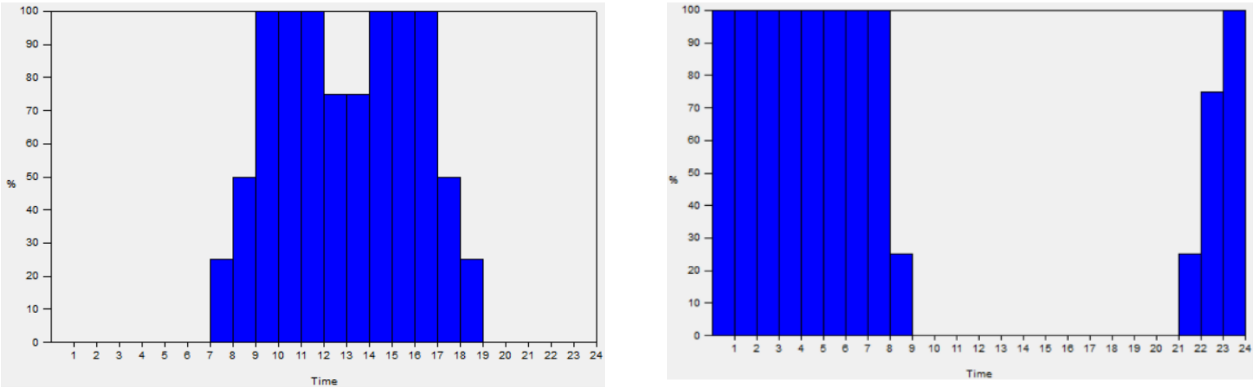


Figure 4: General office weekday occupancy (left); Guest room occupancy all days (right)

Table 1: Thermal Comfort Parameters Setting

Office cooling setpoint temperature	25°C
Circulation area cooling setpoint temperature	26°C
Summer operative temperature range	23-26°C
Activity factor	0.9
Summer Clothing Factor	0.5
Winter Clothing Factor	1

Table 2: Indoor Air Quality Parameters Setting

RH Humidification Set-point	10%
RH Dehumidification Set-point	60%
Minimum Fresh Air	10 l/s
CO_2 Set-point	900 ppm
Minimum CO_2 Concentration	600 ppm

Energy Performance Optimisation

After the initial design and functional zoning, the envelope parameters were optimised, focusing on wall constructions and shading devices. Thereafter various building systems such as lighting and HVAC, were optimised including the use of steam absorption chillers to utilise the waste heat from the biomass plant turbines. The sections below explain each of these iterative optimisations to reduce the building's EPI. Table 3 and Figure 10 summarise all the findings.

External building envelope: The conventional brick-plaster wall (U-value of 1.69 W/m^{2}K – Wall A in Figure 5) was replaced with a wall assembly made of straw-ash blocks. These straw-ash blocks are made using paddy straws and fuel ash from the rice processing plants (conductivity: 0.4 W/mK). Additionally, to improve the insulation of the wall assembly, Rice Husk Ash (RHA) insulation with a conductivity of 0.075 W/mK was used. The RHA is developed from waste from rice processing plants. Using RHA Insulation improves the wall assembly thermal insulation. Whilst achieving target U-value of 0.47 W/m^{2}K (Wall B in Figure 6), as per code requirements, this construction also reduces the building embedded carbon by using carbon negative materials. Additionally, the RHA insulation can be used to increase roof thermal performance. A U-vale of 0.41 W/m^{2}K was achieved by adding 150 mm RHA insulation on a conventional RCC roof.

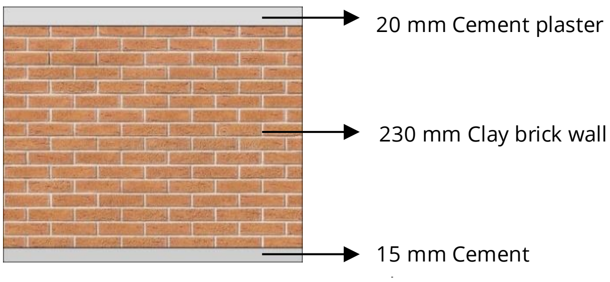


Figure 5: Wall A (U value - 1.69 W/m^2-K)

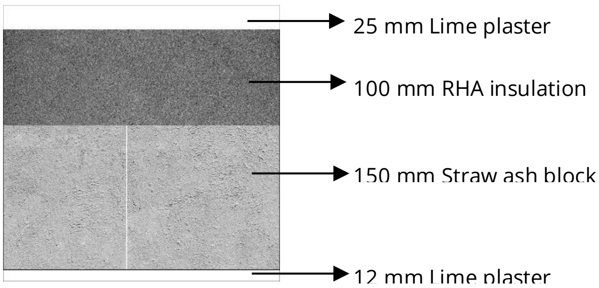


Figure 6: Wall B (U value – 0.47 W/m^2-K)

Shading: Shading devices are a key requirement in building designs in warm climates to minimise solar gains. Through an iterative process of optimising the right shading design, consisting of overhang, louvres and fins, different shading configurations were proposed for different orientations. For windows on East and West, where there is low angle morning and evening sun, a combination of overhang, fins and louvres were used (Figure 7). For North and South windows, a 600 mm overhang was proposed.

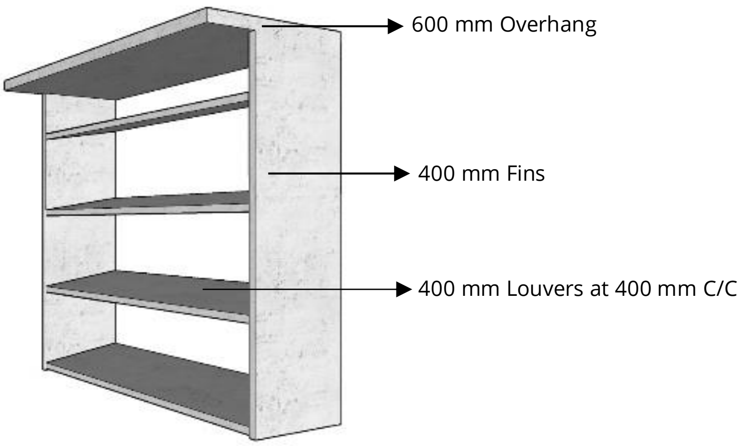


Figure 7: Shading device on East and West facade

Lighting: Efficient LED fixtures with linear dimming controls were used to achieve illuminance levels of 300 lux at 800 mm from ground. Total lighting power density was 7.5 W/m². However, total energy use for lighting was further reduced through integration of daylight seniors, PIR occupancy sensors.

Air Conditioning System: After optimising the fabric and internal gains, the space conditioning system for comfort cooling in the building was designed to use free heat available from the Biomass plant for rice mill processing activities already installed on site. This was done by using an absorption chiller. Waste heat in the form of steam extracted at low pressure (0.1 bar) from steam turbines can be used to heat water to run air conditioning systems as shown in Figure 8. Utilising waste heat will also reduce the water loss in the condenser.

For this purpose, a plate heat exchanger can be introduced downstream of the low-pressure steam turbine extract before the condenser through which water in the buffer vessel is heated up to 90-95°C temperature which is supplied to the generator of the Low-Pressure Hot Water Absorption Chiller for cooling water. The return water at a temperature difference of about 10°C is again pumped back to the buffer vessel. Additionally, a Biomass boiler that uses rice husk as fuel, is also installed in a closed-loop circuit with the buffer vessel as a backup when the biomass plant is not working.

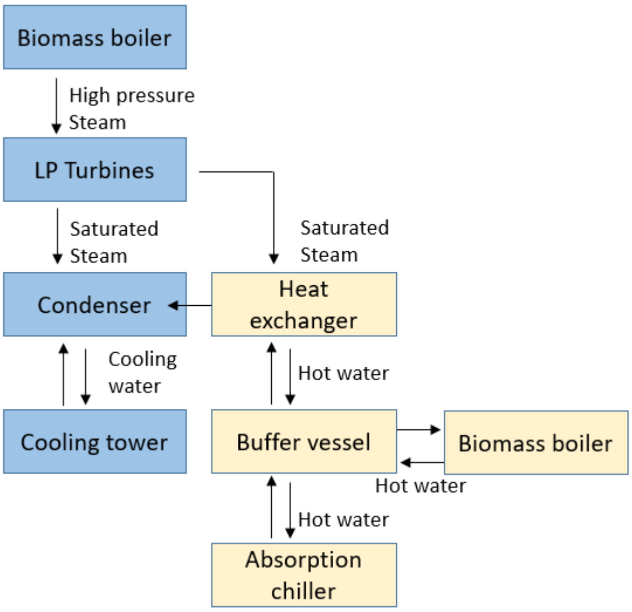


Figure 8: Schematic diagram of the heat recovery system for cooling

Cooling from the absorption chiller was used to precool the fresh air supplied through mechanical ventilation system with heat recovery and to the radiant cooling system (chilled ceilings) in occupied spaces the building.

Figure 9 shows the schematic of the HVAC system modelled in DesignBuilder. Because the heat available from existing biomass plant is free, it is modelled as a district heating system, supplying steam to the absorption chiller. The chiller supplies chilled water at a temperature of 14°C to the radiant ceiling and to the cooling coil in the Variable Air Volume Air Handling Unit (VAV-AHU) which supplies pre-cooled fresh air into the zones. The chiller is connected to a cooling tower for the supply of cooling water to the condenser.

This absorption chiller-based radiant cooling system is more suitable for this building type than a more typical VRF system, due to the free heat available from existing processes and the regular nature of building occupancy. In practice a smaller backup biomass boiler (just to meet building's space cooling requirements) is planned to run the system at times when the primary system not available for any reason.

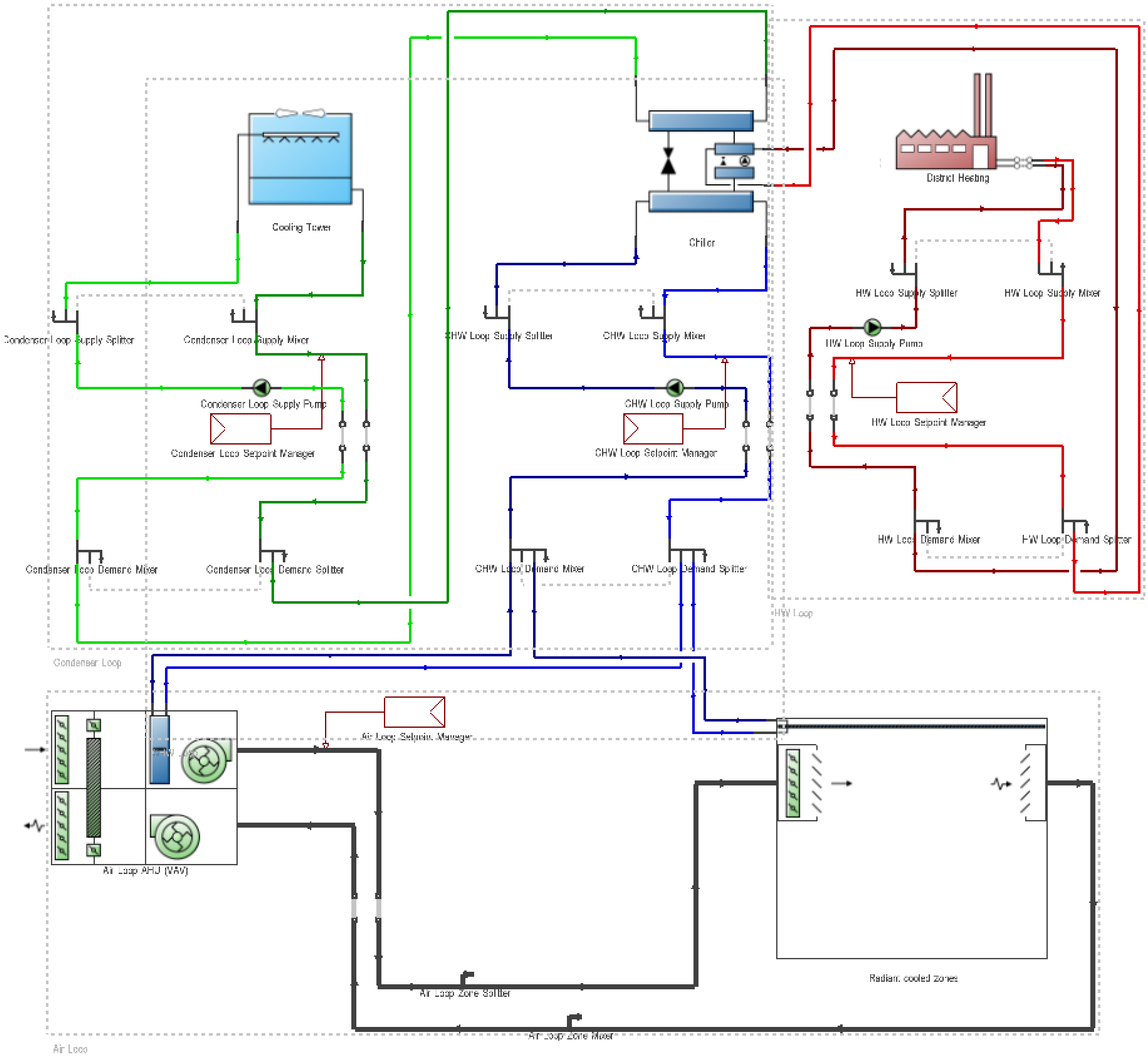


Figure 9: HVAC Schematic Diagram

Iterative Simulations and EPI Reduction

The design of this building was progressively fine-tuned for optimal performance, initially for passive strategies such as fabric and shading and then for active systems for space cooling and ventilation.

Table 3 and Figure 10 show the energy use of various iterations of the model as the design optimisation of the building progressed. Table 3 explains the different settings used in the iterations and step by step reduction of total Energy performance Index (EPI). Figure 10 shows the breakdown of EPI for various end uses.

Table 3: Model settings during iterative EPI reduction

CASES	Wall U value (W/m²-K)	Glazing U-value (W/m²-K)	Roof U-value (W/m²-K)	Lighting (W/m²)	Equip (W/m²)	AC system	EPI (kWh/m²)
1 Base case	1.69	1.6	0.28	15	8	VRF	130
2 Wall optimisation	0.47	1.6	0.28	15	8	VRF	120
3 Window shading	0.47	1.6	0.28	15	8	VRF	119
4 Efficient lighting	0.47	1.6	0.28	7.5	8	VRF	102
5 Radiant cooling	0.47	1.6	0.28	7.5	8	Radiant; water cooled screw chiller + DOAS	79
6 Absorption chiller	0.47	1.6	0.28	7.5	8	Radiant; absorption chiller + DOAS	67

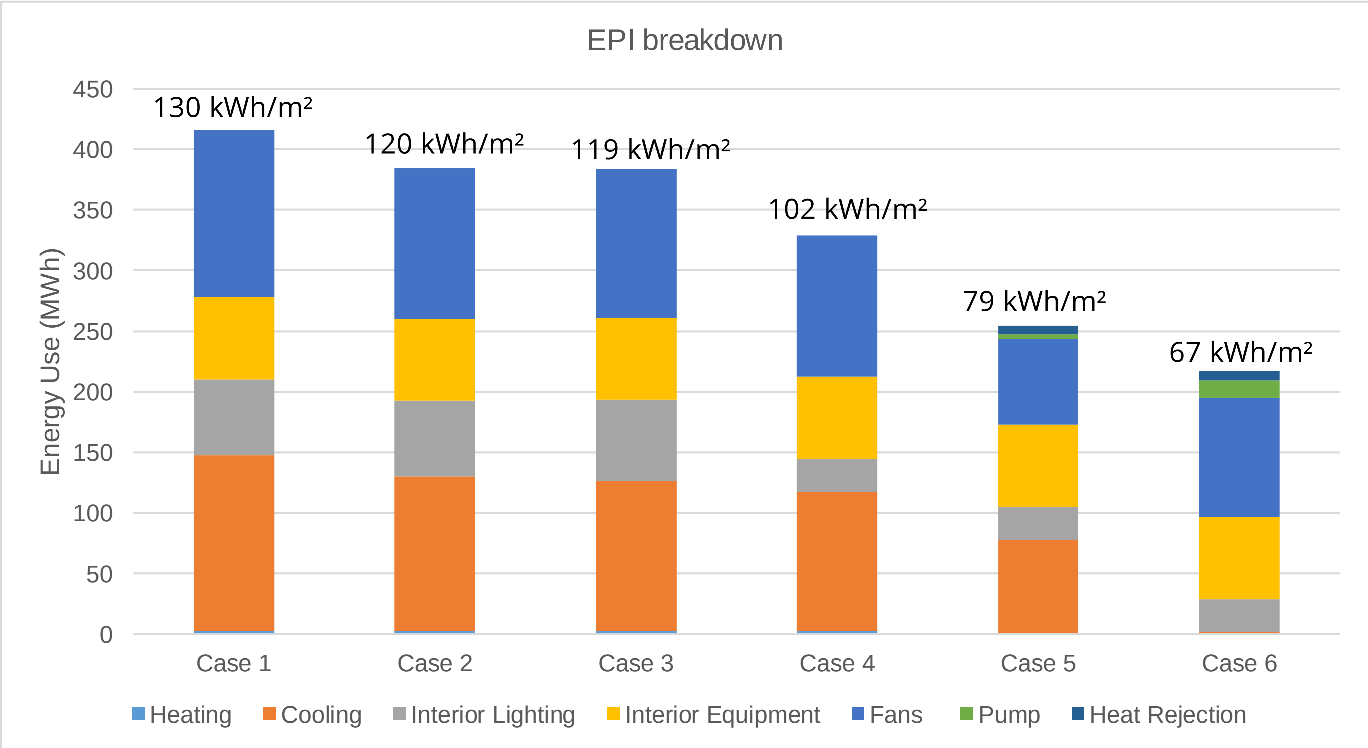


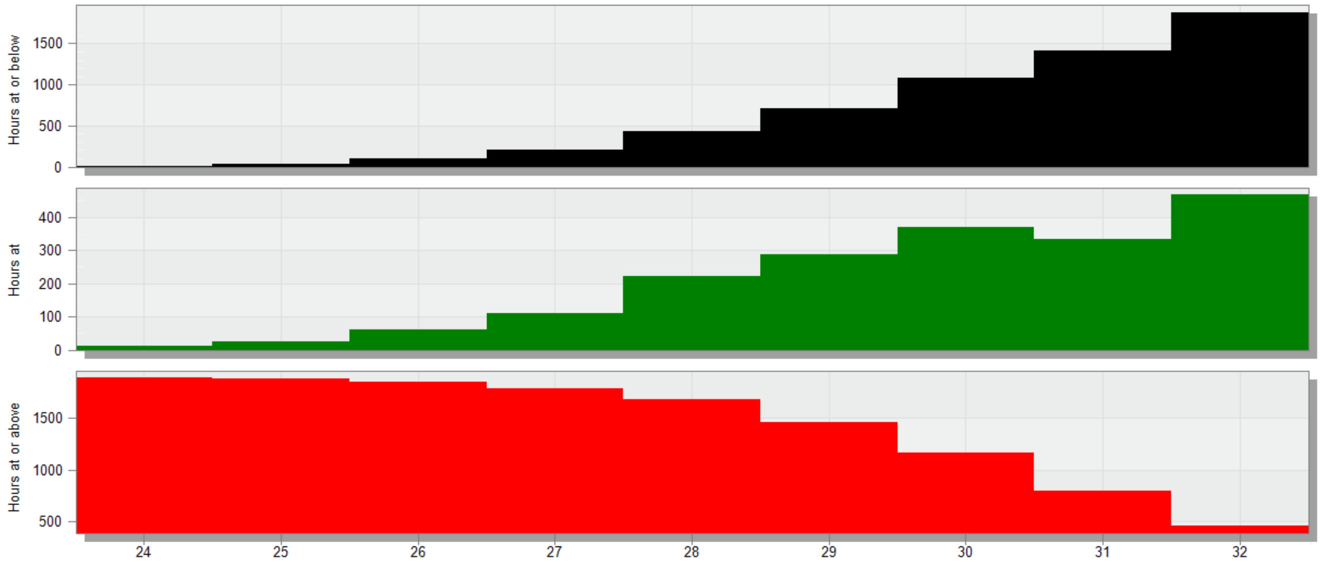
Figure 10: Graph showing reduction in the annual energy consumption

Lifecycle Assessment

The Global Warming Potential factor (GWP) emission factors for Straw-Ash blocks and burnt clay bricks are -0.2 kgCO2/kg and 0.57 kgCO2/kg, respectively. Emissions factors are taken from manufacture provided data and the IFC Database of Indian construction materials. The emission factor for RHA insulation is assumed to be 0 kgCO2/kg as it consists of 88.28 wt % rice husk ash (RHA) which is a carbon-negative material. A Cradle to Gate Life Cycle Assessment (LCA) performed in DesignBuilder revealed a significant drop in Embodied Carbon (EC) of 48% when replacing wall envelope 'Wall A' with 'Wall B'.

Comfort Hour Analysis

The comfort hour calculation (Figure 11) revealed that in the naturally ventilated office area, the operative temperatures are at or below 31°C for 75% of the total occupied hours in summers (April to September), in case 7. Comfort in the remaining 25% hours can be met using strategies like mist or evaporative cooling.



	24	25	26	27	28	29	30	31	32
Hours at or below	12.5	36.0	98.0	208.0	428.0	716.0	1086.0	1418.0	1884.0
Hours at	12.5	23.5	62.0	110.0	220.0	288.0	370.0	332.0	466.0
Hours at or above	1884.0	1871.5	1848.0	1786.0	1676.0	1456.0	1168.0	798.0	466.0

Temperature bins (°C)

Figure 11: Temperature Distribution Graph for ground floor Naturally Ventilated zones

Insights

The building's energy demand is met using the onsite 3 MW biomass plant that supplies electricity to the whole rice processing facility, helping to ensure that it a net zero energy building.

External Wall: A significant reduction of 10 kWh/m²/year in building's EPI was observed while replacing Wall A with Wall B which indicates that the wall assembly made using agricultural waste/by-product can perform better than the widely used 230 mm red brick wall assembly in India.

HVAC system: Radiant cooling systems performed better than conventional VRF system and can also be coupled with absorption chillers for further energy savings. It should be noted that the absorption chiller will use around 1,000 m^3 of more water annually than a screw chiller because of higher variation in cooling water temperatures at the condenser outlet. The source of the water for the cooling tower, if sourced from on-site recycled water, can make the proposed strategy more environmentally friendly.

Overall, the proposed strategy of using industrial waste materials and by-products to support building construction and ongoing operations helps ensure that surrounding buildings benefit by minimising the environmental impact.

Credits

This case study was written by Ibrahim Hitawala. The case study design was developed by Ibrahim and his team (Team Sparikam) as a part of Solar Decathlon India 2021 which is a design competition focusing on designing Net Zero Carbon, Energy and Water buildings of real-life projects. Ibrahim is an Architectural graduate from School of Planning and Architecture, New Delhi and is an energy analyst at PSI Energy Pvt. Ltd., New Delhi (www.psienergy.in).

See Team Sparikam's SDI 2022 competition entry video of this case study project here: https://youtu.be/ylmDDsUt2tQ, and read about the project, covering various aspects of its sustainable design here: https://solardecathlonindia.in/swp-content/uploads/2021/05/1_D4_OFF_SPARIKAM.pdf