Net-zero building design: Demonstrating the use of agricultural waste and industrial by-products from rice cultivation belts

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ABSTRACT: Buildings contribute significantly to global carbon emissions, resulting in high greenhouse gas emissions that contribute to global warming. Stubble burning is a major issue in India, causing severe health and environmental problems every year. The primary reason is the disposal issues associated with rice cultivation by-products such as rice straws and rice husk. This paper aims to explore the means of using building materials made of rice cultivation waste and by-products in making a Net-Zero energy office building, also the possibility of using waste heat from the biomass boilers in running the air conditioning system. A case study of a rice processing plant situated in Karnal, Haryana, where a 3600 m² office building is planned was selected and iterative simulations were performed to analyse the step by step reduction in the annual EPI (Energy Performance Index) while incorporating energy saving strategies. Energy simulation software Design Builder v7.0 was used to assess the building performance. Life Cycle Assessment (LCA) was also performed to assess the reduction in initial carbon emissions while using low carbon building materials over conventional materials.
KEYWORDS: Energy simulation, Life Cycle Assessment, Low carbon, Rice husk, Rice straws

1. INTRODUCTION

Buildings have a significant impact on the environment. Construction of buildings and their operation accounts for 36% of global final energy use and 40% of energy-related carbon dioxide (CO_2) emissions. Also, the building sector has a strong potential to provide long-term energy and greenhouse gas emission savings without high financial costs [1].

To address the climate change challenge and meet the UN Sustainable Development Goals, there is an urgent need for sustainable development. Recycling waste reusing industrial by-products can help to reduce carbon emissions and energy consumption while also providing a healthy and comfortable environment for the occupants.

In the agricultural belt of India, stubble burning of crop residues contributes directly to environmental pollution in the surrounding areas and beyond. However instead of burning, this waste such as rice straws and husk can be used in construction materials and waste heat from milling plants can be used to supplement energy needs. These reuse strategies can lower the building energy use or EPI (Energy Performance Index) and also contribute to addressing the environmental hazard of stubble burning.

In this paper, we explore the energy performance of a case study building designed to reuse some of the agricultural waste and industrial by-products from the rice cultivation areas and nearby mills. This can function as a scalable solution to tackle both energy efficiency improvements and air quality problems of the region.

2. METHODOLOGY

This paper aims to examine the waste and by-products from rice cultivation and rice processing plants (such as rice straws, rice husk and ash) and their applicability in the production of construction materials, to configure a space conditioning system that uses waste steam from the rice processing plant, and to investigate the scalability and implications in a larger context. For the objective, literature reviews were conducted. Building energy simulations and Life Cycle Assessment (LCA) were performed on a proposed design of an upcoming office complex to test the impact of those materials and various energy-saving strategies on the thermal performance of the building envelope, building energy performance, and reduction in initial carbon emissions. For the simulation, DesignBuilder v7.0 software, a graphical user interface to EnergyPlus v9.4, is used.

3. BACKGROUND

Stubble burning is the deliberate incineration of crop residue by farmers following crop harvest. These are cut stalks left on the field after cereal grains or sugarcane stems have been harvested [2]. Stubble burning is one of the world's major sources of air pollution, emitting particulate and gaseous pollutants that have serious consequences for human health and the environment [3]. Stubble burning of crop residues in India generates about 150 million tons of CO_2, more than 9 million tons of carbon monoxide (CO), 0.25 million tons of sulphur oxides (SO_X), a million tons of particulate matter, and more than 0.5 million tons of black carbon [4]. According to the Energy and Resources Institute (TERI), in 2012 ambient and household air pollution caused approximately 2.75 million deaths in the Southeast Asia region [5].

This problem can be addressed by finding alternatives to stubble burning such as incorporating their use in building materials made from rice cultivation and processing by-products. In this paper, we will discuss the use of three major resources present in form of waste in a rice processing facility, rice straws, rice husk, and waste heat from the turbine extraction of the biomass plant used to run the rice mills.

3.1 Straw – Ash Blocks

Out of 82 Mt surplus residues from the cereal crops, 44 Mt generated from rice cultivation each year in India is set to fire According to the Indian Agricultural Research Institute (IARI) [6]. This stubble in form of rice straws can be combined with fuel ash to prepare straw ash blocks in a composition of 60% Paddy straw, 28% Fuel ash, and 12% Binder [7]. These blocks have better thermal and acoustic properties in comparison to conventional burnt clay bricks. These blocks are about 5 times the size of clay brick in India, therefore requiring less mortar for masonry, water for curing the wall after construction, and reducing construction time, thus reducing the overall cost of construction. Table 1 shows the properties of straw-ash and burnt clay bricks.

Table 1:
Wall construction materials properties

Materials	Conductivity (W/m-K)	Specific Heat (j-kg-K)	Density ($kg/m^{3)}$)	Strength (MPa)
Straw-ash block	0.4	690	1400	7.5
Burnt clay brick	0.6	840	1800	7

3.2 Rice Husk Ash (RHA) Insulation

Rice husk is one of the most common agricultural wastes formed during rice processing. Because rice husk has a very low commercial value its disposal creates problems added by its transportation and handling problems due to low density [8]. About 200 kg of husk is produced for every 1000 kg of paddy milled, and when this husk is burned in biomass boilers, about 50 kg of RHA is produced [9]. In 2014 around 31 million tons of rice husk were produced in India resulting in the generation of 4.65 – 5.58 million tons of RHA. This RHA is currently being disposed of in low-lying areas and along roadsides, resulting in deterioration of ambient air quality due to low bulk density and posing health problems. The amount of RHA produced is significant, but it has not been put to productive use in any of the manufacturing processes [8]. However, RHA can be used for making building insulation in a composition of 88.28 wt % rice husk ash (RHA), 9.29 wt % of bentonite, and 2.41 wt % of exfoliated graphite. The thermal conductivity of this insulation is 0.0746 W/m-K [10]. It has the potential to be used as an insulation material to prevent heat loss or gain and also minimizes the negative environmental impact due to the open dumping of rice husk.

A building wall assembly can be made nearly the same thickness as a 230 mm conventional burnt clay brick wall assembly (Fig. 1) using Straw-Ash blocks and RHA insulation (Fig. 2) which can offer better thermal and acoustic performance. Additionally, the RHA insulation can be used to increase roof thermal performance (Fig. 3).

Figure 1:
Wall A (u value - 1.69 W/m^2-K)

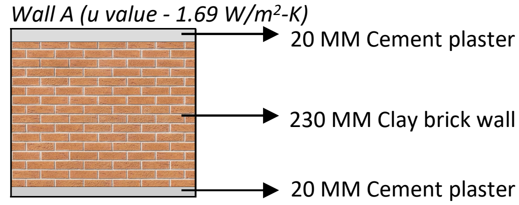


Figure 2:
Wall B (u value - 0.47 W/m^2-K)

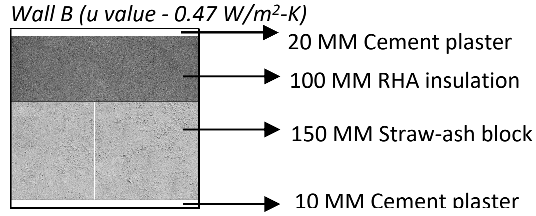
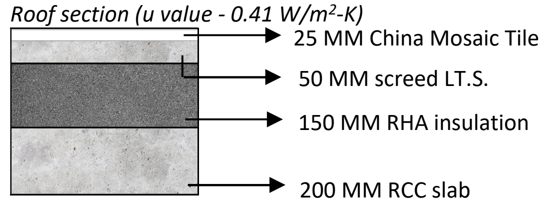


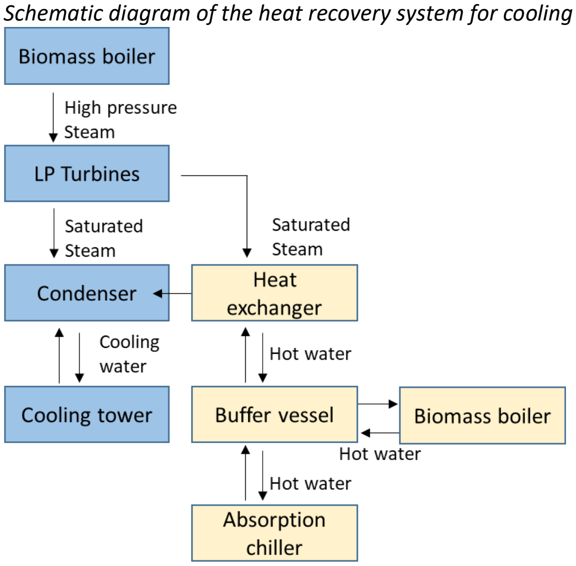
Figure 3:
Roof section (u value - 0.41 W/m^2-K)



3.3 HVAC System

Most rice processing plants use a direct combustion method for producing on-site electricity by burning rice husk in Biomass plants. Rice husk is used as a fuel in biomass plants to generate steam, which turns turbines and generates electricity. Waste heat in the form of steam extracted at low pressure (0.1 bar) from steam turbines can be used to heat water for running air conditioning systems as shown in fig. 4. Utilizing waste heat will also reduce the water loss in the condenser [11].

Figure 4:
Schematic diagram of the heat recovery system for cooling



For this purpose, a heat exchanger [12] can be introduced between the low-pressure steam turbine extract and the condenser through which water in the buffer vessel is heated up till 90-95°C temperature which is supplied to the generator of Low-Pressure Hot Water Absorption Chiller [13] for cooling water. The return water at a temperature difference of about 10°C is again pumped back to the buffer vessel. By storing heat, the buffer vessel improves system efficiency. The stored heat is used the next day to meet the generator's hot water demand while the biomass plant is starting up [14]. Additionally, a Biomass boiler that uses rice husk as fuel, can also be installed in a closed-loop circuit with the buffer vessel as a backup when the biomass plant is not working.

Utilizing waste heat as an alternative to electricity reduces equivalent carbon emissions happening during the production of electricity in thermal power plants.

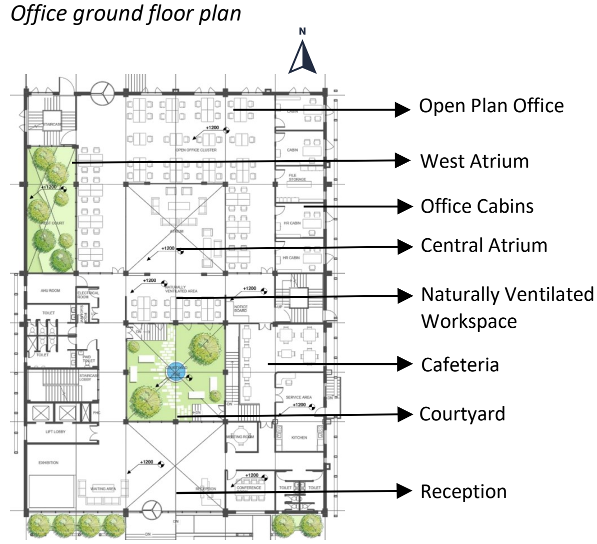
4. CASE STUDY

To explore the use of waste by-products (the materials and strategies mentioned above) and create a net-zero-energy building a 25-acre rice processing plant in the Karnal district of Haryana, India, was used as the case study. In this plant, a 3600 m² office building is planned. The site lies in the composite climate region in India (Max. Temperature of 45°C in summers and Min. temperature of 4°C in winters. The average annual rainfall is 582 mm). The planned office, in the proposed design, has an 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. A 3 MW on-site rice husk biomass plant serves the daily energy demands of the rice mill [15]. Subsequent subsections explain the proposed building design and its characteristics.

4.1 Architecture design

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. Narrow floor plates, linked by the atrium and courtyard, create an open and interconnected environment with ample natural light. The 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 highly occupied open plan office areas due to the low angle sun, the atrium and the core is planned at West and less occupied office cabins at East, respectively as shown in fig. 5. To reduce the cooling load, spaces like the R&D Department and a part of cafeteria seating are planned on the lower ground floor.

Figure 5:
Office ground floor plan



4.2 Building fabric & shading

The building fabric is designed to use the previously discussed materials (RHA insulation and Straw-Ash blocks) and is highly insulated, shown in Figures 2 & 3. The building structure is made of Reinforced Cement Concrete (RCC). Table 2 shows the fabric details.

Table 2:
Building fabric Details

Walls	U-Value = 0.47 W/m²-K
Windows	U-Value = 1.6 W/m²-K SHGC = 0.4, VLT = 0.74
Roof	U-Value = 0.41 W/m²-K

Shading devices are a key requirement in building designs in warm climates to minimize solar gains. Through an iterative process of optimizing the right shading design, consisting of Overhang, Louvers, 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 600 mm overhang, 400 mm side fins, and 400 mm louvers was used. For North and South windows, a 600 mm Overhang was proposed.

4.3 Lighting and equipment loads

The building is designed to have adequate daylight for the most part of the day. Lighting design and efficient LED fixtures were used to achieve an illuminance level of 300 lx at 800 mm above the floor. Total Lighting Power Density (LPD) achieved was 3.5 W/m². However, due to the integration of daylight sensors and Passive Infra-Red (PIR) occupancy sensors, total energy use for lighting was minimized.

Energy-efficient appliances were selected based on the Bureau of Energy Efficiency (BEE) energy rating scale in India. Taking realistic Plug and Process Loads (PPL) power capacities allows for more precise HVAC and electrical component sizing, which saves on operational costs. On average, the peak PPL energy use intensity for offices (without laboratories or data centres) is 0.5 $W/ft^{2,}$ whereas ASHRAE (2009) specifies a 1 W/ft^2 peak PPL energy intensity [16].

Table 3:
Plug and Process load details

Office & Meeting rooms	5 W/m²
Kitchen	30 W/m²
Circulation area	1.85 W/m²
Guest rooms	3.15 W/m²
Toilets	1.85 W/m²

4.4 Building services

Most of the building is mechanically ventilated and conditioned. The cooling system is driven by an absorption chiller utilizing waste heat from the biomass plant as discussed in section 3.3. In comparison to the typically used VRF systems in similar buildings, this absorption chiller-based radiant cooling system is more suitable for this building type due to the free heat available from the biomass plant and the very regular nature of building occupancy. In practice, a backup smaller biomass boiler (just to meet the building's space cooling requirements) is planned to run the system in case of the primary system is not available.

The chiller is supplying chilled water at a temperature of 14°C to the radiant slabs (with embedded 20 mm PEX pipes at 50 mm from the slab bottom) and is connected to a cooling tower for the supply of cooling water to the condenser.

The chiller is also supplying chilled water to the water cooling coil in the Variable Air Volume Air Handling Units (VAV-AHU) equipped with a heat recovery system. In summers the zones are supplied with pre-cooled fresh air at 16°C temperature to meet the latent cooling loads, whereas, in the winter, it meets the fresh air requirements based on occupancy. Toilets have dedicated mechanical exhausts.

The office area planned between the atrium and the courtyard is cooled through Natural ventilation. Night cooling strategy is adopted to let the thermal mass cool overnight. The operative temperature for a naturally ventilated building in Delhi which also lies in composite climate is 30.68°C. The 90% acceptability range for adaptive models in India is ± 2.38°C [17]. Additionally, ceilings fans are provided to increase air velocity and the cooling thermal sensation [18]. The temperature increases of 2.5–3.5 C, for temperatures up to 31.0 C, can be compensated for with 0.7–1.0 m/s air velocities while maintaining the thermal comfort sensation [19, 20, 21].

4.5 Building occupancy and operations

The building is running six days a week and eight hours a day from 7:00 to 19:00 with diversified usage patterns. The total number of full-time occupants are 270. The occupancy, equipment, and lighting schedules follow the same typical profile. (Table 4) shows the thermal comfort parameter settings. 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.

Table 4:
Thermal Comfort parameter settings

Office cooling Set point temperature	25°C
Circulation area cooling Set point temperature	26°C
Summer Operative Temperature Range	23-26°C
Minimum Fresh Air	10 l/s

5. SIMULATION RESULTS

Through the entire design process, iterative simulations were done while changing one parameter at a time for the reduction in the annual EPI of the building to achieve the net-zero target. The EnergyPlus weather file used is of Hisar, Haryana which is 172 km away from the site. Table 5 and Fig. 6 shows the various iterations performed for a subsequent reduction in EPI.

Table 5:

Iterations done to reduce the EPI

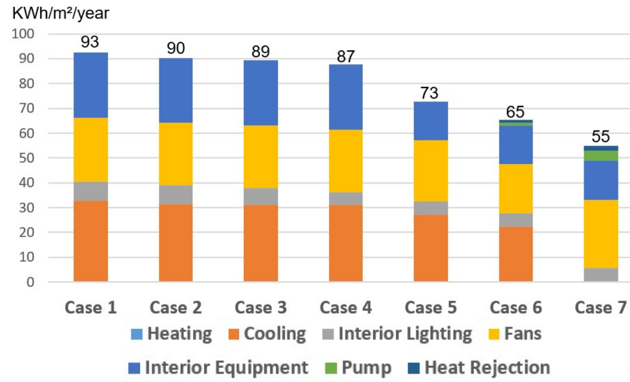
Cases	Wall U value	LPD	PPL	AC System	EPI
Case 1 Base case	1.69	5	11	VRF system + DOAS	93
Case 2 Wall Optimisation	0.47	5	11	VRF system + DOAS	90
Case 3 Window shading	0.47	5	11	VRF system + DOAS	89
Case 4 Efficient lighting	0.47	3.5	11	VRF system + DOAS	87
Case 5 PPL reduction	0.47	3.5	5	VRF system + DOAS	73
Case 6 Radiant cooling	0.47	3.5	5	Radiant cooling + DOAS	65
Case 7 Absorption Chiller using waste heat	0.47	3.5	5	Radiant cooling using Absorption Chiller + DOAS	55

Note: Wall U-Value *(*W/m²-K*)*, LPD (W/m²), PPL (W/m²), EPI (kWh/m²/year)

The roof and glazing U-Values were kept constant throughout the iterations as described in table 2. First, the base case was simulated using conventional burnt clay brick wall envelope (shown in Fig. 1), VRF system with Dedicated Outdoor Air System (DOAS) for air conditioning, equipment, and lighting load to be 11 W/m^2 and 5 W/m^2, respectively. The annual EPI was determined to be 93 kWh/m^2. In case 2 the EPI was then reduced to 90 kWh/m^2/year after the burnt clay brick wall envelope was replaced with the wall assembly made of Straw-ash blocks and RHA insulation (shown in Fig. 2) with all other parameters remaining unchanged. In case 3, the east and west windows were shaded, resulting in an EPI reduction of only 1 kWh/ m^2 /year as the East façade has a WWR of 15% and no windows on the West except for the Lift lobby and staircase. However, shading windows reduces glare and, eventually cooling load in the cabins. In case 4, by the use of efficient lighting fixtures, the lighting load was reduced from 5 W/ m^2 to 3.5 W/ m^2, resulting in an EPI reduction of 2 kWh/m^2/year. Following that, in case 5, the ASHRAE-specified PPL energy intensity of 11W/m^2 was changed to 5 W/m^2, resulting in an EPI of 73 kWh/m^2/year. The reduction in PPL energy and Lighting load resulted in a significant reduction in cooling load. In case 6, for reducing cooling energy consumption, the VRF cooling system was replaced with a Radiant cooling system driven by a Water Cooled Screw Chiller, resulting in an 8 kWh/m^2/year EPI reduction. Followed by case 7, where an absorption chiller was used instead of the electric chiller to utilize waste heat from the biomass plant, resulting in a final EPI of 55 kWh/m^2/year.

Figure 6:

Annual EPI breakdown



In the naturally ventilated office area, the operative temperatures are at or below 31°C for 67% of the total occupied hours in summers (April to September), in case 7.

The Global Warming Potential factor (GWP) emission factors for Straw-Ash blocks and burnt clay bricks are -0.2 $kgCO_2/kg$ and 0.57 $kgCO_2/kg$, respectively. Emissions factors are taken from manufacture provided data and the IFC Database of Indian construction materials [7, 22]. Emission factor for RHA insulation is assumed to be 0 $kgCO_2/kg$ as it consists of 88.28 wt % rice husk ash (RHA) which is a carbon-negative material [23].

A Cradle to Gate Life Cycle Assessment (LCA) is performed as approximately 80% of initial EC can be reduced before construction commences [24]. The assessment revealed a significant drop in Embodied Carbon (EC) by approx. 48% while replacing wall envelope 'Wall A' with 'Wall B'.

6. DISCUSSION AND CONCLUSION

India has about 1,74,000 rice milling units [25]. These building technologies can be implemented at these rice mills for building net-zero energy buildings around them. Also, these building materials are found to be more efficient in terms of cost, durability, and thermal performance with a negative carbon rating.

In India, the annual production of bricks is around 250-300 billion bricks per annum and these numbers are expected to reach 750 - 1000 billion bricks/year in the next 20 years. Around 85% of these bricks are burnt clay bricks. In India, 0.75 billion m^2 of built-up area is expected to be added each year [26]. This emphasizes the importance of using non-fired bricks to replace burnt clay bricks to reduce GHG emissions and topsoil depletion. Annual production of Rice straws and RHA as discussed in sections 3.1 and 3.2, respectively, is capable of replacing a significant amount of burnt clay bricks from the construction industry if used to make construction materials.

The straw-Ash blocks provide better thermal and acoustic insulation than the burnt clay bricks but are weak in showing thermal mass effect because of their low specific heat capacity. Although RHA insulation being a carbon-negative material has promising properties to be used as insulation having a K value – 0.07 W/m-K, However, no information is available about the specific heat capacity or density, which can have an impact on envelope weight.

Additionally, the absorption chiller based radiant cooling system combined with DOAS is found to be more efficient than the VRF system with an EPI difference of 18 kWh/m^2/year between Case 5 and Case 7. A high reduction in cooling load is observed with an increase in fan and heat rejection energy consumption. The high water consumption in the cooling tower can be a concern at locations with low water table.

The final EPI of the building is calculated to be 55 kWh/m^2/year which falls under the GRIHA benchmark for commercial buildings in composite climate [27]. The installed 3 MW biomass plant, using the biomass from the rice mill meets the daily energy demands and enables the building to run in net-zero energy mode.

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