Finishing with net-zero: A case study of the energy systems in an experimental building

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Abstract

Net-Zero Energy Buildings are crucial to addressing climate change in the building sector (IEA, 2019) and catalysing India's goal to achieve net-zero by 2070. An experimental building (EB) in Bengaluru is a testbed for technologies and approaches that can help optimize energy to achieve net-zero performance in other similar buildings. This paper provides a case study of the EB and discusses the evolution of its energy systems and whether the goal to remain net-zero was maintained through this evolution. Since continuous commissioning was not conducted, the evolution of the project requirements thwarted the net-zero goal. Addition of a high-energy consuming lab and a kitchen increased the loads of the building and altered the way the energy would be used. Post-construction studies emphasised the need for continuous monitoring and highlighted specific action items that could restore the EB to perform as net-zero.

Key Innovations

The key innovations in this paper include

- A prototype building for a larger campus where experimentation on the energy systems is conducted.
- A calibrated model that enabled the identification of monitoring equipment flaws.
- An intelligent open-source Operating System that prioritizes energy profiles to ration power during grid failure.

Practical Implications

This paper highlights the need for continuous commissioning for net-zero buildings to include simulations and monitoring through the design, construction, and operation stages of a building.

Introduction

Globally, buildings contribute to 38% of greenhouse gas emissions (IEA, 2019). At COP26, India set an ambitious goal to become net-zero by 2070 and increase renewables in its energy mix to 50% by 2030 (Reuters, 2021). Net-Zero Energy Buildings (NZEBs) can help this effort and catalyse India's net-zero energy transition. In India, NZEBs are currently at a nascent stage. There is a lot to be tested and learned to ensure optimal performance, while also providing comfort across climatic conditions.

A 54-acre educational campus in the temperate climate zone of Bengaluru is planned. The campus will demonstrate innovation in sustainable built environments with net-zero energy-water-waste solutions. A 470 sq.m. experimental building (EB) is constructed as a campus development office, and as a prototype to test the technologies and approaches that are intended for the larger campus (see Figure 1). From its inception, the building design explored strategies for energy efficiency, provision of thermal comfort, and reduction of embodied energy, while documenting the processes, costs, and performance of these approaches. In the EB, there are four energy systems: 1) the envelope system, 2) the equipment and appliances, 3) the renewable energy (RE) system, and 4) the cooling system. An Internet-of-Things (IoT) approach is used for the monitoring system to collect data, measure performance, and support intelligent decision making.

Figure 1: The Experimental Building

The EB was initially intended as a 287 sq.m building with some office spaces and a conference room. Over time, the use of the building expanded. A kitchen and an environmental lab were added, which included significant equipment loads. These changed the energy requirements of the building. This is common in buildings where their uses evolve, and change their energy use (Mohamad Zamhari Tahir, 2015). But, as net-zero energy buildings attempt to use energy efficiently and frugally to balance consumption against limited on-site renewable energy generation, such changes affect their net-zero performance. Continuous commissioning is a quality assurance process in the design, construction and operation of high-performance buildings that monitors how project requirements, design, construction, and actions affect the project goals (ASHRAE, 2014). It provides multiple strategic touchpoints for an integrated multidisciplinary team to evaluate the impact of decisions based on cost and performance analysis. In the EB, continuous commissioning was not performed. However, multiple post-construction studies were conducted to analyse its performance.

This paper will provide a case study of the EB, an intended NZEB in a temperate climate. It will highlight the main learnings about the energy systems in the building over 2 years. The energy systems will be discussed in 3 stages (see Figure 2): (i) initial project requirements set based on the net-zero goal, and the design response; (ii) the evolution in project requirements and the design response; and (iii) learnings from post-construction studies. The paper will describe how these changes impacted the net-zero goal of the EB and the key takeaways. These lessons will be useful for other proposed net-zero energy buildings.

Figure 2: Evolution in requirements and design response

Energy Systems in the EB

Envelope systems

The EB was initially planned as a 287 sq.m NZEB that uses low embodied energy materials and provides adequate thermal comfort to the occupants. The design response for the building envelope was, insulated assemblies with low U-value and low-embodied carbon building materials, and fully airconditioned spaces. Since the EB is meant to be a prototype for experimentation, three different insulated wall assemblies were tested: Compressed Stabilized Earth Blocks (CSEB), Rammed Earth (RE) and Autoclaved Aerated Concrete (AAC). China mosaic and granite were used for cladding. The walls were insulated with 50 mm XPS. As the project requirements evolved, the area of EB was expanded to 470 sq.m. and included spaces such as a kitchen and an environmental lab. In addition, a decision was made to operate the building in mixed mode, and maximize natural ventilation, with only 30% of the spaces air-conditioned.

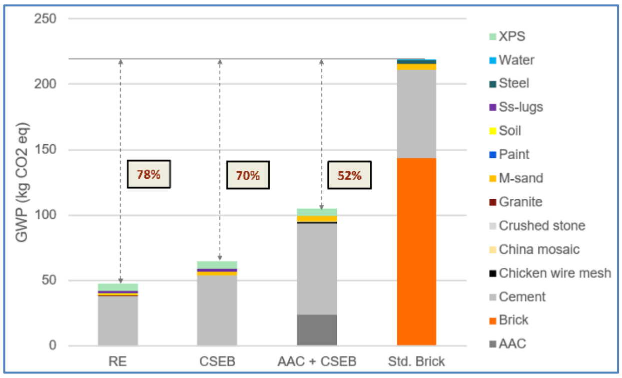

Figure 3: Results from the Life Cycle Assessment

We conducted multiple post-construction studies to measure the performance of the envelope systems. Through a Life Cycle Assessment, the embodied carbon of the envelope systems in the EB was calculated and compared with the embodied carbon of a typical construction of fired brick and plaster. The study showed that the 3 wall assemblies reduce embodied carbon by 52% to 78% (see Figure 3).

We built a calibrated Energy Plus model of the EB, with inputs from as-built drawings, data from an energy audit, Actual Meteorological Year data from a weather station and occupancy schedules from the attendance logs. The simulation outputs from the model were then compared with the data collected by the IoT sensors in the building. Over several iterations, Root Mean Square Error and the Mean Bias Error were brought down to 17% and 10% respectively. When the calibrated model was compared with the baseline brick and plaster construction, the results showed that insulated wall assemblies alone reduced the operational energy by 11%. During the process of calibration, the simulated indoor air temperature was observed to be about 3ºC lower than the measured indoor air temperature. This was true even during unoccupied hours at night when equipment loads were at a minimum. To investigate the source of heat in the space, a thermal imaging camera was used and it was discovered that the IoT Box that housed the temperature sensors contained power supply components that generated heat and increased the air temperature readings of the sensors (see Figure 4).

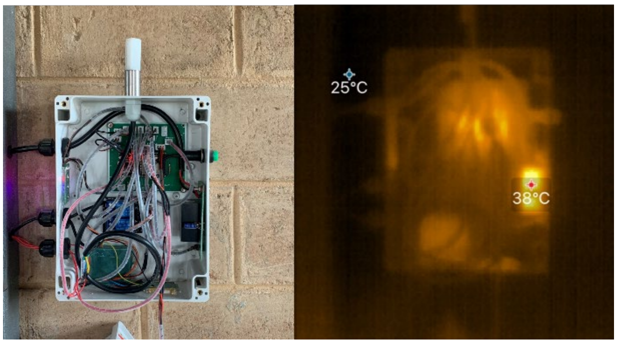

Figure 4: Thermal imaging of the IoT box

It was also found that the probe that measured indoor surface temperature was exposed and uninsulated and was affected by the air temperature.

The calibrated model was used for a cost-benefit analysis of the wall systems. The capital cost of insulating all the buildings on the 55 acres campus is estimated at over £0.5 million. In the lifecycle cost analysis, the utility costs, social cost of carbon, capital costs and maintenance costs were included for 50 years. The results showed that insulated walls had a lower Lifecycle Cost if the building was fully air-conditioned, whereas a mixed mode operations showed a higher Lifecycle Cost for the insulated walls (see Figure 5).

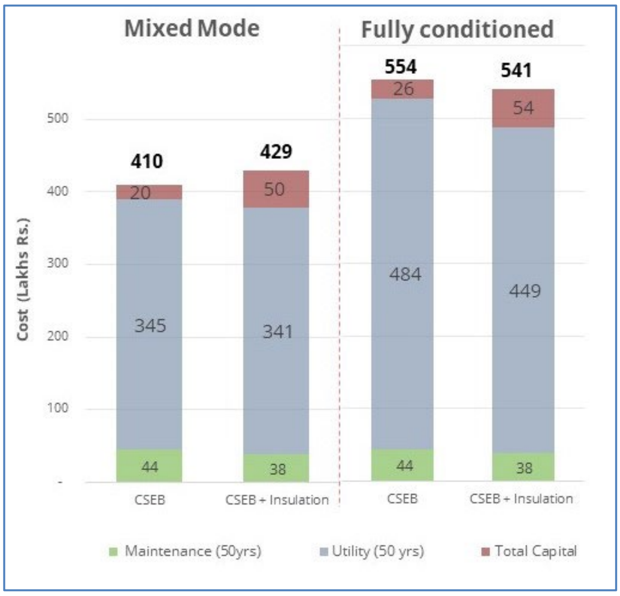

Figure 5: Results from the Cost Benefit Analysis

Equipment and Appliances

The project requirement was to use energy efficient equipment and appliances and keep the loads at a minimum. As a design response, LED lights and Bureau of Energy Efficiency star-rated appliances were used.

Table 1: Increase in EPD in the revised design

	Initial design	Revised design
Lighting Power Density (LPD)	2.5 W/m2	2.5 W/m2
Equipment Power Density (EPD)	16.1 W/m2	53.9 W/m2

The addition of the lab and kitchen revised the project requirements to include more equipment such as a visicooler, autoclave, refrigerator, bain marie and hot-water kettles. This increased the equipment power density significantly (Table 1). In addition, the new requirements included some critical loads such as the IoT servers, and refrigeration equipment in the lab and kitchen that need to be operated for all 8760 hours of a year.

The post-construction energy audit identified high power-consuming equipment such as bain marie and hot water kettles that rated 4.7 kW and 1.8 kW respectively. These were suggested to be replaced with low-energy alternatives like insulated food warmers that consumed no energy and smaller kettles of 0.5 kW. The energy audit also included operational power in addition to the rated power of the equipment, and it provided the load profiles of this equipment. This information was used in the calibrated model. In a study to prioritize the loads in the EB during island mode, i.e., unavailability of grid power, the load profiles of the equipment and appliances were analysed and categorized based on how critical their operation is. Continuous data coming in from the sensors will be used to make decisions about how power will be rationed, and loads will be optimized.

Renewable Energy (RE) System

To balance the EB's annual energy consumption estimated through simulations during the design stage, the net-zero operation required a 6 kWp solar PV array. This was installed along with a 14.8 kWh battery and a 12 kW inverter to sustain the building during grid failure. Net metering was assumed, and excess energy was to be transported back to the grid.

Several issues related to the RE system have resulted in a non-net-zero performance of the building. The output of the PV is lower, and peaks at 4 kW. The EB is currently running on a temporary electricity connection, for which the utility company does not support net-metering. As a result, when the on-site demand is met and the battery is fully charged, energy export is not possible. During this condition, the PV system cannot produce any energy.

The inverters are programmed such that when there is no grid power available, the RE system first charges the battery, and supplies power to support the loads in the building. However, during nights when there is no generation from the PV, the loads are supplied from the battery instead of the grid, and this causes the battery to discharge 3 times each night.

The energy audit also showed the increased energy consumption of the building, and that the PV system needs to be expanded for a net-zero operation.

The next steps are to add more PV capacity and programme the inverters to give the grid priority over the battery to supply the loads.

Cooling system

The project requirement for the cooling system is to provide thermal comfort to the occupants using efficient and cost-effective methods. The initial response was to air-condition the entire building after including insulation in the walls and roof. Later, however, on the one hand, additional cooling loads were added by the increased equipment, and on the other hand, it was decided that many parts of the building would be naturally ventilated (assisted with fans) with no air-conditioning. The building was thus operated in mixed mode.

The energy audit showed that the electrical load of the HVAC equipment was 6.8 kW, accounting for 19% of the total operational power of 34.1 kW. Currently, 24% (113 sq.m) of the EB floor area is air-conditioned using 9 tons of refrigeration, with a Coefficient of Performance of 3.52. In conditioned spaces, the air temperatures have been maintained at 26ºC.

The calibrated model simulations showed that the naturally ventilated spaces fall within the comfort band of the India Model for Adaptive Comfort (National Building Code of India, 2005), 93% of the year (see Figure 6). The results also show that the Operative Temperature (OT) of the insulated building is maintained 1ºC to 2ºC lower than in the uninsulated case. The difference is greater when the outdoor air temperatures are higher. Currently, machine learning algorithms are being explored to predict the OT within each thermal zone, to maximize the use of natural ventilation with ceiling fans for thermal comfort while reducing or eliminating the use of air-conditioning. This can be done by adjusting the OT for the effect of air-speed resulting from the fans, as well as by shifting the adaptive thermal comfort band upward to account for the air-speed (CBE, 2022).

3 wall systems), the counterfactual base case also needs to be included. In the case of operating energy and thermal performance, calibrated models allow setting up of the base case. However, for other aspects such as embodied energy and building performance, a physical base case is necessary. Thus, experiment design, data collection methods, baseline cases, and protocols of analysis all need to be determined in advance to make an experimental building truly successful.

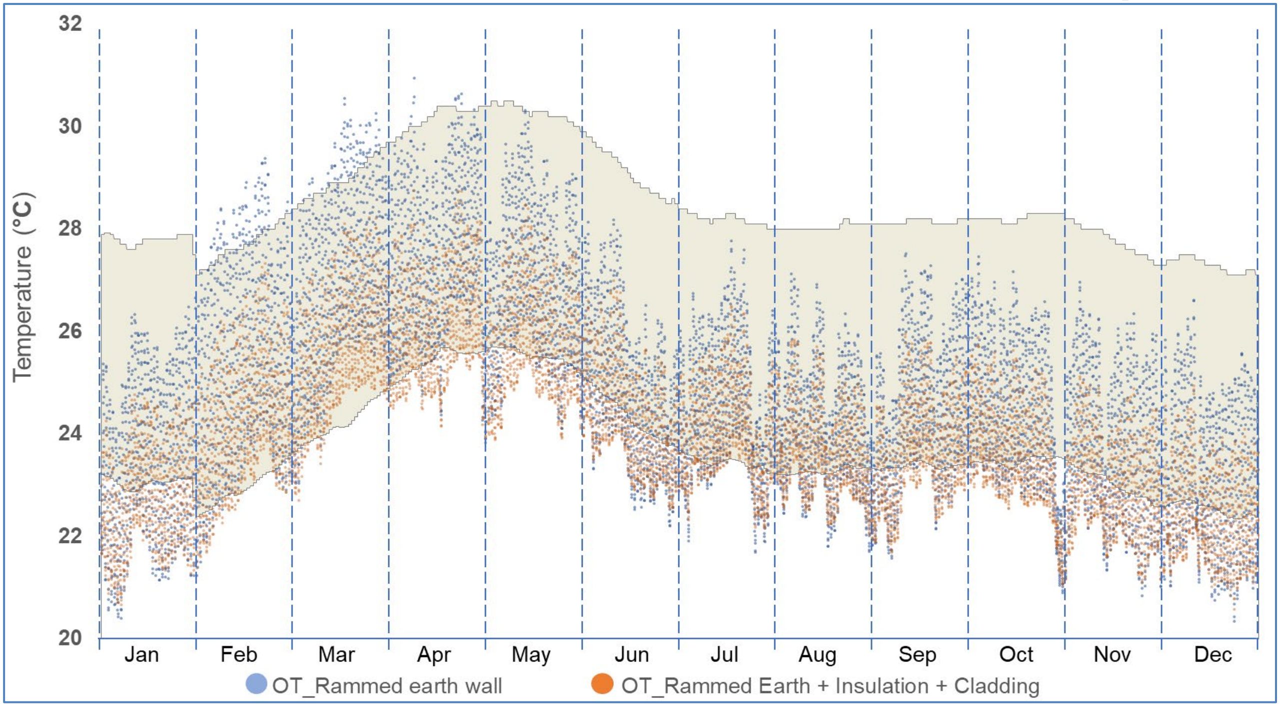

Figure 6: Operative Temperature in insulated and non-insulated wall assemblies

Discussion

The learnings from the EB can be discussed is 5 parts:

1. Low embodied carbon and net-zero energy

In the EB, other than exploring low embodied carbon approaches, there was no quantitative goal for reduction of embodied carbon. However, the results show that a 50% reduction for walls can be a realistic goal. With additional analysis, similar quantitative goals can be set up for other building systems in the other buildings on campus. Further, changes in building function and operation do not affect the embodied carbon savings. Therefore, the embodied carbon goal seems easier to meet and would not require continuous tracking.

Changing the use of a building affects its operational energy, and the net-zero goal. Without continuous commissioning that tracks the operational energy use in the building and the renewable energy output, net-zero energy performance can be compromised easily. During the design stage, this should be done with simulations, and in the operation stage it should be done through continuous monitoring of energy and loads.

2. Experiment design for an experimental building

An experimental building needs to be designed to be suitable for experimentation. This means that other than designing for the building function, the experiment design needs to be reflected in the building systems and their set up. Other than the proposed innovation (in this case, the

3. Value of energy audit

A detailed list of equipment and their load profiles clarifies the energy consumption pattern of the building. During the design stage, hourly consumption profiles based on discussion with users can be useful for grid interactive and net-zero buildings. This granularity of loads is often not available from design stage energy simulations. The energy audit in the EB was conducted to answer the question of whether onsite generation and storage were adequate for operating the building during grid failure, and the answer was 'no'. It also helped to develop a detailed calibrated model of the building. Now, the audit information of the EB is being used to develop load profiles for critical scenarios for islanding the building and as a demand response strategy.

4. Value of simulations and calibrated models

Simulations and calibrated models can answer several questions ranging from the cost-effectiveness of materials to the thermal comfort assessment of passively cooled building. In the design stage, they can help optimize the building envelope, lighting, equipment, and cooling systems. In the operation stage, calibrated models can provide benchmarks for daily, monthly, and annual energy consumption. These benchmarks could be far more useful in the case on highly efficient net-zero buildings, than the traditional benchmarks based on historical data of a comparable building stock. As in the case of the EB, comparison with simulated results can also provide fault detection clues for measurement equipment and energy using equipment.

5. Value of long-term monitoring

Long-term monitoring of a building helps in determining its net-zero performance. It helps to develop calibrated models that can be used to answer critical questions about building performance. In the EB, continuous monitoring helped with experimentation and developing new methods for the islanding approach and comfort. Monitoring also helps in identifying anomalies in the system, for instance the 3-time battery discharge in the EB at night.

Conclusion

This paper provides the main learnings from the energy systems of an intended net-zero energy EB. While the initial project requirements intended for the building to be net-zero, the evolving uses altered its path. The building, however, proved to be a good testing ground for innovative approaches and technologies towards achieving net-zero performance. Post construction studies such as an energy audit, a calibrated model and a cost-benefit analysis were conducted. They helped identify problems in the technologies, systems and processes implemented. They also proved the importance of conducting continuous commissioning and long-term monitoring across building design, construction, and operation stages to ensure that the building is on-track to achieve project requirements. The learnings from the EB will be useful while implementing innovative approaches for the larger net-zero campus.

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