Case Study Title:

As-built building photograph (Please insert only one representative picture in a landscape format, 300 dpi, JPEG)

Project Name	CEPT NZEB: A Living Laboratory
Location	Ahmedabad, Gujarat, India
Climate Zone	**ASHRAE**: Hot-Dry (comparable to *ASHRAE Climate Zone 3B*) **Köppen**: BSh (Hot Semi-Arid Climate)
Latitude/Longitude	23.033°N, 72.566°E
Building Type	Research Centre and Laboratory
Floor Area [sqm]	802 m^2
Building Height [m]	6.9 m
Number of Storeys	Four (Basement + Ground + First + Mezzanine)
Completion Year	March 2015
Project Team	**Project Concept, Execution management and Project Facilitation:** CEPT University USAID ECOIII Project team **Design Development** Vastu Shilpa Consultants **Energy Analysts and Lighting Consultants:** The Weidt Group, USA (NZEB - Energy consultant) Clanton & Associates, USA (Lighting consultant) **Services Consultants:** Pankaj Dharkar Associates (MEP)

	Antech Consultants (Electrical) VMS Consultants Pvt. Ltd. (Structure) **Execution and Implementation Team:** Tripur Builders (Civil and Interior Works) Yogi Engineers (HVAC Contractor) Infinity Technologies (BMS Contractor) Deep Electricals (Electrical Contractor) **Material and Technology Partners:** Owens Corning India (Insulation Systems) Pidilite Industries Ltd. (Sealants and Adhesives) SGL Carbon Pvt. Ltd. (Carbon Panels) Shashwat Cleantech (Renewable Integration Support) Volpak Systems Pvt. Ltd. (Mechanical Systems) **Institutional and Program Support:** USAID ECO-III Project Gujarat Energy Development Agency (GEDA)

*mock-up experiments and other research-based experiments could be included as case study, aside from actual building construction projects if similar information could be provided.

1. Project Description

Project Overview

1. **Project Background**
   CEPT NZEB: A Living Laboratory was conceived as an experimental building and living laboratory to house state of art building performance R&D facilities. It is designed to provide diverse thermal, aural and visual experience to the occupants and visitors. the integrated design process based on design charrettes was followed, involving international experts and local consultants from the domains of architecture, mechanical, electrical, plumbing, structural design, construction and facility management. Completed in March 2015, the facility accommodates building material characterization, thermal comfort and low-energy cooling test beds and workspaces for researchers and scholars. The building was designed for an Energy Performance Index (EPI) of **27 kWh/m²-year**, targeting an **85% reduction** compared to conventional university buildings.

2. **Passive Cooling Interventions**
   Passive design principles underpin the NZEB's thermal performance. The building has a 3:1 aspect ratio, oriented along the east–west axis with no openings on east and west façades and an optimized avg 26% window-to-wall ratio. It has 30% window ratio on south and 80% to the north. Approximately 28% of the total floor area lies below ground, providing subterranean thermal buffering that limits heat ingress. The envelope assembly, comprising externally insulated high-mass walls and a high-SRI (103) reflective roof, moderates diurnal temperature swings. South-facing 30° sloped roofs with operable 450 mm clerestories enable stack ventilation and daylighting, supported by cross ventilation through courtyards, maintaining indoor conditions within 26–30 °C.

3. **Project Achievements**
   The building achieved an annual Energy Performance Index (EPI) of 25.4 kWh/m²-year, confirming its net-zero energy status (2015 -2025). Its east–west orientation, 3:1 aspect ratio, and 26% WWR, with external shading, reduce envelope heat gain by 20% compared to ECBC 2017 baseline.

Daylight autonomy exceeds 70%, minimizing artificial lighting loads. A 30 kWp rooftop photovoltaic system offsets the building's annual electricity consumption, from 9.5% (monsoon) to 59.4%(winter).
Radiant cooling, VRV air-conditioning, and a dedicated outdoor air system (DOAS) with heat recovery complement passive strategies on each floor. As building operational strategy, over 400 sensors including temperature, humidity, CO_2, and illuminance are networked via SCADA-based BMS, with a rooftop weather station and IEQ meters on the first and mezzanine floors; all data streams to a central control room for real-time diagnostics, optimization, and IAQ/IEQ management, informed by regular post-occupancy surveys.

2. Climate & Site Context

Basic Climate Conditions		
Temperature	Annual Average	29.11°C
	Annual Range	5°C (January) – 45°C (March–June)
Relative Humiditiy	Annual Average	55%
	Annual Range	20% (March) – 85% (July–August
Annual Degree-Days (ASHRAE Standard 169-2020)		HDD 18°C: 5 CDD 10°C: 6500

Climate Analysis

Please describe the climate analysis for your project site. (e.g., temperature, wind, solar radiation, humidity, etc.) [Max 150 words]

Ahmedabad experiences a hot semi-arid climate (Köppen BSh) with three predominant seasons: Summer (March – June), Monsoon (mid-June – September), and a mild winter (November – February). During summer, the average maximum temperature is 45 °C and the average minimum 23 °C; in winter, the average maximum is 30 °C and the average minimum is 15 °C, with extremely dry air. Cold northerly winds bring a mild chill in January, while south-westerlies dominate the monsoon, introducing humidity and occasional heavy rainfall. Relative humidity varies from 20 % in dry months to 85 % during the monsoon, with annual rainfall near 760 mm, concentrated in the southwest monsoon. The recorded extremes are 47 °C (May) and 5 °C (January). The combination of intense solar radiation and high diurnal temperature swing makes orientation, external shading, reflective surfaces, and thermal mass critical passive-cooling strategies..

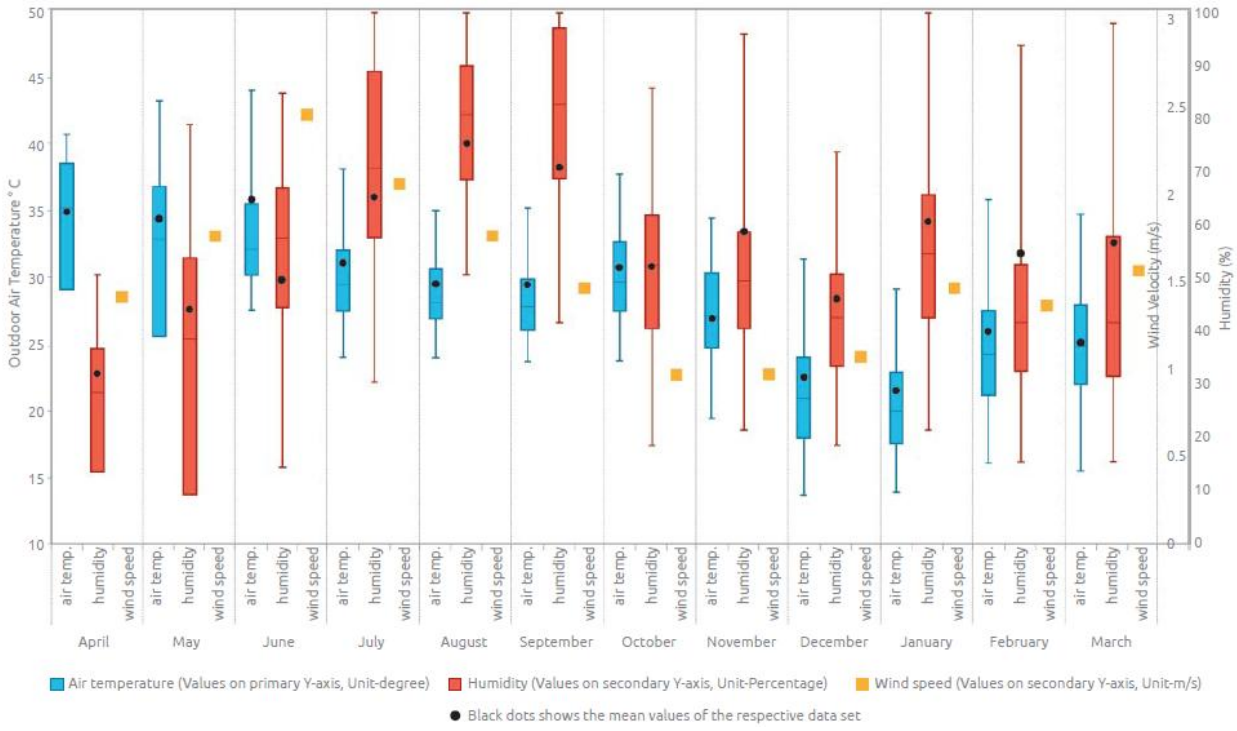


Figure 1 : Monthly Temperature, Humidity and Wind speed from weather station at CEPT University Campus in Ahmedabad for Apr2014 – Mar 2015 (Rawal, Vaidya, Manu, & Shukla, 2015)

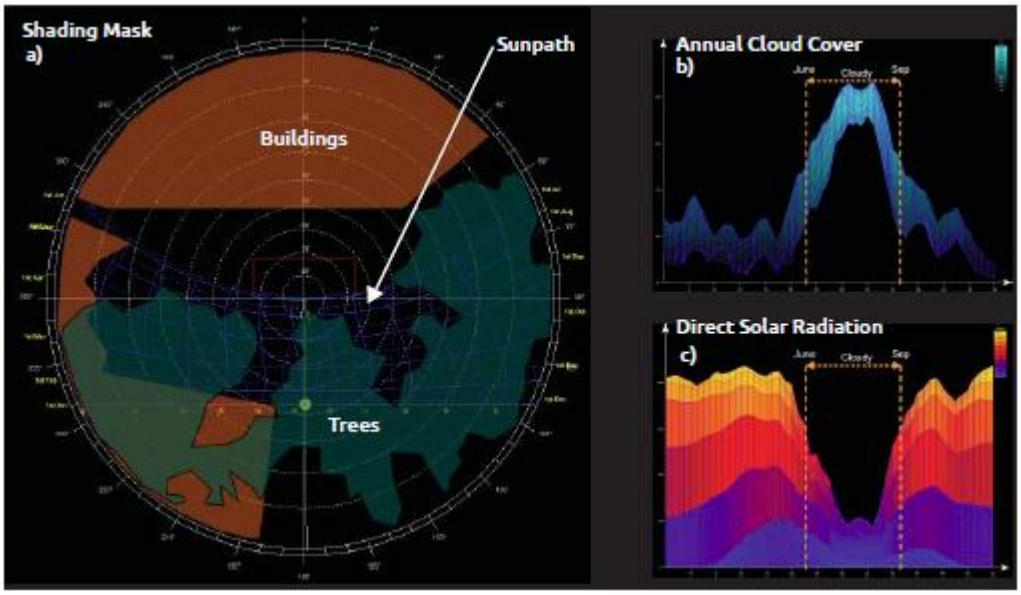


Figure 2 : Climate analysis: a) Sunpath Diagram b) Solar Radiation and c) Cloud-cover (Vaidya & Ghatti, 2017)

Site Analysis

Please describe project site conditions that inform your building design (e.g., topography, building density, landscaping, etc.) [Max 150 words]

The NZEB at CEPT University is sited on a flat, well-drained plot within the Kasturbhai Lalbhai campus, Ahmedabad, characterized by a hot semi-arid climate (Köppen BSh). Approximately 28% of the building's floor area is below grade, leveraging the earth's thermal mass to buffer heat gains and reduce cooling demand. The building has an east–west orientation, with its longest façades facing north and south. This orientation reduces solar exposure while optimizing daylight penetration, guiding the design and placement of clerestory windows, light shelves, and external shading devices. Adjacent low-rise structures and landscaped open areas preserve natural ventilation corridors, supporting mixed-mode ventilation strategies. Peripheral trees and courtyards mitigate reflected heat and dust infiltration, guiding façade articulation and fenestration design. The site conditions, coupled with iterative energy analysis and predesign evaluation of passive and active strategies, enabled targeted interventions to optimize daylighting, reduce heat gains and ensure occupant comfort.

Figure 3 : NZEB floor plans and sections

3. Passive Cooling Design Details

Passive Cooling Strategies (please tick implemented passive cooling strategies)
☑ Building Orientation & Form (site orientation, building shape, etc.) ☑ Envelope Design (insulation, air-tightness, shading, window system, thermal mass, etc.) ☑ Natural Ventilation (cross ventilation, stack ventilation, night ventilation, etc.) ☐ Evaporative Cooling (direct/indirect evaporative cooling, etc.) ☐ Ground Cooling (geothermal, ground-coupled systems, basement/underground space,etc.) ☑ Radiative Cooling (cool roof, night sky radiation, radiant barriers, reflective surfaces, etc.) ☑ Nature-based Solutions (green roof/wall, tree shading, etc.) ☑ Others (human behavior, clothing, semi-passive (fans, etc.)
Description (please describe one strategy per box – you can add more boxes below if needed)

Please describe the feature of the adopted passive cooling strategies [Max 200 words]

1. Building Orientation & Form

- Aspect ratio: 3:1 (East – west orientation)
- Window-to-wall ratio (WWR): 26% overall; north elevation ~80% WWR, south ~30%, with no windows on east or west facades
- 30 kWp SPV system on south-facing roof

The building is oriented along an east–west axis so primary façades face north and south, minimising low-angle solar exposure on east/west facades during peak hours. A 30° inclined south-facing roof with 450 mm operable clerestories at two levels enhances daylight penetration, induces stack ventilation, and provides an optimum angle for Solar Photovoltaic (SPV) installation. The 30 kWp SPV array shades the roof surface through a 450 mm ventilated cavity and supplies renewable electricity to CEPT's internal grid, monitored via BMS. Sub-grade floor area (28% of total; 40% of conditioned area) reduces heat ingress and the indoor air temperature is maintained mostly between 26–30°C, within the 80% India Model for Adaptive comfort band (as per National Building Code), ensuring thermal comfort for occupants.

2. Envelope Design

- Superstructure Walls: 110 mm exposed brickwork (outer layer) + 50 mm XPS insulation (external) + 230 mm internal masonry wall; reported U = 0.42 W/m²·K.
- Substructure (Basement) Walls: 230 mm RCC with waterproof plaster on the exterior
- Roof: 150 mm RCC slab with 45 mm spray-foam (PUF) insulation + geotextile sheet + 50 mm concrete screed + high-SRI white coating (SRI = 103); reported U = 0.38 W/m²·K.
- Windows: uPVC framed double-glazed low-E DGU (AIS Ecosense Exceed – Clear Vision); reported U = 1.8 W/m²·K, SHGC = 0.29, VLT = 0.39; deep overhangs integrated for solar control.
- Peripheral Beams: Internally insulated with 100 mm XPS. to maintain envelope continuity and reduce thermal bridging.
- Floor (Exposed Underside): 150 mm RCC slab with 50 mm XPS insulation and FEWEIS external finish; reported U ≈ 0.55 W/m²·K.

This envelope architecture leverages high-performance insulation, added thermal mass, and precise solar control to reduce conductive and radiative heat gains. Combined with strategic window placement and shading, these passive cooling strategies lower peak cooling loads by stabilizing indoor temperatures and minimizing solar heat ingress. As a result, the building operates efficiently in natural and mixed ventilation modes, reducing HVAC energy demand and enhancing occupant thermal comfort according to the India Model for Adaptive Thermal Comfort (IMAC).

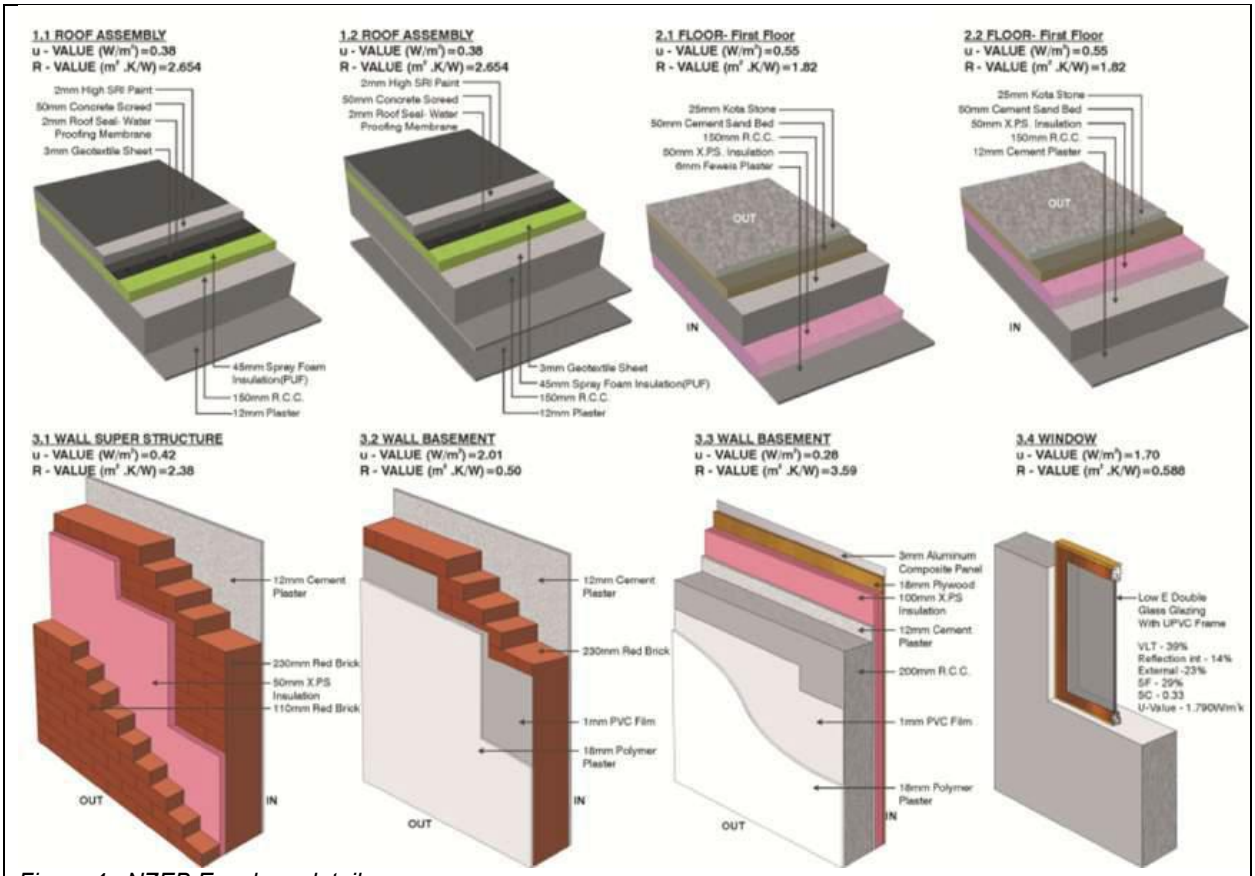
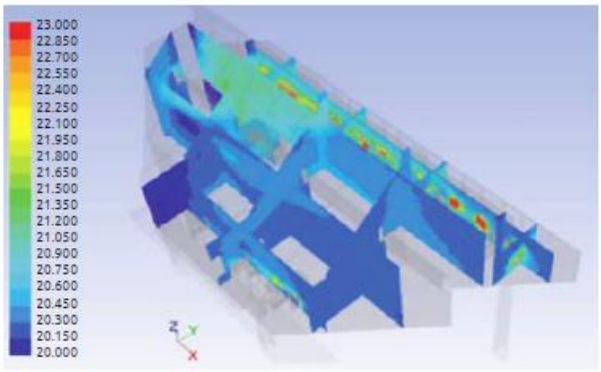


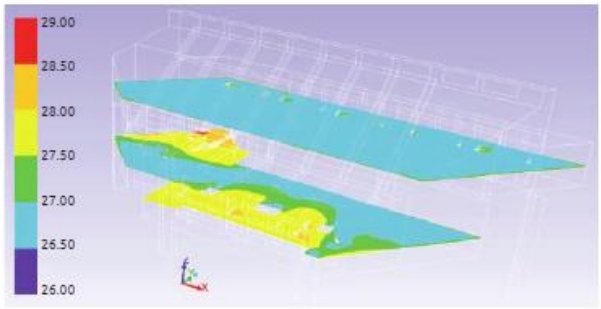
Figure 4 : NZEB Envelope details

3. Natural Ventilation

- Clerestory: 450 mm operable sections at roof level for stack effect
- Cross ventilation: Achieved via north–south oriented windows
- Night ventilation: High-efficiency exhaust fans enable night flushing

Operable clerestories at roof level extract hot air, while windows on north and south façades draw in cooler breezes. During favorable night conditions, exhaust / air inlets and exhaust fans remove accumulated heat, pre-cooling the building mass. This approach reduces reliance on mechanical cooling and supports adaptive comfort.





Month	Morning	Afternoon	Evening
Jan	Window Closed	Window Open	Window Open
Fab	Window Closed	Window Open	Window Open
Mar	Window Open	No	No
Apr	No	No	No
May	No	No	No
Jun	No	No	No
Jul	No	No	No
Aug	No	No	No
Sep	No	No	No
Oct	Window Open	No	No
Nov	Window Open	No	Window Open
Dec	Window Closed	Window Open	Window Open

Figure 5 : CFD model analysis for Thermal comfort with natural ventilation

4. Passive Radiative Cooling

- Roof finish: SRI 103 with high reflectance and emissivity and shared with SPV
- Roof top Solar PV cavity: 450 mm ventilated gap beneath rooftop solar panels

High-SRI roofing combined with a ventilated SPV cavity reduces rooftop heat absorption and promotes radiative heat loss to the night sky, lowering the roof's surface temperature and consequently reducing cooling demand.

5. Nature-based Solutions

- Tree shading: Trees are planted along exposed east facades.
- Sunken courtyard: Provides daylight to the basement and supports cross-ventilation.

Trees shade façades and windows, reducing solar heat gain and improving the local microclimate through evapotranspiration. The sunken courtyard introduces daylight to below-

ground spaces, drives pressure differentials to support natural ventilation, and creates a cooler microclimate, reducing dependence on mechanical cooling

6. Daylighting

The NZEB maximizes daylighting through a combination of architectural and envelope strategies. The building's north-south orientation and a window-to-wall ratio (WWR) of 26% with north WWR at 90% and south at 30% ensure abundant diffuse daylight while minimizing direct solar gain. South-facing 30° inclined roofs and 450 mm high operable clerestory windows at two levels provide uniform daylight distribution deep into the interior, supporting daylight autonomy of at least 75% of the time for 75% of the room at 300 lux. Light shelves and deep overhangs further enhance daylight penetration and reduce glare. High-performance glazing balances daylight transmission with solar control. All lighting fixtures are energy-efficient LEDs, with a combination of ambient and task lighting, occupancy sensors, and personalized controls. The average lighting power density is 2.0 W/m², and the total connected lighting load is 2.7 W/m². Monitored data shows that lighting energy use is as low as 0.1 kWh/m²/year, demonstrating the effectiveness of integrated daylighting and passive cooling strategies in reducing both cooling and lighting loads

4. Active Components

Active (Hybrid) Cooling Strategies
(please describe one strategy per box – you can add more boxes below if needed)

Please describe the feature of the adopted energy-efficient active cooling strategies (e.g., mechanical cooling integration (AC, fans), controlled strategies (automated shading/windows), radiative cooling, evaporative cooling, earth coupled heat exchangers, renewables, etc.) [Max 200 words]

1. Primary: Radiant Cooling (Expanded-graphite ceiling panels) for First and Mezzanine floor

Radiant cooling is the primary sensible-cooling system. Expanded-graphite false-ceiling panels with embedded PEX and copper piping circulate chilled water at ~16°C supply and 20°C return, decoupling sensible from latent loads and lowering fan energy since space cooling is dominated by radiant exchange rather than high-volume air delivery.

An air-cooled scroll chiller (8.2 TR, inverter compressor) supplies the chilled water and modulates to load with measured EERs of 2.9 / 3.7 / 4.0 at 100%, 60% and 40% capacity respectively. Radiant panels permit higher thermostat set-points and reduce peak electrical demand relative to all-air systems by shifting sensible removal to low-velocity radiant transfer. The system choice facilitates research flexibility (panel types, pipe material) while maintaining low operative temperatures appropriate to Ahmedabad's design conditions.

2. Supplementary: Variable Refrigerant Flow (VRF) for peak & latent loads for First and Mezzanine floors:

Eight VRF outdoor units (each ~8 TR equivalent) supplement the radiant system for peak sensible and latent loads on first and second floors. The VRF units provide staged capacity with measured COPs of 6.1 (50%), 4.52 (80%), 3.8 (100%), enabling high part-load efficiency during intermittent peak occupancy. VRF selection avoids multiple chilled-water loops with differing setpoints and provides rapid latent control where radiant alone cannot meet dehumidification needs. VRF operation is integrated with BMS scheduling and setback strategies to minimize simultaneous operation with the radiant loop, preserving system decoupling and minimizing

auxiliary electricity use. Fresh air supply is provided by silent, high-efficiency supply and exhaust fans on the first and mezzanine floors, enabling controlled ventilation and night cooling. These are integrated with the VRF and radiant systems through the Building Management System (BMS) for coordinated operation, maintaining indoor air quality and minimizing energy use

3. Dedicated Outdoor Air System (DOAS) + Heat-Recovery & Digital Scroll (Basement Floor)

Basement ventilation and meeting-room latent loads are handled by a DOAS fitted with a heat-recovery wheel and a digital-scroll compressor (EER ≈ 3.89; COP ≈ 4.1 for heating capability used for experiments) to decouple latent control from sensible cooling. The heat-recovery wheel reduces sensible and latent energy for outdoor-air conditioning; the DOAS is programmable to recirculate return air when heat-recovery benefit is marginal. This configuration improves latent removal effectiveness and reduces chiller duty, particularly during monsoon high-humidity periods critical for maintaining indoor RH <60% at 26°C DB design.

4. Controls, Ventilation Staging, Night Ventilation & PV integration

A modular BMS implements demand-controlled ventilation (CO_2/occupancy), economizer logic (enthalpy-based), chilled-water reset, and chiller optimization algorithms for research-grade control and continuous monitoring .Staged fresh/exhaust fans create controlled mixed-mode operation and enable night purging aided by 450 mm clerestories to exploit stack effect and night ventilation when outdoor conditions permit. Roof-mounted 30 kWp polycrystalline PV offsets electrical consumption of HVAC plant and BMS loads; PV generation is networked to campus internal grid and monitored via BMS for performance analytics. These integrated active strategies preserve thermal comfort while minimizing energy use through system decoupling, part-load optimization, and renewables.

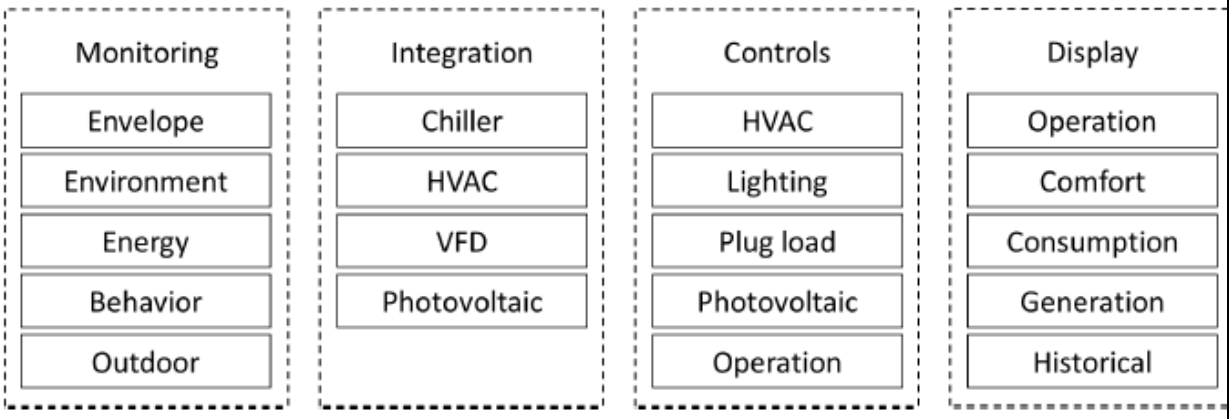


Figure 6 : Conceptual diagram of monitoring and control system through BMS in the NZEB

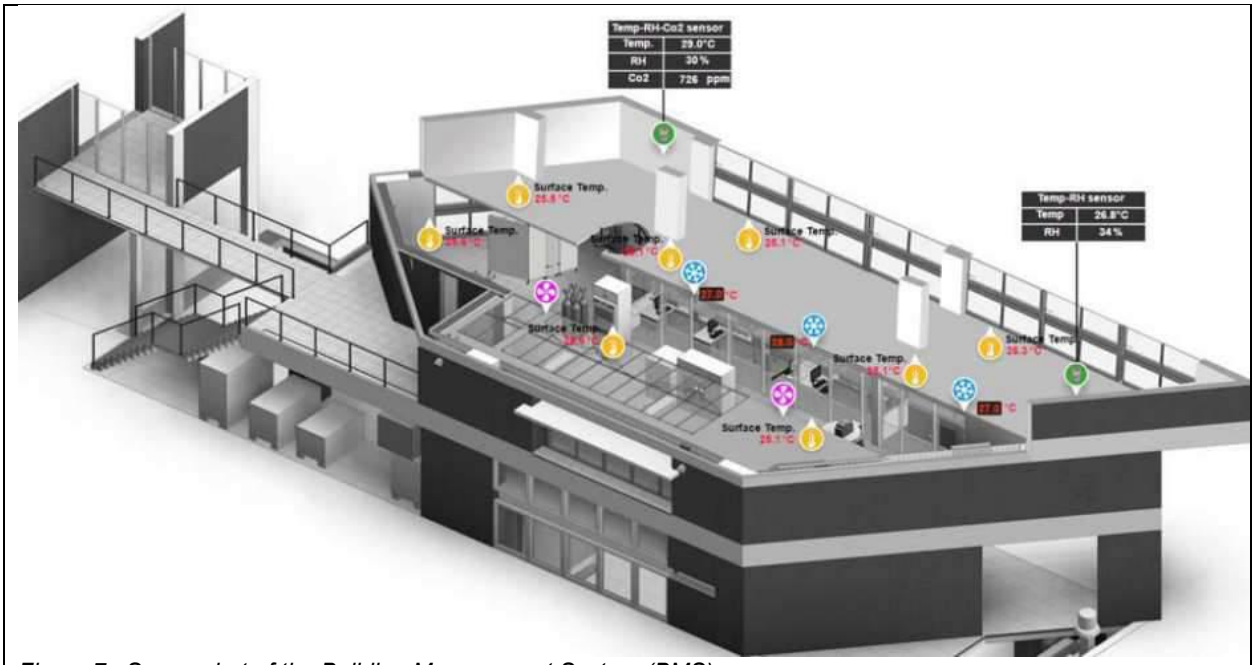


Figure 7 : Screenshot of the Building Management System (BMS)

5. Performance Data

Cooling Energy Use
Please describe the measured or observed reduction of cooling energy due to the introduction of passive cooling measures against baseline. (e.g. annual/peak month cooling energy, peak demand, hours of mechanical cooling, etc.) [Max 200 words] The NZEB building demonstrates substantial reduction in cooling energy through integrated passive and hybrid strategies. Roof and window assemblies provide thermal damping of 32.9°C and 5.6°C, with time lags of 6 and 2 hours, respectively. Seasonal cooling energy ranged from <5 kWh/day in winter to 100–200 kWh/day in summer, with isolated peaks above 250 kWh during research experiments. Radiant panels (RP) pre-cooled the building at night with cooling EPI of 1.60 kWh/m² in summer, while VRV systems handled peak sensible and latent loads, recording 6.59 kWh/m². Peak demand for HVAC reached 8.2 TR for chiller and 8 TR for VRV units in summer, with mechanical cooling operational for 40–50% of daytime hours in summer, and negligible operation in winter. Annual space cooling accounted for 68.8% of total space energy, while total building EPI was 25.4 kWh/m²-year, a 70% reduction compared to the benchmark. PV generation contributed 83.5 MWh/year, meeting over 35% of space energy demand, with seasonal contribution highest in winter (59.4%) and lowest in monsoon (9.5%). Energy use intensity breakdown: HVAC 68.8%, lighting 0.9%, plug loads 7.4%, process equipment 22.9%. Integrated strategies reduced peak loads, hours of operation, and EPI while maintaining energy-positive operation
Indoor Thermal Comfort

Please describe the measured or observed improvement in indoor thermal comfort (e.g., PMV, PPD, adaptive comfort compliance, or occupants' interview, etc.) [Max 200 words]
Monitoring and surveys indicate that indoor environments consistently meet thermal comfort criteria. Indoor dry-bulb temperatures were maintained between 26–30°C, largely within the 80% IMAC acceptability band, occasionally reaching the upper 90% limit. Radiant panels provided pre-cooling during non-daylight hours, while VRV systems addressed latent and peak loads. Occupant surveys on a 7-point thermal sensation scale (-3 'cold' to +3 'hot') show 82% of votes between -1 and +1, and >90% of occupants reported comfort, confirming high thermal acceptability. Surface temperature reduction exceeded 10°C during peak hours, aided by roof and window thermal damping. Mechanical cooling hours were concentrated in summer afternoons, while winter operation was negligible (<5 kWh/day). The building also supports partial natural ventilation during favorable conditions, reducing reliance on active systems. PMV and PPD indices remained within recommended thresholds, indicating controlled indoor air conditions. Heat recovery and demand-controlled ventilation ensured sufficient fresh air, complementing radiant and VRV systems for adaptive comfort. Seasonal trends indicate thermal comfort was maintained even during monsoon, with moderate humidity and high latent loads managed via VRV dehumidification.

6. Financial Data

Cost Benefits
Please describe the financial benefits due to the introduction of passive cooling measures against baseline (e.g., positive return on investment [incremental cost versus saving operational cost], payback periods, IRR, etc.)[Max 200 words] The design optimization demonstrates marked reductions in operational energy costs primarily for HVAC and lighting relative to a conventional university building. Based on modeled energy savings, the incremental investment in high-performance envelope, passive shading, integrated daylighting, and rooftop PV is estimated to yield a payback of around two years against baseline. This figure assumes a standard institutional HVAC schedule; however, a key caveat is that the building often operates in naturally ventilated mode, with mechanical cooling used intermittently. Thus, realized operational savings may differ from modeled projections, especially in user-driven research buildings with variable occupancy and systems use. Regardless, on-site PV ensures that net operational energy costs remain negligible year-on-year, supporting both lifecycle resilience and energy independence.

*Please try to extract passive cooling cost and savings; however, if it is difficult, please annotate the premise. (e.g., the calculation includes the cost for both passive heating and cooling, etc.)

7. Passive Cooling Operation

Maintenance Requirement
Please describe the maintenance requirement to sustain the passive cooling performance [Max 150 words] Sustaining the performance of passive cooling measures requires continuous monitoring and periodic maintenance. The NZEB employs a **sophisticated sensor and controls network** integrated with a building management system (BMS) to track envelope performance, indoor conditions, and system outputs. Maintenance activities implied by the project include: • Calibration and verification of temperature, relative humidity, and globe sensors. • Inspection of insulation integrity and sealant performance.

- Cleaning and visual inspection of glazing and clerestory openings.
- Verification of night-purge ventilation operability and associated fans.

These procedures ensure that passive strategies such as night ventilation, high thermal mass, and envelope insulation continue to deliver expected cooling performance

8. Lesson Learnt / Recommendations

Technical Challenges, Solutions and Achievement
The NZEB structure utilizes a diaphragm system featuring reduced column density with cantilevered spans, enabling flexible use of basement spaces without alterations to the building envelope. This fosters adaptable functionality, suited for evolving research and operational demands, while safeguarding passive cooling performance. Moisture ingress in the basement was mitigated through comprehensive moisture and vapor barrier systems combined with effective waterproofing. In daily operation, intermittent ingress of squirrels, birds, and mosquitos—linked to adjacent vegetation—posed persistent maintenance concerns during natural ventilation. Nevertheless, long-term monitoring reveals that, as Ahmedabad's diurnal range has grown, the deployment of night-flush ventilation has proved increasingly effective, consistently lowering indoor thermal loads prior to occupancy. This finding underscores not only the persistence but the growing relevance of natural ventilation as a core passive strategy, even amidst shifts towards greater humidity and latent loads observed in recent climatic trends.
Financial Challenges, Solutions and Achievement
Please describe the challenges and solutions of passive cooling strategies from the financial perspective (e.g., what are the factors of incremental costs (e.g., imported materials, lack of labor skills, additional analysis cost, etc.), and how could these be mitigated (e.g., tax rebate, preferential loans, subsidies, business incentives, etc.) [Max 150]. The building's high-performance envelope significantly reduced cooling loads, requiring an initial investment in materials and design. However, as the user, the building is primarily operated in a naturally ventilated mode, with air conditioning used only during office hours, minimizing operational energy expenses. Consequently, there is no traditional "payback" through energy cost savings. The intermittent use of high-efficiency HVAC systems further limits energy consumption, while rooftop solar photovoltaic panels effectively offset electricity purchases, eliminating ongoing utility costs altogether. This approach results in minimal operational spending despite upfront investments. Though direct financial recovery through operational savings is limited, the strategy ensures long-term sustainability and resilience. The building's financial model emphasizes lifecycle energy independence supported by renewable energy rather than short-term cost recoupment.
Other Challenges, Solutions and Achievement
An important achievement of the NZEB at CEPT University is the consistent influx of approximately 2000 students annually, reflecting its role as a living laboratory and demonstration facility. This steady engagement facilitates experiential learning, enabling undergraduate and postgraduate students to directly observe and study the effective integration of passive and active energy strategies in a real-world context. The building exemplifies how architectural design, envelope optimization, and advanced HVAC systems operate jointly to achieve energy efficiency and occupant comfort. Furthermore, the NZEB serves as a

benchmark and educational resource, providing a demonstration platform for both technical and design aspects to industry professionals and practitioners, encouraging wider adoption of integrated energy efficiency measures. This ongoing engagement affirms the NZEB's vital role in education and knowledge dissemination within the built environment community.

9. Free Description

Free Description
The design philosophy for the Net Zero Energy Building (NZEB) at CEPT University is founded on holistic integration and interactive collaboration among diverse experts, launched through structured design charrettes and iterative analysis. Anchored in the environmental context of Ahmedabad's hot and dry climate, the project relied on pre-design climate and site analysis to inform critical decisions regarding building massing, orientation, and envelope, ensuring each intervention was responsive and purposeful. Passive design strategies guide every major move: the building's orientation maximizes daylight while limiting unwanted heat gain, and operable fenestration is specified to facilitate natural ventilation and adaptive occupant comfort. The building's form and orientation are carefully optimized to harness passive solar strategies, including shading, natural ventilation, and thermal mass, greatly reducing cooling loads. High-performance façade systems including High performance insulation and low-emissivity glazing form the backbone of envelope efficiency. Each solution is tested through simulation to minimize energy loads before implementing active systems. Where active interventions are necessary, such as radiant cooling, efficient HVAC, and on-site photovoltaics, they are designed to supplement rather than substitute, achieving net-zero annual energy balance through synergy with the envelope and passive design moves. Monitoring and adaptable controls are embedded to support real-time research, enabling the building to serve as an ongoing "living laboratory" for faculty, students, and industry partners. This building stands as both a demonstration of low-energy best practices and as a testbed for validating design, systems, and operational strategies. The NZEB is ultimately envisioned not just as a space for occupancy, but as an academic, research, and demonstration platform bridging rigorous building science, hands-on teaching, and capacity building within India's dynamic context.

10. Annex

Supporting documentations

Please insert any complementary visual materials such as drawings, analysis, performance data, thermal fluid simulation imaging, 3D rendering, as well as descriptions to explain those, etc.

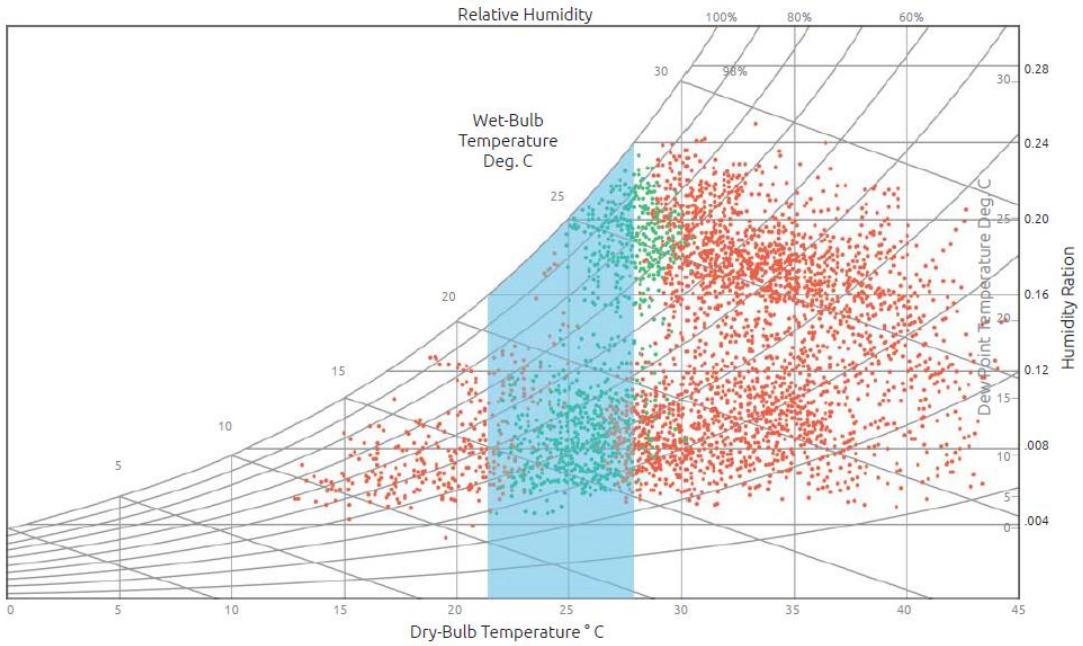


Figure 8 : Psychometric chart depicting that only 23% of the daytime hours fall in the comfort range (Vaidya & Ghatti, 2017)

This psychrometric chart illustrates the distribution of occupied hours with respect to thermal comfort conditions in Ahmedabad. It shows that only 23% of the daytime hours fall within the comfort zone, highlighting the need for both passive and active strategies to achieve year-round comfort in the building.

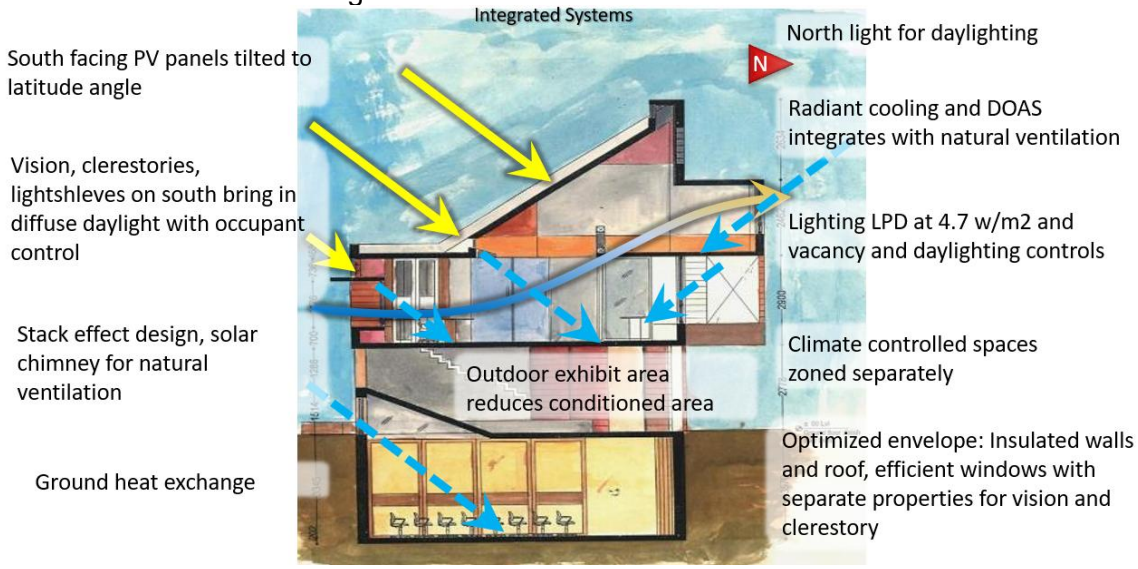


Figure 9 : Sectional view showing strategies in NZEB

This architectural section drawing illustrates the integration of passive and active design strategies in the NZEB. It highlights features such as building orientation, thermal mass,

insulation, operable clerestories, daylighting, and the placement of HVAC and PV systems, providing a visual summary of the holistic design approach

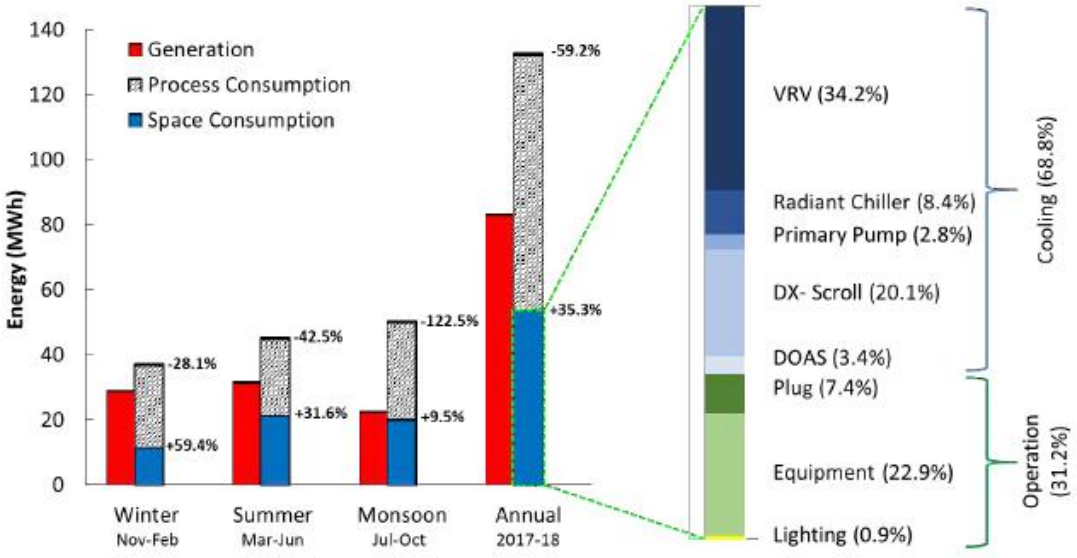


Figure 10 : Annual and seasonal energy generation, process consumption, and space consumption for 2017-2018, along with the percentage share of various operation and cooling loads

This bar graph and breakdown illustrate the total annual and seasonal energy generated by PV, consumed by process loads, and used for space conditioning. The figure also details the percentage share of different operational and cooling loads, providing a comprehensive view of the building's energy balance and end-use distribution

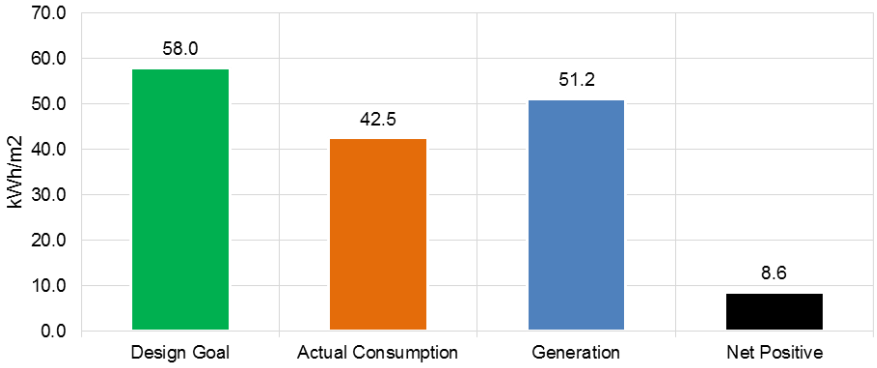


Figure 11 : Energy generation, process consumption, and space consumption with operation and cooling loads

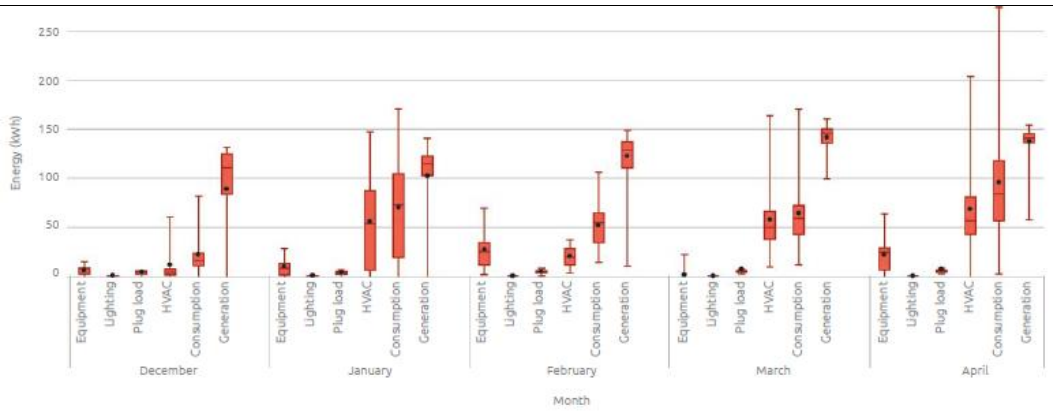


Figure 12 : Whisker plot of NZEB Energy consumption and generation pattern (Dec 2015 – Apr 2016) (Behera, Rawal, & Shukla, 2016)

The whisker plot visualizes the variability and distribution of daily energy consumption and PV generation for the building over several months. It highlights the seasonal and operational fluctuations, as well as the periods when generation exceeds consumption,

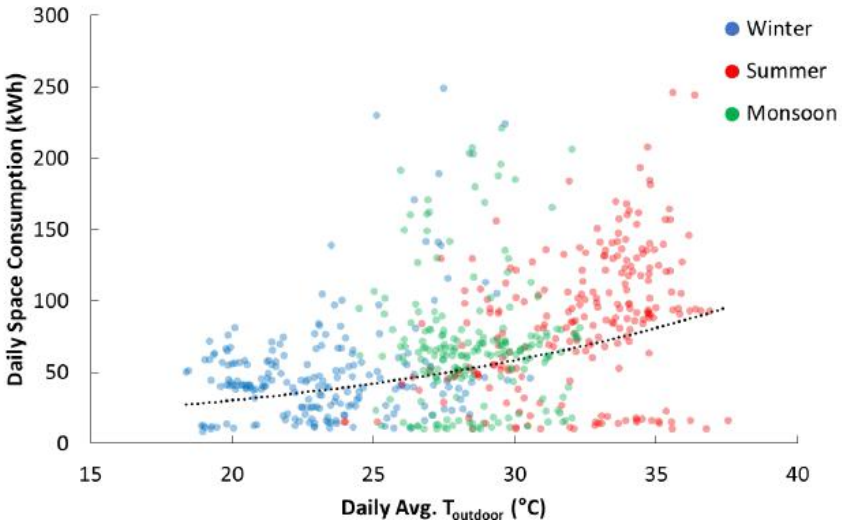


Figure 13 : Seasonal variation of total daily space consumption with daily average outdoor temperature for 2017-2018

This figure shows the relationship between daily space energy consumption and average outdoor temperature across different seasons. It reveals how cooling demand and energy use increase with rising outdoor temperatures, emphasizing the impact of climate on building performance.

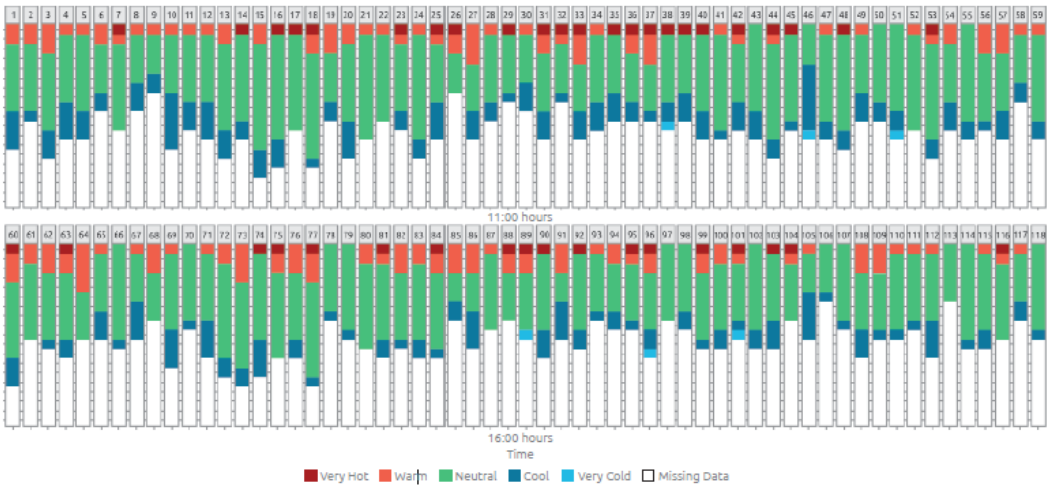


Figure 14 : Thermal sensation of buildings occupants

This histogram or bar chart presents the results of occupant thermal sensation surveys, typically using the ASHRAE 7-point scale. It indicates the percentage of responses in each category, demonstrating that the majority of occupants reported neutral or slightly warm/cool sensations, confirming effective thermal comfort management

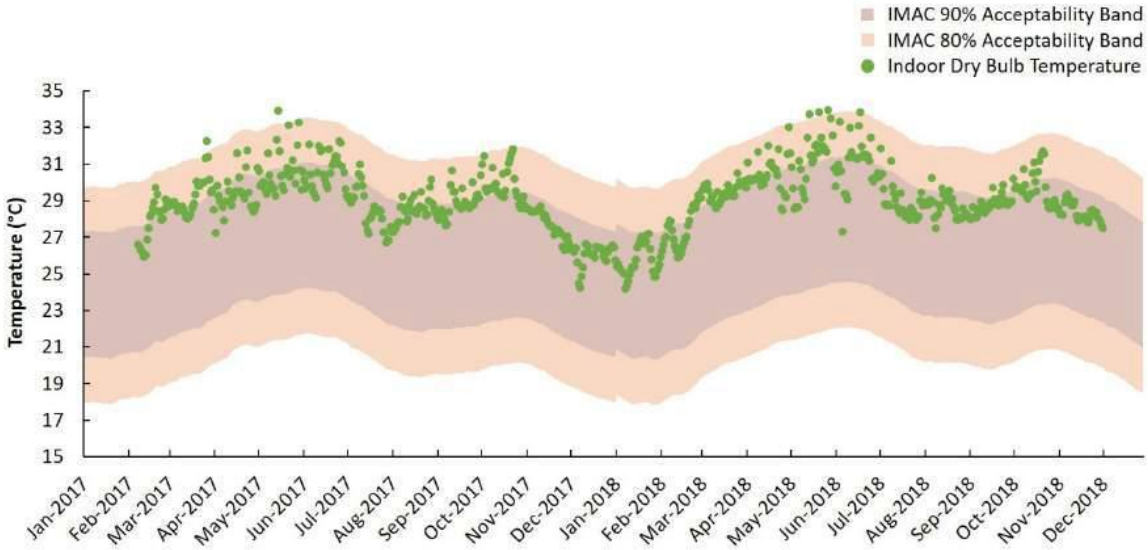


Figure 15 : Comparison of indoor dry bulb temperature against IMAC 80% and 90% acceptability limits for 2017 and 2018

This plot compares measured indoor dry bulb temperatures with the Indian Model for Adaptive Comfort (IMAC) 80% and 90% acceptability bands. It shows that indoor conditions were maintained within or close to the comfort limits for most of the year, validating the building's passive and hybrid strategies

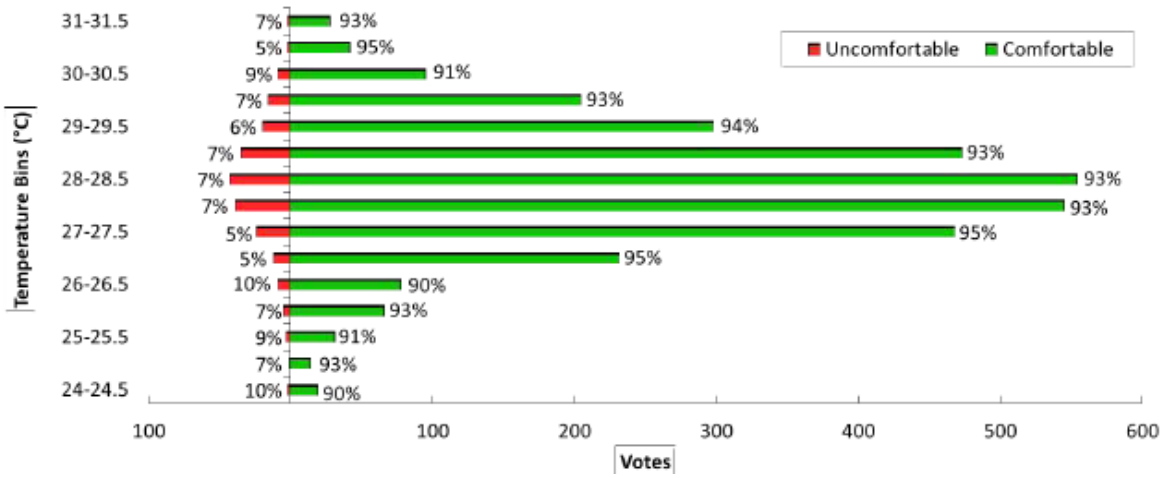


Figure 16 : Variation of comfort with temperature during 2017-2018

This figure correlates occupant comfort votes or acceptability with measured indoor temperatures over the monitoring period. It provides insight into how perceived comfort varies with temperature, supporting the adaptive comfort approach and the effectiveness of the building's environmental controls

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Figure 17 : BMS interface for the whole building

11. Citation

Citation
Please include here the citations/references/links of your project and/or research.

1. CARBSE, CEPT University. (2017). *Net Zero Energy Building: A Living Laboratory, CEPT University, Ahmedabad*. December 2017. PDF Link
2. Rawal, R., Pandya, H., Desai, A., Vardhan, V., Shukla, Y., Manu, S., Shah, A., & Ranjan, A. (2019). *Energy & Thermal Comfort Performance Evaluation of Net Zero Energy Building in Hot Dry Climate – A Case Study*. Proceedings of CATE 2019 – Comfort at the Extremes: Energy, Economy and Climate, Heriot-Watt University, Dubai. Link
3. Rawal, R., Vaidya, P., Manu, S., & Shukla, Y. (2015). *Divide by Net-Zero: Infinite Potential or Calculation Error? A Quasi-Academic Design and Construction Project in India*. Proceedings of the 31st International PLEA Conference, Bologna, Italy. Link

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