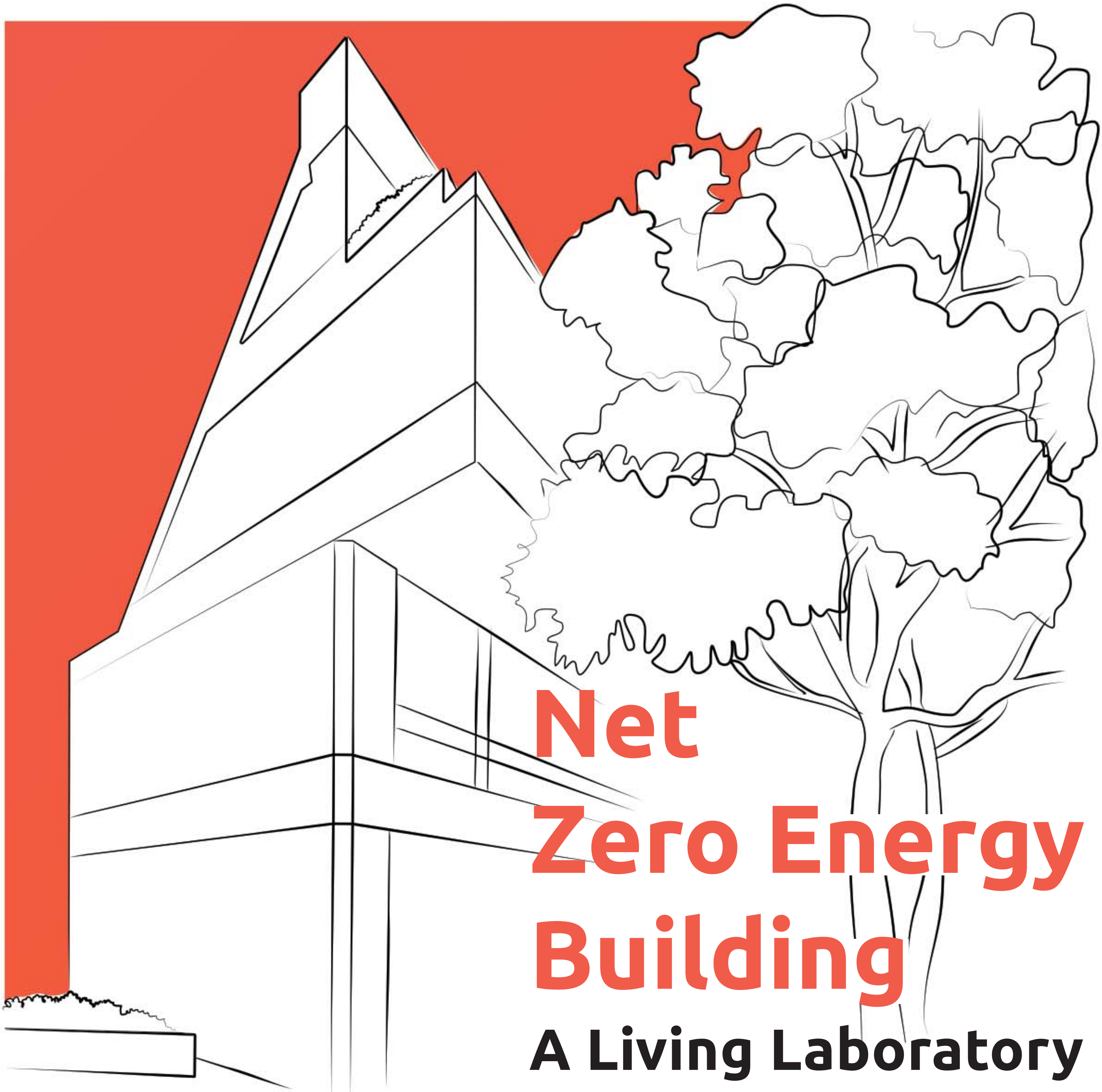

Net Zero Energy Building

A Living Laboratory

CEPT University, Ahmedabad

Report

December 2017

CEPT UNIVERSITY

Centre for Advanced Research in Building Science and Energy

A Report on

Net Zero Energy Building A Living Laboratory

CEPT University, Ahmedabad

December, 2017

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Abbreviations

AWS: Automatic Weather Station
BMS: Building Management System
CFD: Computational Fluid Dynamics
DGU: Double Glazed Unit
ECBC: Energy Conservation and Building Code
GEDA: Gujarat Energy Development Agency
GRIHA: Green Rating for Integrated Habitat Assessment
HVAC: Heating, Ventilation and Air-conditioning
LEED: Leadership in Energy and Environmental Design
MNRE: Ministry for New and Renewable Energy
NZEB: Net-zero Energy Building
PMV: Predicted Mean Vote
PPD: Predicted Percentage Dissatisfied
PV: Photovoltaic
TCC: Thermal Comfort Chamber
USAID: United States Agency for International Development
VLT: Visible Light Transmission

Executive Summary

A net-zero energy building (NZEB) is a building with zero net energy consumption. In such a building, energy consumed is equal or sometimes less than the energy generated by renewable energy technologies installed on site. Various passive and active strategies are deployed to ensure that the building consumes as less energy as possible but works efficiently at the same time. Considering that buildings consume the maximum energy in a city, NZEBs can be a significant step towards building energy efficiency.

CEPT University in Ahmedabad, one of India's premier institutes, initiated the proposal of constructing a NZEB on its campus. The Centre for Advanced research in Building science and energy (CARBSE) took up this challenging task for creation and dissemination of knowledge for energy efficient and sustainable built environment in areas of building envelop design, testing the performance of envelope components such as fenestration and building energy simulation research. CARBSE was successful in forming a group of dedicated and enthusiastic researchers and professionals from around the world, who worked collaboratively to come up with a state-of-the-art NZEB building which would not only function as a living laboratory but also house CARBSE's various equipment for testing and characterization services.

To start with, a thorough analysis was done of Ahmedabad's climate and the site on which the building was proposed to be constructed. An integrated and interactive design approach was considered suitable for designing the building. An extensive pre-design analysis was done to comprehend the challenges and come up with applicable solutions for building massing, orientation, day-lighting and artificial lighting inside the building, natural ventilation, occupant thermal comfort, HVAC and renewable energy systems. Different options were considered for building design and simulation models were designed for in-depth and detailed analysis. After a substantial amount of brainstorming by the academia and industry experts, the design was finalized and construction began in September 2012 and finished in March 2015.

Various high level sensors were incorporated during the construction phase to monitor the performance of the building envelope, environment and systems. They are collectively monitored through a Building Management system (BMS). The indoor environment can also be controlled with the help of BMS. The data collected by the BMS has been analyzed to judge the actual performance of the building.

Some of the lessons learnt while executing this one-of-its-kind project is that the team responsible for execution of the project should have significant understanding and experience in the field of energy efficiency. For a project like NZEB, site supervision is the key to ensure that all the systems – Envelope, HVAC, BMS – are installed as per design. Comprehensive checks such as inspecting envelope and building systems using thermal imaging camera, calibration of sensors, etc. have be conducted during execution and commissioning stage. Providing additional training to installation teams may be required in certain cases.

NZEB had been envisioned to provide an experience that will enable the occupants and visitors to understand the importance of resource efficiency through sensorial aspects of design. The spaces within the facility house various activities and provide varying visual and thermal comfort experiences to enhance the user's understanding of the perceived physical and psychological comfort conditions. It also offers an opportunity to demonstrate strategies used to achieve the targeted comfort levels. The design, as a whole, emphasizes the importance of integrated design process and demonstrate the symbiotic relationship between architecture, interior architecture, structure and services.

About CEPT University

CEPT University is a premier university in India focusing on design and management of human habitat. The University campus came into existence in 1962 and incorporated the language of the Modernist approach expressed in the open naturally ventilated studios, classrooms with double-height spaces for stack ventilation, and deep overhangs.
Its teaching programs aim to build thoughtful professionals and its research programs deepen understanding of human settlements. The belief that educating professionals requires practicing professionals and academics to work closely together, firmly underpins CEPT University's pedagogic philosophy. Therefore, CEPT University works as a collaborative of academics and practitioners. Practitioners adept at decision-making bring their experience to classrooms and academics impart a more thoughtful and critical approach. CEPT University also undertakes advisory projects to further the goal of making habitats more livable. Through its education, research and advisory activities, CEPT strives to improve the impact of habitat professions in enriching the lives of people in India's villages, towns and cities.

The University comprises of five faculties. The Faculty of Architecture was established as the 'School of Architecture' in 1962. It focuses on design in the private realm. The Faculty of Planning, focused on planning in the public realm, was established in 1972 as the 'School of Planning'. The Faculty of Technology, which concentrates on engineering and construction, was established in 1982 as the 'School of Building Science and Technology'. The Faculty of Design was established in 1991 as the 'School of Interior Design'. It deals with habitat related interiors, crafts, systems, and products. Faculty of Management was established in 2013 and it focuses on Habitat and Project Management.

CEPT University takes its name from the 'Centre for Environmental Planning and Technology'. CEPT and the various schools that it comprises were established by the Ahmedabad Education Society with the support of the Government of Gujarat and the Government of India. The Government of Gujarat incorporated CEPT as a university in 2005. In 2007 the University Grants Commission recognized CEPT University under section 2(f) of the UGC Act, 1956. The Department of Scientific and Industrial Research (DSIR) of the Government of India recognizes the University as a Scientific and Industrial Research Organization (SIRO).
(http://cept.ac.in/about/cept-university, 2017)

CEPT Research and Development Foundation (CRDF)

Besides offering education in varied streams, CEPT University has established centers to conduct research and developmental activities and consultancy. These centers interact with industry, government organizations and public at large to generate and disseminate knowledge pertaining to built environment. CEPT Research and Development Foundation (CRDF) manages these consulting, contract research and capacity building activities.

CRDF is organized under thematic groups (or verticals). Each thematic group is focused on a specific area of study and research. The centers which have been established under CRDF are:

a. Center for Urban Equity (CUE)
b. Centre for Advanced Research in Building Science and Energy (CARBSE)
c. Design Innovation and Craft Resource Center (DICRC)
d. Center for Excellence in Urban Transport (CoE)
e. Center for Professional Development (CPD)
f. Center for Urban Land & Real Estate Policy (CULREP)
g. Center for Water and Sanitation (C-WAS)

Each group has a full time coordinator who manages the various research and consulting projects to be undertaken by the group. Various faculty members and students benefit by participating in these research and consulting projects. CRDF is led by an independent board and managed by its Director. (http://cept.ac.in/cept-research-development-foundation-crdf, 2017)

Centre for Advanced Research in Building Science and Energy (CARBSE)

Within India, the building sector uses more than one-third of the national energy use in India, and with further growth in this sector, India faces a formidable challenge in reducing its dependence on fossil fuels, natural resources and energy supply infrastructure. Buildings and cities in other emerging economies are also being challenged by such context. CARBSE at CEPT aims to serve society by providing impetus for creation and dissemination of knowledge for energy efficient and sustainable built environment by working dedicatedly in areas of building envelop design, testing the performance of envelope components such as fenestration and building energy simulation research (Refer Annexure 3).

Goals

- Generate robust knowledge database for strengthening of energy efficiency as a critical focus with the built environment related fields
- Create enhanced knowledge of construction materials, methods and practices for energy efficient architecture in India
- Extend research and dissemination activities in areas of Urban Planning and design with an integrated approach to resource planning including energy, water and land

Objectives

- Establish state-of-art building simulation facilities and conduct training programs for professionals and educators
- Help government to formulate and implement energy conservation policy and initiatives and also help local government to adopt ECBC and formulate local building regulations for code compliance
- Build advance building envelop energy performance laboratory and establish a certification and labeling program for fenestration and related products.
- Construct its own building as a demonstration of best of design and technology - a living laboratory for research in energy efficient buildings

The Center has achieved status of:

a. A 'Regional Energy Efficiency Center' on Building Energy Efficiency by the USAID ECO-III program
b. 'Center of Excellence for Solar Passive Architecture and Green Building Technologies' by the Ministry of New and Renewable Energy, Government of India.
c. CARBSE led the prestigious US-India clean energy research and development project for building energy efficiency titled 'Center for Building Energy Research and Development' (CBERD).
d. CARBSE is supported by Gujarat Energy Development Agency, Shakti Sustainable Energy Foundation (SSEF), industry and various philanthropic organizations. (http://cept.ac.in/center-for-advanced-research-in-building-science-energy-carbse, 2017)

One of the many objectives of CARBSE was to construct a research facility demonstrating best of design and technology – a living laboratory for research in energy efficient buildings where it wanted to house its laboratory testing equipment that will characterize performance of high efficiency components, establish certification and labeling program for fenestrations & related products, conduct thermal comfort experiments in a thermal comfort chamber, establish a state-of-the-art artificial sky simulator and conduct workshops and dissemination activities in the area of building energy efficiency and related fields. Furthermore, there was also a need to provide comfortable workstations for CARBSE's expanding number of researchers and research scholars. In order to fulfill this objective, the idea of building an ultra-efficient Net Zero Energy (NZE) Building at CEPT University campus, was conceptualized and implemented. (http://www.carbse.org, 2017)

01 INTRODUCTION TO NZEB

Amid emerging covers evolving energy prices, energy independence, impact of climate change and the statistics reflect buildings are the primary consumer in India. Significant amount of energy can be reduced in building sector by integrating energy efficient strategies into the design, construction and the operation of new buildings as well as undertaking retrofits to improve the efficiency of existing buildings. The hypothesis of Net Zero Energy Building (NZEB), a building which generates as much energy as it uses over the duration of one whole year, has been evolving from research to reality. (Behera, Rawal, & Shukla, 2016)

Objectives of the building facility to house CARBSE were:

- Demonstration of low energy building design to achieve Net Zero Energy building
- Research and practice of appropriate strategies to achieve thermal comfort
- Harness and maximize the usage of daylight
- Integrate renewable energy sources as part of architectural design
- Monitoring of buildings for their energy efficiency potential by in-house research scholars and use the collected data to develop a comprehensive database accessible to all
- Use of low embodied energy materials and innovative structural system

The architect's - Prof. Balkrishna V. Doshi - vision of the REEC building was aimed at re-establishing the context and importance of sustainable low energy architecture. Since the building is part of the academic and research environment, it was imperative that it not only demonstrate the design and practice of sustainability but also inspire next generation of professionals.

NZEB at CEPT University campus in Ahmedabad, Gujarat, was designed to translate CARBSE's physical working space into living-laboratory where the architectural elements and systems components have a degree of flexibility built-in to allow for experimentation with different systems and operation strategies. NZEB houses the Centre for Advanced Research in Building Science and Energy (CARBSE). In the building, energy consumption has been reduced by 86% compared to business-as-usual buildings in the university through passive and active energy-efficiency measures. The rest of the energy use is balanced by high efficiency Solar PV system. The building design has only incorporated "market-ready" technologies to demonstrate that the net-zero energy building design can be propagated in the market with proper design and execution. (UNEP, 2014)

A team formed under USAID's ECO-III Project with expert consultants from across the world and local consultants' experiences in execution proposed a highly optimized yet, context-appropriate solution. An iterative process and exchange of ideas between a master architect, a design, construction and commissioning team that eventually occupied the building, other consultants, and equipment and material suppliers worked together in the evolution of the building design. The design of the comfort systems and energy monitoring systems for the building formed an important demonstration of the collaboration between academia and industry which is not a usual practice in India. The building itself was intended to offer opportunities to scholars, researcher, industry, and students to experiment with design and technologies, as a test bed not only during the design and construction phase, but also during its operation and usage. The total cost of implementation was ₹ 22 million. The building serves as an example of the challenges and opportunities that integrated design offers and is a tangible example for architecture students, professionals, researchers and industry, who are going to play a vital role in the making of high performance buildings in future. (Rawal, Vaidya, Manu, & Shukla, 2015)

02 BACKGROUND

2.1 Geography

Ahmedabad is located at 23.03°N and 72.58°E in western India at an elevation of 53 mts. The city sits on the banks of the River Sabarmati, in north-central Gujarat. It spans an area of 464 sq. km. According to the Bureau of Indian Standards, the town falls under seismic zone-III, in a scale of I to V (in order of increasing vulnerability to earthquakes).

Ahmedabad is divided by the Sabarmati into two physically distinct eastern and western regions. The eastern bank of the river houses the old city, which includes the central town of Bhadra. This part of Ahmedabad is characterised by packed bazaars, the clustered and barricaded pol system of close clustered buildings, and numerous places of worship. It houses the main railway station, the General Post Office, and few buildings of the Muzaffarid and British eras. The colonial period saw the expansion of the city to the western side of Sabarmati, facilitated by the construction of Ellis Bridge in 1875 and later with the modern Nehru Bridge. This part of the city houses educational institutions, modern buildings, well-planned residential areas, shopping malls, multiplexes and new business districts.

2.2 Site Information

CEPT University campus is located at the Kasturbhai Lalbhai Campus in Navranpura, a much larger campus of the Ahmedabad Education Society (AES). CEPT University is housed in an area of about 80,000 sq. m. The AES colleges of arts, science, commerce, business management and pharmacy and Vikram A. Sarabhai Community Science Centre, Kanoria Centre for Arts and Hutheesing Visual Arts Centre are located in the vicinity. There are over 8000 sq. m. of studios, lecture halls, theatre, workshops, laboratories, library and computer centres and general activity spaces. (Refer Annexure 1)

The campus receives electricity supply from grid from Torrent Power. It is a designated consumer having connected load of 275 kVA. 315 kVA transformer is located on CEPT University campus. Campus receives its water supply from the Ahmedabad Municipal Corporation, its daily usage about 6000 litres. It has underground and overhead water tank for storage. CEPT University campus is 0.3 km from the municipal transport bus stand and 1.1 km from Bus Rapid Transit System. It is 11 km away from international and domestic airport and 4 km from the Railway station.

2.3 Climate analysis

Ahmedabad has a hot semi-arid climate (Köppen climate classification BSh). There are three main seasons: summer, monsoon and winter. Aside from the monsoon season, the climate is dry. The weather is hot through the months of March to June - the average summer maximum is 45°C (113°F), and the average minimum is 23°C (73°F). From November to February, the average maximum temperature is 30°C (85°F), the average minimum is 15°C (59°F), and the climate is extremely dry. Cold northerly winds are responsible for a mild chill in January. The southwest monsoon brings a humid climate from mid-June to mid-September. The average annual rainfall is about 76.0 cm (36.7 inches), but infrequent heavy torrential rains cause the river to flood. The highest temperature recorded is 47°C (116.6°F) and the lowest is 5°C (41°F). On 21 May 2010, mercury touched 46.8°C (116.24°F), making highest temperature recorded in last 40 years in Ahmedabad. In recent years, Ahmedabad has suffered from increasing air, water and soil pollution from neighboring industrial areas and textile mills. (CEPT & ECO-III, 2010)

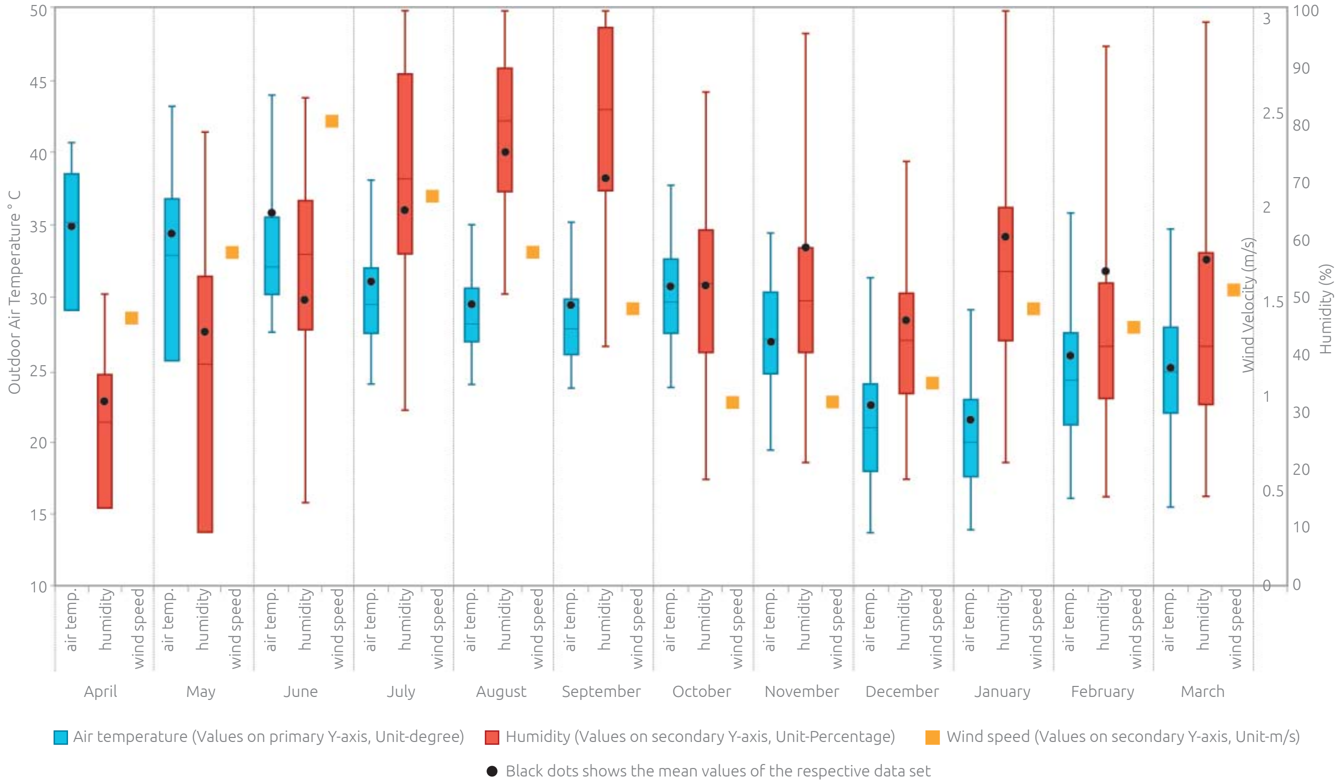


Figure 1: Monthly Temperature, Humidity and Wind speed from weather station at CEPT University Campus in Ahmedabad for Apr 2014 – Mar 2015 (Rawal, Vaidya, Manu, & Shukla, 2015)

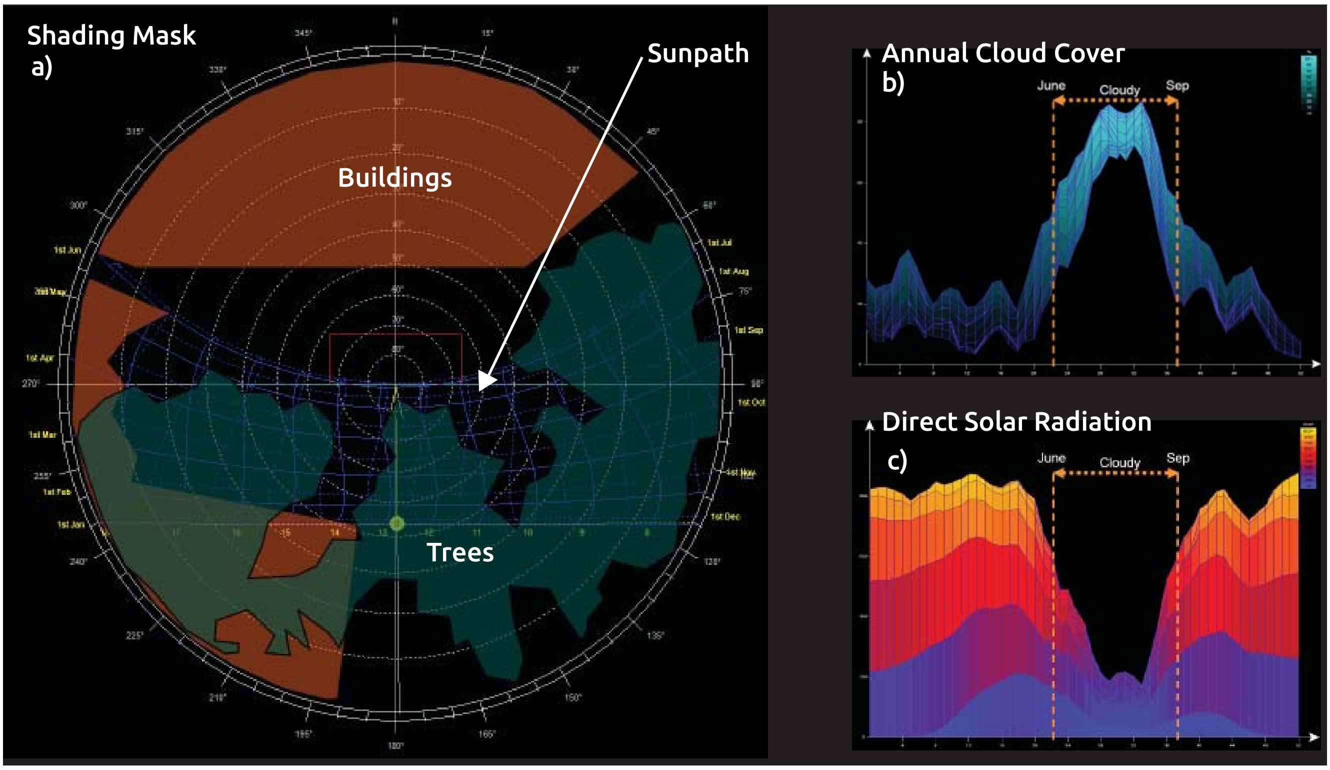


Figure 2: Climate analysis: a) Sunpath Diagram b) Solar Radiation and c) Cloud-cover (Vaidya & Ghatti, 2017)

2.4 Integrated Design Process

Integrated design process was followed during design phase of building. Three design charrettes were conducted with participation from client – promoters, building users, architects, sustainability experts, energy analysts, HVAC, lighting and structure consultants, contractors and legal experts. Each charrette was conducted over two to three days. Each charrette was followed by online meetings and a total of about 30 such meetings were conducted over 12 months. During these meetings, planners and facilitators used strategic planning to overcome conflict. Part of their strategy was to focus on the big picture and the details of the project to produce collaborative agreement about specific goals, strategies, and project priorities. Charrettes established trust, built consensus, and helped to obtain project approval more quickly by allowing participants to be a part of the decision-making process.

There were many benefits of using charrettes early in the design process. Most importantly, charrettes saved time and money while improving project performance. The Integrated design (ID) charrettes provided a forum for those who can influence design decisions to meet and begin planning the project, encouraged agreement about project goals, kicked off the design process by soliciting ideas, issues, and concerns for the project design to help avoid later iterative redesign activities. Also, they promoted enthusiasm for the project and resulted in early direction for the project outcome. Understanding Whole Building Design concepts enabled professionals to think and design the building in an integrated fashion to meet the contextual, aesthetic, programmatic, and performance requirements of the project.

2.4.1 Whole Building Design approach

Whole Building Design consisted of two components: an integrated design approach and an integrated team process. The 'integrated' design approach asked all the members of the building stakeholder community, and the technical planning, design, and construction team to look at the project objectives, and building materials, systems, and assemblies from many different perspectives. This approach was a deviation from the typical planning and design process of relying on the expertise of specialists who work in their respective specialties somewhat isolated from each other. Whole Building design in practice also requires an integrated team process in which the design team and all affected stakeholders work together throughout the project phases and to evaluate the design for cost, quality-of-life, future flexibility, efficiency; overall environmental impact; productivity, creativity; and how the occupants will be enlivened. The 'Whole Buildings' process drew from the knowledge pool of all the stakeholders across the life cycle of the project, from defining the need for the building, through planning, design, construction, building occupancy, and operations.

Design Objectives of Whole Building Design

In buildings, to achieve a truly successful holistic

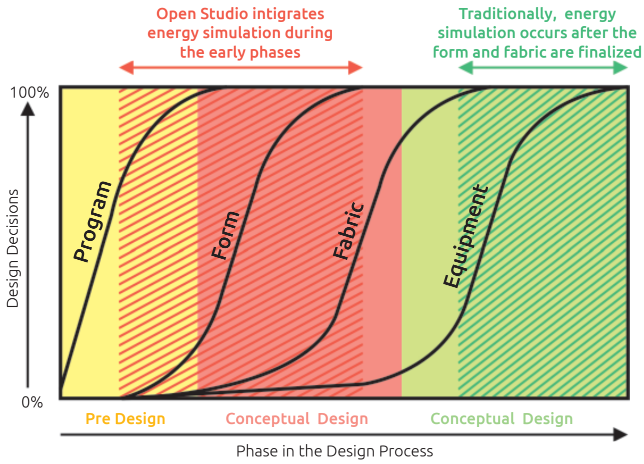


Figure 3: Design decisions during the design process

project, these design objectives must be considered in concert with each other:

- **Aesthetics**: Pertains to the physical appearance and image of building elements and spaces as well as the integrated design process.
- **Functional/Operational**: Pertains to functional programming spatial needs and requirements, system performance as well as durability and efficient maintenance of building elements.
- **Sustainable**: Pertains to environmental performance of building elements and strategies.
- **Cost-Effective**: Pertains to selecting building elements on the basis of life-cycle costs (weighing options during concepts, design development, and value engineering) as well as basic cost estimating and budget control.
- **Productive**: Pertains to occupants' well-being physical and psychological comfort including building elements such as air distribution, lighting, workspaces, systems, and technology.
- **Secure/Safe**: Pertains to the physical protection of occupants and assets from man-made and natural hazards.
- **Accessible**: Pertains to building elements, heights and clearances implemented to address the specific needs of disabled people.
- **Historic Preservation**: Pertains to specific actions within a historic district or affecting a historic building whereby building elements and strategies are classifiable into one of the four approaches: preservation, rehabilitation, restoration, or reconstruction.

As part of the Integrated Design approach, the project goals were identified early on and held in proper balance during the design process; their interrelationships and interdependencies with all building systems were understood, evaluated, appropriately applied, and coordinated concurrently from the planning and programming phase. A high-performance building cannot be achieved unless the integrated and interactive design approach is employed. It meant that all the stakeholders - everyone involved in the planning, design, use, construction, operation, and maintenance of the facility - must fully understand the issues and concerns of all the other parties and interact closely throughout all phases of the project. A focused and collaborative brainstorming session held at the beginning of the project encouraged an exchange of ideas and information and allowed truly integrated design solutions to take form. Team members - all the stakeholders - were encouraged to cross fertilize and address problems beyond their field of expertise. This approach was particularly helpful in complex situations where many people represented the interests of the client and diverse needs and constituencies. Participants were educated about the issues and resolution enabled them to buy into the schematic solutions. Often interdependent issues were explored.

2.4.2 Preliminary explorations

- **Initial Building Simulation Studies:** The Weidt Group presented the results of pre-design energy simulations for a benchmark building that had a matching building program located in Ahmedabad. These simulations were used to understand the impact of various loads on the building and assess opportunities for energy savings. The simulation set included a large variety of energy conservation strategies. The team formulated pre-design bundles of these strategies using an interactive tool to understand how far known energy efficiency measures can reduce the energy consumption of the building. In parallel with this, a net-zero scoping tool was used to understand the potential for onsite energy generation. The scoping of energy generation in combination with the pre-design strategy bundles was used so that the team could agree upon the design parameters that set the direction of design for NZEB at CEPT.

- **Thermal Comfort Conditioning Concepts and Responses:** The primary purpose of a building is to provide comfort to its occupants. Though comfort requirements could vary based on various factors such as adaptability of humans to different climatic conditions. An internationally-accepted definition of thermal comfort, used by ASHRAE, is 'that condition of mind which expresses satisfaction with the thermal environment'. Perceptions of the thermal environment are affected by air temperature, radiant temperature, relative humidity, air velocity, activity and clothing. However field surveys of thermal comfort demonstrate that people are more tolerant of temperature changes if they are provided the ability to control their environment, this approach widely known as the adaptive approach, is one that CARBSE incorporated in NZEB design.

Thermal comfort also emerges as a significant factor that contributes to energy consumption as an outcome of the Heating Ventilation Air-conditioning and Ventilation (HVAC) systems selected in a building. Therefore, the NZEB followed a methodology highlighted in Figure 1to evaluate thermal comfort conditioning systems while optimizing the energy consumption of the building aligning to its aim of achieving a net zero energy building. The methodology

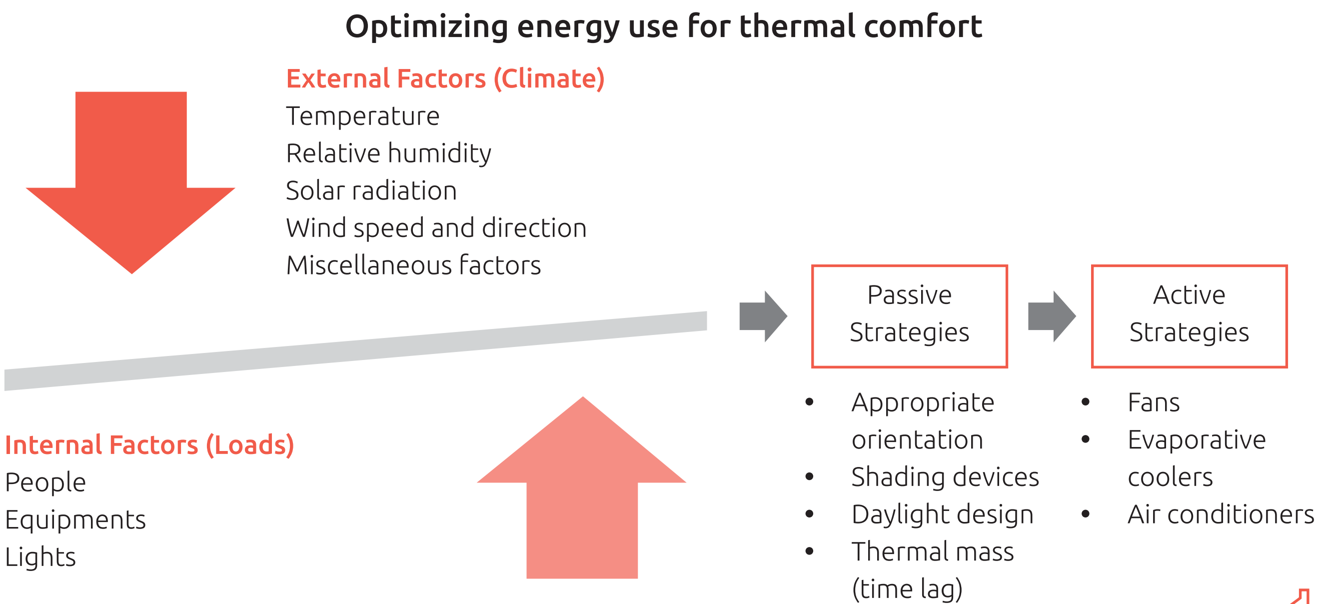


Figure 4: Methodology to Evaluate Thermal Comfort Conditioning Systems

was a stepped approach leading to the reduction in energy consumption at each step. The methodology included:

1. Understanding External and Internal Factors

Comprehensive analysis was undertaken to understand the climatic conditions of Ahmedabad and how they couple with the internal loads of the building to determine the cooling and ventilation requirements of the building.

2. Exploring Passive Strategies

Climatic analysis coupled with thermal comfort conditioning set a platform for the team to explore appropriate passive strategies that could be incorporated in the building to provide comfort and reduce the energy consumption. Psychometric studies were undertaken highlighting the occupied hours outside comfort range providing an opportunity to identify passive strategies and to evaluate the extent to which they would be able to provide comfort. Some applicable passive strategies explored were building shading, natural ventilation and thermal mass.

3. Exploring Active Strategies

The team after incorporating passive strategies evaluated the occupied hours that still remained outside the comfort range. For these hours high efficiency thermal conditioning systems were evaluated such as radiant conditioning. (CEPT & ECO-III, 2010)

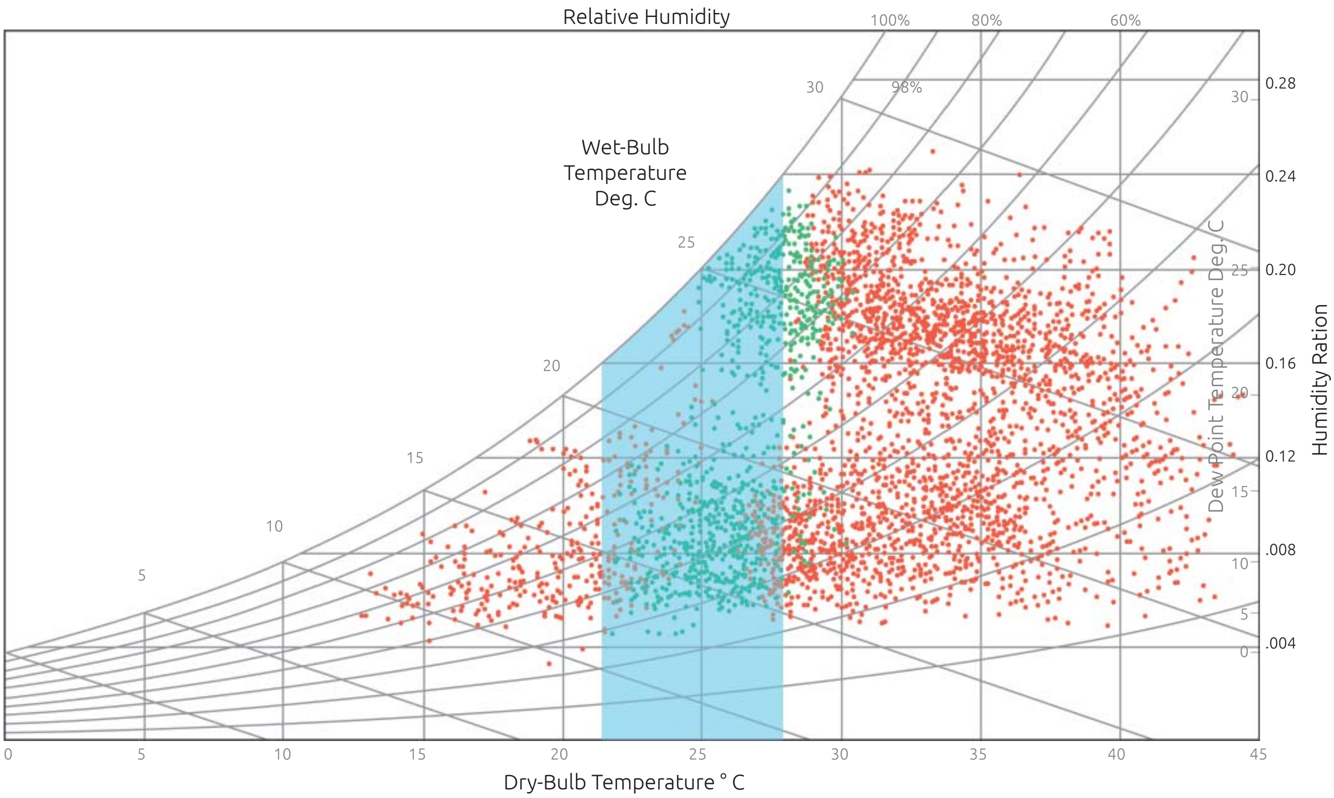


Figure 5: Psychometric chart depicting that only 23% of the daytime hours fall in the comfort range (Vaidya & Ghatti, 2017)

03 ANALYSIS AND CONCEPTUAL DESIGN

The design team followed a process that was rigorous and front-loaded with analysis, to explore as many design decisions as possible with quantitative assessment. This led to an optimized solution with a mix of strategies and an estimated payback of two years.

The iterative and sequential design process included the following stages of analysis:

- **Predesign**: climate analysis; technical potential energy analysis; site analysis, mutual shading from tress and surrounding buildings
- **Conceptual design**: passive thermal comfort analysis; building massing/orientation energy analysis; HVAC system energy and life-cycle analysis
- **System development**: building envelop optimization; windows design, fenestration shading, day lighting analysis; active system thermal comfort analysis; HVAC sizing and capacity optimization analysis; natural ventilation scheduling, CFD analysis for thermal comfort; renewable energy sources identification and optimizing energy generation system
- **Systems optimization**: individual energy conservation measures (ECM) energy analysis; bundled ECM energy analysis

Table 1: Pre- design direction for NZEB

Consumption limit	70 kWh/m2
Massing	• 3-1 building aspect ratio • 20% WWR
Lighting	• Dimming control of lighting • LPD 6.0W/m^2 • Occupancy sensor controls
Plug load	30% reduction and occupancy sensor controls
HVAC	• Direct evaporative system • Adaptive thermal comfort standard • CO_2 control of outside air
PV panels	50% roof coverage

3.1 Technical Potential Analysis

The team previewed energy generation potential on site and established an energy consumption goal that would be less than the potential on-site generation. They reviewed energy analysis of a similar benchmark building in Ahmedabad, to understand how various ECMs would help in reducing the energy consumption. The group discussed additional design approaches to reduce the energy consumption further. These ECMs, evaluated as a bundle, provided the technical potential of savings. These strategies and approaches provided a direction for design as well as metrics for evaluation in the design process. (Rawal, Vaidya, Manu, & Shukla, 2015)

3.2 Thermal comfort analysis

The intent of the thermal comfort analysis was to understand the effect of variation on thermal comfort metrics such as Operative Temperatures, Predicted Mean Vote, (PMV), and Predicted Percentage Dissatisfied (PPD). The analysis was done in two stages:

a. **Preliminary Analysis:** Thermal comfort simulation was done for design days, to represent hot-dry and hot-humid days identified from a TMY3 weather file. The design day conditions were simulated with three (3) different radiant system water temperatures. Preliminary thermal comfort results were presented for Operative Temperatures, Predicted Mean Vote, (PMV), and Predicted Percentage Dissatisfied (PPD) to the Design Team. During the presentation meeting, the water temperature variables were narrowed down for the second stage analysis and other variables were identified that affect thermal comfort such as opaque envelope or glazing characteristics

b. **Final Analysis:** Thermal comfort simulation was done for an identified season or for the entire year with the identified variables. Final thermal comfort results were presented for Operative Temperatures, Predicted Mean Vote (PMV), and Predicted Percentage Dissatisfied (PPD) to the Design Team. (TWG, Preliminary Thermal Comfort Analysis results report, 2011)

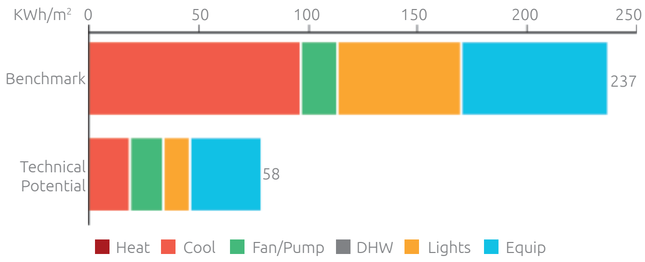


Figure 6: Predesign energy analysis of a benchmark building and technical potential of readily available technologies and design approaches (Rawal, Vaidya, Manu, & Shukla, 2015)

3.3 Building Massing and Orientation Analysis

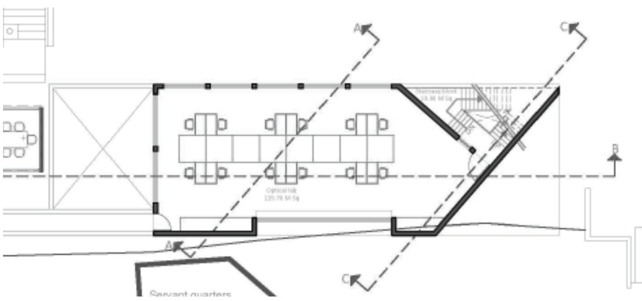
The focus of the building massing analysis was to show the impact of building shape, orientation, space programming, and passive solar aspects of the massing options. These aspects of design have an impact on the day lighting potential and the energy use of the building.

The Design team identified four massing options for energy analysis. The opportunities and challenges for the massing options are shown below. HVAC zoning concepts were discussed with the design team during the introductory meeting. Each massing option has been simulated with and without dimming day-lighting controls and with unitary mechanical system approach.

Table 2: Opportunities and challenges for Massing options (TWG, Building Massing Analysis Results Report: NZEB at CEPT, 2011)

Option 1

Floor Area: 514 sq. m.



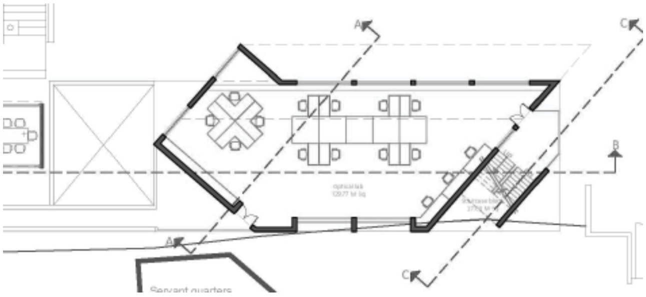
Sun penetration: South facing windows in Optical lab may need interior light shelf to control direct sun. Sun penetration through West and North facing windows in the Optical and Simulation labs maybe limited due to adjacent buildings and trees.

Day lighting: Available to all the spaces. The basement areas may have reduced daylight availability from the North side due to adjacent buildings and trees.

HVAC Zoning:

- Non-conditioned- Circulation, Storage, Restroom
- Semi-conditioned- Offices, Conference room, Seminar room, Simulation Lab
- Fully conditioned- Optical Lab

Option 2
Floor Area: 516 sq. m.



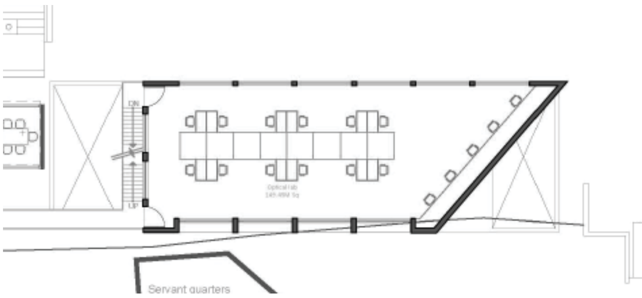
Sun penetration: South facing windows in Optical lab may need interior light shelf to control direct sun. Sun penetration through Northwest, Southeast and North facing windows in the Optical and Simulation labs maybe limited due to adjacent buildings and trees, but may need to be evaluated.

Day lighting: Available to all the spaces. The basement areas may have reduced daylight availability from the North side due to adjacent buildings and trees.

HVAC Zoning:

- Non-conditioned- Circulation, Storage, Restroom
- Semi-conditioned- Offices, Conference room, Seminar room, Simulation Lab
- Fully conditioned- Optical Lab

Option 3
Floor Area: 549 sq. m.



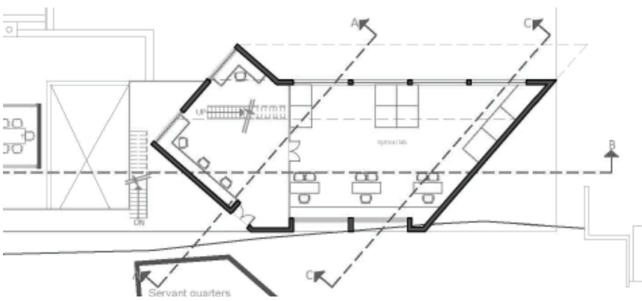
Sun penetration: South facing windows in Optical lab may need interior light shelf to control direct sun. Sun penetration through West and North facing windows in the Optical and Simulation labs maybe limited due to adjacent buildings and trees.

Day lighting: Available to all the spaces. The basement areas may have reduced daylight availability from the North side due to adjacent buildings and trees.

HVAC Zoning:

- Non-conditioned- Circulation, Storage, Restroom
- Semi-conditioned- Offices, Conference room, Seminar room, Simulation Lab
- Fully conditioned- Optical Lab

Option 4
Floor Area: 515 sq. m.



Sun penetration: South facing windows in Optical lab may need interior light shelf to control direct sun. Sun penetration through Northwest and North facing windows in the Optical and Simulation labs maybe limited due to adjacent buildings and trees, but may need to be evaluated.

Day lighting: Available to all the spaces. The basement areas may have reduced daylight availability from the North side due to adjacent buildings and trees.

HVAC Zoning:

- Non-conditioned- Circulation, Storage, Restroom
- Semi-conditioned- Offices, Conference room, Seminar room, Simulation Lab
- Fully conditioned- Optical Lab

Key observations after analysis:

- Option 3 showed the highest energy consumption partly because of its larger floor area and additional window area.
- Option 2 was the best with about 9000 kWh savings with daylighting controls.
- Option 4 and Option 2 were very similar and the additional saving in Option 2 was a result of the location of the seminar room in the basement.
- Option 1 had about 8500 KWh of savings with daylighting controls. (TWG, Building Massing Analysis Results Report: NZEB at CEPT, 2011)

3.4 Day-lighting analysis

Day-lighting design became the basis of architectural massing and fenestration. Options for fenestration, shading, and materials were evaluated using multiple metrics such as illuminance under clear and overcast skies, daylight factor, useful daylight index, and daylight autonomy.

Initial Daylight model

- **Basement:** During the winter months, direct sun through the Basement Monitor might have created glare in the Office and Meeting Room if there had been no shading. The average illuminance of 8260 lux was excessive. Even in the shaded areas the illuminance was 3000 lux, which was 10 times the target illuminance.
- **First Floor:** During the winter months, direct sun through the South View Windows would have created glare for the workstations adjacent to these windows.
- **Second Floor:** The sloped ceiling is the key architectural feature for the first and second floors, but was the darkest surface in the space.

Proposed Daylight model

- **Basement:** By reducing the width of the Basement Monitor glazing and adding a light shelf to reflect the sunlight and control glare, the average illuminance was reduced to 400 lux, which is much more reasonable.
- **First Floor:** Tilting the exterior shading downward improved the shading for the view window, and discouraged birds from nesting. To maintain visibility through the exterior shading, perforated metal with 1mm holes spaced at 2-3mm were used.
- **Second Floor:** Widening the second floor monitor improved the ceiling surface brightness for the second floor. Another strategy discussed in meetings (but not shown in this model) was to add a clerestory and light shelf at the bottom of the sloped ceiling to improve the brightness of this feature and benefit both the first and second floors. (Roederer, Sanders, & Clanton, 2011)

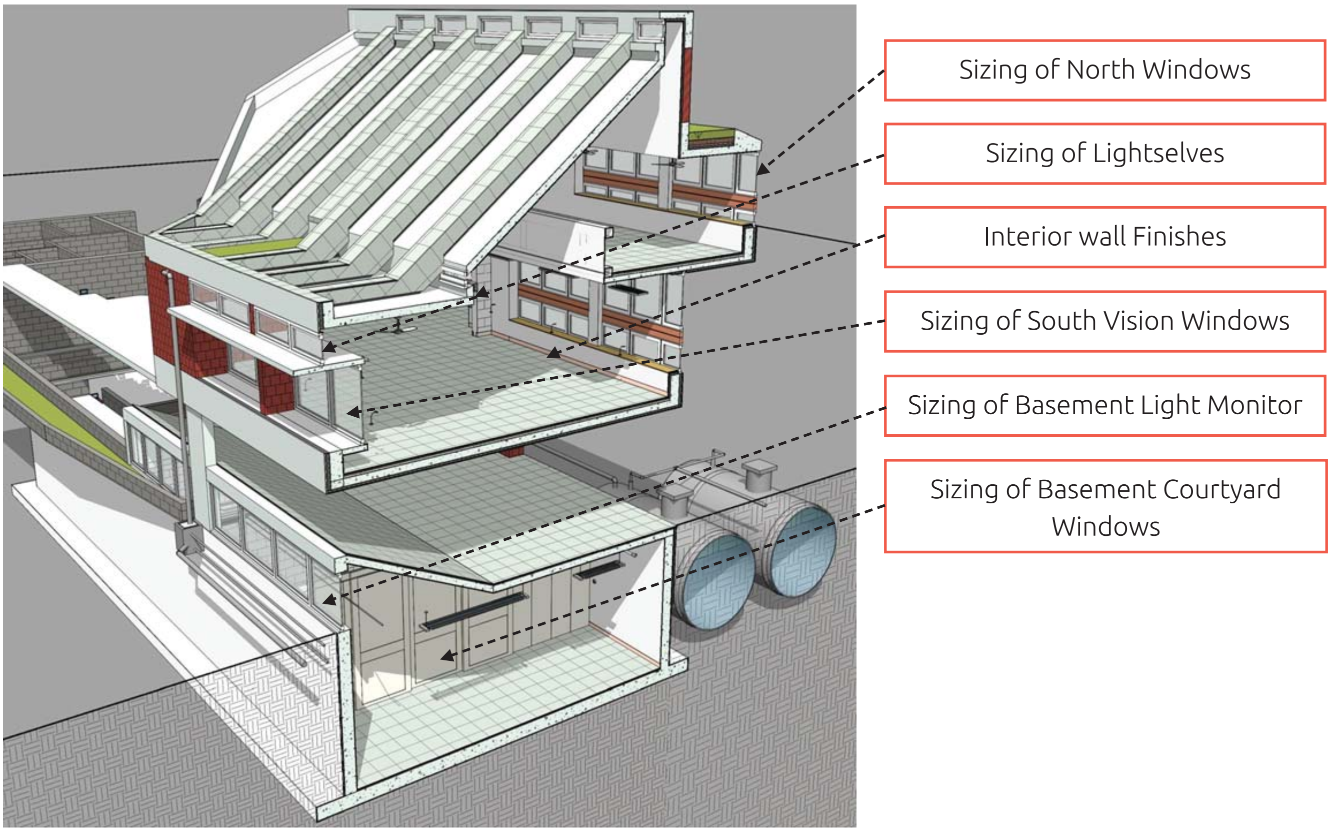
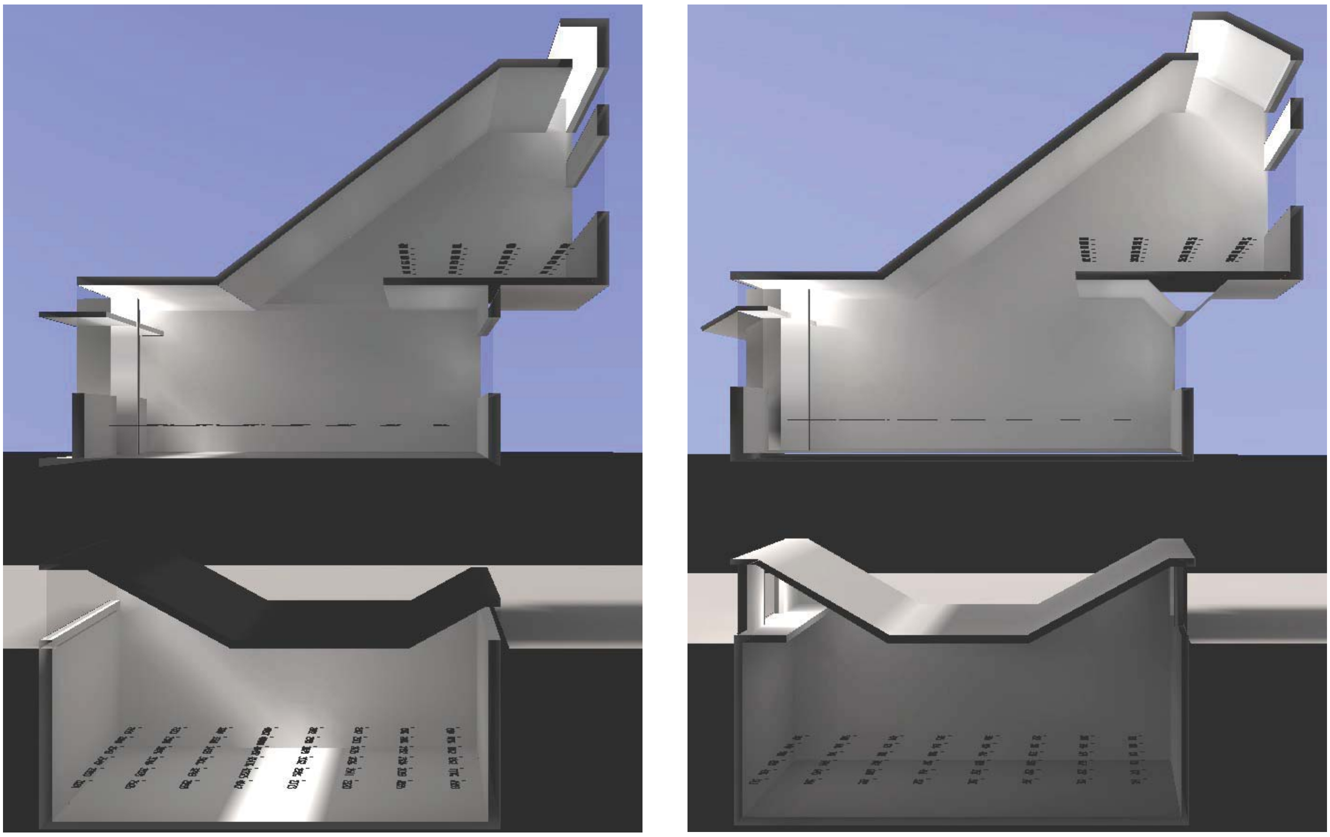


Figure 7: Building elements which were evaluated for day-lighting performance



Calculation Summary - Initial				
Label	Avg	Max	Min	Max/Min
2nd Floor	1483	1822	1124	1.62
1st Floor	9149	49169	1542	31.89
Basement	8261	48497	1589	30.52

December 21 - Noon - Clear Sky

Calculation Summary - Proposed				
Label	Avg	Max	Min	Max/Min
2nd Floor	2361	2993	1660	1.8
1st Floor	2085	3426	1342	2.55
Basement	396.24	745	149	5.01

December 21 - Noon - Clear Sky

Figure 8: Daylight simulation models for Option 4: a) Initial design and b) Proposed design for noon of December 21 for clear sky conditions (Roederer, Sanders, & Clanton, 2011)

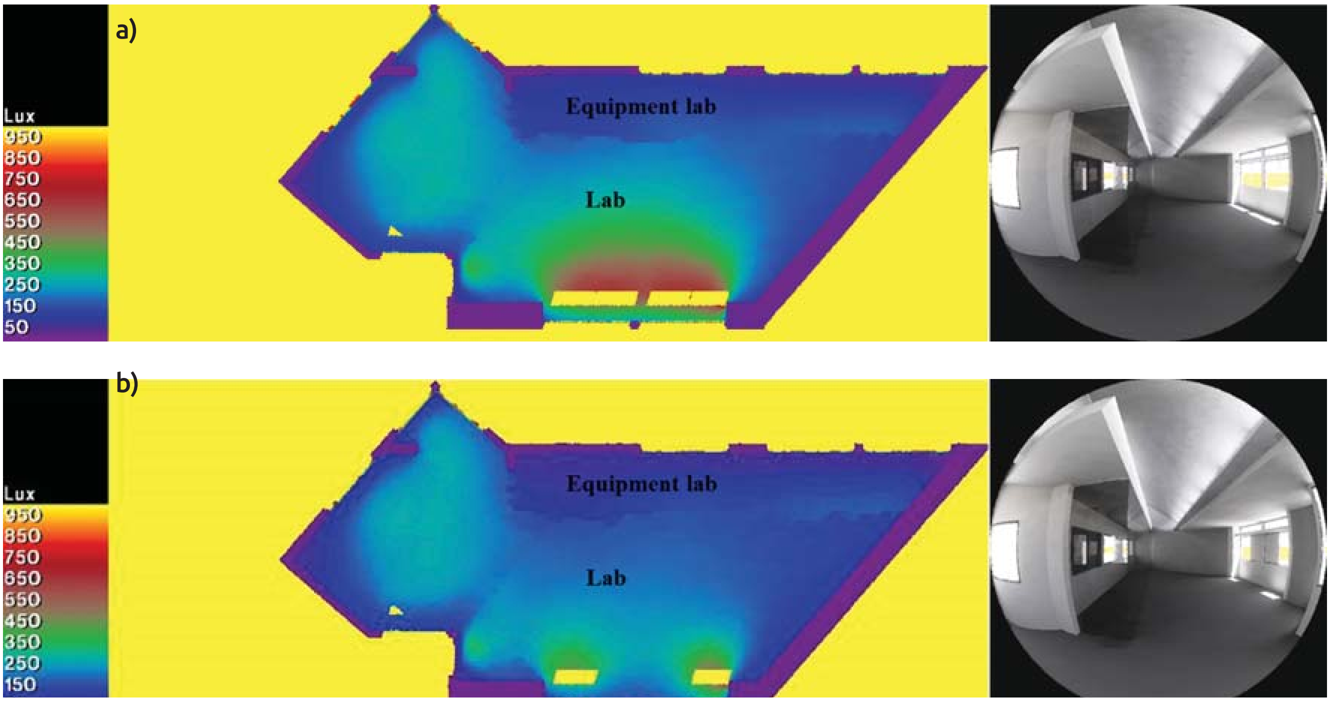


Figure 9: Illuminance plans for the first floor under clear sky

Figure 9 (a) shows the illuminance plan with 2.8m wide vision windows. It is clear that in this case, the daylight in the space was insufficient. Figure 9 (b) shows the illuminance plan with 1.4 m wide vision windows. Reduced width also reduced some daylight throughout the space and helped in reducing high contrast/glare near windows. But, reduced width has almost no impact on daylight autonomy.

3.5 Artificial Lighting analysis

Since 100% of the spaces were intended to be day-lighted for 90% of the daylight hours, there had to be little to no lighting energy used during the day. At night, with a combination of controls and lower lighting power densities, energy use had to be a minimum. The design needed to be aggressive in order to meet the 90% energy reduction for a net zero energy building.

Below are lighting design features that helped in achieving the 90%+ energy reduction goals for NZEB:

1. Incorporating lighting layers (ambient, accent and task)
2. Using indirect lighting for ambient lighting (fluorescent and/or LED)
3. Using LED lighting for accent and task
4. Designing addressable dimmable controls for all lighting
5. Incorporating vacancy and daylighting sensing
6. Providing personal task light controls

Layered lighting design created beautiful architectural lighting and gives the occupants the correct amount of light for personal tasks. It also has the potential to reduce lighting power densities by 30%, as compared

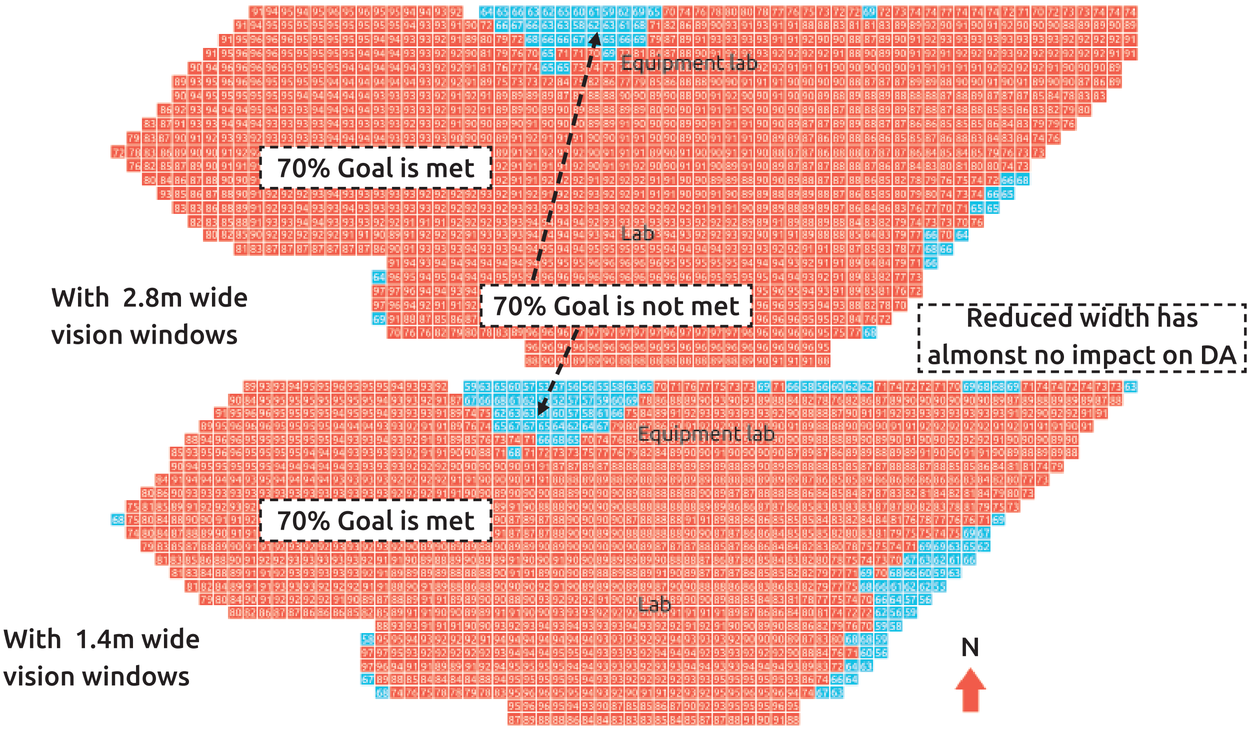


Figure 10: Continuous Daylight autonomy: Goal of 300 lux more than 70% of the time on the First floor (TWG, Daylighting Analysis Results Meeting: Energy Design Assistance, 2011)

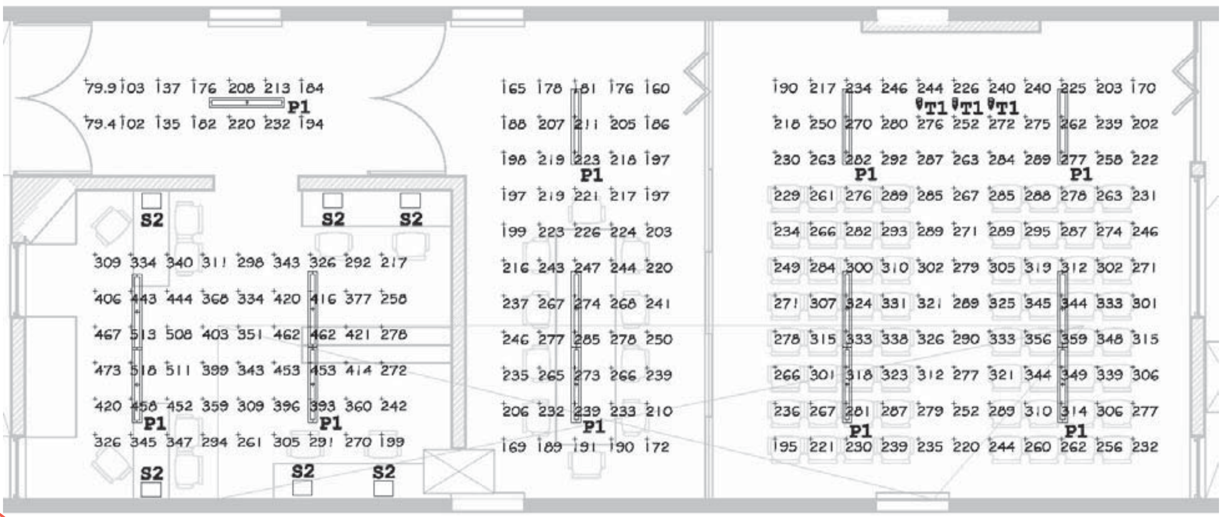


Figure 11: Preliminary Design for NZEB Basement

to ASHRAE 90.1 2007 Baseline. Selecting appropriate luminaires, lamps, gear and controls have additional energy reduction potential of 50%.

Figure 11 shows a preliminary lighting proposal for the basement where Type T1 Track lights were expected to highlight the white-board's vertical surface for accent lighting, Type S2 Luminaire for task lighting at each work space and Type P1 Luminaires were expected to provide the ambient lighting layer. (Clanton, 2011)

3.6 Natural ventilation mode analysis

CFD modeling was done to assess the operative temperatures in the building for comfort as per ASHRAE-55 2010 (ASHRAE, 2010) for naturally ventilated spaces. The table in Figure 13 shows the results of the analysis for each month and period of the day when windows could be opened or closed to achieve thermal comfort. "No" indicated when thermal comfort could not be achieved with windows open or closed, and either a mixed mode ventilation or mechanical cooling would be required.

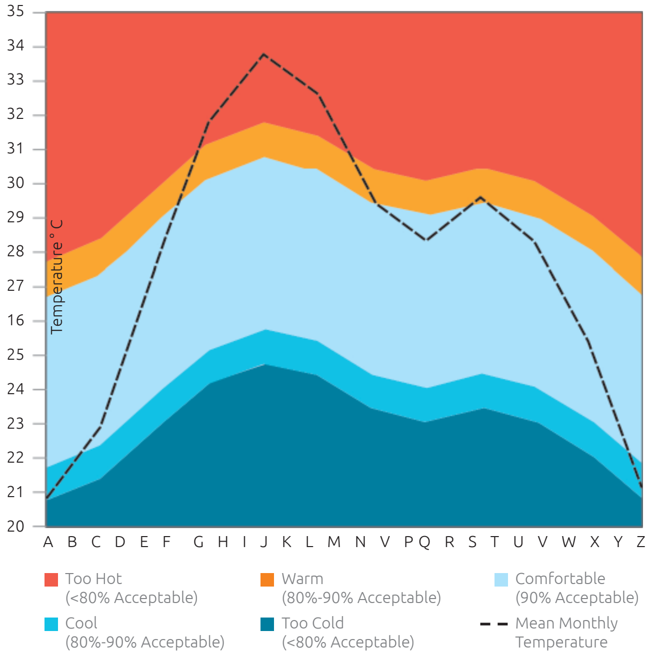
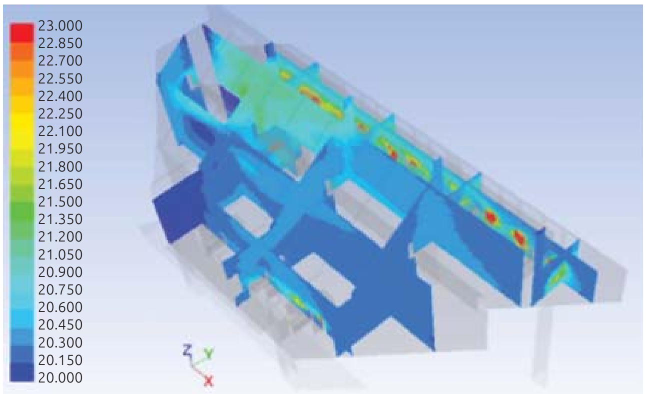
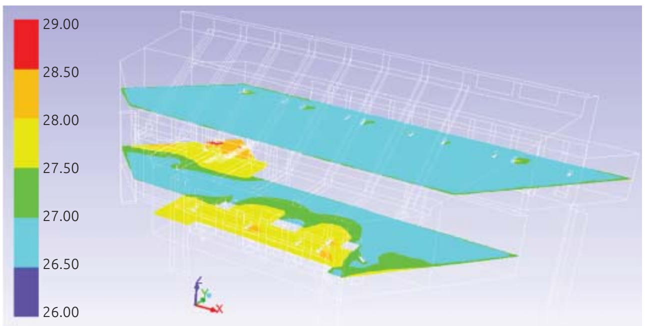


Figure 12: Typical Annual ASHRAE 55 Operative Temperature comfort bands for Naturally ventilated spaces in Ahmedabad, India (Taniguchi, 2011)





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 13: CFD model analysis for Thermal comfort with natural ventilation

3.7 HVAC systems analysis

The analysis utilized DOE-2.1E, a sophisticated building simulation program that performs thermal and illuminance calculations on an hour-by-hour basis. It uses typical yearly climatic data to determine the energy loads and system requirements for the building. Building description input involves defining the building's geometry including interior spaces and the building envelope.

The Weidt group made assumptions on some of the building's characteristics since detailed information was not available early in the design stage. Such assumptions included building materials, expected equipment load, lighting design and some aspects of the mechanical systems. Building envelope and lighting systems were modeled at the minimum levels prescribed by the energy code. Mechanical options were modeled based on discussions with the design team. The Weidt group collected information on the expected use of the building and conceptual thermal zoning of the options studied. The computer models were simulated using weather data for the building location and the expected utility rates for the project.

During the design phase, multiple HVAC options were identified for the building. Based on extensive discussions with consultants, five possible system types were selected for comparison. The final system design of the building was selected to provide high efficiency as well as flexibility for research experiments.

The following options were considered for HVAC installation:

- **Option A**: Packaged DX, Constant volume
- **Option B**: Packaged DX, Variable air volume
- **Option C**: Rainwater harvest cooling + Supple mented by pony chiller cooling
- **Option D:** Radiant cooling with ground-source heat pump
- **Option E**: VRF system, Constant volume (TWG, HVAC Analysis results report - Revised draft, 2011)

Building cooling loads vary with the building massing and orientation. The graphs below show the yearly cooling load for each massing option as mentioned in Table 2.

3.8 Photovoltaic (PV) systems analysis

CEPT and the Design team had agreed to an energy performance goal of NZEB with 35-40 kWh/sqm. energy use intensity on the Predesign basis. At the Charrette, the team estimated the renewable energy that could be generated using PV panels on the roof of the proposed NZEB building and the adjacent School of Interior design building. The PV panels were decided to be tilted at about 23° facing due south and would generate about 157 kWh/sq m of PV panel area. Assuming 50% roof coverage for the two buildings with the PV panels, where the remaining roof area may be needed for other uses or activities, the on-site energy generation potential was estimated to be about 70kWh/sqm. Thus for the building to be net-zero, the maximum energy consumption (EPI) had to be 70kWh/sqm. This EPI was the upper limit for energy efficiency strategies during design and operation. (TWG, Energy Design Assistance, 2011)

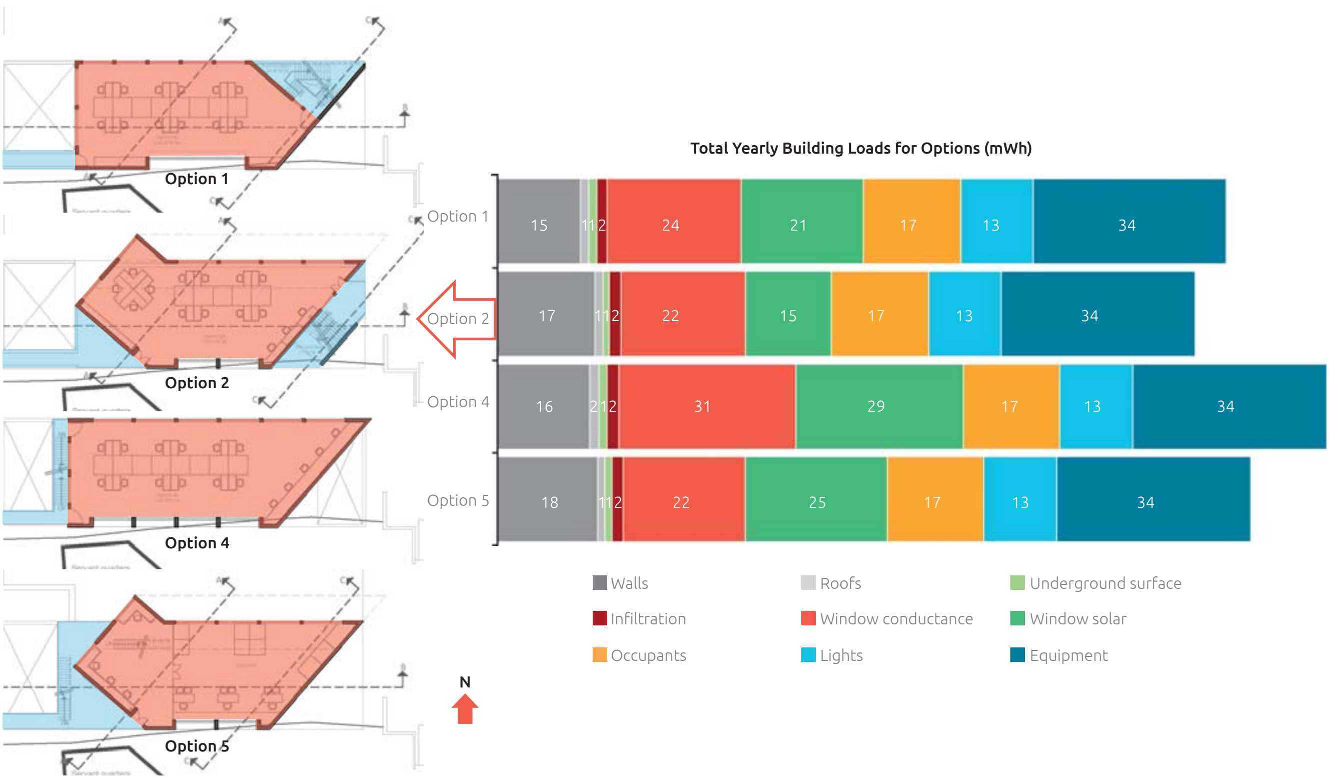


Figure 14: Analysis of building cooling loads w.r.t. Building massing and orientation (Vaidya & Ghatti, 2017)

04 FINAL DESIGN

4.1 Strategies implemented

Strategy 1: Building massing and orientation
The CARBSE building is designed with a 3:1 building aspect ratio (length to width ratio) with a longer East-West axis. Window to wall ratios (WWR) optimized at 26. No windows are provided on East and West façade. This optimizes daylighting and reduces heat gain. South facing 30° inclined roof with 450mm high operable clerestories at two levels provide opportunity for daylighting in addition to creating stack effect and providing optimum angle to install Solar Photovoltaic (SPV) panels. SPV installed over inverted structural beams on roof generate electricity and shade the roof surface with 450mm ventilated air cavity between them. 28% of floor space is below ground level, which substantially reduces heat ingress.

Strategy 2: Optimised building envelope characteristics with material and construction technology selection
The building envelope has insulation on the outside and high thermal mass inside. Walls have 110mm thick exposed brick on outermost layer followed by 50mm XPS insulation and 230mm thick cement plastered brick masonry wall inside with U-value of 0.42 W/m2K. In-situ Reinforced Cement Concrete roof with 32% flyash content has a 45mm thick 50 kg/m3 rigid urethane foam insulation on top with 50mm concrete screed and white paint with Solar Reflective Index of 103 as protective surface . Roof assembly has U-value of 0.38 W/m2K. Intermediate floors such as first and second level RCC slabs exposed to the outdoor environment have 50mm XPS external insulation. Construction details have been executed carefully to minimize any thermal bridging. Windows have uPVC frame with insulated double glazed unit (DGU) having low-e glass. Visual Light Transmittance (VLT) of the windows is 39% with Solar Heat Gain Coefficient of 0.29 (SHGC) and U value of 1.7 W/m2K.

Strategy 3: Optimized thermal and luminous indoor environment
To enable the building to operate in natural ventilation mode, mixed mode and air-conditioned mode considering usage pattern of spaces, three types of cooling and ventilation systems have been installed. Radiant cooling is the primary cooling system. False ceiling panels made of expanded graphite with anisotropic thermal character have been used for radiant cooling. Two types of panels with pipes have been used, one type has PolyEthelyne Cross link (PEX) pipes and the other has copper pipes embedded within expanded graphite panel. These panels carry supply and return water at temperature of 16°C and 20°C respectively. Demand-controlled fresh air supply in the space is provided by staging fresh and exhaust fans. The basement floor is supplemented by a Dedicated Outdoor Air System (DOAS) with a Heat Recovery Wheel and Digital Scroll Cooling for providing conditioned fresh air for peak cooling periods and latent loads. The HVAC system design decouples the sensible and latent heat extraction and incorporates multiple system types in the building for efficient operation. An air cooled scroll chiller of 8.2TR supplies chilled water to the radiant system, with an inverter controlled compressor to modulate the capacity of the chiller and provide Energy Efficiency Ratio (EER) of 2.9, 3.7, and 4.0 at 100%, 60%, 40% capacity respectively. The first and second floors have 8 supplementary Variable Refrigerant Flow (VRF) units for peak cooling periods and latent loads. The VRF units are 8TR with COP of 3.8, 4.52, and 6.1 at 100%, 80%, 50% capacity respectively. The digital scroll system has an EER of 3.89 for cooling.

Figure 15: Sectional view showing strategies in NZEB

The NZEB building is designed to maximize daylight inside the building throughout the day/year to ensure minimal dependence on artificial lighting. All lighting fixtures are energy efficient LEDs. A combination of ambient and task lighting provides the required illuminance for all the spaces. Task lights can be continuously dimmed (10-100%) as well as provide a change in correlated colour temperature (CCT) of light – this enables the users to personalize their lighting environment and save electricity.

Strategy 4: Building Energy and Indoor Environment Management, Controls and Communications

The building incorporates array of high accuracy sensors and sophisticated control strategies such as demand controlled ventilation, economizer based on enthalpy, chilled water reset, heat recovery wheel optimization algorithm, and chiller performance optimization for building operation and research level monitoring. Modular and flexible control system allows conducting various research experiments on building performance optimization. The HVAC equipment has controllers with networking capability for continuous monitoring and control of the equipment through a BMS network. The energy meters setup to monitor energy consumption by zones and end uses are networked and linked to the BMS system for continuous monitoring. Key energy and operational parameters such as current building operation, energy generation and energy consumption of the building is continuously displayed on a screen at the first floor. Polycrystalline SPV with efficiency of 15.34% and capacity of 30kWp is installed on south facing sloping roof. Electricity generated from SPV is supplied to the internal grid of CEPT University campus.

Indoor Design conditions: 26°C DB, <60% Relative Humidity

Outdoor Design conditions: Cooling - 41°C dry bulb temperature, 23.2°C mean coincident wet-bulb temperature (ASHRAE 2005 Fundamentals, 1% Cooling); Dehumidification - 26.6 Dew Point, 22.3 Humidity Ratio, 29.9°C mean coincident dry bulb temperature (ASHRAE 2005 Fundamentals, 2% Dehumidification)

4.2 Project timeline

Parameters	*Initially planned*	*Actual execution*
Conception	July, 2011	July, 2011
Start of architectural design	October, 2011	October, 2011
Start of work on site	September, 2012	September, 2012
Project completion	December, 2014	March, 2015

4.3 Form and space planning

The NZEB has a site area of 386 sq. m. and a built up area of 800 sq. m. The long sides of the facility face due north and south.

Space layout for NZEB is distinctly divided for specific purposes:

- Basement has a Thermal Comfort Chamber, Seminar Room and Conference Room as well as two Courtyards on either side for providing light, ventilation and multipurpose use.
- Ground Floor has a dedicated space for building systems such Chillers, AHUs, Electrical Panels along with other equipment for radiant cooling system. It also has a large multipurpose semi-open space.
- First Floor houses the admin area and meeting space. Majority of the first floor space is dedicated for equipment such as Guarded Hot Box, Climate Chamber, Single Patch Sky Simulator, Mirror Box, etc. which are integral part of the Material Testing Facility at CARBSE. It also has BMS and control panel. A bridge connects First Floor to CARBSE's existing research facility.
- Mezzanine Floor overlooks the first floor and has workstations for researchers and meeting space.

Figure 16: NZEB exterior perspective views

Figure 17: NZEB Basement plan

Figure 18: NZEB Ground floor plan

Figure 19: NZEB First floor plan

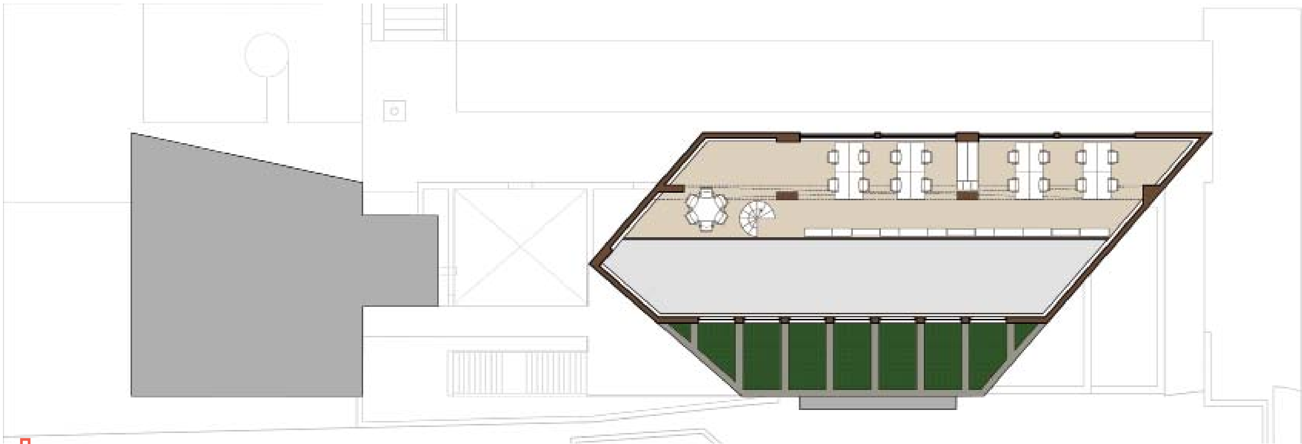


Figure 20: NZEB Mezzanine floor plan

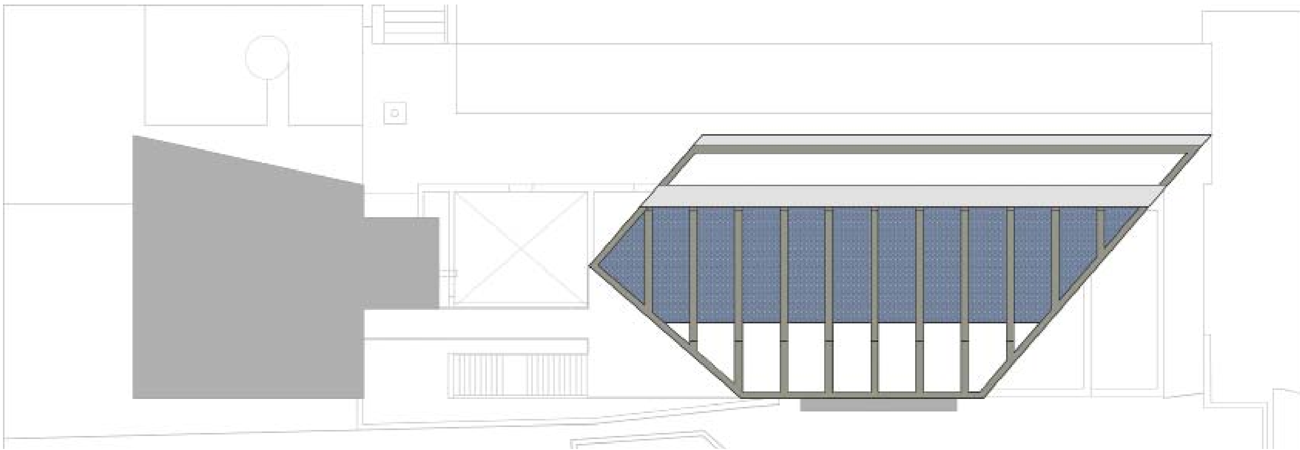


Figure 21: NZEB Roof plan

Figure 22: NZEB Building section

Figure 23: NZEB Building section

4.4 Envelope

The building envelope is designed to provide an opportunity to operate building in natural ventilation, temporal mixed mode and air-conditioned mode. Successful attempt was made to downsize mechanical cooling demand and electric lighting. Walls and roof have external insulation and higher internal thermal mass. Building is targeted to provide thermal comfort as per India Model for Adaptive Thermal Comfort (IMAC) in all three modes of operation.

The ceiling concrete in the building contains fly ash contents to minimum embodied energy of the building.

Double glazed high-efficiency windows have been installed in the building. The operable windows have been installed near occupant sitting to provide them opportunity to get fresh air as well as to provide them adaptive measures for control.

4.4.1 Material and construction details:

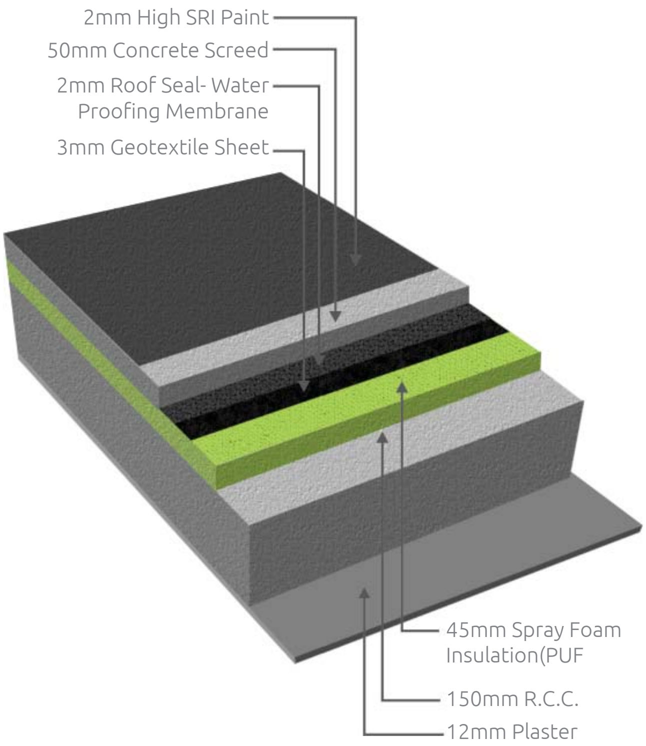
NZEB has a very high performance external envelope. It is a RCC frame structure with thick in-fill walls. All the external surfaces (exposed floor, wall and roof) are well insulated as well as provide high thermal mass inside.

Table 3: Envelope details

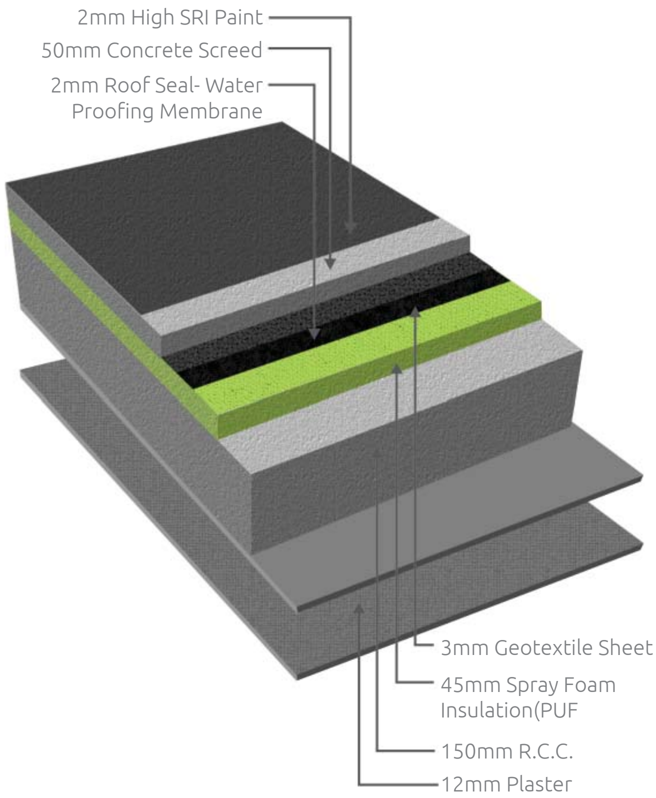
Elements	Details
Exterior exposed walls	110mm of exposed brickwork on the outside followed by 50mm XPS insulation and 230mm brick wall on the inside (U = 0.42 W/m2K).
Basement Retaining wall	230mm RCC with waterproof plaster on the outside
Internal walls	None; it is one open space without any opaque partitions.
Internal surfaces	Plastered and painted with putty finish
Floor slabs	Made from 150mm RCC. RCC has a 50mm cement sand bedding upon which polished Kota stone is laid. The first floor slab, which is exposed to the outdoor conditions due to absence of an enclosure on ground floor, has 50mm XPS insulation at the bottom with FEWEIS finish on the outside (U = 0.548 W/m2K).
Roof	Made of 150mm RCC with PENETRON waterproofing and a 45mm spray foam (PUF) insulation, geotextile sheet, 50mm concrete screed and high SRI (value 103) paint on the top (U = 0.38 W/m2K). It has inverted beams with 50mm XPS exterior insulation and 50mm concrete screed painted with high SRI paint.
Peripheral beams	100mm XPS insulation on the inside
Windows	Double glazed units (DGUs) with AIS-Ecosense-Exceed-Clear vision 6mm low-e glass (VLT = 0.39; SHGC = 0.29) and 12mm air gap (U = 1.7 W/m2K).

Design detailing with a 110x150mm ledge supports exposed brick work wall and makes continuity of insulation possible. Thermal bridging around windows and other critical structural areas has been minimized. Most of the windows face south and north to minimize glare and direct solar radiation and to maximize daylight. Windows on south have a deep projection for shading. Window-to-wall ratio (WWR) on south facade is about 10% and on north is 90%. East and west facing windows in the basement are well shaded by adjacent retaining walls and trees. (Rawal, Vaidya, Manu, & Shukla, 2015)

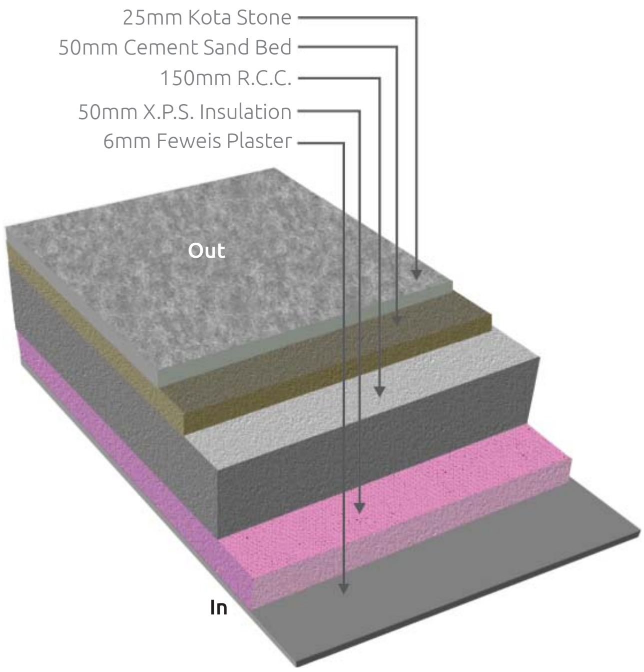
1.1 ROOF ASSEMBLY
u - VALUE (W/m²)=0.38
R - VALUE (m² .K/W)=2.654



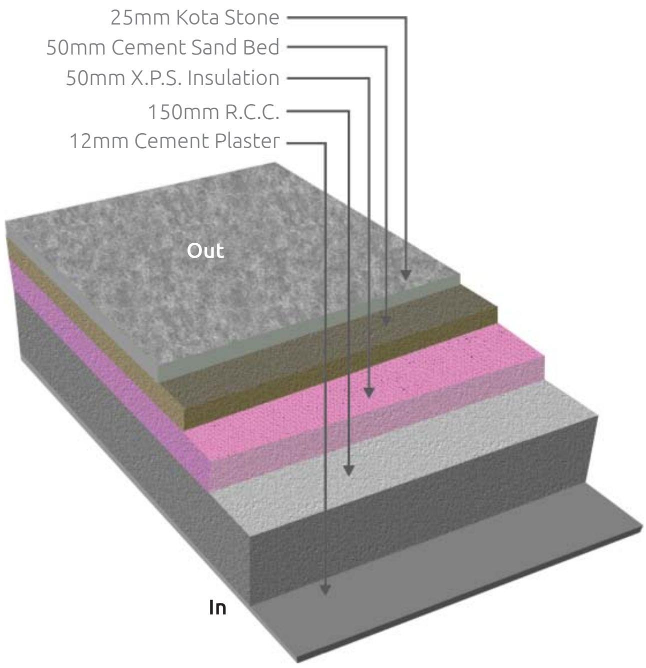
1.2 ROOF ASSEMBLY
u - VALUE (W/m²)=0.38
R - VALUE (m² .K/W)=2.654



2.1 FLOOR- First Floor
u - VALUE (W/m²)=0.55
R - VALUE (m² .K/W)=1.82



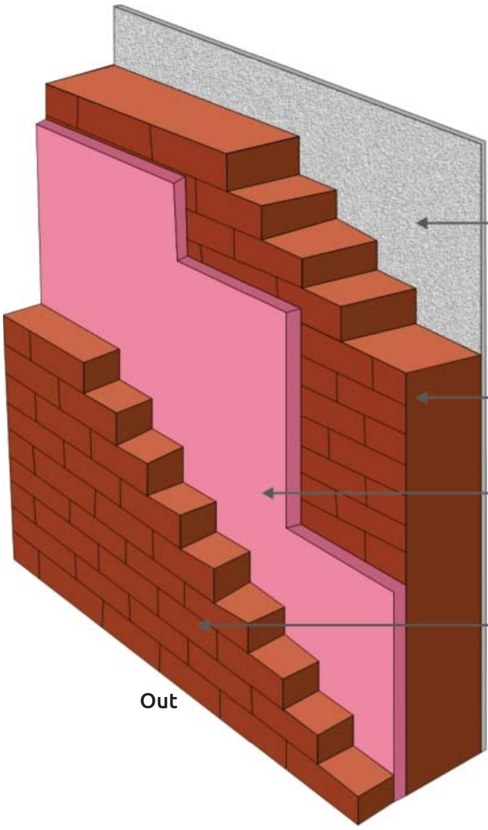
2.2 FLOOR- First Floor
u - VALUE (W/m²)=0.55
R - VALUE (m² .K/W)=1.82



3.1 WALL SUPER STRUCTURE

u - VALUE (W/m²)=0.42

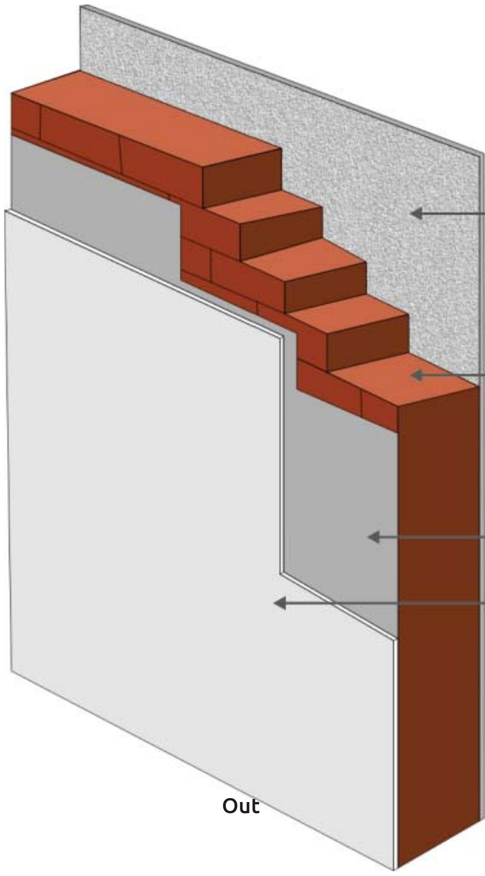
R - VALUE (m² .K/W)=2.38



3.2 WALL BASEMENT

u - VALUE (W/m²)=2.01

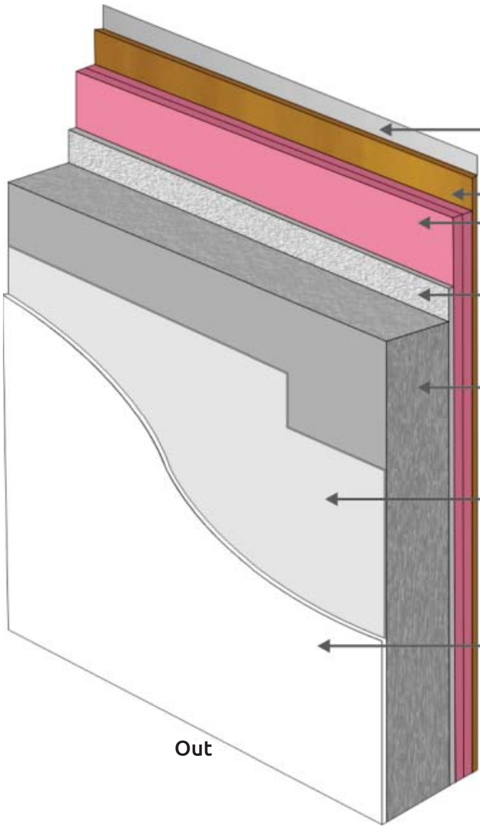
R - VALUE (m² .K/W)=0.50



3.3 WALL BASEMENT

u - VALUE (W/m²)=0.28

R - VALUE (m² .K/W)=3.59



3.4 WINDOW

u - VALUE (W/m²)=1.70

R - VALUE (m² .K/W)=0.588

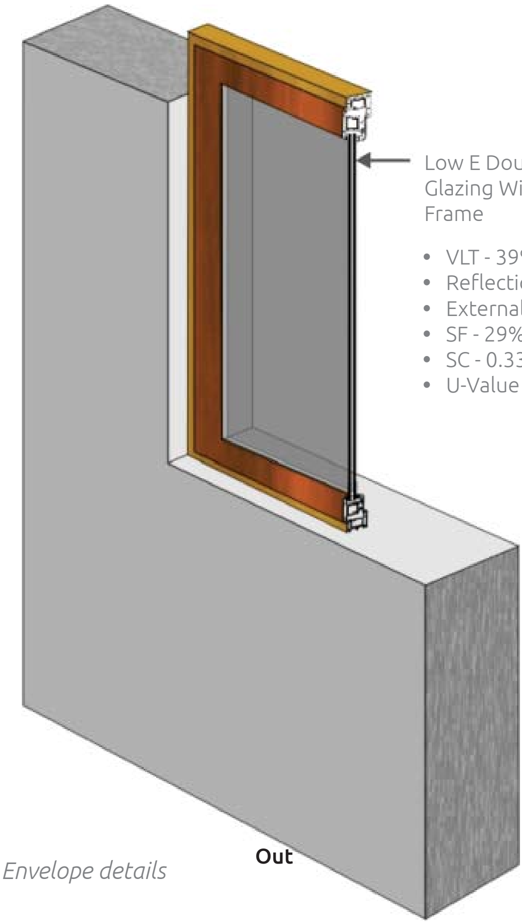


Figure 24: NZEB Envelope details

4.5 Systems

4.5.1 HVAC systems

The HVAC system design separates the sensible and latent heat extraction and incorporates multiple system types for efficient operation. Three types of cooling and ventilation systems installed are:

1. Radiant cooling is the primary cooling system. False ceiling panels made of expanded graphite with anisotropic thermal character have been used for radiant cooling. An air-cooled scroll chiller supplies chilled water to the radiant system, with an inverter controlled compressor to modulate the capacity of the chiller. Demand-controlled fresh air supply in the space is provided by staging fresh and exhaust fans.
2. The basement floor has a Dedicated Outdoor Air System (DOAS) with a Heat Recovery Wheel and Digital Scroll Cooling for providing conditioned fresh air for peak cooling periods and latent loads.
3. The first and second floors have supplementary Variable Refrigerant Flow (VRF) units for peak cooling periods and latent loads.

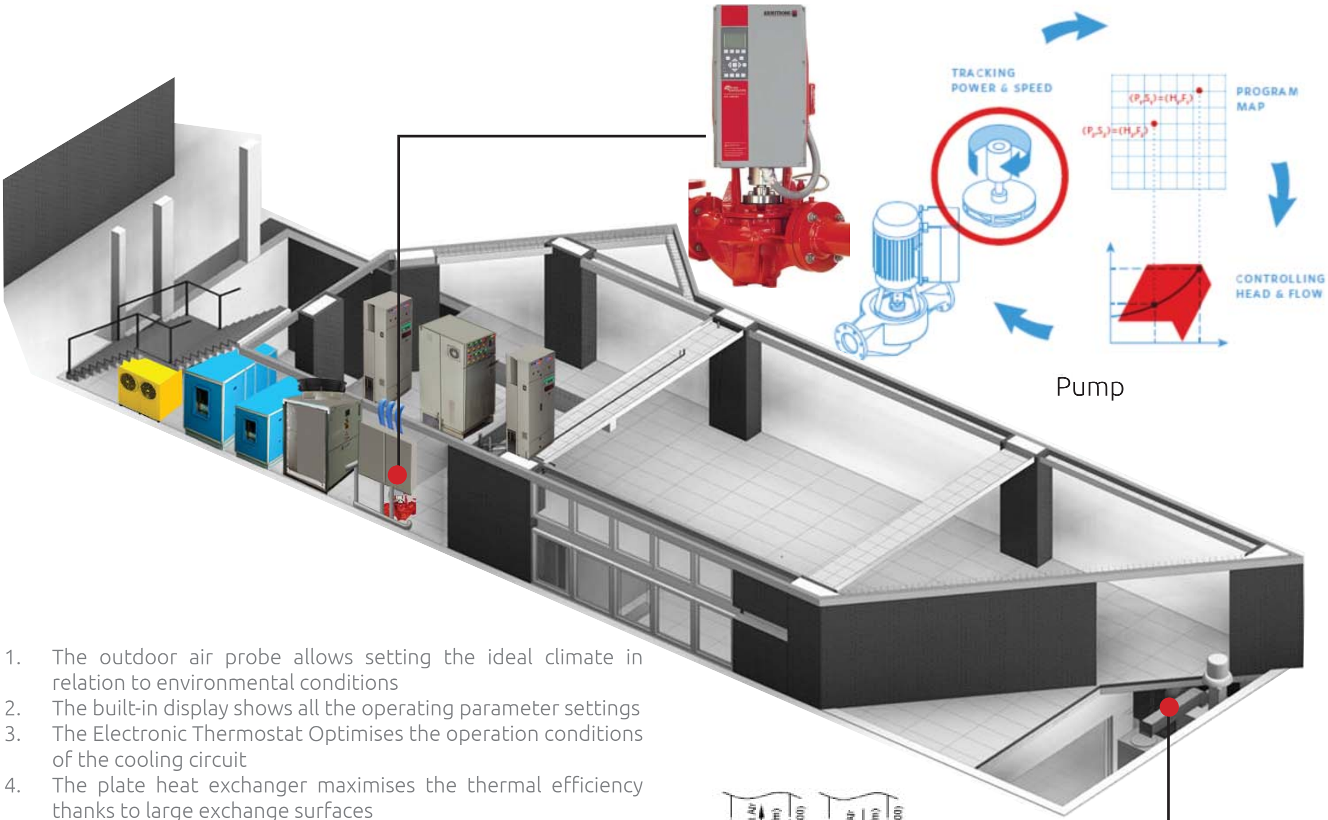
The total air-conditioned area of the building is 416 sq.m. The building contains a radiant cooling system as a primary mode of cooling. The first and second floor have 8 variable refrigerant flow (VRF) units to supplement during peak cooling periods and for latent loads. Fresh air in the space is provided by staging fresh and exhaust fans. The basement floor is supplemented by dedicated outdoor air units with digital scroll cooling system for bringing conditioned fresh air for peak cooling periods and latent loads. The HVAC system philosophy decouples the sensible and latent heat extraction and incorporates multiple system types in the building for efficient operation. The secondary system has been specifically selected to be a non-water based variable flow variable capacity system to avoid installing and operating multiple chillers with different set point requirements (radiant with 16/20˚C and chilled water loop with 7/12˚C).

The radiant ceiling panels are lightweight and contain expanded natural graphite materials with embedded water pipes designed for 15˚C supply and 20˚C return water temperatures. The ceiling radiant panels were selected instead of slab integrated radiant panels to decouple system and building costs as well as to provide opportunity to modify radiant panel design, layout, and operation for research. The VRF units on first and second floor are served by 8TR outdoor units with COP of 3.8, 4.52, and 6.1 at 100%, 80%, 50% capacity respectively. The building contains silent and high efficiency fans to directly supply fresh air as well as to exhaust air from the first and second floors. The fans are also positioned to create an artificial draft to operate in night ventilation mode.

The dedicated outdoor unit (DOAS) has a heat recovery wheel to meet the fresh air requirements for the meeting rooms in the basement. This DOAS has been customized to re-circulate return air when expected benefits from heat recovery wheel are not significant. DOAS is connected to a digital scroll system, with energy efficiency ratio (EER) of 3.89 for cooling and COP of 4.1 for heating, as a supplemental air conditioning system. While heating is not needed in Ahmedabad, heating capability has been incorporated for research experiments.

High efficiency air cooled scroll chiller of 8.2TR has been installed to supply chilled water to radiant system. Inverter controlled compressor in the chiller can continuously and efficiently modulate the cooling capacity of the chiller. At 15˚C supply temperature and outdoor temperature of 35˚C, the chiller is expected to provide 2.9, 3.7, and 4.0 EER (EER EN14511) at 100%, 60%, 40% capacity respectively. High efficiency pump with variable speed drive is integrated with the chiller to deliver chilled water through the radiant system. (Rawal, Vaidya, Manu, & Shukla, 2015)

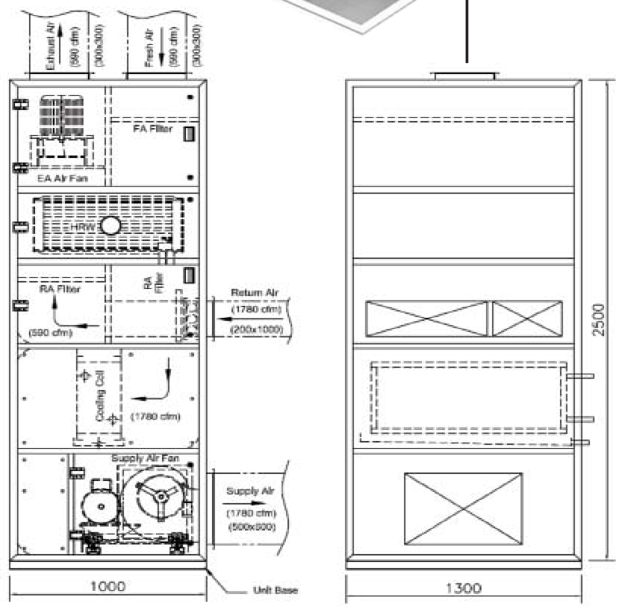
Figure 25: HVAC System details



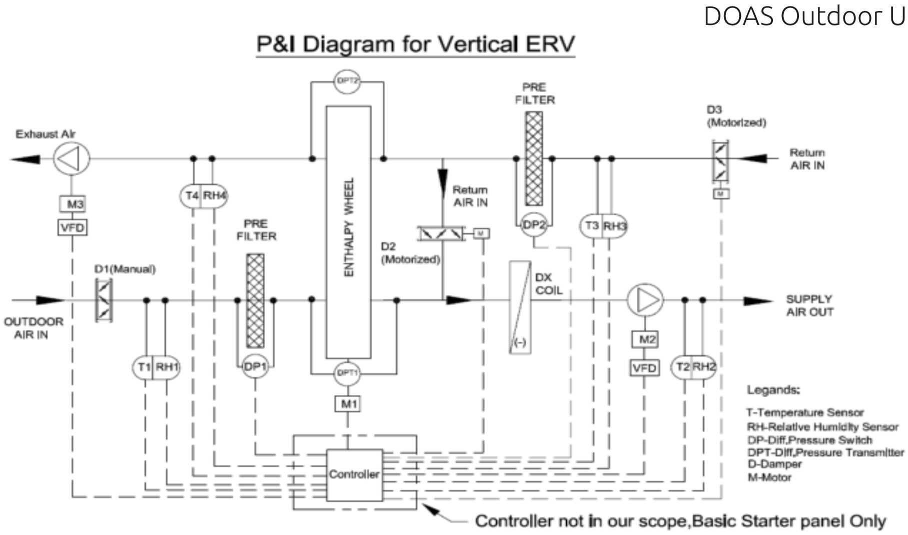
Pump

1. The outdoor air probe allows setting the ideal climate in relation to environmental conditions
2. The built-in display shows all the operating parameter settings
3. The Electronic Thermostat Optimises the operation conditions of the cooling circuit
4. The plate heat exchanger maximises the thermal efficiency thanks to large exchange surfaces
5. The Inverter DC Compressor allows high seasonal efficiency thanks to the modulation
6. The optimized fan profile guarantees extremely quiet operation in every operating mode. The fan varies its speed according to the conditions, increasing its quiet operation.
7. The Hydrophilic Battery ensures a better cleaning maintaining thermal exchange efficiency and reduced defrost time

Chiller



DOAS Outdoor Unit



Digital Scroll

Figure 26: HVAC System details

4.5.2 Photovoltaic (PV) systems

NZEB solar generation started 15th Dec 2015 onwards. Solar Photovoltaic system of 30kWp capacity is installed on south facing sloping roof. The system is connected to Internal Grid of CEPT University campus and the generated electricity is used within the Campus. The system is connected with BMS for data collection and monitoring the performance. Each polycrystalline PV panel of 1975mmx990mm has rated capacity of 300Wp.

For NZEB, the data distribution of solar generation varies consistently between 80 to 160 kWh. For generation the mean always lies below median. The upper quartile of the energy generation always lies above 100 kWh. Upper quartile of consumption lies above 50 kWh. (Dec 2015- Apr 2016) (Behera, Rawal, & Shukla, 2016)

Figure 27: NZEB Terrace with PV panels

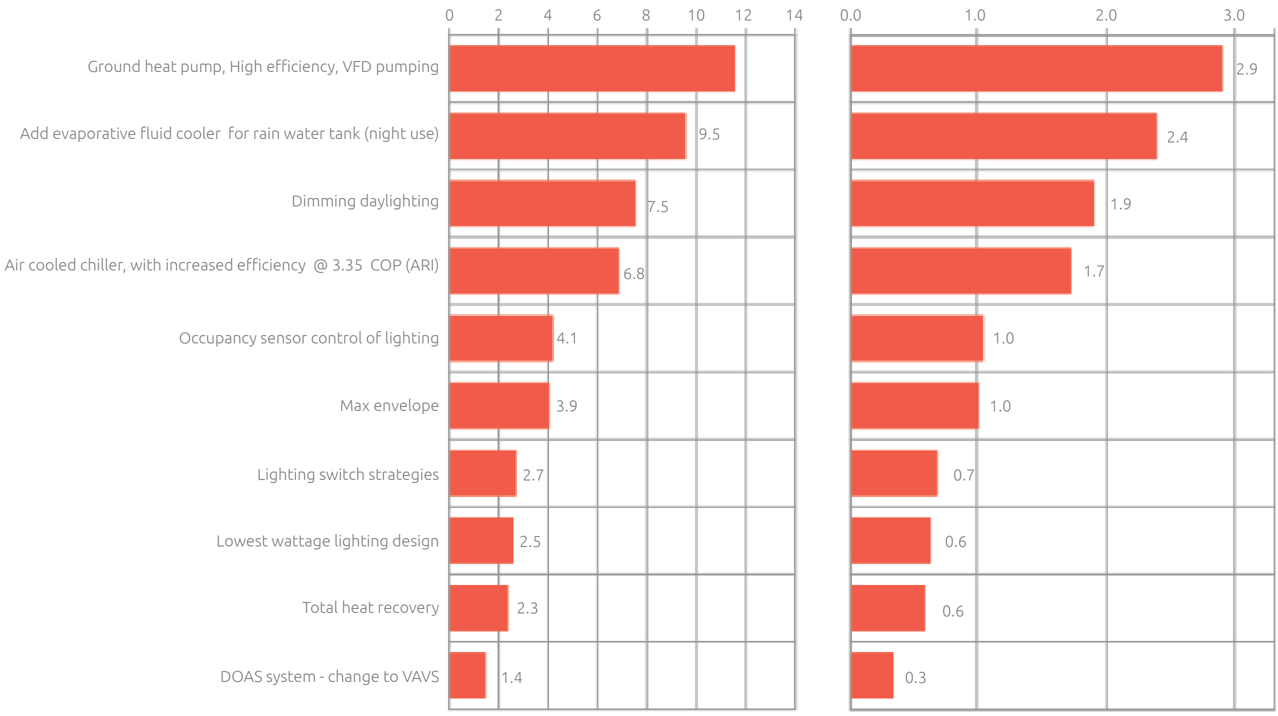


Figure 28: Parametric Simulation for System Optimization-Best opportunities for energy savings and reducing PV capacity (Vaidya & Ghatti, 2017)

4.5.3 Lighting and Daylighting

The building is designed to maximize daylight inside the building throughout the year to ensure minimal dependence on artificial lighting and improve occupant health and wellbeing as well as productivity. All rooms in the building are designed to achieve a 75% Daylight Autonomy (continuous) for 75% of the room at 300 Lux.

Spaces are illuminated by a combination of ambient and task lighting, along with occupancy sensors. All work desks and meeting tables have LED electric task lights with personalized control. Task lights can be continuously dimmed as well as provide a change in correlated colour temperature (CCT) of light to allow the users to personalize their lighting environment. This gives excellent control to users to personalize lighting condition as well as save electricity.

Common areas and passages have wall mounted LED light fixtures with indirect lighting for ambient illumination as well as emergency and occupancy sensors. All fixtures have LEDs to minimize energy consumption. The average lighting power density in the building is 2.0 W/m2. The first and second floors contain a switch in the space controlling manual, off, or auto operation of ambient lights. In auto mode, the lights in common office areas and passages are turned off based on occupancy sensors. The conference and seminar rooms in the basement are also fitted with occupancy sensors but used for monitoring only. Total connected lighting load of the building is 2196W ($2.7W/m^2$). (Rawal, Vaidya, Manu, & Shukla, 2015)

Figure 29: NZEB inside view

05 VISUAL DOCUMENTATION

5.1 During Construction


January 2013


May 2013

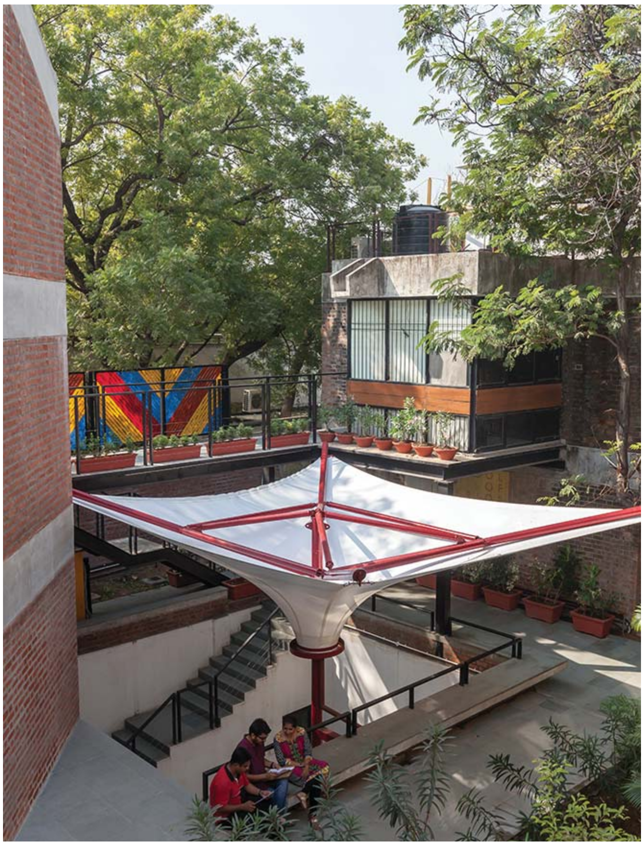

June 2013


December 2013


April 2014


June 2014

5.2 Post-construction



06 BUILDING OPERATION

NZEB serves as a test-bed not only during the design and construction phase, but also during its operation and usage. The building operates as per the following schedule:

Office: 08:30 to 18:30 hours – 250 days/year
Seminar room: 09:30 to 17:30 hours – 100 days/year
Test labs: 09:30 to 17:30 – 250 days/year

The building is either operated in natural ventilation mode, mixed mode, or mechanical system mode based on outdoor weather and indoor comfort conditions. The building operators have the ability to configure various indoor comfort condition algorithms (such as custom adaptive thermal comfort equation or a PMV model based algorithm) in the building control system to determine suitable indoor comfort conditions.

In natural ventilation mode, the active air-conditioning system is turned off and chimney windows are opened to create a draft to cool the building naturally.

When the indoor environment does not meet the comfort requirements for specified length of time, the operation switches to mixed mode; windows are opened and artificial supplemental draft is also created using pedestal and exhaust fans in the building. The objective in mixed mode operation is to ensure that the building is switched to mechanical system mode only when needed.

In mechanical system mode, the primary system (active radiant system) and fresh air fans are first turned on to maintain indoor thermal comfort conditions. If the primary cooling system is unable to achieve comfort conditions in the space, secondary cooling system (VRV for the first and second floor, and DOAS in basement) is turned on. In mechanical system mode, the building incorporates demand based ventilation controls where fresh air is modulated to maintain CO_2 levels in the space.

The algorithms and conditions that are most suitable to operate the building in natural, mixed and mechanical system modes are continuously tested at the laboratory through a sophisticated Building Management System (BMS). One of the key research areas is to determine the appropriate time for switching over between the three modes. (Rawal, Vaidya, Manu, & Shukla, 2015)

Electrical system is divided into five parts with separate wiring lines for each - Lighting, HVAC, Plug Loads, Equipment Loads and Solar PV Panels. This enables efficient sub-metering using smart energy meters with RS485 communication facility for integration with BMS.

07 POST CONSTRUCTION MONITORING AND CONTROL

To achieve the goal, NZEB contains a sophisticated and flexible control system named Building Management System (BMS) that can support continuous research experiments on building monitoring and performance optimization. The control system in the building is designed to meet the following objectives:

a. To serve as a single platform for monitoring and controls in the building
b. To provide test bed for development of new technologies and control algorithms To integrate with test chambers for effective operations and controls
c. As shown in Figure 30, the control system is mainly divided in four components – monitoring, integration, controls, and display.

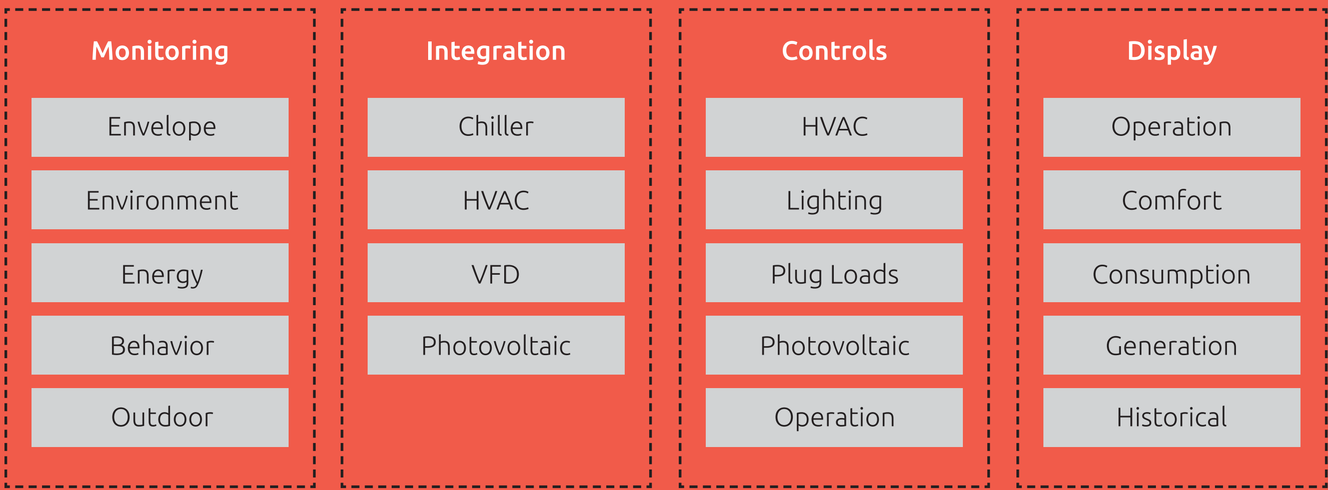


Figure 30: Conceptual diagram of monitoring and control system through BMS in the NZEB

The controls in this building incorporate an array of high accuracy sensors for research level monitoring as well as sophisticated and flexible control system for conducting various research experiments on building energy efficiency.

Monitoring component incorporates high accuracy research grade sensors to continuously monitor building performance and occupant comfort. Air conditioning and envelop monitoring system contains built-in controllers with networking capabilities (Ethernet port) and are integrated with the building management system. Envelope, energy, and environment systems have been specified with built-in controllers for integration with the building control system.

Building controls system continuously monitors installed components and uses efficient algorithms to optimize building performance. Key energy and operational parameters (such as building information, current operation, historical energy consumption, and current energy consumption) are continuously displayed on display screen located on the first floor.

All plug loads in NZEB are monitored using Smart Power Strips, which provide information for device IDs, usage time, and electricity consumed for each equipment on the desk. Smart Power Strips are connected to a centralized server through Wi-Fi, which stores the data for every minute. Smart strips allow detailed understanding of usage pattern for various types of connected devices as well as provide load profile for entire building to develop strategies for plug load management.

Electricity generated by solar panels and energy used in the building operations and research experiments is measured and monitored by using Smart energy meters[1] connected with BMS.

Table 4: Details of monitoring and control strategies (Rawal, Vaidya, Manu, & Shukla, 2015)

System	Key monitoring and control points	Key control strategies
Envelope	Temperature, Heat flux	Monitoring only
Environment	Air & globe temp, RH, CO2, room pressure	Adaptive, PMV, and temp/RH based algorithm; optimum building mode
Energy	Voltage, current, power factor, etc.	Monitoring only; energy signatures for system operation
Behaviour	Window contacts, vacancy, fan operation, comfort vote	Light control, personalized control
Radiant	Surface temp, dew point, valves	Variable flow constant setpoint, constant flow variable setpoint
Supply and ventilation fans	Pressure, flow, status, current, and temp	Demand based ventilation
Variable refrigerant units	loading, operation, power and efficiency	System operation optimization based on energy and comfort
Air cooled chiller, DX scroll, DOAS	loading, operation, power and efficiency, Temp, RH	System optimization based on efficiency curve and building demand
Chilled water loop	Operation, power, temp	Supply temp setpoint reset
Outdoor	Temp, RH, wind velocity & direction, solar radiation, rain gauge	Economizer mode; optimum building mode
PV generation	Temp, power, efficiency	Load distribution based on demand

Figure 31: BMS interface for the whole building

[1] EM6400 Schneider smart energy meters have been enabled with RS485 Modbus communication protocol. Energy meters measure True RMS, one second update time, four quadrant power and energy. The accuracy for meters is Class 1.0 as per IEC 62052-11 and IEC 62053-21; Class 0.5S (Optional) as per IEC 62052-11, 62053-22; Class 0.2* (optional).

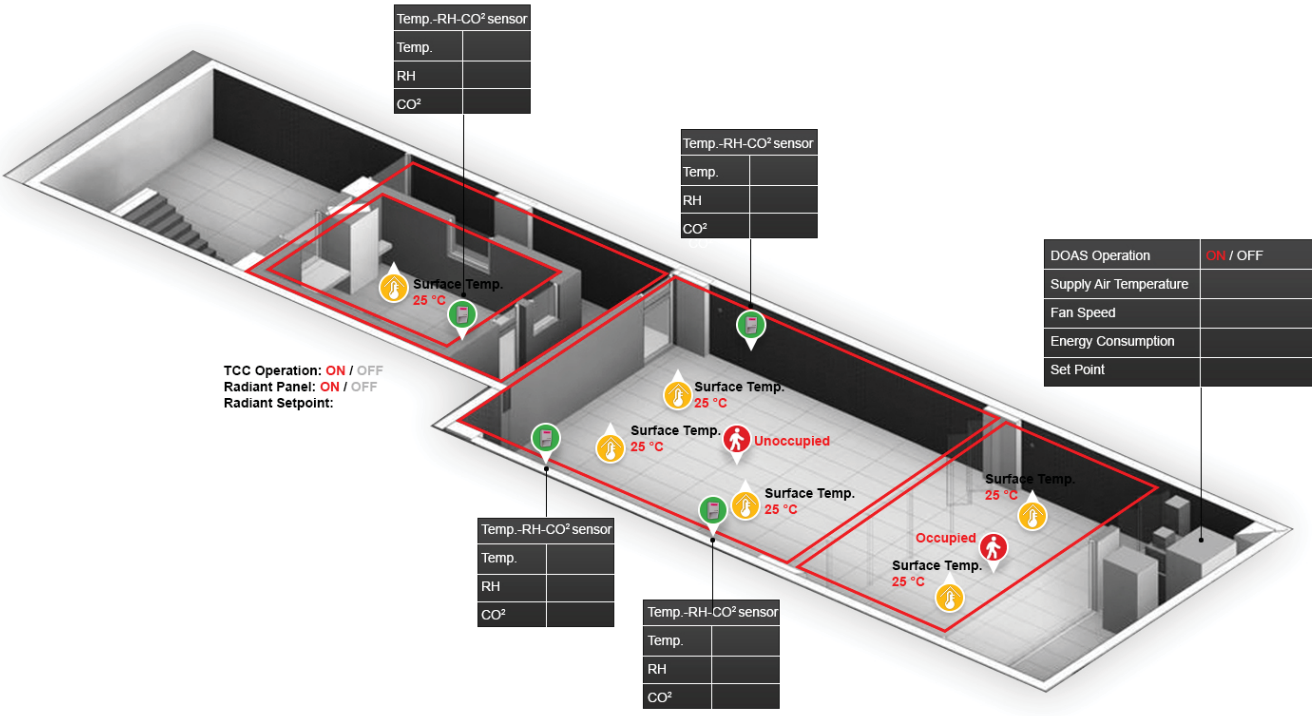


Figure 32: BMS dashboard for the Basement

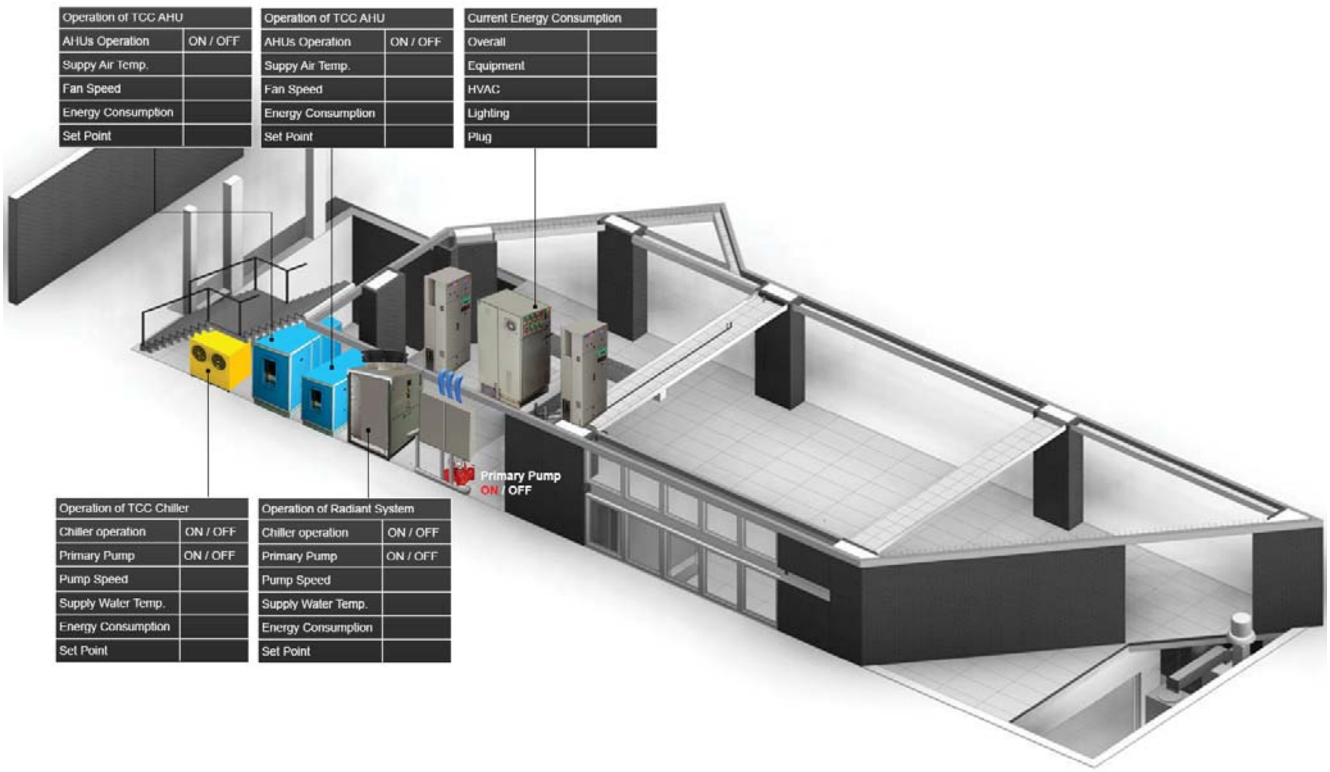


Figure 33: BMS dashboard for the Ground floor

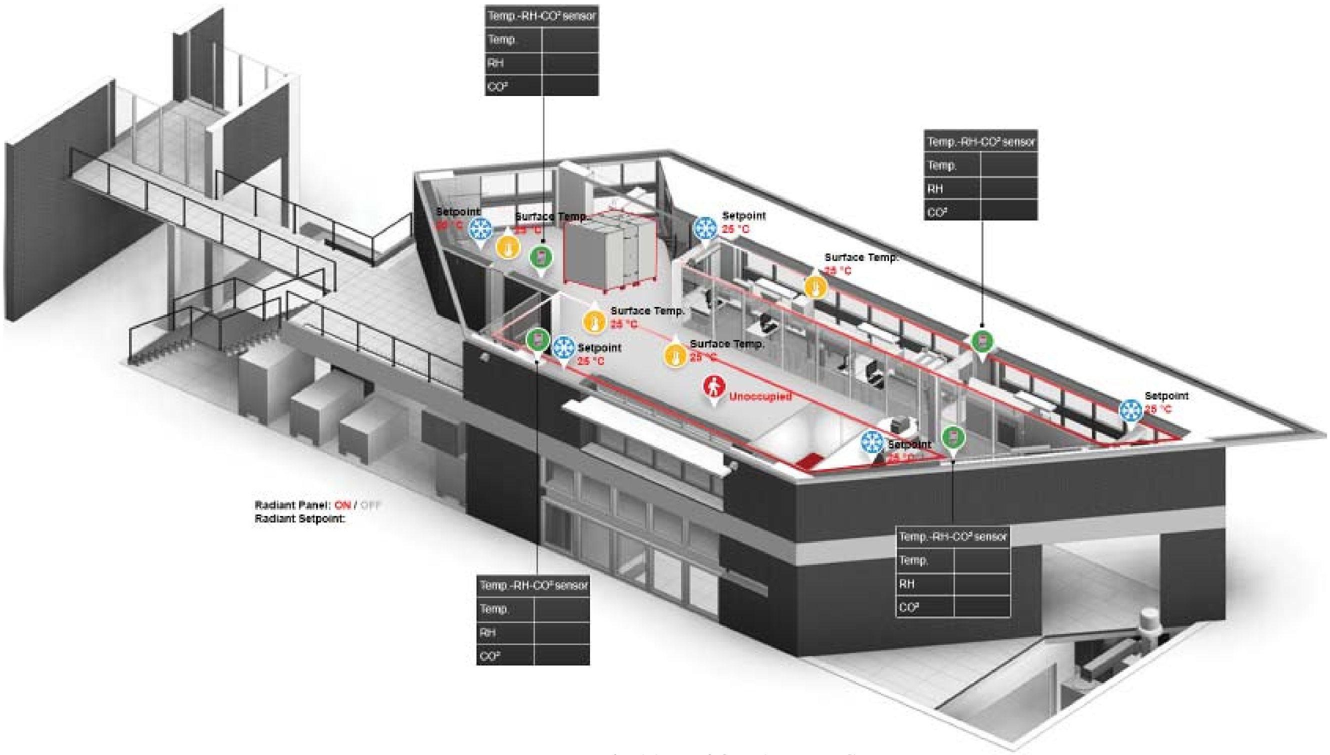


Figure 34: BMS dashboard for the First floor

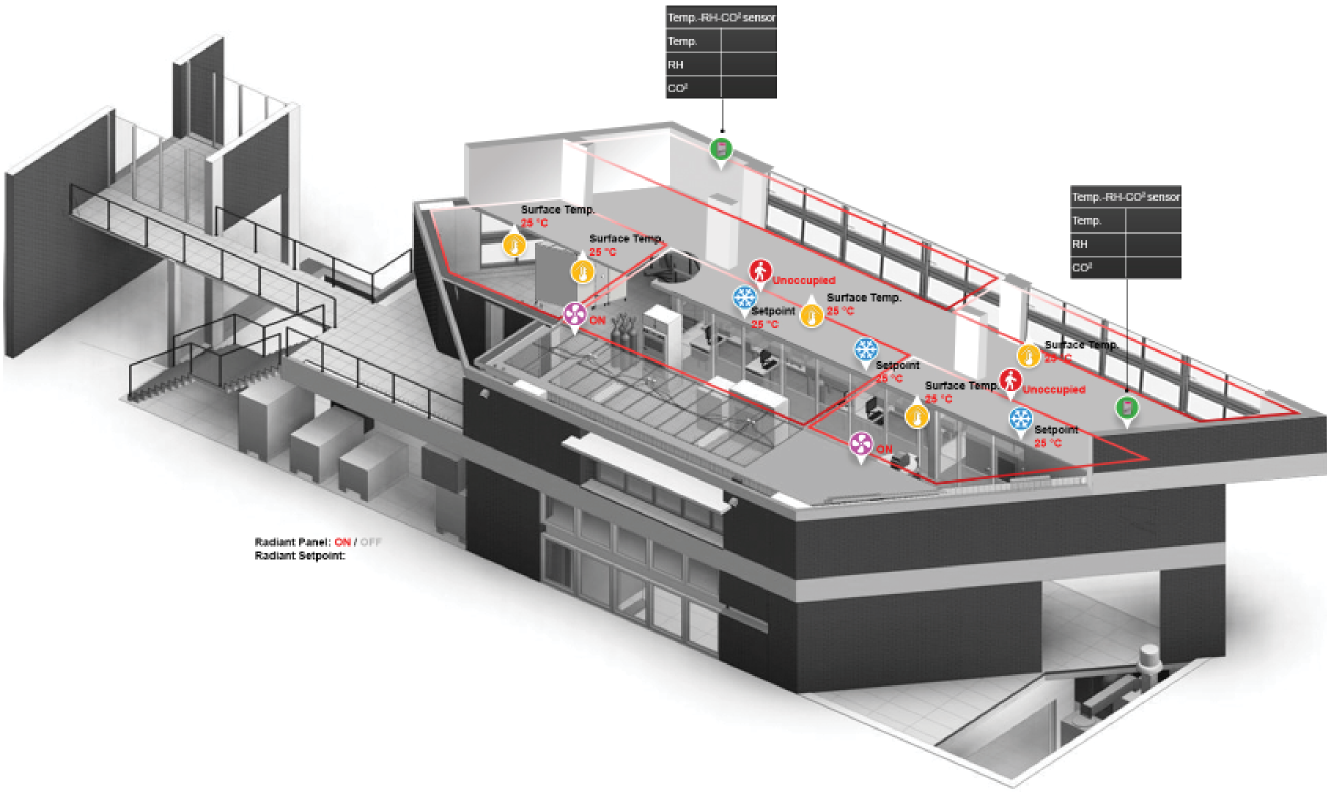


Figure 35: BMS dashboard for the Second floor

7.1 Envelope and Environment monitoring

Environment monitoring incorporates both indoor environment as well as outdoor environment. For NZEB, building and system level sensors along with data loggers are used for monitoring the indoor environment and the envelope. For monitoring and recording the outdoor weather data, an Automatic Weather Station was installed at CEPT University.

7.1.1 Data loggers for environmental parameters

There are 48 sensors in the building used to measure dry bulb temperature, relative humidity, surface temperature and globe temperature which are connected with data nodes.

Dry bulb temperature, relative humidity and surface temperature

Data nodes[2] are used to measure dry bulb temperature, relative humidity and surface temperature. They wirelessly transmit the data to a centralized data collection system within a self-healing mesh network.

There are two different kinds of data nodes used. One is a 4-channel wireless data node with four analog ports which is used to measure dry bulb temperature and surface temperature. The other one is a 4-channel wireless data node with DBT-RH sensor port and two additional analog ports used to measure dry bulb temperature, relative humidity and surface temperature. Both data nodes wirelessly transmit real time data to the data receiver, reducing the inconvenience associated with manual data offload. Also, there are data routers installed which are used to strengthen the communication within network between data nodes and data receiver. The data receiver is connected to the system through USB cable which can readout the data using the company software.

Dry bulb temperature is measured through TMC6-HD, TMC20-HD, and TMC50-HD temperature sensors. Relative humidity is measured through DBT-RH sensors (2m temperature-relative humidity sensor probe). Surface temperature is measured through TMC6-HE sensors. These three environmental parameters are measured at 15-minutes interval.

Globe temperature

Data loggers are standalone devices which are used to measure globe temperature and a direct USB interface is used for launching and data readout with the help of company software. It is a four-channel data logger with one analog port which is used to measure globe temperature. Globe temperature is measured through TMC1-HD temperature sensors at 1 hour interval.

7.1.2 Building and system level sensors

There are 357 sensors for building level and system level monitoring which are connected with BMS. These are used to measure dry bulb temperature, relative humidity, surface temperature of the envelope, globe temperature, occupancy, and CO2 at 1 minute interval. They help in monitoring and controlling the systems in the building. The data is stored and can be accessed and visualized using BMS.

Figure 36: HOBO logger and HOBO node installed inside NZEB

[2] The measurement range is -40°C to 70°C (-40°F to 158°F) for dry bulb and surface temperature and 0% to 100% for relative humidity. The accuracy of dry bulb and surface temperature measurement is ± 0.21°C; over 0° to 50°C (± 0.38°F over 32° to 122°F). The accuracy of relative humidity measurement is ±2.5% from 10% RH to 90% RH typical to a maximum of ±3.5% including hysteresis at 25˚C (77˚ F); ±5% typical for RH below 10% and above 90%.

In total, there are 405 sensors in NZEB as mentioned in Table 5.

Table 5: Total number of sensors

#	Type	Floor	No. of sensors	Total no. of sensors
1	BMS Sensors (Building level)	All	38	357
	BMS Sensors (System level)	All	319	
2	BMS HOBO® ZW Sensors	Basement	10	42
		First Floor	13	
		Second Floor	13	
		Roof	6	
3	HOBO® ZW Globe Sensors	First Floor	2	6
		Second Floor	4	
			Total	**405**

7.1.3 Automatic weather station

Outdoor weather data is vital to analyze the performance of the NZE building. A GSM / GPRS based Automatic Weather Station (AWS) has been installed inside CEPT campus. It is a compact, modular, rugged, low-cost system for collecting meteorological data. The AWS data logger, at the heart of the system, consists of:

- Air Temperature and Humidity Sensor (KDS-011)
- Ultrasonic Wind Speed and Direction Sensor (KDS-101)
- Atmospheric Pressure Sensor (KDS-021)
- Global Solar Radiation Sensor (KDS-051)
- Tipping Bucket Rain Sensor (KDS-071)

All the environmental data is recorded hourly by the weather station and is downloaded on a monthly basis by authorized personnel.

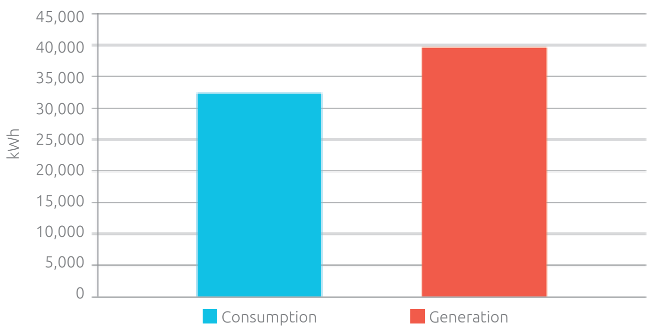


Figure 37: Actual energy consumption vs. generation through PV panels for year 2016 (Vaidya & Ghatti, 2017)

7.2 Energy monitoring

Continuous monitoring and data collection for energy and indoor environmental condition during building operation allows conducting detailed performance analysis. It also helps to calibrate simulation models. It helps in evolving optimized strategies for operation such as balancing between the use of primary (Radiant Panels) and secondary (VRF) cooling system for space conditioning. Also, it helps in comparison of energy consumption and generation through photovoltaic panels in NZEB. As depicted in Figure 37 to Figure 39, the annual solar power generation exceeds the energy consumed by the building and its systems.

The energy consumption and environmental parameters variation from October 2015 to April 2016, is shown in Figure 40 along with solar energy generation data. Here, indoor environment parameters have also been taken into consideration. HVAC for experiment indicates running of thermal comfort chamber (TCC) in NZEB, which is used to perform experiment on thermal comfort. Both outdoor and indoor temperature considered for analysis are weighted average temperature on daily basis. (Behera, Rawal, & Shukla, 2016)

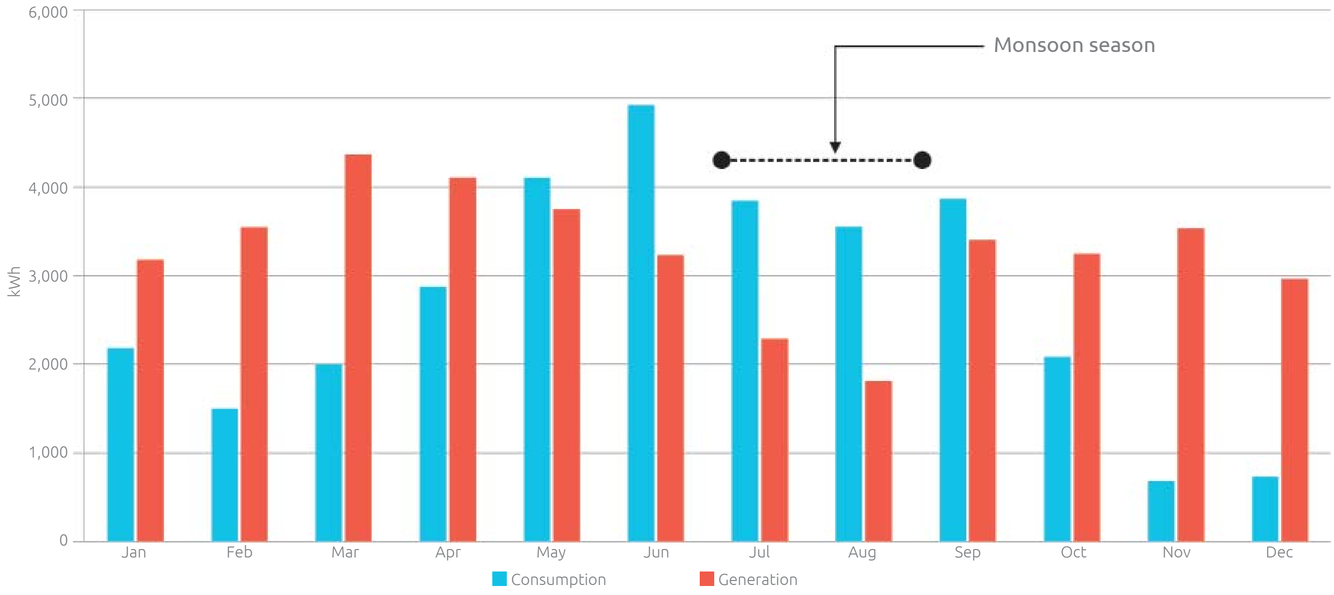


Figure 38: Monthly Energy consumption and generation statistics in the year 2016 (Vaidya & Ghatti, 2017)

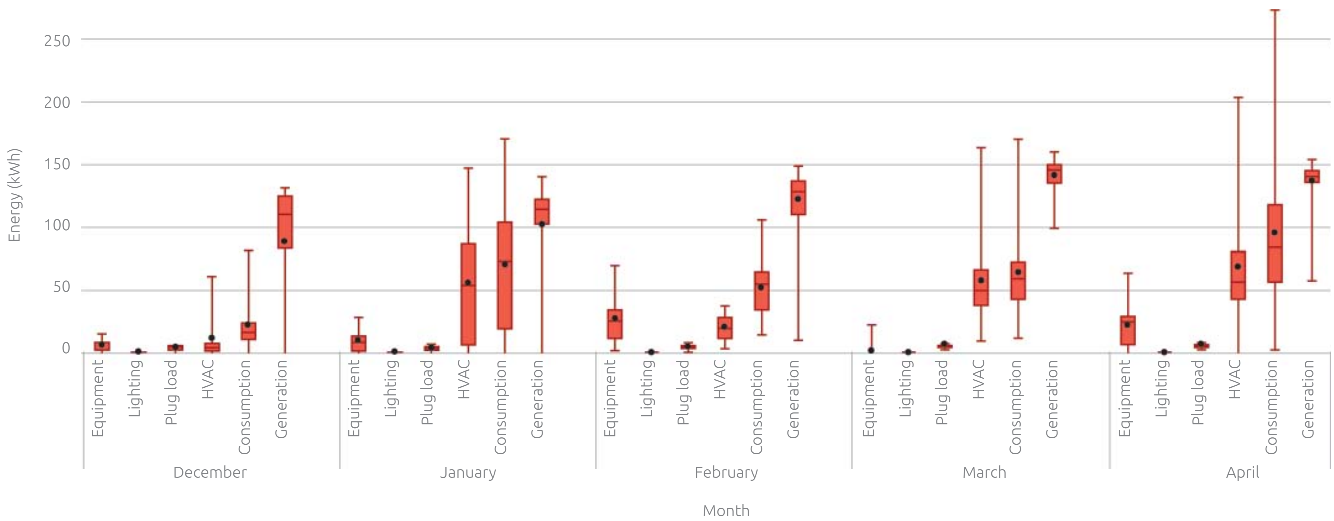


Figure 39: Whisker plot of NZEB Energy consumption and generation pattern (Dec 2015 – Apr 2016) (Behera, Rawal, & Shukla, 2016)

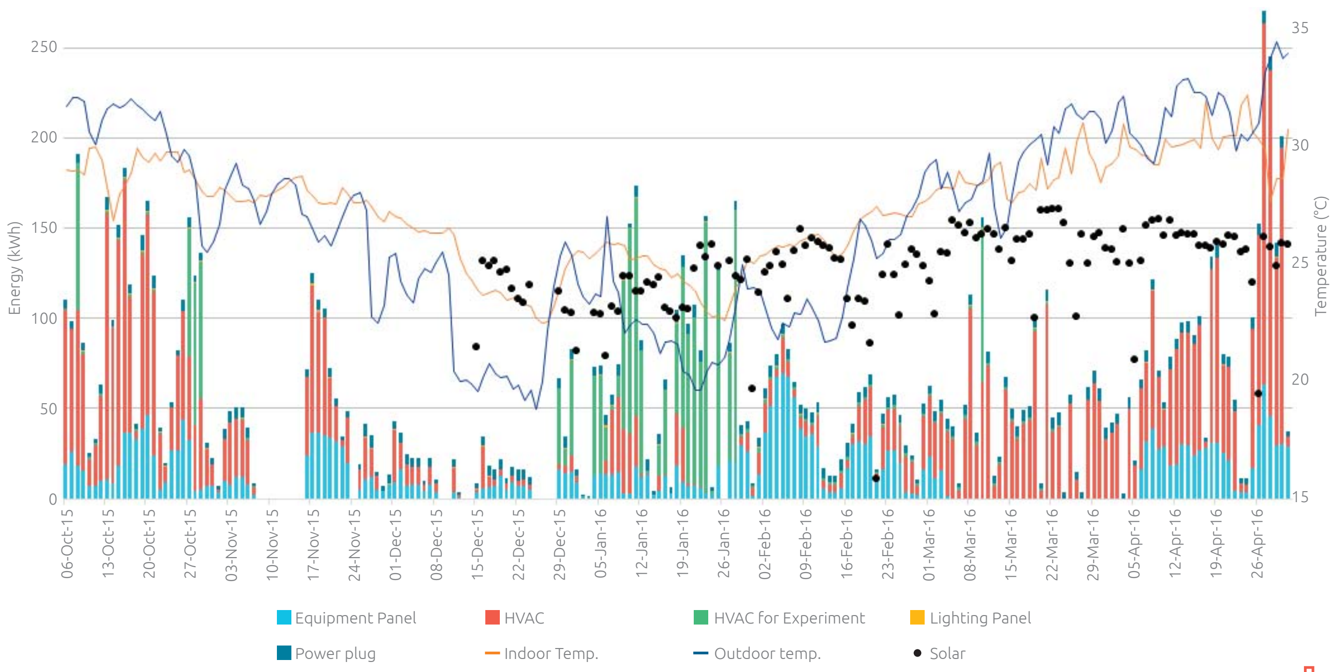


Figure 40: NZEB energy vs environment plot

Following things can be concluded from the graph in Figure 40:

- During winter (Nov 2015 – Feb 2016), the HVAC panel consumption becomes minimum.
- As the outdoor temperature increases, HVAC energy consumption increases in synchronization to that.
- It can be clearly observed that solar generation is always considerably higher than the total building energy consumption.
- Lighting load energy consumption is always negligible to other load energy consumption. It demonstrates the day lighting ability of the building.
- HVAC consumes 50%, equipment consumes 38% and power plug consumes 12% of the total energy consumption.
- At the end of April 2016, the HVAC energy consumption was a bit high as the radiant panel of the building had started on an experiment basis.
- The period when data is missing indicates holidays. There was no energy consumption during that period as the building was in shutdown mode. (Behera, Rawal, & Shukla, 2016)

7.3 Occupant behavior

Practice of appropriate strategies to achieve thermal comfort was one of the primary objectives of building the NZE building. The user experience and feedback on performance of the building is vital to establish the degree of success of the NZEB.

As part of post-occupancy evaluation, building users take daily surveys to provide feedback on thermal environment and air quality. The user feedback allows the facility manager to take informed decisions for fine-tuning building operation to provide satisfactory and healthy workspace and save energy. As an example, based on user surveys, air motion devices had been installed adjacent to the workspaces to provide personalized control over air velocity and thermal comfort.

7.4 Data analysis

In this section, the data gathered from the monitoring systems and occupant surveys over the period of a year (Sep 2016 – Aug 2017) have been analyzed under different heads.

7.4.1 Envelope surface temperatures

The building envelope is monitored by measuring surface temperature using HOBO data nodes. Following are some graphs plotted using year-long data (Sep 2016 – Aug 2017) of envelope surface temperatures of NZEB:

- **Near Admin desk (First floor)**

The graph shown in Figure 41 represents the variation in average, maximum and minimum value of inside and outside surface temperatures measured near admin desk on first floor over the year. The wall in consideration faces the south direction. It can be seen that the indoor temperatures range is significantly less compared to the outdoor temperature range during the summer months of April to June. During monsoon and winter season, the temperatures ride close to each other.

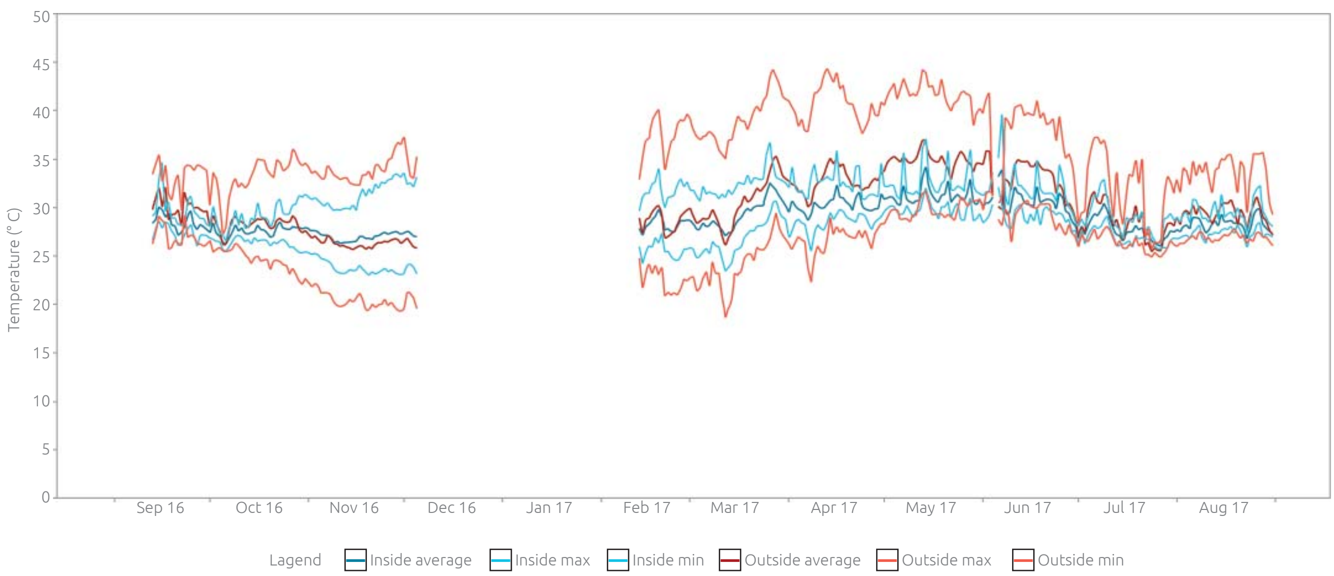


Figure 41: Surface temperature (indoor and outdoor) near admin desk on first floor

- **Equipment Chamber (First floor)**

The graph shown in Figure 42 represents the variation in average, maximum and minimum value of inside and outside surface temperatures measured inside equipment chamber on first floor. The wall in consideration faces the north direction. It can be seen that the indoor temperatures range is significantly less compared to the outdoor temperature range specifically during the summer months. During other months, the temperatures ride very close to each other.

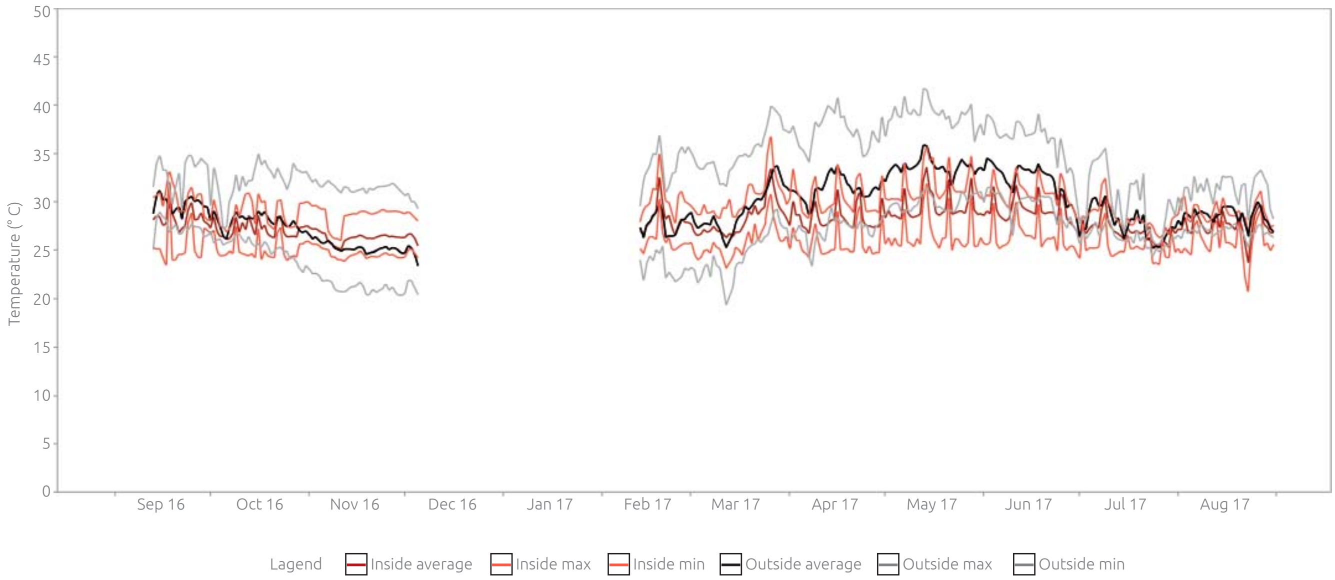


Figure 42: Surface temperature (indoor and outdoor) inside equipment chamber on first floor

7.4.2 Typical week consumption profile

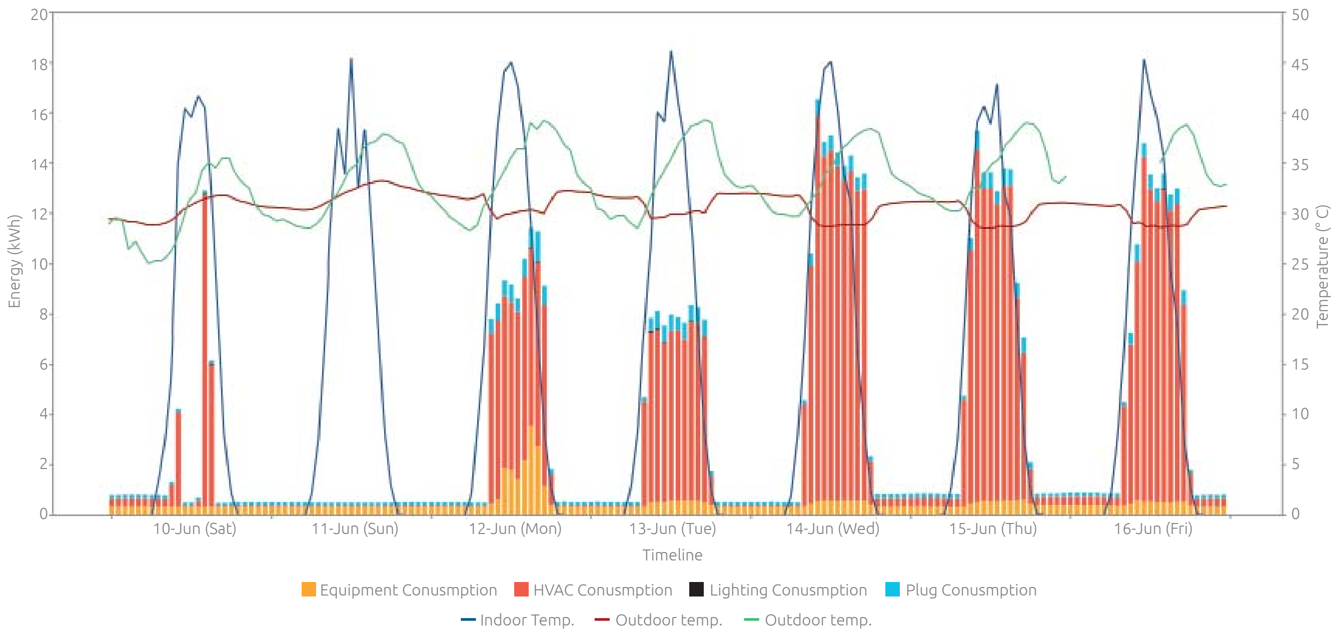


Figure 43: Hourly total energy generation and consumption profile with outdoor and average indoor temperature for a week before summer typical week

The graph shown in Figure 43 represents total energy generation and consumption with outdoor and average indoor temperature on hourly basis for a week before summer typical week (10th June 2017 to 16th June 2017).

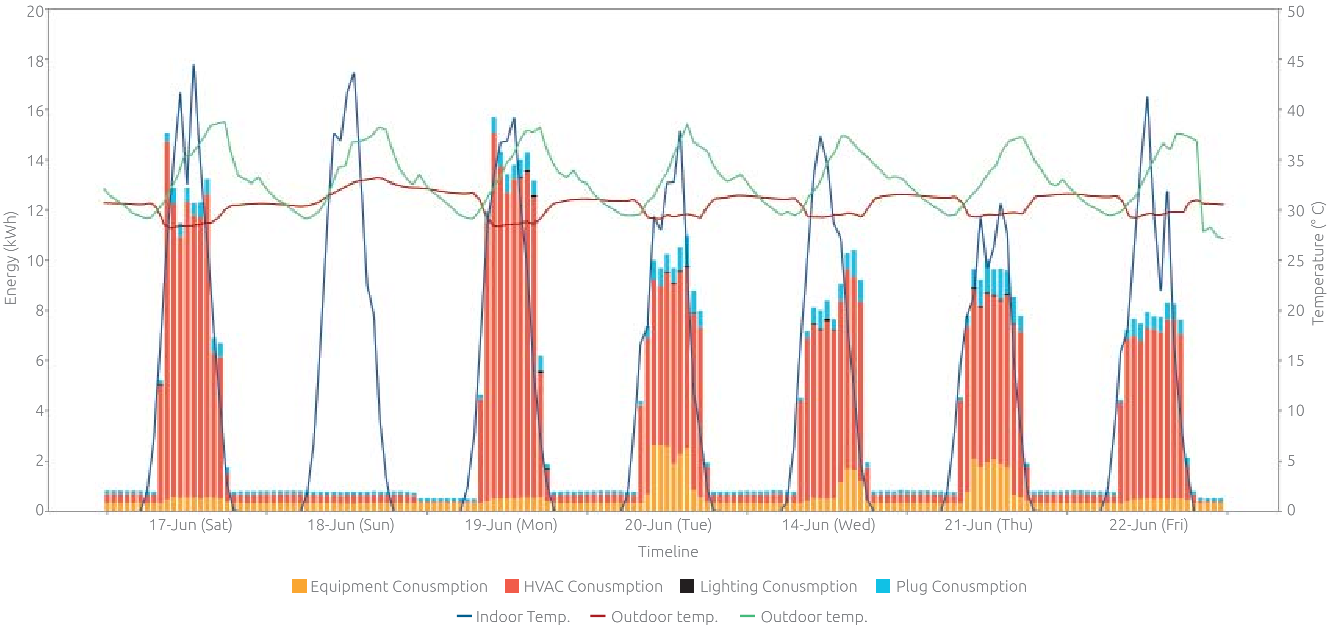


Figure 44: Hourly total energy generation and consumption profile with outdoor and average indoor temperature for summer typical week

The graph shown in Figure 44 represents total energy generation and consumption with outdoor and average indoor temperature on hourly basis for summer typical week (17th June 2017 to 23rd June 2017).

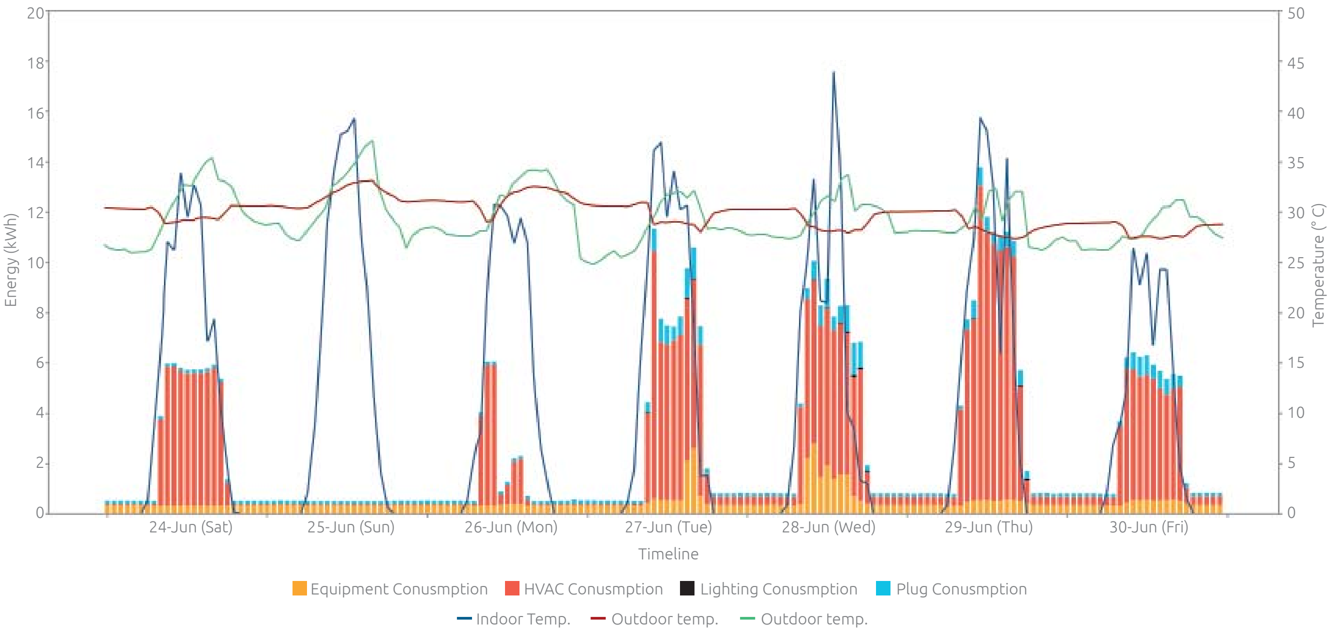


Figure 45: Hourly total energy generation and consumption profile with outdoor and average indoor temperature for a week after summer typical week

The graph shown in Figure 45 represents total energy generation and consumption with outdoor and average indoor temperature on hourly basis for a week after summer typical week (24th June 2017 to 30th June 2017).

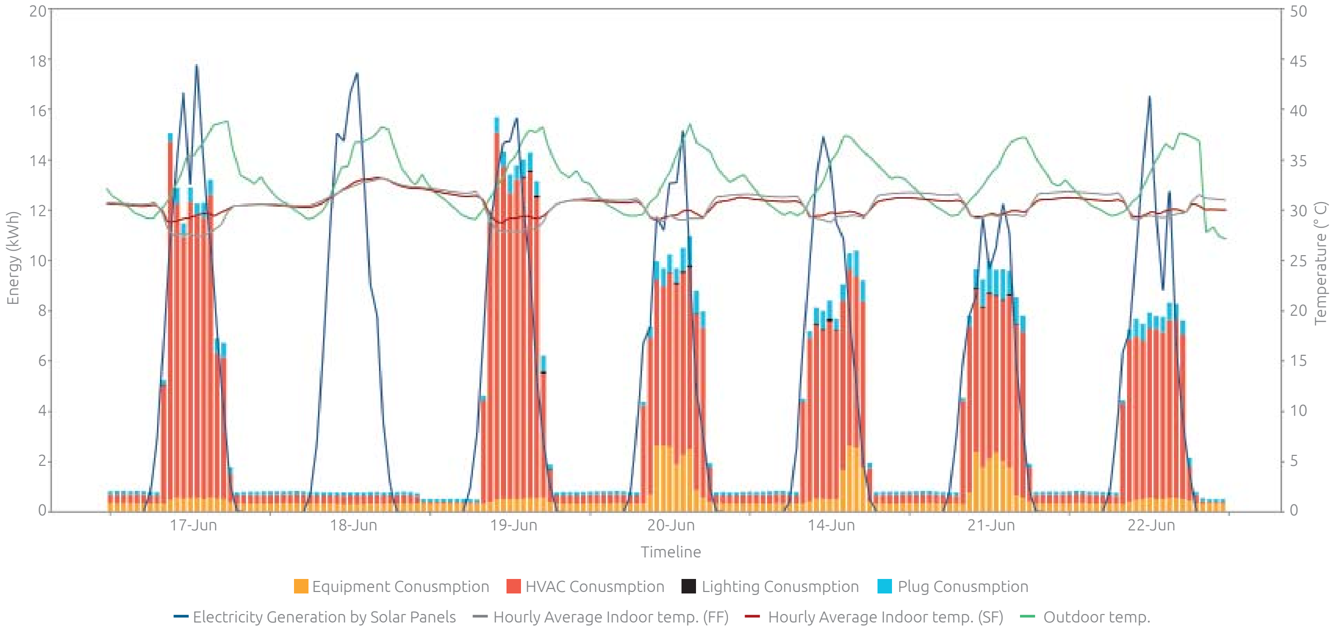


Figure 46: Hourly total energy generation and consumption profile with outdoor temperature and floor wise average indoor temperature for summer typical week

The graph shown in Figure 46 represents total energy generation and consumption with indoor and outdoor temperature on hourly basis for summer typical week (17th June 2017 to 23rd June 2017) for first (FF) and second (SF) floor.

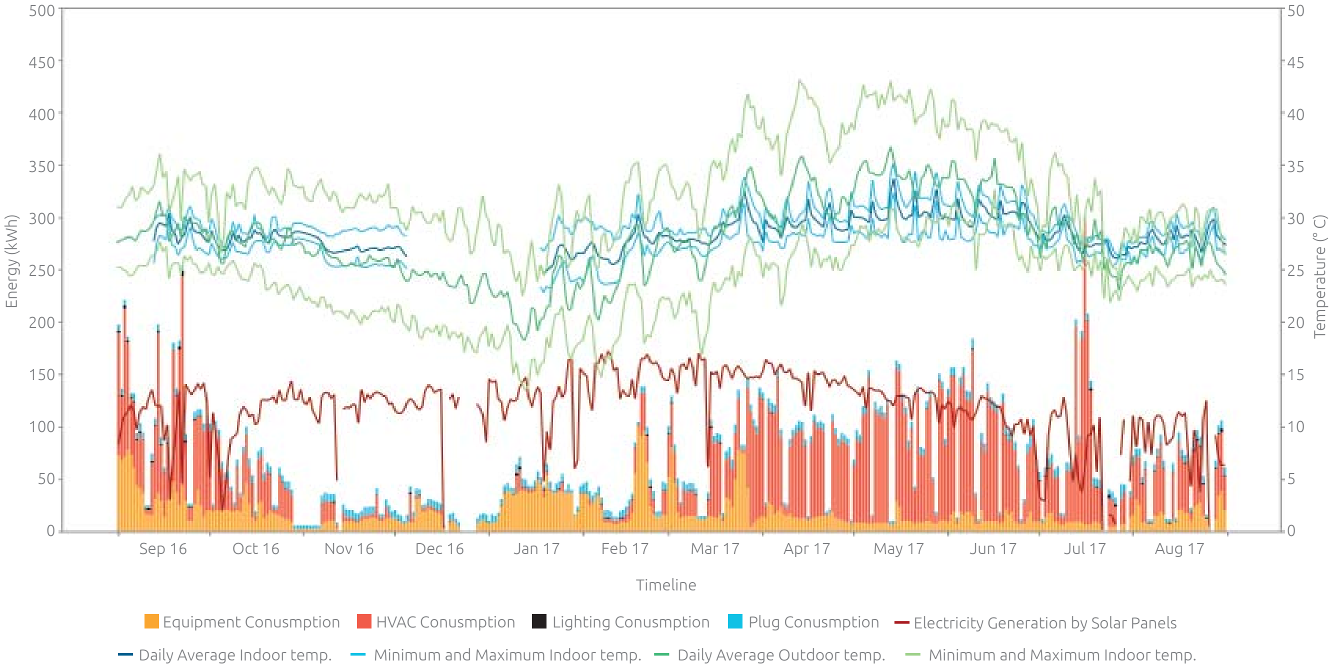


Figure 47: Daily total energy generation and consumption with indoor and outdoor temperature for the year 2016-2017

The graph shown in Figure 47 represents total energy generation and consumption with indoor and outdoor temperature on daily basis for the year (1st September 2016 to 31st August 2017).

7.4.3 Operation hours and occupancy patterns

The building operates from 08:30 hours to 18:30 hours every day except on holidays. Table 6 shows operating hours out of total 8760 annual hours for various systems.

The building was occupied for 2730 hours considering 10 working hours a day and eliminating 92 holidays in one year. On an average, NZEB is occupied by 20 users on a working day. The graph shown in Figure 48 represents the occupancy pattern – the total number of occupants present in NZEB for the period from 01 September 2016 to 31 August 2017.

Table 6: Operating hours of various systems

#	System Name	Operating hours (approx.)
1	Power Plug DB	2721
2	Lighting DB	47
3	Equipment Panel	6904
4	APFCR	8181
5	DX Scroll	198
6	DOAS	191
7	VRV Outdoor	1906
8	Radiant Chiller	524
9	Primary Pump	664
10	TCC Main AHU	1123
11	TCC Chiller	1146
12	TCC Personal AHU	0

Figure 48: Annual Occupancy Pattern

7.4.4 Occupant Thermal comfort survey

Thermal comfort surveys[3] are being taken by the occupants to evaluate occupant comfort and behavior in the building for the entire year. The survey includes 14 questions, which ask the occupants about their acceptance of thermal environment, thermal sensation, thermal comfort, air quality, air movement along with fan operation and window opening status, activities recently engaged in and clothing details.

The surveys are taken twice a week on Monday and Thursday at 11:00 hours and 16:00 hours.

The analysis of 'right-here-right-now' thermal comfort surveys taken by the occupants to evaluate occupant comfort and behavior in the building for the period of 8 months (from 31st January 2017 to 31st August 2017), is given below.

[3] The surveys have been designed by using SurveyMonkey online survey tool. Survey response can be readout and downloaded using the same tool.

- **Acceptance of thermal environment**

The graph shown in Figure 49 represents the acceptance of thermal environment by the occupants. Each bar in the first row depicts the acceptance level of the occupants at 11:00 hours on Mondays and Thursdays alternatively. The second row records their responses at 16:00 hours. It can be seen that the majority of occupants are satisfied with the thermal environment inside NZEB.

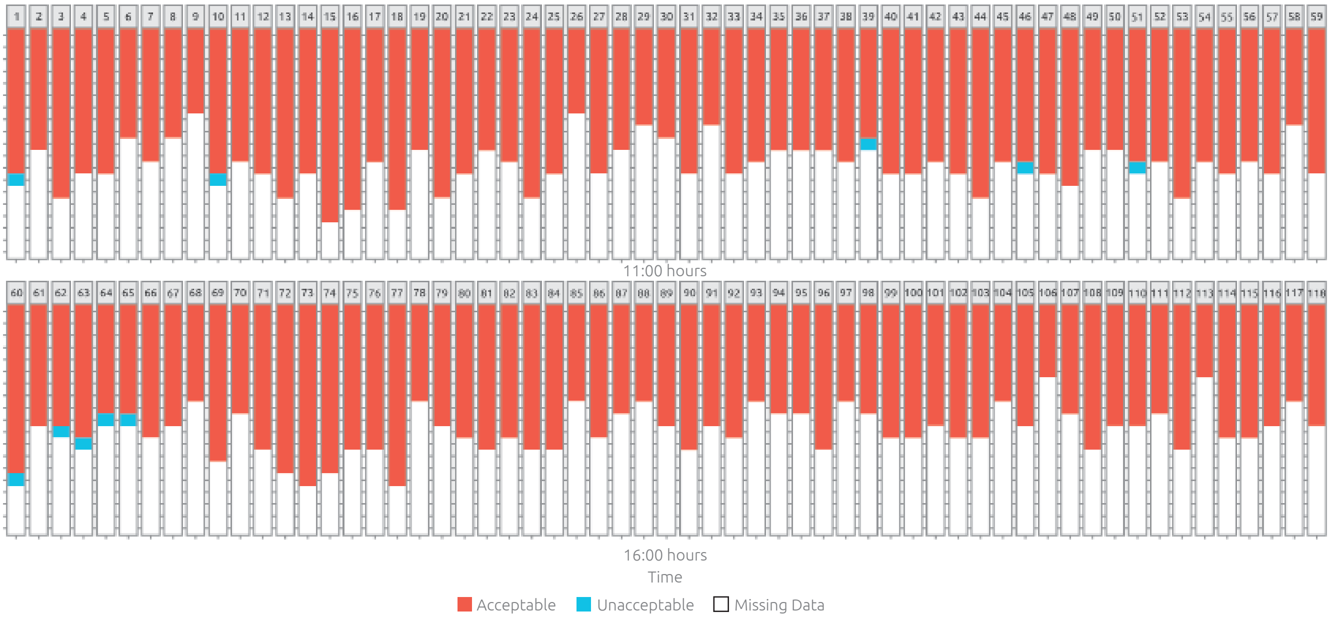


Figure 49: Acceptance of thermal environment by building occupants

- **Thermal sensation**

The graph shown in Figure 50 represents the thermal sensation felt by the occupants. The majority of the occupants have voted that they were feeling neutral during the time of the survey. There were few instances when some occupants were feeling warm or cool and fewer when they felt very hot or very cold.

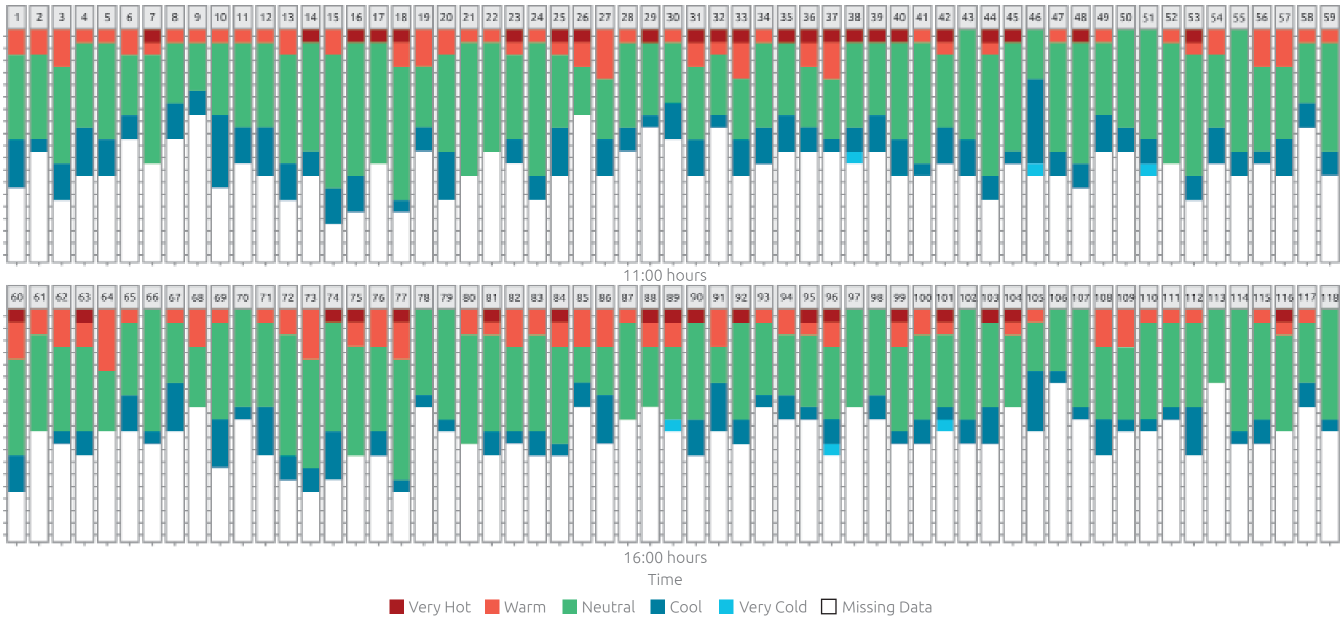


Figure 50: Thermal sensation of building occupants

- **Comfort Vote**

The graph shown in Figure 51 represents the thermal comfort felt by the occupants. The majority of the occupants have voted that they were feeling very comfortable during the time of the survey. There were few instances when some occupants were feeling comfortable and fewer when they felt uncomfortable.

Figure 51: Comfort Vote by building occupants

7.5 Energy Performance Index (EPI):

The EPI is expressed in kWh/m2 which measures the total energy consumption used in a building divided by the gross floor area in square meter. (http://www.sciencedirect.com, 2015)

The whole Building EPI (without credit for renewable energy credits) for NZEB is 78.4 kWh/m2. The EPI break up by each end use is monitored and provided below:

- Building HVAC EPI - 45.3 kWh/m2 includes energy consumption by air conditioning equipment to maintain indoor space temperature and indoor air quality (including removal of heat dissipated by research equipment in the space);
- Ambient Lighting EPI - 0.3 kWh/m2 includes energy consumption by artificial ambient lighting devices;
- Plug Loads EPI - 4.5 kWh/m2 includes energy consumption by computers, personalized fans, and task lights;
- Research Equipment EPI - 28.4 kWh/m2 includes energy consumption by research instruments such as envelope characterization devices.

08 CONCLUSION

The process of designing the net zero energy building at CEPT allowed all stakeholders involved to partake in a real life integrated design case study and realize it within an academic environment. It also allowed for a unique academia-practice-industry partnership where the academicians were able to define a theoretical problem and identify new avenues for research. Also, the professional experts expanded their boundaries of problem solving by providing practical solutions. Pre-design analysis helped in establishing set goals, make informed decisions, optimize performance to achieve 78% energy savings and after construction, operate the building with an understanding of the EUI budget and impact of operational decisions.

There were multiple challenges faced in the design and construction of the NZEB. In order to improve the building envelope, exterior insulation was an important strategy. But it did not align with the exposed brick and concrete aesthetic of the other buildings on campus. This issue was resolved by providing an additional brick layer on the external surface of the insulation. This had the added advantage of increasing the thermal mass of the NZEB and helped operate the building in mixed mode along with night time ventilation.

Glazing at the scale of the NZEB building is typically done using single pane glass with steel frame. To achieve the desired thermal performance for the double glazed units (DGUs), aluminum frame with thermal break was considered and then rejected due to cost. Instead, uPVC frame was selected with a dark veneer wood finish; window dimensions were measured and orders were placed only after the walls and floors slabs had been completed on site. Clearstory frame was removed to get more visible light transmission (VLT) and the glazing was fixed with sealants only.

The sloped RCC roof had complex steel reinforcement and laying the radiant cooling pipe was a challenge. This was solved by using non-structural radiant panels in the interior. Non-structural radiant cooling also provides better control, faster response time and poses a reduced risk of water leakage compared to structural radiant cooling. It also allows greater flexibility to change internal space layouts. This radiant cooling approach allowed better cash flow management since the money for the radiant system was not required at the time of RCC casting. The sloping roof and low ceiling height in certain areas could not accommodate ceiling fans. Therefore, pedestal fans were used to generate high air speeds during mixed mode operation. The efficient envelope and lighting design reduced the cooling loads. In addition, the radiant system needed 14-16˚C supply water which reduced the chiller load to such an extent that it was a challenge to find a modulating chiller of 8TR capacity. It had to be imported from outside India.

An additional challenge was to achieve the net zero goal with a program that dictated that the building be an experimental set-up or a living laboratory. An NZEB needs precision and refinement while one must allow for wide ranges of operational parameters for experimentation and they may result in a conflict in design and operation. The need for experimentation has led to the use of multiple systems leading to what may be considered 'over-designed' and expensive but it is envisioned to help optimize the cost for such buildings in future from the knowledge it will generate and help make them affordable.

CEPT NZEB also revealed the feasibility of designing buildings to operate in mixed-mode in a hot and dry climate like that of Ahmedabad. It demonstrates that high performance buildings do not need to look 'different' from the norm and that common sense and conventional architectural language allows for a range of possibilities of aesthetic expressions for such buildings. Another observation that was made during the design and construction of the CEPT NZEB was that there is an abundance of technological solutions available for building envelop, HVAC and lighting but most of them are not appropriate for small buildings. There is a potentially rich market in India for technologies that could work at a small scale to make high performance buildings. Lastly, the owners felt that the concept of 'return on investment' was not the right way to look at the economics of an NZEB because such buildings use minimal or no energy. That means potentially low savings in the long term as compared to a business-as usual building. (Rawal, Vaidya, Manu, & Shukla, 2015)

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Annexures

Annexure 1: CEPT Campus map

P	Parking	OFFICES	Student Services	01	CEPT Canteen
C	Cafeteria		Admission Office	02	CEPT Stores
FA	Faculty of Architecture		Career and Alumni Services		Stationary Shop
	Sagra basement		Outreach Service		Printing Shop
FP	Faculty of Planning		Summer Winter School Office	03	Kanoria Centre for Arts
	Auditorium		UG Office	04	Hutheesing Art Centre
	Computer Lab		PG Office	05	Vikram Sarabhai Community Science Center
	Administration Area		Doctoral Office	06	CEPT Workshops (Old)
FT	Faculty of Technology		Exchange Programs Office	07	Hussain Doshi Gufa
FD	Faculty of Design	NZEB	Net Zero Energy Building	08	Herwitz Gallery
				09	GIDC Bhavan

Annexure 2: Meters details

#	Meter Name	Purpose	Action	End Use
1	Power Plug DB	Building Operations	Measure	Electricity consumed by use of computers and laptops, printers, fans, task lights
2	Lighting DB	Building Operations	Measure	Electricity consumed by use of lights
3	Equipment Panel	Research Equipment	Measure, Monitor and Control	Electricity consumed by use of equipment (Includes Single Patch Sky Simulator, Guarded Hot Box, Solar Calorimeter, Thermal Comfort Chamber, Hygrothermal Characterization Facilities, Lasercomp Fox 600 and NeslabTF900 Chiller, Spectrophotometer, Fourier Transform Infra-Red Spectrometer (FTIR), Air Leakage Chamber, Stand Alone Data Loggers, Indoor Air Quality Handheld Meters, IAQ meter for Instantaneous measurements, Surface Temperature Measurements RTD-PT100, SLR luminance measurements, Weather Station, Universal light monitor)
4	APFCR (Automatic Power Factor Controller Relay)	-	Measure	Electricity consumed by charging capacitor bank which is used to improve or maintain the total power factor
5	Main Incomer	Building Operations and Research Experiments	Measure and Monitor	Total electricity consumed in the building (Includes all the meters which measure or monitor electricity consumed by building systems or research equipment)
6	Sub Incomer	NA	NA	NA (Combination of few meters)
7	Incomer Solar	Building Operations and Research Experiments	Measure	Electricity generated by solar panels
8	HVAC Panel	Building Operations and Research Equipment	Measure, Monitor and Control	Electricity consumed for all HVAC systems and sub-systems (Includes TCC Main AHU, DX Scroll, VRV Outdoor, TCC Chiller, Radiant Chiller, Primary Pump, TCC Personal AHU, DOAS)
9	DX Scroll	Building Operations and Research Equipment	Measure, Monitor and Control	Electricity consumed by use of centralized HVAC system in the basement
10	DOAS	Building Operations and Research Equipment	Measure, Monitor and Control	Electricity consumed by use of centralized HVAC system in the basement
11	VRV Outdoor	Building Operations	Measure, Monitor and Control	Electricity consumed by use of 1 outdoor and 8 indoor HVAC units for first and mezzanine floor
12	Radiant Chiller	Building Operations	Measure, Monitor and Control	Electricity consumed by use of Radiant Chiller
13	Primary Pump	Building Operations	Measure, Monitor and Control	Electricity consumed by use of primary pump to supply water to all the radiant panels
14	TCC Main AHU	Research Equipment	Measure, Monitor and Control	Electricity consumed by main Air Handling Unit of Thermal Comfort Chamber
15	TCC Chiller	Research Equipment	Measure, Monitor and Control	Electricity consumed by use of Thermal Comfort Chamber Chiller
16	TCC Personal AHU	Research Equipment	Measure, Monitor and Control	Electricity consumed by personal Air Handling Unit in Thermal Comfort Chamber

Annexure 3: Testing and Characterization services at CARBSE

Building Material and Construction Characterization

Thermo-Physical-Optical performance of building material and energy performance of building components play major role in achieving energy efficient building. CARBSE: CRDF has capabilities to characterize energy performance of building envelop material such as insulation products. CARBSE: CRDF also has competence to test glazing material and fenestration products. A State-of-art facilities is set up at CEPT campus working continuously with industry and research scholars to establish robust database of generic building materials. Combined with component and whole building simulation capabilities, CARBSE: CRDF offers unique platform to evaluate energy performance of insulating materials, glazing materials, fenestration products, roofing products and paints. Presently, CRDF has capabilities to characterize following parameters:

1. Thermal Conductivity to derive R value and U Value
2. Thermal diffusivity and Specific heat
3. Air Leakage of Fenestration Products like Windows and Doors
4. Transmittance, Absorptance, Emittance and Reflectance of glazing material
5. Reflectivity of thermal mirrors.(Curved Surfaces)
6. U-Factor and Solar Heat Gain Coefficients of fenestration products
7. Post Occupancy Evaluation of Building for their environment and energy performance.
8. Performance evaluation of various materials and products on the energy demand of building.

CARBSE: CRDF facilitates government initiatives towards implementation of GRIHA and ECBC by providing an unbiased testing facility to all the stakeholders such as architectsdesigners, builders-developers and material processors and manufacturers.

Equipment	Material	Type of Test	Range	Standards	Sample Size in mm
Heat flow meter	Insulation	Thermal Conductivity	0.01 to W/m.K to 0.2 W/m.K	ASTM C-518	600 x 600
Thermal Constants	Building Materials	Thermal Conductivity	0.005 to 500 W/mk	Meets ISO standard (ISO/DIS 22007-2.2)	100x100x50
		Diffusivity	0.1 to 100 mm2/s		
		Specific Heat	Up to 5MJ/m3K		
Spectrophotometer (With angular measu rement facility)	Glazing	Optical Properties	UV / VIS and NIR	ISO 9050/EN 410/ ASTM E 903	100×100 (Max. thick. 16) 60×60 (Max. thick. 16)
FTIR using Set	Glazing	Emissivity	IR (Approx. 1300 nm – 44000 nm)	EN 673	100×100 60 x 60
Air Leakage Chamber	Fenestration	Air Leakage Rate	-	NFRC 400, ASTM E 283	Windows : 1200 x 1500, Curtain Walls: 2000 x 2000
Solar Caloriemeter	Fenestration	SHGC	-	NFRC 201	1500 x 1500
Guarded Hot Box	Wall / Window	U Value	0.1 to 5 W/m2k	ASTM C 1363	1000 x 1000 x upto 300
Single Patch Sky Simulator (SPSS)	Scaled architectural Models	Daylighting	5 to 100000 lux	-	1200 x 1200 x upto 450
Mirror box	Scaled architectural Models	Daylighting	0.001 to 1 daylight factor	-	2000 x 2000 x upto 600
Environmental Chamber	Building Materials	Sorption Isotherm	Temperature range of +15.6°C to +37.8°C and a humidity range of 40% to 98% RH as limited by a +4.5° C dew point temperature.	ASTM C1498	having mass more than 10g
Pressure Plates	Building Materials	Moisture retention Curve	Humidity ≈ 95 to 100% RH	ASTM C1699	five pieces of approx 15cm2having thickness as minimal as possible ≈ 5mm
Vapometer Cups and Environmental Chamber	Paper, Plastic films or sheet materials	Water Vapor Transmission	Temperature range of +15.6°C to +37.8°C and a humidity range of 40% to 98% RH as limited by a +4.5° C dew point temperature.	ASTM E96/ E96M	Thickness should be less than 5mm Diameter in Between 65 mm to 75mm
Water Bath	masonry materials, plaster and insulating material	Water Absorption Coefficient	-	ASTM C1794	Area of specimen must be greater than 50cm 2100mmX 100mm Preferable Thickness should be more than 5mm

Testing Characterization facilities

Single Patch Sky Simulator

CARBSE's Single Patch Sky Simulator system consists of a turntable, mirror and Fresnel lamp. By emulating one sky patch out of the total 145 virtual divisions with equal area of the sky dome, as per Tregenza's model, a building model placed on the turntable can be rotated so that the lamp is directed from each of the sky dome's 145 divisions, and illuminance levels can taken. These measurements are then aggregated so that they accurately reflect the daylight performance of the space under the whole sky dome. The advantage of this is that because the measurements are taken according to 145 patches, once measured physically only once, the effective sky can be altered to simulate any sky condition simply by adjusting the weightage of individual patches, and calculating the effect on the building's illuminance levels.

Guarded Hot Box

A Guarded Hot Box is used to test the thermal performance of non-homogenous specimens, such as complex wall assemblies, cavity walls, ventilated shaded wall assembly or walls with phase change materials (PCM). It determines the amount of heat transfer through a given material or assembly of various materials. This is done by controlling the temperature on both sides of the material and minimizing the extraneous heat transfers other than those through the given material, which can be used to determine the thermal transmittance of a homogenous as well as non-homogenous specimen, and can test a specimen with a maximum thickness of 350mm. The metering chamber is cooled using chiller and the guard chamber is maintained at same temperature using an HVAC system. The climatic chamber is maintained at higher temperature using electric coils. Surface, water and air temperature sensors are placed for temperature control along with humidity (RH), pressure, and air velocity sensors placed at equal distances.

Solar Calorimeter

The solar calorimeter measures the solar gain through fenestration products. This is the fundamental test by which the solar gains through the window assembly of any such components can be measured. It can also be used for the measurement of the solar efficiency of photo voltaic cells used in Solar PV panels. The solar calorimeter is an insulated enclosure designed to permit the continuous introduction and extraction of a measured flow of fluid mass and equipped with an empty aperture into which a fenestration system is inserted for characterization. The main components of this equipment include room side metering chamber, guard chamber, surround panel for installing test specimen, calibration panel, heliostat and enclosure.

Thermal Comfort Chamber

The Thermal Comfort Chamber (TCC) is a chamber sized 6m x 5m x 3m, which can precisely simulate a wide range of indoor environmental conditions with temperatures ranging from 15°C to 40°C and relative humidity from 16% to 95%, along with changing air distribution patterns and speed. This particular capability is useful for Indian studies because it allows researchers to measure the impact of air velocity, a necessary criteria in a context dependent on the use of fans for cooling. These conditions are maintained and monitored by sophisticated air conditioning systems and control devices. The purpose of the TCC is to conduct experiments to evaluate the impact of various indoor environmental conditions on occupant comfort, productivity, and wellbeing. People participating in the research would sit on four workstations in the TCC and experience thermal conditions set by the research team.

Hygrothermal Characterization Facilities

CARBSE employs hygrothermal test facilities, which employ three types of test for material characterization. The first determines the sorption isotherm, the second derives water vapor transmission, and the third quantifies water uplift characteristics due to capillary action. The material properties derived from these tests help in calculating the water content of building materials subjected to various temperatures, pressure and RH conditions. Such characterization aids the understanding of moisture migration occurring in opaque building assemblies, which impacts structural stability, indoor air quality and energy demand for the maintenance of desired indoor conditions.

Lasercomp Fox 600 and NeslabTF900 Chiller

The lasercomp fox 600 is used to test the Thermal Conductivity and characterization of materials. The Thermal Conductivity of a specimen is determined by measuring the Heat Flux, specimen thickness, and temperature difference across the specimen. This microprocessor based instrument carry out tests according to ASTM C 518 and ISO 8301. Materials like PU Foam, Insulating Material from Industry, Thermocol, Formular, Expanded and Extruded Polystyrene, glass wool sandwiched between two plywood sheets, Styrofoam, etc. can be characterized. Specimen size 600mm x 600 mm and of thicknesses upto 200 mm are characterized for the thermal conductivity range from 0.01 to W/m.K to 0.2 W/m.K.

Spectrophotometer

Spectrophotometer is a photometer (a device measuring light intensity) that can measure intensity as a function of colour (or more specifically the wavelength) of light.

Spectrophotometer provides the facility for characterization of optical properties of glazing materials, architectural materials and systems of relevant to energy transfer in flat specular glazing materials. The glazing may be monolithic, coated, with applied film, laminated, etc. The Solar Absorbtence, Reflectance and Transmittance of material are determined using Spectrophotometer and Integrating Spheres. The tests are performed in accordance with EN 410 and ISO 9050. Specimen size 100mm x 100 mm and of thicknesses is compensated are tested for the optical properties.

Fourier Transform Infra Red Spectrometer (FTIR)

The emissivity of glazing and architectural materials is measured in Infra Red (IR) range (Approx. 1300 nm – 44000 nm) by Fourier Transform Infra Red Spectrometer (FTIR). Fourier transform spectroscopy is a measurement technique whereby spectra are collected based on measurements of the coherence of a radiative source, using time domain or space domain measurements of the electromagnetic radiation or other type of radiation. It can be applied to a variety of types of spectroscopy (FTIR, FT-NIRS). The tests are performed in accordance with EN 673.Specimen size more than 60mm x 60mm of thicknesses is compensated are tested for emissivity.

Air Leakage Chamber

Air Leakage Chamber is used to determine the air-leakage rates of windows, doors and curtain walls. NFRC 400 document based on ASTM E 283 determines the testing procedure. Air leakage chamber is not of the shelf-ready to use equipment- it needs to be constructed according to the use. The Air leakage chamber will help in evaluating the relative performance of various fenestration products. ASTM E 283 is a laboratory test method that has been used for many to measure air leakage rated under controlled conditions. Air leakage chamber will help to evaluate present construction practices as well as new improved construction practices.

Stand Alone Data Loggers

Data loggers are useful equipments to monitor environmental conditions inside and outside buildings. It can log data for long time (up to 3 years) at regular defined intervals for temperature, humidity, luminance and also if needed can measure CO/CO2 with additional probe. The data loggers measures the temperature range from -20° C to 70°C, Relative humidity of 5% to 95%, and light intensity from 1 to 4500 foot candles.

Indoor Air Quality Handheld Meters

Indoor air quality meters can help in conducting Post Occupancy Evaluation studies as well as help in determining user perceive thermal comfort standards. These handheld meters are capable of logging as well as taking instantaneous measurements for environmental parameters.

IAQ meter for Instantaneous measurements

Indoor air quality meters can help in conducting Post Occupancy Evaluation studies as well as help in determining user perceive thermal comfort standards. These handheld meters are capable of logging as well as taking instantaneous measurements for environmental parameters.

Surface Temperature Measurements RTD-PT100

Basic function of the RTD sensor is to measure surface temperature. By using these RTD sensors the thermal performance of materials and thermal lag of building can be studied and understood. Experimental set up to find out the U-Value of material, assemblies and components.

SLR luminance measurements

A light meter is used to measure the amount of light. It helps in conducting Post Occupancy Evaluation studies. This instrument help in color correction functions – luminance ratio and peak luminance measurements.

Weather Station

The micro weather station with a four-sensor data logger helps in multi-channel monitoring of microclimates in one or more locations and it uses a network of smart sensors for taking measurements. Key features of the smart sensors are Automatic detection, Easy expansion, Digital network, Weatherproof. The micro sensors also helps in optimizing Lifecycle Energy Performance of commercial and residential Building (which measures temperature, RH, Rain, wind speed and direction, soil moisture, solar radiation and photosynthetic active radiation (PAR).

Universal light monitor

Light meter is used for conducting Post Occupancy Evaluation studies, daylight penetration studies and need for electric light and related energy usage in conditioned environments. These are the handheld meters capable of logging as well as taking instantaneous measurements for lux level.

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