Design guidelines for Net Zero Energy Building (NZEB) in Warm and Humid Climate of India

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Abstract: The concept of Net Zero is emerging in the field of architecture nowadays. After the Paris climate agreement carbon reduction becomes one of the primary strategies in field of building construction. This paper discusses the evolution of net zero energy in architecture, classification of net zero energy buildings, and active, passive strategies used to achieve net zero goal in high-performance commercial buildings followed by renewable energy generation. This paper includes basic design strategies based on climate analysis of a selected city and building codes ECBC and GRIHA for the warm and humid climate of India. Different strategies are analyzed through the selected NZEB case studies in the warm and humid climate after that in-depth. This paper concludes design recommendations and strategies for Net Zero Energy Building in the warm and humid climate of India.

***Keywords* – Net Zero Energy, Warm and Humid Climate, Passive strategies, Active strategies, Renewable Energy.**

I. Introduction

India is third largest greenhouse gas emitter which is 6.55% of global greenhouse gas emissions and fifth largest energy consumer in the world. Due to rapid growth in population India's building sector is majorly accountable for greenhouse gas emissions and energy consumers. India's renewable energy resources are not developed as other developing nations have which makes us more rely on non-renewable energy resources. Rapid increase in electricity demands leads us using of coal more and more. India's graph of consuming coal is sharply increasing by usage of 48.1 metric ton in 1975 to 424 metric ton in 2017 as per the carbon brief profile of India. India's coal fleet has tripled since 2000. (Hickman, 2019)

After the Paris climate agreement in 2015, the country had decided to minimize the carbon emissions intensity of 33-35% by 2030, compared to 2005 levels and 40% of its installed electricity to be generated nuclear or renewable sources by 2030. India's development in renewable sector is growing rapidly from 2017 onwards. (Pradeep Kini, 2016)

The country has also launched a national smart grid mission, which is nothing but a rating system that evaluates the energy performance of commercial buildings and another for small industries to support more environmentally friendly manufacturing. It basically conveys the architects must have to minimise the use of energy- and carbon-intensive technologies such as lighting and HVAC, and should look low-tech solutions such as passive strategies like low building envelope, ventilation, daylighting etc.

II. Aim & Objective

The aim of this research work is to understand the concept of Net Zero and analyze strategies to achieve net zero goal in high performance office buildings. This research work recommends designing strategies for a Net Zero Energy Building in India's warm and humid climate.

The objective of this research work are as follows:

- To understand the concepts of net zero architecture.
- To study the intervention of net zero concept in architecture.
- To explore the relation between net zero architecture and warm and humid climate.
- To recognize and recommend the parameters and strategies for designing a Net Zero Energy Building in India.

III. Research Methodology

- First of all, net zero as a concept has been studied followed by different classification and types of net zero buildings are explored through the help of literature study.
- Second, with the help of climate analysis and literature review of ECBC AND GRIHA codes, parameters are explored which are essential in designing of an energy efficient or a Net Zero Energy Building. Mainly Active, Passive and Renewable strategies are generally used for the designing a NZEB. These strategies are deeply explored and studied w.r.t warm and climate of India.
- Active, passive and renewable strategies are considered as parameters for analyzing different case studies that are selected on the basis of HDD50 (Heating Degree Days), CDD65 (Cooling Degree Days) and most importantly Indian climate classification by National Building Code, 2016.
- Once the comparative analyses have been done, inferences are carried out from the literature review, climate analysis and observations from case studies. After that design recommendation are concluded from the inferences for a NZEB in warm and humid climate.

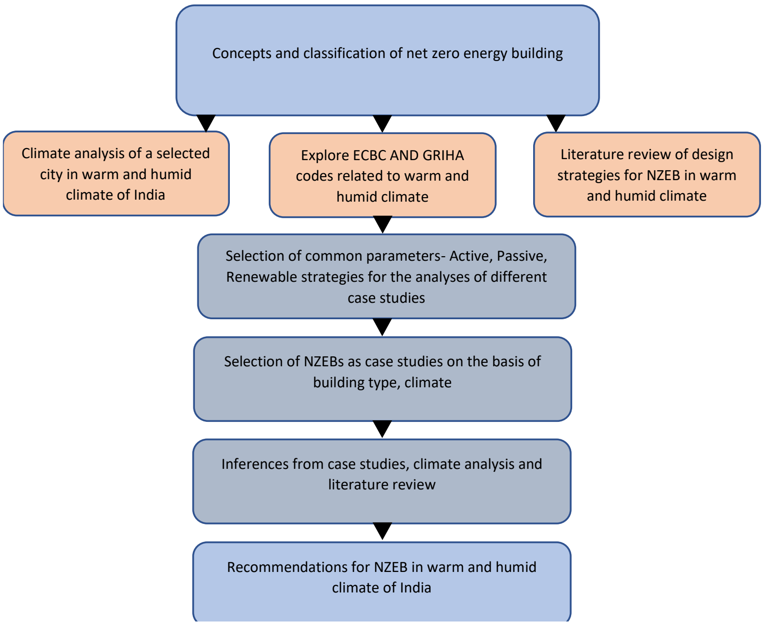


Figure 1 Methodology Structure (Author, 2021)

IV. Net Zero Energy Buildings

A net zero energy building or a zero-energy building is a type of building in which energy consumption throughout the year or annual energy consumption of the building is net zero, which means the total energy consumed by the building throughout the year is to be generated by the building on site or off site through the means of renewable energy. Net Zero Energy Buildings have less EUI in comparison with other conventional buildings as they reduce their energy demands by using energy efficient technologies and materials. But this definition and terminology varies between the countries and their organizations.

The concept or the idea of energy balance in a built environment was originated from the field of ecology in 1920 by Frederick Soddy, who was an English chemist and a Nobel prize winner. He was the first one who related the energy with social progress and wealth. In 1919 a group of alliance called "Technical Alliance" was formed which comprises of engineers, scientists, and technicians based in New York City. They started an energy survey in North America about wastefulness which was the first attempt to quantify the "net energy". One of the first attempts towards net zero in built form was solar passive house in 1930s. In 1939 MIT Solar House and Bliss House were the first buildings to introduce solar water collector, water storage, solar air collector and rock mass storage. (Hu, 2018)

4.1 Classification of Net Zero Energy Buildings

Classification based on the renewable energy resources

- **Net Zero Site Energy**: A net zero building that produces at least as much energy on-site that it consumes annually or throughout the year.
- **Net Zero Source Energy:** A net zero building that produces at least as much energy that it consumes in a year, when accounted for at the source. Source energy basically means the primary energy consume to generate, process and export the energy to the site.
- **Net Zero Energy Costs**: In a cost net zero energy building (NZEB), the amount grid pays to the owner of the building for the renewable energy export should be equal to the amount building owner pays to the grid for using its energy services over the year.

- **Net Zero Energy Emissions:** If a net-zero building generates at least as much green carbon-free renewable energy as it consumes from the sources which generates energy from emission-producing methods is counted in as net zero emission building. (P. Torcellini, 2006)

Classification based on the grid connection

- **Off grid connection:** Off grid zero energy buildings are basically standalone buildings which are not connected to any off-site energy or electricity utility which means they have to store their energy throughout the year for winters or any particular season keeping in mind of solar radiation. These types of buildings have unique application which makes a commercial building difficult to be an off-grid net zero.
- **On grid connection:** On grid zero energy buildings are basically the buildings that are connected to the grid or energy utility and borrows the half or more energy from the grid and later return the same amount of energy over the course of year. Most of the zero energy buildings are in the world and in India are grid connected except one Sun Omega, Bhopal. (Igor Sartori, 2012)

Classification based on energy generation

- **Nearly Net Zero Buildings:** Buildings that are not absolutely net zero. As they fall bit short in renewable energy generation to cancel out the energy consumption. But these buildings are also considered as nearly net zero as they are driven on same goal and pattern just like absolute net zero buildings.
- **Positive Net Zero Buildings:** Buildings that generate more energy than what it consumes throughout the year. Either these buildings sell their energy to the grid or they use their energy by themselves and reduce the energy demand from the grid.

4.2 Climate Analysis

Warm and humid climate regions have generally high temperature ranges throughout the year. These regions receive solar radiation throughout the year especially areas near the equator. High humidity is the main reason which causes discomfort in this climate zone. These zones are characterized by high humidity, high temperatures, small diurnal temperature difference, moderate wind speed, and receives high solar radiation, except on rainy days due to cloud cover.

Mumbai as representative city is selected for the warm and humid climate analysis in India. Climate consultant software is used for the analysis and for the recommendation of strategies in warm and humid climate. The psychrometric chart is also used to identify the passive strategies that can be implement for comfort inside the building envelope. Mumbai has mainly four seasons: Summer (March to June); Monsoon (July to September), Post monsoon (October to November) and winter (December to February). Mumbai has humid climate with strong solar radiation on clear days. In summer, temperatures can reach as high as 30-35°C during the day and 25-30°C at night. In winter, the maximum temperature is between 25°C to 30°C during the day and 20°C to 25°C at night. The relative humidity (RH) is generally high, about 60-90% throughout the year. Precipitation is also high, around 2000 mm per year. The wind velocity throughout the year is in the range of 6-15m/s. Wind movement is desirable as it causes sensible cooling of the body.

Analysis on the basis of psychometric chart

After implementing active and passive strategies we can clearly see in the image above the no of comfortable hours changing by introducing strategies one by one. The no of comfortable hours before introducing strategies are 121 hours out of 3650 hours. Time period selected for the day is from 10 AM to 7PM. After introducing strategies 100% comfortable hours are achieved and mostly by mechanical cooling with dehumidification.

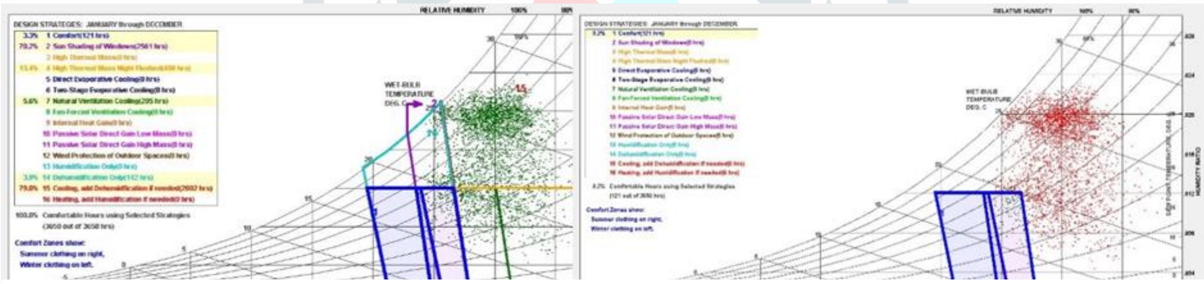
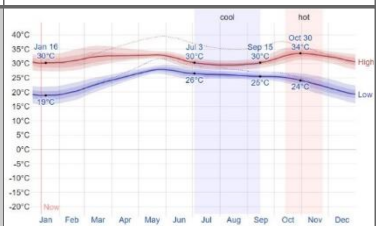
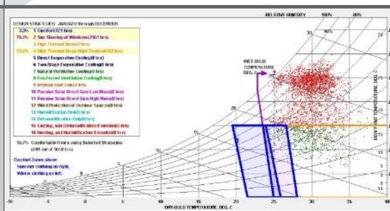
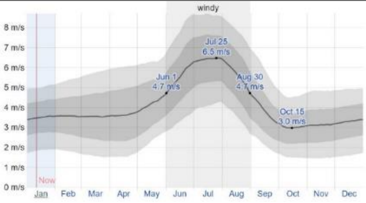
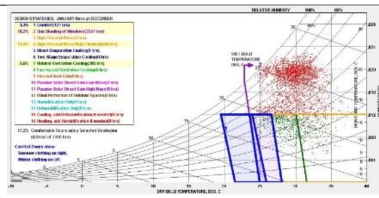
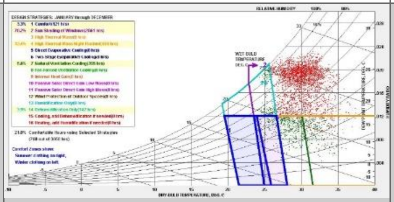
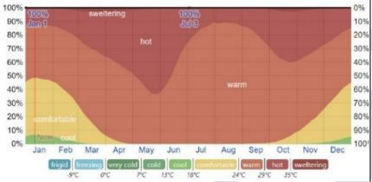
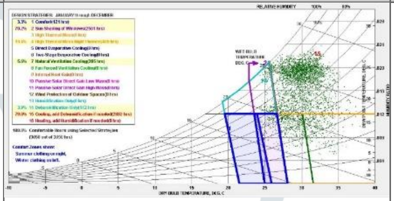
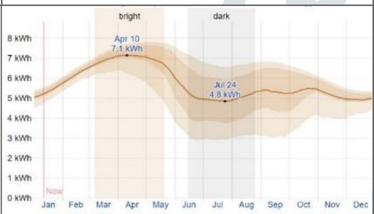
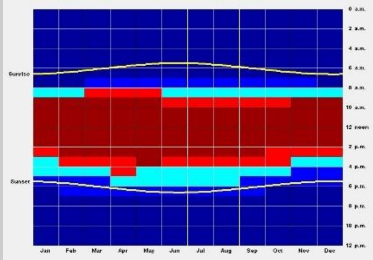
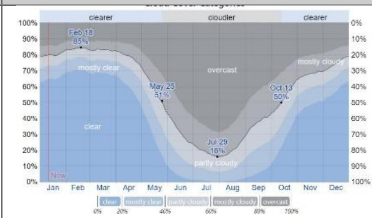


Figure 2 After and Before implementing strategies (Climate Consultant, 2020)

Table 1 Analysis based on Psychometric chart (Author, 2020)

PARAMETERS	GRAPHS	STRATEGIES	PSYCHOMETRIC CHART	INFERENCES
TEMPERATURE	 OBSERVATION: Hot season is from October to November with high temperatures of about 33C and cool season is from almost July to September with lowest temperature around 19C	1.) Sun shading of windows 2.) High thermal mass	 Sun shading and high thermal mass strategies increases 488 comfortable hours throughout the year	1.) High thermal mass to be used to absorb the heat during the day time for reducing the cooling load. 2.) Shading to be provided at all openings in order to reduce the heat gain and thus reducing the energy consumption. This also helps in reducing the glare.

WIND	 OBSERVATION: The windier part of the year is from June to august where avg speed is around 4.7m/s	1.) Natural ventilation cooling	 Natural ventilation techniques are not much helpful in commercial buildings. Natural ventilation contributes just 17 comfortable hours in the year.	1.) Natural ventilation is important in this climate as it reduces load on mechanical strategies but natural ventilation alone does not contribute much in this climate. 2.) It can be achieved by narrow building floor plan, orientation, wind towers, air tunnels etc.
HUMIDITY	 OBSERVATION: The humid conditions lies from mostly march to December and the extremes are in the month of July.	Dehumidification only	 Dehumidification strategies contributes 142 comfortable hours throughout the year	1.) Dehumidification is must strategy in warm and humid climate but dehumidification alone cannot provide much comfortable hours throughout the year.
SEASON	 OBSERVATION: Mumbai experiences warm climate in most parts of the year from may till September and most comfortable months are from February to March and October to November.	Mechanical cooling systems are needed along with natural ventilation to provide much more comfort for a selected period of year	 As in warm and humid climates mechanical cooling is most important out of all the active and passive strategies. Mechanical cooling with dehumidification contributes 2882 comfortable hours throughout the year.	1.) In warm and humid climate mechanical cooling and dehumidification is the most important strategy which contributes significant number of comfortable hours throughout the year.
SOLAR RADIATION	 OBSERVATION: Most brighter parts of the year are from March to May with clear skies whereas darker or overcast months are from mostly June to August	Solar radiation can be harvested as it is a good source of energy in the areas near equator		1.) Energy can be generated from solar radiation by planning it according to the brighter months where solar energy can be harvested in sufficient amount.
SKY CONDITIONS	 OBSERVATION: Mumbai and other coastal warm and humid areas have extreme season al variations in rainfall pattern. The rainy period is from May to November where overcast conditions and cloud cover is mostly there.	Cloud cover and overcast periods reduces the efficiency of solar renewable energy generation so, it should be planned according to the overcast seasonal variations.		1.) Coastal areas have overcast and high cloud cover periods in the year which can reduces down the efficiency of solar energy. So, it should be planned according to the seasonal patterns

Analysis on basis of Mahoney's table

Table 2 Analysis based on Mahoney's Table

Location	Mumbai, Maharashtra, India
Longitude	72.82 East
Latitude	18.9 North
Altitude	11m

Rainfall, mm	0	1	0	1	11	556	835	566	341	68	6	1	2386	Total

	J	F	M	A	M	J	J	A	S	O	N	D
Wind, prevailing												
Wind, secondary												

	J	F	M	A	M	J	J	A	S	O	N	D		
													High	AMT
Monthly mean max.	28.4	28.6	30.4	31.9	32.8	31.7	29.4	29.3	29.5	31.8	31.7	30.3	32.8	26.05
Monthly mean min.	19	19.3	22	24.4	26.6	26.1	25	24.4	24.5	24.2	22.3	20	19.3	13.5
Monthly mean range	23.7	23.9	26.2	28.1	29.7	28.9	27.2	26.8	27	28	27	25.1	Low	AMR

Relative humidity: %

	J	F	M	A	M	J	J	A	S	O	N	D
Monthly mean max. a.m.												
Monthly mean min. p.m.												
Average	61	57	67	72	71	82	84	84	80	77	64	60
Humidity group	3	3	3	4	4	4	4	4	4	4	3	3

Humidity group:		
	1	If average RH: below 30 %
	2	30-50 %
	3	50-70%
	4	Above 70 %

Comfort limits		AMT over 20 °C		AMT 15-20 °C		AMT below 15 °C	
Humidity groups		Day	Night	Day	Night	Day	Night
	1	26-34	17-25	23-32	14-23	21-30	12-21
	2	25-31	17-24	22-30	14-22	20-27	12-20
	3	23-29	17-23	21-28	14-21	19-26	12-19
	4	22-27	17-21	20-25	14-20	18-24	12-18

INDICATORS

Applicable when: Meaning:	Indicator	Thermal stress Day	Thermal stress Night	Rainfall	Humidity Group	Monthly mean range
Air movement essential	H1	H			4	
		H			2,3	Less than 10
Air movement desirable	H2	O			4	
Rain protection necessary	H3			Over 200 mm		
Thermal capacity necessary	A1				1,2,3	More than 10
Out-door sleeping desirable	A2		H		1,2	
		H	O		1,2	More than 10
Protection from cold	A3	C				

AMT 26.05

	J	F	M	A	M	J	J	A	S	O	N	D
Monthly mean max.	28.4	28.6	30.4	31.9	32.8	31.7	29.4	29.3	29.5	31.8	31.7	30.3
Day comfort: upper	29	29	29	27	27	27	27	27	27	27	29	29
lower	23	23	23	22	22	22	22	22	22	22	23	23
Monthly mean min.	19	19.3	22	22.4	26.6	26.1	25	24.4	24.5	24.2	22.3	20
Night comfort: upper	23	23	23	21	21	21	21	21	21	21	23	23
lower	17	17	17	17	17	17	17	17	17	17	17	17
Thermal stress: day	O	O	H	H	H	H	H	H	H	H	H	H
night	O	O	O	H	H	H	H	H	H	H	O	O
Humidity group	3	3	3	4	4	4	4	4	4	4	3	3

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Humid: H1				*	*	*	*	*	*	*			7
H2													0
H3						*	*	*	*				4
Arid: A1	*	*	*								*	*	5
A2													0
A3													0

Indicator Totals from Table 2					
H1	H2	H3	A1	A2	A3
7	0	4	5	0	0

Indicator totals from Table 2					
H1	H2	H3	A1	A2	A3
7	0	4	5	0	0

Layout

			0-10			*	1	Orientation north and south (long axis east-west)
			11,12		5-12			
					0-4		2	Compact courtyard planning

Spacing

11,12							3	Open spacing for breeze penetration
2-10						*	4	As 3, but protection form hot and cold wind
0,1							5	Compact lay-out of estates

Indicator Totals from Table 2					
H1	H2	H3	A1	A2	A3
7	0	4	5	0	0

Air movement

3-12						*	6	Rooms single banked, permanent provision for air movement
1,2			0-5					
			6-12				7	Double banked rooms, temporary provision for air movement
0	2-12							
	0,1						8	No air movement requirement

Openings

			0,1		0		9	Large openings, 40-80%
			11,12		0,1		10	Very small openings, 10-20%
Any other conditions						*	11	Medium openings, 20-40%

Indicator Totals from Table 2					
H1	H2	H3	A1	A2	A3
7	0	4	5	0	0

Walls

			0-2				12	Light walls, short time-lag
			3-12			*	13	Heavy external and internal walls

Roofs

			0-5			*	14	Light, insulated roofs
			6-12				15	Heavy roofs, over 8 h time-lag

Out-door sleeping

				2-12			16	Space for out-door sleeping required

Rain protection

			3-12			*	17	Protection from heavy rain necessary

Size of opening

			0,1		0		1	Large: 40-80%
					1-12	*	2	Medium: 25-40%
			2-5					
			6-10				3	Small: 15-25%
			11,12		0-3		4	Very small: 10-20%
					4-12		5	Medium: 25-40%

Indicator totals from Table 2					
H1	H2	H3	A1	A2	A3
7	0	4	5	0	0

Position of openings

3-12						*	6	In north and south at body height on windward side
1-2			0-5					
			6-12				7	As above, openings also in internal walls
0	2-12							

Protection of openings

					0-2		8	Exclude direct sunlight
		2-12				*	9	Provide protection from rain

Walls and floors

			0-2				10	Light, low thermal capacity
			3-12			*	11	Heavy, over 8 h time-lag

Indicator totals from Table 2					
H1	H2	H3	A1	A2	A3
7	0	4	5	0	0

Roofs

10-12			0-2				12	Light, reflective surface, cavity
			3-12			*	13	
0-9			0-5					Light, well insulated
			6-12				14	Heavy, over 8 h time-lag

External features

				1-12			15	Spaces for out-door sleeping
		1-12				*	16	Adequate rainwater drainage

Inferences of climate analysis

Table 3 Inferences of Climate Analysis (Author, 2020)

PSYCHOMETRIC CHART	MAHONEY TABLE
Sun shading of windows	Orientation in north and south direction (long axis east-west)
High thermal mass night flushed	Open spaces for wind circulation but protection from hot winds
Natural ventilation cooling	Rooms should have permanent provision for air movement
Dehumidification only	Buildings should have medium size openings of about 20-40%
Mechanical cooling with dehumidification	Buildings should have openings in north and south direction on windward side
	Heavy external, internal walls and floors over 8hour lag
	Roofs should be light and well insulated
	Protection from heavy rain is necessary and should have adequate water drainage

The outcome of climate analysis from Mahoney's table and psychometric chart for the city Mumbai, are some active and passive strategies, that are derived for warm and humid climate of India. The strategies extracted from the analysis of climatic data and its principles are as follows: -

- Orientation of the building is one of the most important pre design strategy. Buildings with longer axis oriented in east-west direction provide glare free light on northern and southern facades and also reduces heat gain from the east and west facades.
- Natural ventilation is an important strategy in warm and humid climate. Provision of natural ventilation can significantly reduce the energy consumption by mechanical ventilation and HVAC. This kind of climate requires permanent air movement for dehumidification and it increases comfortable hours throughout the year.
- Buildings should have openings and fenestration in northern and southern direction on windward side to provide cross ventilation throughout the building. According to climate analysis buildings should have medium size openings of about size 20-40%.
- Sun shading of window is one of the key strategies to reduce the heat gain in hot climates. Areas near equator receive heavy amount of solar radiation on low angles in east and west direction. Therefore, shading strategies are different for each direction.
- Heavy external- internal walls and floor means materials with high density have high thermal mass. These materials have the properties to absorb the heat in daytime and flush the heat in night hours and provides comfort in night time. Materials like brick and concrete with high thermal insulation have thermal lag which means these materials have the properties to absorb and store heat for longer period of time. These properties of material provide better thermal insulation to the building.
- High performance buildings in these climates need mechanical ventilation as only passive strategies won't be efficient enough in these extreme hot climates. Mechanical cooling with dehumidification is the most important strategy out of all these which provides maximum no. of comfortable hours throughout the year.
- Warm and humid areas near the coastal regions receive heavy amount of rainfall throughout the year. Mumbai receives 2386mm of rainfall throughout the year. Protection from heavy rain and adequate water drainage is an important and necessary strategy in this climate.

4.3 Green building rating systems and codes in India

Green building rating systems and codes are generally standards and mandatory guidelines formed by government or private bodies for the development of green buildings in India. These systems provide ratings to the green buildings who achieve their standards and follow their mandatory guidelines. Apart from mandatory guidelines, rating systems also provide optional active and passive strategies for different climates to reduce energy consumption. These green rating systems talk about environmental, economic and energy conservation benefits for green building design with an emphasis on sustainable site planning, energy optimization, efficient building materials, and sustainable construction practices, water and waste management strategies and indoor environmental quality.

- India currently has the below green rating systems for buildings.
- Green Rating for Integrated Habitat Assessment (GRIHA)
- Leadership in Energy and Environment Design (LEED)
- IGBC rating systems

In this research work only GRIHA guidelines and ECBC (Energy Conservation Building Code 2017) are discussed and inferences are derived from the help of these codes.

Energy conservation building code 2017 (ECBC 2017)

Energy conservation building code (ECBC 2017) is applicable to the buildings that have connected load of 100KW or above for the commercial purpose. Residential buildings are not covered under this code. These codes mainly focus on passive and active strategies to provide minimum requirements for the energy-efficient design and construction of buildings.

Green Rating for Integrated Habitat Assessment (GRIHA 2019)

Green Rating for Integrated Habitat Assessment (GRIHA 2019) is applicable to the buildings that have built up area of more than 2500m2 which excludes parking, basement area. In this research work GRIHA's section 3 energy optimization is only discussed. As this section discusses about reducing energy consumption through installation of various active and passive strategies.

Table 4 ECBC vs GRIHA (ECBC, 2017) (GRIHA, 2019)

		ECBC MANDATORY			**GRIHA MANDATORY**	**GRIHA POINTS**	**ECBC PRESCRIBED STRATEGIES**	**GRIHA PRESCRIBED STRATEGIES**
EPI		ECBC	ECBC+	S. ECBC	90 (5 days a week) $0\% \leq x < 10\%$ - $10\% \leq x < 20\%$ $20\% \leq x < 30\%$ $30\% \leq x < 40\%$ $40\% \leq x < 50\%$ $x \geq 50\%$	- 1 2 4 6 8		
	Max allowed EPI ratio Base case AC area> 50% - 182 AC area< 50% - 101	1 1	0.86 0.86	0.76 0.76				
ORIENTATION							Building should be oriented in Northern and Southern directions away from equator	Massing of the building should be done in a way to reduce the heat gain from mutual shading.
INTERNAL PLANNING LAYOUT							1.) Buffer spaces like service core, corridors should be placed in east and west direction to minimise heat gain. 2.) Planning should be done in a way so that rooms on east side should be used during the afternoon and rooms on the west side during the morning hours.	The service areas, staircases, lifts, etc., may be placed along the unfavourable orientation according to the climate and location of the project. This will ensure buffer spaces between the harsh sunlight and regularly occupied spaces
COMPACTNESS							Building should have optimum S/V ratio to minimize heat gains	
VENTILATION					60% of occupied hours of the building should be thermal comfort zone.		1.) Areas of higher humidity should have proper cross ventilation strategies in mixed mode ventilation system. 2.) Buildings should have openings in windward direction	1.) Provide courtyards so that warm air gets rises and cool air from ground floor flows into the building 2.) Wind tower can be used as passive strategies to provide ventilation in the building. 3.) Solar chimneys enhance ventilation due to stack effect.
BUILDING ENVELOPE	Roof U- Value Wall U- Value Window 1.) U- Value 2.) SHGC non north 3.) Min VLT Cool roofs Solar reflectance	0.33 0.40 3.0 0.27 0.27 0.60	0.20 0.34 2.20 0.25 0.27 0.60	0.20 0.22 2.20 0.25 0.27 0.60	SHGC Non-north- 0.27 VLT- 0.27	Mandatory	1.) Warm humid regions have insignificant diurnal difference in temperatures so, it is important to use lightweight materials with low thermal capacity and high reflectivity from solar radiation i.e., cool roofs 2.) The outer surface of the wall should be shaded, light coloured and reflective as much as possible 3.) WWR should be restricted to 40% as per ECBC to avoid glare and overheating	

WWR		<=40			<=60	4	WWR should be restricted to 40% as per ECBC to avoid glare and overheating	Ensure that the WWR does not exceed 60% and the vertical fenestration complies with minimum VLT of 0.27
VEGETATION								Providing vegetation next to critical facades provide glare free and indirect sunlight into the building and reduces solar heat gain from the building envelope.
DAYLIGHTING	Daylight hours	40%	50%	60%				Light shelves can be used to provide daylight deep inside the building as these light shelves divide the windows in 2 parts, one is viewable portion and another let's light in
SHADING	Projection Factor	$0.25 \leq PF \geq 1.0$					1.) Any surrounding man-made or natural sunlight obstructers shall be considered as a permanent shading of PF equal to 0.4 2.) North and South facades can be protected by overhang. East and west direction needs special shading devices like louvres etc.	
HVAC	Air cooled chillers <260 >=260 Water cooled chillers <260 ≥260 & <530 ≥530 &<1,050	2.8 3.0 4.7 4.9 5.4	3.0 3.2 5.2 5.8 5.8	5.8 6.0 6.3	1.) 90% of occupied hours of the building should be thermal comfort zone in mixed mode ventilation. 2.) Building should not exceed 300 unmet hours in fully airconditioned spaces.		1.) Mechanical heating and cooling equipment in all buildings shall be installed with controls to manage the temperature inside the conditioned zones. 2.) Occupancy controls shall be installed to minimize the ventilation and/or air conditioning systems when there are no occupants. 3.) Buildings which use low energy comfort systems for 50% cooling, count in as ECBC+ and 90% cooling, count in as superECBC.	1.) Desiccant cooling systems are open cycle systems, using water as refrigerant in direct contact with air. The thermally driven cooling cycle is a combination of evaporative cooling with air dehumidification by a desiccant, that is, a hygroscopic material. 2.) Radiant cooling is the use of cooled surfaces to remove sensible heat primarily by thermal radiation and only secondarily by other methods such as convection.
LIGHTING	Lighting Power Density (LPD) Interior Artificial Lighting sensor Exterior Artificial Lighting	9.50 Building size>= 20000m2 80 l/wt	7.60 90l/wt	5.0 100l/wt			90% of interior lighting fittings in building or space of building larger than 300 m2 shall be equipped with automatic control device.	
EQUIPMENT						1		Equipment installed within the project should be either BEE-star labelled or of equivalent performance.
RENEWABLE ENERGY	Area<20000m2 Area>20000m2	2% 3%	4% 6%			Mandatory 1 2 3 5		

V. PARAMETERS FOR NET ZERO BUILDING

Net Zero Energy Buildings are highly energy efficient buildings which reduces their energy demand by using energy efficient strategies, energy efficient technologies and depends upon renewable energy generation. NZEBs work mainly on three parameters

- Passive Strategies
- Active Strategies
- Renewable Energy

5.1 Passive strategies

Passive design strategies like orientation, form, shading significantly reduces the energy demands of the building which includes artificial lighting, cooling demand in summer and heating demand in winter. Another way to define passive strategies is to harvest free energy from the environment. Net zero buildings are very dynamic in nature, because of which they have to use active and passive strategies in mixed mode. Designing conventional buildings which active systems are much easier than designing a mix mode building.

Form and Orientation

These are two most important early design strategies which reduce the energy consumption of the building and improves thermal comfort for the occupants of the building. Orientation varies for different buildings and context of surroundings related to it. It largely depends upon the climate and site location. However, the underlying principle remains same for warm climates to minimise solar heat gain in heat dominant areas. Beside these factors it also plays important role in wind direction. North-South or East-West axis orientation is preferable in warm and humid climates (Figure 3) as it reduces solar heat gain from the east and west facades. (Farheen Bano, 2020) (PACE-D, 2020)

Building form plays important role in solar heat gain for warm and humid climates. With increase in volume heat gain and heat also increases. So, in warm and humid regions it is preferable to have compact planning so that heat gain can be reduce respectively from the building envelope. The optimum aspect ratio for warm and humid climate ranges from 1:1.3 to 1:1.7. Rectangular plan form is beneficial with longer facades in north and south direction to reduce heat gain from shorter sides in east and west direction. (K. Sudhakara, 2019)

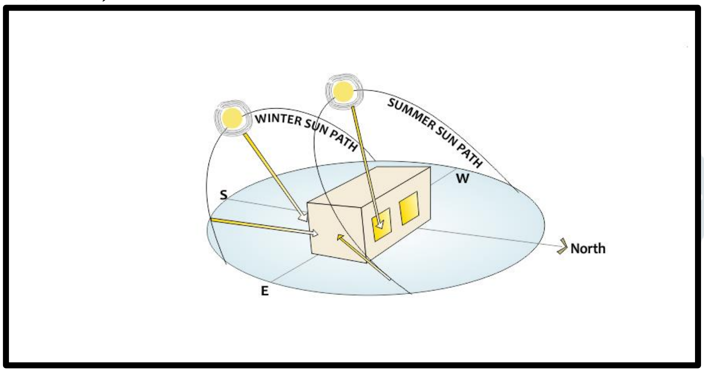


Figure 3 Orientation (https://nzeb.in/knowledge-centre/passive-design/form-orientation/)

Daylighting

Daylighting is one the major passive strategies to reduce the dependency on artificial lighting which also significantly reduces the energy demand. Passive strategies help in harvesting sun light inside the building. Integrating daylighting with artificial lighting reduces the energy consumption but on other side it also increases the cooling load on air-conditioning due to solar heat gain. So indirect daylighting methods helps in harvesting natural sunlight with minimising solar heat gain. (PACE-D, 2020)

The buildings programs are analysed according to the lighting requirements based on space and activity type. Daylighting zones can be categorized according to the activity and zoning can be done in such a way that areas which require same amount of lighting can be placed adjacent to each other. Daylighting areas are divided into three zones, which are fully daylit, partially daylit, non-daylit areas. With less dependency on artificial lighting reduces the internal heat gain of the building.

Sidelighting and toplighting are one of the traditional methods of using natural light without allowing direct sun rays penetration into the building. Toplighting (Figure 4) is favourable and effective for the spaces which are direct below the roof whereas sidelighting (Figure 4) blocks the direct sun beam and provide a glare free light into the building. In this technique direct sun rays are reflected towards the ceiling after which provides diffuse light throughout the area. (Hootman, 2013)

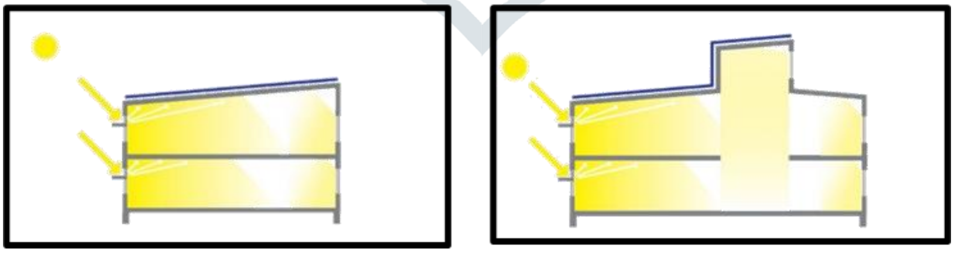


Figure 4 Sidelighting (left) and Toplighting (Right) (Hootman, 2013)

Natural Ventilation

Natural ventilation is one of the most important passive strategy in warm and humid climate which reduces the load on mechanical ventilation and cooling. Fresh air insertion in the building improves the thermal comfort and indoor environment quality inside the building for occupants in humid climate. With natural ventilation 50% of energy used in mechanical ventilation can be conserved.

Natural ventilation strategies can be achieved through form, orientation and openings in the building envelop (doors, windows, skylights). In hot and humid conditions natural ventilation or intake of fresh air can cause discomfort to the occupants of the building due to the high humidity level in outside air. These regions require dehumidification process and strategies to provide natural cool and dehumidify air inside the building. Natural ventilation can be done in two ways either cross ventilation (Figure 5) or stack ventilation (Figure 5). Cross ventilation depends upon building orientation, size of openings and placement of fenestration. Stack ventilation can be done through advance passive techniques of natural ventilation like courtyard design, stack effect, wind tower, air earth tunnel etc. For all these passive techniques desiccant dehumidification should be applied first due to warm and humid conditions. Silica gel and zeolite modules can be used for humidity absorption. (Wei Feng, 2019) (K. Sudhakara, 2019)

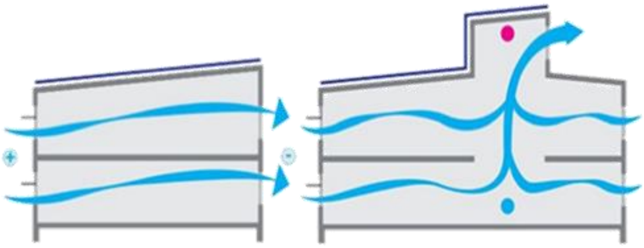


Figure 5 Cross Ventilation (left) Stack Ventilation (Right) (Hootman, 2013)

Building Envelope

Building envelope is the most common element which is exposed to sun rays throughout the year. Building envelope contains three basic elements of building which are walls, roof and windows. Building envelope plays main role in solar heat gain in extreme warm climates. Envelope in these regions should be well insulated with low thermal transmittance values (U- value).

- ***Wall:*** Walls are the most exposed surface in the building envelope which is exposed to solar radiation. In extreme hot climates, thermal transmittance (U- Value) should be less to reduce solar heat gain from the walls. Light weight construction materials should be used to provide less thermal transmittance values. These values can also be reduced by providing thermal insulation materials like fibre wool, rockwool, mineral wool extruded polystyrene, cellulose, urethane or phenolic foam boards etc in the wall construction. Other passive wall techniques can be used in hot climates like cavity walls, thermal mass, external reflective materials, light- coloured finishes etc.

Thermal mass plays an important role in maintaining thermal comfort inside the building for occupants. Materials according to thermal mass are placed with consideration of climate. Warm and humid climate needs high thermal mass materials to store the heat in daytime and can flush it in during night hours. (Wei Feng, 2019)

- ***Fenestration:*** Fenestration (windows, skylights, openings in a building etc) play important role in solar heat gain in warm and humid climatic regions. Glazing in windows and skylight traps the solar radiation inside which substantially increases the temperature inside the building. Passive fenestration techniques can reduce the mechanical heating and cooling load and also reduces the artificial lighting hours by harvesting the daylight through windows and openings without getting solar heat gain. (PACE-D, 2020) (K. Sudhakara, 2019)

Orientation and window size plays important role in heat dominating climates. In hot and humid areas window floor ratio should be around 15-20% and the window wall ratio (WWR) should be around 20-40% for warm and humid climate. Furthermore, fenestration should have low U- value with low solar heat gain coefficient as low heat is transferred into the building. Double or triple pane windows with low-e value have low U values which reduces significant solar heat gain inside the building. There are many low thermal transmittance glazing technologies like electrochromic or thermal- electrochromic, reflective glazing etc. (Wei Feng, 2019) (K. Sudhakara, 2019)

Methods to reduce solar heat gain through windows are:

- Size and Orientation
- Glazing
- Internal shading devices
- External shading devices

Roof: Roofs are one major areas of solar heat gain in summers and in heat dominating areas. Cool roofs and shading devices on roof significantly reduce the thermal heat gain through roofs.

Cool roofs are basically the roofs that are painted in light coloured shades or have reflective material coating so that it reflects most of the solar radiation and reduces the thermal heat gain. As per the studies it is seen that conventional roofs reach about 60C temperature in summers whereas cool roofs stay 28C cooler than conventional roofs. Besides that there are other passive roof strategies. Low thermal transmittance (U- Value) roof construction can be used to reduce heat gain from roof assembly. Solar panels or rooftop BIPV system can also act as a second skin on roof to provide shade, which can also reduce solar heat gain through roof assembly. (PACE-D, 2020) (Wei Feng, 2019)

Shading

Shading device is equally important feature just like choosing glazing type and size of fenestration for reducing the solar heat gain through openings as, it also reduces the mechanical cooling demands inside the building. Shading devices are designed by considering the orientation and size of the openings and solar radiation angle falling on the fenestration. Sun path is at higher elevations during summers and lower in winters in southern direction. So shading devices on southern fenestration only allows low angle sun paths for winters and penetrate higher solar radiation in summers while shading devices on north fenestration are only meant to block higher sun angle during summers (Wei Feng, 2019). Southern façade requires only horizontal shading devices and strategies to penetrate solar radiation whereas, east and west direction requires special shading devices to penetrate extreme solar radiations. Egg-crate shading devices are helpful in penetrating harsh solar radiations in east and west direction (K. Sudhakara, 2019).

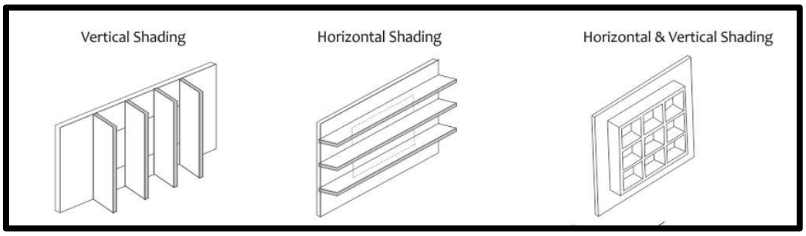


Figure 6 Shading devices (https://nzeb.in/knowledge-centre/passive-design/shading/)

Vegetation

Vegetation or green cover plays vital role in changing the environment of both site level and interior spaces. Vegetation used as a shading element which reduces the direct sun light striking to the exposed building surfaces and avoids heating them up. Vegetation alters the micro climate of the site through the means of evapotranspiration. In this process plants and green cover in the site evaporates their water through the means of transpiration which reduces the temperature of surrounding and cools down the area around the site. (PACE-D, 2020)

- Vegetation can be used in multiple ways like:
- Shading of exposed surfaces (Figure 7)
- Shading of open ground in site
- Shading of horizontal or vertical surfaces (Green walls)
- Roof garden (green or cool roof)
- Buffer against cold and hot winds
- Blocks the direct sun glare (diffuse lighting)

Green roofs or terrace garden (Figure 7) helps in reducing the thermal heat gain through roofs which are the most exposed part of the building for solar radiation. Terrace garden also provides an extra thermal insulation to exposed roof and green cover reduces the temperature over the roof by evapotranspiration. But green roofs have extensive soil depth around 300mm which increases the dead load on roof and makes it bit difficult task to achieve it as a passive strategy. In the summer, green roofs can reduce heat through building roofs by about 80%, and green roofs can reduce energy consumption by 2.2%–16.7% in summer, compared to traditional roofs. (PACE-D, 2020) (Wei Feng, 2019)

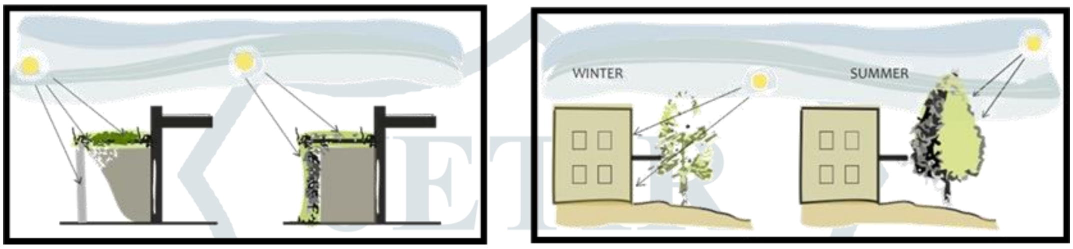


Figure 7 Green wall (left) & Shading (Right)(https://nzeb.in/knowledge-centre/passive-design/vegetation/)

5.2 Active strategies

Commercial buildings are complex structures which requires hybrid or integrated modes of systems for ventilation and air conditioning. Passive strategies reduce the load on mechanical or active systems and reduces the energy demand but not self-sufficient throughout the year for the whole building. Active system mainly includes three parameters HVAC, lighting and energy efficient appliances.

Passive strategies serve as the foundation for heating, cooling, lighting and ventilation. But Integrated or hybrid systems include working of both passive and active systems. Energy use from these active systems, referred to by the term regulated energy use, which basically consumes 50-75% of building energy and remaining energy that is used is referred as plug load energy. (Hootman, 2013)

To achieve net zero goal, energy consumption in active systems should also be reduced down by 40-60%. Efficient active systems are as important as passive systems. Blend of both reduces the energy demand of the building at a significant amount. Passive strategies like shading reduce the cooling load or superinsulation of building envelope reduces the heating load. Daylighting decreases down the dependency on artificial lighting. Passive strategies basically harness the free energy from the climate to provide the services to heat, cool, ventilate and light passively. (Hootman, 2013)

Heating ventilation and air conditioning (HVAC)

NZEBs have advance ventilation system which works with passive strategies to reduce the energy demand of heating or cooling load. These advance HVAC systems have advance mechanical ventilation system.

Designing an energy efficient HVAC system depends upon building climatic zone and the comfort level to be achieved by the building. Besides choosing energy efficient machinery for EE HVAC it is also important to select the correct system type, size to be equipped in the building. These systems are broadly classified into main categories:

- Centralized air conditioning plant (air- and water-cooled chilled system)
- Distributed system (DX system): VRF, window ACs, Unitary Systems (PACE-D, 2020)

Energy efficiency of HVAC systems depends upon many factors listed below:

- Load calculation
- Heating and Cooling equipment
- Design of HVAC system
- Operations and maintenance
- Commissioning
- Radiant cooling
- Heat pumps
- Solar air conditioning

Lighting

Lighting is one the primary consumer of energy in the commercial building. Energy efficient or net zero buildings maximize the utilization of daylighting to reduce dependency on artificial lighting. Besides the passive daylighting techniques net zero buildings work on the energy efficient lighting system.

Harvesting the sunlight for daylighting purposes also increase the risk of solar heat gain. According to ASHRAE standards values of SHGC should be minimum and values of VLT should be higher for heat dominating climates and opposite in colder climates. So, LSG values should be higher for harvesting daylight in warm areas. (Hootman, 2013)

- **Solar heat gain coefficient (SHGC):** Measures the solar heat gain through the openings (windows, skylights). Value of SHGC should be higher for warm climates and lower for cold climates.
- **Visual light transmission (VLT):** Visible light that passes through the openings (windows, skylights). Higher value of VLT means higher sun light penetration.

Lighting control system

High performance building has lighting control systems and energy efficient lighting systems like LEDs, OLEDs which creates a significant difference in energy consumption by artificial lighting. This system provides convenience, flexibility and control to the occupants to manage lighting system efficiently. (PACE-D, 2020)

Lighting control system covers many layers like manual, automated and sensor-based control system which works according to luminance level required by occupants for various kinds of activities. Lighting control systems should work on the parameters like vacancy/occupancy, time clock, daylighting levels which reduces the load on manual system and also reduces the energy consumption. Occupancy sensors basically sense the vacancy and occupancy of the space and changes the lighting system according to the user engagement. Smart lighting systems are sensors-based lighting system which also senses the daylight levels and dim the light levels according to it. These systems can also be change manually by individuals as per their visual comfort levels.

Energy efficient light source technology

Energy efficient lighting control system also requires low energy light sources which are energy efficient and have longer lamp life. These include HIDs (High Intensity Discharge lamps), fluorescent lamps, linear fluorescent lamps, light emitting diodes (LEDs) and organic light emitting diodes (OLEDs). These low energy light sources also reduce the internal heat gain and improves the occupant's mental health and wellbeing at the same time. (Wei Feng, 2019)

Energy efficiency in lighting systems is based on following factors:

- Light Source
- Luminaires
- Lighting system design
- Controls of Lighting System

Energy efficient appliances

Apart from HVAC and lighting systems energy used in other activities is referred to as plug load energy. This means energy used by the electrical appliances is counted in as plug load energy. Plug load energy is a part of one third energy consumption in the building. Therefore, it becomes important to use energy efficient appliances to reduce the energy consumption by plug load.

- **Energy rated appliances:** Energy rating scheme was launched on May, 2006 which provides energy rating to electrical appliance according to their energy usage. Rating starts from 1 to 5 star rated appliances where 5 rated appliances are much more energy efficient in comparison with 1 or 2 rated appliances. This star rating is issued by Bureau of Energy Efficiency (BEE). Apart from star rating by BEE, appliances that are imported from outside India have energy star labels which is a U.S based rating system for energy efficient appliances. Energy efficient appliances play significant role in reducing the energy losses by the plug loads. (PACE-D, 2020)
- **Solar based appliances:** Solar based appliances are also energy efficient appliances which completely works on solar energy rather than consuming plug load energy. These are of two types:
    - **Solar photovoltaic appliances:** Appliances that use electricity produced from solar energy. For example, solar street lighting.
    - **Solar Thermal Appliances:** Appliances that use heat produced from solar energy for heating purposes. For example, solar cooker, solar water heaters. (Hootman, 2013)

5.3 Renewable energy resources

Renewable energy system are key features a net zero energy building. After achieving active and passive strategies, designing a RE system according to building's energy consumption is the most important part of it. Active and passive strategies reduce the energy demands of the building and remaining energy demands are fulfilled by RE systems. Success of a net zero building depends upon its RE system.

There are various types of RE systems used to generate energy but all are not favourable for every location and the type of building. Buildings with low height cannot use wind as tier RE source as wind speeds at this height are very slow. High rise buildings can have this type of RE systems. So, there are 4 types of RE system that are most widely used throughout the world:

- Solar PV System (Photo Voltaic)
- Solar thermal
- Wind Energy
- Biomass

Solar power or solar PV system

Solar power is the most common type of renewable energy that is abundantly available in most parts of the world. Most of the energy efficient or Net zero buildings use solar PV panels to generate their renewable energy. It is because this energy is available in surplus amount throughout the year and maintenance and construction cost of this type of RE systems are very low in comparison to other RE systems. (Wei Feng, 2019)

Most of the PV installed buildings are grid connected (Figure 8). So, when a net zero buildings produces more energy by RE system then its consumption need it is called a positive net zero building. As it is very difficult for buildings to store energy for future use then this energy is exported to the grid to reduce the fossil fuel use by the grid. There are various types of advanced PV technologies. (Hootman, 2013)

- Multijunction Solar Cell PV System
- Heterojunction Solar Cell PV System
- Photovoltaic System
- Concentrating PV System

Factors affecting Solar PV System are:

- **Location, Orientation, Tilt:** Sun path and radiational angle is the most important factor for the working of PV system. To utilize most of the sun energy it should be tilted based on sun path.
- **Weather, Seasonal Variation, Overshading:** Weather, clouds also affect the working of PV system as it blocks the sun rays incident on panels. Other site characterises like neighbouring buildings, green cover also affects the working of PV system by blocking sun rays incident on solar panels. (PACE-D, 2020)
- **Temperature:** With increase in temperature by 1C, efficiency of PV panels decreases by 0.4-0.5%. So, provisions of natural or mechanical ventilation are provided to cool down these panels. (Wei Feng, 2019)

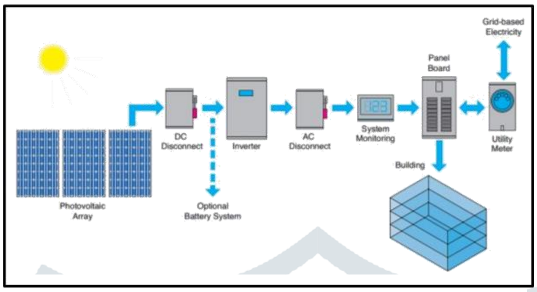


Figure 8 BIPV System (Hootman, 2013)

Solar thermal system

Solar energy is not only used for the production of electricity but also used in heating purposes. Buildings that need energy to heat water for domestic hot water applications or need cooling through absorption chillers uses solar thermal system. In extreme hot regions, solar thermal system can provide 60-70% of hot water requirement for bathing, cooking and other domestic purposes. (Wei Feng, 2019)

Solar thermal systema are of two types:

- **Open Loop System or direct system:** In this system the water is collected in collector panels and heated directly by solar thermal panels and stored in a container which can directly accessible to the taps.
- **Close Loop System or indirect system:** In this system a fluid called glycol which is an anti-freeze fluid is heated in collector panels and then it is passed through a heat exchanger where heat is transferred by the fluid to water. This system is mainly for cold climates where freezing of water is a common problem. (Hootman, 2013)

Wind energy

Wind energy systems are not very common in NZEBs. These systems need to be installed at higher levels or in high rise buildings where wind speeds are enough to generate energy. Wind RE systems need specific location for their smooth working as they need areas where wind velocity is enough to be converted into mechanical energy through turbine. Wind RE systems are more specific towards the wind pattern and they need a specific height where wind movement is high. (Wei Feng, 2019)

There are 2 types of wind RE system:

- **Horizontal Axis Wind Turbines (HAWT):** This is a conventional and most effective method of wind RE system. In this method rotor is in horizontal direction and it works when it is placed in the direction of wind flow. This is the most common type of wind RE system. Commercial buildings mostly used this type of system. (PACE-D, 2020)
- **Vertical Axis Wind Turbine (VAWT):** In this method rotor blades are in vertical direction. So, this type system can work for all types of wind direction. As this system is not wind direction sensitive. But this system is not as productive as HAWT system. (PACE-D, 2020)

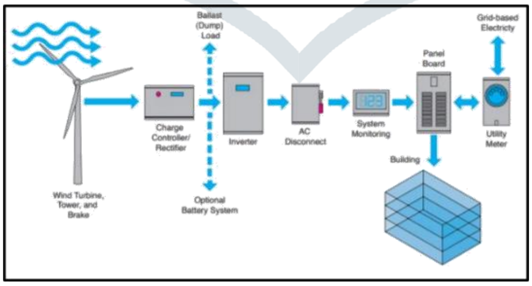


Figure 9 Wind RE System (Hootman, 2013)

VI. Case Studies

Case studies are selected on the basis of specific criteria related to climate and building information. Case studies are analysed on the basis of active, passive and renewable strategies. These parameters are basically energy efficiency strategies in warm and humid climate which help in reducing the building's annual energy consumption.

6.1 Selection criteria of case studies:

- **Building Location:** Buildings are selected from India as well as from other parts of the world, as India doesn't have much net zero buildings in warm and humid climate.
- **Climate:** All the 4 case studies are selected on the basis of warm and humid climatic parameters of India.
- **Building Type:** Only commercial buildings are selected as energy consumption in this sector is highest among in all the building sectors.

- **Building Classification:** Only net zero buildings are selected as case study.

Based on the selection criteria four case studies are analysed which includes Godrej13 Annexe (Mumbai), Malaysia energy commission headquarters (Diamond Building, Malaysia), Pusat Tenaga Zero energy office (PTM ZEO, Malaysia), Building and Construction Authority office (BCA, Singapore).
Analysis of the case studies has been performed on following parameters: -

- **Passive Strategies:** Site and Internal planning (Orientation, Plan Depth, Building height, Aspect ratio, Compactness ratio), Daylighting, Ventilation, Building Envelope (Wall, Roof, Window), WWR (Window Wall Ratio), Shading and Vegetation.
- **Active Strategies:** Lighting, HVAC, Energy Efficient Equipment, Lighting Control System.
- **Renewable Energy**

6.2 Analysis of Passive Strategies

Table 5 Comparative Analysis of Case Studies (Author, 2020)

			GODREJ13	DIAMOND BLDG	PTM ZEO	BCA
Building Information		**Location**	Mumbai	Malaysia	Malaysia	Singapore
	Climate Information	**Climate**	Warm and Humid	Warm and Humid	Warm and Humid	Warm and Humid
		Köppen Climate Classification	Aw	Af	Af	Af
		Cooling Degree Days (CDD50) Heating Degree Days (HDD65)	CDD50-12209 HDD65-0	CDD50-12081 HDD65-0	CDD50-12081 HDD65-0	CDD50-11896 HDD65-0
		Rainfall (in mm)	2386	2486	2486	2378
		Gross Area (in m^2)	24443	14685	4000	4500
		EPI (kWh/m2/yr)	75	65	30	40
	Site and Internal	**Orientation (Axis)**	SW-NE	Cardinal Directions	E-W	N-S
		Plan Depth (in m)	30	30	11	18
		No. of Floors	G+4	G+7	G+3	G+2
Passive Strategies		**Aspect Ratio**	3:2	1:1	3:1	3:1
		Compactness Ratio	0.05	0.06	0.11	0.11
	Building Envelope	**Daylighting**	Sidelighting and Toplighting Daylighting shaft, Atriums, Pergolas, Courtyard as light well	Sidelighting and Toplighting Roof Light Trough, Mirror light shelves, Reflective window sills, Skylights, Atrium (50% Daylit)	Sidelighting and Toplighting Light shelves, Skylights, Transparent roofs, Semi-transparent PV roofs, Atriums (100% Daylit)	Sidelighting and Toplighting Lightwell, Light shelves, Mirror ducts, Light pipes, Semi-transparent PV modules in service core (50% Daylit)
		Ventilation	Small courtyards, Mechanical ventilation	100% Mechanical Ventilation	100% Mechanical Ventilation	Solar chimneys, Mechanical ventilation
		Wall (U value in W/m^2.k)	AAC Blocks U-0.79	Brick wall U-0.52 Metal clad U-0.07	AAC Blocks with mineral wool insulation U-0.38	(South) 150mm Precast concrete (white) U-4.05 (East) 150mm Dry Wall (light grey) U-0.29
		Roof (U value in W/m^2.k)	2" XPS/PUC/PIR Insulation U-0.33; SRI paint on top (cool roof)	8" Reinforced Concrete with 4" Styrofoam insulation U-0.194	150mm thick Styrofoam U-0.39 and 150mm thick mineral wool insulation U-0.22	150mm Rock wool insulation with 1mm thick PVDF coating (cool roof) U-0.22
		Glazing (U value in W/m^2.k)	Double Glazing SHGC-0.3 U-1.7	(East/ West) Double Glazing SHGC-0.37 U-0.072 (North/ South) Double Glazing SHGC-0.46 U-0.95 VLT-56%	Double Glazing SHGC-0.5 VLT-50% with blinds	(South)24mm thick double glazing green DGU glass U-2.19 SHGC-0.33 (East) 6mm low e glass U-4.10 SHGC-0.42
		WWR	36	Fully glazed facade	35	41
		Shading	Vertical and Horizontal shading through niche type window	Diamond shape building form. Upper floors provide shades to lower floors due to the building form. 25° tilting façades would provide self-shading on the north and south façades.	Eggcrate like building form shades itself. Upper floors provide shades to lower floors due to the building form. Vertical and horizontal shading devices. Mirror lightshelf also act as a horizontal shading device.	Shaded by external corridor on western facade, PV module as horizontal and vertical shading device
		Vegetation	Adaptation of native species makes eco-friendly landscaping and provides diffuse daylight into the building. Terrace garden on 4th floor reduces heat gain of the building	3600m^2 of landscape area which reduces the heat gain in lower floors of the building and provide diffuse daylight into the building. Terrace garden on 8th floor reduces the heat gain of building	PTM ZEO doesn't have as such vegetation passive techniques.	Green wall as skin is used to provide shading to the walls. Green roof on the roof top of the staircase to protect the core from heat gain.
Active Strategies	Lighting	**Lighting (LPD in W/m^2)**	L.E.D fixtures, Daylight sensors, Occupancy sensors LPD-5.1	T-5 suspended ceiling lights, Task lights, L.E.D fixtures, Dimmers, Daylight sensors LPD-8.0	L.E.D fixtures, Daylight sensors, Occupancy sensors LPD-3.8	L.E.D fixtures, Task lights, Daylight sensors, Occupancy sensors, sensor grids LPD-5.3
		Lighting Performance Index (kWh/m2/yr)	20	16	1.5	20
	HVAC	**HVAC (Coefficient of Performance- COP)**	High efficiency HVAC system COP-5.02	Radiant cooling system through roof and floor cooling COP-3.8	50% Radiant cooling system and 50% Convection cooling system COP-6.5	Single Coil Twin Fan air conditioning system (SCTF) provides demand ventilation and demand cooling. Energy efficient variable fan speed AHUs. COP-3.8
		HVAC Performance Index (kWh/m2/yr)	40	32	21	30
		Energy efficient equipment (Power Load Density in W/m^2)	PLD-1.38	5 star rated ENERGY STAR appliances	PLD-2.5	PLD-4.0
		Lighting Control System	BMS (Building Management System), occupancy sensors, daylight sensors	Advance Demand Control System with motion and occupancy sensors	BMS (Building Management System), occupancy sensors, motion sensors, daylight sensors	Smart Sensor Grid System, dimmers, occupancy sensors
		Annual Energy Consumption (kWh)	1825276	12,48,225	120000	184500
Ren ewa		**Solar Panel Power (Power in kW$_p$)**	120kW$_p$ BIPV panels	71.4kW$_p$ second generation thin film BIPV panels	92kW$_p$ BIPV system (roof)+ semi-transparent PV modules (atrium).	190kW$_p$ BIPV panels+ PV railings+ PV modules as shading devices+ semi-transparent PV modules

		Units generated/ Year (kWh)	148487	102000	120000	196493
		Onsite Renewable energy%	8%	10%	100%	100%
		Offsite Renewable energy%	92%	90%	-	-
		Net Surplus Energy (kWh)	-	-	-	12071
		Area of PV Panel (in m^2)	1200	1000	700	1540
	Efficiency	Area required for $1kW_p$ (in m^2/ kW_p)	10	14	7.6	8.1
		Electricity generated from 1kW solar PV (kWh/year).	1287	1428	1304	1035

Site and Internal planning

All the selected case studies have rectangular plan form except Diamond building which has square plan form. PTM ZEO harvest more daylight than BCA due to its E-W orientation and plan depth of about 11m and receives daylight from south direction and indirect light from north façade whereas BCA has N-S orientation with plan depth of 18m and uses 50% daylight for its daytime uses. Thus, PTM ZEO's lighting index is very less as compared to BCA. PTM ZEO has core placement in east direction. BCA also has core and lobbies in N-E direction which acts as a buffer zone for the building.

Godrej13 has rectangular plan form with aspect ratio of 3:2 (Figure 12) whereas Diamond building has aspect ratio of 1:1 (Figure 12) because of its square compact plan. Both the buildings have 30m plan depth from the center of the building. Diamond building has less S/V ratio (Surface Area/ Volume of the Building) than the Godrej13 due to having (G+7) 8 floors in the building in comparison with Godrej13(G+4). Thus, Diamond building has lower Energy Performance Index (EPI) than Godrej13.

Figure 10 BCA and PTM ZEO plan (Xiaonuan Sun, 2018) (Norafida Ab Ghafar, 2011)

Figure 11 Aspect Ratio (Author, 2020)

Figure 12 Aspect Ratio (Author, 2020)

Daylighting

Godrej13 have daylighting shafts, skylights and atriums (Figure 14) which harvest maximum daylight into the building. These strategies significantly reduce the artificial energy light consumption of the building. Godrej13 has lighting performance index of (20Kwh/m^2/yr) and Diamond Building has (16Kwh/m^2/yr). Diamond building has light shelves, reflective window sills, skylight and there are automated blinds that regulates amount light penetration into the atrium and these 24 automated blinds can form six configurations throughout the day according to the outdoor daylight levels. These blinds allow 30% of daylight for the offices or spaces facing atrium. Diamond building has lower Lighting performance index due to advance daylighting strategies and also has much higher WWR in comparison with Godrej13.

PTM ZEO's daylighting strategies are skylights, semi-transparent PV modules and light shelves on northern and southern façade. Atriums have large semi-transparent PV modules on top which harvest the daylight into the building and also generates solar energy. Daylight from southern and northern façade reflects from the light shelves and the ceiling and provide diffuse light into the working spaces of the building. PTM ZEO uses 100% natural light for its daylight uses whereas BCA uses 50% of natural light for its daylight uses. It is probably because of deep plan of BCA around 18m whereas PTM ZEO is of around 11m.

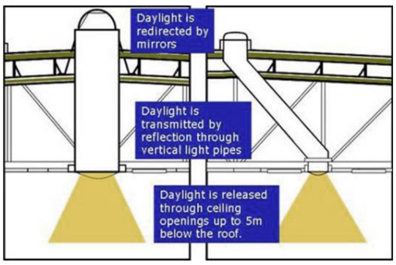


Figure 14 Light Pipe in BCA (S. Wittkopf, 2015)

Figure 13 Daylighting Strategies in Godrej13 (PACE-D, 2020)

Natural Ventilation

Most of the commercial high-performance buildings don't rely on passive techniques of natural ventilation. The reason is that commercial buildings tend to be large, internal-load-dominated, and in cooling mode much of the year. In warm and humid climate these high-performance buildings mostly rely on high efficiency HVAC systems and low energy HVAC strategies.

Out of all the 4 case studies, BCA have both natural ventilation and HVAC system. One third of the gross floor area in BCA is cooled by solar chimney system. Four solar chimneys are installed on roof top, which have ducts hidden in the building envelope. These chimneys provide air movement inside the building of around 2m/s. Rest of the cooling demand is fulfilled by HVAC system while Godrej13 has a small courtyard which acts as a passive strategy for ventilation in the building. Both PTM

ZEO and Diamond building have high coefficient of performance (COP) and low energy HVAC systems are installed throughout the building.

Building Envelope

BCA building envelope is of Dry wall(U- value 0.29 W/m^2.k) with 150 mm thick rock wool insulation in roof coated with 1mm thick PVDF (U- value 0.22 W/m^2.k) and 24 mm thick tempered double glazing unit on windows (U- value 2.19 W/m^2.k and SHGC 0.33) while PTM ZEO's building envelope is of AAC blocks mineral wool insulation (U- value 0.38 W/m^2.k) with mineral wool and foam insulation in roof (U- value 0.4 W/m^2.k) and double glazing in windows (SHGC 0.5) which results in their heat gain and performance of HVAC system. But PTM ZEO has better HVAC index due to efficiency of machinery and orientation of the building.

Similarly, Diamond building has high thermal resistance envelope in comparison to Godrej13. Diamond building and Godrej13 have almost same conditioned area but because Diamond building envelope is of Brick wall(U- value 0.52 W/m^2.k) with 8" reinforced concrete insulated with 4" thick Styrofoam insulation in roof finished with 0.5" fiber cement board and waterproofing membrane(U- value 0.19 W/m^2.k) and double glazing unit on windows (U- value 0.956 W/m^2.k and SHGC 0.46) while Godrej13 building envelope is of AAC blocks (U- value 0.79 W/m^2.k) with 2" of XPS insulation in roof (U- value 0.33 W/m^2.k) with coating of SRI paint and double glazing in windows (U- value 1.7 W/m^2.k and SHGC 0.3) which results in their performance of HVAC system.

Window Wall Ratio

Window wall ratio of PTM ZEO(WWR-35) is lower than the BCA(WWR-41) still PTM ZEO has better daylighting strategies. PTM ZEO uses 100% natural light for its daylight uses whereas BCA uses 50% of it. It is due to the building orientation of PTM ZEO which harvest daylight from southern facade and indirect light from north façade than BCA due to its E-W orientation and plan depth of 11m helps indirect light to penetrate deep inside the building. Furthermore, PTM ZEO has less HVAC performance index due to its less WWR.

Shading

PTM ZEO has higher air-conditioned area and has less EPI (30 kWh/m^2/yr) than BCA which has EPI of (40 kWh/m^2/yr). This is due to building form (Figure 15) and overhang on windows which provides shade itself to the lower floor of the building, PV module as shading devices are used in both the buildings and BCA has used vertical shading devices and external corridor acts as buffer space for the building.

Both Godrej13(75Kwh/m^2/yr) and Diamond building(65Kwh/m^2/yr) have their EPIs according to the air-conditioned areas of the building. Godrej13 has niche type windows which provides vertical and horizontal shading to the windows of the building while Diamond building has its form (Figure 16) derived from the diamond where upper floors provide horizontal shading to the lower floors of the building and vertical louvres inside the building significantly reduces the heat gain of the building.

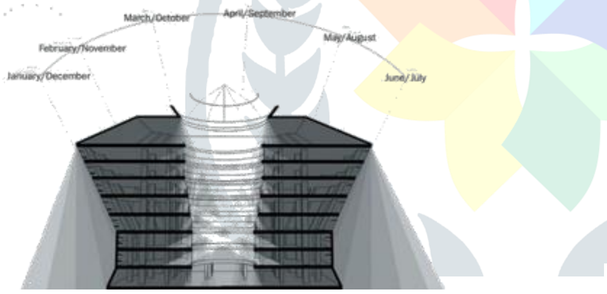


Figure 16 Diamond Building self-shading form (T. L. CHEN, 2013)

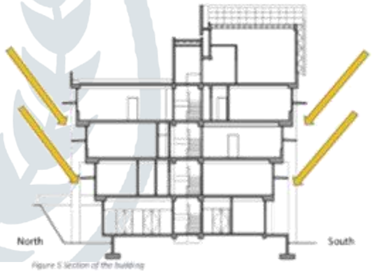


Figure 15 PTM ZEO's self-shading form (Bhattacharyya, 2019)

6.3 Analysis of Active Strategies

Lighting

Diamond building has highest WWR (window wall ratio) among all the 4 case studies. Due to its square plan, it harvests daylight from all the directions which reduces the load on artificial lighting despite having higher lighting power density (LPD). Thus, Diamond building has the low lighting performance index(16Kwh/m^2/yr) than Godrej13(20Kwh/m^2/yr). Godrej13 have L.E.D fixtures and daylight and occupancy sensors which reduces the energy consumption on the building. Diamond building have suspended ceiling T5 tubes with electronic ballast and L.E.D light fixtures of LPD (lighting power density- 8W/m^2).

BCA has higher energy consumption for artificial lighting than PTM ZEO. PTM ZEO oriented in E-W direction. PTM ZEO uses 100% natural light for its daylight uses whereas BCA uses 50% of it as it is oriented in N-S direction. Thus, PTM ZEO lighting power density is (LPD- 3.8W/m^2) and BCA lighting power density is (LPD- 5.3W/m^2). Both the buildings use L.E.D light fixtures with advance daylight and occupancy sensors to reduce the artificial lighting load.

Heating Ventilation and Air-Conditioning

Diamond building has low energy district cooling system which provides chilled water that runs through PERT pipes which acts as a heat exchanger for the slab and slab works as "cooling rechargeable battery". Due to low energy HVAC system Diamond building has less HVAC performance index of about 32Kwh/m^2/yr than Godrej13 which has performance index of 40Kwh/m^2/yr despite having less energy efficient machinery COP-3.8. One reason for better HVAC performance of Diamond building is due to better building envelope than Godrej13 against thermal transmittance.

PTM ZEO has same low energy radiant cooling and high efficiency HVAC system. PTM ZEO's cooling demand is fulfilled by 50% radiant cooling and other 50% by convection cooling HVAC system. PTM ZEO has highest coefficient of performance (COP 6.5) in all the 4 buildings. BCA has SCTF (single coil twin fan) air conditioning system which is fulfilled by three chillers which are supported by water pumps and cooling towers. A single coil, twin fan air conditioning system provides demand ventilation and demand cooling. BCA has (COP 5.02) coefficient of performance for HVAC system which reduces the energy consumption and improves against the typical range of (138 to 174 kWh/m2 per year) for similar non energy efficient office buildings. Thus, PTM ZEO has better HVAC performance index than BCA.

Energy Efficient Appliances

Energy efficient appliances and low energy consumption plug loads reduce the energy demand used by the appliances in the commercial building like laptops, computers, electronic devices and other. High performance buildings use high star rating appliances which have less energy consumption.

Godrej13 has lowest power density appliances installed in the building which has power density of 1.38W/m^2 after that PTM ZEO (2.5 W/m^2) and BCA (4.0W/m^2). Diamond building has installed 5-star Energy star appliances to reduce the plug load in the building.

Lighting Control System

All the buildings have BMS (Building Management System) system with occupancy and daylighting sensors. These are named as stand-alone systems. These systems use time switches or photocells to switch lights. BCA has installed dimmers (Figure 17) throughout the building which reduces the amount of artificial light as per the lux level of any space. Diamond building has BAS (Building Automation System) which controls electric lights via daylight zones. All the work tables have individual task lights which are coordinated with occupancy sensors and dimmers to provide flexibility and comfort of individual light control. These systems reduce the lighting consumption which results in the energy performance index of the building (EPI).

Figure 18 Daylight Sensors in PTM ZEO ((Poul E. Kristensen, 2007)

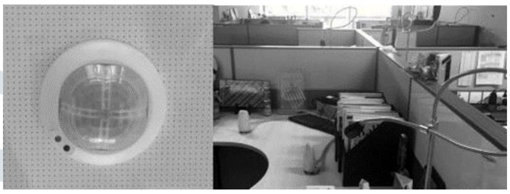


Figure 17 Daylight Sensors in BCA (S. Wittkopf, 2015)

6.3 Analysis of Renewable Energy Strategies

All the four buildings have solar power as their renewable energy resource and BIPV (Building Integrated Photovoltaics) system is installed on the roof tops. This system integrates the PV panels with building facade and serves the dual purpose of building envelope material and power generator, thereby reducing the energy demand of the building.

BCA, PTM ZEO and Diamond building have installed semi-transparent PV modules for dual purposes. These semi-transparent PV modules generate energy as well as harvest daylight into the building. But these panels are not as much efficient as normal PV modules. Diamond building has (71.4KW$_p$) 2nd generation thin film panel BIPV system which yields 102000 kWh/yr. These panel generate 10% of total energy consumption and rest is fulfilled by offsite renewable energy under the PPA (Power Purchase Agreement). Diamond building BIPV system is equipped with sensors which measures the surface temperature of panels. Godrej13 has also BIPV system of 120 KW$_P$ which generates 148487 kWh/yr the most in all the 4 buildings. This generation is just 8% of the total energy consumption of the building. Rest is fulfilled by offsite renewable energy resources under the PPA (Power Purchase Agreement).

PTM ZEO has (92 kW$_p$) BIPV system which generates 120000 kWh/yr. Building generates 100% onsite renewable energy. To increase the efficiency of PV modules the PV system is tilted at angle of 15 to the west. BCA has (190 kW$_p$) BIPV system which yields around 196493 kWh/yr. BCA is a positive net zero building as it yields more energy than consumption of about 12071 kWh/yr. Building generates 100% on site renewable energy. Building has PV solar modules on roof top, balcony railings, as shading devices and semi-transparent PV modules in staircase corridors and on windows to harvest maximum energy from solar radiation.

After analysis 1kW$_p$ of PV panels require 7-14m^2 of area in the building. Diamond building PV system efficiency (102 kWh/m2/yr) which is least in all the 4 buildings. BCA efficiency (127 kWh/m2/yr); Godrej13 (124 kWh/m2/yr). PTM ZEO has the most efficient BIPV system which generates (171 kWh/m2/yr). It is probably due to the placement of BIPV system at a particular angle and in particular direction to harvest the maximum energy from solar radiation.

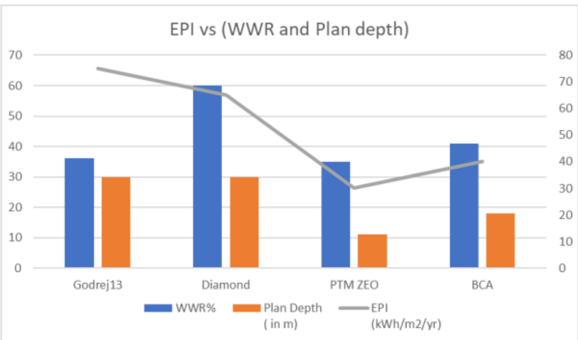


Figure 20 EPI vs WWR & Plan Depth (Author, 2020)

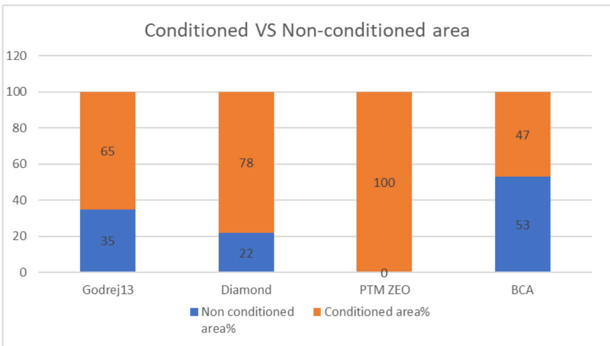


Figure 19 Conditioned vs Non-Conditioned (Author, 2020)

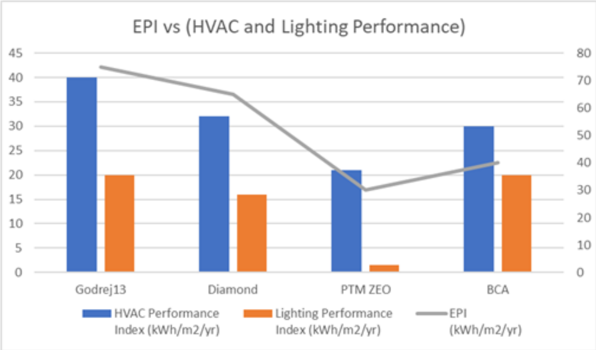


Figure 21 EPI vs HVAC & Lighting (Author, 2020)

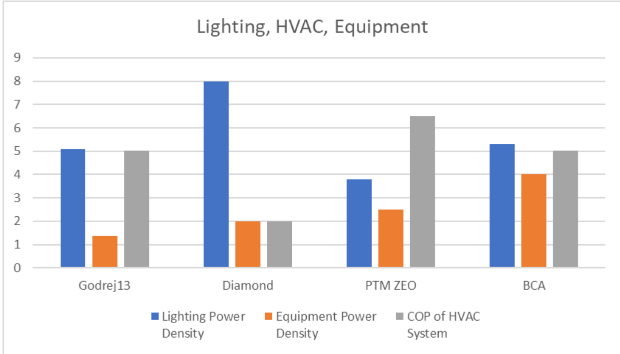


Figure 22 Lighting, HVAC, Equipment (Author, 2020)

6.4 Comparison of EPI (Energy Performance Index)

PTM ZEO has lowest EPI (30 kWh/m2/yr) among all the 4 buildings that are studied. PTM ZEO and BCA have rectangular plan form with same gross areas, same aspect and compactness ratio, window wall ratio. However, BCA has more EPI (40 kWh/m2/yr) than PTM ZEO despite having 50% less airconditioned area (Figure 19). It is due to using only 50% daylight for daytime uses whereas PTM ZEO uses 100% daylight for daytime uses. E-W axis orientation of PTM ZEO helps to harvest daylight from both south and north facade with plan depth of just 11m. On the other side BCA has N-S axis orientation with plan depth of 18m which reduces the direct daylight deep in the building despite of having much daylighting passive strategies. PTM ZEO has better active strategies like artificial lighting (3.8W/m2), HVAC system (COP-6.5) and equipment (2.5W/m2) than BCA which has artificial lighting (5.3W/m2), HVAC system (COP-5.02) and equipment(4W/m2).

Diamond building has less EPI (65 kWh/m2/yr) than Godrej13 which has EPI of (75 kWh/m2/yr). Both the buildings have same compact ratio of about (0.05). Diamond building has aspect ratio of 1:1 as building has compact square plan and it also has less S/V ratio than Godrej13 which has aspect ratio of (3:2). Both the buildings have same plan depth of 30m but orientation and higher WWR ratio of Diamond building harvest much more daylight and reduces artificial lighting consumption(16kWh/m2/yr) than Godrej13 which has (20kWh/m2/yr) (Figure 22). Diamond building has less HVAC energy consumption (32kWh/m2/yr) than Godrej13 which has HVAC energy consumption of (40kWh/m2/yr). One of the reasons for lower HVAC energy consumption is that Diamond building has low thermal transmittance (U value) in all the 4 buildings. Diamond building's form also provide shade to its building envelope which significantly reduces the thermal heat gain of the building which results in lower HVAC consumption of the building.

VII. Inferences

Table 6 Inferences Table (Author, 2020)

		Prescribed as per ECBC, GRIHA, Climate literature study	Observation from analysis	Inferences
	EPI	90 (Daytime occupancy for 5 days a week)	All the buildings have less EPI, range (30-80) than prescribed by ECBC and GRIHA	Buildings in India should follow GRIHA, ECBC prescribed values to achieve minimum requirements for the energy-efficient design and construction of buildings.
Passive Strategies	**Orientation (Axis)**	E-W (for max daylight use from north, south facades and reduce solar heat gain from east and west façades)	PTM ZEO has orientation E-W axis and BCA has orientation N-S axis. Thus, PTM ZEO has better daylight use than BCA. PTM ZEO has better lighting and HVAC index than BCA	• Observation from analysis shows that E-W axis orientation prescribed from climate study is the most beneficial orientation for a net zero building in warm and humid climate • In tropical climate like India, long facades of buildings oriented towards north- south are preferred.
	Internal planning layout (service core, buffer spaces)	Buffer spaces (Lobbies, staircase, service cores) should be in east and west direction to reduce solar heat gain	PTM ZEO has staircase core in East direction and BCA has in North- East direction. External corridor is running on eastern side of the building which act as buffer space	After observation from analysis, it shows that staircase, service core and lobbies act as buffer spaces for the building. Optimal locations for building service cores are in East and West direction, where building receive maximum solar radiation throughout the year.
	Compactness (Building form, Compactness ratio, Aspect ratio, Plan depth)	Compactness of plan reduces the lighting; HVAC load and heat gain of the building and daylighting is available throughout the building due to lower plan depth	Diamond building has more compact plan with square form (aspect ratio 1:1) than Godrej 13 which has rectangular plan form (aspect ratio 3:2). Thus, Diamond building has better lighting and HVAC index than Godrej13	In Warm and humid climate, the surface to volume(S/V) ratio, aspect ratio and compactness ratio of the building should be as low as possible to minimize heat gain (compact plans have greater thermal efficiency, e.g., a square plan is more thermally efficient than a rectangular one)
Passive Strategies	**Daylighting**	Sidelighting and Toplighting (Lighshelves, light pipes, atrium, and skylights can be used to increase glare free daylight levels in the building) Minimum 40% (UDI requirement in office buildings as per GRIHA)	All the buildings have incorporated sidelighting and toplighting as passive strategy. Light shelves and skylight are most prominent strategies in all the buildings. Mirror ducts are used in BCA as toplighting.	After observation from analysis and prescribed methods • Use advanced daylight harvesting methods in case of large window area such as use of external light shelves, light tubes, a higher ceiling height and other similar technologies, would help to distribute the daylight deeper into the building • Large buildings can get daylight into more spaces by having central courtyards or atria,

				or having other cut-outs in the building form (Toplighting) • Minimizing plan depth would provide deeper daylight inside the building.
	Ventilation	Courtyard and stack effect (solar chimney) can help in warm and humid climates for passive and mixed mode of ventilation	Commercial buildings mostly rely on 100% mechanical ventilation systems or mixed mode of ventilation system. Courtyard is there in Godrej13 and BCA has solar chimneys that reduce 30% of HVAC load.	After observation from analysis, it is realized that passive ventilation techniques like courtyards, solar chimneys help in reducing the load on mechanical ventilation and HVAC system
Passive Strategies	**Building Envelope**	For area> 10000 • Wall- 0.40 • Roof- 0.33 • Window- 3.0 For area< 10000 • Wall- 0.63 • Roof- 0.33 • Window- 3.0	Both Diamond building(area>10000) and PTM ZEO (area<10000) has similar building envelope values as prescribed by ECBC which leads them to comparatively lower EPI than other buildings Godrej13(area>10000) and BCA (area<10000) which are in their area range	After observation from analysis, it is realized that buildings in India should follow GRIHA, ECBC prescribed building envelope values to achieve minimum requirements for the energy-efficient design and construction of buildings.
	WWR	Max 40% allowed If WWR<= 40% SHGC- 0.25 WWR<=60% SHGC- 0.20	All the buildings have WWR ratio under the prescribed values except Diamond building which has WWR around 60. But Diamond building has high performance glass with extreme low U value to reduce the heat gain.	Buildings in India should follow GRIHA, ECBC prescribed values of WWR to achieve minimum SHGC requirements for the energy-efficient design and construction of buildings.
	Shading	Vertical and horizontal shading devices (Louvres, PV modules as shading devices, vertical blinds) Roof garden and green wall as shading strategy for building envelope.	Diamond building and PTM ZEO both have self-shading form which significantly reduces the HVAC load of the building. All the buildings have other vertical and horizontal shading devices too like Louvres, PV modules and vertical blinds.	After observation from analysis and prescribed methods • Building form plays important for shading and daylighting purposes. • And shading, longer sides of a building should be oriented North- South which is preferred to minimize overall solar gain through the envelope. • Use of vertical and horizontal shading devices also helps in minimising the solar heat gain through the windows.
	Vegetation	Vegetation cover provides shading to the building façade and provides glare free light inside the building. (Roof garden, Green walls)	Vegetation in Diamond building provides glare free light inside the building and also provides shading to the building envelope. Green roof is one of the passive strategies that are used in most buildings to reduce the heat gain from the roof.	After observation from analysis and prescribed methods • Vegetation cover around the building (especially in east and west direction) provides shading to the external walls and also provides glare free light inside the building. • Green roofs provide extra insulation layer to the roof through which solar heat gain can be minimised • Green walls (on east and west façade) also provide vertical layer of insulation against the harsh solar radiations to the exposed building walls
Active Strategies	**Lighting**	L.E.D fixtures, T-5 suspended lights, CFLs with daylight and occupancy sensors to reduce to lighting performance index of the building ECBC • LPD- 9.50 ECBC+ • LPD- 7.60 Super ECBC • LPD- 5.0	All the buildings have less lighting power density (LPD) than prescribed values. All the buildings have energy efficiency lighting fixtures like L.E.Ds, T-5 tubes and other with daylighting and occupancy sensors.	Buildings in India should follow GRIHA, ECBC prescribed values of lighting power density (LPD) for artificial lighting to achieve minimum lighting power index for the energy-efficient design and construction of buildings.
	HVAC	• **Air cooled chillers** <260 TON MinCOP-2.8 >=260 MinCOP-3.0 • **Water cooled chillers** <260 Min COP- 4.7 ≥260 & <530 Min COP- 4.9 ≥530 &<1,050 Min COP- 5.4	All the buildings have more COP (Coefficient of Performance) values of HVAC system than minimum prescribed value.	Buildings in India should follow GRIHA, ECBC prescribed values of Coefficient of Performance for HVAC to achieve minimum HVAC power index for the energy-efficient design and construction of buildings.
Renewable Energy	**Renewable Energy**	5% mandatory for 5 days a week occupancy in commercial building (As per GRIHA) • If Area>20000- 3% of total electricity • If Area<20000- 2% of total electricity (As per ECBC) • Space required for 1 kW of solar PV installation is in the range of 7 – 14 sq. m	All the buildings have more renewable energy generation% than minimum prescribed value under their area range.	All the buildings have more renewable energy generation values than the minimum prescribed value as per ECBC, GRIHA

VIII. CONCLUSION AND RECOMMENDATIONS

The aim of this research work is to analyse and recommend most effective design strategies for net zero energy building in warm and humid climate of India. With the help of case studies, strategies are thoroughly analysed and investigated to determine their role and impact on energy optimization in energy efficient buildings. All the strategies are interdependent on each other. Sometimes these strategies increase or decrease the efficiency of other strategies that are implemented in the building.

Net zero buildings mainly work on three parameters, passive and active strategies followed by renewable energy systems. The main principle of these buildings should follow passive strategies first to optimize energy consumption from active strategies. Residual energy demands are fulfilled by renewable energy systems. Energy Performance Index (EPI) of the selected buildings is in range from 30-75 kWh/m2/yr. Conventional buildings in India have EPI of around 200 kWh/m2/yr. Thus, all the cases have 60-85% of reduction in energy consumption as compared to conventional building's EPI.

Recommendations

The recommendations are suggested from the inferences which is the outcome of literature review and analysis of case studies. These recommendations provide specific design solutions related to warm and humid climate of India for a commercial building. Following recommendations are driven from the research work: -

Passive Strategies

- ***Orientation:*** Building orientation is one of the most important and primary strategy for the pre-design considerations for most of the net zero energy buildings. It should respond both sun and wind path. E-W axis orientation is most beneficial as, it reduces solar heat gain from the east and west facades and provides maximum use of daylight from north and south facades. Also, from climate point of view low sun angles in winter provide heat gain from the east and west facades and in summer higher sun angles can be easily shaded.
- ***Internal Layout and Planning:*** This strategy directly affects the daylighting levels and solar heat gain inside the building. Buildings should have compact plan form to reduce solar heat gain and it also provides deep penetration of daylight into the building. Spaces which have high internal heat gains like data centres or mechanical room should be placed on the edges or perimeter of the building. As, these spaces can also act as a buffer space for internal part of the building from external heat gain. Corridors and service cores should be placed on east or west edges to reduce heat gain from harsh solar radiations as it can act as a buffer space for the building.
- ***Daylighting:*** Daylighting is one of the most important strategies for net zero energy buildings because, it can lead to substantial energy savings. Sidelighting and Toplighting are the two strategies that can help in achieving the desirable daylight levels inside the building. Building orientation plays important role in sidelighting. The south and north are ideal orientations for sidelighting applications. North orientations do not need any shading or solar control as it provides diffuse daylight into the building. Toplighting is effective for spaces directly below roofs; but toplighting can also contribute to lower floor levels through the use of atriums, light wells, or other devices.
- ***Ventilation:*** High performance commercial buildings mostly rely on mechanical ventilation systems. But operable windows can work with low-energy HVAC systems like radiant or desiccant cooling systems. Courtyard and stack effect are the most common strategies for the natural ventilation. With the help of solar chimneys stack effect can be created inside the building spaces.
- ***Building Envelope:*** Envelope with low thermal transmittance (low U value) should be designed and constructed to reduce the cooling load inside the building. Walls, roof and windows should have U- value as per ECBC 2017. Thicker walls and roof with insulation are beneficial in warm and humid climate. High performance windows are necessary in this climate for commercial buildings. U value, SHGC and VLT for fenestration should be according to ECBC codes. Window Wall Ratio (WWR) should not exceed beyond 40%.
- ***Shading:*** Building orientation and shading should respond to the sun's path. East and West façade windows need special type of horizontal and vertical shading devices. South facing windows do not require any special kind of shading devices. A horizontal overhang can provide effective shading on south facing windows. Self-shading can also be provided by selecting the building form. As in these buildings upper floors provide shading to the lower floors of the building.
- ***Vegetation:*** Vegetation through landscaping can provide shading to the lower floors of the building façade. It also reduces striking of direct sunlight and provides diffuse daylight into the building. Vegetation also includes green roofs and walls. These are secondary strategies to provide shade to the building envelope. Green walls as skin can be used to provide shade to the external walls. Although the maintenance cost of these systems is quite high.

Active Strategies

- ***Heating Ventilation and Air-conditioning:*** Mixed mode and low energy HVAC systems can be used to reduce down the energy consumption from the mechanical cooling system. Coefficient of Performance (COP) is the factor to measure the efficiency of HVAC system. For a net zero energy building, selection of equipment should exceed the efficiency requirements of ECBC. Values of COP are mentioned in ECBC and the table below.
- ***Lighting:*** North and South edge spaces are not much dependent on artificial lighting in daytime hours. While designing a NZEB, super ECBC values should be followed which is LPD- 5W/m^2 for artificial lighting in the commercial buildings. Low energy lighting fixtures like LEDs and luminaires should be used with task lighting functions to provide visual comfort to the occupants of the buildings. Lighting control systems should be used with occupancy sensors to reduce energy consumption by reducing unnecessary artificial lighting usage.
- ***Energy Efficient Equipment:*** Plug loads have a significant part in energy consumption of the building after lighting load. As per recommendation of GRIHA rating system, equipment installed in the building should be of BEE star labelled or of equivalent performance.

Renewable Energy Systems

- Warm and humid areas receive heavy amount of solar radiation throughout the year. This is one of the most common sources of renewable energy in net zero energy buildings. As per ECBC+ buildings which have renewable energy systems should generate minimum 4% of electricity of its total consumption throughout the year but net zero buildings have to generate same amount of energy what they consume throughout the year. Solar energy systems depend upon the factors like location, orientation of BIPV system, type of BIPV system and efficiency of it. Efficiency of these systems depends upon temperature of PV panels and climatic factors like cloud cover.

Table 7 Recommendation summary and Design Matrix

Strategy	Description	Strategy Types	Design Matrix			
PASSIVE STRATEGIES			Lighting	Ventilation	Cooling	Heating
Orientation	E-W axis orientation • Reduction in heat gain from east and west sides • Max daylight use from north and south facades	E-W axis orientation				
Internal Layout and Planning	• Buffer spaces should be in east and west direction • Rectangular plan form is beneficial	Rectangular plan form				
Building Form	• Compact form of building means low S/V ratio • Plan depth should be kept minimum	Compact form				
Daylighting	• Longer facades in North and South direction • Minimize floor plate depth for lighting in deep spaces • Use advance daylight harvest strategies • As per super ECBC min 60% daylight hours should be there	**Toplighting:** Daylighting shaft, Atrium, Pergolas, Roof Light Trough, Transparent Roofs, Mirror Ducts, Light Pipes **Sidelighting:** Light Shelves, Reflective sills **Window:** clerestory windows				
Natural Ventilation	• Orientation should be in windward direction • Use air circulation strategies to allow natural ventilation into the building • Window openings should be diagonal to each other • Window design plays important role in ventilation	**Cross Ventilation:** Canopy, Louvres, Sashes in windows **Stack Ventilation:** Courtyard, Solar Chimney				
Building Envelope	• Building envelope should have min U- values as per ECBC • Heavy walls and roof should be used to provide time lag. • Thermal insulation should be provided in these climates • Use materials which have high thermal mass	**S. ECBC U-values** Roof U-value – 0.20 Wall U-value – 0.22 **Window:** U-value – 2.20 SHGC - 0.25 Min VLT – 0.27				
WWR	• WWR should respond to daylighting and ventilation strategies • Case studies indicate WWR should be maximum 40% as per ECBC standards and analysis from case studies	WWR<=40				
Shading	• South facing windows require horizontal overhangs • East and west facing windows require special vertical and horizontal shading strategies • Building form can also provide self-shading to its lower parts	**SOUTH:** Horizontal shading devices- overhangs, pergolas **EAST AND WEST:** Vertical shading devices- louvres, blinds, egg crate str, Vertical projections				
Vegetation	• Vegetation can provide diffuse or glare free light into the building • Landscaping around the built form provides shade to the building envelope and lower parts of the building	1.) Evergreen trees for east and west facing walls 2.) Deciduous trees for north and south facing walls 3.) Green walls and roof as skin for building envelope 4.) Vegetation helps in channelizing wind				
ACTIVE STRATEGIES						
HVAC	• Mixed mode of ventilation systems should be used to reduce energy consumption • Also, low energy mechanical systems can be used to optimize energy consumption • Buildings should follow mandatory COP values for ECBC • 90% of occupied hours should be in thermal comfort zone	**Mixed mode:** Radiant cooling Desiccant cooling for dehumidification **Super ECBC values:** **Water cooled chillers:** <260 - 5.8 ≥260 & <530 - 6.0 ≥530 &<1,050 - 6.3				
Lighting	• Lighting design should respond passive daylighting strategies • Lighting should be according to space's functional requirement • Use low energy lighting fixtures to reduce energy consumption • Buildings should follow mandatory LPD values for artificial lighting as per ECBC	**Low energy efficient lighting:** LEDs, T-5 light, Task lights, Luminaries, Recessed lighting **Super ECBC values:** LPD - 5.0				
Energy Efficient Equipment	• Energy efficient equipments should be used to reduce energy consumption from plug loads					

	• BEE or any other star rating appliances should be used					
RENEWABLE ENERGY						
Solar Energy	• These systems should be designed according to climate and location like cloud cover and amount of solar radiation received in the area • Efficient BIPV system should be selected • Renewable energy generation should be according to ECBC codes					

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