RACHNA 2.0

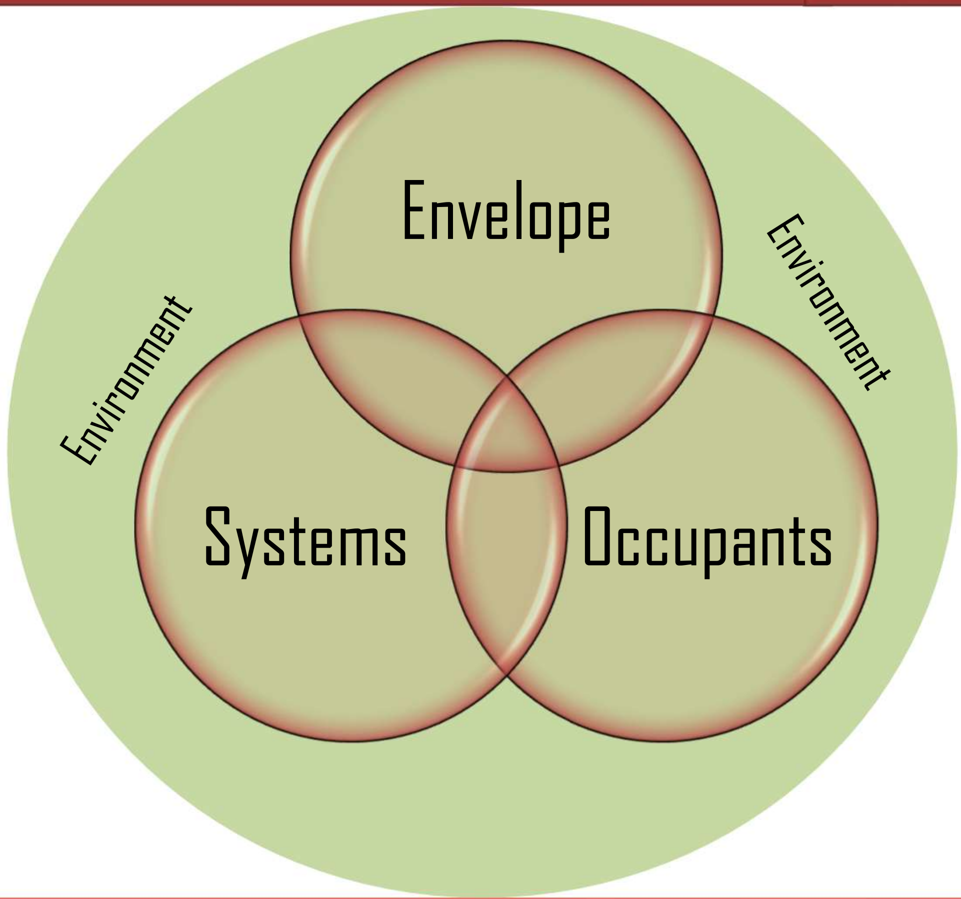
RESILIENT, AFFORDABLE AND COMFORTABLE HOUSING THROUGH NATIONAL ACTION

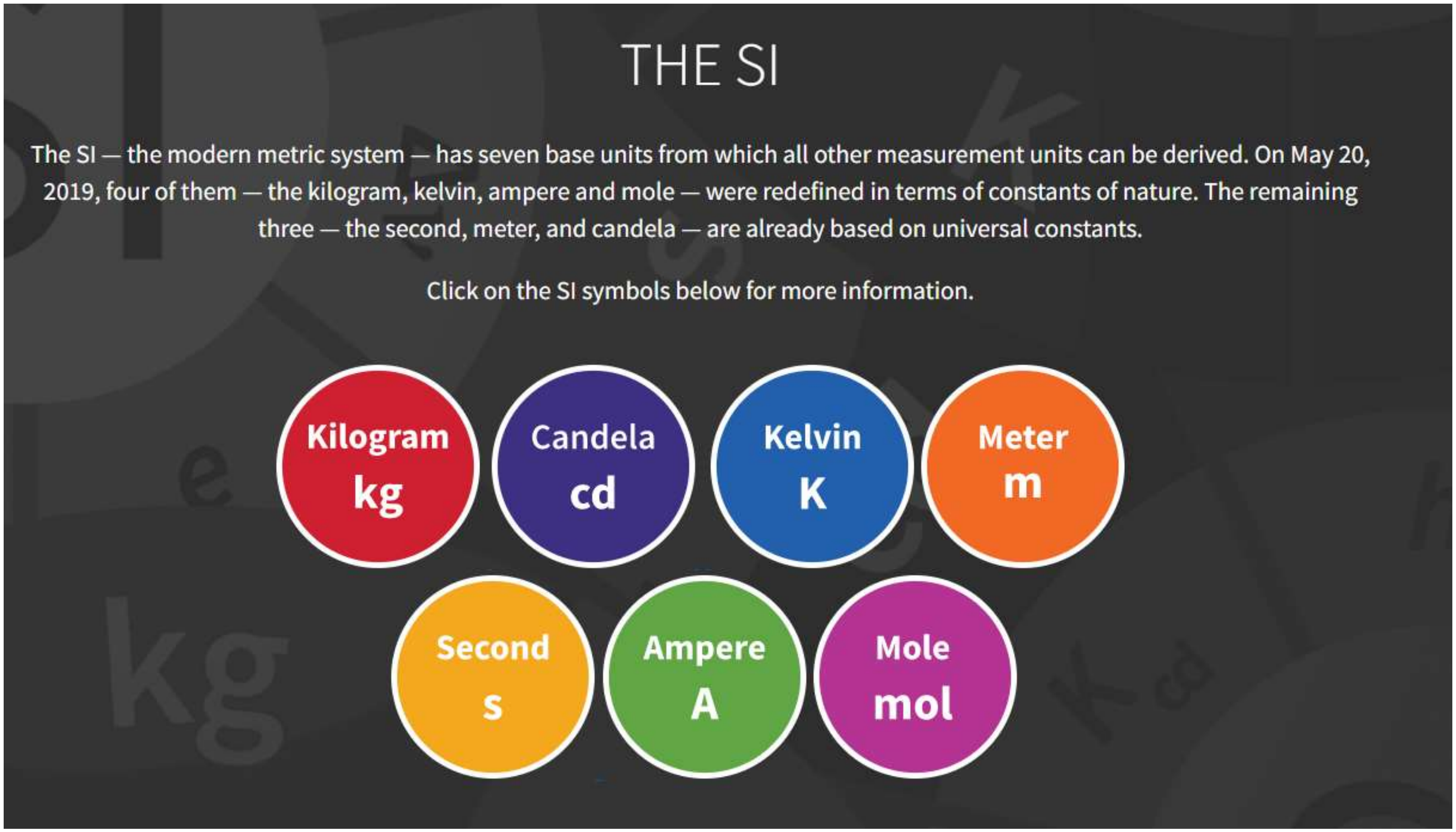
Building Physics and Thermal Comfort

Aviruch Bhatia

March 31, 2023

Building Physics




THE SI
The SI — the modern metric system — has seven base units from which all other measurement units can be derived. On May 20, 2019, four of them — the kilogram, kelvin, ampere and mole — were redefined in terms of constants of nature. The remaining three — the second, meter, and candela — are already based on universal constants.
Click on the SI symbols below for more information.
Kilogram kg
Candela cd
Kelvin K
Meter m
Second s
Ampere A
Mole mol

Temperature

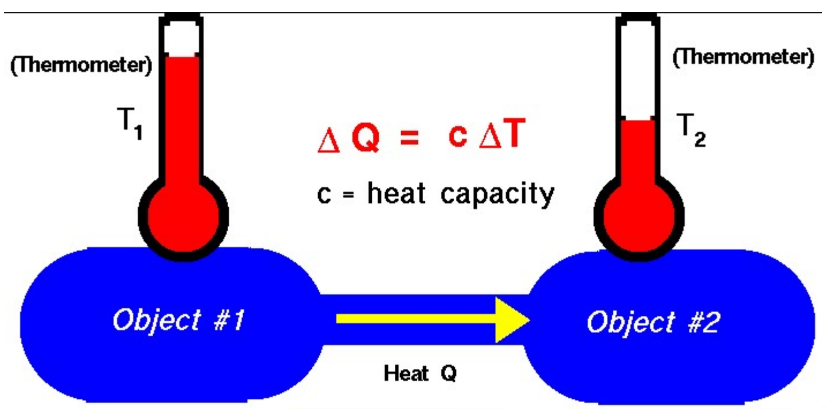
- A measure of the random motion of atoms/molecules

- A symptom-as the outward appearance of the thermal state of a body

- If energy is conveyed to a body, the molecular movement within the body increases and it appears to be warmer

Heat transfer

- Flow of heat from hot body to a cold body
- Heat is thermal energy.
- It is transferred between bodies of different temperature.
- It is expressed in units of Joules (J) or kilowatthours (kWh).
- 1 Joule corresponds to 0.278×10^{-6} kWh.
- 1 kWh corresponds to 3.6 MJ (Mega Joules).



Specific heat capacity

- The energy content of a substance depends on its:
  - temperature
  - mass
  - specific heat

- The specific heat capacity c of a substance denotes the amount of needed heat to raise the temperature of a unit mass of a substance 1 K. The unit of specific heat is thus: $J \cdot kg^{-1} \cdot K^{-1}$

Material	C_p [J/kg K]
Brick	800
Concrete	840
Limestone	910
Plaster	1000
Light weight concrete	1000
Mineral wool	1000
Wood	1200
Water	4187
Air	1006

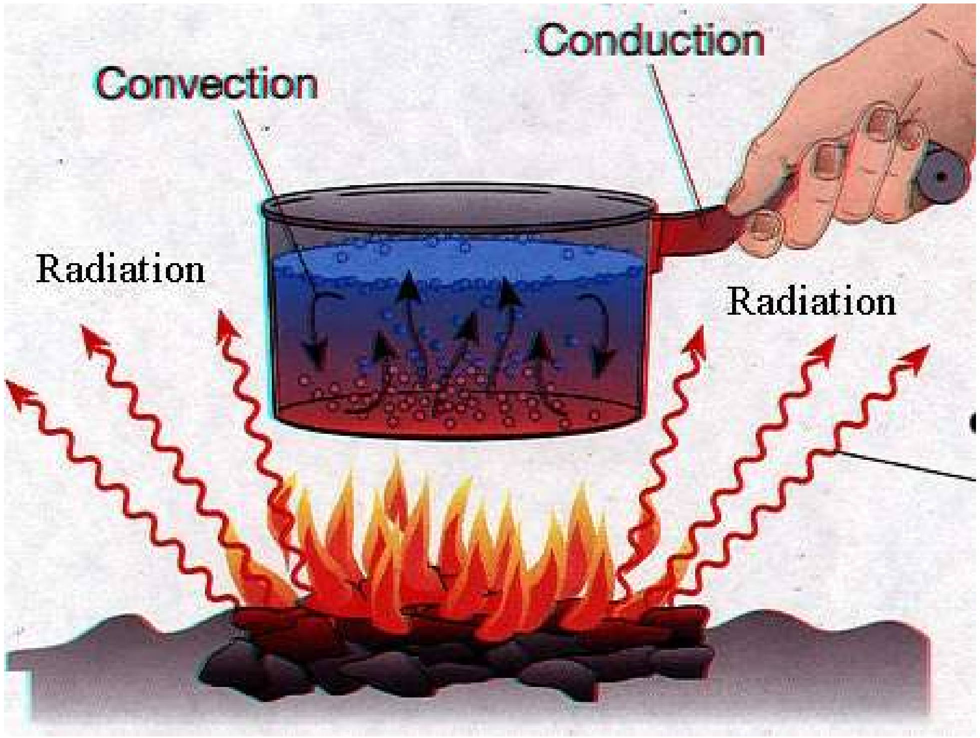
Laws of Thermodynamics

- First law of thermodynamics: Energy can neither be created nor be destroyed

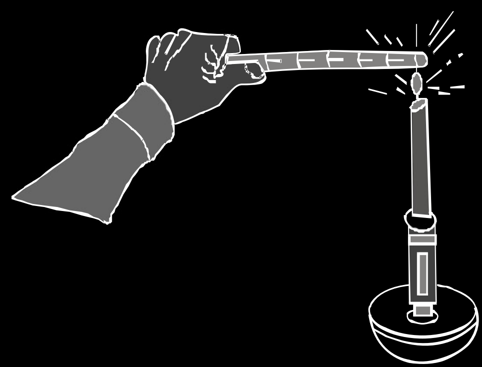
- Second law of thermodynamics: Heat cannot pass spontaneously
  - Heat tends to distribute itself evenly
  - Flow from high temperature to lower temperature bodies
  - Directly proportional to temperature difference

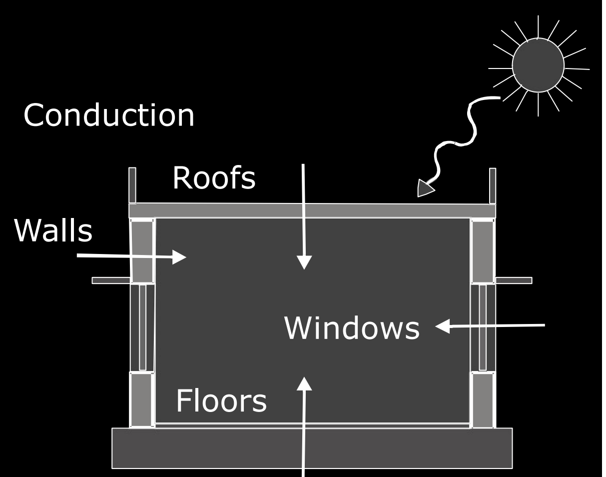
Modes of heat transfer

- Conduction
- Convection
- Radiation



Conduction

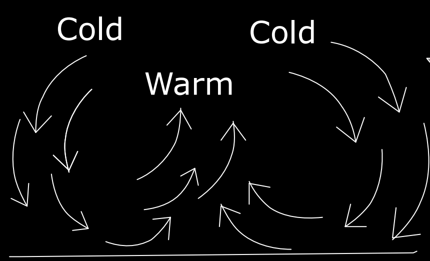




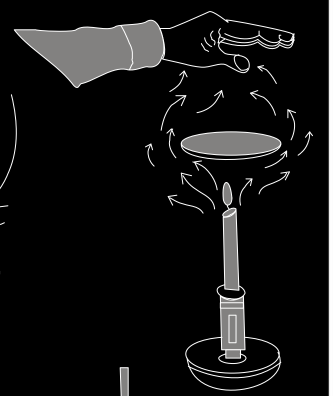
Conduction through building envelope

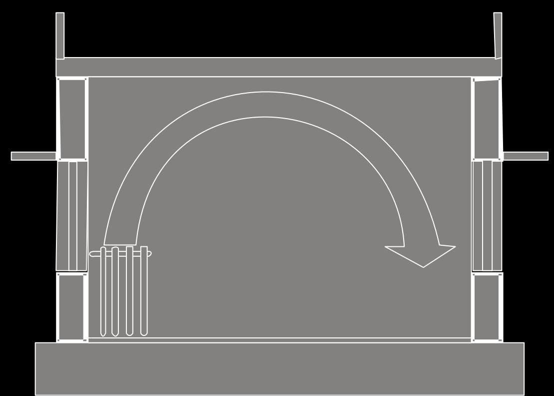
- The flow of heat through a material by direct molecular contact
- Conduction take place when a temperature gradient exists in a solid (or stationary fluid) medium
- Energy is transferred from the more energetic to the less energetic molecules when neighbouring molecules collide
- Reduces with increase in thickness and reduction in thermal conductivity

Convection



Fluid movement of air



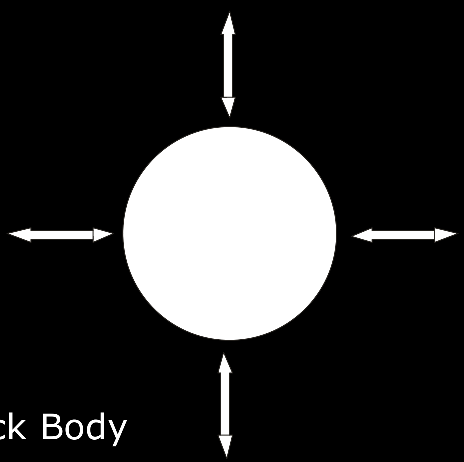


Convection

- The transfer of heat by the movement or flow of molecules (liquid or gas) with a change in their heat content
- Convective heat transfer may take the form of either in Buildings
  - Forced convection
  - Natural convection

Radiation

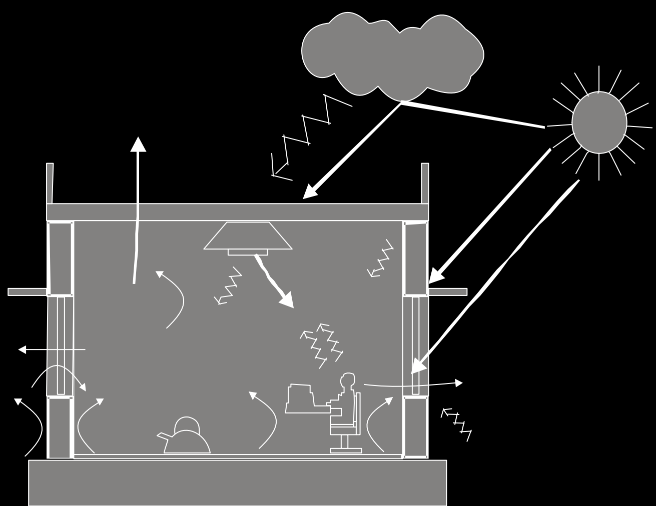
Radiation



Black Body

- Radiation is the transfer of heat by electromagnetic waves through a gas or vacuum.
- It requires a line of sight connection between the surfaces involved
- A black body is defined as a body that absorbs all radiation that falls on its surface.

Heat gain and heat loss



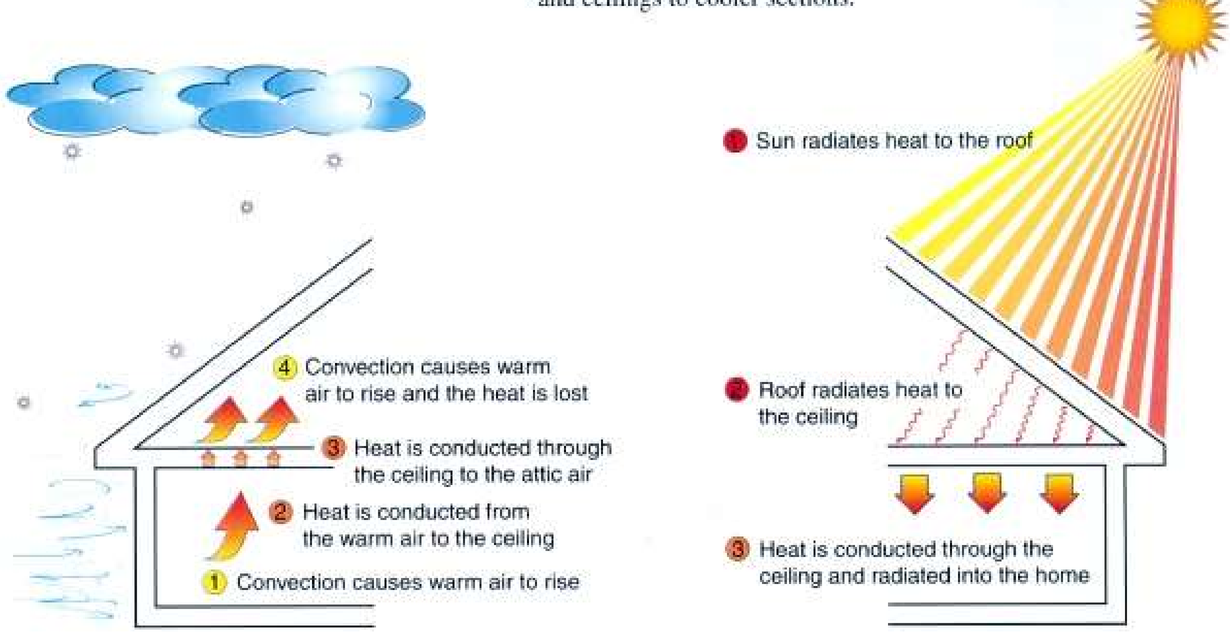
Heat Gain and Heat Loss

- Heat tends to flow from higher temperatures to lower temperature zones by conduction, convection and radiation
- The rate of heat flow by any of the three forms is determined by the temperature difference between the two zones or areas considered. The greater the temperature difference, the faster the rate of heat flow

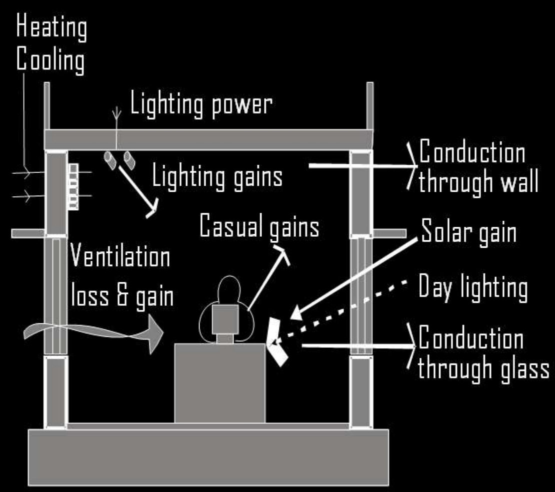
Heat transfer in buildings

Your Home Loses and Gains Heat in 3 Ways

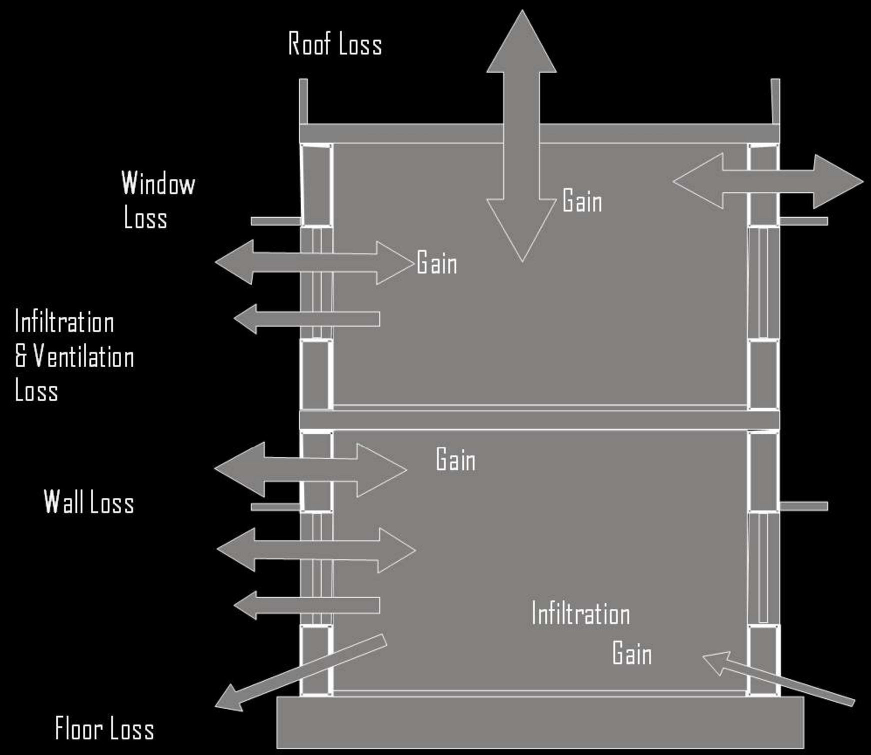
	Convection	Conduction	Radiation
Definition:	The transfer of heat by moving air.	The transfer of heat through a solid material.	The transfer of heat in the form of electromagnetic waves.
Example:	Warm air rises and transfers heat to the ceiling	Heat is transferred from warmer sections of the walls and ceilings to cooler sections.	Heat is transferred from the roof to the ceiling.



Heat flow in buildings



Heat Transfer through Envelope



Seasonal Heat Gain and Heat Loss

Heat flow in buildings

Mode of Heat Transfer	Affected By	ECBC's role in regulating Heat Transfer
CONDUCTION	Thermal Properties of Materials & Effectiveness of Insulation	U-factors/ R-values of roofs & walls
CONVECTION	Air movement at the surface	Building Envelope Sealing Requirements
RADIATION	Indirect and direct solar radiation	• R-values of roofs & walls • Cool Roofs

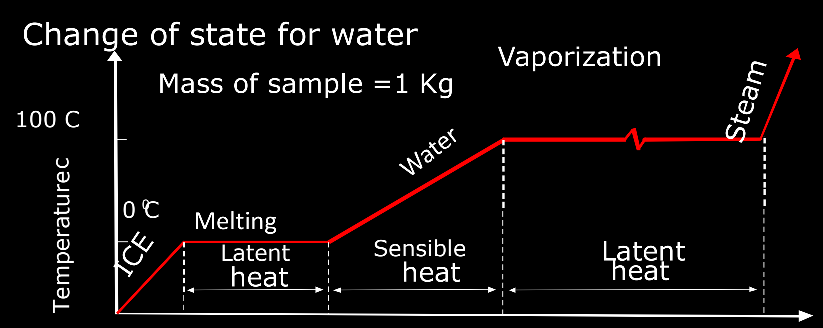
Sensible & Latent heat

Sensible Heat

- Heat that results in a temperature change is said to be "sensible" and sensed by humans

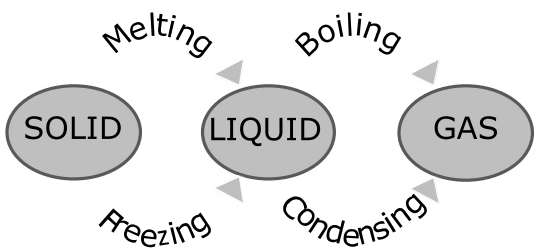
Latent Heat

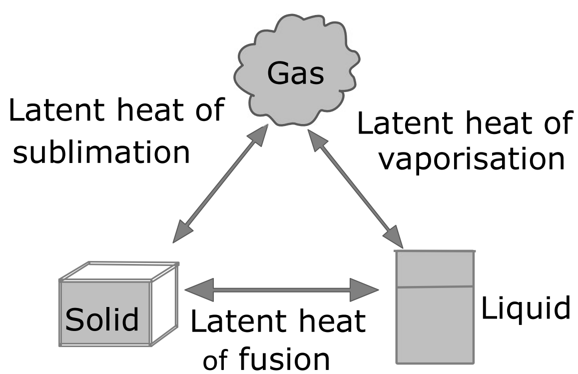
- Latent Heat is the energy needed to change a substance to a higher state of matter
- No temperature change and thus no change in the kinetic energy of the particles in the material



Latent heat

Change of State

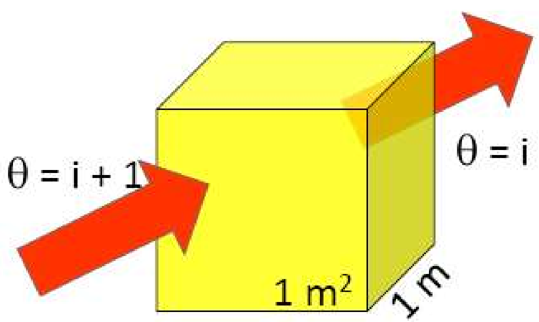




- Science: Change in the physical state of a material (solid, liquid, or gas)
- State change occurs at a constant temperature but still entails the movement of energy
- Ex. Evaporation absorbs energy and condensation releases energy
- It involve the absorption or release of heat energy, called latent heat, without change in temperature of the material

Thermal Conductivity

- Thermal conductivity in W/m K



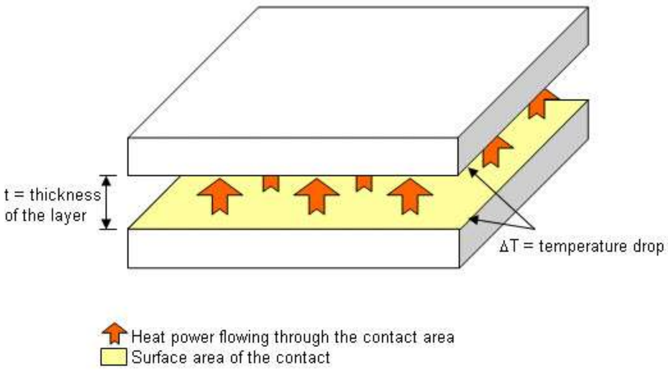
Thermal conductivity of various materials

Material	l [W·m⁻¹·K⁻¹]
Brick	0.6
Concrete	1.7
Granite	3.5
Gypsum	0.22
Iron	84
Light-weight concrete	0.14
Mineral wool	0.04
Wood	0.14

Thermal Resistance

- The value of the thermal resistance is the temperature difference across the material required to produce one unit of heat flow per unit area
- Unit : m^2-K/W

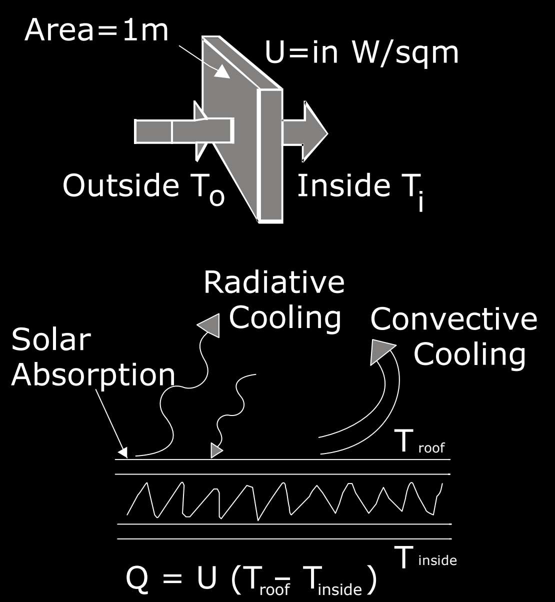
Air Space Resistance



Factors that affects air-surface resistance:

- Thickness of the airspace
- Flow of air in the air-space
- Lining of air-space (normal/reflected)

Thermal Transmittance



- Thermal transmittance from thermal resistance can be expressed as
  - $U = 1 / R$ where
  - U = thermal transmittance ($W/m^2\ K$)
  - R = thermal resistance ($m^2\ K/W$)
  - Overall thermal transmittance can be expressed as $U = 1 / (\Sigma R)$

Roof compliance example

Type	U-factor (W/m²-°K)	U-factor (Btu/h-ft²-°F)
RCC slab with mud phuska and clay tiles	2.797	0.493
RCC slab with foam concrete or perlite	0.069	0.012
Inverted clay/pots with mud phuska	2.244	0.396

- Taking case of RCC with mud-phusca
- Default U=2.797, Target U=0.261 (e.g. call centre/IT/hotel building)
- $R_{assembly} = R_{roof} + R_{insulation}$
- $(1/0.261) = (1/2.797) + R_{insulation}$
- $R_{insulation} = 3.47$, $R_{insulation} = L/k$
- $K_{perlite} = 0.04 W/mK$, $L = 0.14m$
- $K_{PUF} = 0.03$, $L = 0.1m$
- $K_{air} = 0.024$, $L = 0.08m$, (caution!!! Insulation of air cavity does not increase linearly for ever)

Wall compliance example

Type	Description	U-factor (W/m²-°K)	U-factor (Btu/h-ft²-°F)
Mass single wall	Single wall with no insulation, plaster on both sides	1.99	0.351
Mass double wall	Double brick wall with air gap	1.23	0.216
Curtain wall	Curtain wall	2.11	0.371

- Double brick wall with air gap is not sufficient
- Taking case of single brick wall
- Default U=1.99, Target U=0.44)
- $R_{assembly} = R_{wall} + R_{insulation}$
- $(1/0.44) = (1/1.99) + R_{insulation}$
- $R_{insulation} = 1.77$, $R_{insulation} = L/k$
- $K_{hardboard} = 0.16W/m\text{-}K$, $L = 0.28m$
- $K_{PUF} = 0.03$, $L = 0.05m$
- $K_{air} = 0.024$, $L = 0.04m$

Surface Resistance

- It is the resistance is offered by a thin layer of air film separates the body from the surrounding air.

- The measure of this phenomenon is the 'surface or film resistance' expressed in units of resistance and reciprocal of it being film-conductance (f) with units $W/m^2\ ^0C$.

Surface Conductance

- If the layer of air on both sides of wall is considered as per the concept of surface conductance, heat transfer from air on one side to air on other side takes place. Hence the overall 'air-to-air resistance (R)' will be the sum of the body's resistance and the surface resistance on both sides of wall: $R = 1/f_o + R_b + 1/f_i$

- The value of surface or film conductance (f) is a function of surface qualities such as smoothness and of the velocity

$1/f_o$ is film resistance on outer side of wall

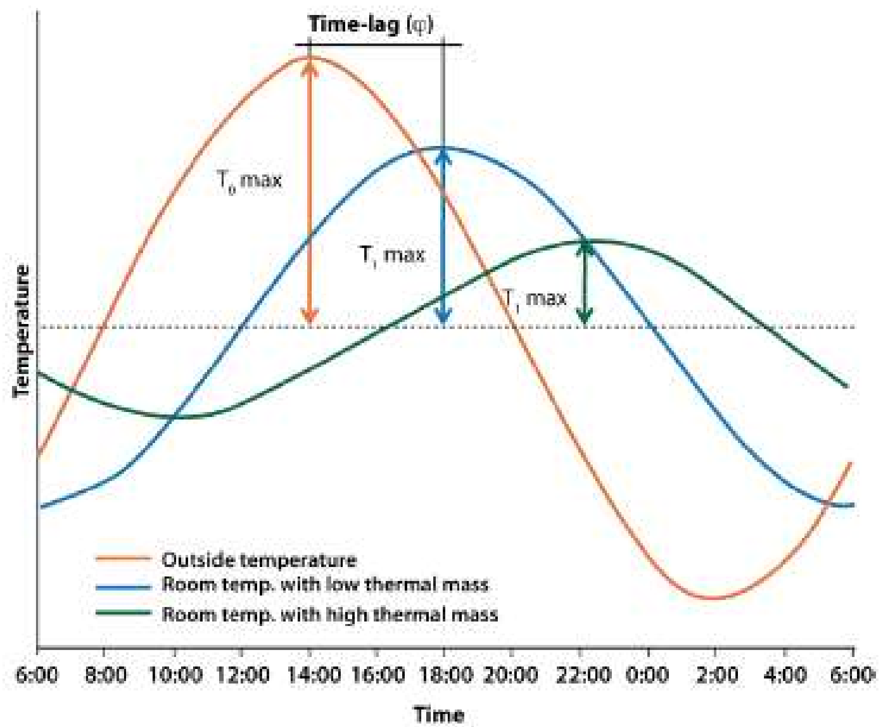
$1/f_i$ I s film resistance on inner side of wall

R_b is the resistance of wall or body

unit m^2 K/W.

Transient behavior of building

- Each particle of the wall material absorbs certain amount of heat depending upon its mass and specific heat jointly known as heat capacity.



$$\text{Decrement factor } \mu = \frac{T_i \text{ max.}}{T \text{ max.}}$$

Transient heat flow estimation

$$Q = U A [(Tm - Ti) + \mu (T \phi - Tm)]$$

q is momentary heat transfer rate in W

A is area in m^2

U is U-value in $W/m^{2}\,{}^{0}C$

Tm is daily mean outdoor temperature

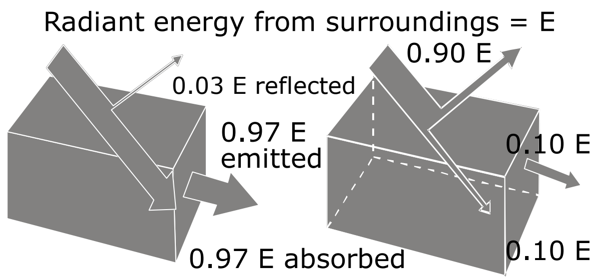
Ti is indoor temperature (assumed to be constant)

Tϕ is outdoor sol-air temperature φ hours earlier than the time of investigation

μ is decrement factor

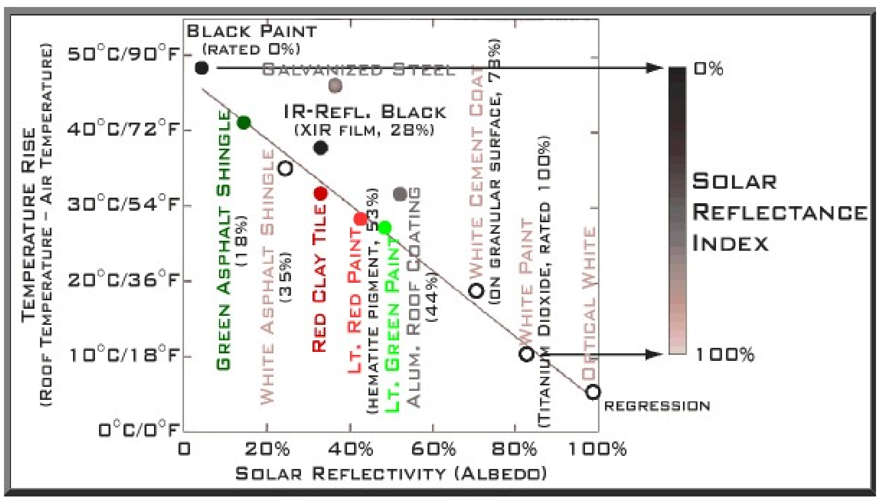
φ is time lag in hours

Emissivity

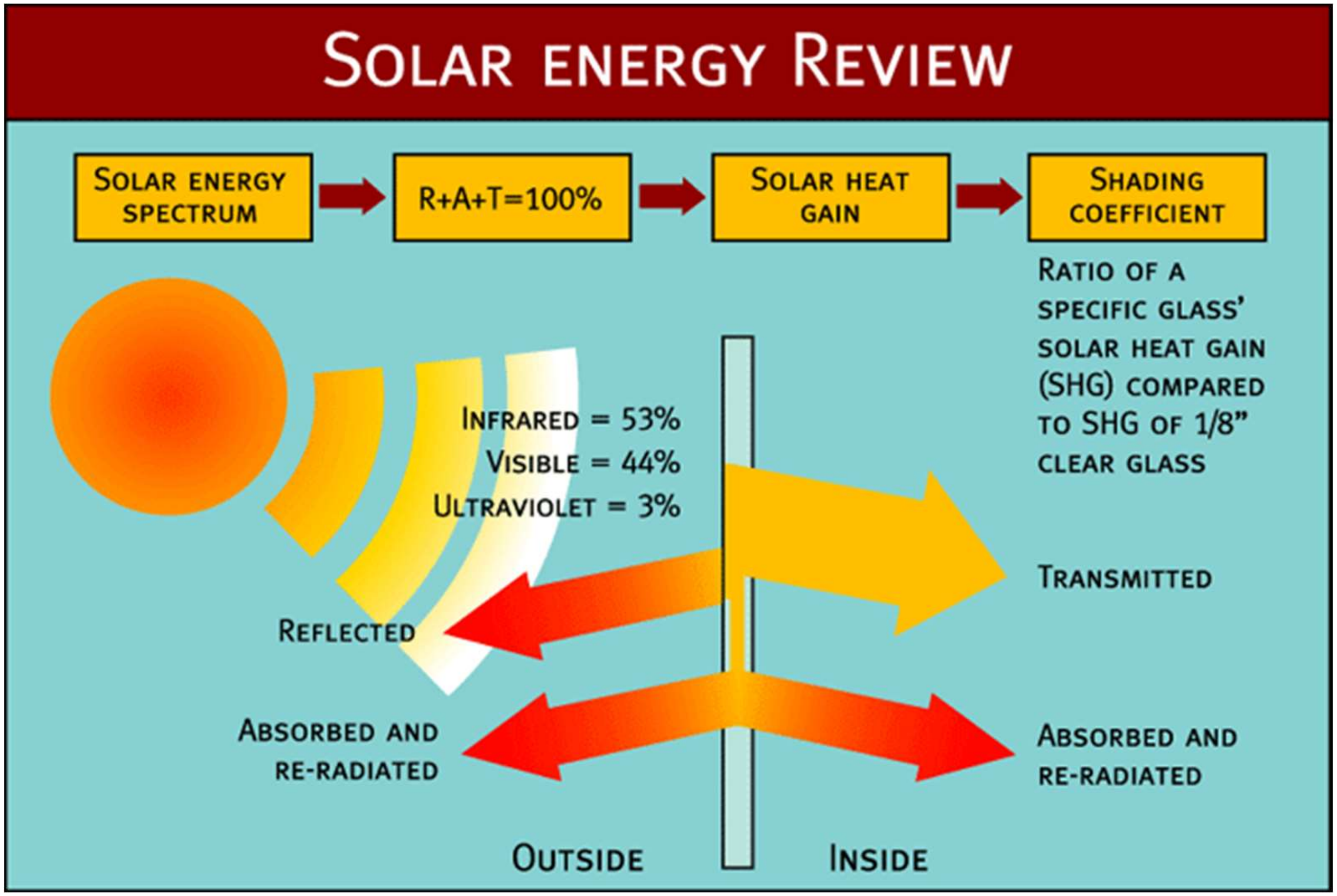


Lampblack and Silver coated block

- The ratio of the radiant energy emitted from a surface at a given temperature to the energy emitted by a black body at the same temperature
- The lower the emissivity rating, the better the insulation characteristic



Transparent Components



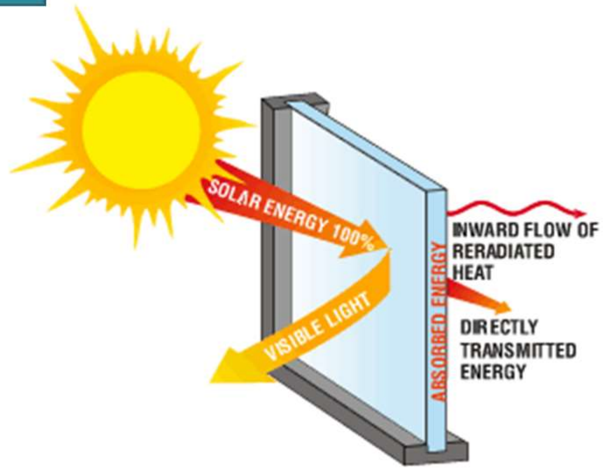
Solar Heat Gain Coefficient

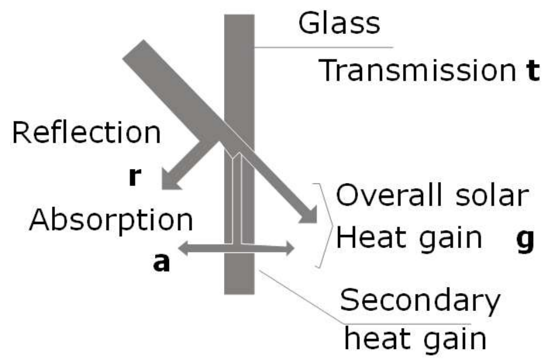
Solar Heat Gain

- Heat gain from the sun, entering a room through transparent surfaces (kW/m²)

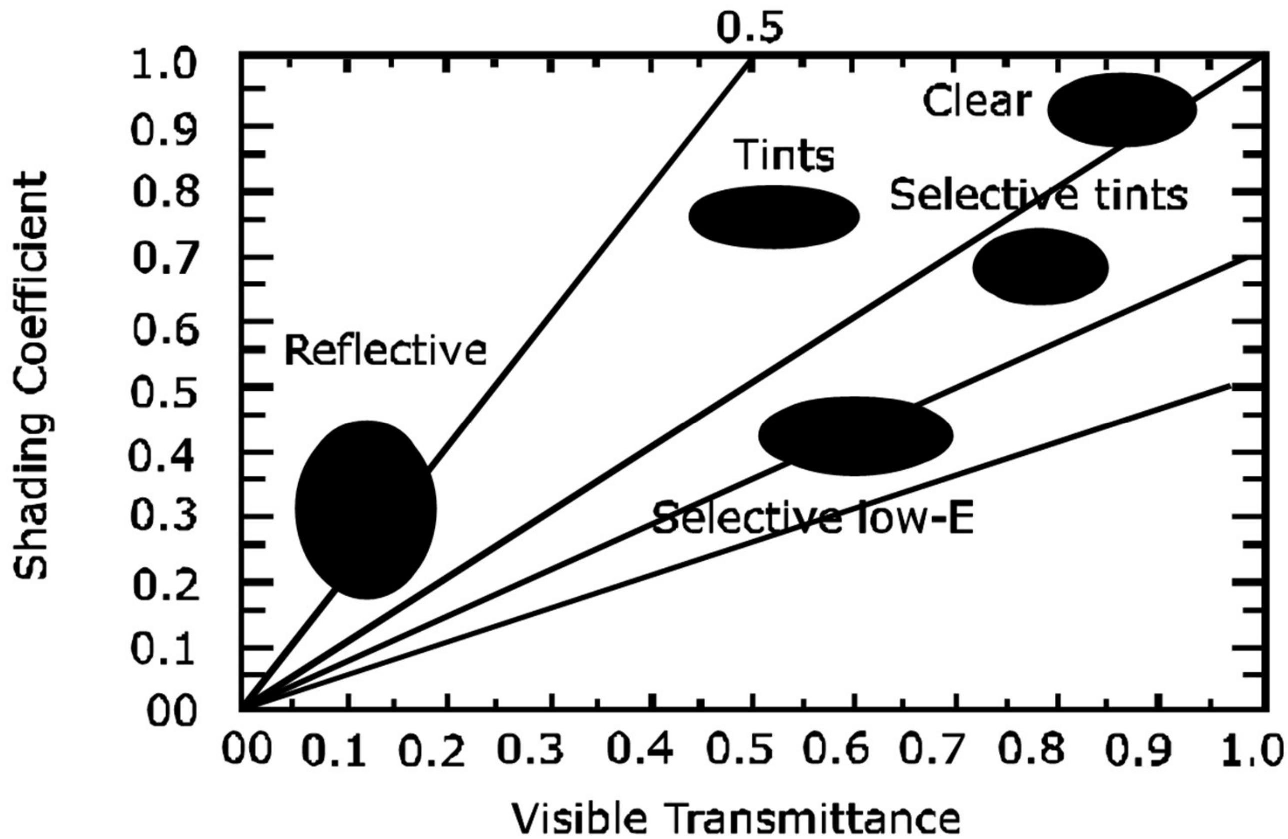
Solar Heat Gain Coefficient

- The percentage of solar energy directly transmitted or absorbed and re-radiated into a building
- Ratio of the sum of directly transmitted solar radiation and the amount of absorbed radiation entering the space through a window to the external solar radiation



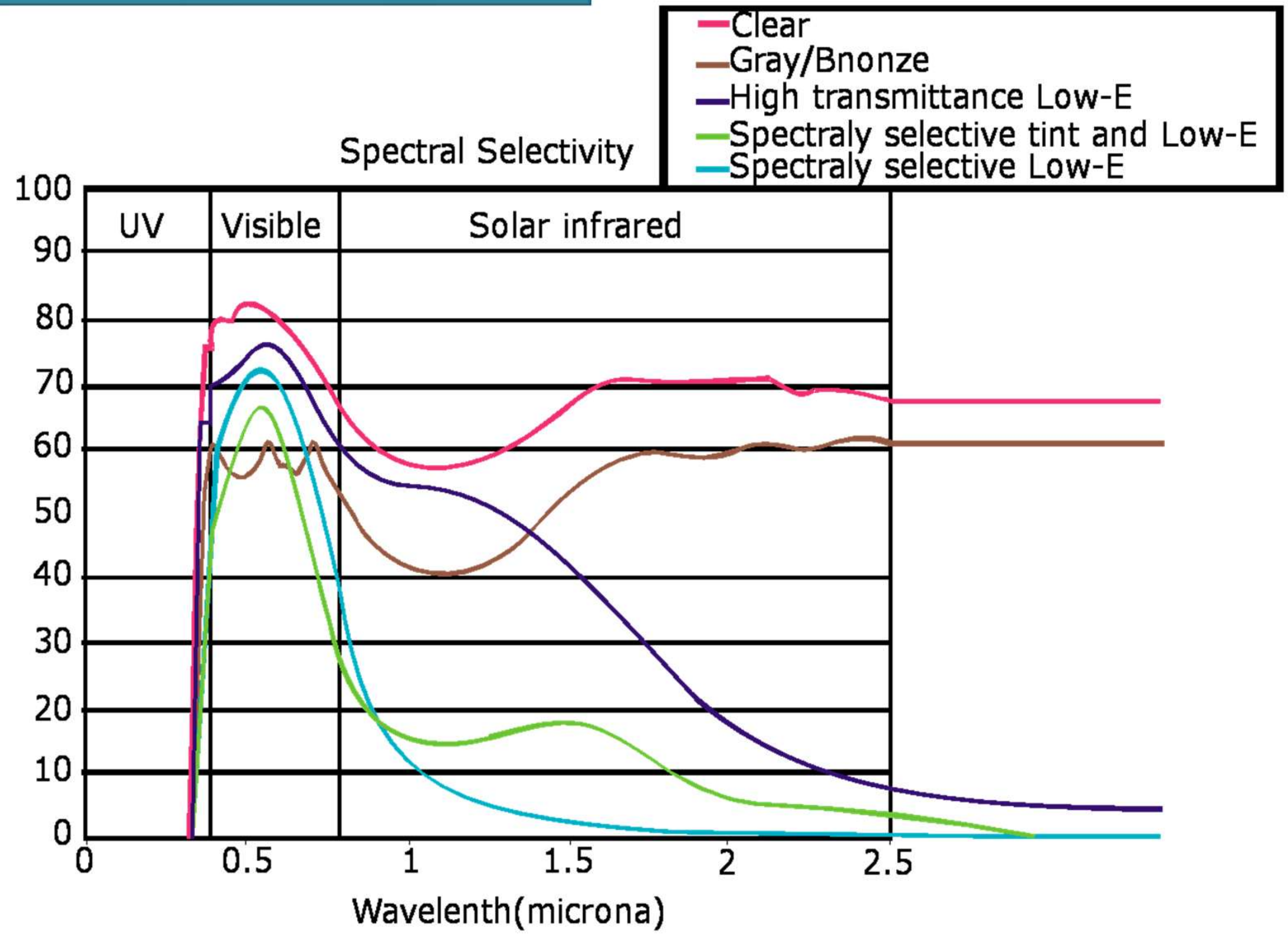


SHGC vs VLT



0.5
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
00
Shading Coefficient
Clear
Tints
Selective tints
Reflective
Selective low-E
00
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Visible Transmittance

Spectral Selectivity

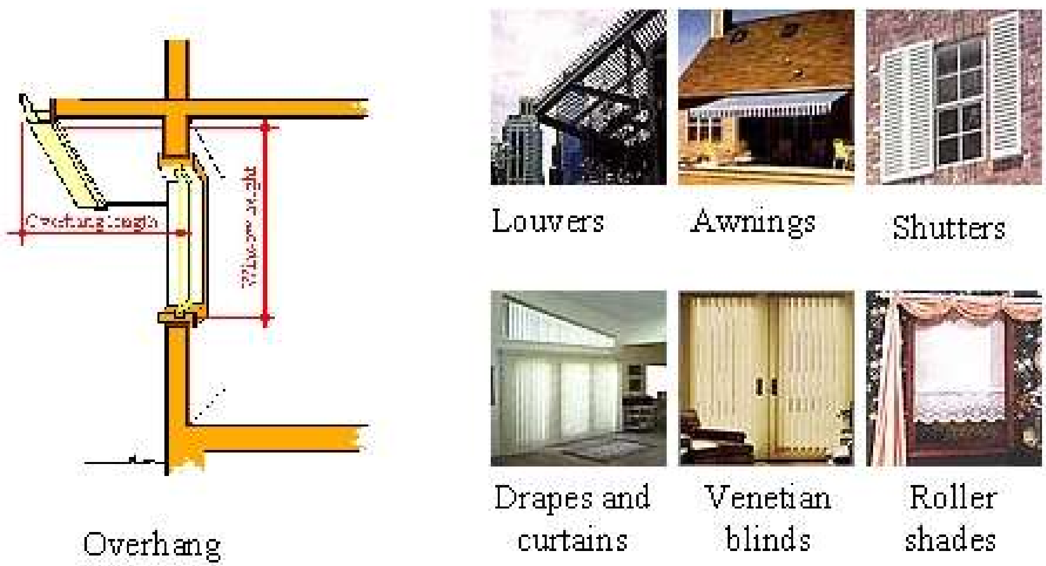


Effective SHGC

Same glass but different SHGC

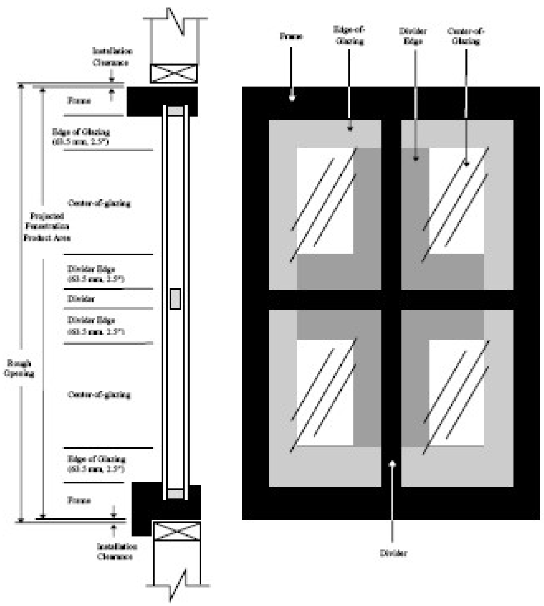
Effective SHGC

Same glass but different SHGC



Shading devices (external and internal)

U value of Fenestration

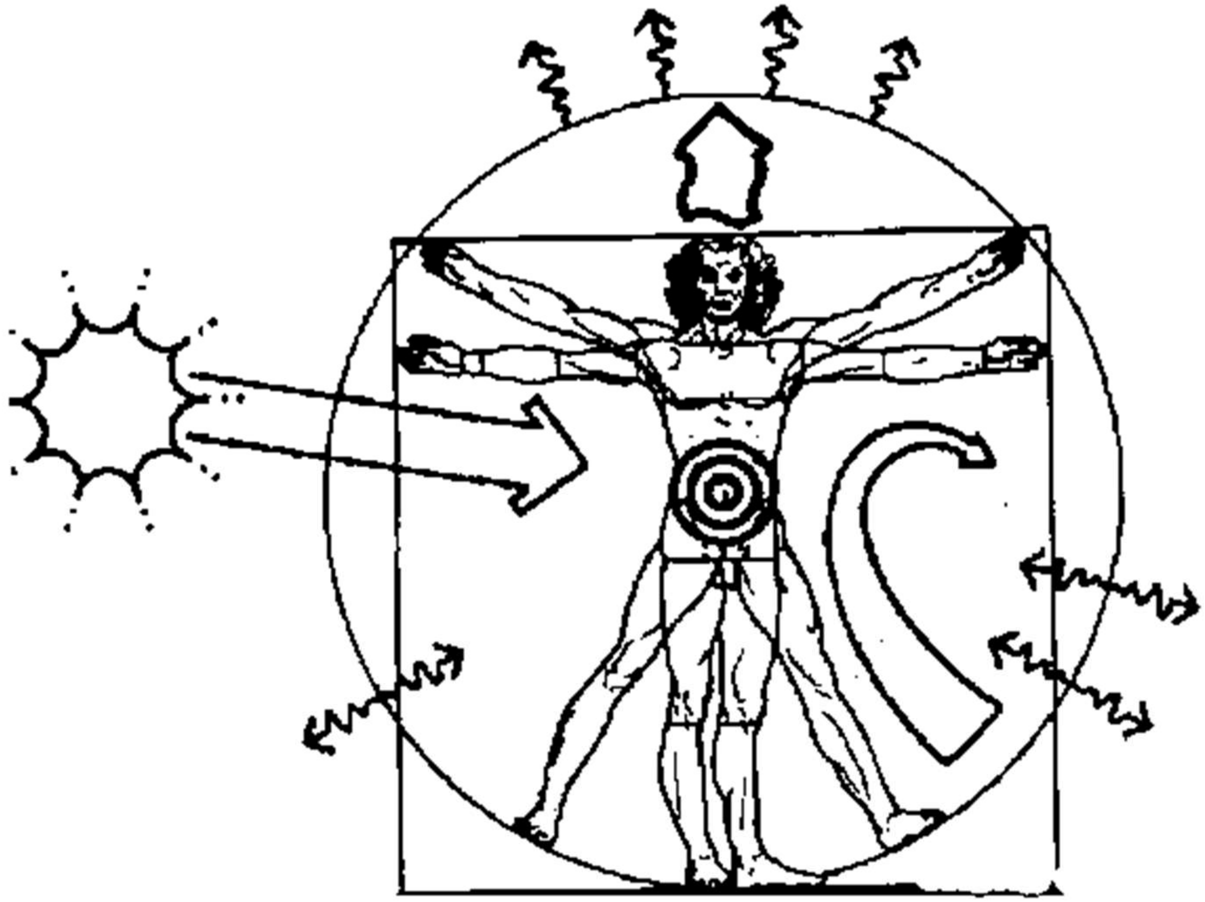


Total Product U-factor

- Insulating values of the glazing assembly
- The edge effects in the IG Unit
- The insulating value of the frame & sash

Center-of-Glazing U-factor

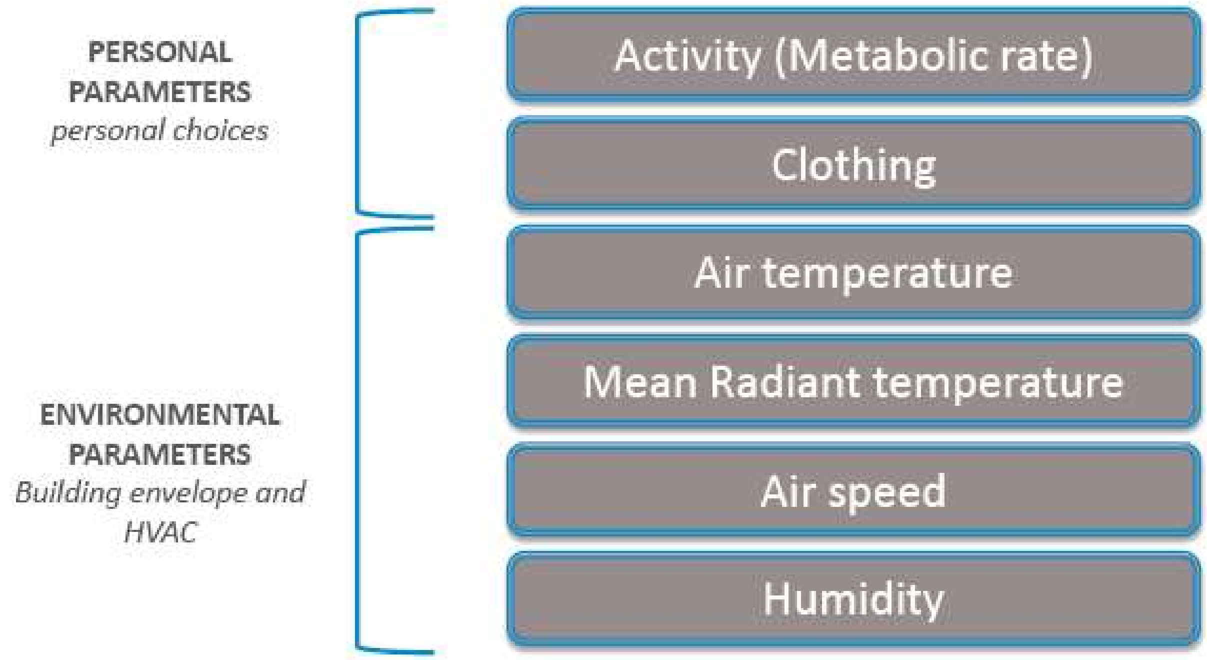
- Total number of glazing layers, the dimension separating the various layers of glazing,
- Type of gas that fills the separation, Characteristics of coatings on the various surfaces.



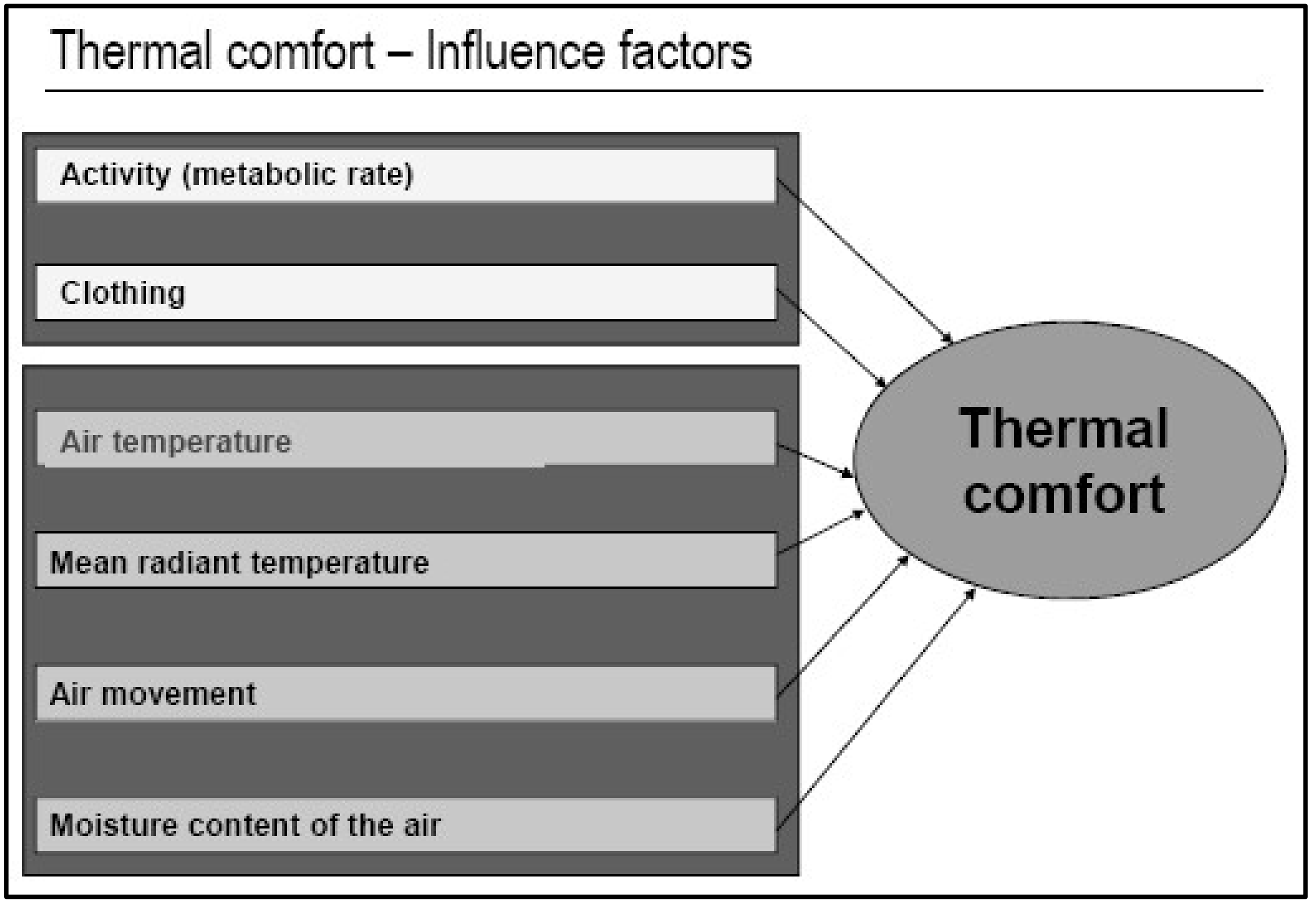
Thermal Comfort…

Thermal Comfort

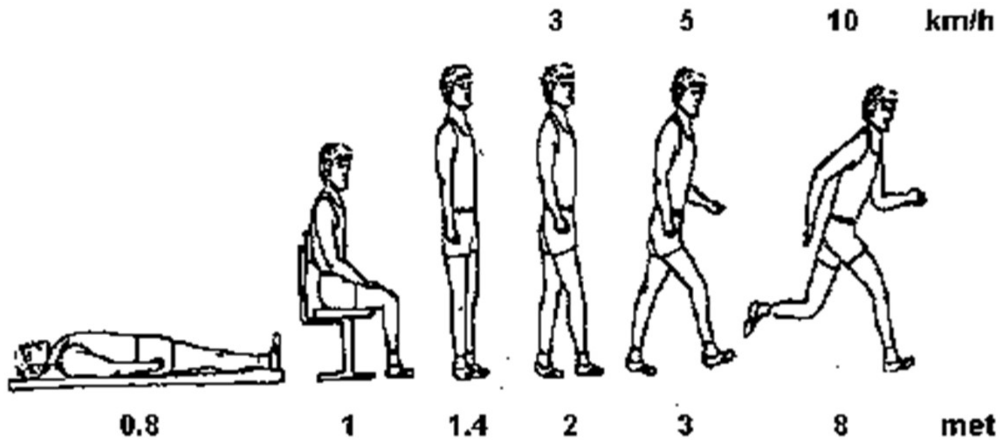
- That condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation"



Comfort Parameters



Activity

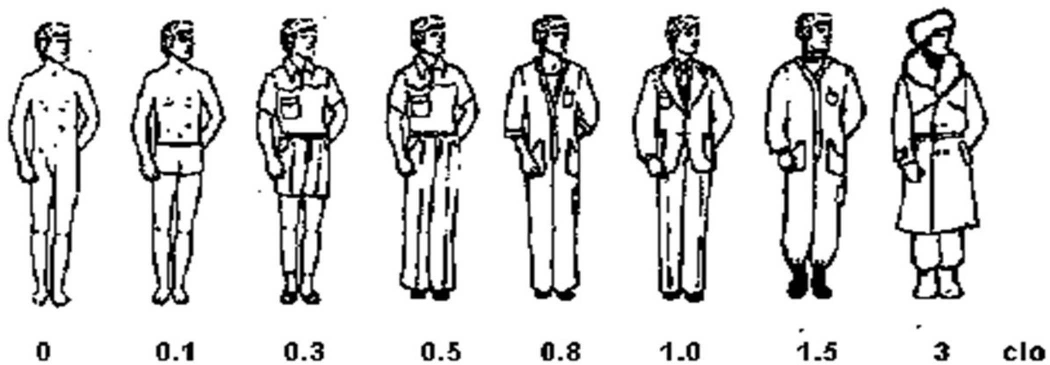


- M(metabolic rate): the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface or met units
- 1 met = 58.2 W/m2, which is equal to the energy produced per unit surface area of an average person, seated at rest

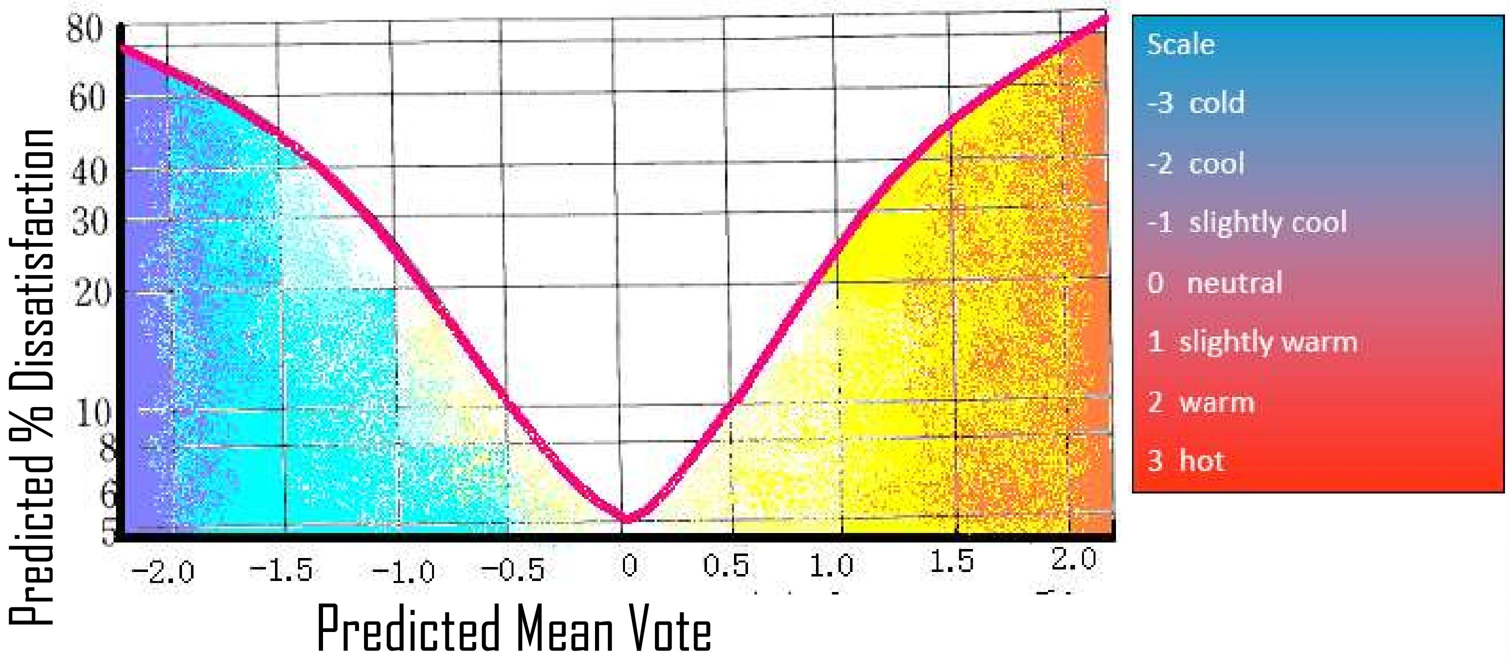
Clothing

- clo: a unit used to express the thermal insulation provided by garments and clothing ensembles
- 1 clo = 0.155 m2·K/W

Ensemble Description	I_{cl} (Clo)
Trousers + short-sleeved shirt	0.57
Long-sleeved coveralls + T-shirt	0.72
Sweat pants + sweat shirt	0.74
Trousers + long-sleeved shirt + suit jacket	0.96
Insulated coveralls + long-sleeved thermal underwear (+ bottoms)	1.37



PMV & PPD



80
60
40
30
20
10
8
6
5
Predicted % Dissatisfaction
-2.0
-1.5
-1.0
-0.5
0
0.5
1.0
1.5
2.0
Predicted Mean Vote
Scale
-3 cold
-2 cool
-1 slightly cool
0 neutral
1 slightly warm
2 warm
3 hot

Radiative temperature

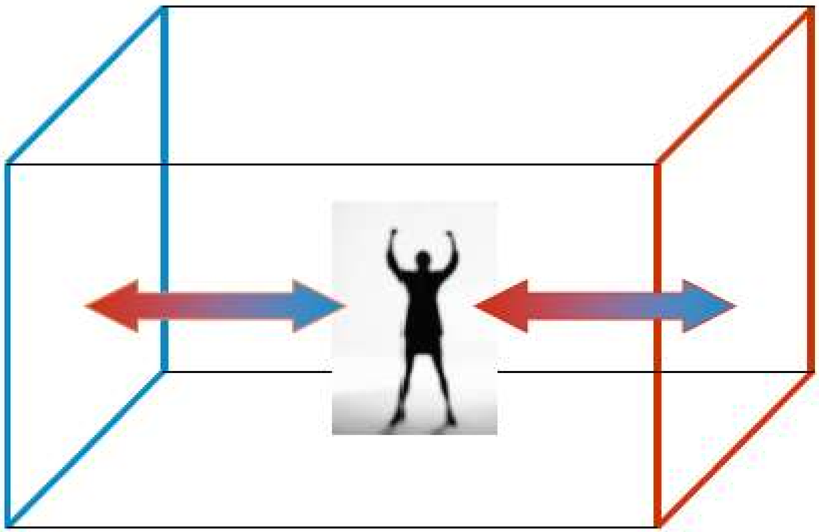
Radiation exchange

θ_U mean radiant temperature (MRT)

Rough approximation:

$$\theta_U \approx \frac{(\sum A_i \theta_i)}{\sum A_i}$$

θ Surface temperature
A Area



Operative temperature

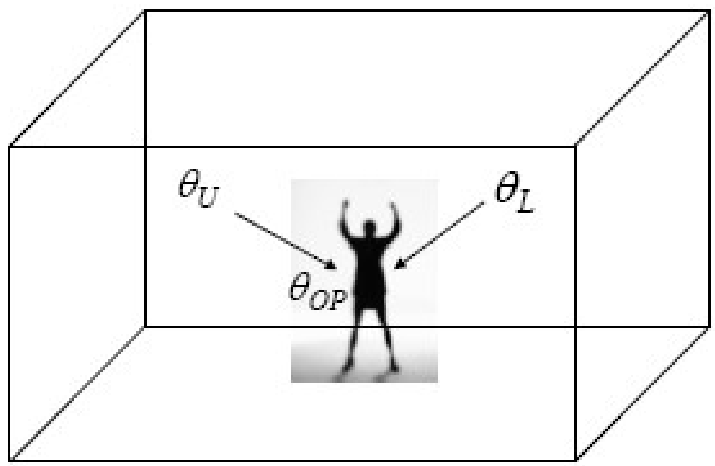
Operative Temperature

Operative Temperature (dry resultant or perceived temperature)

q_L Air temperature

q_U Mean radiant temperature

$$\theta_{OP} \approx \frac{\theta_L + \theta_U}{2}$$



Thank you

RACHNA 2.0

RESILIENT, AFFORDABLE AND COMFORTABLE HOUSING THROUGH NATIONAL ACTION

One-Day Online Training Program on Thermal Comfort in Affordable Housing

Importance of Passive Design for Comfort and Energy Efficiency in Residential Buildings

Ms. Sowmya Chinta

March 31, 2023

Sustainable Development Goals

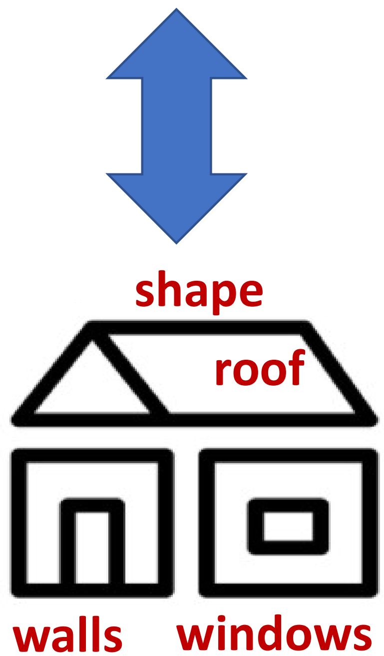
Affordable homes at locations of employment and economic opportunity with access to public transport and social amenities. Livelihoods in an inclusive construction economy

Resilience of urban living in cases of infrastructure breakdown and disasters, with sufficiency of habitable space and environmental security – water, air, recycled waste.

Use of low-carbon and resource-efficient modes of production for construction of housing and selecting building types for minimum operational energy.

Build-in resilience against extreme events, shade and green for a habitable outdoors against heat waves, aggregate rain harvest and water efficiency, minimize hard ground and motor vehicles for low UHI

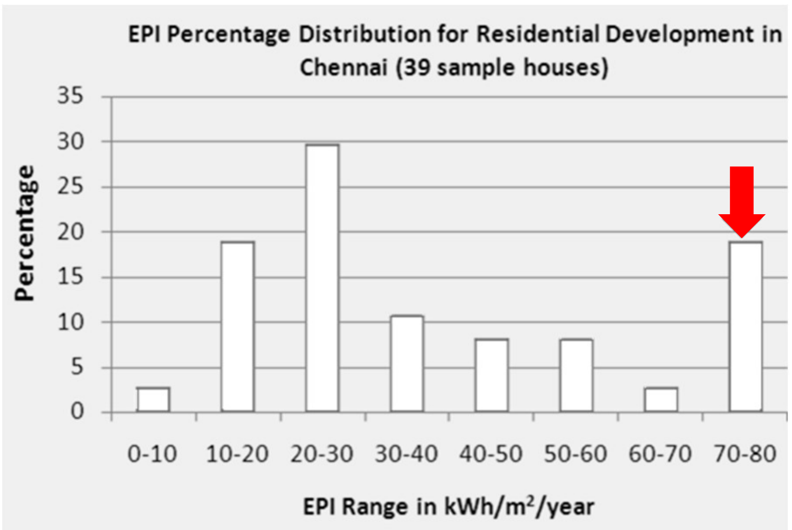
The climate and its seasonal and diurnal patterns vary from place to place

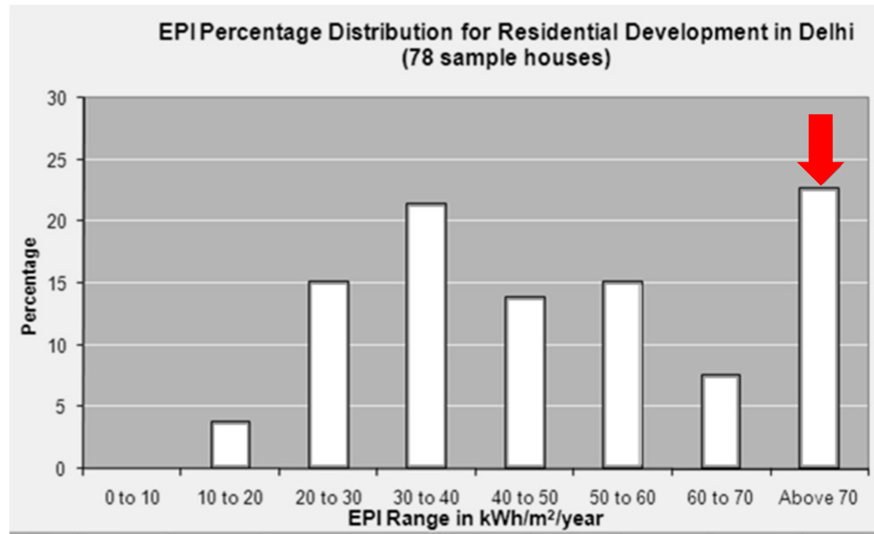


Passive design strategies would be climate responsive

Building design would respond to seasonal and diurnal variations

ELECTRICITY CONSUMPTION PATTERN : sample household survey





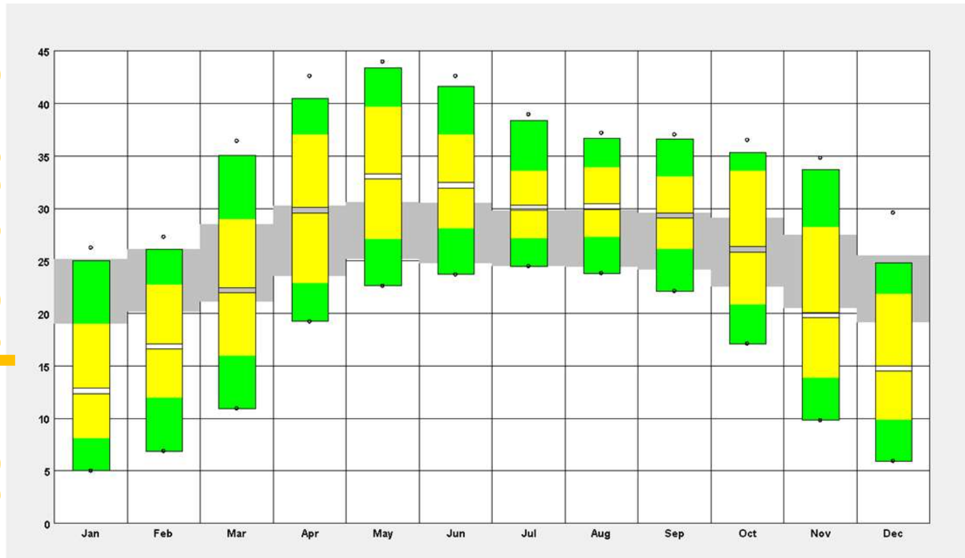
There is an emerging trend of houses with EPI above 80 kWh/sq.m./year which are typically houses with 2 or more air conditioners and 4 or more occupants. This trend is visible in both climate types.

Delhi

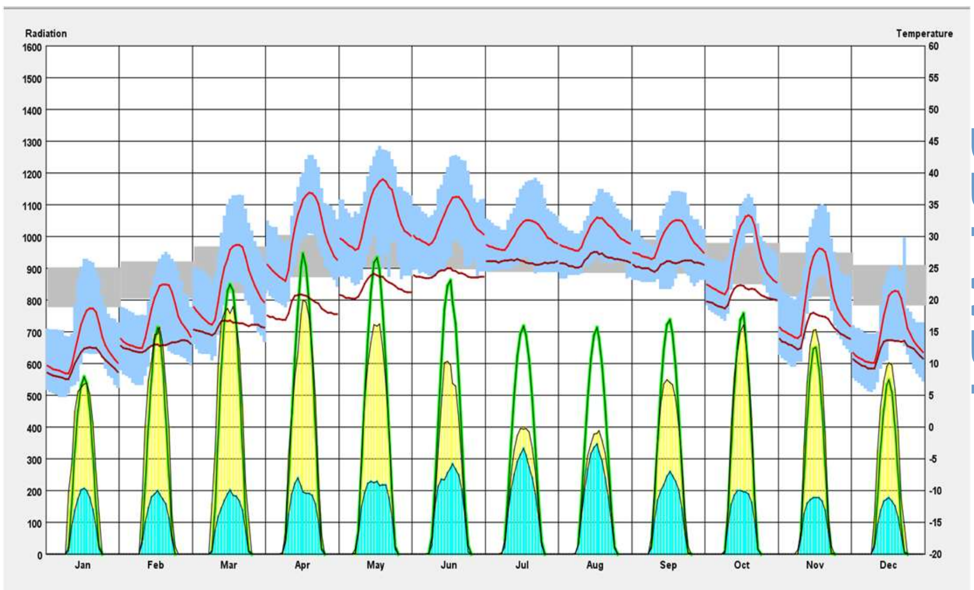
cold..pleasant...hot...humid...pleasant..

Note diurnal range variation!

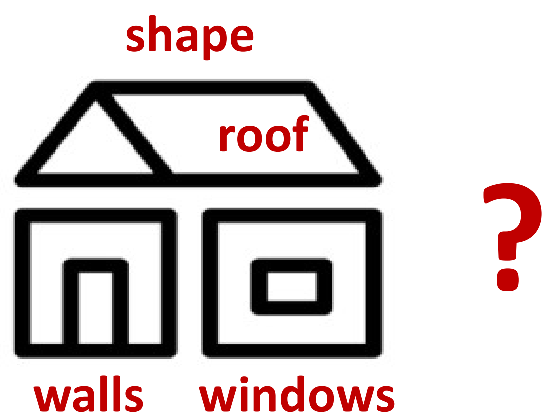
temperature



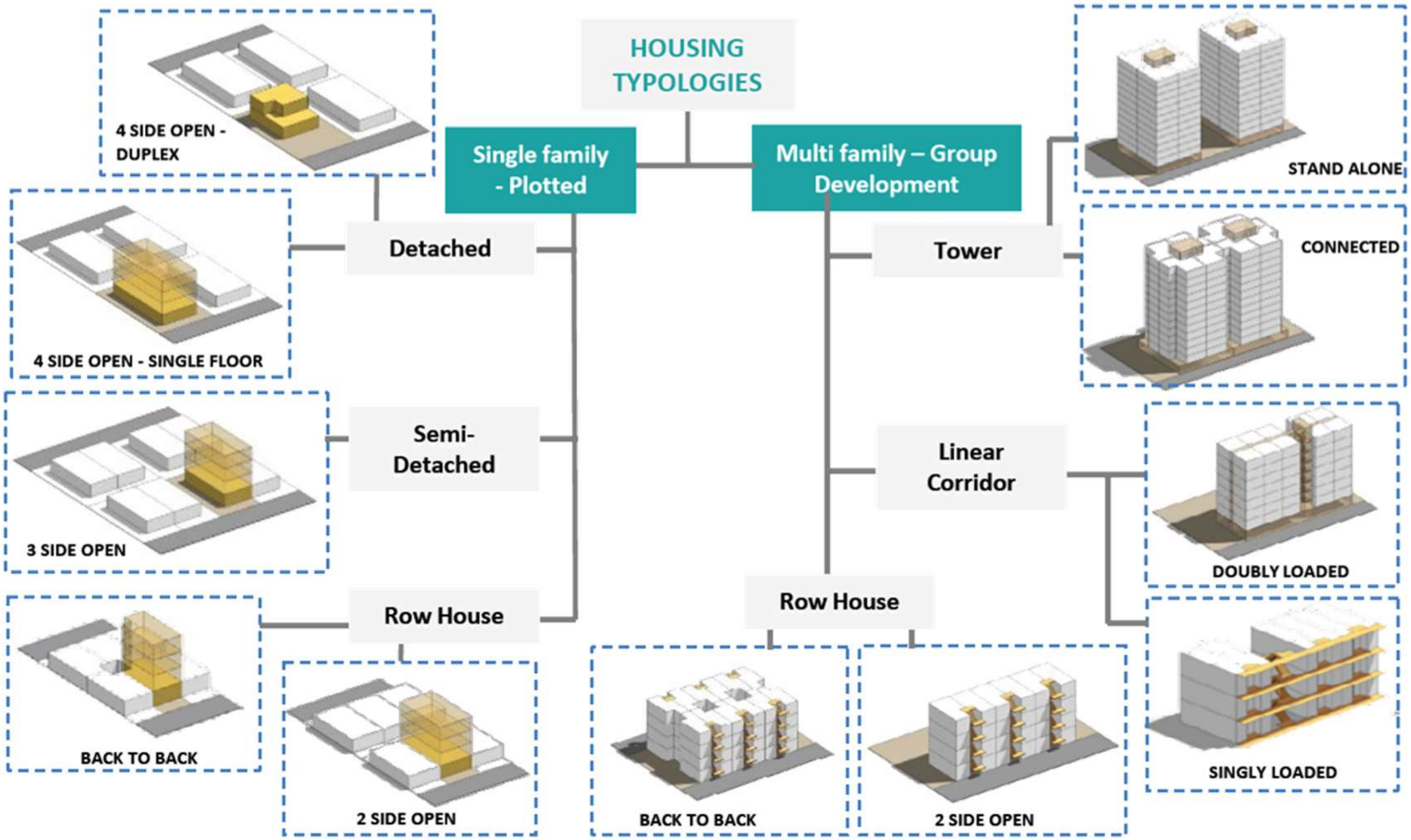
radiation



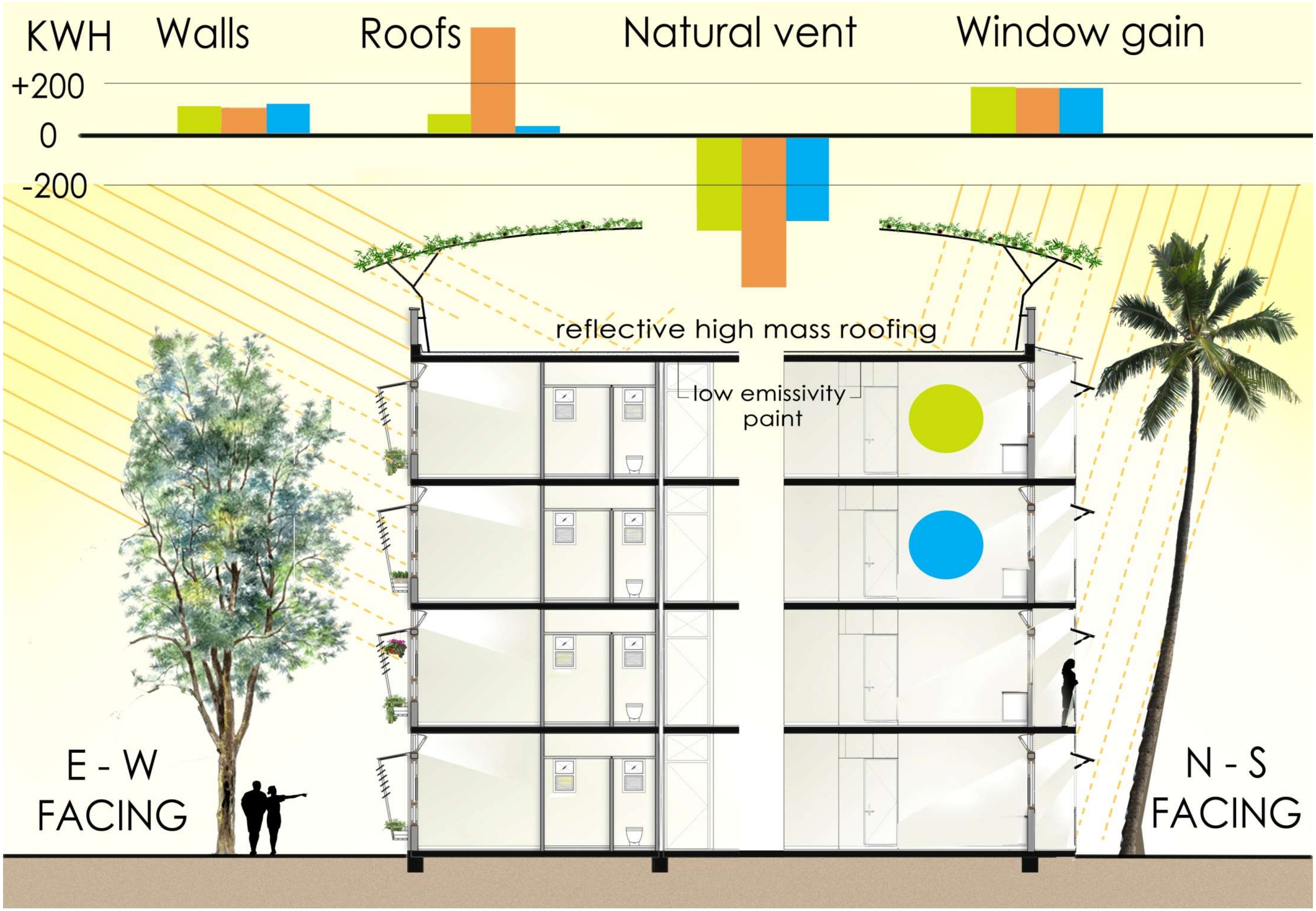
DBT-WBT



Residential Typologies



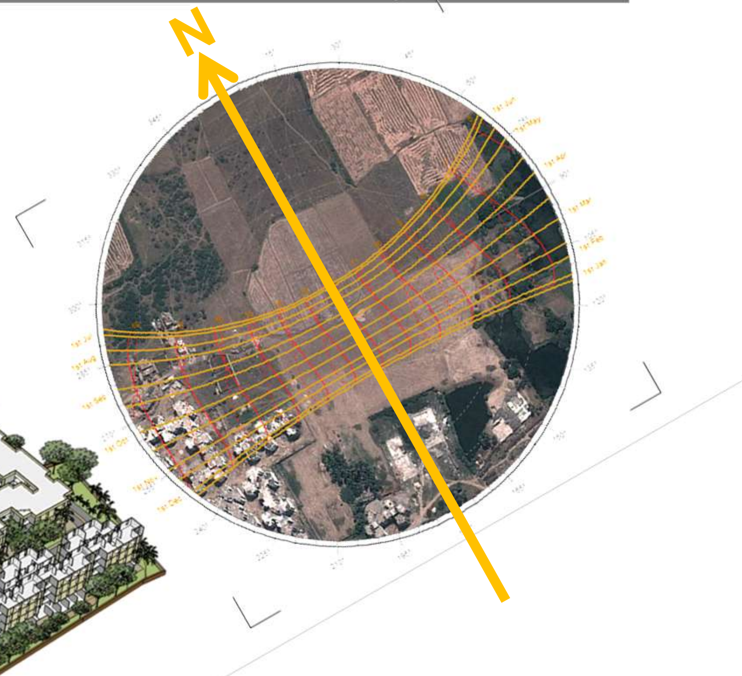
STRATEGIES	TECHNIQUES
• EXPOSURE to Solar, ambient air and wind Adjacent microclimate	– Shape, surface area – Orientation / shading,
• INSOLATION	– Shading device/system
• HEAT TRANSFER	–Thermal mass, insulation, surface reflectance
• HEAT EXCHANGE	– Ventilation, infiltration control
• HUMIDITY CONTROL	– Vapour barrier
• HEAT SINKS / SOURCES	– Evapo-transpiration, Sky, Earth, Water body
ENGINES	- Passive engines - Low energy cooling/heating systems


KWH
Walls
Roofs
Natural vent
Window gain
+200
0
-200
reflective high mass roofing
low emissivity paint
E - W FACING
N - S FACING

EXPOSURE

- Row housing to reduce peripheral wall exposure.
- External shading system – balconies and sun shade frames.
- End wall shading

SITE LEVEL STRATEGY – ORIENTATION and MICROCLIMATE FOR THERMAL COMFORT



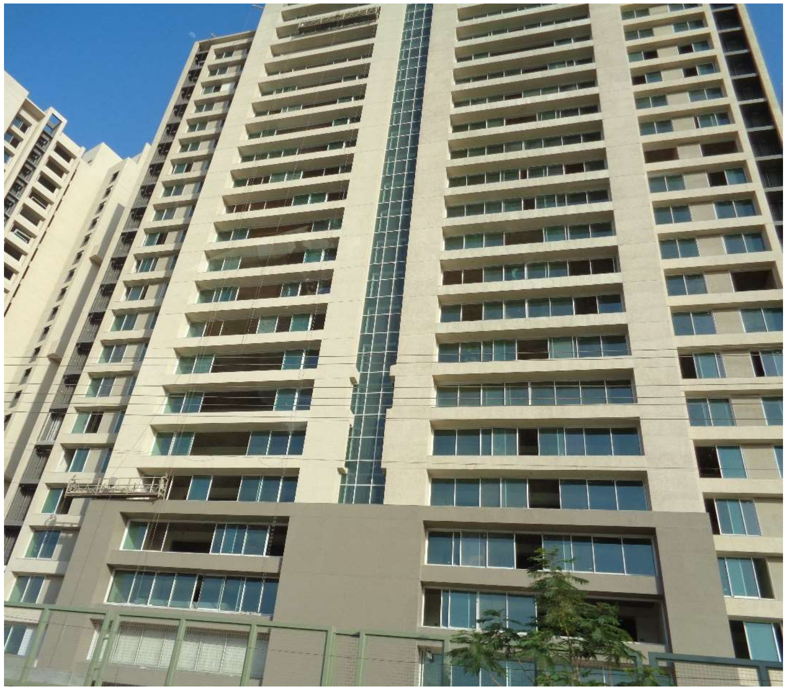
BUILDING LEVEL STRATEGY – WINDOWS AND BALCONIES

BUILDING LEVEL STRATEGY – WINDOWS AND BALCONIES

Happinest Avadi, Chennai

Design recommendations for thermal comfort

- **Reduce heat gains from the sun through windows**
  - Optimize the size of windows, as *glass* transfers **3-6** *times more heat* than walls
  - Shade the window- **use external movable shading** or **partially opaque shutters**



TYPICAL SHADING DEVICE FRAMEWORK

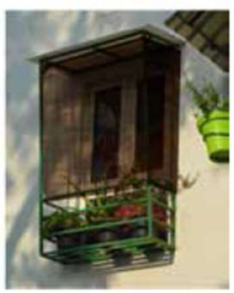
BRIEF DESCRIPTION

If a projected frame of light metal section is fixed on the wall surrounding the window opening is provided (as shown in the wall section), it will help to attach the shading panels or screens conveniently. This frame would allow the user to easily install shading screens/chiks/cloth, etc. These screens can be either fixed or movable type. The extent of the shading panel would depend on the orientation of the window. (See illustrations)

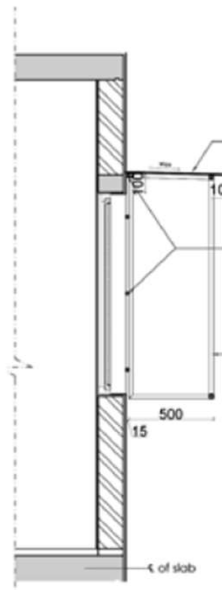
Framework: The framework is a support system designed to easily fix shading screens corresponding to the orientation. This typical box frame is made up of MS sections; other alternative options include aluminium, stainless steel, and GI. However, the box frame cost is provided for MS section.

The chhajja projection at the top should ideally be a lightweight, non-porous material such as cement board. One may also use stone or any other waterproof boards. The frame should be attached to the external wall with minimum surface area in contact with the wall. PVC sleeves can be used to separate the frame and wall and limit the conduction heat gains from the shading device to the envelope.

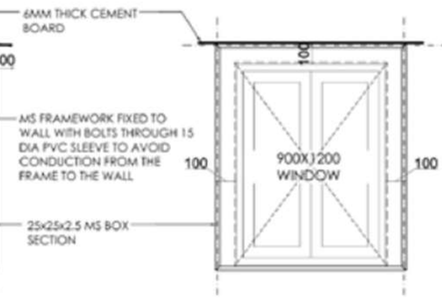
The fixed shading elements may be provided by the builder at the time of making the building, whereas roll-up/pull-down screens may be left to the user to install. Figure A provides the sketch of the assembly. The construction steps are shown in Figures 1 to 4. The details of the front elevation and wall section are shown in Figures B and C, respectively.



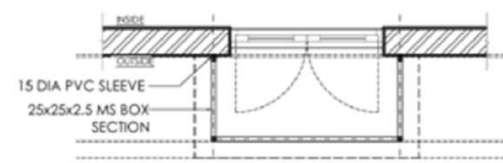
₹3000
Cost/m²



C) Wall Section



B) FRONT ELEVATION

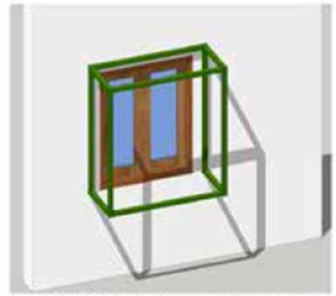


A)Plan

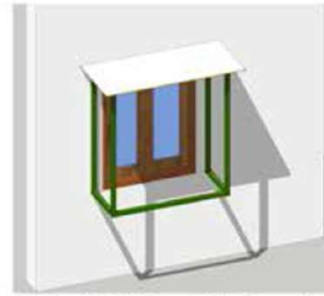
CONSTRUCTION STEPS

1 Taking the case of 900x1200mm standard window

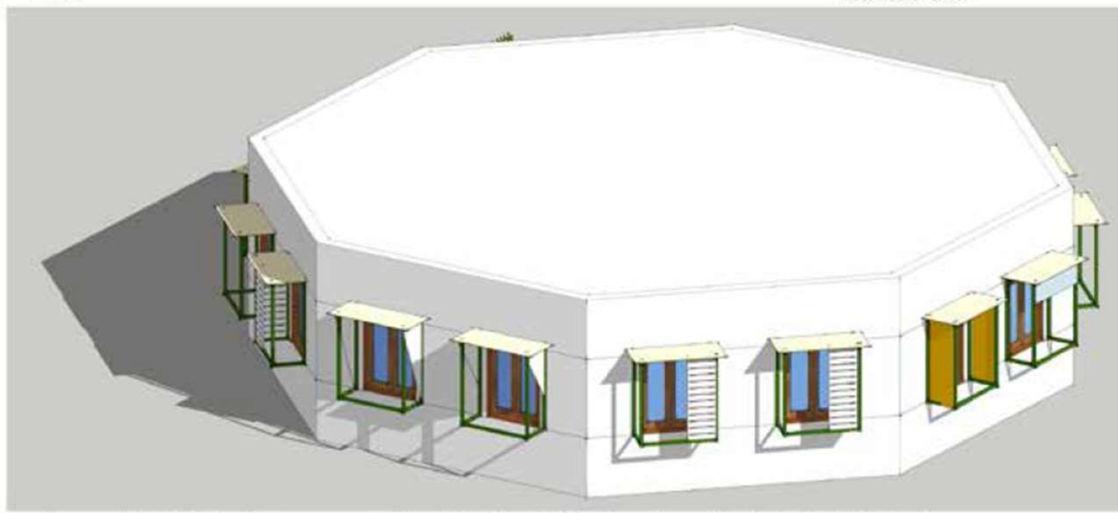
2 Drill holes, fit PVC sleeve that project out by about 15 mm and align them in one plane.



3 Fix the MS box frame with bolts, each frame can come seprately and bolted.



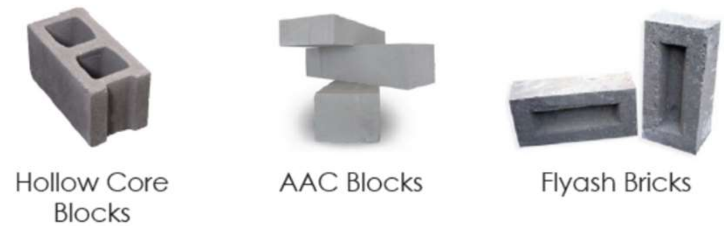
4 Once the MS frame is fixed properly, different shading devices can be installed over it.



The shading device acts as a framework to further fix shading screens, chiks, perforated panels etc. depending on the orientation of the facade.

Design recommendations for thermal comfort

- **Reduce heat gains through the roof and walls**
  - Insulate / shade roof. Reflective roof finish
  - Insulate / shade walls



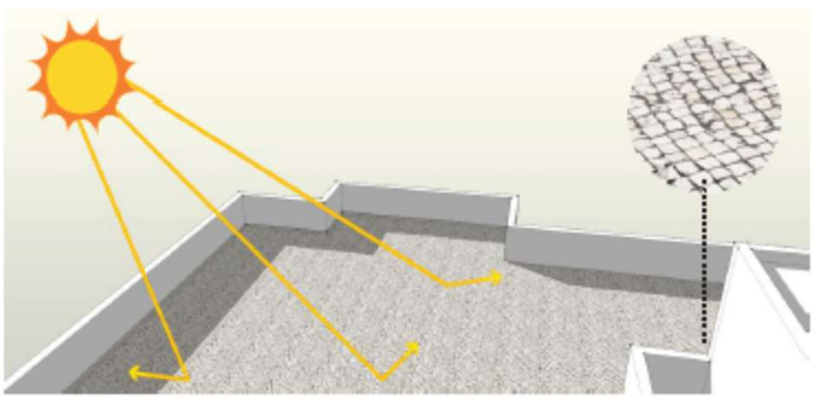


Figure 12: 4 bedrooms taken for further analysis

Energy simulation was carried out in these sample bedrooms to calculate peak temperature inside the flats on a typical summer day as well as cooling loads.

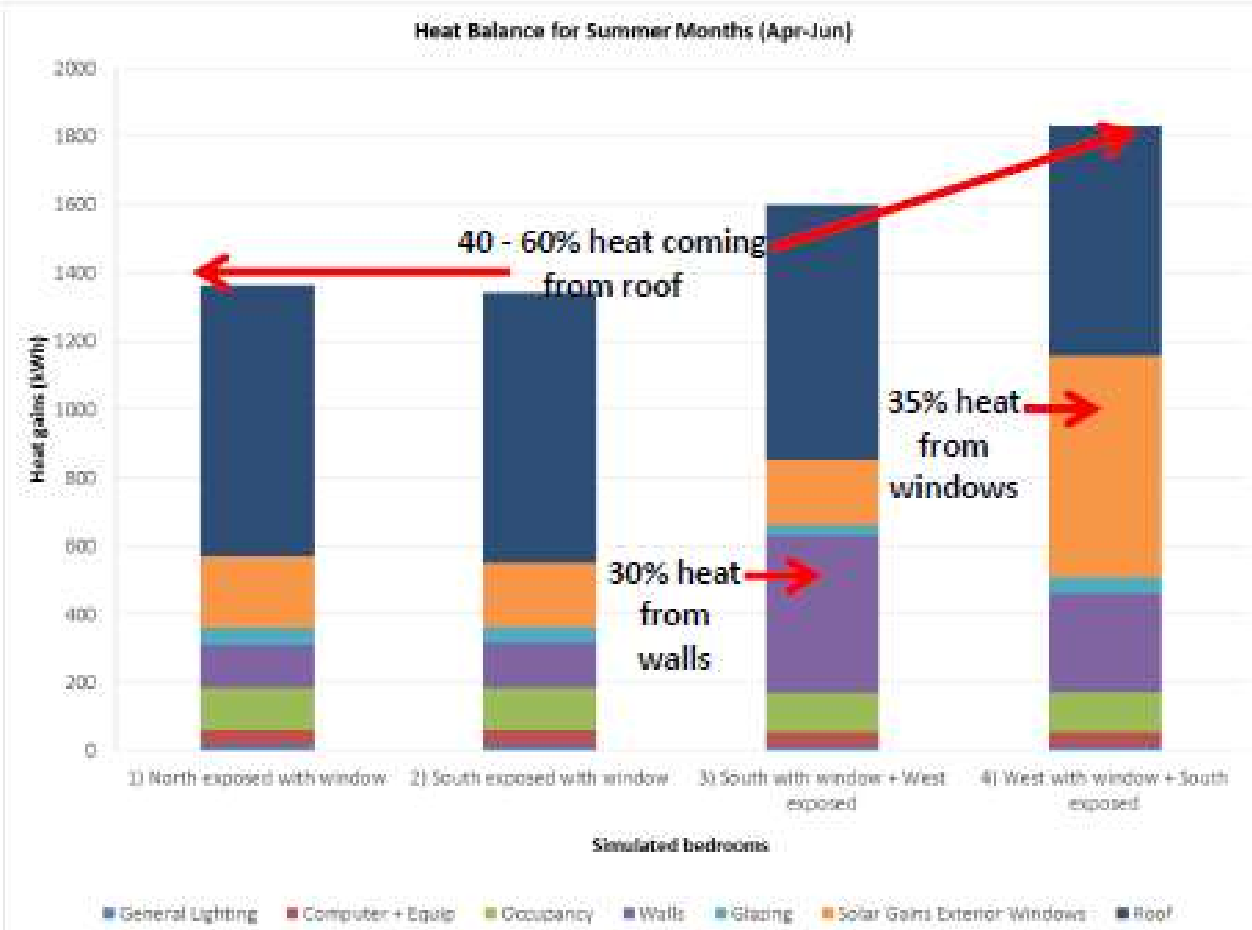


Figure 17: Heat balance for summer months for top floor

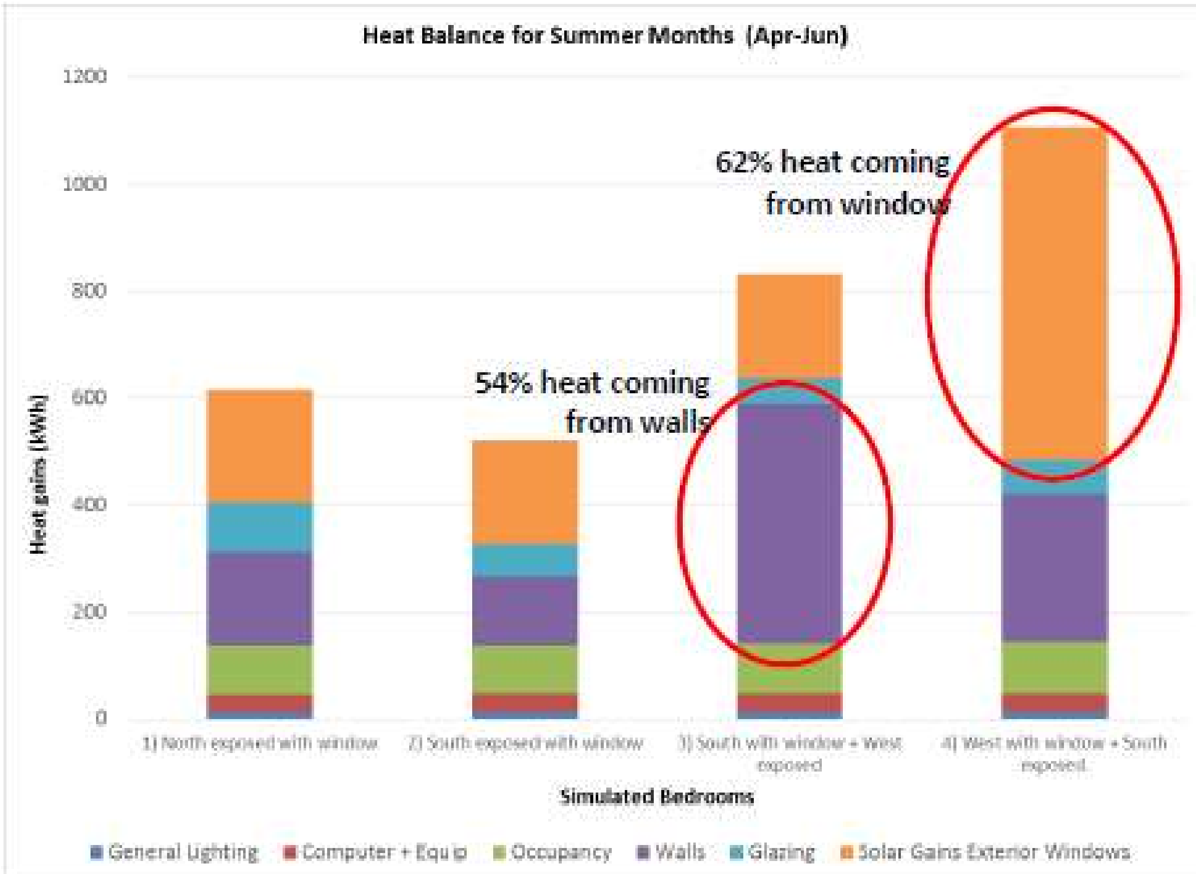


Figure 16: Heat balance for summer months for intermediate floor

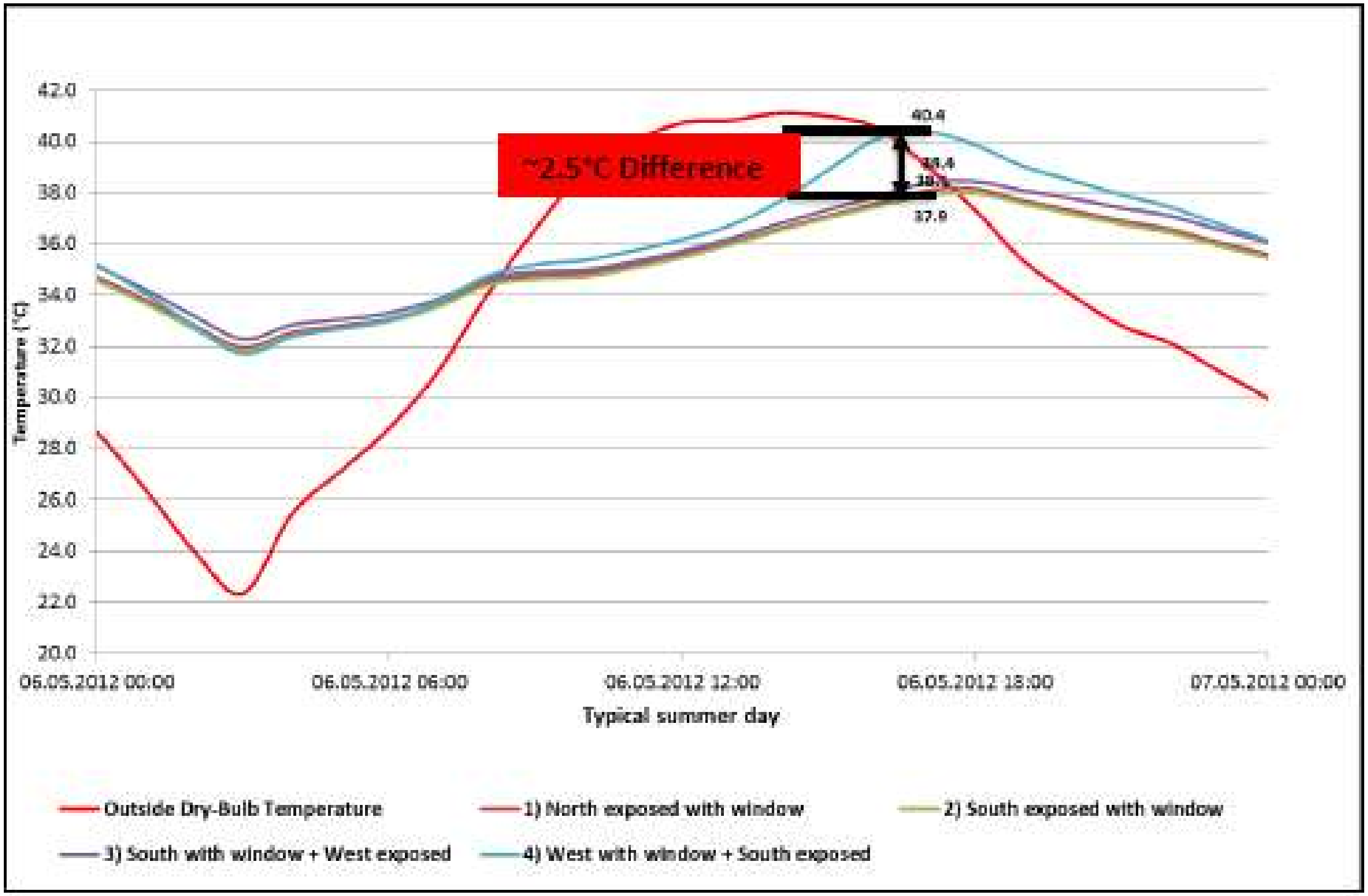


Figure 14: Inside temperatures on a typical summer day on the top floor

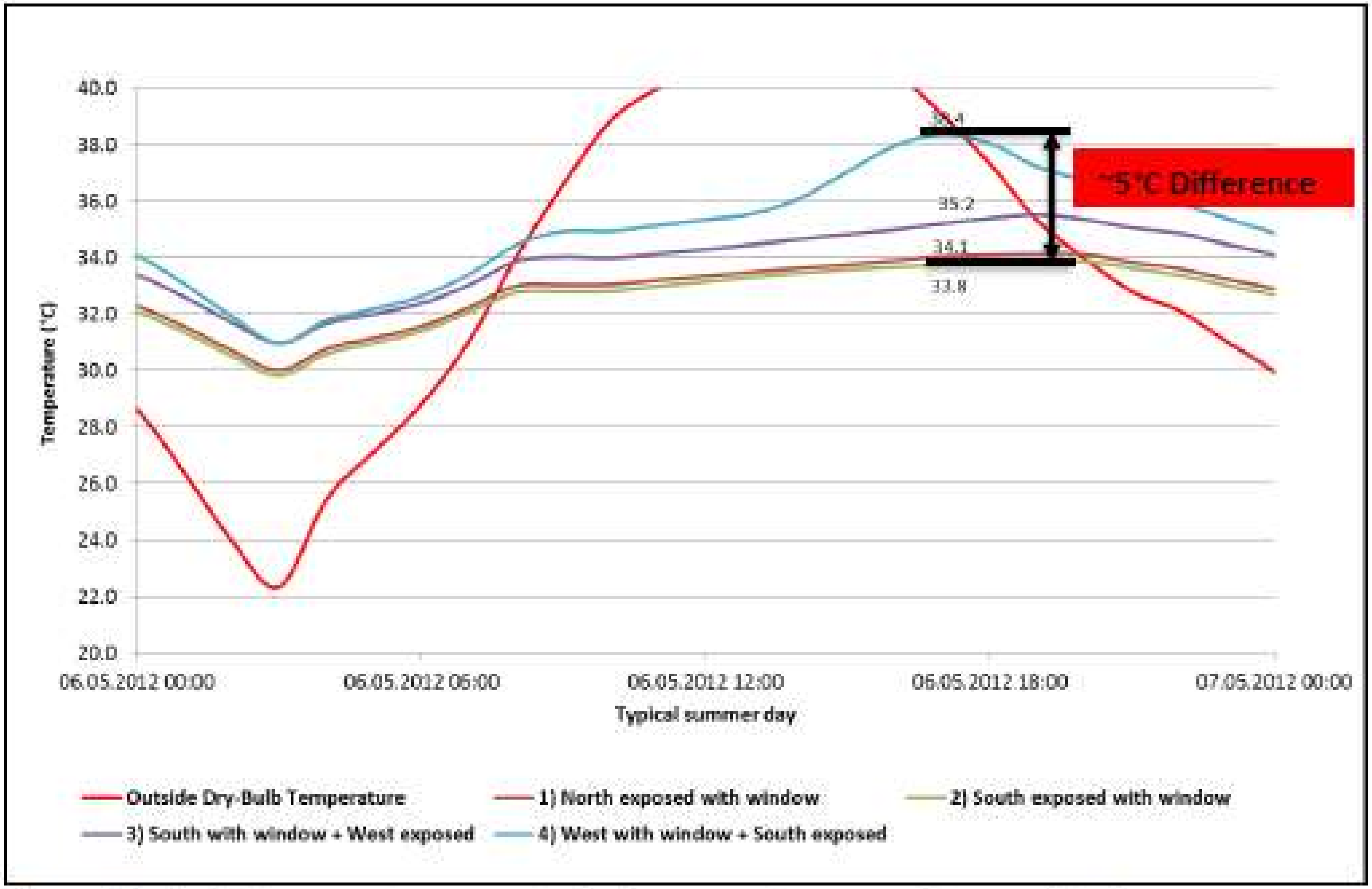


Figure 13: Inside temperatures on a typical summer day on an intermediate floor

6.2.1.4 Insulated walls: AAC blocks

The analysis of the base case also showed that the exposed walls facing the west also allow significant heat gains into the building. Using insulating walling material will reduce the transfer of heat through walls. Autoclaved Aerated Concrete (AAC) Blocks are good insulating material. They are also lightweight, reducing load on the structure and thus reducing the structural steel requirement.

Figure 22: AAC block

Constructing with AAC blocks requires skilled labour and careful handling of the blocks. Some care also needs to be after building occupation. AAC blocks must be procured from known and reliable manufacturers.

6.2.1.5 Roof insulation

For the top floor, the highest heat gains are from the roof. It is thus very important to insulate the roof and this leads to considerable reduction in inside temperature for the top floor. Figure 23 shows the detail of the roof with insulation.

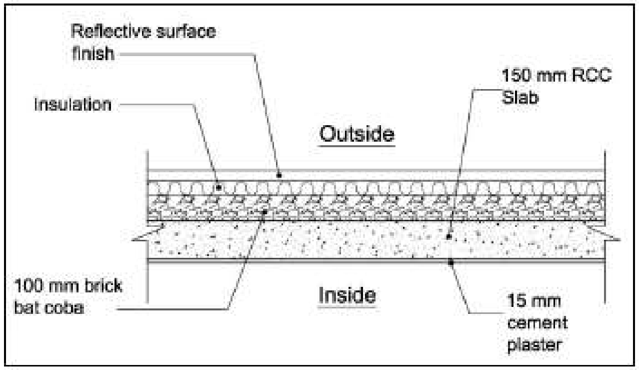


Figure 23: Roof detail with insulation

6.2.1.1 Window shading

Currently all windows have a 600mm overhang or open into a 1300mm balcony. The following addition is proposed in all windows facing east and west.

1) Fixed louvred screen above lintel height. This is proposed to be added by the developer.
2) Movable screens or "chiks" below lintel height. It is suggested that some vertical framing be provided by the developer. This would provide the occupants some way of attaching "chiks" later.

The additional shading is shown in Figure 18, Figure 19 and Figure 20.

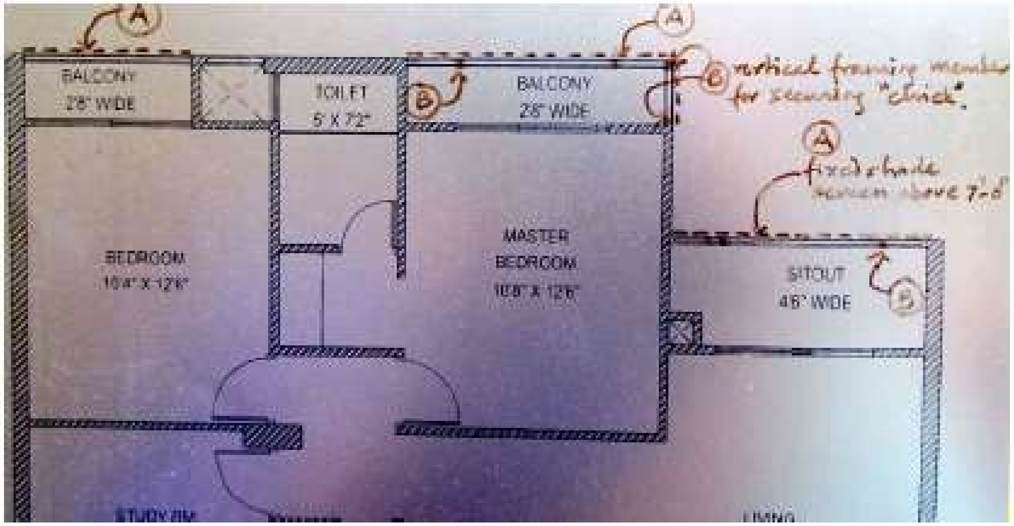


Figure 18: Proposed shading: 2.5 BHK unit

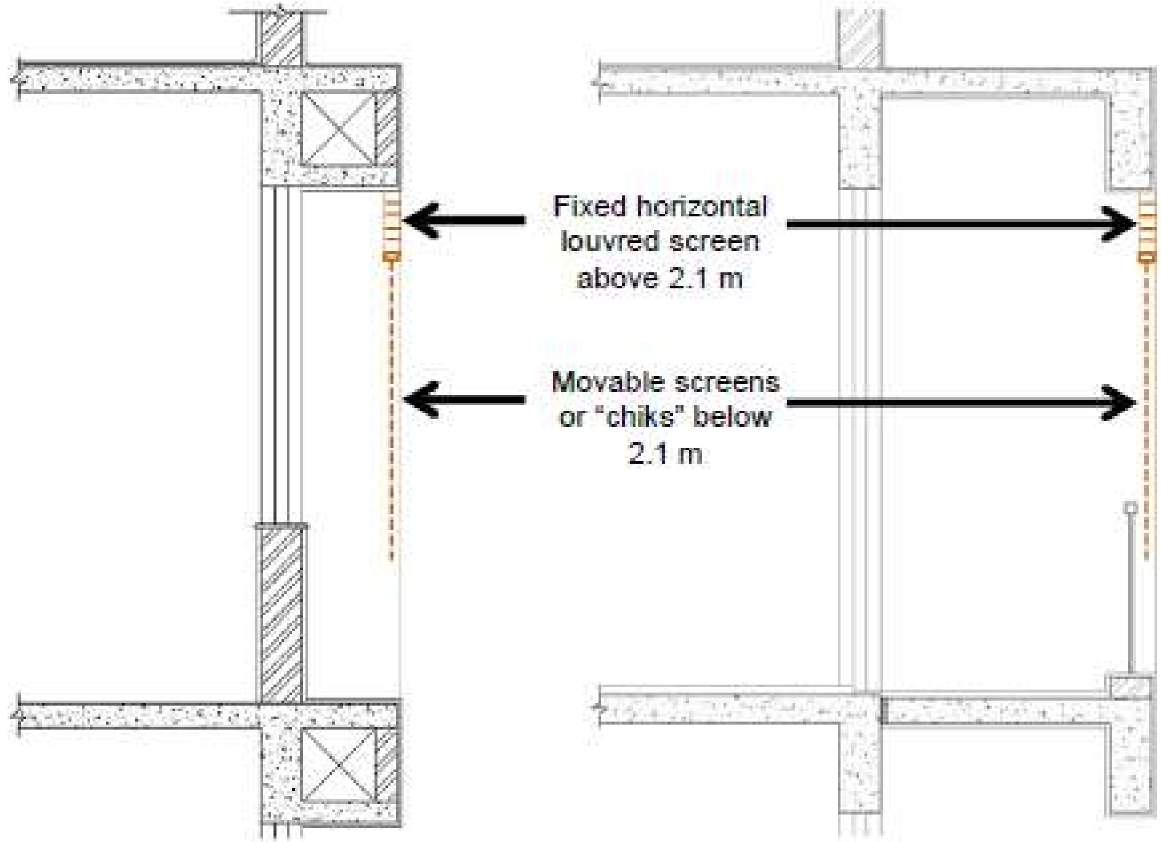


Figure 20: Section showing proposed shading

These strategies were simulated for the worst of the sample bedrooms, i.e. Bedroom 4 (Bedroom with south and west façade exposed with window / glass door on west façade) on the top floor.

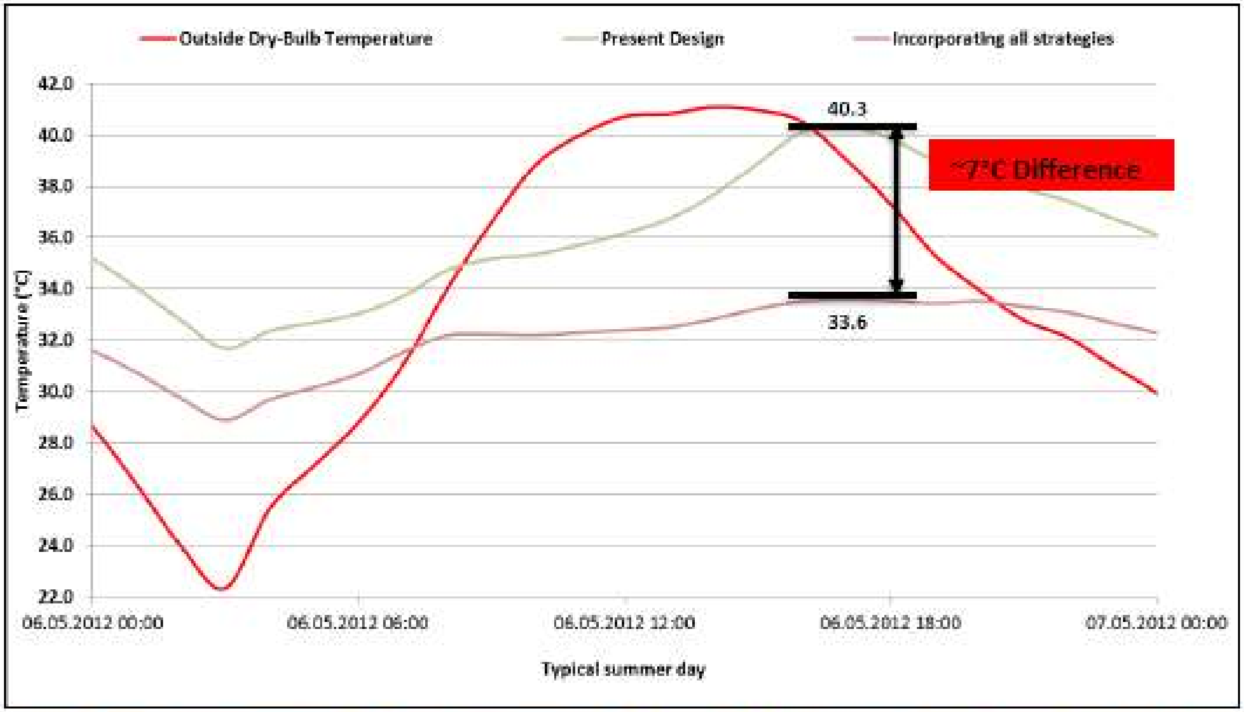


Figure 25: Inside temperature of Bedroom 4 on the top floor with and without the passive strategies

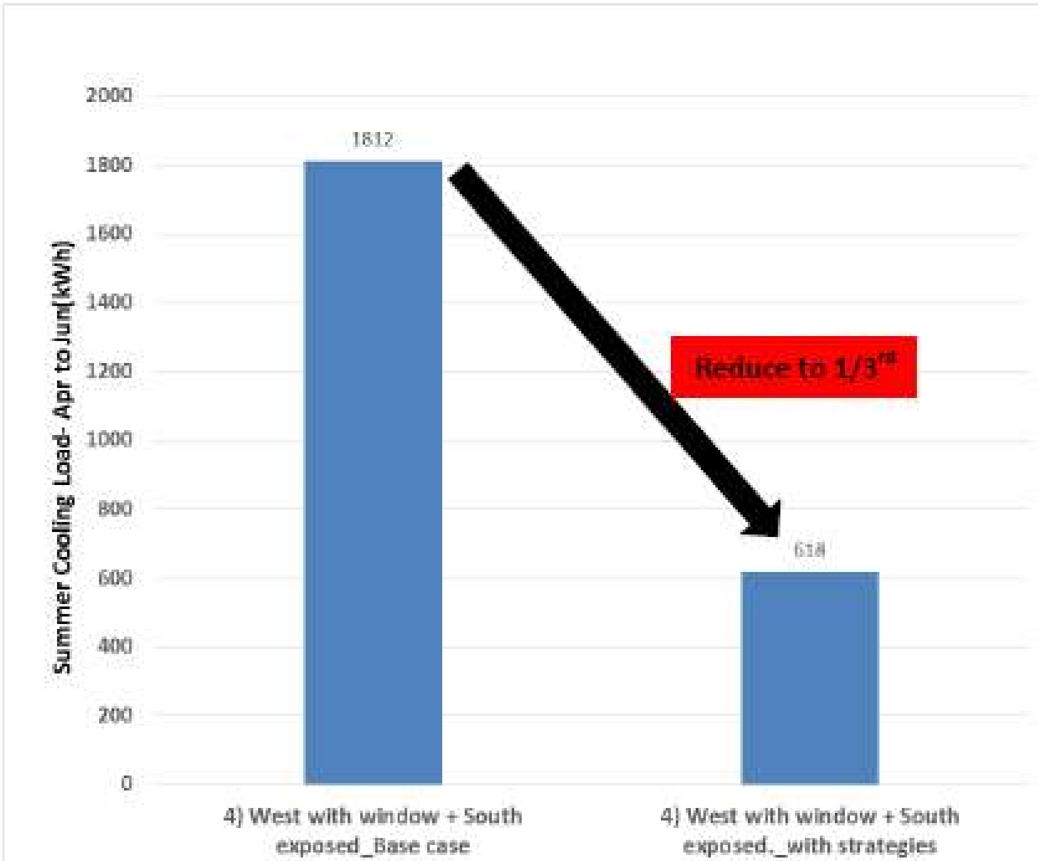


Figure 26: Cooling load of Bedroom 4 on the top floor with and without the passive strategies

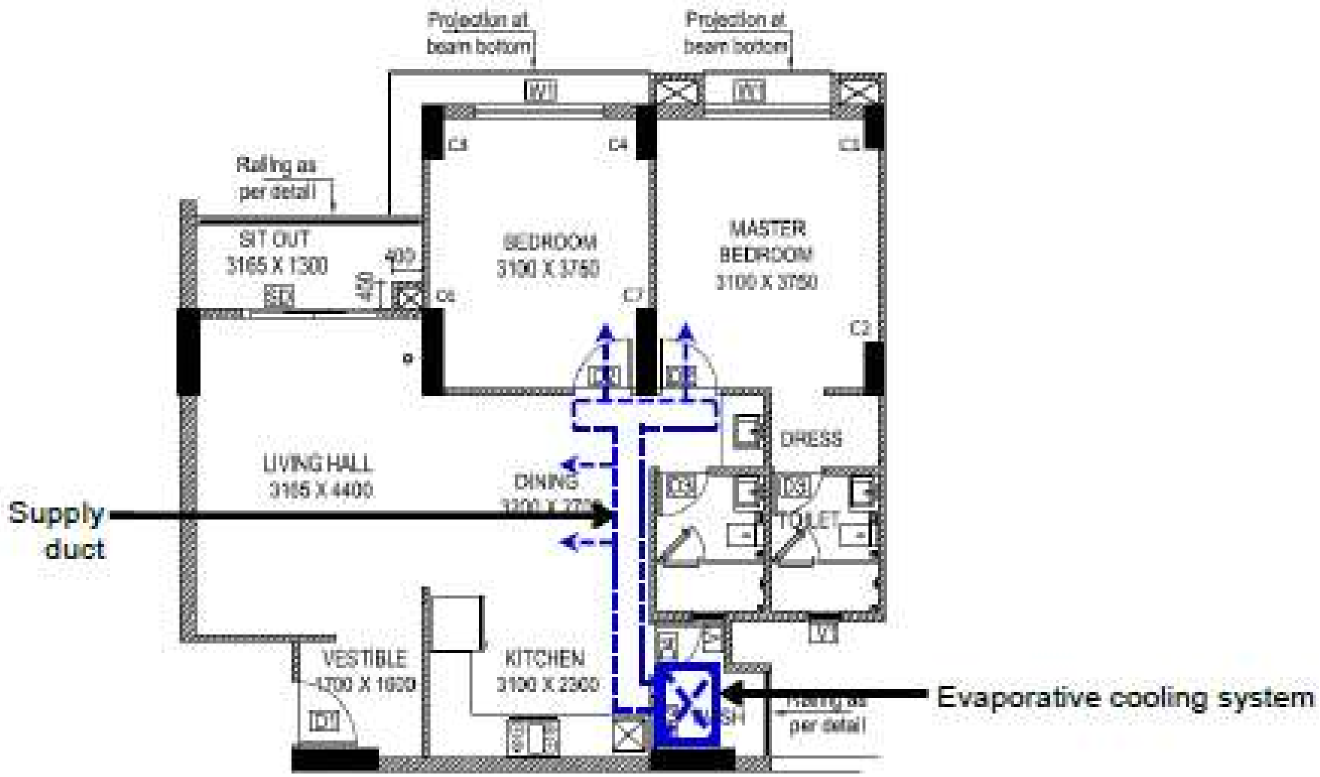


Figure 28: Possible scheme for evaporative cooling in flats

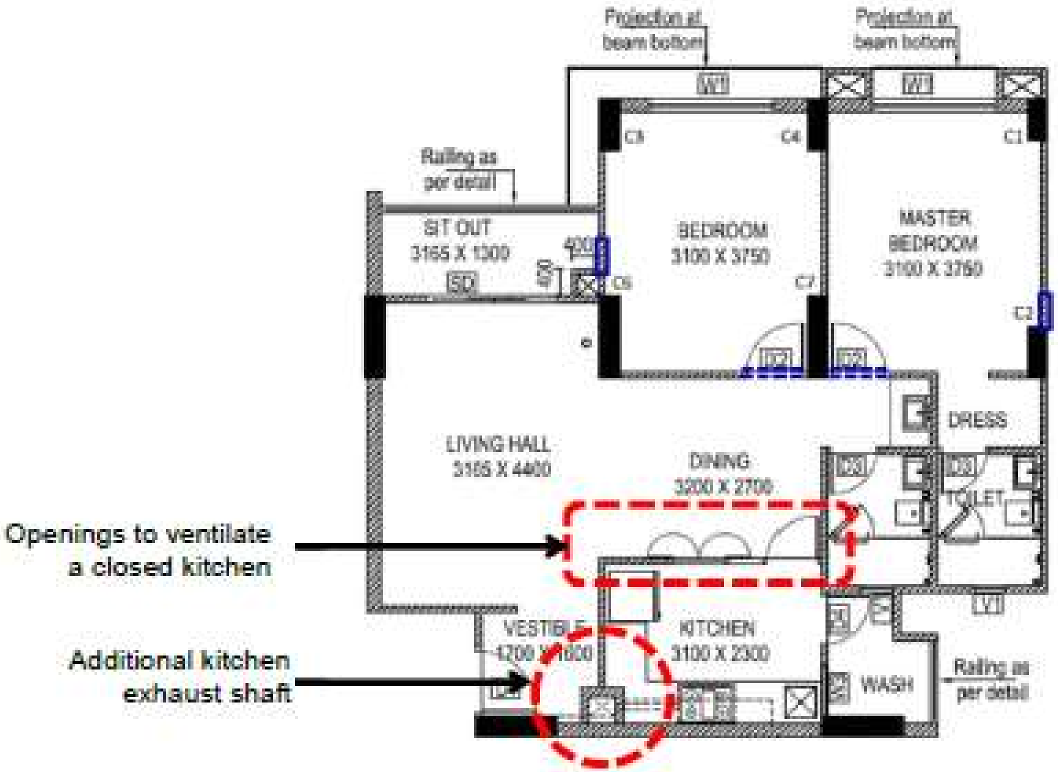


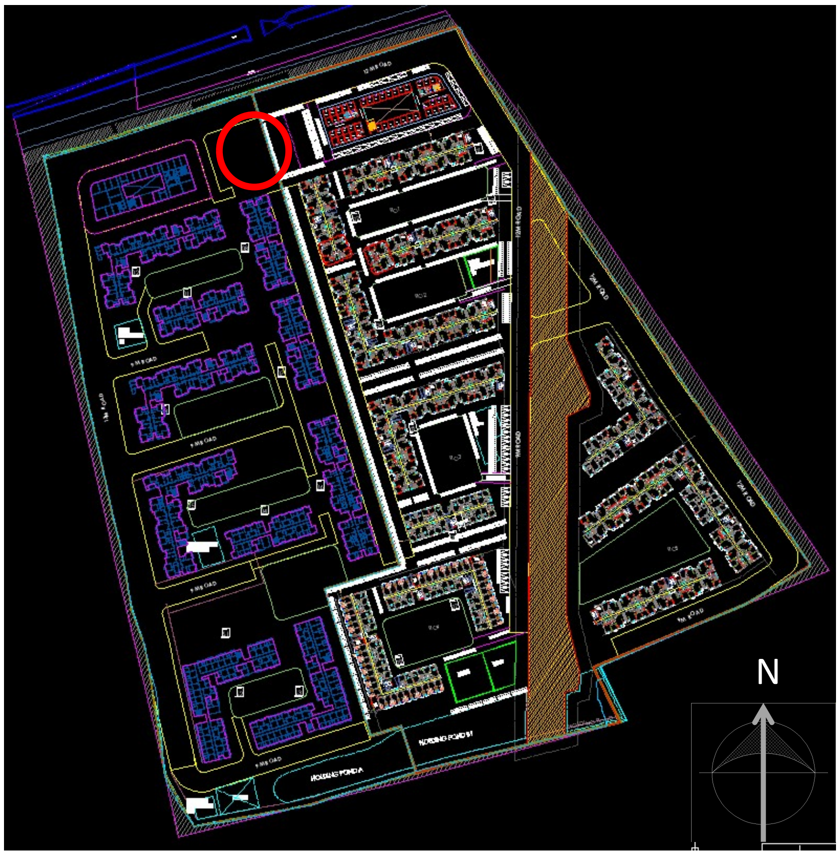
Figure 31: Additional shaft and openings for kitchen ventilation

Impact of window / shading design on window heat gains, ventilation, cooling electricity and thermal comfort

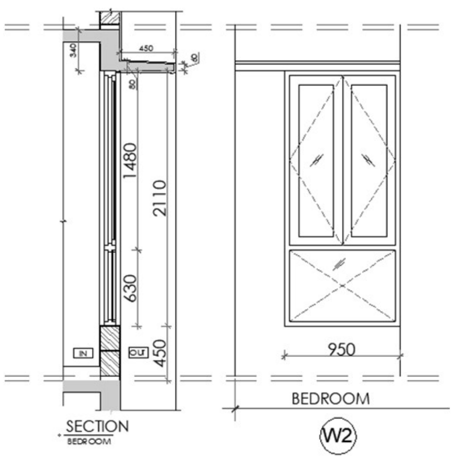
Analysis done for Mahindra Life Spaces by Indo-Swiss BEEP

08 June 2020

Selection of unit for detailed simulation



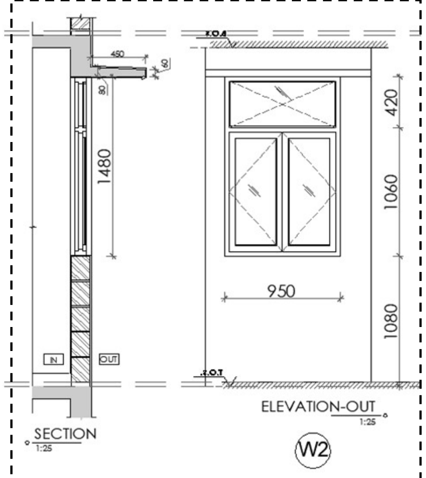
Design alternatives for comparison



Case 1:

Window size: As per current design

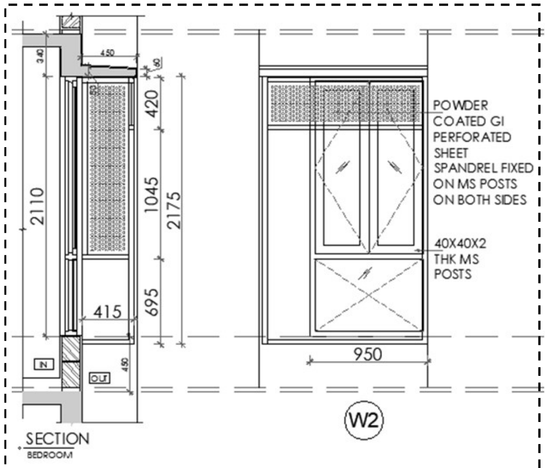
Shade: As per current design



Case 2:

Window size: As per Part 1 design (Fixed part of Glass at bottom is removed)

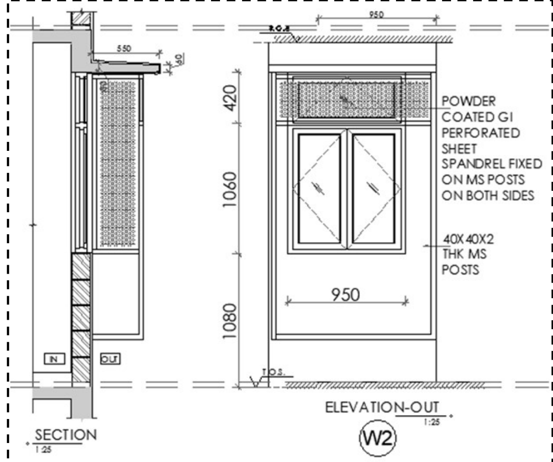
Shade: As per current design



Case 3:

Window size: As per current design

Shade: As proposed (side fins – up to 1.48 m from top, front screen – up to 0.42 from top of window)



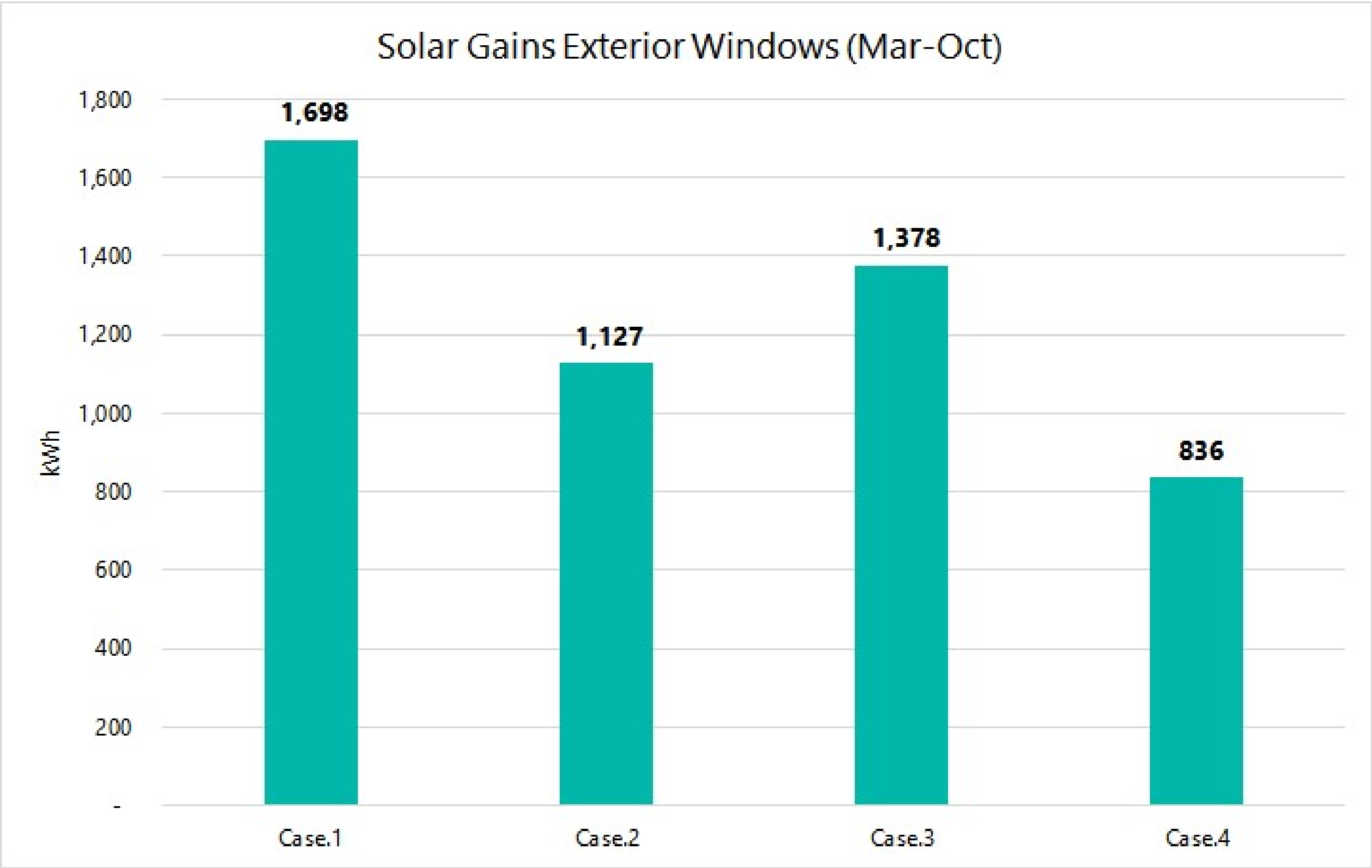
Case 4:

Window size: As per Part 1 design (Fixed part of Glass at bottom is removed, while top part of the window in Bedroom and Living room is also openable)

Shade: As proposed (side fins – up to 1.48 m from top, front screen – up to 0.42 from top of window)

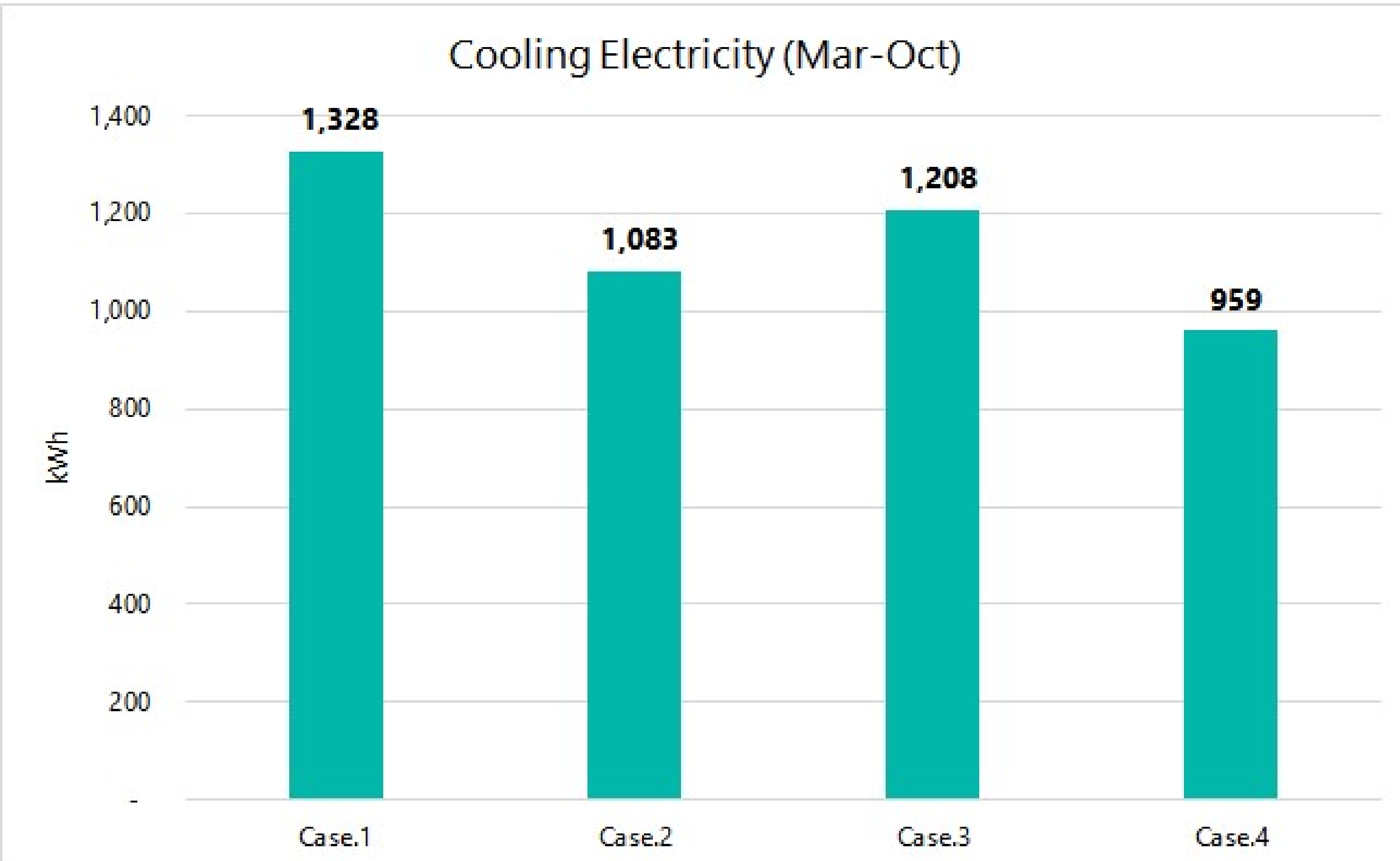
Case 5: Assisted ventilation is added in Case.4

Result 2: Impact on direct solar gains



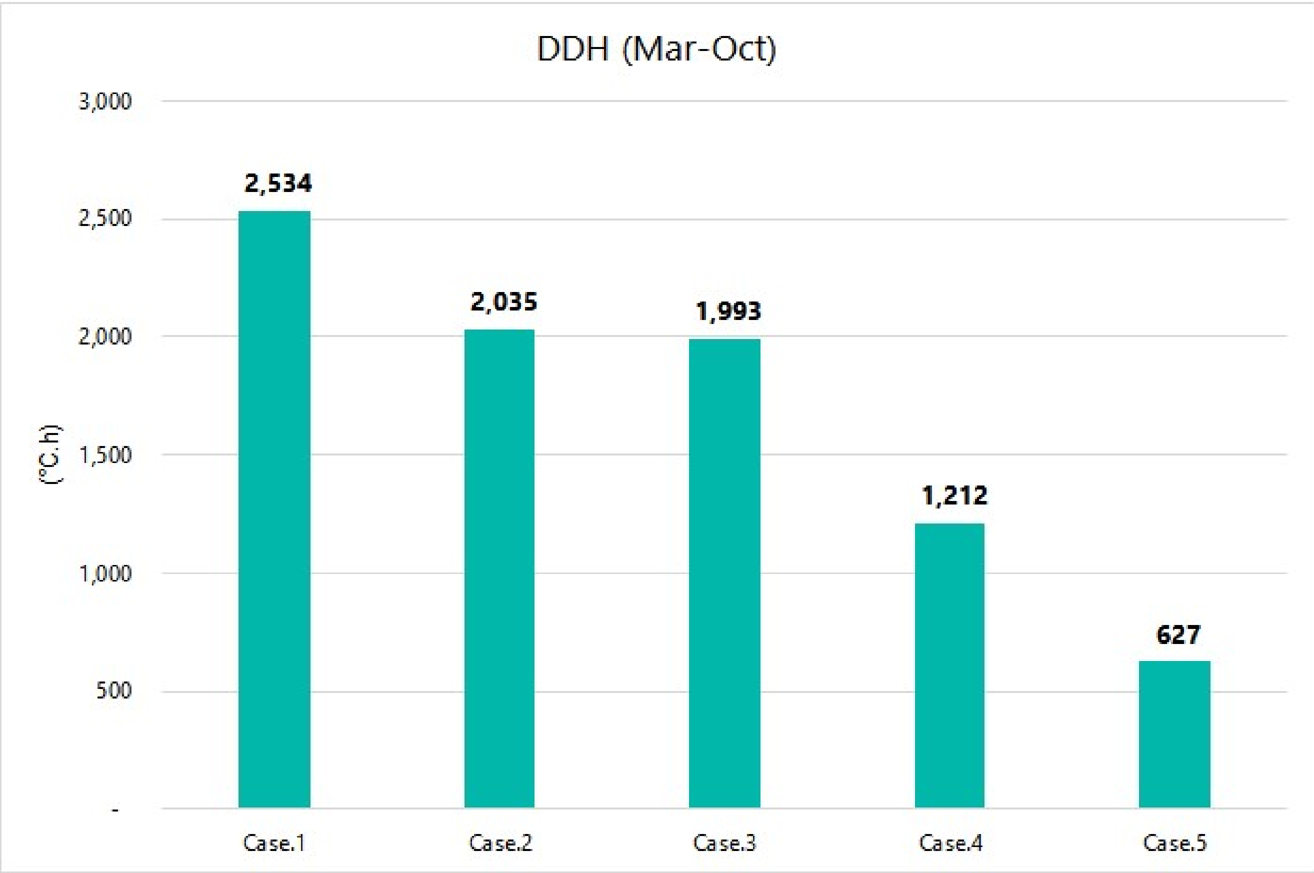
- **51% less direct heat gain from window by reducing glass area and adding shading (Case.4 vs Case.1)**
- 34% & 19% less direct heat gain from window by reducing glass area (Case.2 vs Case.1) & by adding shading (Case.3 vs Case.1)
- May lead to selection of lower TR of AC for the flat

Result 3: Impact on cooling electricity



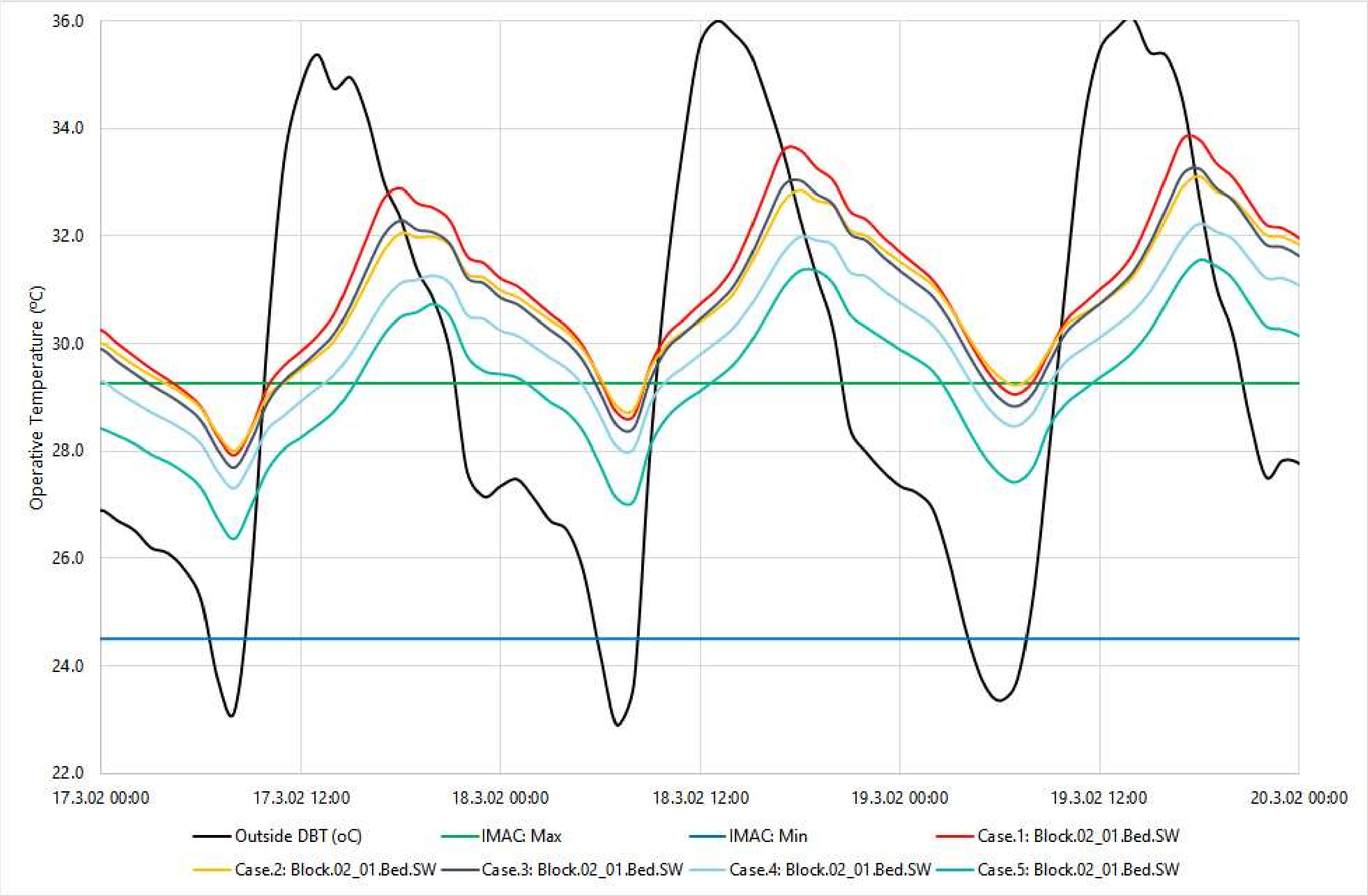
- **28% less cooling electricity required by by reducing glass area and adding shading (Case.4 vs Case.1)**
- 18% less cooling electricity required by reducing glass area (Case.2 vs Case.1)
- 9% less cooling electricity required by adding shading (Case.3 vs Case.1)

Result 4: Impact of window/shading design on Discomfort Degree Hour (DDH)



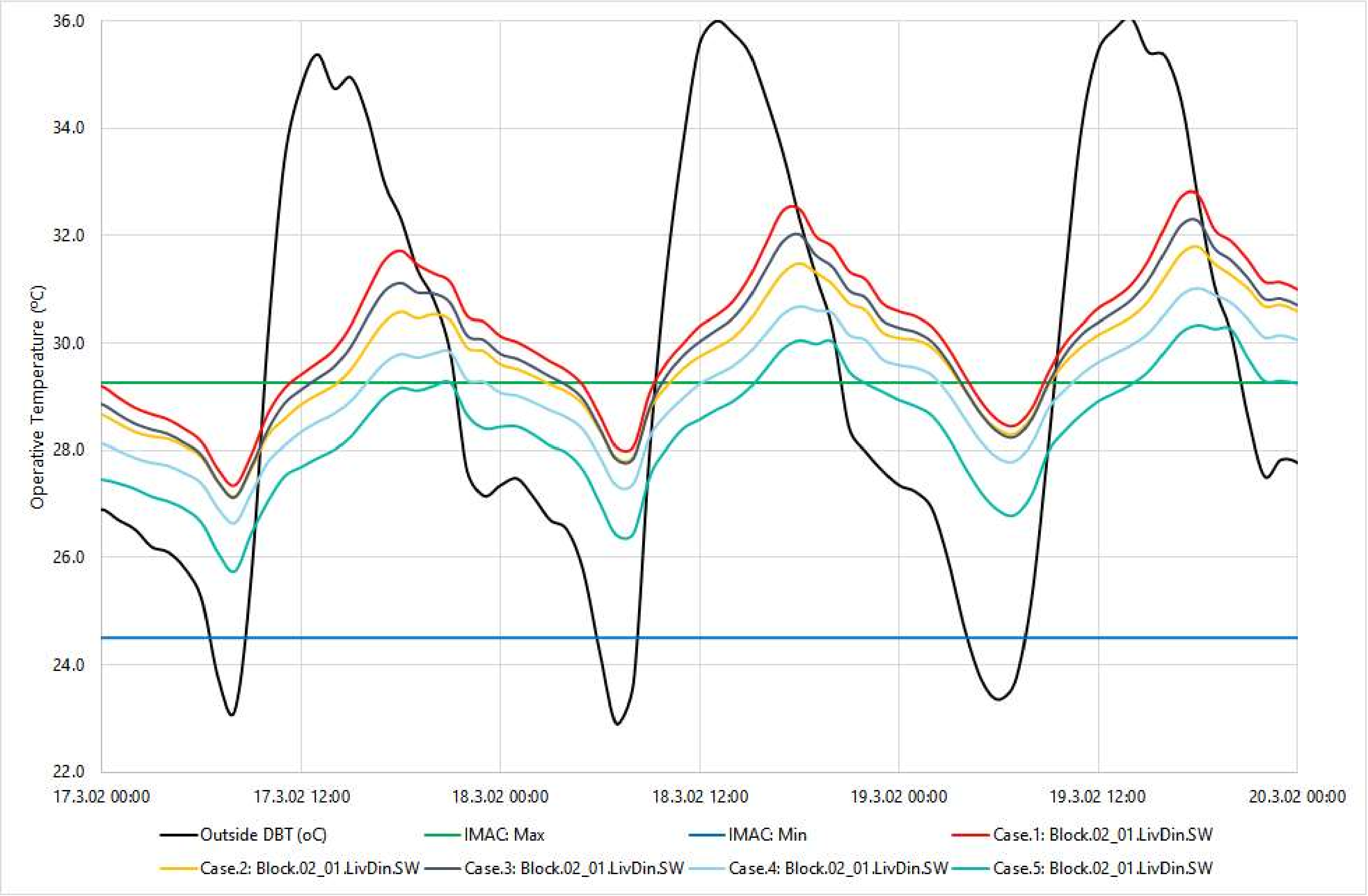
- **52% reduction in DDH** by reducing glass area and adding shading (Case.4 vs Case.1);
  75% reduction by adding assisted ventilation with improved design (Case.5 vs Case.1)
- ~20% reduction in DDH due to either reducing glass area (Case.2 vs Case.1) or by adding shading (Case.3 vs Case.1)
- Significant reduction in the operational time (hours per day and operating days per month) for the AC with Case.4 or Case.5

Result 5: Indoor operative temperature



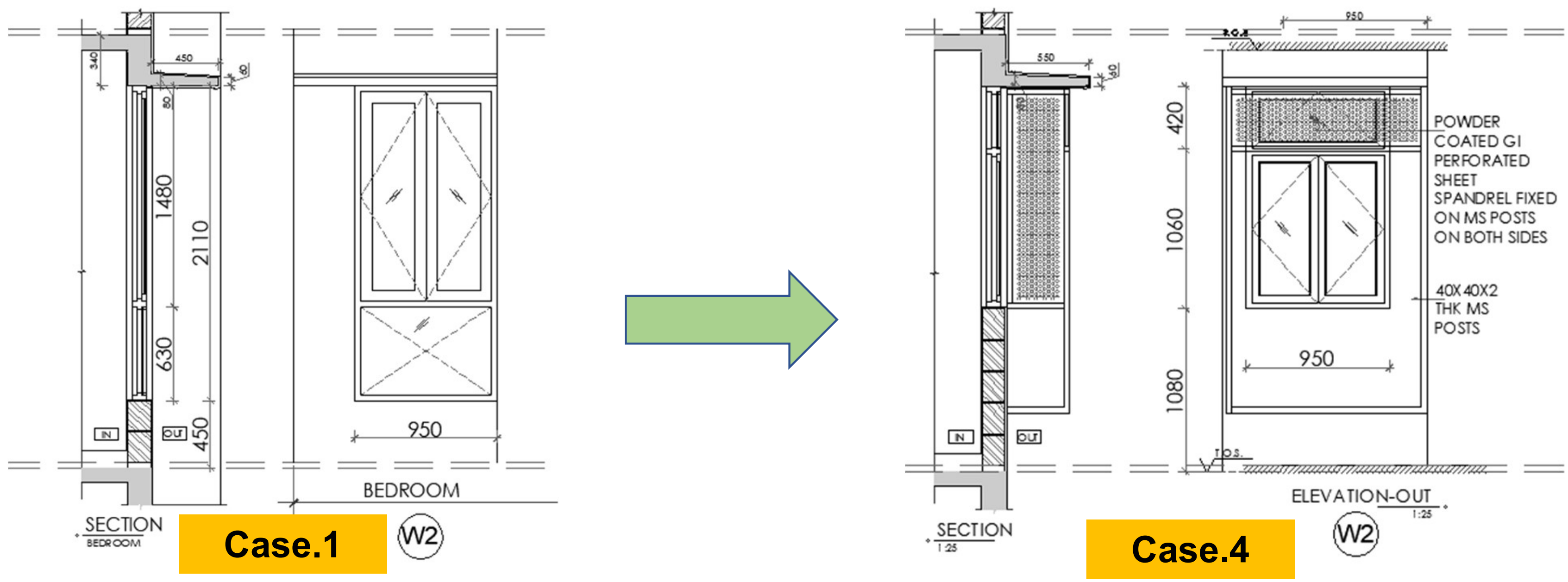
- 2-2.5°C reduction by adding assisted ventilation (Case.5 vs Case.1); **Can comfortably sleep without AC**
- 1.5-2°C reduction by reducing glass area and adding shading (Case.4 vs Case.1)
- ~1°C reduction with either reduced glass area (Case.2 vs Case.1) or by adding window shading (Case.3 vs Case.1).

Result 5: Indoor operative temperature



- ~2.5°C when assisted ventilation is added with improved design (Case.5 vs Case.1); **Most of hours come within IMAC band**
- ~2°C reduction in peak inside operative temperature with reduced glass area and shading (Case.4 vs Case.1)
- ~0.5 and ~1°C reduction in peak inside operative temperature by adding window shading (Case.3 vs Case.1) and with reduced glass area (Case.2 vs Case.1), respectively.

Key recommendations for improving Case 1



- **Replace the lower glass part with (or add) opaque material.**
- **Add vertical shading on side and top.**
- **Shading frame enables residents to install rollup screens conveniently.**
- **Give suitable openings for installing ventilation/exhaust fans.**

Key inferences from simulation results

- **Huge impact of window design** on solar gains and hence on DDH (in naturally ventilated mode) and cooling electricity (in air-conditioned mode).

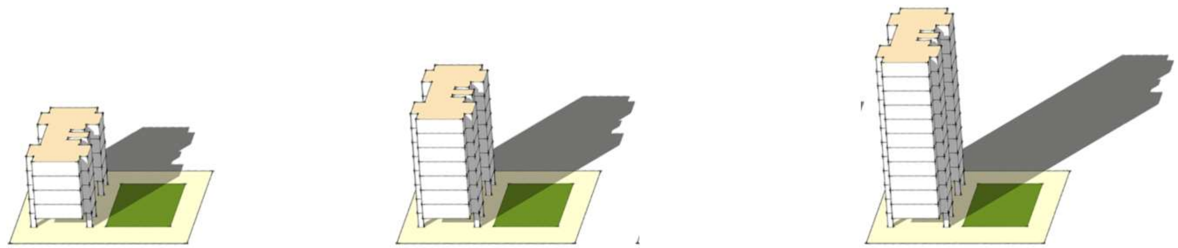
- **28% reduction in cooling electricity and 52% reduction in DDH** for Case.4.

- **~2.5°C reduction in peak indoor operative temperature** for Case.4 and Case.5. Will lead to reduced AC operational time (hours per day and operating days per month).

- **75% reduction in DDH with improved design with assisted ventilation (Case.5). This means, one may not buy an AC. Nights become comfortable and one can sleep comfortably without AC as well.**

Methodology for Evaluation

In this study, the buildings are classified in 3 typologies :

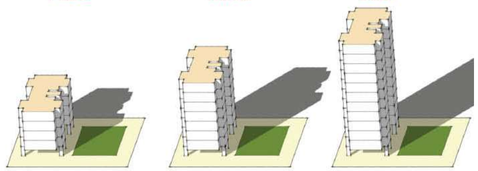


Low rise(<16.5m), **Medium rise**(16.5-25m) **High Rise**(>25m)

This study has evaluated the potential of Low Carbon resource-efficient affordable housing on various parameters over 3 scales:

Building Level **Neighbourhood Level** **City Level**

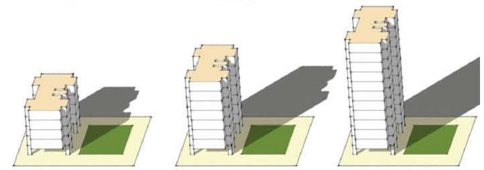
Comparison of Building Typologies



Criteria of Comparison	Low Rise	Medium Rise	High Rise
Sustainability	**High**	**Medium**	**Low**
Environmental Impact	**Low**	**Medium**	**High**
Suitability for Housing Category	**EWS/LIG** (<50m^2)	**LIG/MIG** (50-90m^2)	**MIG/HIG** (>90m^2)
Demand	Maximum ***70%***	Moderate 20%	Least 10%

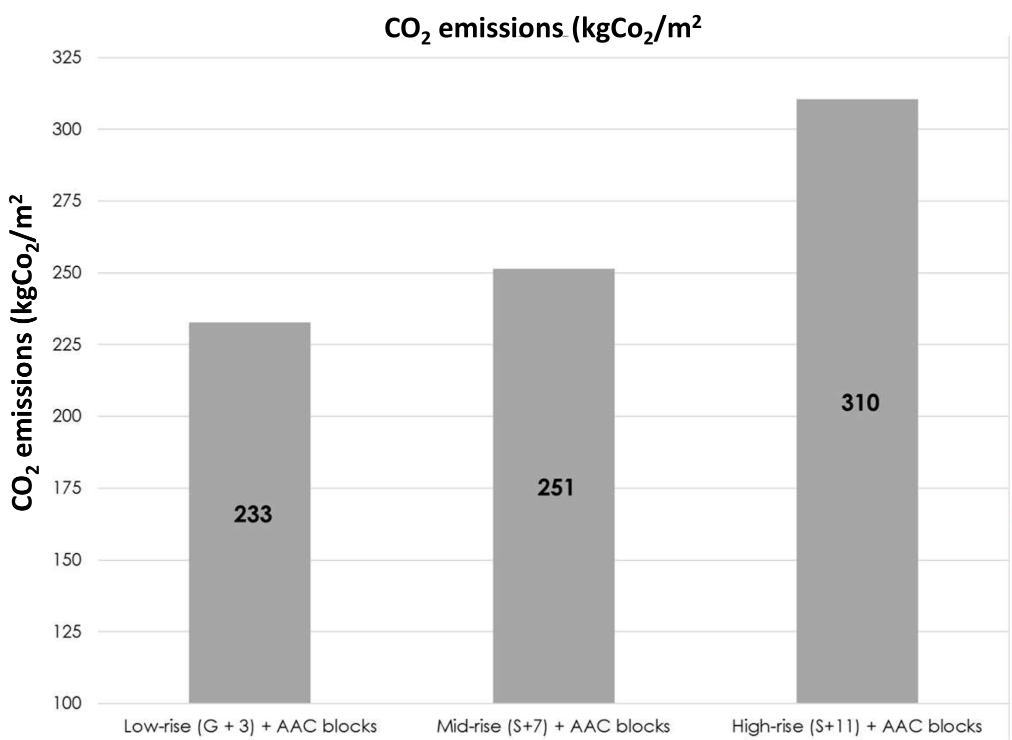
The high rise development is least suitable from a Low Carbon perspective and thus should be avoided.

The preferred typology should be Low rise but if Land Cost are very high one may go for a Medium Rise.



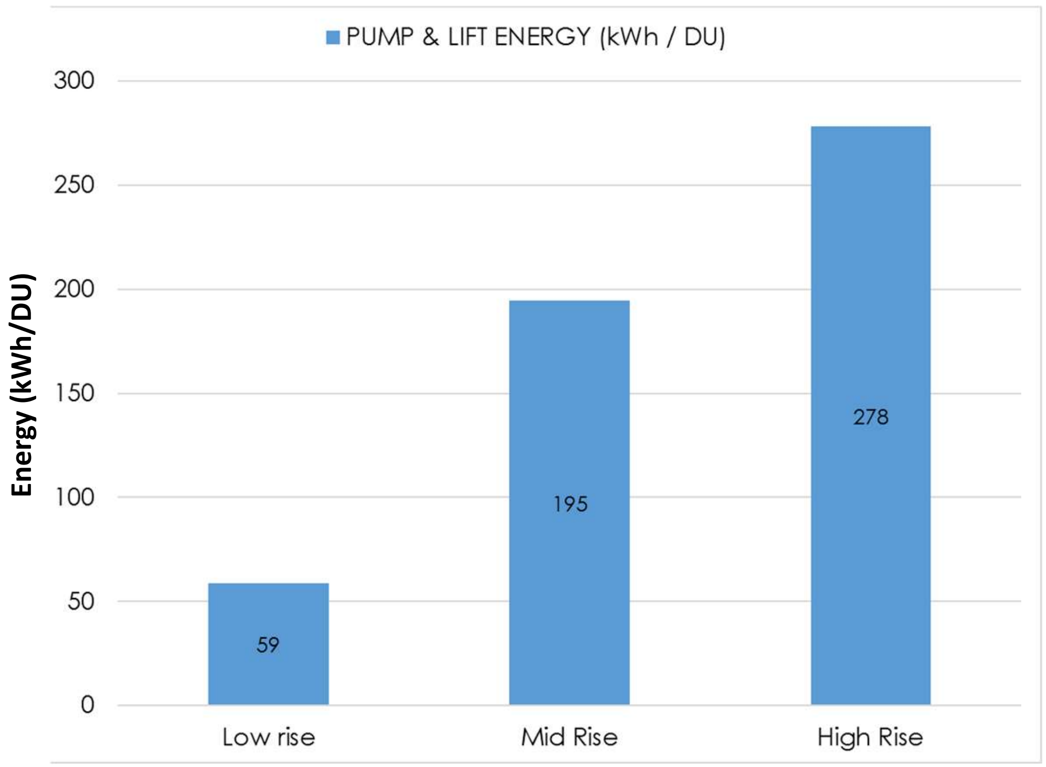
Criteria of Comparison	Low Rise	Medium Rise	High Rise
Affordability	**Most**	**Less**	**Least**
Open Area per Person	⬤	●	•
Embodied Energy efficiency	⬤	●	•
Operational Energy efficiency	⬤	●	•
Solar-Roof Potential	⬤	●	•
(Carpet Area)/ (Built Up area)	⬤	●	•
Construction Cost affordability	⬤	●	•
Quick Construction Time	⬤	●	•
Maintenance affordability	⬤	●	•
Disaster/ Breakdown resilience	⬤	●	•

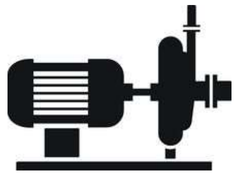
Embodied Energy Efficiency



- Given the same walling material, the taller our buildings are, greater will be the CO_2 emissions, due to higher steel and cement content.
- As we go from low-rise to mid-rise and high-rise buildings, CO_2 emissions will increase around 15% and 35% respectively.
- The CO_2 emissions are higher if we use brick and monolithic concrete instead use AAC/Hollow-core/Fly ash bricks/ Hollow-core/ Hollow burnt- clay brick

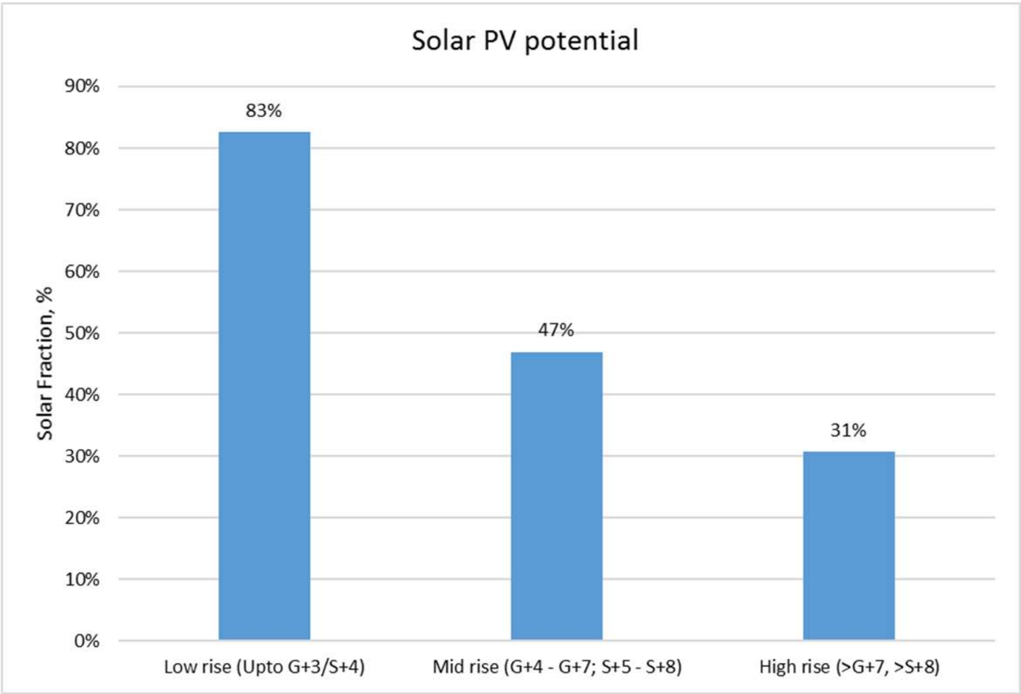
Operational Energy Efficiency

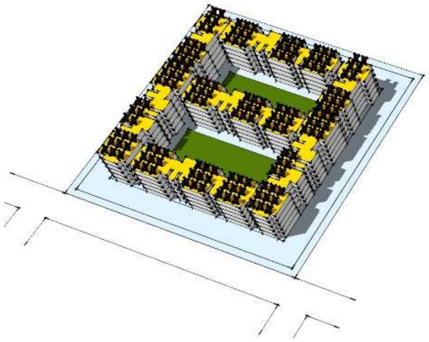




- **Increase in common service energy (pump + lift) by 4 to 5 times as we go from low-rise to high rise**

Rooftop Solar Potential





- **80% of the energy requirement in a low-rise building can be met by rooftop solar energy. Low rise buildings have the potential to be Net Zero due to better Rooftop Area to Electricity Demand Ratio.**

- **Building higher decreases Solar potential.**

Residential Typologies & House sizes

Low Rise (Building Height <15m)

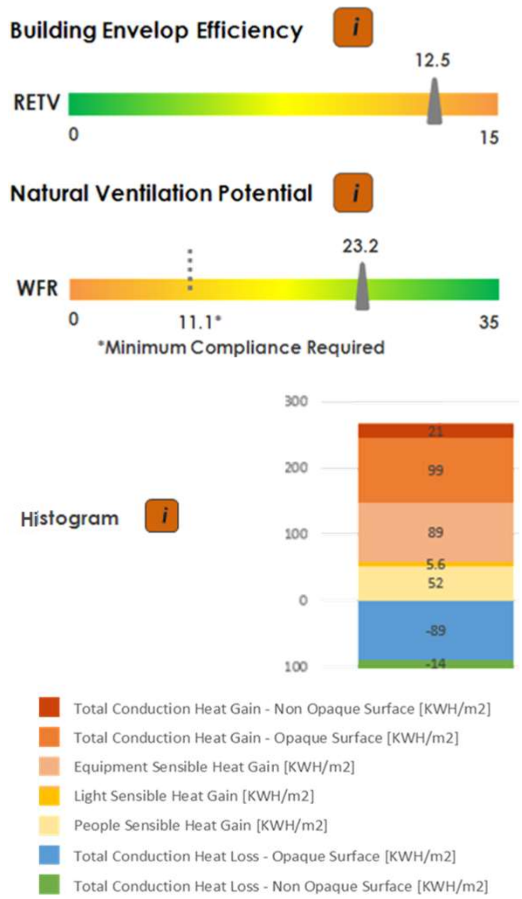
	Back-to-Back Row house	1 BHK (30 sqm) (1.1A)	2 BHK (41 sqm) (1.2A)	3 BHK (55 sqm) (1.2D)	
	Two side open Row House	1 BHK (32 sqm) (1.1B)	2 BHK (48 sqm) (1.2B)	3 BHK (68 sqm) (1.3A)	3 BHK (68 sqm) (1.3C)
	Doubly Loaded Corridor	1 BHK (30 sqm) (1.1C)			

Mid/High Rise (Building Height >15m)

	Doubly Loaded Corridor	1 BHK (44sqm) (1.2C)	2 BHK (65 sqm) (1.3B)	3 BHK (85 sqm) (1.4A)	
	Connected Towers	3 BHK (105sqm) (1.4B)	3 BHK (125 sqm) (1.5A)		
	Stand-Alone Towers	3 BHK (105sqm) (1.4C)	3 BHK (125 sqm) (1.5B)	3.5 BHK (156sqm) (1.6A)	4.5 BHK (225 sqm) (1.7A)

Energy performance

Energy Simulation
The building design - architectural, mechanical and electrical systems are replicated in the energy simulation software to analyze the energy data, design effectiveness and energy demand. **Software used:** Design builder/Energy plus **Outputs:** Energy performance Indicators, Life cycle cost, Payback No. of hours of Natural Ventilation

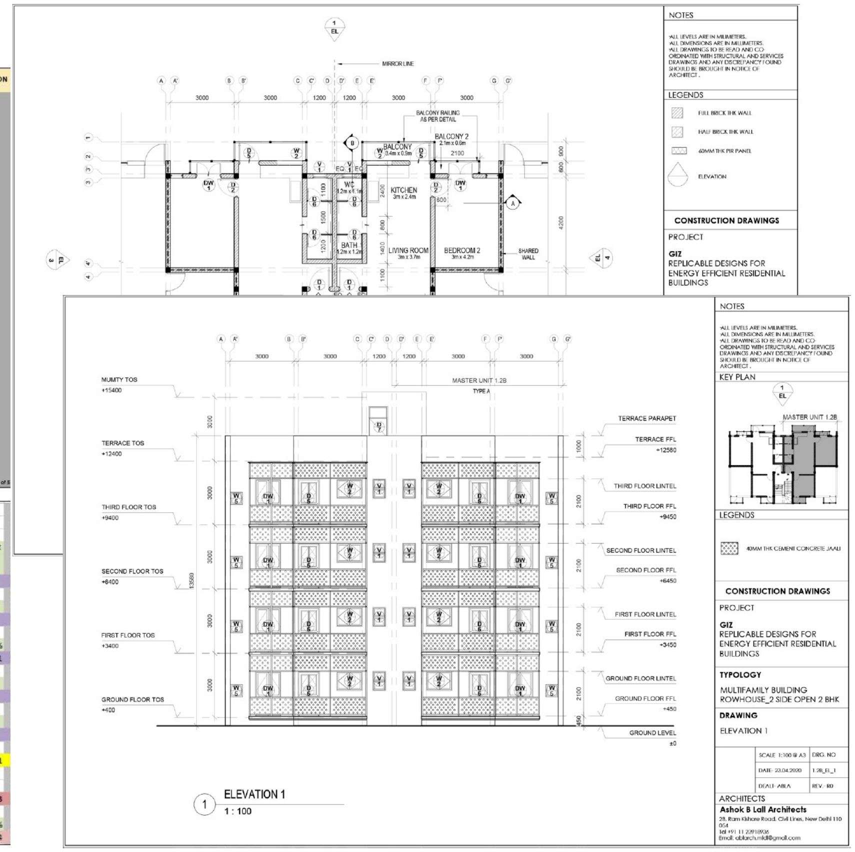


Master Set-Design & Construction data

Windows & Shading design

BUILDING TYPE 1.2B		COMPOSITE & HOT DRY							
		BASE		MODERATE		GOOD		HIGH	
		N & S	E & W	N & S	E & W	N & S	E & W	N & S	E & W
		Contribution of cost	Contribution of cost	Contribution of cost	Contribution of cost	Contribution of cost	Contribution of cost	Contribution of cost	Contribution of cost
Item of Work		Amount	Amount	Amount	Amount	Amount	Amount	Amount	Amount
CIVIL WORK (Building Envelop)		74.3%		72.3%		62.7%		56.1%	
TOTAL		275259		262874		262874		262874	
DOOR, WINDOW & BALCONY		16.1%	17.4%	18.0%	18.9%	29.0%	29.7%	25.9%	26.6%
TOTAL (Composite & Hot dry)		59779	65415	65453	69664	121499	125711	121499	125711
FINISHING (External Walls & Terracing)		8.3%		8.5%		7.3%		7.2%	
TOTAL		30750		30750		30750		33577	
INSULATION		1.2%		1.2%		1.1%		10.9%	
TOTAL		4463		4463		4463		50909	
TOTAL COST OF CONSTRUCTION (INR)		370250	375887	363540	367751	419586	423798	468859	473071
Unit Carpet Area (sqft)	518								
Cost/ sqft carpet area		714	725	701	709	809	817	904	913
Percentage increase over Base				-1.8%	-2.2%	13.3%	12.7%	26.6%	25.9%
Cost Increase over Base (INR)				-6710	-8136	49336	47911	98609	97184

Bill of quantities



Working Drawings

Sustainable Development Goals

10 REDUCED INEQUALITIES

Affordable homes at locations of employment and economic opportunity with access to public transport and social amenities. Livelihoods in an inclusive construction economy

11 SUSTAINABLE CITIES AND COMMUNITIES

Resilience of urban living in cases of infrastructure breakdown and disasters, with sufficiency of habitable space and environmental security – water, air, recycled waste.

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Use of low-carbon and resource-efficient modes of production for construction of housing and selecting building types for minimum operational energy.

13 CLIMATE ACTION

Build-in resilience against extreme events, shade and green for a habitable outdoors against heat waves, aggregate rain harvest and water efficiency, minimize hard ground and motor vehicles for low UHI

Thank you!

प्रधान मंत्री आवास योजना-शहरी
Pradhan Mantri Awas Yojana-Urban

GLOBAL HOUSING TECHNOLOGY CHALLENGE INDIA

Ministry of Housing and Urban Affairs
Government of India

आज़ादी का अमृत महोत्सव

bmtpc

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One-Day Online Training Program on Thermal Comfort in Affordable Housing

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asci
Leadership through Learning

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RESILIENT, AFFORDABLE AND COMFORTABLE HOUSING THROUGH NATIONAL ACTION

Building Codes, Affordable Housing and Thermal Comfort

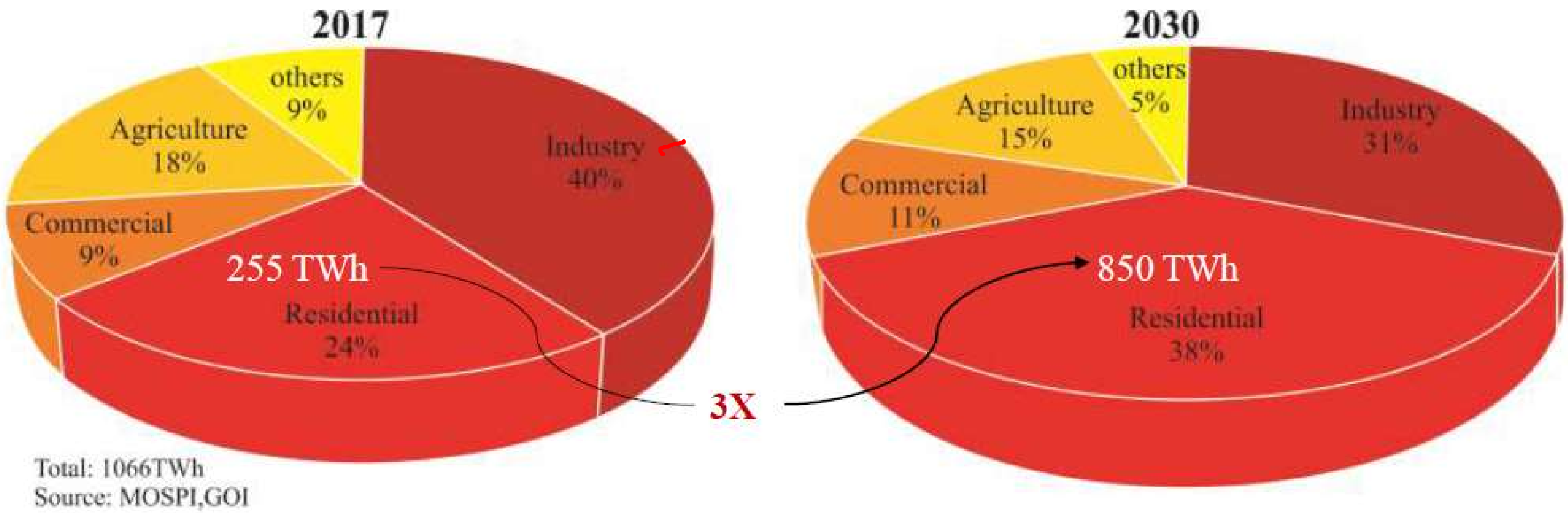
MARCH 31, 2023

Dr Aviruch Bhatia

Outline

- Introduction
- Affordable Housing
- Thermal Comfort
- Energy Codes
- ENS Tool
- Conclusions

Energy Consumption in Residential Buildings



Affordable Housing Programs in India

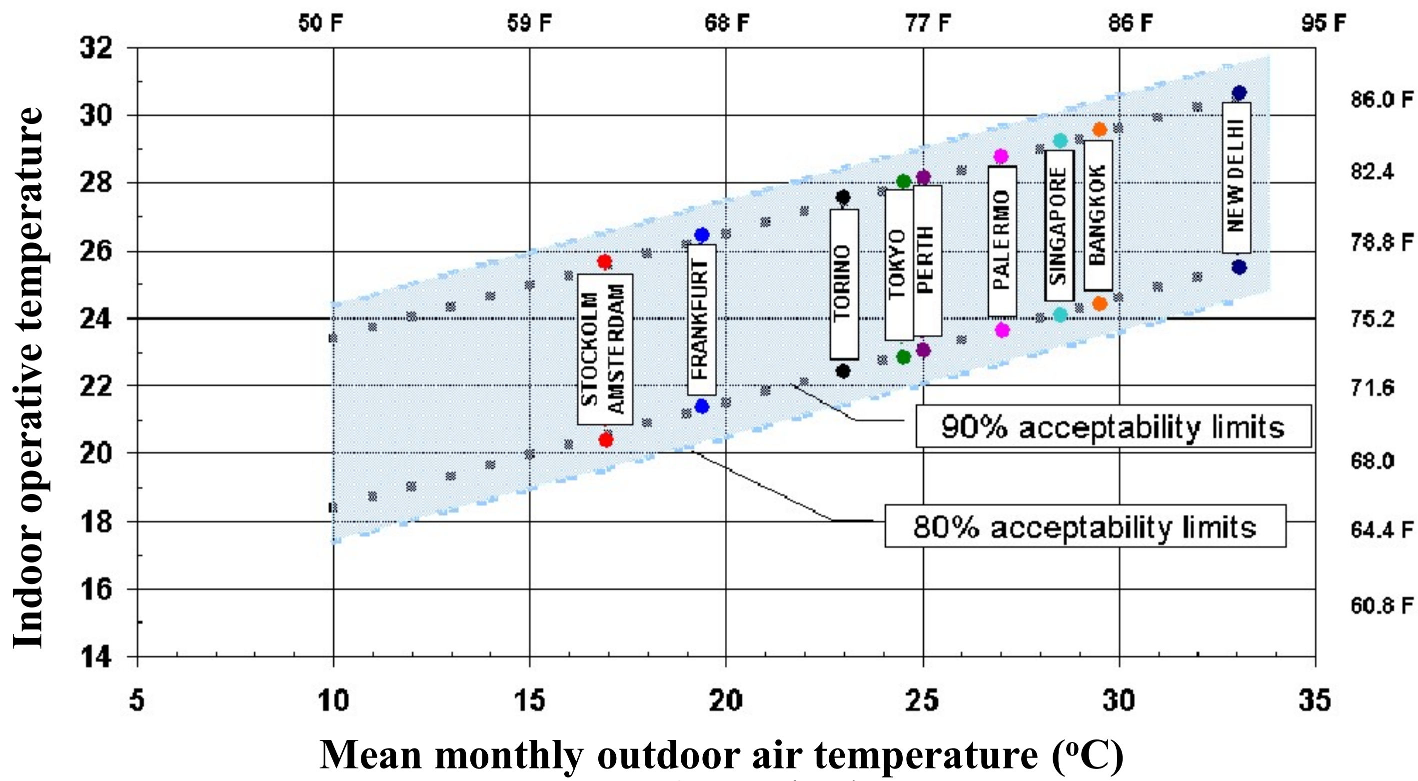
- Address the vision of 'AatmaNirbhar Bharat' by creating affordable rental housing for urban migrants/ poor
- Provide dignified living with necessary civic amenities near their workplace on affordable rent
- Create conducive ecosystem for Public/ Private Entities to leverage investment in rental housing

Pradhan Mantri Awas Yojana - Urban (PMAY-U)
Affordable Rental Housing Complexes (ARHCs)

Thermal Comfort

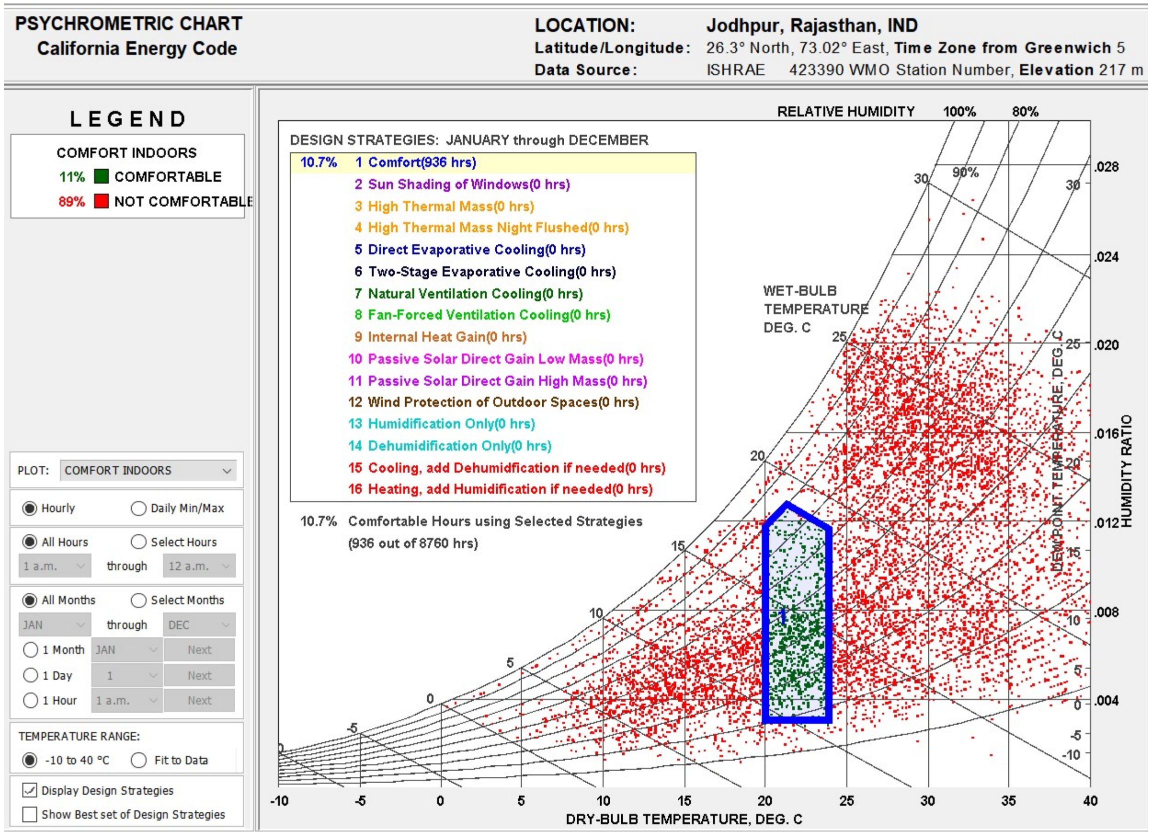
Environment	Personal
➢ Air temperature	➢ Clothing ensembles
➢ Mean radiant temperature	➢ Metabolic rate or activity
➢ Relative humidity	
➢ Air movement	

Acceptable Temperature Ranges

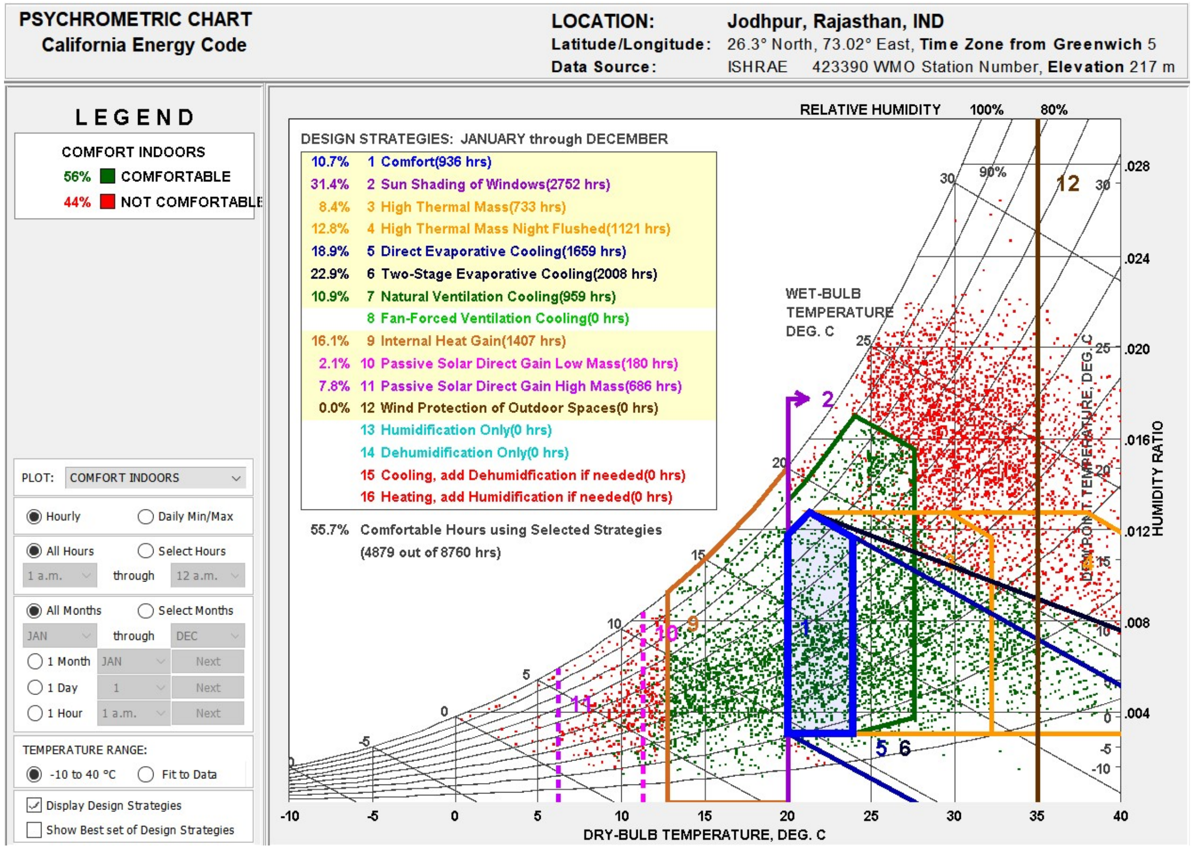


Source: Olesen BW (2005)

Context: Affordable Housing



Context: Affordable Housing



Types of Building Energy Codes

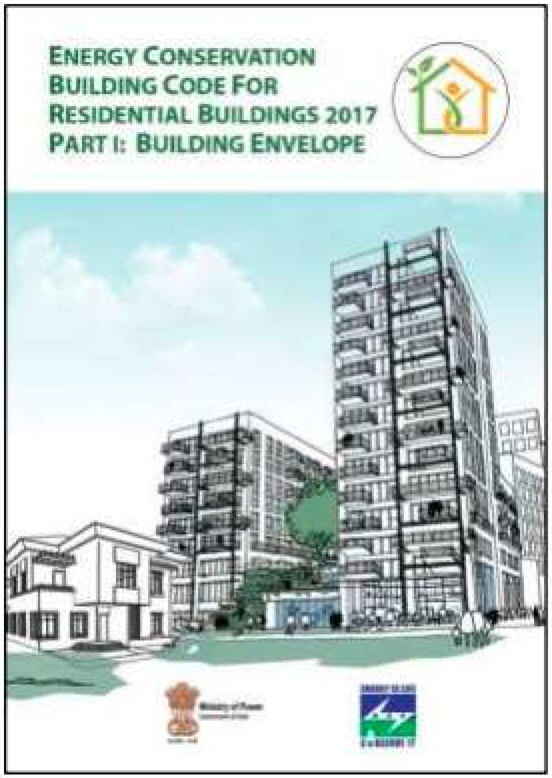
- Prescriptive codes
- Trade-off codes
- **Performance codes**
- Outcome-based codes

Types of Building Energy Codes

Prescriptive codes	**ECBC – R** Eco Niwas Samhita – 1 Eco Niwas Samhita - 2	**ECBC 2017** ECBC ECBC+ Super ECBC
Trade-off codes		
Performance codes		
Outcome-based codes		

ECO NIWAS SAMHITA

Eco Niwas Samhita (ENS, ECBC-Residential) (Part-I Building Envelope)



PROVISIONS FOR BUILDING ENVELOPE

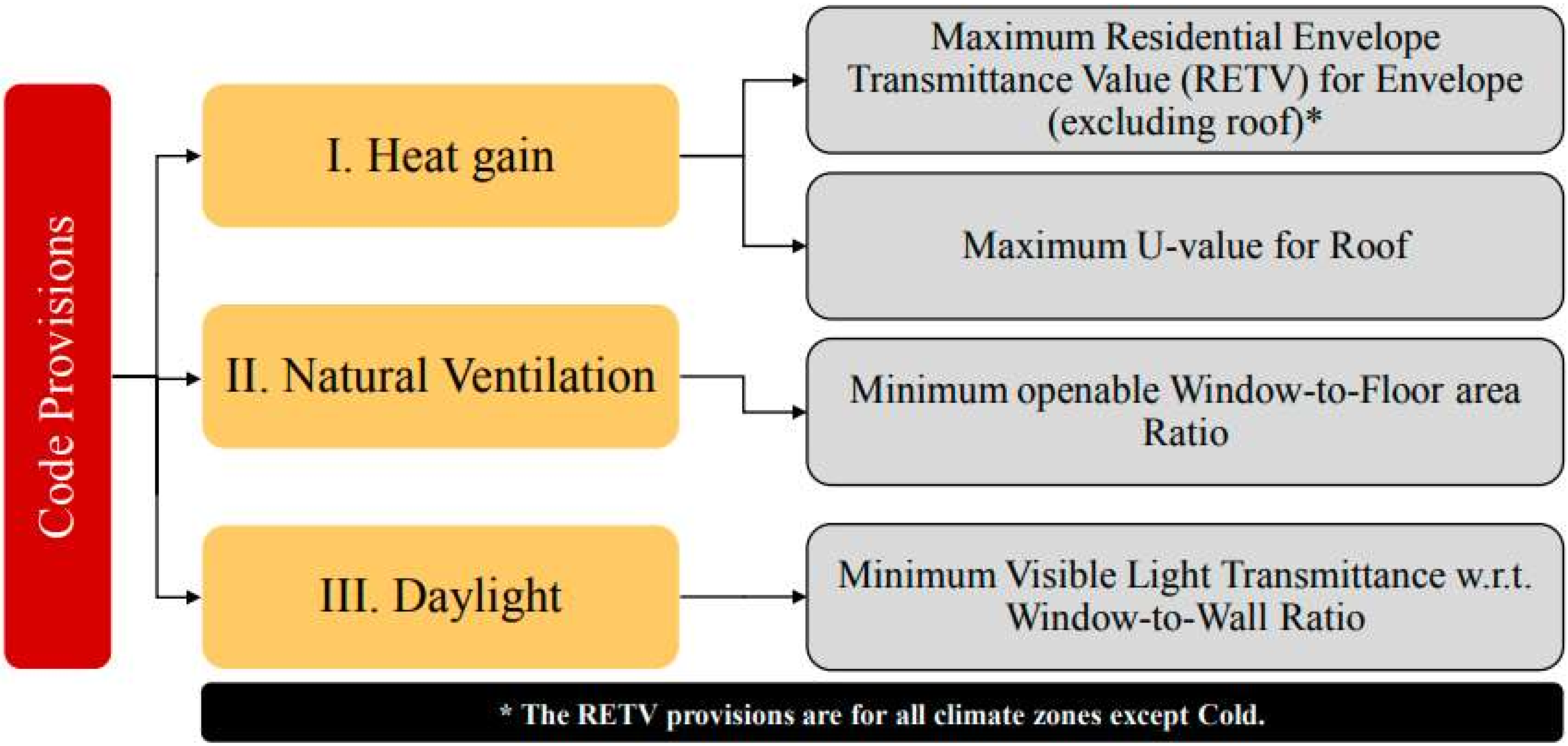
Reduce Heat Gain/Loss
Improve Natural Ventilation & Daylighting

↓

Improved thermal comfort & reduced energy consumption

Source: Bureau of Energy Efficiency, Government of India, & Ministry of Power. (2018). Eco-Niwas Samhita- Part I: Building Envelope. Retrieved from

Overview of Code Provisions



Code Provision: Heat Gain

Reducing Heat Gain:

Maximum RETV for building envelope (except roof)	RETV ≤ 15 W/m^2 For all climate zones except Cold
Roofing material's maximum thermal transmittance value (for all climate zones)	$U_{roof} \leq 1.2\ W/m^2K$

Source: Bureau of Energy Efficiency, Government of India, & Ministry of Power. (2018). Eco-Niwas Samhita- Part I: Building Envelope. Retrieved from

Residential Envelope Transmittance Value (RETV)

The net heat gain rate (over the cooling period) through the building envelope, walls, and windows (excluding the roof) divided by the area of the building envelope (excluding the roof), is measured in W/m^2.

Observations and Calculations

RETV: Formula and Calculations

$$RETV = \frac{1}{A_{envelope}} \times \left[\left\{ a \times \sum_{i=1}^{n} \left(A_{opaque_i} \times U_{opaque_i} \times \omega_i \right) \right\} + \left\{ b \times \sum_{i=1}^{n} \left(A_{non-opaque_i} \times U_{non-opaque_i} \times \omega_i \right) \right\} + \left\{ c \times \sum_{i=1}^{n} \left(A_{non-opaque_i} \times SHGC_{eq_i} \times \omega_i \right) \right\} \right]$$

Wall Conductive Heat Gains

Window Conductive Heat Gain

Window Radiation Heat Gain

Code Provisions: Natural Ventilation

The openable window-to-floor ratio (WFR_{op}) is the ratio of openable area to the built-up area of the dwelling units.

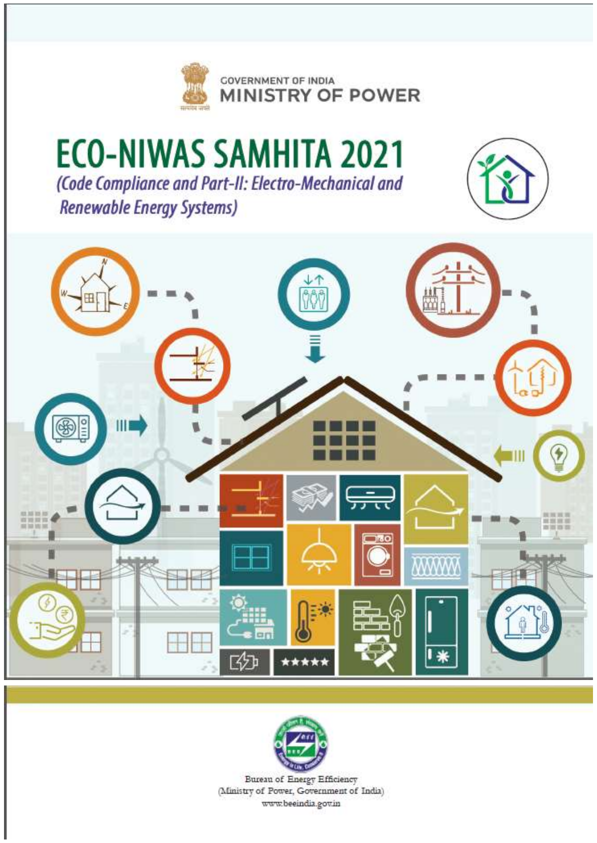
$$WFR_{op} = \frac{A_{openable}}{A_{built-up}}$$

Climate Zone	**Minimum WFR_{op} %**
Composite	12.5
Hot-Dry	10.0
Warm-Humid	16.6
Temperate	12.5
Cold	8.3

Openable Window-to-Floor Area Ratio

- Higher WFR_{op} helps in enhancement in
- Natural Ventilation
- Thermal comfort
- Cooling Energy Savings

Eco-Niwas Samhita 2021 (Code Compliance and Part-II)



- Scope
- Code Compliance
- Mandatory Requirements
- Prescriptive Requirements
- Point System Method

Mandatory Requirements

- All requirements for building envelope under mandatory section as mentioned in Chapter 4 of ENS Part I.
- Power Factor Correction
- Energy Monitoring
- Electric Vehicle Charging System
- Electrical Systems

Point System Method

Section	Components	Minimum points	Additional Points	Maximum Points
6.4	Building Envelope			
	Building Envelope	47	40	87
6.5	Building Services			
	Common area and exterior lighting	3	6	9
	Elevators	13	9	22
	Pumps	6	8	14
	Electrical Systems	1	5	6
6.6	Indoor Electrical End-Use			
	Indoor Lighting		12	12
	Comfort Systems		50	50
	ENS Score	70	130	200

Section	Components	Minimum Points	Additional Points	Maximum Points
6.7	Renewable Energy Systems			
	Solar Hot Water Systems		10	10
	Solar Photo Voltaic		10	10
	Additional ENS Score		20	20

ENS Score

Thermal transmittance of roof (U_{roof})

Maximum Score	7 Points

Score breakup for the thermal transmittance of roof is as mentioned in the Table 10

Table 10: Points for Thermal Transmittance of Roof (U_{roof})

Minimum, if opted: Thermal transmittance of roof shall comply with the maximum Uroof value of 1.2 W/m²·K.	Up to 3 Points
Additional: 1 Point for every reduction of 0.23 W/m²·K in thermal transmittance of roof from the Minimum requirement prescribed under §6.1(a).	Up to 4 Points

Residential Envelope Transmittance Value (RETV)

The RETV for the building envelope (except roof) for four climate zones, namely, Composite Climate, Hot-Dry Climate, Warm-Humid Climate, and Temperate Climate, shall comply with the maximum RETV of 15 W/m^2.	44 Points
For RETV less than 15 and up to 12 W/m^2, score will be calculated by following equation: $74 – 2 \times (RETV)$	Up to 50 Points
Additional: For RETV less than 12 and up to 6 W/m^2, score will be calculated by following equation: $110 – 5 \times (RETV)$	Up to 80 points
Additional: For RETV less than 6 W/m^2	80 Points

Building Services

Minimum: The Lighting power density (LPD) and Luminous efficacy (LE) of permanently installed lighting fixtures in common area of the ENS building shall meet the requirements of either maximum LPD or minimum luminous efficacy given in Table 13, Table 14 and as mentioned in section 6.5.1 (ii) and 6.5.1 (iii) for all the areas/ zones applicable for the building for which compliance is sought. If a particular area/ zone is not applicable to a building for which compliance is sought, the performance requirement of the respective zone/ area is not required.	3 Points
Additional: Installing all the permanently installed lighting fixtures with lamp luminous efficacy of 95 lm/W in areas mentioned below Area/ Zones — Points Corridor lighting and stilt parking — 1 Basement Lighting — 1 Exterior Lighting Areas — 1	Up to 3 Points
Additional: Lamps for all exterior applications apart from emergency lighting shall be controlled by photo sensor or astronomical time switch that is capable of automatically turning off the exterior lighting when daylight is available, or the lighting is not required. Installing all the permanently installed lighting fixtures in all corridor lighting, stilt parking, basement lighting and exterior lighting with lamp luminous efficacy of 105 lm/W. Area/ Zones — Points Corridor lighting and stilt parking — 2 Basement Lighting — 2 Exterior Lighting Areas — 2	Up to 6 Points

Building Services - Points for Air Conditioners

Minimum, if opted: Unitary Type: 5 Star Split AC: 3 Star VRF: 3.28 EER Chiller: Minimum ECBC Level values as mentioned in ECBC 2017	20 Points
Additional : Split AC: 4 Star VRF: Not Applicable as on date, however, whenever BEE Star label-ling for VRF is launched, Star 4 will be applicable Chiller: Minimum ECBC+ Level values as mentioned in ECBC 2017	9 Points
Additional : Split AC: 5 Star VRF: Not Applicable as on date, however, whenever BEE Star label-ling for VRF is launched, Star 5 will be applicable Chiller: Minimum SuperECBC Level values as mentioned in ECBC 2017	21 Points

Building Services - Points for Renewable Energy Systems

Minimum, if opted: The ENS compliant building shall provide a solar water heating system (SWH) of minimum BEE 3 Star label and is capable of meeting 100% of the annual hot water demand of top 4 floors of the residential building. or 100% of the annual hot water demand of top 4 floors of the residential building is met by the system using heat recovery	5 Points
Additional: Additional points can be obtained by installing SWH system as per as per following: 100% of the annual hot water demand of top 6 floors of the residential building (2 points) 100% of the annual hot water demand of top 8 floors of the residential building (5 points)	Up to 5 Points

Building Services - Points for Renewable Energy Systems

Minimum, if opted: The ENS compliant building shall provide a dedicated Renewable Energy Generation Zone (REGZ) – Equivalent to a minimum of 2 kWh/m².year of electricity; or Equivalent to at least 20% of roof area. The REGZ shall be free of any obstructions within its boundaries and from shadows cast by objects adjacent to the zone.	5 Points
Additional: Additional points can be obtained by installing solar photo voltaic as per following: Equivalent to a minimum of 3 kWh/m².year of electricity or Equivalent to at least 30% of roof area (2 points) Equivalent to a minimum of 4 kWh/m².year of electricity or Equivalent to at least 40% of roof area (5 points)	Up to 5 Points

Affordable Housing

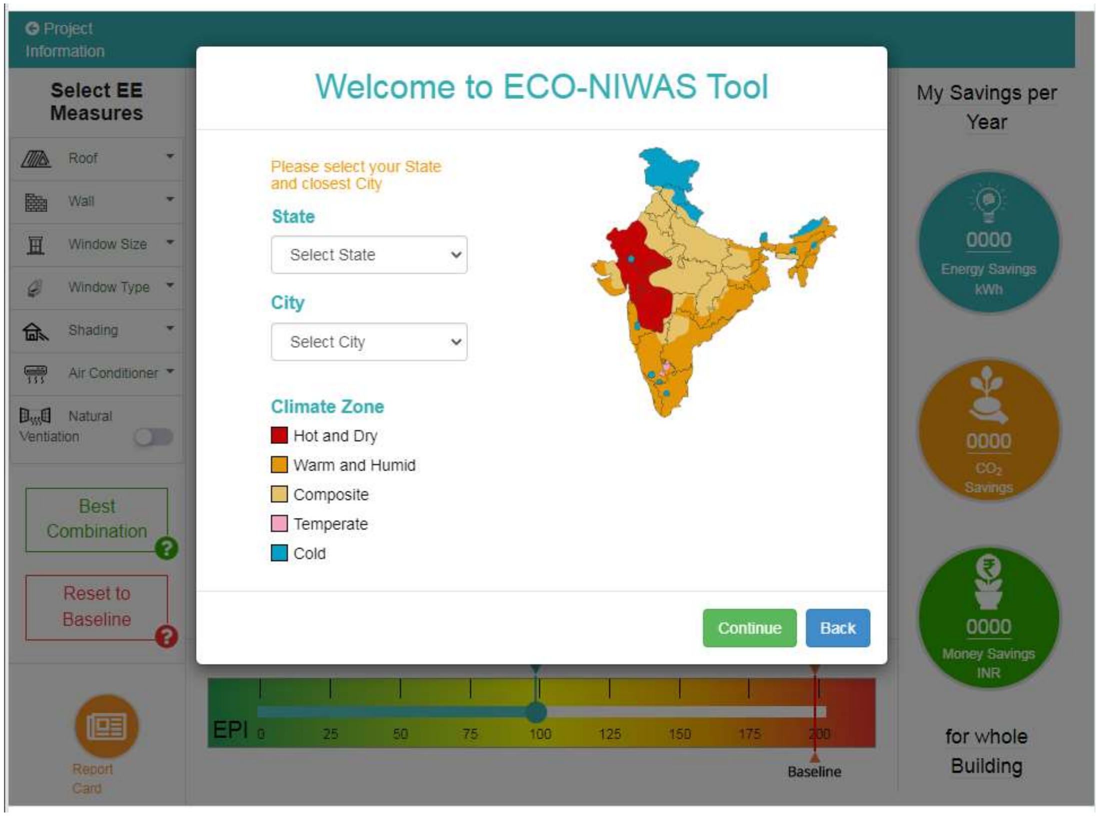
- Affordable houses are Dwelling Units (DUs) with Carpet Area less than 60 sqm. It also includes Economically Weaker Section (EWS) category and Lower Income Group (LIG) category (LIG-A: 28-40 sq. m. and LIG-B 41- 60 Sq.m.).
- Projects using at least 60 percent of the FAR/ FSI for dwelling units of Carpet Area not more than 60 sqm will be considered as Affordable housing projects.
- This definition could be changed time to time by Ministry of Housing & Urban Affairs and respective states and latest definition for the respective state shall be considered.

Minimum ENS Score Requirement

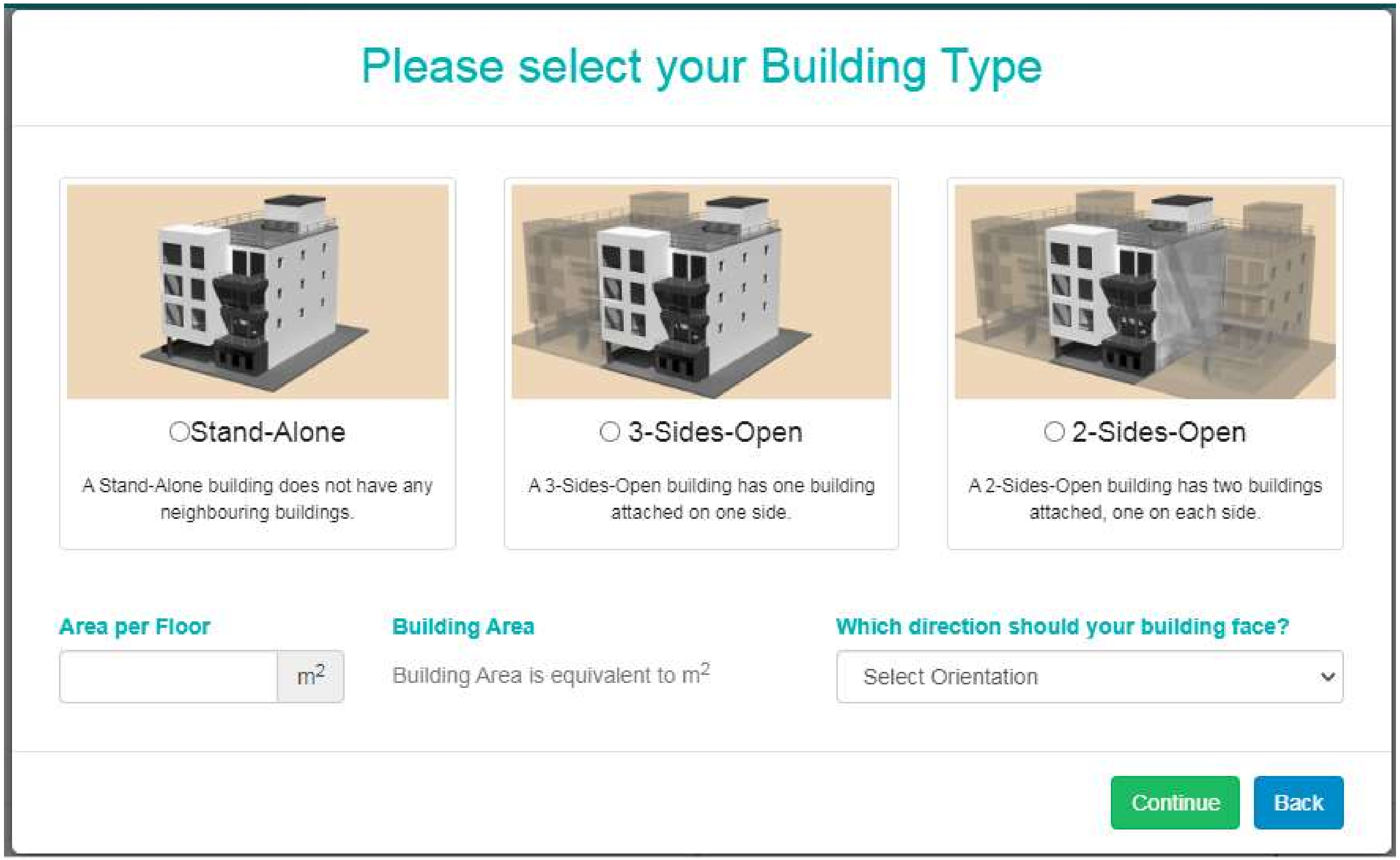
Project Category	Minimum ENS Score
Low rise buildings	47
Affordable Housing	70
High rise buildings	100

ENS Tool

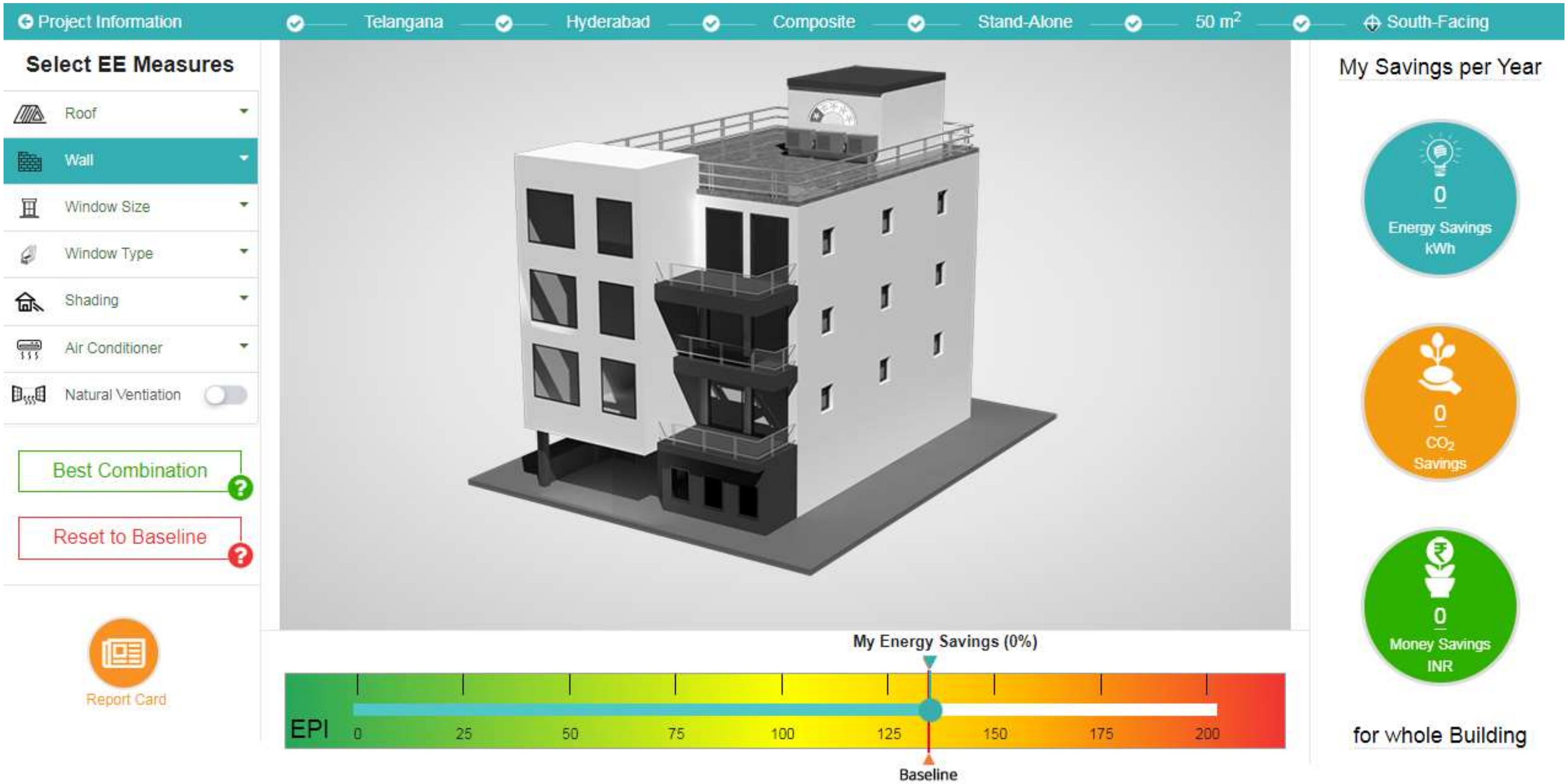
ENS Tool: https://www.econiwas.com/tool/



ENS Tool

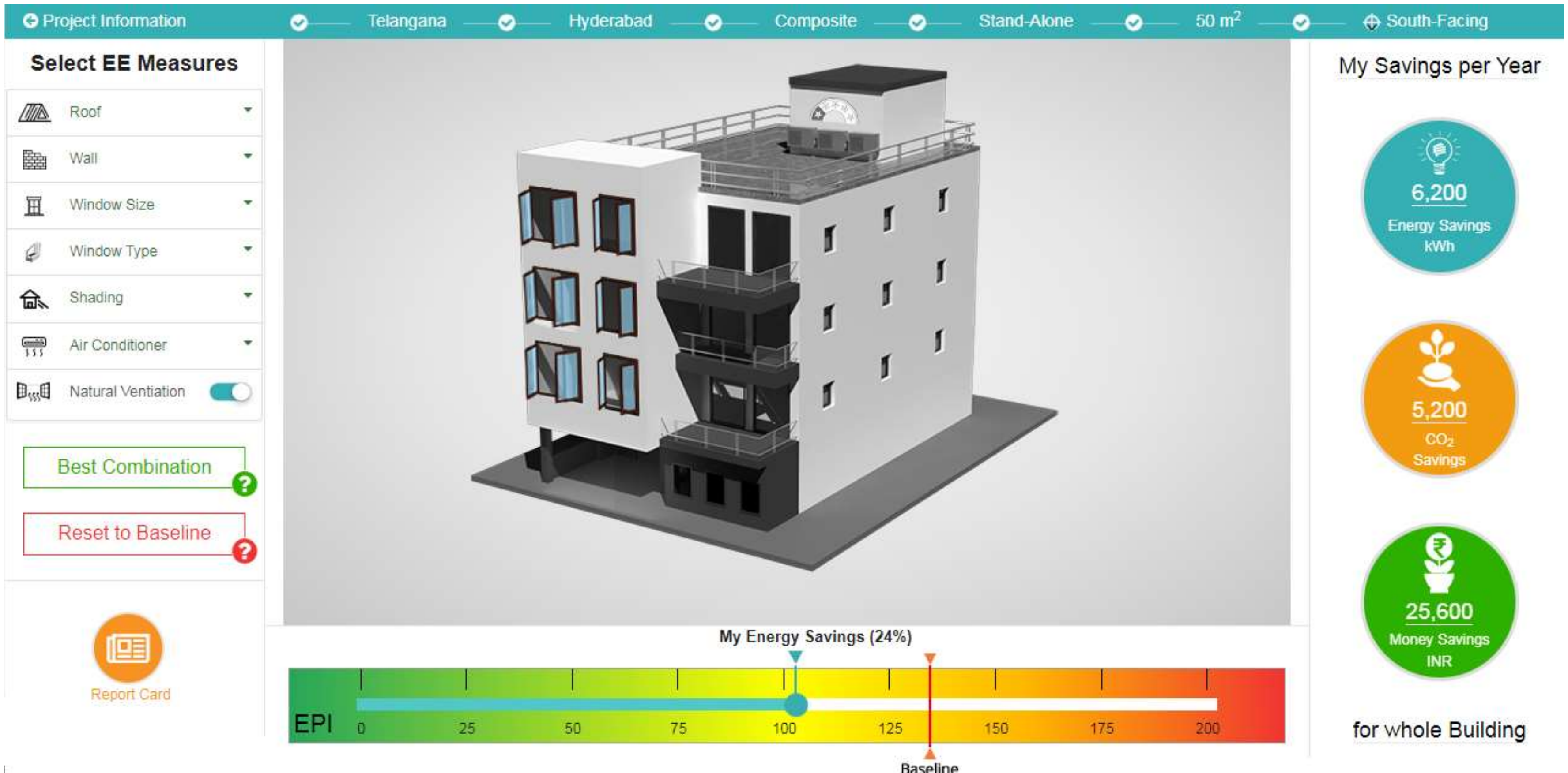

Please select your Building Type
Stand-Alone
A Stand-Alone building does not have any neighbouring buildings.
3-Sides-Open
A 3-Sides-Open building has one building attached on one side.
2-Sides-Open
A 2-Sides-Open building has two buildings attached, one on each side.
Area per Floor
m2
Building Area
Building Area is equivalent to m2
Which direction should your building face?
Select Orientation
Continue
Back

ENS Tool



Project Information
Telangana
Hyderabad
Composite
Stand-Alone
50 m2
South-Facing
Select EE Measures
Roof
Wall
Window Size
Window Type
Shading
Air Conditioner
Natural Ventilation
Best Combination
Reset to Baseline
Report Card
My Energy Savings (0%)
EPI
0 25 50 75 100 125 150 175 200
Baseline
My Savings per Year
0
Energy Savings kWh
0
CO2 Savings
0
Money Savings INR
for whole Building

ENS Tool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Hyderabad
Composite
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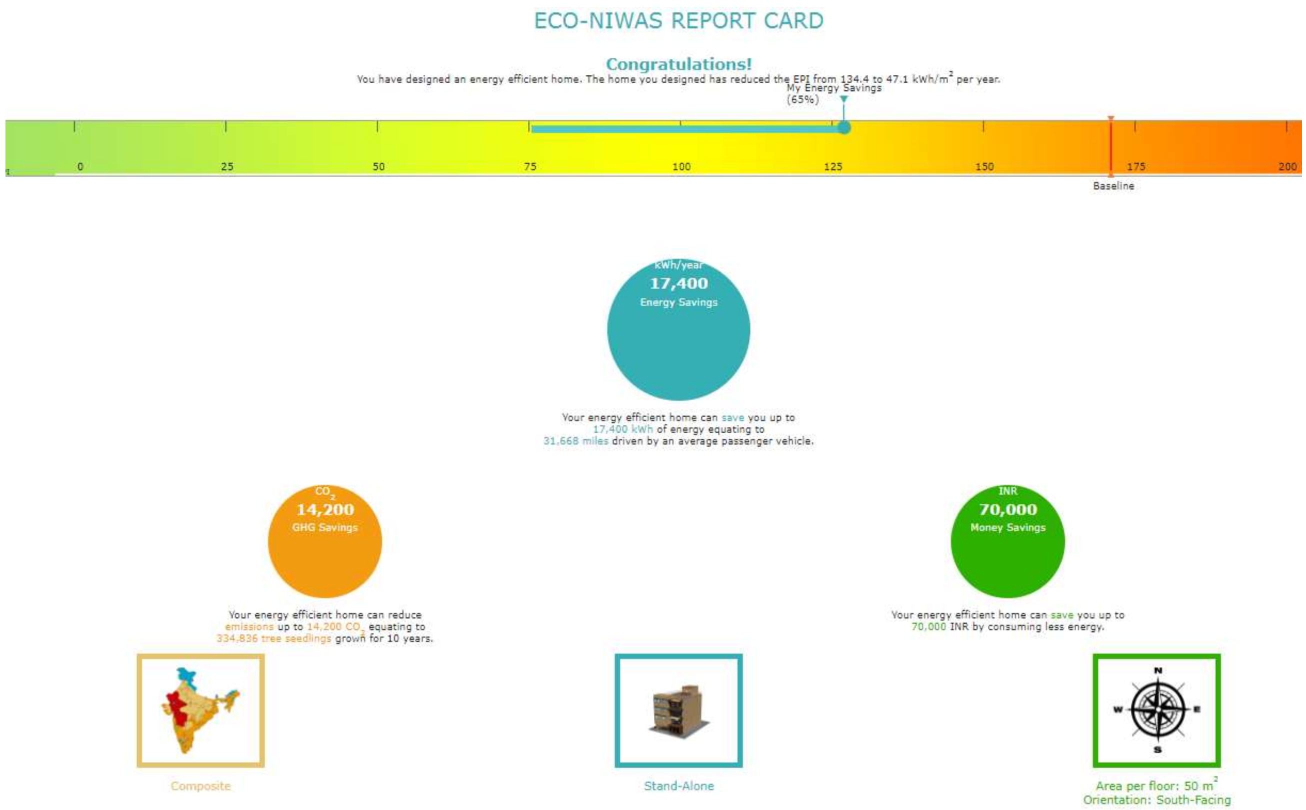
50 m²
South-Facing
Select EE Measures
Roof
Wall
Window Size
Window Type
Shading
Air Conditioner
Natural Ventiation
Best Combination
Reset to Baseline
Report Card
My Energy Savings (24%)
EPI
0
25
50
75
100
125
150
175
200
Baseline
My Savings per Year
6,200
Energy Savings
kWh
5,200
CO2
Savings
25,600
Money Savings
INR
for whole Building

ENS Tool

Project Information
Telangana
Hyderabad
Composite
Stand-Alone
50 m2
South-Facing
Select EE Measures
Roof
Wall
Window Size
Window Type
Shading
50% Shading
100% Shading
Air Conditioner
Natural Ventilation
Best Combination
Reset to Baseline
Report Card
My Energy Savings (65%)
EPI
0
25
50
75
100
125
150
175
200
Baseline
My Savings per Year
17,400
Energy Savings
kWh
14,200
CO2
Savings
70,000
Money Savings
INR
for whole Building

ENS Tool



ECO-NIWAS REPORT CARD
Congratulations!
You have designed an energy efficient home. The home you designed has reduced the EPI from 134.4 to 47.1 kWh/m² per year.
My Energy Savings (65%)
0
25
50
75
100
125
150
175
200
Baseline
kWh/year
17,400
Energy Savings
Your energy efficient home can save you up to 17,400 kWh of energy equating to 31,668 miles driven by an average passenger vehicle.
CO2
14,200
GHG Savings
Your energy efficient home can reduce emissions up to 14,200 CO2 equating to 334,836 tree seedlings grown for 10 years.
INR
70,000
Money Savings
Your energy efficient home can save you up to 70,000 INR by consuming less energy.
Composite
Stand-Alone
N
W
E
S
Area per floor: 50 m²
Orientation: South-Facing

Conclusions

- Affordable Housing
- Thermal Comfort
- Energy Codes
- ENS Tool

Thank you!

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RESILIENT, AFFORDABLE AND COMFORTABLE HOUSING THROUGH NATIONAL ACTION

One-Day Online Training Program on Thermal Comfort in Affordable Housing

Ms. Sowmya Chinta
March 31, 2023

BUILDING ENERGY SIMULATION

Outline

- Introduction to Energy Simulation
- ENS Tool
- ECBC Compliance software
- Conclusions

INTRODUCTION

- Building energy simulation, also called building energy modeling (or energy modeling in context), is the use of software to predict the energy use of a building.

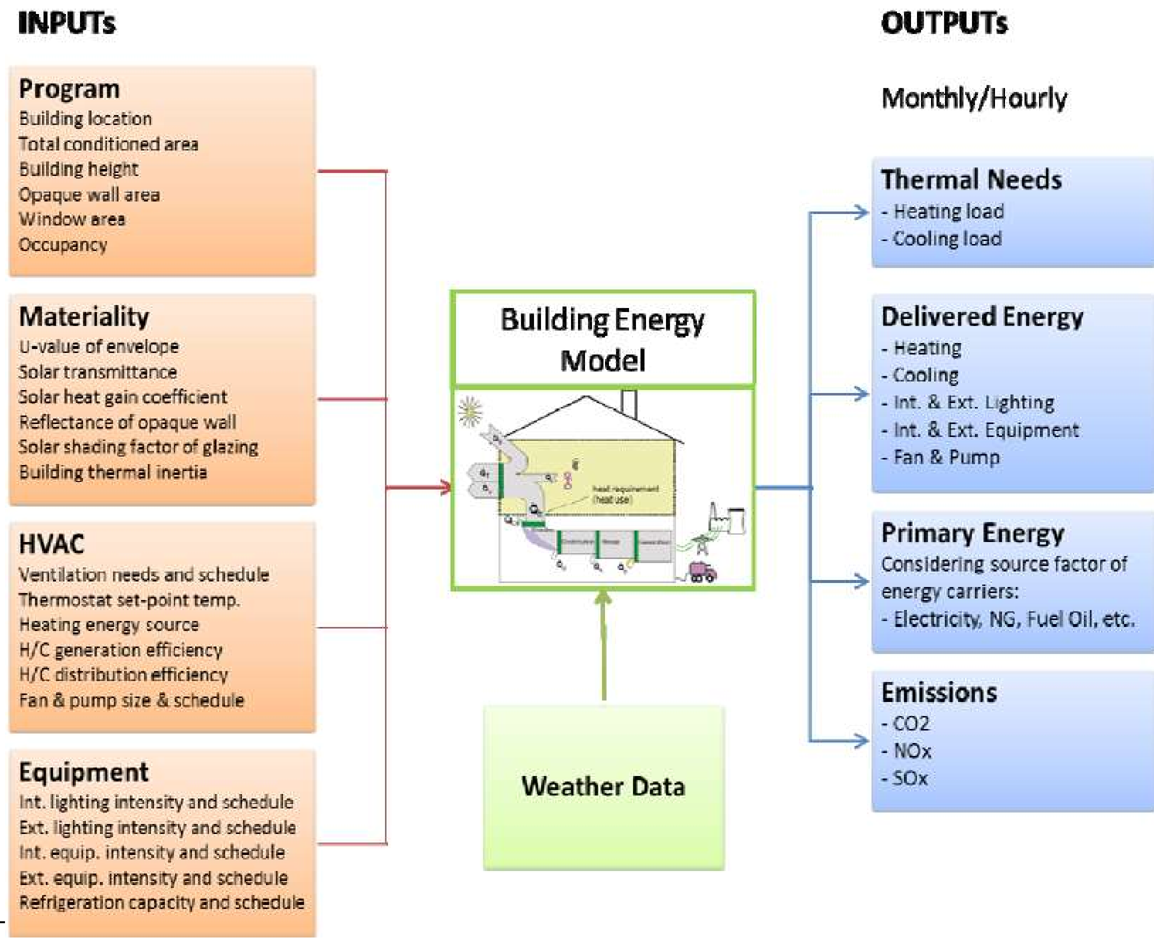
- Energy modeling has been used as an alternative method to the prescriptive approach to comply to building standards.

ENERGY SIMULATION SOFTWARE

INPUTS

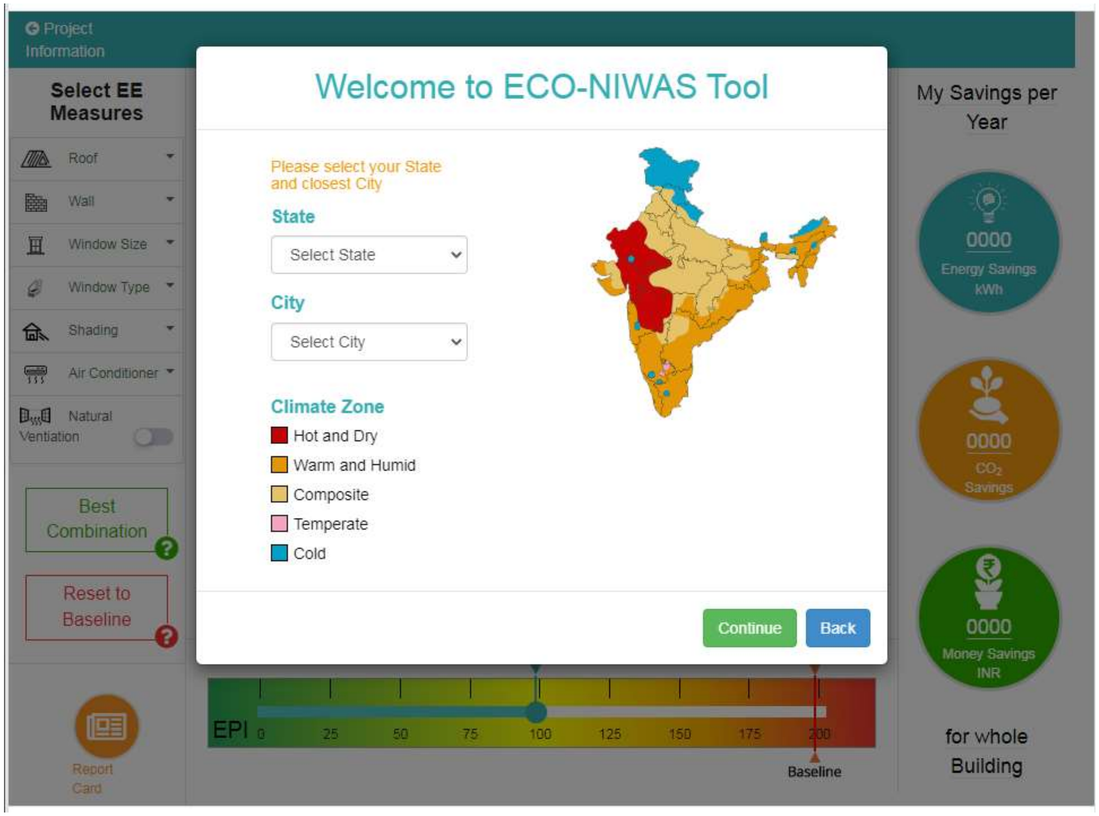

Detailed geometry,
Location and Orientation
Operational Profiles
Envelope
Performance
Energy
Generation
Internal Gains
HVAC System and
outdoor air ventilation

PROCESS

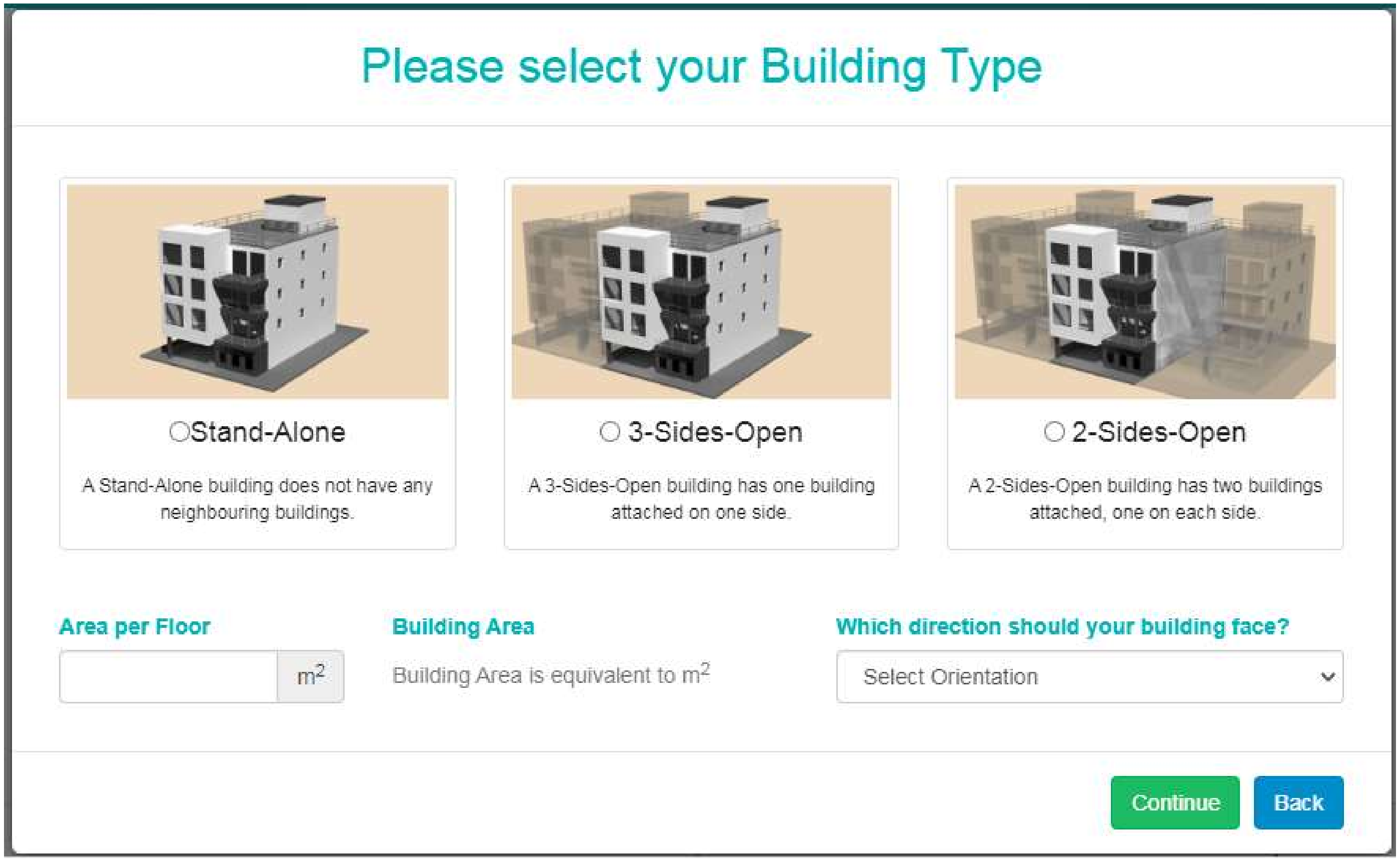

INPUTs
Program
Building location
Total conditioned area
Building height
Opaque wall area
Window area
Occupancy
Materiality
U-value of envelope
Solar transmittance
Solar heat gain coefficient
Reflectance of opaque wall
Solar shading factor of glazing
Building thermal inertia
HVAC
Ventilation needs and schedule
Thermostat set-point temp.
Heating energy source
H/C generation efficiency
H/C distribution efficiency
Fan & pump size & schedule
Equipment
Int. lighting intensity and schedule
Ext. lighting intensity and schedule
Int. equip. intensity and schedule
Ext. equip. intensity and schedule
Refrigeration capacity and schedule
Building Energy Model
Weather Data
OUTPUTs
Monthly/Hourly
Thermal Needs
- Heating load
- Cooling load
Delivered Energy
- Heating
- Cooling
- Int. & Ext. Lighting
- Int. & Ext. Equipment
- Fan & Pump
Primary Energy
Considering source factor of energy carriers:
- Electricity, NG, Fuel Oil, etc.
Emissions
- CO2
- NOx
- SOx

ENS Tool

ENS Tool: https://www.econiwas.com/tool/



ENS Tool



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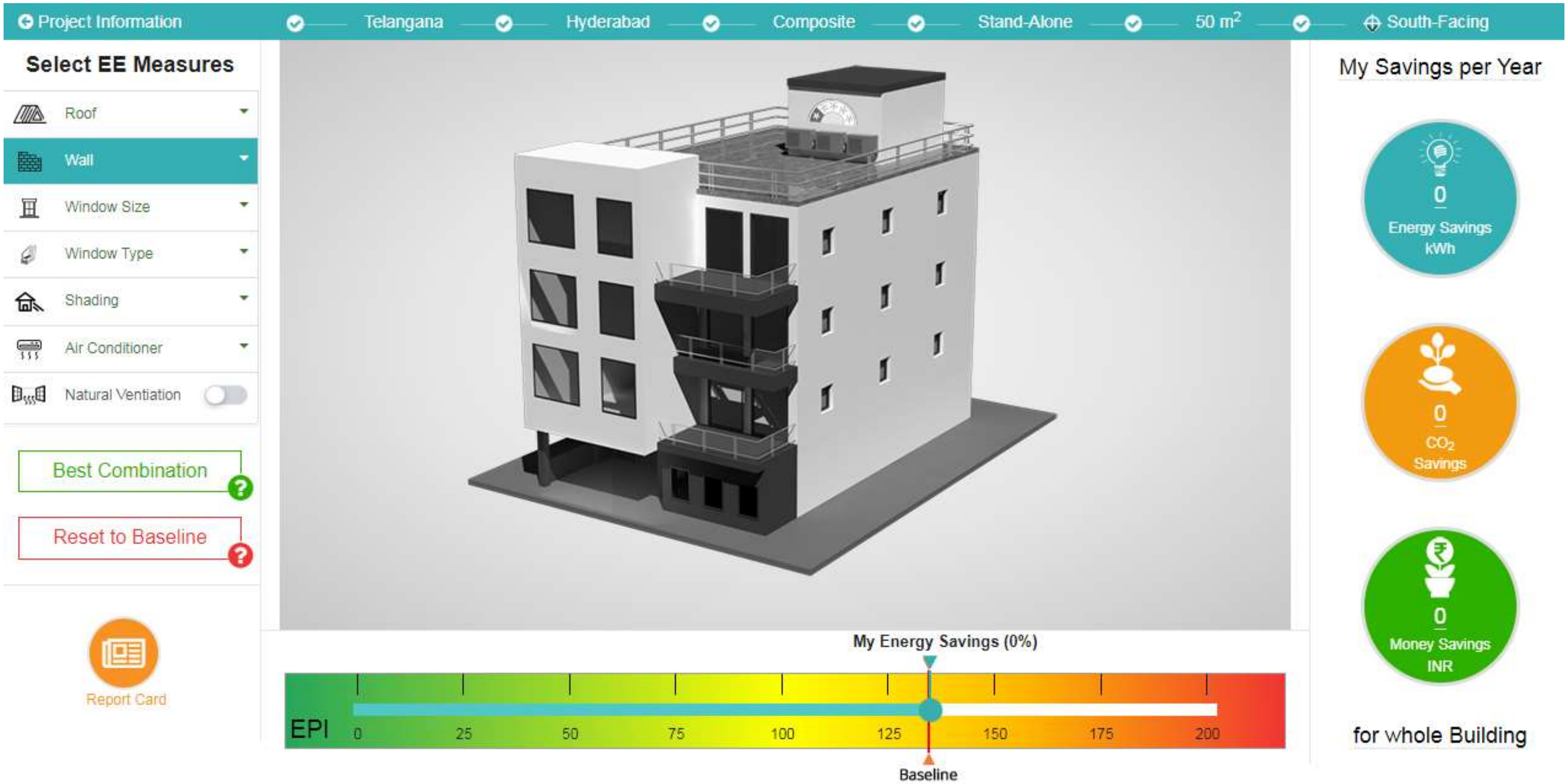
Area per Floor
m2
Building Area
Building Area is equivalent to m2
Which direction should your building face?
Select Orientation
Continue
Back

ENS Tool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Stand-Alone
50 m²
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Select EE Measures
Roof
Wall
Window Size
Window Type
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Natural Ventilation
Best Combination
Reset to Baseline
Report Card
My Energy Savings (0%)
EPI
0
25
50
75
100
125
150
175
200
Baseline
My Savings per Year
0
Energy Savings kWh
0
CO2 Savings
0
Money Savings INR
for whole Building

ENS Tool

Project Information
Telangana
Hyderabad
Composite
Stand-Alone
50 m2
South-Facing
Select EE Measures
Roof
Wall
Window Size
Window Type
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Air Conditioner
Natural Ventiation
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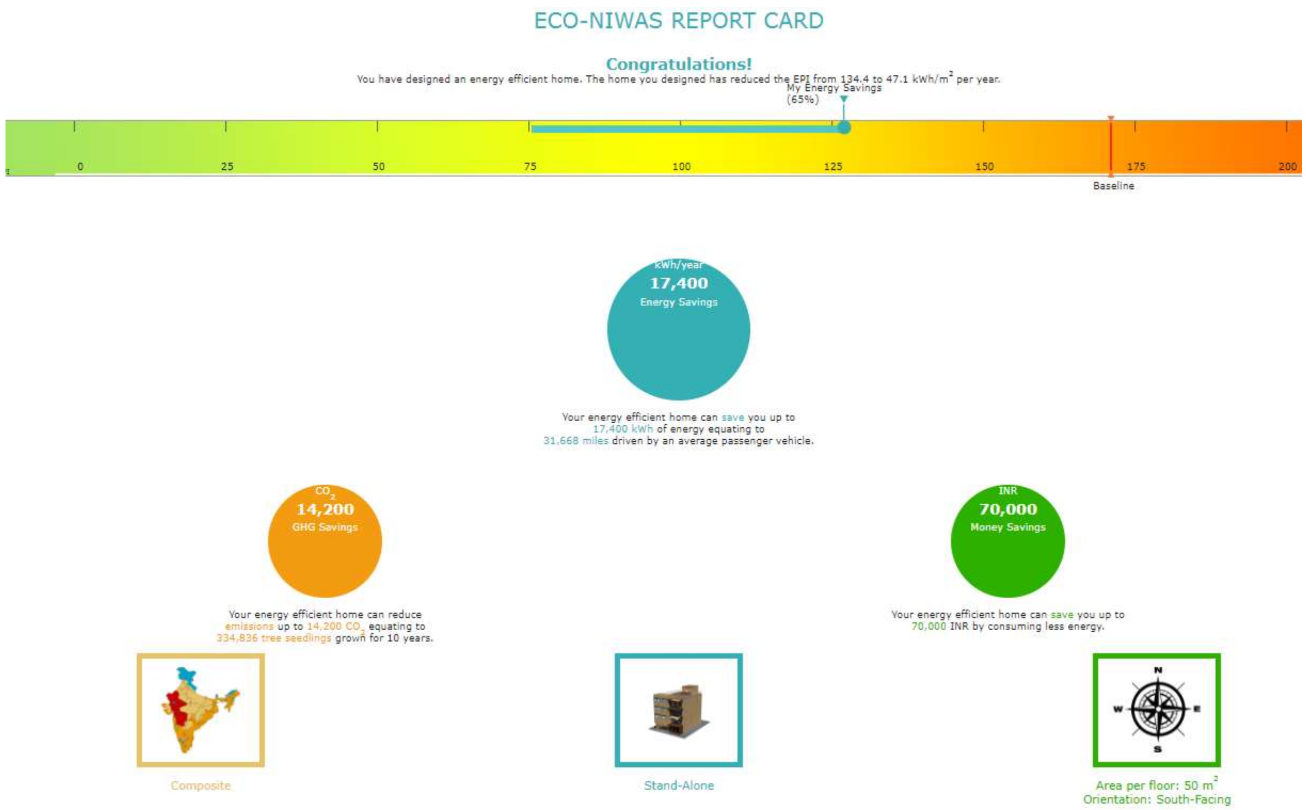
Report Card
My Energy Savings (24%)
EPI
0
25
50
75
100
125
150
175
200
Baseline
My Savings per Year
6,200
Energy Savings
kWh
5,200
CO2
Savings
25,600
Money Savings
INR
for whole Building

ENS Tool


Project Information
Telangana
Hyderabad
Composite
Stand-Alone
50 m²
South-Facing
Select EE Measures
Roof
Wall
Window Size
Window Type
Shading
50% Shading
100% Shading
Air Conditioner
Natural Ventilation
Best Combination
Reset to Baseline
Report Card
My Energy Savings (65%)
EPI
0
25
50
75
100
125
150
175
200
Baseline
My Savings per Year
17,400
Energy Savings
kWh
14,200
CO2
Savings
70,000
Money Savings
INR
for whole Building

ENS Tool



ECO-NIWAS REPORT CARD
Congratulations!
You have designed an energy efficient home. The home you designed has reduced the EPI from 134.4 to 47.1 kWh/m2 per year.
My Energy Savings (65%)
0
25
50
75
100
125
150
175
200
Baseline
kWh/year
17,400
Energy Savings
Your energy efficient home can save you up to 17,400 kWh of energy equating to 31,668 miles driven by an average passenger vehicle.
CO2
14,200
GHG Savings
Your energy efficient home can reduce emissions up to 14,200 CO2 equating to 334,836 tree seedlings grown for 10 years.
INR
70,000
Money Savings
Your energy efficient home can save you up to 70,000 INR by consuming less energy.
N
W
E
S
Composite
Stand-Alone
Area per floor: 50 m2
Orientation: South-Facing

ECBC COMPLIANCE SOFTWARE

Simulation General Requirements

- **Energy Simulation Program**
- Approved Simulation Program
- Minimum Hours Per Year-8760 hours
- Hourly variations and separate design Schedules of operation
- Thermal Mass effects
- Ten or more Zones
- Part load performance curves
- Economizers
- Design Load Calculations

Approved Analytical Tools for Whole Building Performance

Open Studio

IES-VE

- Equest,
- Energy plus,
- Design Builder,
- Open Studio,
- IES-VE,
- DOE2
- AECOsim,
- HAP,
- IDA-ICE,
- Simergy,
- Trace700,
- TRNSYS,
- Visual DOE

Approved Analytical Tools for Daylighting

Open Studio **IES-VE**

The following are also some of the approved tools

- Open Studio,
- IES-VE,
- Design Builder,
- Groudhog,
- Sefaria,
- AGI32 (Licaso),
- Daysim,
- DIVA,
- RadianceRhino-Grasshopper with Daylighting,
- Plugins,
- Sensor Placement + Optimization Tool (SPOT)

Thank you!