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Reducing Heat Gain through Roofs: A Comparative Study of Passive Strategies for Mid-Rise Commercial Buildings in Composite Climate

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Abstract: With the increase in population, urbanization, and growth in living standards of people, the energy demand also increases. 20% of the total energy consumed in the world is by buildings, and it can further increase up to 25% by 2050 (EIA, Future of Cooling, 2018). There have been massive carbon dioxide emissions due to the use of different energy sources. These CO2 emissions and fossil fuel consumption have led to global warming and evident climate changes. This energy and environmental challenge has become a global concern. To address the challenge of increasing energy demand, one can either produce energy from renewable energy resources or reduce or control the energy demand in the building.

The more sustainable solution to address this problem is to reduce the demand by applying effective strategies to reduce energy demand in buildings. In India, the share of the cooling load on the total electric load from buildings was 10.5%. Therefore, this study focuses on reducing the heat gain in buildings through passive techniques, to reduce this load. The roof of a low to mid-rise building receives a far greater amount of solar radiation than walls. Unlike walls, the roof is exposed to solar radiation throughout the day and hence heat transfer from the roof is considerably notable for its impact on the user comfort. The effect is considerably high in small-scale buildings such as individual homes, apartments, and low-rise buildings contributing to about 70% of the total heat gain in hot climates. Therefore, careful design and treatment of the roofs can have a significant reduction in the solar heat gain in buildings, maintain thermal comfort and thus save energy. A comparative study of techniques has been done to find the thermal performance of different techniques applied to the roofs using design builder software.

***IndexTerms* –energy demand, cooling load, passive techniques, heat-gain, building envelope, roofs.**

I. Introduction

In the past few decades, the energy demand has been increasing all over the world. With time, as the population and their living standards rise, the energy demand will also increase further in future. In India, the energy consumption has increased three times from 1990 to 2018. According to EIA (Energy Information Administration), official energy statistics organization of the US government, 45% of the Total energy consumption in India in 2018 was generated by using coal, 26% by petroleum and other liquids and 20% energy was generated by the traditional Biomass and waste. Other renewable resources had a little contribution in the overall energy production (EIA, Energy Statistics Report, 2021). This use of fuel for the production of energy leads to high greenhouse gas emissions which is harmful for the environment. These greenhouse gas emissions majorly comprise of carbon dioxide (CO2) emissions. CO2 emissions and the fossil fuel consumption in the power plants can cause thermal accumulation which is a major contributor in climate change which the world is facing.

Although the rise in global energy demand is evident in all the sectors, but as shown in Figure 1, the rise in share of energy for cooling will be the highest 37%, by 2050. As shown in Figure 2, in India, the share of cooling load on the total electric load from buildings was 10.5% in 2016 and with growing urbanization and improvement in living standards; the same is estimated to be 44.1% by 2050. By the use of efficient cooling systems the share of cooling load on the total electric load is estimated to be 19.3% by 2050 (EIA, Future of Cooling, 2018). Thus, one of the highest consumption of energy is due to the air conditioning in buildings to maintain thermal comfort for its users or occupants. Even with the usage of efficient cooling systems, there is a growth of 8.8% in the cooling load from 2016 to 2050 in India.

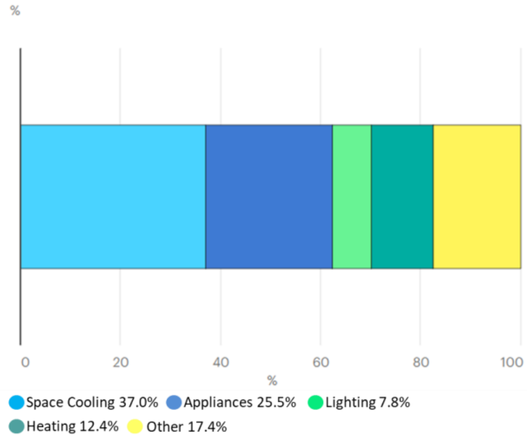


Figure 1 Global Energy Demand Growth by 2050 (EIA, Future of Cooling, 2018)

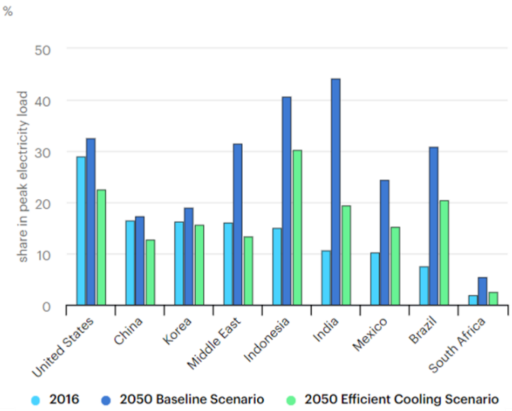


Figure 2 Share of Cooling in Electricity System Peak Loads (EIA, Future of Cooling, 2018)

The power sector is the greatest contributor of the CO_2 production in the country as shown in Figure 3. Residential and commercial buildings together are responsible for the production of 35-40% of CO_2 (EIA, Energy Statistics Report, 2021).

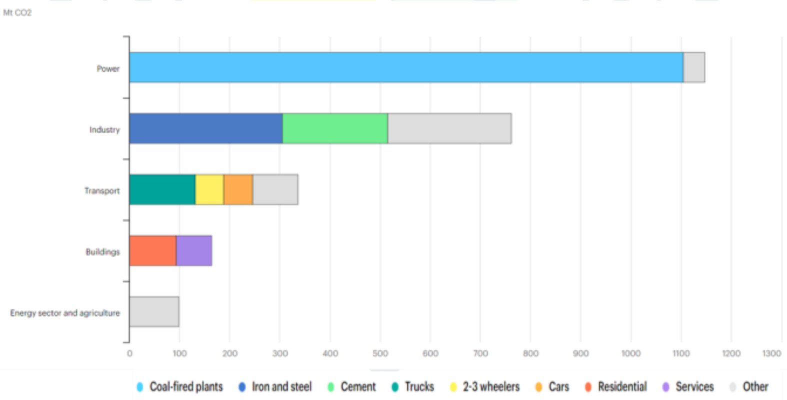


Figure 3 CO_2 emissions from the Indian energy sector, 2019 (EIA, Energy Statistics Report, 2021)

The power plants burn fossil fuels and release greenhouse gases which contribute to global warming. Carbon dioxide is the main gas that is released from a thermal power plant which pollutes the environment. It increases the temperature and pollutes the air leading to an overall deteriorated environment. 'Prevention is better than cure': in context of buildings and the increasing energy demands, apart from producing sources of clean energy, it would be better to design our buildings to reduce the amount of energy needed to maintain a comfortable indoor environment. Certain techniques can be applied to the buildings that help minimize the cooling load, thus reducing the energy demand; these strategies are known as passive strategies.

Need and significance-

The rising energy demand for the population, dependency on several energy resources, and subsequent climatic changes need to be addressed. The cities have been developed over the years by cutting down trees and tampering the natural landscapes. This has led to the development of urban spaces with insufficient green areas with huge building mass increasing the temperature in urban areas. Thus, it leads to more heat gain and more significant requirement of energy for cooling. A simple and sustainable solution for reducing the energy needs for cooling is the application of passive design strategies in our buildings. Passive strategies help maintain thermal comfort, daylight requirement, etc., with the help of building features and design.

Roof has always been a significant factor of heat gain in buildings and thus passive cooling/ heating strategies in roof design can be an essential factor in reducing the energy consumed by the building. Unlike walls, the roof is exposed to solar radiation throughout the day and hence heat transfer from the roof is considerably notable for its impact on the user comfort. This is more applicable for low to mid-rise buildings. Therefore, careful designing of the rooftops can have significant reduction in the solar heat-gain and thus save energy.

Aim-

The aim of the study is to analyze the effectiveness of passive techniques, in reducing heat-gain in buildings through roofs, for mid-rise commercial buildings in composite climate.

Objectives-

1. To study the types of passive strategies and their working.
2. To understand the techniques that can be applied on roofs in composite climate that can contribute to heat-gain reduction.
2. To study and analyze each strategy and the amount of heat-gain reduction.
3. To study the role of roof component in maintaining the indoor thermal comfort.

Methodology-

1. Studying in detail the passive techniques.
2. Understanding the application of different passive methods for the roofs through existing literature and case studies.
3. Studying the parameter that can be used to analyze the effectiveness of the passive techniques.
4. Simulations with selected type of techniques.
5. Conclusion of the study based on entire research.

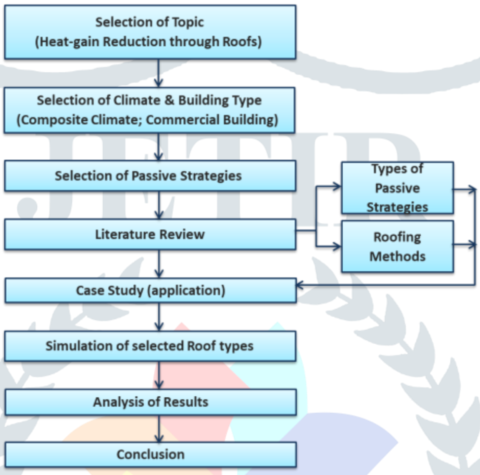


Figure 4 Methodology (author)

Scope and Limitations-

1. The study shall be focused on the techniques minimizing heat gain through roofs only. It will not be covering the heat-gain through walls and openings.
2. The building typology is commercial building and mid-rise G+4.
3. The study shall be limited to composite climate only.
4. The structural load calculations shall not be taken into consideration

II. Literature Study

Introduction to Passive Strategy-

Passive cooling systems are a set of design strategies that use natural processes for heating or cooling a building or a space, to achieve balanced indoor conditions for a comfortable indoor environment. These strategies or techniques are used in buildings to create a comfortable microclimate for the occupants, so that the dependency on mechanical systems can be minimized. It involves non-mechanical design features, such as the climatic requirement, building orientation, building shape, selection of right building materials for the building envelope, ventilation, fenestrations, shading devices etc. The natural cooling techniques works by transferring heat from one space to another to reach a temperature that is lower than the surrounding environment. This happens by the simple process of either ventilation or heat transfer through conduction, convection and/or radiation. These passage strategies can also be combined with active strategies or mechanical cooling systems for better results. Active strategies use mechanical systems and electrical power to function. Passive strategies are used in buildings to reduce the amount of energy needed for cooling of spaces using mechanical methods such as air conditioners, and HVAC systems etc. (Kamal, 2012)

Principles and Classification of Passive Cooling Strategies-

Passive cooling works on two principles: accessibility to a heat sink that has lower temperature as compared to the indoor air and by promoting heat transfer to heat sink. Heat sinks are the components that dissipate or absorb heat. It promotes the flow of heat from higher to lower temperature. For passive cooling, natural resources are used as heat sinks such as wind, water body or soil etc. Heat sinks that are used in passive cooling are: (i) Outside Air, (ii) Water, (iii) Earth and (iv) Night Sky. These heat sinks are used to transfer heat and cool spaces (Song, Ghaida , Rasool , Darani, & Khdair, 2021).

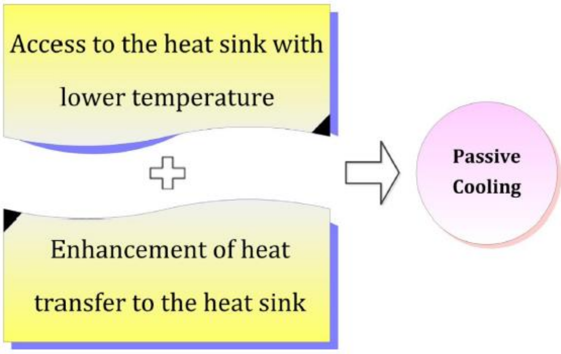


Figure 5 Principle of Passive Cooling (Song, Ghaida , Rasool , Darani, & Khdair, 2021)

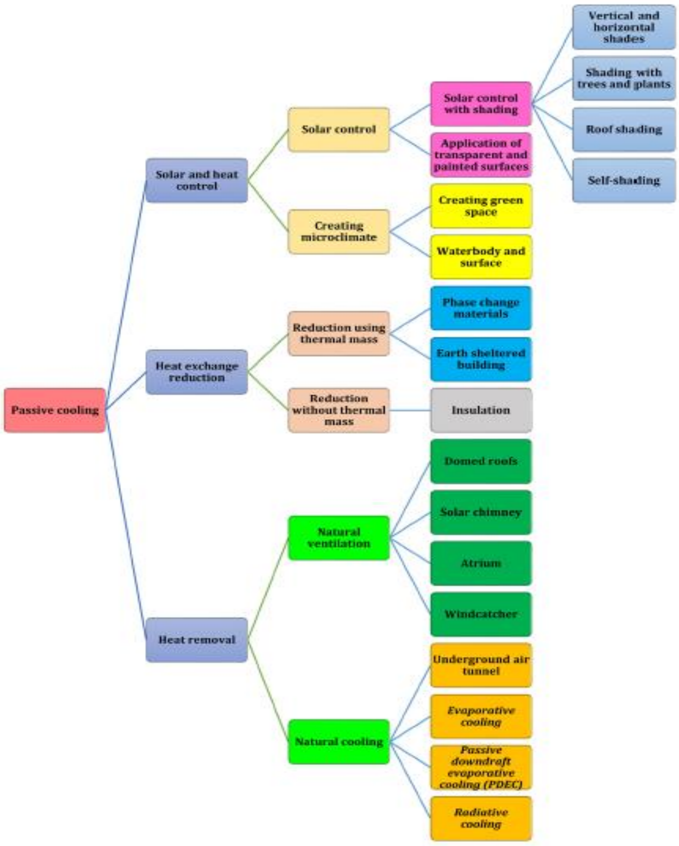


Figure 6 Classification of Passive Techniques (Song, Ghaida , Rasool , Darani, & Khdair, 2021)

According to the paper, "A review on conventional passive cooling methods applicable to arid and warm climates considering economic cost and efficiency analysis in resource-based cities", 2021, the authors have classified passive cooling techniques into three main categories based on the process used for cooling. The three categories are solar and heat control, heat exchange reduction and heat removal.

- Solar and Heat Control: Solar control methods are adopted for such a method of passive cooling. This means cutting down direct rays of sun penetrating inside a building, shading of the building envelope, creating a micro-climate by vegetation and plant cover.
- Heat Exchange Reduction: This passive cooling method works by reducing the amount of heat that can pass through the building envelope to the interior spaces.
- Heat Removal: This method of passive cooling uses either natural ventilation or natural cooling to remove the heat of the interior spaces.

Building Envelope and the Significance of Roof in Reducing the Overall Heat Gained in Buildings-

Building envelope is the outermost layer of components of a building which separates the interior and exterior of a building. It includes walls, openings such doors, windows etc., and roof. The building envelope design is one of the main factors responsible for the indoor environment. It directly impacts thermal comfort and hence the energy consumption in buildings. The traditional architecture focused primarily on the building envelope design parameters to address the occupant comfort. In the current scenario, with the vast availability of the mechanical systems to attain user comfort, barely any attention is given to exploring the building envelope's designing opportunities for the same.

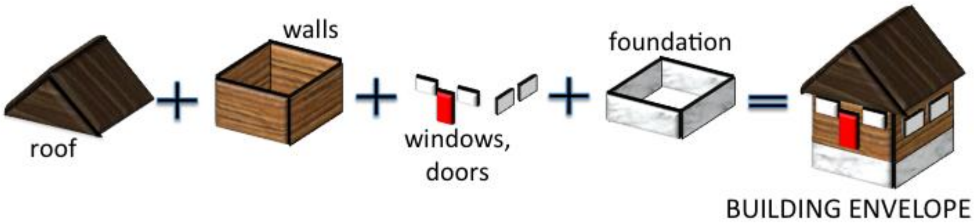


Figure 7 Components of the Building Envelope (J.M.K.C & Donev, 2021)

The building envelope consists of the outer structure as shown in Figure 7. The building enveloped can be put into three categories: (i) Support; (ii) Control; and (iii) Finish (J.M.K.C & Donev, 2021). The support category stands for the structural support components like foundation of the building. The control category refers to the components that define the interior space and act as a barrier between the exterior and the interior. These components are also responsible for the exchange of air, moisture, heat etc. from outside to inside of a building. The finish category is either for aesthetic purpose or acts as an extra protective layer to the main structure, while performing the control function as well. The exposed part of the envelope that is the walls, openings and roof are responsible for the heat gain in the buildings.

Roofs play a very important part in maintaining the temperature inside in a building. Due to the movement of sun, all of the external walls do not receive sunlight during all hours of a day. The eastern façade receives the morning sun, the south façade receives the mid-day sun and the western façade receives sun in the latter half of the day. However, the roof remains continuously exposed to the sun, regardless of the orientation of the building. The intensity of radiation received on the roofs is highest due to the sun exposure throughout the day. Therefore, it becomes important to treat the roofs so as to minimize the heat-gain due to this excess exposure to the sun throughout the day.
This heat gain through roofs in buildings has a huge impact on the occupant comfort. This effect is more is more significant in small scale & low rise buildings such as homes, apartments, commercial buildings etc. The heat gain through roofs in such specified building typology, contributes to 70% of the total heat gain for hot climates (agarwal & Sadevi, 2019).

The Bureau of Energy Efficiency had launched Energy Conservation Building Code, abbreviated as ECBC, to establish minimum energy performance standards for buildings in India. The code provides certain set of standards following which the building can be made energy efficient and become ECBC compliant building. The code specifies that the building's roof assembly should have low thermal transmittance that is U-value, to ensure minimal heat transfer. Another specification in ECBC states that roofs that are not covered by any renewable energy generating system such as solar photovoltaic panels or solar heaters etc. should be either cool roofs or green roofs (ECBC, 2017).

Types of Passive Strategies for Roofs-

Based on the classification of the passive strategies as shown in Figure 6, the passive strategies can be categorized based on the parameter it uses for serving its purpose that is either reducing the heat transfer or providing cooling effect. The passive cooling strategies for roofs are shown and listed as in Figure 8.

There can be three broad categories of methods that can be adopted for passive cooling applicable on roofs. The three methods are: Solar and Heat Control; Heat exchange Reduction; and Heat Removal. Solar and heat control method can be executed by preventing the surface of the roof from direct sunlight. This can be done by creating a barrier between the incident rays and the roof surface. Here, creating barriers s imply refers to shading of the surface. Also, the solar and heat control method can be incorporated with the help of green roofs. It means creating a microclimate by adding vegetative layer on roof. The second method is Heat Exchange Reduction, which can either be implemented through insulated roofs or through cool roofs. An insulated roof uses insulation materials which prevent transfer of heat and cool roofs use reflective material which reflects the radiations falling on it. The third method, Heat Removal, works by using natural cooling techniques like evaporative cooling. Roof ponds can be made on roofs for evaporative cooling and thereby removing heat.

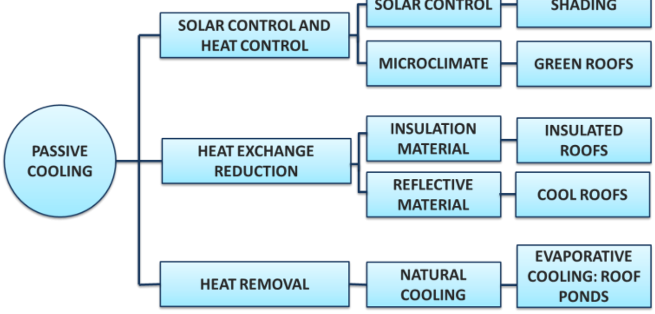


Figure 8 Categories of Passive Cooling Strategies through Roofs (author)

Therefore, the types of passive cooling roof strategies that we get based on the above discussed methods are as follows:
1. Roof Shading
2. Green Roofs
3. Insulated Roofs

4. Cool Roofs
5. Roof Ponds

1. Shaded Roof-

Shading of roof is an important method to reduce heat gain in buildings. Roofs shading can be done by providing roof cover of concrete, fiber sheets, canvas etc., and plants. The shading should not interrupt the cooling of the roofs during night. The shading provided using concrete cover or galvanized iron sheets are efficient in providing shade to the roofs but it hinders the escape of heat that is cooling of roofs at night (Kamal, 2011). Another system that is becoming popular is the solar photovoltaic panels. These solar photovoltaic panels are used to generate energy using the sunlight. Arrays of these panels can be installed on roofs. It not only provides shading but also generates clean energy.

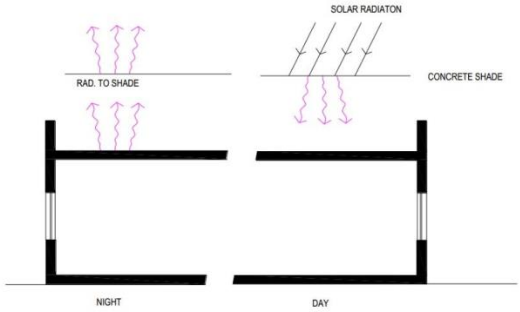


Figure 9 Shading using a Concrete Cover (Elborombaly & Prieto, 2015)

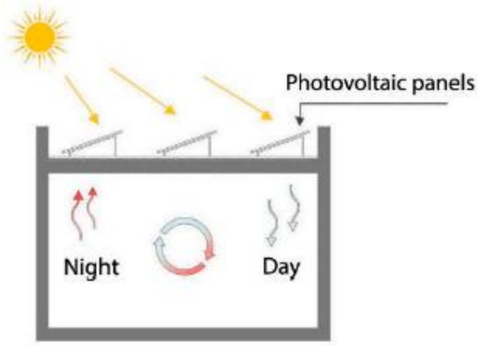


Figure 10 Roof Shading using Solar Photovoltaic Panels (Abuseif & Gou, 2018)

Provision of solar panels has a significant contribution in making a building net zero or nearly zeros energy building. Roofs are the best place for installing the solar panels due to maximum and consistent exposure to sun throughout the day. These panels are tilted at a certain angle, based on the latitude of the location, for better performance on the solar photovoltaic panels. The main function of solar panels is to generate electricity and usually the shading aspect is not the major reason for installing the solar photovoltaic panels. This can be an added benefit of shading using the solar photovoltaic system (agarwal & Sadevi, 2019).

Shading of roofs can also be done by the plant foliage either by keeping potted plants on roofs or by plantation on roofs. Shading using plants is beneficial as it is eco-friendly, and also does not hinder escape of heat during night. When plantation is done on roofs, using layer of soil and other various supporting mediums in subsequent layers, it is termed as green roofs.

2. Green Roof

Green roofs are a type of roof that has a layer of vegetation on top of it. They are also known as eco roof, planted roof or living roofs. Green roofs have gained its popularity because it minimizes the negative impact of buildings on the environment. Green roofs have a number of benefits such as passive cooling and energy-efficiency, enhanced air quality, reduced rainwater run-off, minimized heat-island effect and is aesthetic. It helps buildings to be more energy-efficient and reduce their carbon footprint.

Green roof is wise use of the roof space. It can be used in environmental, social and economic aspects. Green roofs can be installed on any building type and at any preferred height, if there is access for maintenance. These vegetated roofs provide shade that is it prevents the solar radiation to reach the surface below through the plant foliage and also prevents the heat radiation to reach the structure by providing insulation through the layer of soil. Apart from obstructing the heat, it also creates a cooling effect due to evaporation of water from the vegetative and soil layer. This is how green roofs help in reducing the heat flux through roofs leading to reduced cooling load and energy savings in buildings (Abuseif & Gou, 2018).

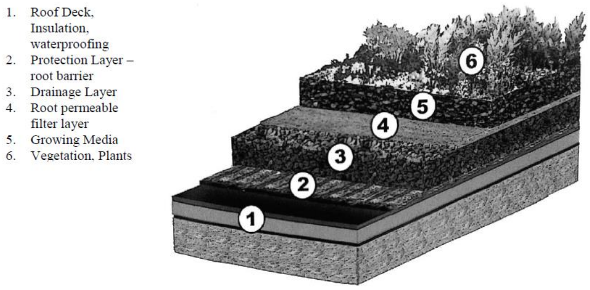


Figure 11 Layers of a Green Roof (Snodgrass & Mclntyre, 2010)

There are several components of a green roof from top to bottom layers as shown in Figure 11. Topmost layer is the vegetation layer, then growing medium known as substrate, followed by filter layer and drainage layer for moisture retention, further layer is the root barrier and the final layer just above the structural component is the waterproofing layer (Besir & Cuce, 2018). Green Roof can be sub-divided into three main categories: (i) Extensive, (ii) Semi-Intensive (iii) Intensive. These categories are differentiated based on the weight, type of plantation, substrate layer, maintenance etc. Extensive roofs are lighter as they have a shallower substrate layer. They are easier and more economical for maintenance. Intensive roofs are heavier and require high maintenance. Deeper growth substrates offer plenty of vegetation (Dobbelsteen, Raji, & Tenpierik, 2015).

Table 1 Comparative Overview of the Categories of Green Roof (Dobbelsteen, Raji, & Tenpierik, 2015)

	Extensive green roof	Semi intensive green roof	Intensive green roof
Maintenance	Low	Periodically	High
Irrigation	No	Periodically	Regularly
Plant communities	Moss-Sedum-Herbs and Grasses	Grass- Herbs and Shrubs	Lawn or Perennials, Shrubs and Trees
Cost	Low	Middle	High
Weight	60–150 kg/m^2	120–200 kg/m^2	180–500 kg/m^2
Use	Ecological protection layer	Designed green roof	Park like garden
System build- up height	60–200 mm	120–250 mm	150–400 mm underground garages ≥ 1000 mm

The planted roofs can be turned into multi-functional space for human delight and relaxation, especially in urban areas where pollution is remains at peak and insufficiency of green and open spaces.

A comparative study of various roof types conducted by Yang et al. in 2015 concluded that green roof performed better in hot climates as compared with other roofing methods in terms of thermal performance. As compared to exposed roof, the green roof was able to provide a better indoor temperature. There was a temperature difference of 0.9-1.0°C indoors in case of a green roof as compared to that of an exposed roof (Zingre, Yang, & Wan, 2015).

3. Insulated Roof

Insulated roof refers to the thermal insulation of roofs. Thermal insulation is a method to reduce transfer of heat from one medium to another. Layers of material that have good insulation properties are used over the structure component of the roof, so as to prevent transfer of heat. This creates a comfortable indoor environment. As it reduces the transfer of heat as shown in Figure 12, keeping the spaces comparatively more comfortable, it reduces the cooling load and thus saves energy.

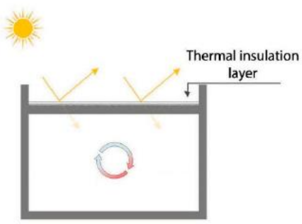


Figure 12 Thermal Insulation applied on a Rooftop (Abuseif & Gou, 2018)

There are a lot of insulation materials available for the roof. The selection of the insulation material can be made based on its thermal characteristics, material properties and ability to withstand load as per the requirement of space. Insulation types used in flat roofing systems should have not only high thermal characteristics but also sufficient mechanical properties to be able to withstand loads.

Insulation practices have been going on from ages for protection against the harsh sun and extreme weather. Insulation is a widely opted technique and even made mandatory in a lot of countries especially in colder regions to prevent heat loss. The insulation performance of materials depends on the materials thermal conductivity (k) and the thickness of the insulation layer provided (Abuseif & Gou, 2018). Gupta & Maji in "Encyclopedia of Renewable and Sustainable Materials", 2020 have defined thermal conductivity as: "the time rate of steady state heat flow through a body of per unit area (1sq. m) by inducing per unit (1K) thermal gradient in the perpendicular direction of isotropic substance". In simple words, thermal conductivity is the amount of heat that can be transferred through a unit cross-section of a material at a given pace via conduction.

There have been several studies comparing different types of insulation materials and their thermal performance. In a study conducted by Kumar and Suman, 2015, the R-value is studied for different materials. 'Dictionary of Energy', Second edition, 2105, states, "The term R-value stands for thermal resistance and is a measure of the level of resistance to heat flow a given material or an assembly can offer as a result of suppressing conduction, convection, and radiation."

The materials selected for the study were EPS (expanded polystyrene insulation), PUF (polyurethane foam), foam Concrete, fiberglass, styropor, peripor and neopor. The R-values were recorded for each material of the roof assembly. Higher the R-value better is the insulation property. The U-value which is thermal transmittance meaning the rate of heat transfer is also calculated. The values are shown in Table 2. The thickness of the layers of roof was taken as: 150mm RCC slab, 50mm mud-phuska, 50mm burnt clay brick tile and 50mm thick layer of insulation material. The values of other layers such as RCC, mud-phuska, brick tile are the same. The variation in the total U-value and R-value of the assembly calculated by Abuseif and Gou, 2018, is because of the different insulation material. Reduced heat flux (heat flow rate) percentages are also calculated.

It was observed that PUF (polyurethane foam) has highest reduction in the heat flux 79.480% and has the highest total R-value of 2.330 and lowest total U-value of 0.429. Also, it can be concluded that the materials with higher R-value and lower U-values offer better thermal insulation properties.

Table 2 R-value and corresponding Heat-Flux Reduction (Abuseif & Gou, 2018)

Insulation Materials	R-Value 1 Insulation Materials	R-Value 2 RCC	R-Value 3 Mud Phuska	R-Value 4 Brick Tile	R-Total with Insulation	R-Total without Insulation	U-Value Total with Insulation	U-Value Total without Insulation	Reduce in Heat Flux %
	Kumar and Suman, 2015				Abuseif and Gou,2018				
EPS (K = 0.035)	1.429	0.119	0.096	0.063	1.907	0.478	0.524	2.092	74.930
PUF (K = 0.027)	1.852	0.119	0.096	0.063	2.330	0.478	0.429	2.092	79.480
Foam concrete (K = 0.070)	0.714	0.119	0.096	0.063	1.192	0.478	0.839	2.092	59.910
Fiberglass (K = 0.040)	1.250	0.119	0.096	0.063	1.728	0.478	0.579	2.092	72.340
Styropor (K = 0.032)	1.558	0.119	0.096	0.063	2.036	0.478	0.491	2.092	76.520
Peripor (K = 0.028)	1.786	0.119	0.096	0.063	2.264	0.478	0.442	2.092	78.880
Neopor (K = 0.033)	1.511	0.119	0.096	0.063	1.989	0.478	0.503	2.092	75.960

4. Cool Roof

Cool roofs are most widely adopted method used to control heat gain n buildings. A cool roof simply uses highly reflective surfaces over the main roof structure to reflect back most of the sun radiation falling on it. These reflective materials can be light color paint, reflective paint, reflective tiles or shingles. These keep the buildings indoor environment 'cool' by reducing the absorbed heat and reflecting it back. The advantages of the cool roofs are that it reduces the energy demand, caters the heat-island effect, easy to install/apply and maintain (Rallapalli & Gupta, 2020).

The Figure 13 shows the basic principle of how cool roof works and helps in reducing the heat-gain in building and maintaining indoor temperature. It also shows a comparison between the conventional roof and the cool roof. The conventional roof absorbs most of the radiation falling on its surface. This would lead to temperature rise inside the building creating uncomfortable indoor environment. On the other hand, the cool roof has a high reflective index and thus reflects back the radiation falling on its surface.

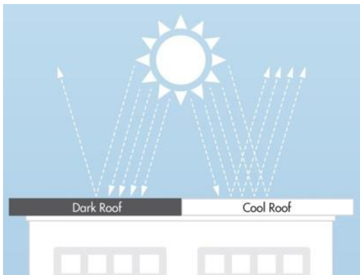


Figure 13 Conventional Roofs vs. Cool Roofs (Six Truths About Cool Roofs, 2021)

This roofing system for passive cooling is usually more popular in the hot climates like arid and tropical climates. This method is not feasible for cold weather as it blocks the heat gain and also is capable of preventing the heat loss from indoors. It can be worked out by combining it with thermal insulation. The heat flux can be reduced around 33% using the cool roof strategy. As compared with roofs shaded with solar photovoltaic panels and with green roof, a cool roof provides a comparatively lower temperature at surface. This low surface temperature makes the night cooling easier (Abuseif & Gou, 2018).

The Energy Conservation Building Code, abbreviated as ECBC, states that the roofs without provision of solar panels or any other form of clean energy generation should be either green or cool roofs (ECBC, 2017). There are also several initiatives taken by the Indian government for adopting and promoting the cool roofs. Some of the initiatives are: "The Telangana Cool Roofs Program", "City-level cool roof initiatives by Indore and Surat", "Ahmedabad cool roofs initiative: Addressing cool roofs as a response to extreme heat, 2017 and 2018" and "Cool roofs initiatives in Delhi" (Rallapalli & Gupta, 2020).

5. Roof Pond

Roof pond is a passive strategy based on the concept of evaporative cooling. The main component of the roof pond is water. When the surface of the water gets heated, it starts evaporating which leads to cooling. This is an age old technique and be seen in Mughal architecture in India (Abuseif & Gou, 2018).

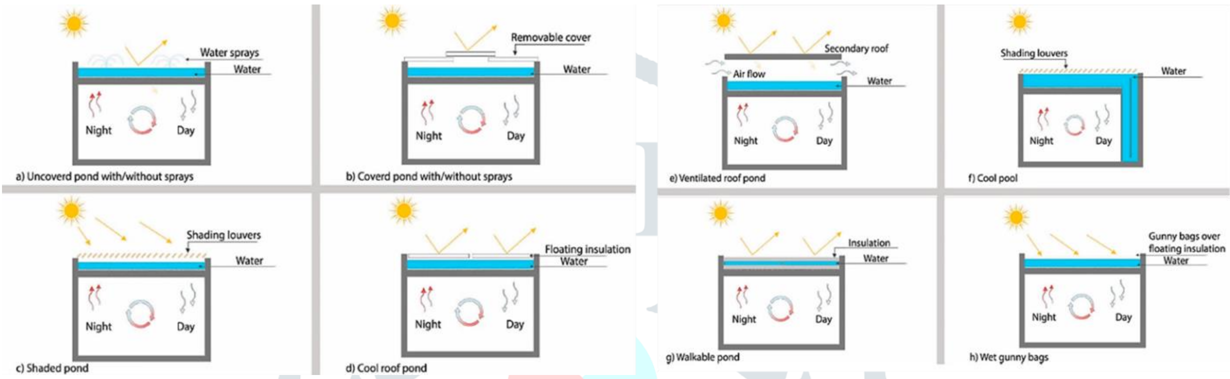


Figure 14 Different Types of Roof Pond (Abuseif & Gou, 2018)

Such water-filled ponds when installed on roofs provide benefits both by "indirect evaporative cooling" and/or "radiant cooling". Roof ponds acts as a heat exchange medium in both processes. It also works as a heat sink and absorbs the indoor heat and the heat from the sun. The ceiling of the roof that is the inner surface of roof also gets cooled because of the roof pond through radiation and convection (Ayyoob & Yamagata, 2015).

There are different ways in which roof ponds can be installed depending on the requirements of the user as shown in Figure 14. It does not increase the humidity indoors as it just provides a heat exchange medium and behaves as a protective blanket on the roof surface.

Literature Case study (Experimental) –

This experimental case study aims at comparative study of cool roof, green roof and insulated roof in a single-storey building located in Singapore.

Location: Nan yang Technological University, Singapore
Climate Type: Tropical Climate
Building Rise: Single storey
Roof Area: 40 sq. m
About the study:

A single story building was selected for study in the Nanyang Technological University in Singapore for the performance analysis of the different types of roofs. The building was selected so as to create a reference for the simulation model. The analysis was done using simulation. The simulations were done to establish better performing roof type and the maximum heat gain reduction offered. This study has been carried out by Zingre, Yang and Wan in 2015 for their research titles as "Performance Analysis of Cool Roof, Green Roof and Thermal Insulation on a Concrete Flat Roof in Tropical Climate".

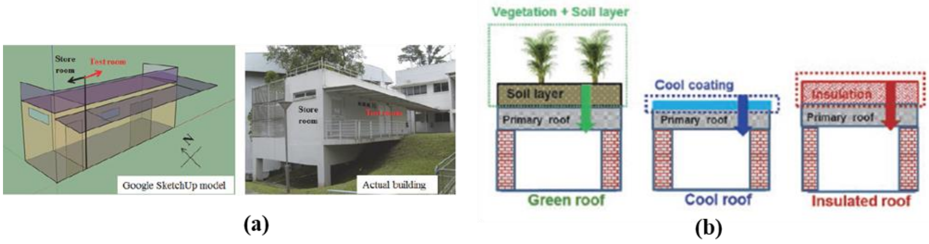


Figure 15 (a)SketchUp Model and the actual Test building, (b) Basic diagram for Representation of the Simulation Model Types (Zingre, Yang, & Wan, 2015)

The building consists of 2 rooms: a store room and the test room. The slab of the building is made up to 100mm thick concrete and 10mm plaster on the ceiling. The store is unoccupied and the floor is in contact with air. The test room is air conditioned and the floor is in contact with the grass. For simulation purposes, the test room is assumed adiabatic with no contact to outdoor conditions. Ground temperature is taken 27ºC. The results of the simulations are only for the test room and not the store room. The simulations are done for three different cases that are for green roof, cool roof and insulated roof. A basic diagram representing the three types of roof and the test room are shown in Figure 15. The base case that is the actual built space has a conventional concrete roof which is used for comparison in the study.

Table 3 Properties of simulated (a)green roof, (b)cool roof and (c)insulated roof (Zingre, Yang, & Wan, 2015)

Parameter	Value
Height of plant	0.15 m
Leaf area index	1.2
Leaf solar reflectance	0.10
Leaf thermal emittance	0.86
Minimum stomatal resistance	120 s/m
Max volumetric moisture content of soil	0.32
Min volumetric moisture content of soil	0.01
Initial volumetric moisture content of soil	0.15
Density of soil	960 kg/m^3
Specific heat of soil	1500 J/kg-K
Thermal conductivity of soil	0.4 W/m-K
Soil layer thickness	0.1 m

(a)

Building material	Thermal conductivity (W/m-K)	Thickness (mm)	Density (kg/m^3)	Specific heat (J/kg-K)
Air[e+]	0.03	-	1.23	1008
Concrete[e+]	0.65	100[a]	2450	840
Cool coating[a]	0.05[a]	0.5[a]	1053[a]	**
Glazing[e+]	0.70	3.5[a]	-	-
Plastered concrete block[e+]	1.10	125[a]	800	920
Plaster[e+]	0.25	10[a]	850	1000
Wood[e+]	0.15	50[a]	608	1630

[a] Thermo-physical properties are obtained from the manufacturers.

(b)

Properties	Value
Thermal conductivity	0.03 W/m-K
Thickness	0.05 m
Density	24 kg/m^3
Specific heat	1590 J/kg-K
Roughness	Medium

(c)

Table 4 Results of Simulation (author)

Roof Type	Annual Heat-gain Reduction
New Cool Roof	89% - 90%
Aged Cool Roof	59%-63%
Green Roof	32%-41%
Insulated Roof	62%-72%

The green roof is simulated using the EnergyPlus software. It considers the evapotranspiration of the vegetative layer and evaporation from the soil layer, soil properties and heat exchanges through convection and radiation. For the cool roof a 5mm thick cool roof coating has been modeled in EnergyPlus. The solar reflectance of the material is 0.74 and thermal emittance of 0.90. The material chosen for the insulted roof is EPS (extruded polystyrene insulation). The thickness of insulation is considered 0.05m. The properties of all the roof types and materials are given in Table 3.

The simulations were based on the modeling of a single storey air-conditioned structure in tropical climate which remains warn throughout the year. The thermal performance of all three types of roofs is compared based on the simulation results. The performance is measured by the annual heat gain reduction. The results are shown in the Table 4. The study concludes that the annual net heat gain reduction by cool roof is highest amongst the three techniques applied. It can be concluded that for tropical type of climate cool roofs can be the best possible strategy to reduce the heat gain in such scale of buildings (Zingre, Yang, & Wan, 2015).

III. DATA ANALYSIS

This section aims at reaching to the conclusion of the study. The studied techniques are first analyzed on the basis of literature for application on the selected building typology that is commercial buildings. The techniques that seem reasonable for commercial buildings are simulated for further results. The simulation results shall be analyzed to see the effectiveness of these techniques.

Review of Studied Passive Techniques-

The types of roofs studied are as follows: Roof Shading, Green Roofs, Insulted Roofs, Cool Roofs and Roof Ponds. All of these techniques help in passive cooling. Based on the literature study, each of the discussed technique is not practicable for application in commercial building. A commercial building hosts profit intended ventures of one or different types of activities under the same roof. The floor spaces are divided and can be owned by one or more buyers. In such small to medium scale commercial complexes, the maintenance of the roofs without generating any monetary profit from it can be an issue. This study aims at finding passive cooling strategies applicable on roofs of commercial buildings only. Therefore, the studied strategies will be further reviewed with respect to application on commercial buildings.

Roof Shading- Shading is the simplest technique that can be used for lowering the surface temperature. Shading the roofs can be done by various materials. Materials with greater thermal mass such as concrete and iron sheets are not reasonable for use as it radiates its own stored heat during night and hinders the cooling down of roof at night. (Kamal, 2011) As discussed earlier, solar photovoltaic panels if feasible can be a great option for shading as it would also generate clean energy. Some lightweight fiber sheets can be used for shading of roofs. These are economical, easy to install and barely need any maintenance.

Green Roof- Green roofs are an ecological solution for lowering the roof temperatures and thereby maintaining comfortable indoor temperatures. There are two main types of green roofs: extensive and intensive. The intensive green roofs are heavily planted and require high maintenance whereas extensive green roofs are basically simple grass cover over soil layer and require low maintenance (Dobbelsteen, Raji, & Tenpierik, 2015). Plantation on roofs helps in lowering the temperature of the surroundings by around 5 degrees (Maleki, 2011). The commercial buildings where the roofs can be provided with some revenue or profit based activity such as an open air cafeteria or some other activity, then maintenance would not be an issue and the roofs can be treated by plantation. Providing a green roof also requires structural calculations and alterations.
Therefore, as a generalized solution for commercial building green roof cannot be implemented on all types of commercial buildings. Apart from this, there already has been intensive research on the subject and due to the time and resource constraints, green roof is not further taken up for the comparative analysis.

Insulated Roof- There are a lot of materials available for insulation of roofs such as EPS (expanded polystyrene insulation), PUF (polyurethane foam), foam Concrete, fiberglass, styropor etc. It works by preventing the transfer of heat from one surface or medium to another. Insulation materials have high R-value and low U-value. Based on this, the study conducted by Yang, Zingre and Wan, 2015, showed that usage of PUF (polyurethane foam) resulted in 79.48% reduction in heat flux which was the maximum compared to other materials that were EPS (expanded polystyrene insulation), foam concrete, fiberglass, styropor, peripor and neopor (Abuseif & Gou, 2018). Insulation of roofs is an easy process and can be applied in commercial buildings. For further study and simulation, PUF (polyurethane foam) insulation will be used.

Cool Roof- Cool roofs are most widely used technique to keep the roofs of buildings 'cool'. From simplest method of painting the roof in a light color to application of reflective tiles with high solar reflective index, everything is categorized as cool roof. Cool roof is an effective method and is also promoted by the government through various programs. It is easy to be installed and barely requires any maintenance. A research conducted by Rawat and Singh, 2020, concluded that cool roofs can reduce the indoor room temperature by 2.4ºC (Rawat M, 2020). Thus, cool roof being an effective and low maintenance technique is applicable for mid-rise commercial buildings and will be further studied through simulation.

Roof Pond- Roof ponds require water for working. The amount of water will depend on the area of the roof and the depth of the pond. This system is although efficient in lowering the indoor temperature but requires skillful construction. As the pond has stagnant water, there is also a need of cleaning and maintenance and replacing of the volume of water at regular time intervals. Water being an important resource should be used wisely. This is an ancient technique that was used to create a comfortable indoor temperature and micro-climate. It was widely used at the time when technology and invention of heat-resistant materials had not happened. There are options of sustainably using the water such as use of conserved rain-water or use of recycled water. This will require additional structures for storage and techniques for recycling. If the water is thoughtfully used in a sustainable way, it can be considered for application. We can conclude that roof pond technique requires consistent maintenance and also uses water which is a valuable resource. Therefore, the places where maintenance and water shortage is not an issue can be provided with the roof pond systems. Due to this roof pond is not considered for further study and simulations.

The techniques that can be further studied via simulation for application in a mid-rise commercial building in composite climate based on the discussions above are Shading, Insulated Roofs and Cool Roofs.

Analysis through Simulation-

The following assumptions/considerations are taken into account for carrying on with the further study:

- The simulations will be done using Design Builder Software.
- Simulation is carried out to only find the reduction in heat-gain through roof.

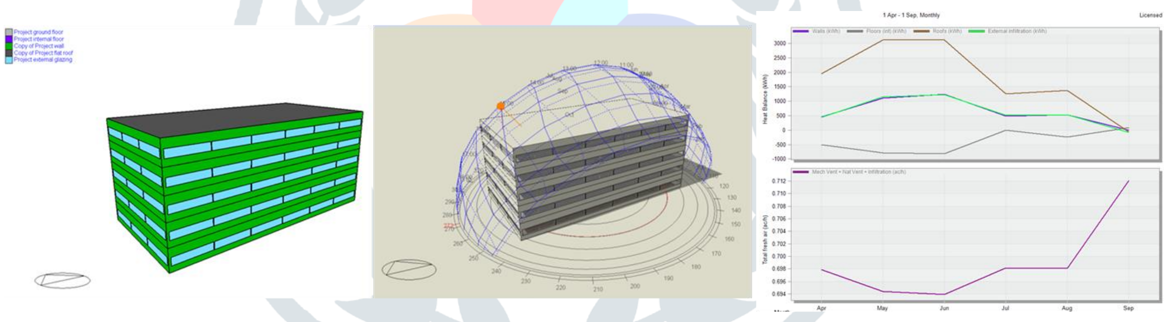
- There are a total of four cases to be simulated for the study: (i) Base Case, (ii) Shaded Roof (iii) Insulated Roof and (iv) Cool Roof.
- The parameter/outcome that will be compared and analyzed for the simulated models will be internal heat gain through roof.
- The base case or the building to be simulated is a commercial office building. The building is mid-rise, G+ 4 storeys high.
- The dimensions of the building are 20m X 40m.
- The location for the building is considered in Lucknow, Uttar Pradesh, India. The city falls into composite climate zone of India.
- The simulations are carried out for the summer months of 1st April to 1st September, which are the peak summer months in composite climate.

The models will be simulated to obtain the comfort temperatures. The value that is considered in the simulation is the internal gains value. Internal heat gain through roof is recorded for all the cases after simulation. The internal heat gain value is obtained through the fabrics and ventilation option present in the simulation tab of design builder. This simply gives the sum of the entire heat gained into the selected zone or space of the building through the building envelope or the exterior surfaces. The values are in kilowatt hour (kWh) that is amount of heat energy in kilowatt that can enter the building through a surface in an hour. As this study is intended towards the study of minimizing heat-gain through roofs the values of heat-gain through roofs only shall be recorded and compared to come to a conclusion.

1. Case 01- Base Case

Commercial buildings usually have an open floor space plan which is partitioned according to the needs of the investors. Therefore for the simulations a building block is being considered with no partitions.
A 20m x 40m building block with a total height of 17.5m is taken up for the simulations. The walls are 230mm thick brick wall with 20mm cement mortar plaster on each side. The roof slab consists of 150mm concrete slab with thermal conductivity of 0.16W/m-K and 30mm cement mortar plaster on the outside and 20mm thick gypsum plaster on the inward side. The window to wall ratio is 30%. For next cases, each of the above specification will be kept the same. Only the roof layers will be modified for simulations. The building model showing all components, one view with solar chart and the result of internal heat-gain simulation chart are shown in Figure 16.

The results of the simulation for the internal heat gain through roof for the entire run period in the case of conventional concrete roof was found to be 10750.77 kWh.

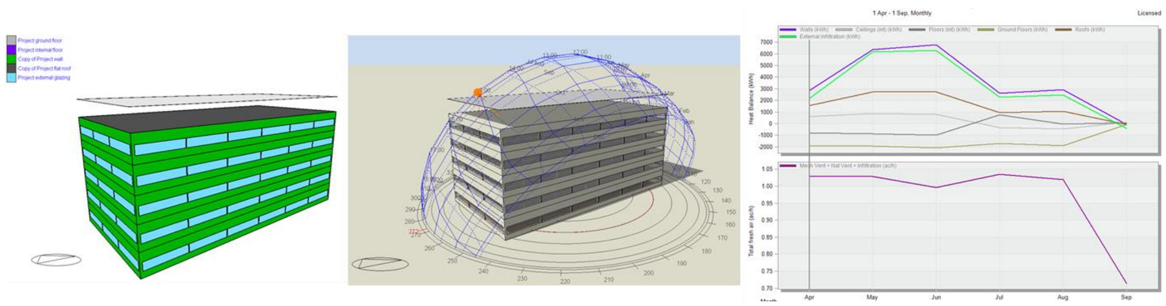


(a) (b)

Figure 16 Base Case: (a) Model View (b) Internal Gains Chart (author)

2. Case 02- Shaded Roof

For shaded roof model, all other values have been taken the same as the base case of a conventional concrete slab, just the roof has been provided with a cover or shade. To provide roof shade, polycarbonate sheet 2mm thick having thermal conductivity of 0.2W/m-K is provided over the roof at 2.8m height. The building model for shaded roof showing all components, one view with solar chart and the result of internal heat-gain simulation chart are shown in Figure 17. The results of the simulation for the internal heat gain through roof for the entire run period in the case of shaded roof was found to be 8940.32 kWh.

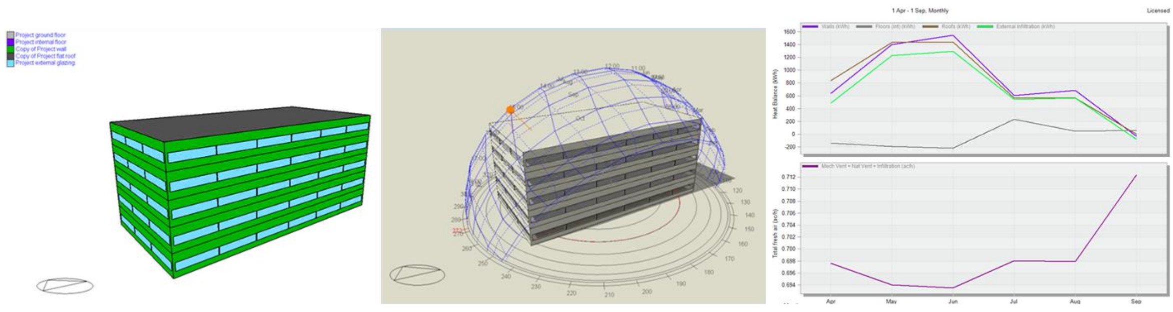


(a) (b)

Figure 17 Shaded Roof: (a) Model View (b) Internal Gains Chart (author)

3. Case 03- Insulated Roof

All values for modeling have been taken the same as the base case of a conventional concrete slab; just the roof has been modified to insulated roof. For this an insulation layer has been added using PUF (Polyurethane Foam) of thickness 50mm having thermal conductivity of 0.028W/m-K. The building model for insulated roof showing all components, one view with solar chart and the result of internal heat-gain simulation chart are shown in Figure 18. The results of the simulation for the internal heat gain through roof for the entire run period in the case of insulated roof was found to be 4834.81 kWh.

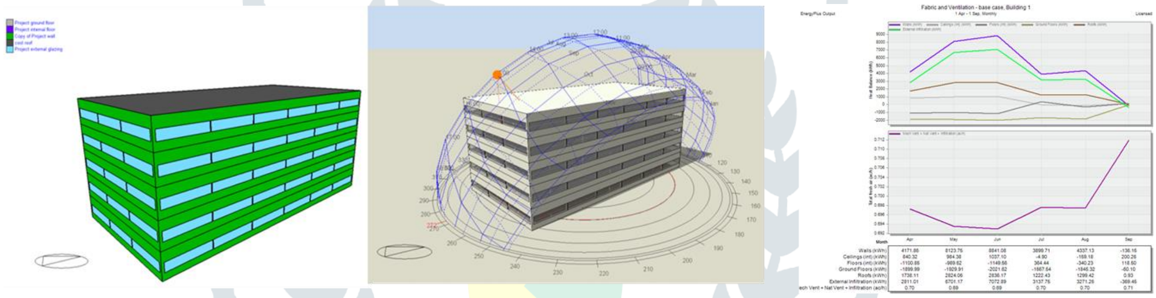


(a) (b)

Figure 18 Insulated Roof: (a) Model View (b) Internal Gains Chart (author)

4. Case 04- Cool Roof

For cool roof model, all other values have been taken the same as the base case of a conventional concrete slab; just the roof has been modified to cool roof. For this an additional layer of ceramic tiles of 10mm thickness is added on the exterior surface of roof with thermal conductivity of 0.5 W/m-K and solar reflective index of 0.4. The building model for cool roof showing all components, one view with solar chart and the result of internal heat-gain simulation chart are shown in Figure 16. The results of the simulation for the internal heat gain through roof for the entire run period in the case of cool roof was found to be 9921.12 kWh.



(a) (b)

Figure 19 Cool Roof: (a) Model View (b) Internal Gains Chart (author)

IV. Conclusion and Recommendation

This section consists of the results of the simulation and conclusions based on it.

Comparative Analysis of Simulations-

The output of simulation through EnergyPlus using the Design Builder software is given in Table 5.

Table 5 Internal Gains obtained from Simulations (author)

S.No.	Roof type	Description	April	May	June	July	August	September	Total Heat Gain (KWh)	Difference (KWh)	% Reduction in heat transfer
1	Base Case	conventional concrete roof	1944.85	3118.97	3109.74	1260.7	1374.36	-57.85	10750.77	–	–
2	Shaded Roof	shading at 2.8m from roof using 2mm thick polycarbonate sheet	1563.62	2745.71	2737.62	925.8	1042.24	-74.67	8940.32	1810.45	16.84
3	Insulated Roof	50mm thick PUF insulation	833.51	1430.06	1438.26	566.34	564.23	3.41	4835.81	5914.96	55
4	Cool Roof	10mm thick ceramic tiles	1738.11	2824.06	2836.17	1222.43	1299.42	0.93	9921.12	829.65	7.71

Based on the above results, the technique which is most effective in minimizing the heat-gain and hence lowering the indoor air temperature is the insulation of roof using the PUF insulation. The percentage reduction in heat gain as compared to the conventional base case of concrete roof, using the PUF (Polyurethane Foam) insulation was found to 55%. This is a huge reduction stating the effectiveness of the applied technique.

The next case which was found to be effective was the shaded roof. Here, the shading was done using polycarbonate sheet. The percentage reduction in heat gain in this case as compared to the conventional base case of concrete roof, was found to be 16.84%. Shading using such light-weight sheets is easy to install and economic.

The cool roof case was found to be least effective in the given circumstances. The reduction in heat gain in this case as compared to the conventional base case of concrete roof, was found to be 7.71%. This is also a good amount of reduction in the heat-gain but comparatively is not as effective as the other available options.

The aim of the study was to study heat-gain reduction through roofs, comparing the different types of strategies that can be used for a commercial building in composite climate which has been fulfilled deriving from a comparative analysis. The reduction in the heat-gain in each case will result in reduction of cooling load leading to energy and monetary savings.

If the techniques are applied to roof only, and the remaining building envelope is not treated, then the results might not overall be as effective. For better results the whole building envelope must be optimized. Also combination of these techniques can be applied for better results. Further research in future can be done on combining two or more strategies together for better thermal performance of roofs.

As this study was meant to focus on roofs only, no treatment was provided to the external walls and openings which if also optimized in future researches, can help in obtaining much better results. Thus, the study opens the opportunity for further research in the subject by using combinations of two more techniques on roofs or by optimizing other components like walls, openings etc. along with roofs.

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