Energy Evaluation of Daylighting Systems of Buildings

Thesis Submitted by

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I, Biswajit Biswas registered on 23-05-2018 do hereby declare that this thesis entitled **"Energy Evaluation of Daylighting Systems of Buildings"** contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

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CERTIFICATE FROM THE SUPERVISOR/S

This is to certify that the thesis entitled **"Energy Evaluation of Daylighting Systems of Buildings"** submitted by Mr. Biswajit Biswas, who got his name registered on 23-05-2018 for the award of Ph.D (Engg.) degree of Jadavpur University is absolutely based upon his/her own work under the supervision of Prof. Biswanath Roy and that neither his/her thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

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(Biswajit Biswas)

Abstract

India is one of the fastest growing economies in the world. Energy consumption in India has become more than double since 2000 due to population growth and economic development. Energy is closely related to the growth of human civilization in all over the world. Energy is required in every aspect of modern day to day life. Fossil fuels are the main source of energy in India. Among the fossil fuels, coal is the largest source in the energy mix. Significant amount of emissions come from the combustion of fossil fuels. India is globally third largest emitter of CO_2.

Residential and commercial building sector in India accounts for 32% of the total electricity consumption. It is predicted that electricity demand expected to increase from 421 TWh in 2022 to 2,421 TWh by 2047. The building sector in India consumed 13% of total energy consumption in 2023-24 and the energy consumption is expected to increase at 5% each year. Total commercial building floor area in India in 2017 was estimated to be 1.1 billion m^2 and predicted to reach an estimated 1.78 billion m^2 by 2027. Commercial building sector is expanding at over 9% per year due to economic growth in India. It has been estimated that more than 50% of building floor area that will exist in the year 2030 is yet to be built. So, there is immense scope of energy conservation with the adoption of energy efficiency measures in building sector in India.

Daylighting is an important strategy in modern building architecture to replace artificial lighting to reduction of the building energy consumption and better visual comfort. In the present study clear glass window combinations are considered as daylighting systems in buildings. Energy performance of buildings with eleven different window combinations, five different WWR has been investigated in three different locations in India.

The result of this study quantify the energy savings opportunity in commercial buildings through the parametric study of WWR, distribution of glazed surface and slat angle along with control of artificial lighting of the buildings according to available daylight inside the building working space. Energy savings in the building from this strategy is used to quantify long term energy savings, economic benefits and capacity avoid due to potential daylight integration in Indian commercial buildings.

Contents

Page No.

List of Figures **Page No.**

List of tables **Page No.**

Abbreviations

BES	Building Energy Simulation
ACH	Air changes per hour
BEE	Bureau Of Energy Efficiency
BES	Building Energy Simulation
BU	Billion Units
CEA	Central Electricity Authority
DST	Department of Science and Technology
ECBC	Energy Conservation Building Codes
ECO-II	Energy Conservation and Commercialization Project
EW	East West combination
EWN	East West North combination
EWS	East West South combination
GDP	Gross Domestic Product
GHG	Green House Gases
GoI	Government of India
HVAC	Heating Ventilation and Air conditioning
IEA	International Energy Agency
INR	Indian Rupee
MNRE	Ministry of New and Renewable Energy
MoP	Ministry of Power
NBC	National Building Code
NDC	Nationally Determined Contributions
NE	North East combination
NS	North South combination
NSE	North South East combination
NSEW	North South East West combination
NSW	North South West combination
NW	North West combination
NZE	Net Zero Emissions
RCC	Reinforced Cement Concrete
SE	South East combination
SHGC	Solar Heat Gain Coefficient, %
SW	South West combination
USA	United States of America
USAID	United States Agency for International Development
UV	Ultra violet
VT	Visible transmittance, %
WFR	Window-to-Floor Ratio, %
WWR	Window-to-Wall Ratio, %

Symbols

A	Area of glass, m^2
A_i	Anisotropic index for sky
d	Separation between slats, cm
D_λ	Relative spectral distribution of illuminant D_{65}
h_0	Heat transfer coefficient of outer surface of the glass, W/m^2 K
h_i	Heat transfer coefficient of inner surface of the glass, W/m^2 K
I_b	Total beam radiation on a surface, W/m^2
I_d	Total diffuse radiation on a surface, W/m^2
I_T	Total radiation on a tilted surface, W/m^2
R_b	Tilt factor for beam solar radiation
R_d	Tilt factor for diffuse solar radiation
T_0	Outdoor temperature, ^0C
T_i	Indoor temperature
U-value	Overall heat transfer coefficient, W/m^2 K
$V(\lambda)$	Spectral luminous efficiency for photopic vision
w	Slat width, cm
τ_b	Transmittance for beam solar radiation
α_b	Absorbance for beam solar radiation
α_a	Altitude angle of sun, degrees
β	Tilt angle of the surface, degres
$\beta_{cut-off}$	Cut-off angle of the slat, degrees
δ	Declination angle of earth, degrees
θ	Angle of incidence of beam solar radiation, degrees
θ_z	Zenith angle , degrees
$\tau(\lambda)$	Spectral transmittance of the glazing
τ	Transmittance of glass
τ_λ	Optical transmittance of glass
ρ_g	Ground reflectance for solar radiation
γ	Azimuth angle of surface, degrees
γ_s	Solar azimuth angle, degrees
Φ	Latitude, degrees
ω	Hour angle, degrees
Ω	Solar profile angle, degrees
$\Delta\lambda$	Wavelength interval

1. Introduction

1.1 Background and motivation

Energy is closely related to the growth of human civilization in all over the world. Energy is required in every aspect of modern day to day life. In ancient age people used their muscle power to meet their energy requirement for agriculture, transportation etc. In modern days gradually the scenario changed with the application of science and technology. Different types of machines have been invented to reduce the effort of doing work. These machines need primary or secondary energy for functioning.

With industrial revolution, life style of the people has changed drastically. Automation technologies have been involved in different sectors of society and need of energy has become a primary requirement in modern day life. The demand of energy in primary and secondary form has increased drastically and increasing every year. In present days, electricity is the most convenient form of energy in all sectors of development. Hence combustion of fossil fuel has increased many times to meet the increasing electricity demand. The use of fossil fuels emit lot of greenhouse gases (GHG) causing global environmental damage. Moreover the reserve of fossil fuels is depleting very fast and the human society is at door of future energy crisis.

Generation of energy from renewable sources are increasing to meet the ever increasing demand of energy. Renewable sources are less harmful to environment but it has many limitations. Renewable sources are intermittent in nature and need proper storage system. A suitable solution to the energy crisis is demand side management of energy and energy efficiency. The transition towards new and cleaner energy sources is very much important to developing county like India. India is increasing the use of renewable and cleaner energy sources like solar, wind, biomass, green hydrogen etc towards the energy mix to reduce emissions to achieve committed sustainable development and climate action. It is reported that the energy efficiency schemes of Bureau Of Energy Efficiency (BEE) has saved 6% of total primary energy consumption during the year 2023-24 which is equivalent to 53.60 Mtoe which includes 321.39 billion units (BU) of electricity. The savings of energy due to implementation of energy efficiency measures saved INR 200,212.84 crores during the period (BEE, 2024). In present study, opportunity of energy savings in buildings with the application of daylighting is initiated and the findings of the study is used to predict long term benefits of daylighting in commercial building sector in India.

1.2 World energy scenario

Fossil fuels meet most of the present energy requirement of the world. Generation of energy from fossil fuels is not a sustainable option as the reserves of fossil fuels are depleting very fast. Moreover, fossil fuels cause huge amount of emissions of green house gases (GHG) during the process of energy conversion. These green house gases are severe to the environment as it causes global warming. Despite lot of actions taken, global consumption of primary energy is increasing annually by almost 2% for the last ten years **(BP statistical review, 2017)**. Energy consumption in building sector is increasing very fast due to rapid urbanization and economic growth. Buildings consume almost 151 EJ of the world's final energy consumption. Operation of buildings is almost responsible for 30% of the global energy consumption **(United Nations Environment Programme, 2020).** Building floor area is increasing rapidly with the growth of population which in turn increase energy consumption in building sector. IEA reported that energy demand of the building sector increased around 20% between 2000 and 2017 **(IEA, 2019).** Improvement in energy efficiency is essential in building sector to decrease global building energy consumption. It is found that the investment in energy efficiency is only $1 for $37 investment in the conventional construction **(IEA, 2021).**

1.3 Energy scenario in India

India is one of the fastest growing economies in the world. Energy consumption in India has become more than double since 2000 due to population growth and economic development. Previous researches show that the primary energy demand in India has grown from about 450 mtoe in 2000 to about 770 mtoe in 2015 and the same is to increase to about 1250 - 1500 mtoe in 2030 **(Sahoo et al., 2016).** It is predicted that generation of electricity in India in 2050 expected to increase eight fold compared to 2005. Total energy production would be more than104EJ in 2050 and 230EJ in 2095 **(Shukla and Chaturvedi, 2013**).

Over 900 million people in India have gained access to electrical connection in less than two decades. Fossil fuels are the main source of energy in India. More than 80% of energy in India comes from fossil fuels. Among the fossil fuels, coal is the largest source in the energy mix. Significant amount of emissions come from the combustion of fossil fuels. India is globally third largest emitter of CO_2. Carbon intensity of Indian power sector is significantly higher than global average and the emission of particulate matter is a major cause of air pollution, which is one most sensitive social and environmental issue in India **(Energy in India today, 2021).**

It is estimated that 270 million people are likely to be added to urban population in India by 2040. Due to the large increase in urban population, building floor space will increase proportionally which will cause large demand of building energy. Building floor space that will exist in 2040, have yet to be built and hence there exist considerable scope of application of Energy Conservation Building Codes (ECBC) as well as other innovative strategies to conserve building energy **(India Energy Outlook, 2021).** India is the third largest producer of electricity in the world. Present installed capacity in India is more than 470GW **(Nity Ayog, 2025)**. Source wise installed capacity in India is shown in figure 1.1. It is found that coal fired power plants contribute 47% of the total installed capacity in India which is significantly less that the contribution in the year 2016-17 which was 59% of total installed capacity. This decline is due to effort to shift away from fossil fuels to renewable energy sources. This growth of renewable energy emphasise the dedication of our country to Nationally Determined Contributions (NDC) target of achieving 50% non-fossil fuel capacity by 2030.

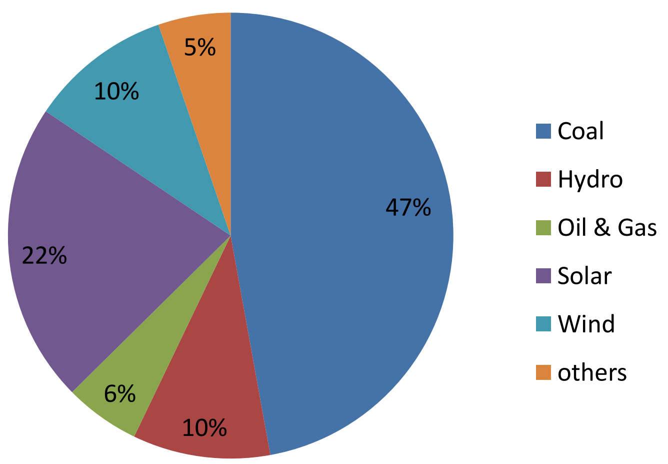

Figure 1.1: Energy generation by source in India.

1.4 Building energy

Residential and commercial building sector in India accounts for 32% of the total electricity consumption. It is predicted that electricity demand expected to increase from 421 TWh in 2022 to 2,421 TWh by 2047 (IESS, 2023). The building sector in India consumed 13% of total energy consumption in 2023-24 and the energy consumption is expected to increase at 5% each year. Total commercial building floor area in India in 2017 was estimated to be 1.1 billion m^2 and predicted to reach an estimated 1.78 billion m^2 by 2027 **(Kumar et al., 2018).** Commercial building sector is expanding at over 9% per year due to economic growth in India. It has been estimated that more than 50% of building floor area that will exist in the year 2030 is yet to be built. So, there is immense scope of energy conservation with the adoption of energy efficiency measures. Star rating program is an initiative to incorporate energy efficient measures in building. Star rating of buildings are rated on a 1-5 scale based on the annual energy consumption per unit floor area where 5-star labelled buildings are the most energy efficient building.

Main electricity consumption of building is due to lighting, cooling and heating. A significant portion of building energy consumption accounts for space cooling. Growth in buildings floor space in the country along with extreme climate pattern is expected to increase cooling energy demand in India. It is observed that 57% of cooling energy demand in India is due to buildings (Kumar et al., 2018). Cooling energy consumption accounts for 7% of global GHG emissions which is expected to double by 2050. India was responsible for 8% of global emission due to space cooling in 2016 and the same is predicted to rise at 30% in 2050 (IEA, 2018). The World Population Review indicates that India has become the highest populated country in the world. Growing population, rapid urbanisation and commercial development needs much energy requirement. At the same time it is essential to achieve climate goals for sustainable development. Hence, the building sector in fast developing and populated country like India emerges as a critical area for intervention.

1.5 Need of daylighting in building

Daylighting is an important strategy in modern architecture to replace artificial lighting to reduction of the building energy consumption and better visual comfort **(Apian et al. 1998; Chen et al., 2014).** Building energy simulation tools help to estimate the potential daylight integration through windows for optimum energy performance of building **(Loutzenhiser et al., 2007).** Suitable control strategies during the design stage as well as after the building construction are required for energy efficient utilization of daylighting in buildings **(Ghadi et al, 2017)**. Optimum use of daylighting into office building can reduce lighting, heating and cooling energy consumption **(Anna et al., 2017).** Mohsan et al. studied on energy performance of building in view of daylighting in scale model as well as in computer simulation **(Mohsenin et al, 2015)** .Motamedi et al. mentioned the optimization of daylight in building and provide guideline to building designers to select proper daylighting device (**Motamedi et al, 2017).** Many more research work have been found on the effective daylighting in building **(Gene et al, 2017; Antonis et al, 2017; Lidia Badarnah, 2016)**

1.6 Objectives

The objective of this study is to quantify the potential of energy savings in commercial buildings through the parametric study of WWR, distribution of glazed surface and slat angle along with control of artificial lighting of the buildings. Energy savings in the building from this strategy is used to quantify long term energy savings, economic benefits and capacity avoid due to potential daylight integration in Indian commercial buildings.

1.7 Unique contributions

A number of studies related to energy efficient operation of buildings are conducted by the researchers. In most of the cases potential of energy conservation in building was studied. The area of study was focused on building thermal mass, building envelope, cool roof and green roof technology, glazing materials, vacuum glazing, double glazing, daylighting, window to wall ratio, window to floor ratio, aspect ratio, orientation, climate condition and many more. All the study contributed valuable findings and identified energy savings potential in building sector.

Unique contribution in the field of building energy is found in a number of recent studies. Passive solar design to integrate daylight into the building is one of them to conserve energy. Adaption of building energy codes to find energy benefits in nationwide is another valuable contribution to Indian building sectors **(Yu et al., 2017).** In the present study main focus is given towards daylighting and energy performance of the window glazing system of the building in tropical climate condition. Performance of different window glazing system in Indian climate conditions signifies the role of window glazing in building envelope in view of energy conservation (Singh et al, 2009; Kumar et al., Oct, 2018). Role of window glazing in other part of the world also reflected from many research works. Apart from the window glazing material, area of window and orientation in building envelope are the key parameters for daylighting and energy efficient building design **(Andrea et al, 2011; Siu et al, 2017).** Daylight is a potential supplement of artificial light in buildings which results energy savings in building **(Gene et al, 2017; Li et al, 2005; Lidia Badarnah, 2016).** Rapid growth in building floor space in India is predicted in the coming years and demand of energy is likely to increase many fold **(Kumar et al, 2018; AEEE, 2018).** Energy savings in the buildings due to application of proper daylight strategy is an important metric to predict future energy savings, economic benefits and capacity avoid in India.

1.8 Prospective application potential

Energy efficiency is termed as the 'first fuel' in clean energy transition. It provides one of the most cost effective and fastest emission mitigation alternatives to support energy security. Energy efficiency is the most prime measures to avoid energy demand in the Net Zero Emissions (NZE) by 2050 **(Energy Efficiency, 2024**). Building energy research initiative under Department of Science and Technology (DST) in India has set a voluntary target to reduce the emission intensity of its GDP by 33 to 35% by 2030, compared to 2005 levels. Reduction of emission intensity can be achieved through energy generation from renewable sources and promoting energy efficiency programs throughout the nation. Installed capacity of renewable energy sources in India is increasing every year. Installation of rooftop solar has increased to 14.45 GW in 2024-25 from only 1 GW in 2017-18 reflecting a sharp yearly growth rate of 46% (MNRE, 2024). Building sector in India accounts for almost 35% of the total energy consumption, and therefore energy efficiency and energy conservation in Indian building sector is imperative. Adaption of building energy code in different part of the world shows reduction of energy consumption in buildings. Energy conservation regulation in China predicts 29% energy savings in buildings sector **(Wang et al, 2010).** In Gujarat, it is predicted that cumulative electricity savings in buildings with ECBC adaption would be around 419,800 GWh by 2050. More over this saving in electrical energy could avoid 134,400 MW of cumulative electricity capacity additions from 2010 to 2050 **(Yu et al., 2017).** In the present work, energy savings with daylight integration in Indian building following ECBC code is studied. The result of the study is used to predict long term benefits in commercial building sector in India.

1.9 Thesis organization

In chapter 1, introduction of the thesis is presented. In this section, motivation, background, unique contribution and prospective application potential of the research is presented. In chapter 2, a brief literature review is presented to show the present state of the art research which is already carried out in this field. The research gap is identified to decide the objectives of the present work. In chapter 3, application of daylight in building through window glazing is carried out to find energy savings opportunity and optimal size of window glazing in the building. In chapter 4, energy savings in building with different daylighting conditions are carried out. In chapter 5, parametric study is carried out for energy savings in building with controlled daylighting. In chapter 6, long term economic benefit of daylighting in building is carried out with the results of the study. In chapter 7, conclusions and future scopes of this study are presented.

2 Review of earlier works

2.1 Introduction

Building sector is one of the major energy consumers in all over the world. The operations of building sector consume 30% of global final energy consumption and also responsible for 26% global energy related emission into the atmosphere. The emissions of green house gas due to different human activities are the cause of climate change and global warming. Efficient energy use in building is essential for sustainable development. Sustainable development is considered as the most rational goal in the present days. Promoting energy efficiency measures in building sector will reduce dependency on fossil fuels as well as environmental impact. Energy efficiency is termed as the ‘first fuel’ in clean energy transition. It provides one of the most cost effective and fastest emission mitigation alternatives to support energy security. The present study focuses on the application of daylighting to improve energy efficiency of the buildings in tropical climate condition and its long term effect on energy savings, economy and power generation.

2.2 Basic concept towards building energy

Energy consumption of building is mainly due to heating, cooling, lighting and powering appliances and equipment in the buildings. Building sector is one responsible for large amount of energy consumption and emissions. Different electrical appliances and equipments, HVAC, various lighting systems are responsible for energy consumption in building. Building envelope influences heat gain or loss of the building which is a deciding factor for cooling and heating energy consumption. Improved thermal properties of building materials are required for energy efficient buildings. Different energy codes around the world recommend the desired properties of building material for energy efficient building design. Energy audit is a process used to analysis the energy usage in the building to point out the area of improvement for optimum energy consumption. Application of higher mass material i.e. building thermal mass in the building envelope influence indoor thermal comfort as well as the cooling and heating energy consumption. Application of glass surface is increasing in modern building architecture. Glass surface in the building envelope is most thermally weak part of the building. Optical and thermal properties of glass facades increase daylight as well as heat gain into the building working space which influences lighting and cooling energy demand of the building. Building floor area in India is increasing very rapidly in India due to population growth, urbanization and economic development which predict many fold increase of building energy consumption in next few decades. Efficient building design improves both comfort level and energy cost on the other hand reduces maintenance cost and emissions.

2.3 Factors affecting building energy consumption

From the literature review, it is clear that building energy consumption is highly dependent on building materials, design, orientation and climate condition of the location. Building envelope and fenestrations are directly exposed to the external environment which significantly influences the energy consumption. Some of the important factors related to building energy and their contribution to energy consumption is mentioned in this section.

2.3.1 Building envelope

Energy consumption in building in tropical climate is mainly depends on lighting and cooling and equipments. Cooling energy consumption in building is largely depends on heat gain through building structure, Solar radiation through window glazing, air exchange, lighting, sensible and latent heat gain due inhabitant and equipments. Building structure or thermal mass of the building influences building energy consumption. It is found that concrete floors, walls and roofs used in commercial buildings dampen the effects of heat gains through the structure of building. It reduces heat gain to the interior air. This leads reduced peak cooling load to the building system compared to less massive structures (**Lee et al, 2008)**. It is found that coupling thermal mass of building envelope with natural ventilation act as passive cooling system to improve indoor thermal comfort (**Zhou et al, 2008**). Zhu et al. presented their work on the detail energy saving performance analysis on thermal mass. They have found that the utilization of thermal mass in building can be one of the most effective ways of reducing building heating and cooling load (**Zhu et al, 2008)**. The effect of thermal mass on the thermal and energy performance have mentioned in numerous research work. Table 2.1 shows some of the related works on thermal mass in view of building energy performance.

Table 2.1: Research work on building thermal mass for energy efficiency

Author (Year)	Study parameter	Area of study
Alayed et al, (2022)	Thermal mass with insulation	Energy performance of building
Jie et al. (2019)	Effectiveness of the thermal mass of external walls	Impact of thermal mass on heating and cooling energy consumption
Jeanjean et al. (2013)	Selection criteria of thermal mass	Reduction in energy consumption and GHG emission.
Kuczyński et al. (2020)	Thermal mass of building	Thermal comfort and reduction of cooling energy
Fadejev et al. (2017)	Thermal mass of building	Impact of interior thermal mass on peak loads and energy consumption
Al-Sanea et al. (2012)	Effect of thermal mass of building	Savings in cooling and heating energy
Kumar et al. (2018)	Thermal mass and natural ventilation	Thermal comfort of indoor space
Balaras (1996)	Thermal mass of building	Impact of thermal mass on the peak cooling load of building.
Yang et al. (2008)	Thermal mass and night ventilation	Cooling load reduction by using thermal mass and night ventilation.
Roche et al. (2004)	Thermal mass and ventilation	Effects of thermal mass on passive cooling.
Shaviv et al. (2001)	Thermal mass and night ventilation	Passive cooling of building

2.3.2 Daylighting and window glazing

Natural daylight has an important role on visual comfort of human beings. Daylighting in buildings has substantial impact on health productivity and performance of the occupant **(Jeong et al, 2013; Gon et al, 2010; Li et al, 2003).** A study was conducted in a building without window to find the impact of daylight among a group of children i.e., the building was equipped with only artificial lighting instead of natural light. The result shows alteration in basic hormonal patterns among the children which affected the ability of cooperation and concentration. Buildings with larger window glazing areas are increasing due to the positive impact of natural light on the occupant **(Kuller, 1992).**

Integration of daylight into buildings can save lot of lighting energy as reported in many research papers. Daylighting through glass window in the building allows lot of heat gain inside the indoor working space. Hens **(Hens, 2009)** mentioned in his study that Office buildings are responsible for higher lighting energy consumption per unit area due to operational requirements. Daylight integration into the buildings can reduce building energy consumption which in turn reduces emission and environmental impact. Window size and orientation can improve the amount of daylight access into the building. Daylight through the window of building has positive impact on energy consumption by reduces lighting energy requirement **(Hosseini, 2024).** The impact of different parameters related to thermal and lighting energy performance of the building are essential to study for energy efficient design of the building **(Ke et al, 2013; Shen et al, 2013).** Daylightinig and heat gain through glass window of the building depends on optical, thermal and geometrical parameter of the window glazing. The increasing window to floor area ratio allows the reduction of annual required heating energy. Inversely, the annual cooling energy requirement increases with increasing the windows to floor area ratio. This is due to the effect of the unwanted solar heat gain into the building space. Larger window area may increase the indoor space temperature to levels higher than the ambient temperature **(Guechchati et al, 2012**). Pal et al. developed a mathematical model of one dimensional heat flow into the building space through the window glazing in a tropical climatic condition in India (**Pal et al, 2009**). Different types of advanced glazing are used in window to minimize energy consumption of the building. Aritra et al. measured thermal and daylight performance of evacuated and vacuum glazing in a cold climate zone **(Aritra et al, 2016)**. Aguilar et al conducted simulation study with double glazing windows in Mexico to quantify the energy performance of different glass window **(Aguilar et al, 2016)**. Kiran et al. mentioned the role of different window glazing materials and their orientation in four different climatic zones in India in terms of energy consumption **(kiran et al, 2017).** Singh et al worked on energy rating of different window glazing materials having different thermal and optical properties for Indian climates on three different types of buildings depending on envelope construction **(Singh et al, 2009).** Lot of research work have been performed on different improved glazing such as double glazing, vacuum glazing, reflective glazing, low-e glazing etc in different climatic conditions. Such high performance glass façades were investigated in tropical climatic zone of Singapore. It is observed that the cooling energy savings with improved glazing for the whole year may goes up to 60% compared to clear float glass **(Bui et al, 2017)**. In a similar study, the influence of different type of insulating glazing compared to clear glass was studied in Amman, Jordon. The study was conducted to evaluate the effect of glass area on energy consumption of a building in different orientation **(Hassouneh et al, 2010).** Andrea et al worked on the examination and modelling of window systems in terms of energy performance in a well insulated residential building. Impact of different kinds of glazing systems, window size (from 16% to 41% of window to floor area ratio), orientation, winter and summer energy need and peak loads for the climatic condition of Paris, Milan, Nice and Rome were studied **(Andrea et al, 2011**). Ramit et al. conducted study on daylight performance of a naturally ventilated building in Mumbai, India and mentioned that the effect of window glazing for daylighting are maximum when the window is placed at south east orientation for the particular location **(Ramit et al, 2017).** Doris et al. studied on optimization of design of perforated solar façades to balance daylighting through window glazing and thermal performance. The study mentioned the way to achieve the annual overall balanced solution between daylighting and thermal performance of perforated solar screen **(Doris et al, 2017).** Daylight admission and heat gain through the window glazing system of the building depends on optical parameters and thermal parameter of the glass used to construct the window. Window-to-wall-ratio (WWR), visible transmittance, U-value and solar heat gain coefficient (SHGC) are parameters of the glass responsible for daylighting and heat gain through the window. Louis et al developed a linear model with SHGC, U-value and VT to select suitable window glazing properties for the building **(Louis et al, 2017)**. Zakirullin et al. proposed angular selectivity of the directional light transmission through the grating optical filter pasted on window glazing of the building. The filter used on the window system provides comfortable daylight into the building space by blocking the direct radiation and transmitting the diffuse radiation without using daylight redistribution devices **(Zakirullin et al, 2019)**. Elisa et al. mentioned that application of solar control film on window glazing in moderate climate reduces 60% solar radiation through the window which results decrease in cooling energy demand by 29% and the heating energy increases by 15% **(Elisa et al, 2015).** Integration of daylighting with artificial lighting of the building certainly reduces the lighting energy consumption of the building. In a study in Saudi Arab reveals that the daylight integration into the building reduce lighting energy up to 71% depending on the types of the window glazing. It was also observed that total energy consumption of the building reduces up to 15.8% **(Mohammed et al, 2015).** Danny et al. carried out detailed studies on daylighting performance in office buildings and school buildings where 25% of the total electric lighting energy consumption could be saved with the integration of daylighting **(Danny et al, 2007)**. Bodart et al. developed a calculation model to predict the energy consumption of the building when daylight is linked with artificial lighting system. It is mentioned that daylight could reduce the energy consumption of artificial lighting system by 50 - 80% **(Bodart et al, 2002)**. Li et al. found that application of high frequency dimming control of the artificial lighting according to available daylight can reduce more than 30% of total energy consumption of building **(Li et al, 2005).** Gene et al. investigated daylight performance and users visual appraisal for two green building offices in Malaysia. It is found that both the office buildings in Malaysia saves 53% and 41% lighting energy as a result of daylight integration **(Gene et al, 2017)**. Many researchers mentioned the impact of daylight and effect of daylight on the reduction of energy consumption of the building as shown in table 2.2.

Table 2.2: Research work on effect of daylighting on building energy.

Author (Year)	Study parameter	Area of study
Syahrul et al (2015)	Application of daylighting	Energy and cost savings
Eric et al (2014)	Daylight control strategy	Energy savings
Li et al (2005)	Daylighting in building	Effect of daylighting on peak load of building
Moncef et al (2005)	Application of daylighting	Lighting energy savings
Paul et al (2005)	Dalight link lighting	Lighting energy savings
Raphaela et al (2013)	Impact of daylight	Total energy savings
Anna et al (2016)	Impact of daylight	Energy savings

2.3.3 Shading devices

Application of shading device on window gazing controls the daylight penetration into the building space and reduces excessive heat gain. Excessive and uncontrolled daylight increase heat gain of the building especially in tropical region in country like India. This heat gain increases the cooling energy consumption of the building. Lim et al. **(Lim et al, 2012)** conducted a simulation study to evaluating the impact of daylight on a typical government office building in Malaysia. It is found that suitable window glazing along with interior blinds improve daylight quality and visual comfort. Shading device controls the daylight penetration into the building space and reduces excessive heat gain. Application of internal or external shading devices to windows has great impact on thermal performance, energy consumption and associated greenhouse gases emission **(Nikoofard et al, 2014).** Performance of Shading device on window system in selected cities in USA and China have been carried out and result shows that application of proper shading reduce total building energy consumption up to 37.8% in selected cities in USA and 24.8% in selected cities in China **(Lai et al, 2017).** Similar benefit of shading device is also observed in Qatar **(Touma et al, 2017)** and Indonesia **(Mangkuto et al, 2019)** also.

2.3.4 Window-to-wall-ratio (WWR)

Window-to-wall-ratio represents the area of window glazing on the building envelope and useful parameter to access daylight into the building space. Higher WWR in modern building not only used to access daylight in to the building but also used to improve the aesthetic view of the buildings. Increasing WWR of a building allows more heat and daylight inside the working space. Fung et al. conducted a simulation study in EnergyPlus to evacuate thermal performance of window glazing for different orientation of window and WWR in Hong Kong **(Fung et al, 2017)**. Orientation of window in building envelope and WWR is an important parameter which influences building energy consumption. Increasing WWR of a building allows more heat and daylight inside the working space. As a result of higher heat gain of the indoor space, cooling energy demand of the building increases. Thermal performance of different orientation and WWR in public rental housing in Hong Kong was evaluated in EnergyPlus simulation software by Siu et al. (**Siu et al, 2017)**. Energy savings opportunity with Optimal WWR and daylight link has been evaluated in India. Result of the study reflects energy savings potential of the daylight integration into the building **(Biswas et al, 2024).** Goia **(Goia, 2016)** studied to find optimal WWR for office building in different European climates to identify the minimum total energy use for heating, cooling and lighting.

2.4 Building energy codes and its application

Building codes and standards provide suitable guideline regarding building materials, safety, water efficiency, energy efficiency, thermal comfort, visual comfort etc. Building energy codes deals with energy savings which in turn saves money as well as avoid capacity addition of electric power generation. Adaption of building energy code gives long term economic and environmental benefit. Energy Conservation Act 2001 in India has been introduced by Government of India (GoI) to reduce energy consumption. Bureau of Energy Efficiency (BEE), an autonomous body under Ministry of Power (MoP) was set up to implement energy efficiency measures in the country. BEE along with United States Agency for International Development (USAID) under its Energy Conservation and Commercialization Project (ECO-II Project) launched the first version of ECBC code in India. To ensure efficient energy utilization in commercial building, Energy Conservation Building Code 2017 (ECBC) has been developed for newly constructed commercial buildings having a connected load of 100 kW or contract demand of 120 kVA or above. A number of energy efficiency measures have been taken by BEE to reduce energy consumption in different area during eleventh five year plan of the country **(Shui and Hariss, 2006).** These initiatives of BEE have resulted in an avoided capacity generation of 10836 MW during the period **(Sahoo et al., 2016).**

2.5 Identification of research gap

From the literature survey it is found that a number of study related to daylighting were carried out on window glazing system and most of the work concentrated on the points such as daylight linked lighting system, window orientation, locations and climate conditions, window glazing materials, window to wall ratio (WWR), window aspect ratio, heat gain and cooling and heating load. Most of the research work has been conducted with single window in particular orientation for daylighting in building. A little attention was paid to the distribution of windows in different cardinal direction for better daylighting and scope of energy savings in the building sector.

2.6 Scope of present study

The review of literature shows that there is not much reported literature in the area of daylighting in building through distribution of window in different cardinal directions. In this study, a new strategy to daylight integration in view of energy conservation is used

- The window glazing area (WWR) is distributed equally to different building walls for higher daylighting in to the building and artificial lighting is controlled (continuous dimming control) according to the available daylight at the reference points.
- Balance between heat gains through the higher window area and daylighting is achieved with parametric variation of slat tilt angle of shading device.

Hence the parametric study of WWR, distribution of glazed surface and slat angle along with lighting control provides a new strategy for building energy conservation in the present study. Energy savings in the building from this strategy is used to quantify long term benefits of daylight integration in Indian commercial buildings.

2.7 Novelty and contribution

This study presents a novel strategy for integrating daylight in commercial buildings with a focus on energy conservation. The key contributions are as follows:

1. Optimized Window Design and Lighting Control: The window-to-wall ratio (WWR) is distributed equally across different building facades to maximize daylight penetration, while the artificial lighting system is controlled using continuous dimming based on the available daylight at reference points.

2. Parametric Optimization of Shading Devices: A balance between increased heat gains from larger window areas and daylighting benefits is achieved through parametric variation of the slat tilt angle of external shading devices.

3. Integrated Parametric Study: The combined parametric evaluation of WWR, glazed surface distribution, and shading slat angle, along with daylight-responsive lighting

control, establishes a comprehensive strategy for reducing building energy consumption.

4. Quantification of Energy Savings: The energy savings resulting from this integrated strategy are quantified, demonstrating the long-term benefits of daylight integration for Indian commercial buildings.

Overall, this work provides a systematic approach to optimizing building façade design and lighting control, contributing to sustainable energy management and improved building performance.

3 Application of daylight in building through glass window

3.1 Introduction

Window glazing and glass facade are the integral part of building design. Window glazing allows daylight into the building and also provides aesthetic view to the modern commercial buildings **(Ghosh et al, 2018).** Natural daylight has an important role on visual comfort of human beings. Daylighting in buildings has substantial impact on health **(Kim et al, 2013; Kim et al, 2010),** productivity and performance of the occupant **(Li et al, 2003).** Integration of daylighting systems can save lot of lighting energy as reported in many research papers but the glass surface as a window in the building allows lot of heat inside the indoor working space. Lighting energy requirement of building is greatly influenced by daylight availability into the building. Heat gain due to daylight increases the cooling energy requirement of the building. Selecting a window glazing in view of energy conservation in building is one of the prime issues for achieving energy efficient building design.

In India, building sector is responsible for 38% of total annual primary energy consumption and 31% of the total annual electricity consumption **(AEEE, 2017).** Perez-Lombard et al stated that the energy consumption by both residential and commercial buildings in developed countries account for 20–40% of total energy used. Those energies are mainly used for space heating and cooling for residential buildings and lighting for commercial buildings **(Pérez-Lombard, 2008)**. The major electric loads in a building are lighting, air conditioning, and equipments. Residential and commercial in India consumes 33% of total electrical energy consumption. Consumption of energy in residential and commercial buildings sectors is predicted to rise by 5 folds and 3 folds respectively by 2032 **(Impact of Energy Efficiency Measures, 2022).** A number of studies have already been conducted on application of daylight in building. The impact of glass facades and shading controls on energy consumption for lighting and cooling was investigated. Different ways of saving energy and maintaining indoor thermal comfort conditions have been studied **(Shen et al, 2017)**. Eskin et al. conducted study on the effects of window parameters and their impact on the cooling energy and peak energy load of the building **(Eskin et al, 2008).** The impact of different types of window glazing, window size and orientation on the winter and summer energy consumption and peak loads of the residential building was investigated **(Gasparella et al, 2011).** This work intended to optimize the window glazing area in view of energy efficient building design in Indian climatic condition. In this study, the building is modelled according to Energy Conservation Building code and National Building Code in India **(ECBC, 2017; NBC 2016).**

From the literature survey it is found that a number of study related to daylighting were carried out on window glazing system as a single unit and most of the work concentrated on the points such as daylight linked lighting system, window orientation, locations and climate conditions, window glazing materials, window to wall ratio (WWR), window aspect ratio, heat gain and cooling and heating load etc. A little attention was paid to the combination of windows for daylighting and its effect on energy consumption of the building and optimum WWR for the window combinations.

The purpose of this research work is to study the integration of daylight and hence optimize the window glazing area compared to reference building model in the Indian climatic condition. The study examines the effect of distribution of window glazing in different cardinal directions compared to single window in Kolkata (22°33' N, 88°21' E), Delhi (28°40' N, 77°12' E), and Chennai (13°04' N, 80°14' E), in India. Attention is given to increasing window glazing area within targeted energy consumption in the building. The study identifies the optimum WWR for different combination of windows allowing daylight into the building.

3.2 Methodology

In the present study attention has been given to integrate daylight into the building through the glazing of different window combination. Benefit of integration of daylight through different window combinations were investigated as compared to reference building model developed following ECBE 2017 and National Building Code in India. As the study locations are in northern hemisphere, window position of the reference buildings are placed in south wall. The window-to-wall-ratio (WWR) of the reference building model is chosen as 10% for this study. Clear glass having universal heat transfer coefficient (U-value) of 5.8 W/m^2K, solar heat gain coefficient (SHGF) of 0.79 and visible transmittance 87.8% has been chosen as window glazing material. Cooling, Lighting and total energy consumption for the reference building models for Kolkata, Delhi and Chennai are simulated using EnergyPlus building energy simulator. The total energy consumption in the reference building has been considered as benchmark for increasing daylight through the window glazing and finding optimum WWR for the window combinations.

Window glazing area is distributed to different cardinal direction of the building to improve daylight into the building interior space. WWR of the building under study is taken as 10%, 15%, 20%, 25% and 30%. Increasing window area in different walls influences the energy consumption of the building. Artificial lighting system of the building is controlled according to the available daylight at the reference point which reduces energy consumption of the building. Impact of distribution of window to different walls has been compared with the reference building for optimum WWR. Building models for eleven different window combinations and five different WWR are developed for energy simulation and the results are compared with the reference building model to find optimum WWR. In all the building models, material and all specification are same except the WWR and orientation of window glazing. Window combinations used in this study are shown in table 3.1.

Table 3.1: Window combinations in different building model.

Window Combination	Direction of Window
EW	East West
NE	North East
NS	North South
NW	North West
SE	South East
SW	South West
NSW	North South West
NSE	North South East
EWS	East West South
EWN	East West North
NSEW	North South East West

3.2.1 Location of the study

The location of the present study is Kolkata, India and the results are validated with two different locations Delhi and Chennai. The buildings are modelled according to NBC and ECBC code in India. Energy savings due to distribution of window in different cardinal direction and daylight integration with artificial lighting system were computed in Kolkata (22°33' N, 88°21'E) which is located in worm and humid climatic zone in India [5]. The results were validated with two more locations Chennai (13° 4' N, 80° 14' E) situated at lower latitude and Delhi (28° 38' N, 77° 13' E) situated at higher latitude compared to Kolkata. Building energy consumption depends on the weather condition of the study location. Monthly average temperature, global solar radiation and relative humidity of the three study location are shown in figure 3.1, figure 3.2 and figure 3.3.

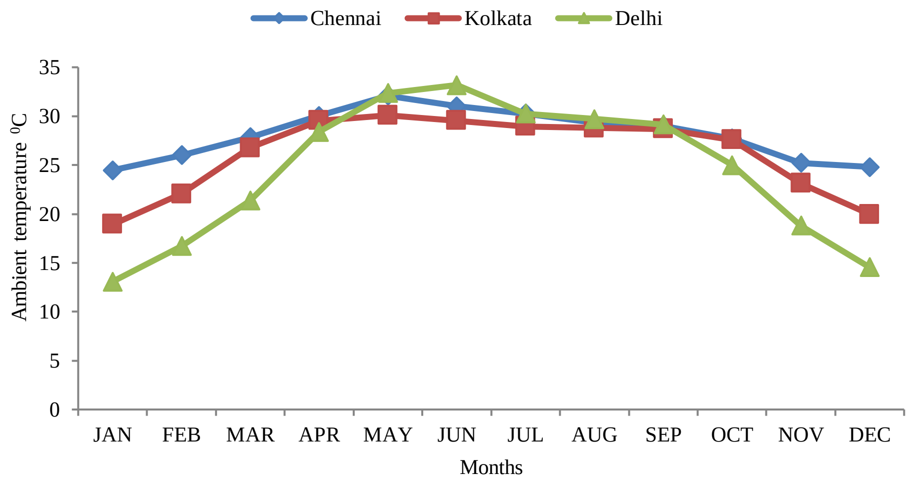

Figure 3.1: Monthly average ambient temperature in Kolkata, Delhi and Chennai.

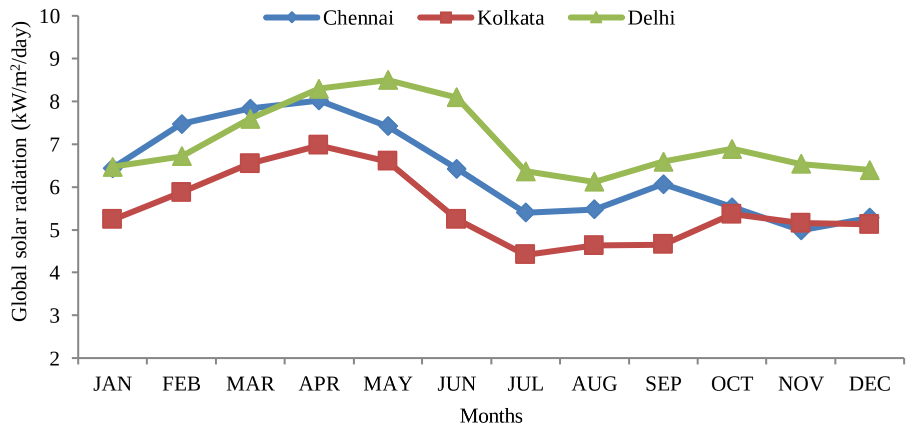

Figure 3.2: Monthly average global solar radiation in Kolkata, Delhi and Chennai.

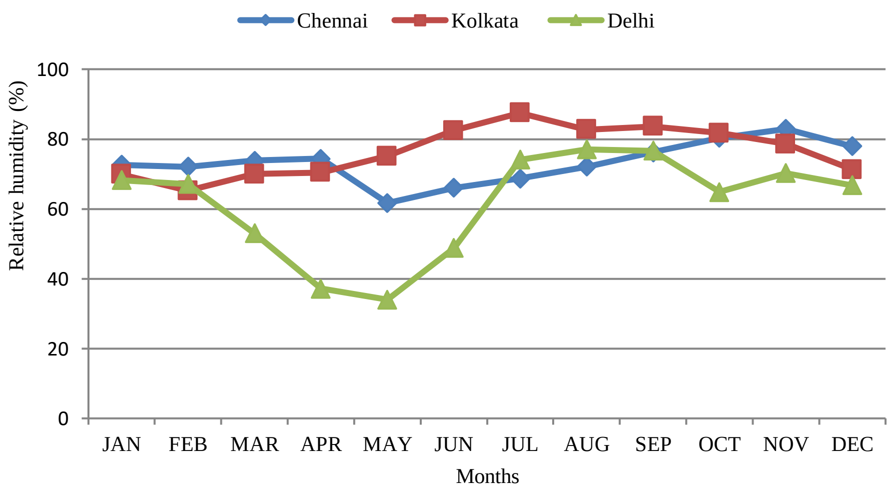

Figure 3.3: Monthly average relative humidity in Kolkata, Delhi and Chennai

3.2.2 Solar radiation on window surface

The solar radiation on window surface is one of the deciding factors for energy consumption in the building. Solar radiation on the building surface depends on a number of angles related to solar geometry such as tilt angle (β) of the receiving surface, surface azimuth angle (γ), solar azimuth angle (γ_s), hour angle (ω), altitude angle (α_a), zenith angle (θ_z), declination angle (δ) and latitude (Φ) of the location. When solar radiation falls on a surface, the angle between beam radiation and normal to the surface is called the angle of incidence. It is important to mention that the entire beam radiation coming from the direction of the beam radiation (I_{bn}) will not be received by the surface unless until the angle of incidence is zero. This angle signifies how much solar beam radiation (I_b) will be received by the surface. Global solar radiation consist of three components namely beam radiation, diffuse radiation and reflected radiation. Beam radiation (I_b) received by any surface is given by:

$$I_b = I_{bn} \cos\theta \qquad (3.1)$$

Where I_{bn} is the entire beam radiation coming from the direction of the sun, θ is angle of incidence and Cos θ is given by:

$$cos\,\theta = sin\,\varphi(sin\delta\, cos\beta + cos\,\delta\, cos\,\gamma\, cos\,\omega\, cos\,\beta) + cos\,\varphi\,(cos\,\delta\, cos\,\omega\, cos\,\beta - sin\,\delta\, cos\,\gamma\, sin\,\beta) + cos\,\delta\, sin\,\gamma\, sin\,\omega\, sin\,\beta \qquad (3.2)$$

Where β is tilt angle of the receiving surface, γ is azimuth angle of the surface receiving solar radiation, ω is hour angle, δ is declination angle and Φ is latitude of the location. When β=0, equation (2) gives zenith angle θ_z

$$\cos\theta_z = \sin\varphi(sin\delta + \cos\delta\cos\gamma\cos\omega) + \cos\varphi\ \cos\delta\cos\omega \qquad (3.3)$$

The amount of global radiation on a surface of a building considering isotropic sky is given by

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r \qquad (3.4)$$

Solar radiation received on a surface considering anisotropic sky is given by **(Duffie & Beckman, 2006)**

$$I_T = (I_b + I_d A_i) R_b + I_d\,(1 - A_i) \frac{(1+cos\beta)}{2} \left[1 + f\, sin^3 \frac{\beta}{2}\right] + I\rho_g \left(\frac{1-cos\beta}{2}\right) \qquad (3.5)$$

Where R_b is tilt factor of beam radiation, R_d is tilt factor of diffusion radiation, R_r is tilt factor of reflected radiation and A_i is anisotropy index which is nearly equal to 1.

$$R_b = \frac{\cos\theta}{\cos\theta_z} \qquad (3.6)$$

$$R_d = \rho_g \frac{(1+\cos\beta)}{2} \qquad (3.7)$$

$$R_r = \rho_g \frac{(1-\cos\beta)}{2} \qquad (3.8)$$

Window is considered as vertical surface hence β is 90^0 and the equation (3.2) reduces to

$$\cos\theta = \sin\varphi\cos\delta\cos\gamma\cos\omega - \cos\varphi\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega \qquad (3.9)$$

$$\theta = cos^{-1}(\sin\varphi\cos\delta\cos\gamma\cos\omega - \cos\varphi\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega) \qquad (3.10)$$

Equation 3.1 through 3.10 is useful to calculate solar radiation received by different building surfaces.

3.2.3 Solar radiation on different building surface

Building energy consumption is highly dependent on structural load of the building. Heat gain of the building through the building envelope depends on the thermal properties of the building materials as well as climatic condition of the location. Solar radiation on the exposed building surfaces is a major cause of indoor heat gain. Global Solar radiation received on external surface of north wall of the building is comparatively higher in Chennai due to lower latitude of the location. The same is comparatively lower in higher latitude in Kolkata and Delhi due to higher latitude. Monthly received solar radiation on north wall in the study locations are shown in figure 3.4. Global solar radiation received on south surface is higher in Delhi due to higher latitude and lowest in Chennai due to lower latitude. Global solar radiation on south wall in Kolkata is intermediate of these two locations as shown in figure 3.5. Due to higher declination of earth during winter, solar radiation received on the south wall is higher compared to summer when profile angle is much higher and during some period of time it is even greater than 90^0 hence no beam solar radiation is received during that period of time. Global solar radiation during the year on the east and west wall of the building is shown in figure 3.6 and figure 3.7. Solar radiation received on east and west wall in Delhi is higher compared to other two locations due to higher solar radiation in Delhi. In Kolkata, solar radiation received on both east and west is lowest among the three locations during the year. Solar radiation on roof surface is maximum among all the building surfaces as shown in figure 3.8.

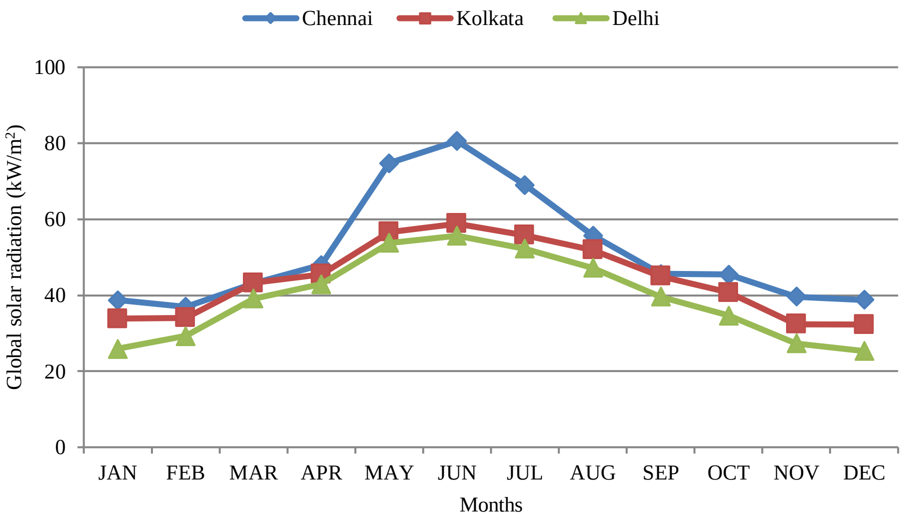

Fig. 3.4 Monthly global solar radiation on north surface

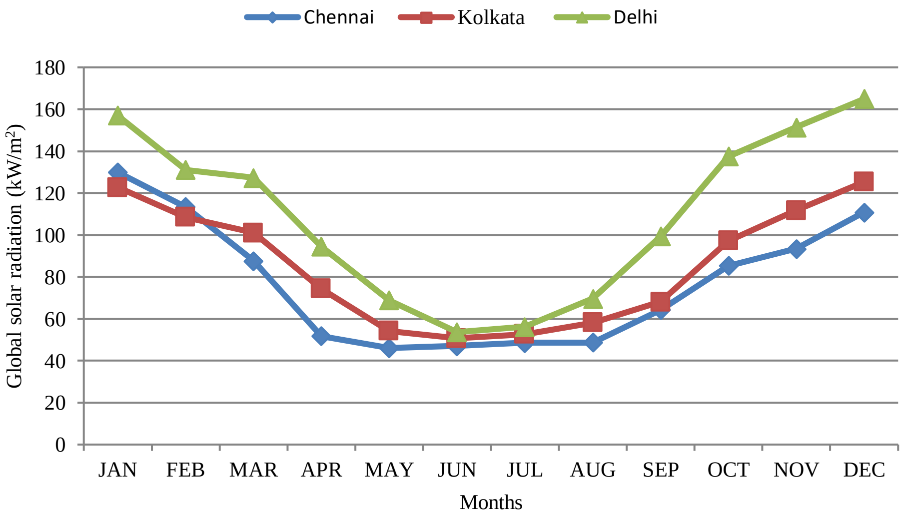

Figure 3.5: Monthly global solar radiation on south surface

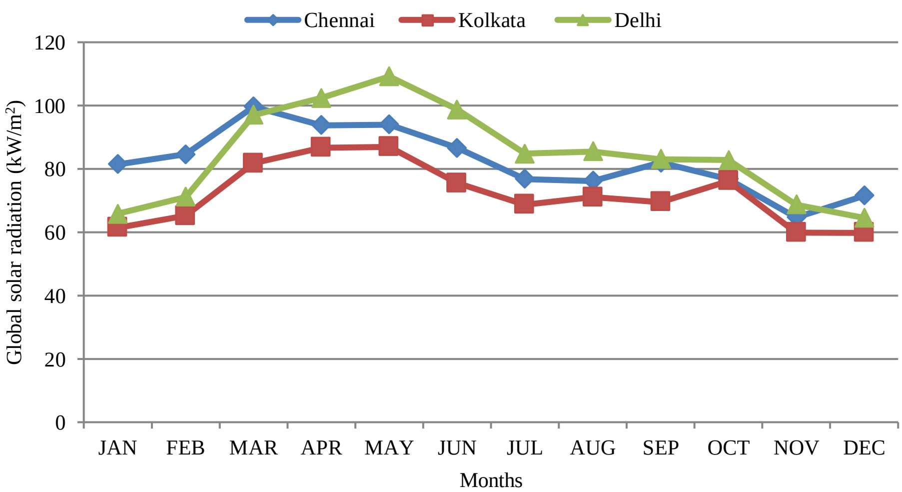

Figure 3.6: Monthly global solar radiation on east surface

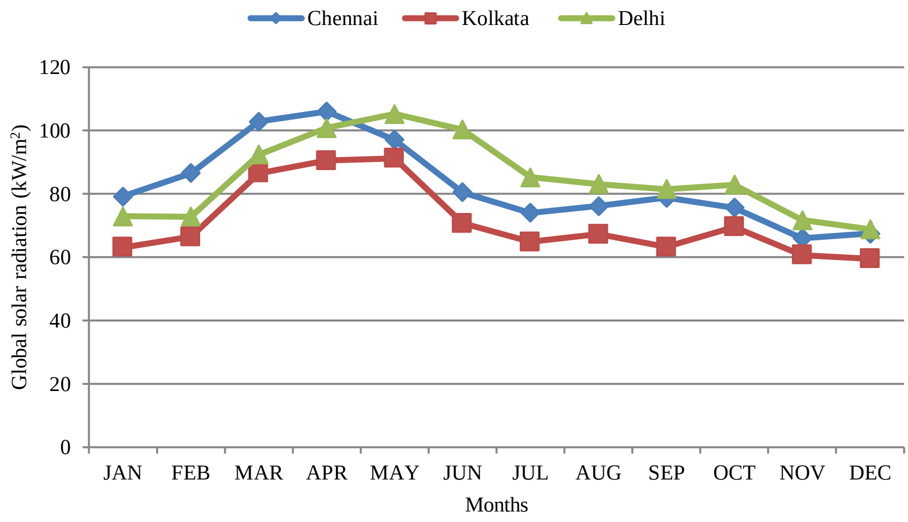

Figure 3.7: Monthly global solar radiation on west surface

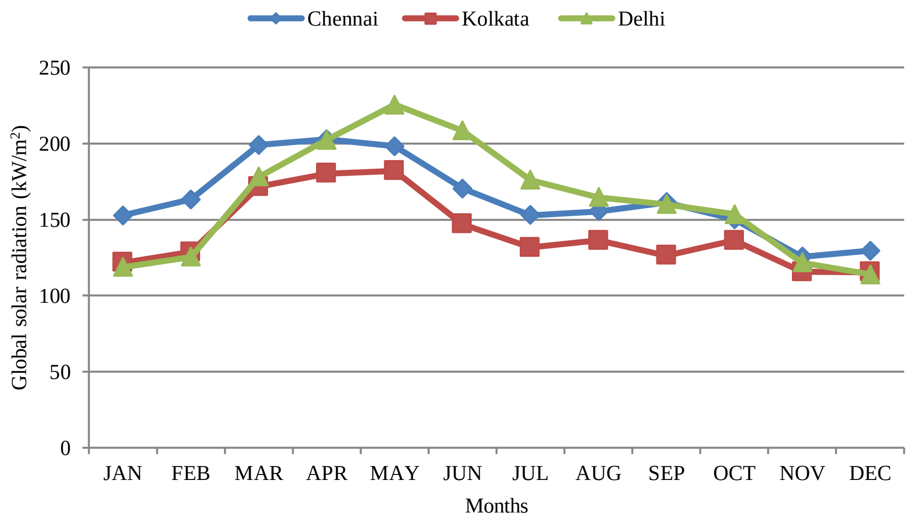

Figure 3.8: Monthly global solar radiation on roof surface

Annual energy consumption is also dependent on the annual solar radiation received on different wall of the building. Figure 3.9 shows annual global solar radiation received on different external surface of the building. It is found that north wall in Chennai received maximum solar radiation due to lower latitude followed by Kolkata and Chennai. South wall in Delhi received maximum solar radiation due to higher latitude followed by Kolkata and Chennai. In east and west wall, solar radiation received is minimum in Kolkata as the monthly average solar radiation in Kolkata is comparatively lower than Chennai and Delhi. Exposed roof surface of the building receive solar radiation for longest period of time during the entire year. As a result of this, solar radiation received by roof surface is considerably high and contribute huge amount of heat load into the building working space. Solar radiation received on exposed roof surface in Delhi and Chennai is high due to higher solar radiation in Delhi and Chennai compared to Kolkata. Among the building surfaces, north wall receives lowest solar radiation in all three locations.

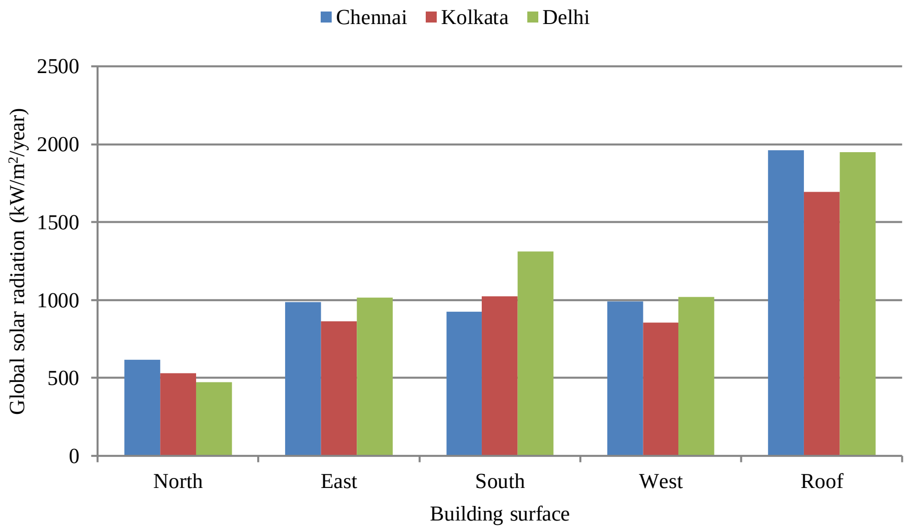

Figure 3.9: Yearly global solar radiation on different building surface

3.2.4 Simulation tools

A number of simulation tools for building energy such as EnergyPlus, DesignBuilder, DOE2, ECOTECT, TRNSYS, Energy Quest, BSim used to analysis building energy performance. In the present study EnergyPlus has been used as the building energy simulation tool. EnergyPlus has been developed by department of energy of USA. It is one of the widely used whole building energy simulation software. Whole building energy simulation (BES) models are very effective to determine optimal parameters for energy efficient building design. In the present study, energy consumption of all the building modes is determined in EnergyPlus building energy simulator. EnergyPlus is a whole building energy simulation tool developed by department of energy of USA on the basis of work carried out on DOE-2. EnergyPlus is a widely used simulation tool to determine energy performance of building **(Shabunko et al, 2018; Bernardo et al, 2017; Albert et al, 2017)** as well as thermal performance of the building **(Phan et al, 2014)** in different location of the world.

3.2.5 Building model

In the present study, the dimensions of the reference building are 9 m X 9 m X 3 m **(Singh et al, 2009)**. The reference building is modelled according to the specifications mentioned at National Building Code of India **(NBC (2016)** and Energy Conservation Building Code 2017 **(ECBC, 2017)** for all three study location in India. The walls roof and floor of the building model is constructed with a number of layers of different material suitable for Indian climatic condition and following ECBC 2017 and NBC 2016 code existing in India. From outside to inside, the layers of the developed building walls are cement plaster layer, brick layer and cement plaster layer. The roof is constructed with RCC with cement layer in inner side. In floor the layers are brick, concrete and cement plaster layer. Window is placed only in south wall and WWR in the reference building is 10%. A typical view of the building model is shown in figure 3.10. Properties of the building materials are shown in table 3. 2.

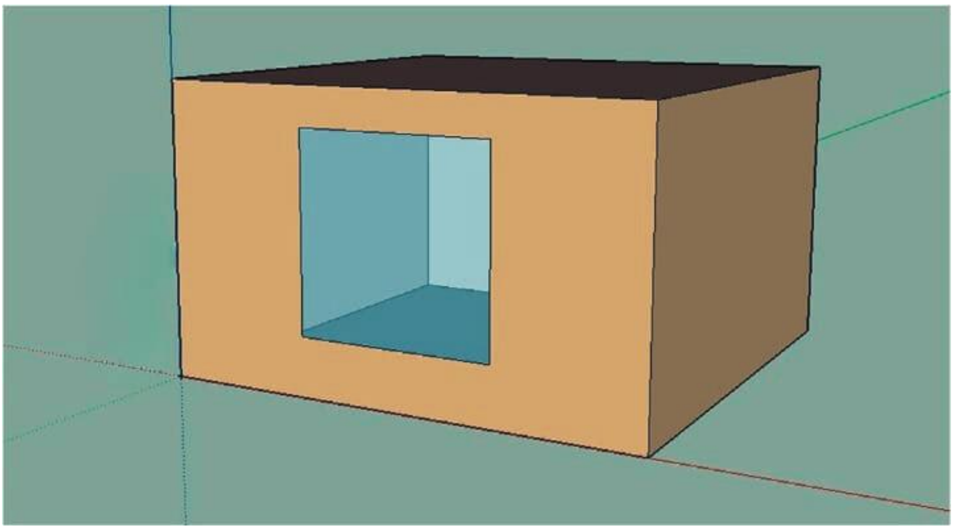

Figure 3.10: A typical view of the building with single window.

Table 3.2: Properties of the building materials used in the study.

Components	Layers (outside to inside)	Materials	Thickness (mm)	Conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kg K)
Walls	Layer 1	Cement Plaster	13	0.721	1762	840
	Layer 2	Brick	254	0.811	1820	880
	Layer 3	Cement Plaster	13	0.721	1762	840
Roof	Layer 1	RCC	135	1.58	2280	880
	Layer 2	Cement Plaster	13	0.721	1762	840
Floor	Layer 1	Brick	254	0.811	1820	880
	Layer 2	Concrete	101	1.78	2410	880
	Layer 3	Cement Plaster	13	0.721	1762	840

Building models other than reference models are simulated with five different window-to-wall-ratios (WWR) namely 10%, 15%, 20%, 25% and 30%. The WWR of the building model are calculated following the NBC code of India. The window is made of clear glass with U-value of 5.6 W/m^2K, solar heat gain coefficient of 0.83 and visible transmittance of 77.8%. In the present work window glass area corresponds to 10%, 15%, 20%, 25% and 30% window to wall ratio are 10.8 m^2, 16.2 m^2, 21.6 m^2, 27 m^2 and 32.4 m^2 respectively. The glass area of the building models were equally distributed to different wall to investigate the impact of combination of window glazing on building energy performance. Eleven number of window combinations for each WWR were formed by distributing the glass area into different walls of the building. In all combination the window sill height is fixed to 1m above the floor height complying with the NBC code in India. Internal gain of the building from lighting is fixed to 9.5 W/m^2. Constant ventilation with outside air of 0.5 air changes per hour (ACH) has been considered to maintain healthy indoor air quality **(Singh et al, 2009)**. The building models are meant for 10 hours of operation and the indoor temperature is controlled to 25^0 C with the help of HVAC system. The artificial lighting of the building is linked to delighting to reduce the energy consumption of the building. A continuous control of artificial lightings is designed based on daylight through window combinations to maintain the illuminance level at 500 LUX at reference points at a height of 0.8 m from the floor of the building **(Ghosh et al, 2018)**. Dimming of the artificial lights are continuous and linearly from maximum light output to minimum light output as the daylight illuminance increases continuously. At minimum dimming level the light output of the artificial lighting is fixed to 30% of its full illumination and further increase in the daylight illuminance will not dim the artificial lighting.

3.3 Result and discussion

The building models of all three locations are simulated in EnergyPlus to determine annual cooling, lighting and total energy consumption. The building was simulated for two different cases.

Case1: In this case reference building for all three locations is simulated and annual cooling, lighting and total energy consumption is determined. Annual cooling energy consumption of reference building in Kolkata, Delhi and Chennai are 8092.5 kWh, 8051.7 kWh and 9895.6 kWh respectively. Annual lighting energy consumption is 2008.4 kWh in all three locations as there was no lighting control incorporated in the reference buildings during the hours of operation. Annual total energy consumption is 10101 kWh, 10060.1 kWh and 11904 kWh in Kolkata, Delhi and Chennai respectively. Energy consumption of reference buildings are considered as benchmark for optimizing glass area in the building in different window combinations as a result of daylight integration into the building.

Case 2: Building with different window combinations are simulated with and without integrating daylight with the artificial lighting system of the building. Annual cooling, lighting and total energy consumption of different building model with increasing WWR are evaluated for all three locations.

3.3.1 Building energy performance in Kolkata

Energy consumption with different window combination with and without daylight integration is simulated for different WWR. From the result, it is evident that increasing WWR compared to reference building increases total energy consumption of the building in the study location as shown in figure 3.11. Integration of daylight into the building significantly reduces total energy consumption of the building with all window combinations as shown in figure 3.12. From figure 3.11 and figure 3.12, it is clear that daylight integration to the building greatly reduces the total energy consumption.

Figure 3.12 suggest that WWR can be increased in all combinations within the reference energy consumption of 10101kWh. WWR of the building can be increased to allow more daylight through the window combinations. Increasing WWR may increase the heat gain of the building which in turn increases the cooling energy. But at the same time lighting energy is greatly reduced from 2008.4 kWh; lighting energy consumption without daylight integrating. This reduction in lighting energy reduces the internal heat gain of the building which reduces cooling energy of the building. Hence a balance between heat gain due to daylight through window glazing and energy saving is required. Annual energy consumption of the building with different window combinations in Kolkata is given in table 3.3.

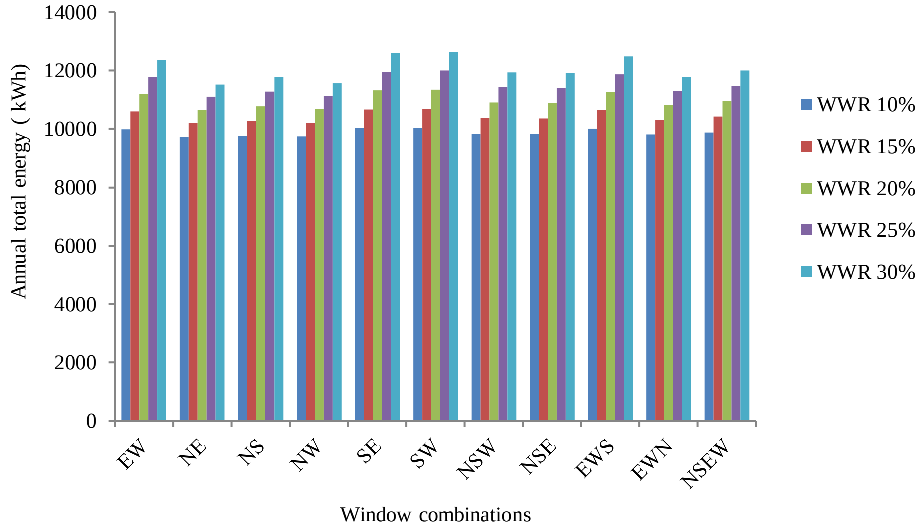

Figure 3.11: Annual total energy consumption without daylight integration in Kolkata.

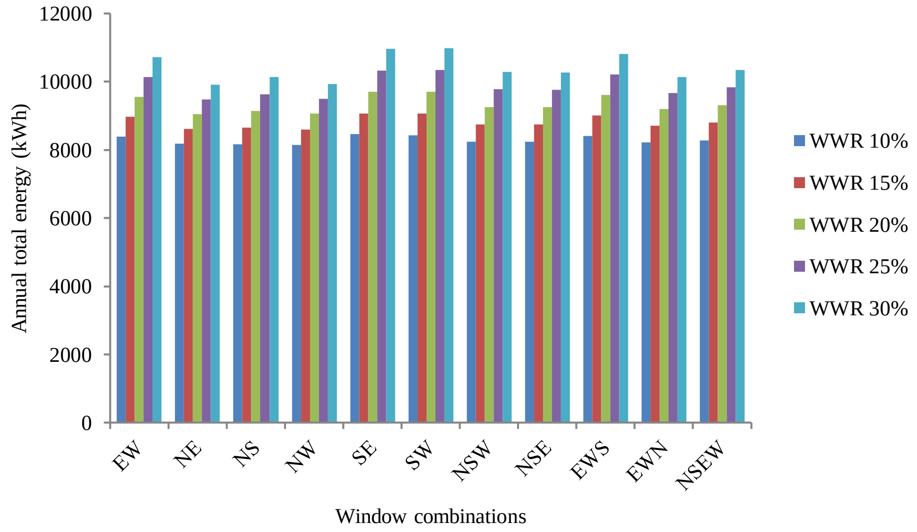

Figure 3.12: Annual total energy consumption with daylight integration in Kolkata.

Table 3.3: Annual energy consumption for different window combinations in Kolkata.

WWR (%)	Window Combination	With daylight			Without daylight
		Annual Cooling Energy(kWh)	Annual Lighting Energy(kWh)	Annual Total Energy(kWh)	Annual Total Energy(kWh)
10	EW	7658.4	729.4	8387.8	9992.8
	NE	7406.7	777.5	8184.2	9727.9
	NS	7428.4	736.3	8164.7	9763.3
	NW	7412.0	740.2	8152.2	9740.4
	SE	7692.6	768.3	8460.9	10025.4
	SW	7696.9	735.2	8432.1	10036.4
	NSW	7504.2	732.9	8237.1	9839.1
	NSE	7498.7	745.7	8244.4	9831.1
	EWS	7673.4	734.0	8407.4	10011.0
	EWN	7484.5	734.7	8219.2	9815.2
	NSEW	7537.2	740.5	8277.7	9870.4
15	EW	8255.3	716.4	8971.7	10595.5
	NE	7865.5	747.9	8613.4	10194.0
	NS	7923.9	721.2	8645.1	10266.6
	NW	7880.8	723.1	8603.9	10213.7
	SE	8324.3	743.5	9067.8	10668.9
	SW	8336.5	720.8	9057.3	10685.0
	NSW	8029.3	717.1	8746.4	10371.5
	NSE	8018.7	726.3	8745.0	10359.2
	EWS	8287.6	718.5	9006.1	10633.7
	EWN	7987.2	719.1	8706.3	10322.8
	NSEW	8073.1	722.3	8795.4	10413.7
20	EW	8846.9	709.8	9556.7	11191.1
	NE	8318.4	733.5	9051.9	10650.8
	NS	8424.8	713.4	9138.2	10772.9
	NW	8342.7	714.4	9057.1	10678.2
	SE	8966.1	730.8	9696.9	11318.6
	SW	8984.2	713.1	9697.3	11339.7
	NSW	8553.1	708.3	9261.4	10900.2
	NSE	8537.7	715.7	9253.4	10883.8
	EWS	8902.5	709.6	9612.1	11254.7
	EWN	8480.8	709.9	9190.6	10819.6
	NSEW	8604.7	711.6	9316.3	10950.5
25	EW	9431.5	705.5	10137.0	11778.3
	NE	8761.5	725.0	9486.5	11096.1
	NS	8928.0	708.7	9636.7	11280.2
	NW	8794.9	709.0	9503.9	11131.8
	SE	9609.6	723.0	10332.6	11967.7
	SW	9633.5	708.1	10341.6	11993.5
	NSW	9073.1	702.6	9775.7	11424.3
	NSE	9053.2	709.2	9762.3	11403.4
	EWS	9514.8	704.0	10218.8	11871.7
	EWN	8964.0	704.3	9668.3	11305.1
	NSEW	9129.9	704.8	9834.7	11479.5
30	EW	10008.2	702.8	10711.0	12357.1
	NE	9185.3	719.4	9904.7	11520.7
	NS	9431.2	705.6	10136.8	11786.2
	NW	9228.4	705.2	9933.6	11565.6
	SE	10241.5	717.9	10959.4	12603.2
	SW	10270.1	704.8	10974.9	12632.6
	NSW	9587.4	698.8	10286.2	11941.0
	NSE	9562.5	704.7	10267.3	11915.5
	EWS	10121.1	700.2	10821.3	12480.9
	EWN	9435.7	700.5	10136.2	11777.7
	NSEW	9647.3	700.1	10347.4	11999.6

3.3.2 Building energy performance in Delhi

Energy consumption of the building without daylight integration and with daylight integration for different window combinations in Delhi is shown in figure 3.13 and figure 3.14. Similar to Kolkata, total energy consumption in each window combinations is reduced as a result of daylight integration into the building. Result of the study indicates that WWR of different window combinations may be increased within the reference energy consumption as a result of daylight integration. It shows that the application of daylight through optimum use of window glazing is also valid in Delhi. Table 3.4 shows the energy consumption of the building with all the window combinations.

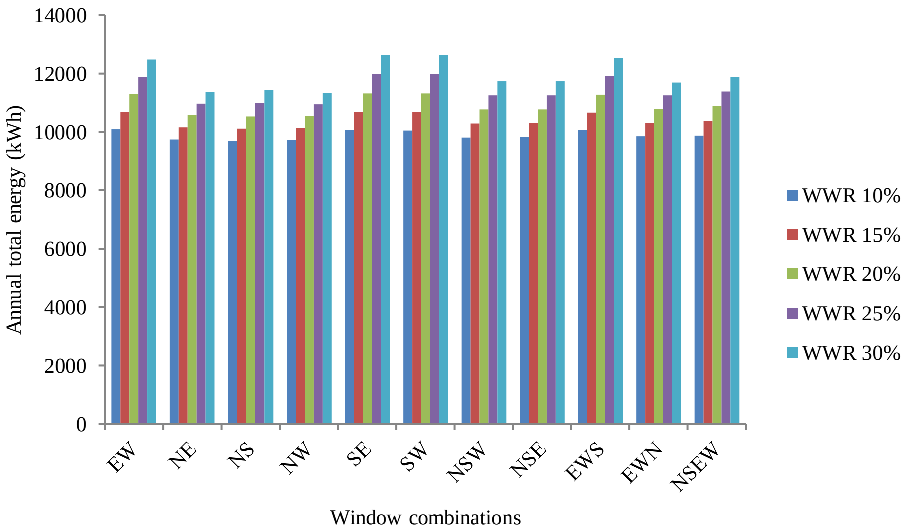

Figure 3.13: Annual total energy consumption without daylight integration in Delhi.

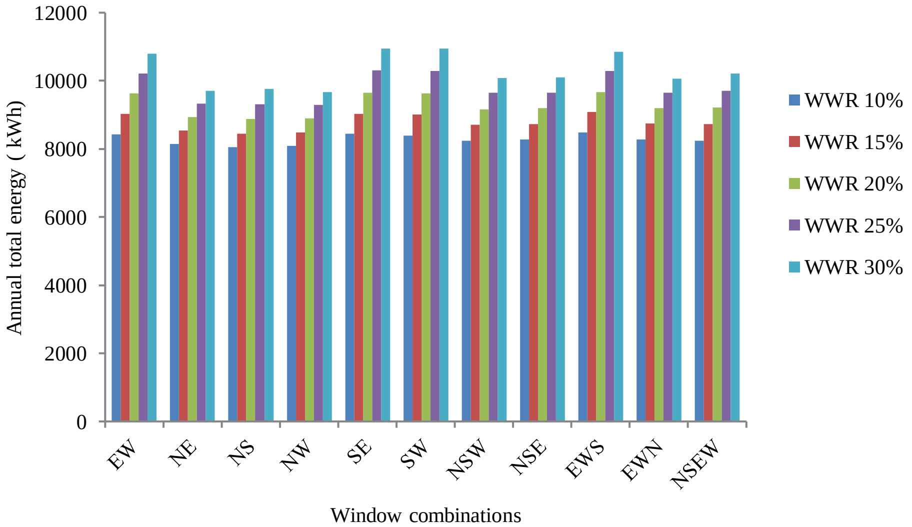

Figure 3.14: Annual total energy consumption with daylight integration in Delhi.

Table 3.4: Annual energy consumption for different window combinations in Delhi.

WWR (%)	Window Combination	With daylight			Without daylight
		Annual Cooling Energy(kWh)	Annual Lighting Energy(kWh)	Annual Total Energy(kWh)	Annual Total Energy(kWh)
10	EW	7788.5	645.4	8433.9	10084.4
	NE	7450.7	691.4	8142.1	9736.0
	NS	7391.7	652.1	8043.8	9686.8
	NW	7427.8	662.5	8090.3	9716.2
	SE	7766.1	673.5	8439.6	10064.1
	SW	7747.4	650.6	8398.0	10048.5
	NSW	7513.8	732.9	8246.7	9809.8
	NSE	7526.4	745.7	8272.1	9821.0
	EWS	7759.0	734.0	8493.0	10058.9
	EWN	7548.7	734.7	8283.4	9840.3
	NSEW	7583.9	651.3	8235.2	9879.0
15	EW	8389.7	639.0	9028.7	10690.2
	NE	7871.0	662.8	8533.8	10160.1
	NS	7807.8	643.3	8451.1	10108.4
	NW	7842.8	645.4	8488.2	10134.2
	SE	8378.0	654.7	9032.7	10686.8
	SW	8361.7	641.1	9002.8	10672.8
	NSW	7985.1	717.1	8702.2	10286.6
	NSE	7999.8	726.3	8726.1	10300.0
	EWS	8358.5	718.5	9077.0	10666.1
	EWN	8022.0	719.1	8741.1	10316.8
	NSEW	8083.9	641.7	8725.6	10384.2
20	EW	8987.2	636.0	9623.2	11291.3
	NE	8284.1	652.6	8936.7	10575.1
	NS	8233.1	639.3	8872.4	10539.8
	NW	8252.8	639.4	8892.2	10545.6
	SE	9009.6	646.7	9656.3	11328.5
	SW	9000.3	637.1	9637.4	11318.8
	NSW	8459.8	708.3	9168.1	10767.4
	NSE	8473.6	715.7	9189.3	10778.7
	EWS	8966.4	709.6	9676.0	11281.8
	EWN	8487.1	709.9	9197.0	10784.1
	NSEW	8582.6	637.3	9219.9	10887.4
25	EW	9580.3	634.1	10214.4	11887.4
	NE	8687.0	647.4	9334.4	10978.5
	NS	8671.6	637.1	9308.7	10983.4
	NW	8654.7	636.5	9291.2	10947.7
	SE	9657.9	642.5	10300.4	11984.5
	SW	9655.1	634.8	10289.9	11980.0
	NSW	8939.3	702.6	9641.9	11251.6
	NSE	8948.2	709.2	9657.4	11258.7
	EWS	9581.8	704.0	10285.8	11903.2
	EWN	8943.2	704.3	9647.5	11241.7
	NSEW	9080.7	634.6	9715.3	11389.9
30	EW	10168.9	633.2	10802.1	12478.6
	NE	9067.8	644.2	9712.0	11359.4
	NS	9121.3	635.6	9756.9	11437.0
	NW	9037.3	634.7	9672.0	11329.8
	SE	10303.7	639.9	10943.6	12636.5
	SW	10314.3	633.5	10947.8	12643.8
	NSW	9382.9	698.8	10081.7	11736.0
	NSE	9386.7	704.7	10091.4	11739.2
	EWS	10161.1	700.2	10861.3	12526.1
	EWN	9353.4	700.5	10053.9	11688.9
	NSEW	9577.3	632.9	10210.2	11889.6

3.3.3 Building energy performance in Chennai

Energy consumption of the building without daylight integration and with daylight integration for different window combinations in Chennai is shown in figure 3.15 and figure 3.16 respectively. From the result it is found that daylight integration reduces energy consumption in all window combinations. Similar to Kolkata and Delhi, WWR of building for different window combinations can be increased compared to reference building as a result of daylight integration. Energy consumption in each window combination in Chennai is shown in table 3.5.

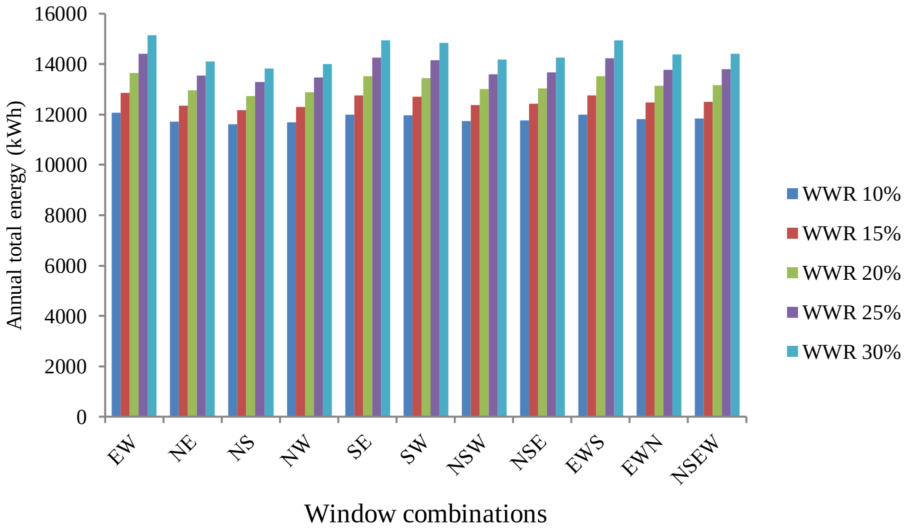

Figure 3.15: Annual total energy consumption without daylight integration in Chennai.

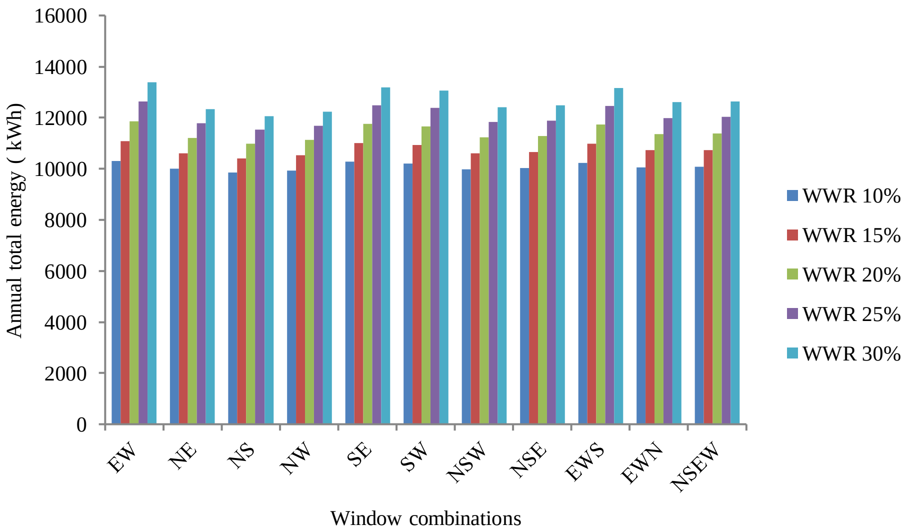

Figure 3.16: Annual total energy consumption with daylight integration in Chennai.

Table 3.5: Annual energy consumption for different window combinations in Chennai.

WWR (%)	Window Combination	With daylight			Without daylight
		Annual Cooling Energy(kWh)	Annual Lighting Energy(kWh)	Annual Total Energy(kWh)	Annual Total Energy(kWh)
10	EW	9659.2	645.9	10305.1	12068.2
	NE	9321.9	687.0	10008.9	11719.3
	NS	9203.3	652.3	9855.6	11608.1
	NW	9286.7	652.9	9939.5	11688.4
	SE	9590.9	681.6	10272.4	11994.4
	SW	9551.4	650.4	10201.8	11959.9
	NSW	9339.5	647.6	9987.1	11745.6
	NSE	9362.6	660.4	10023.0	11767.4
	EWS	9591.9	649.6	10241.5	12001.0
	EWN	9413.6	650.1	10063.7	11818.8
	NSEW	9423.4	652.7	10076.1	11829.7
15	EW	10454.7	638.3	11093.0	12865.5
	NE	9940.8	662.6	10603.4	12342.6
	NS	9775.0	641.3	10416.3	12181.2
	NW	9891.6	642.4	10534.0	12294.6
	SE	10354.5	660.0	11014.5	12762.8
	SW	10298.5	641.0	10939.5	12709.1
	NSW	9973.8	638.3	10612.1	12381.3
	NSE	10007.7	644.8	10652.5	12415.2
	EWS	10353.9	639.2	10993.1	12765.2
	EWN	10080.3	639.7	10720.0	12487.2
	NSEW	10096.6	641.0	10737.6	12504.9
20	EW	11235.2	634.8	11870.0	13646.0
	NE	10547.6	651.6	11199.1	12949.9
	NS	10336.3	636.9	10973.3	12741.6
	NW	10482.7	637.8	11120.4	12884.8
	SE	11107.2	650.0	11757.2	13516.5
	SW	11033.0	636.5	11669.5	13443.5
	NSW	10593.3	634.1	11227.4	13000.1
	NSE	10638.8	638.2	11277.0	13045.9
	EWS	11100.0	634.8	11734.8	13511.2
	EWN	10730.3	635.3	11365.6	13136.7
	NSEW	10753.3	635.8	11389.1	13161.3
25	EW	11999.7	633.0	12632.7	14409.1
	NE	11136.8	645.5	11782.3	13538.0
	NS	10885.4	634.7	11520.1	13288.7
	NW	11056.5	634.8	11691.2	13456.8
	SE	11843.0	644.3	12487.3	14251.6
	SW	11750.0	634.2	12384.2	14159.1
	NSW	11196.0	631.8	11827.8	13601.1
	NSE	11253.0	630.0	11883.0	13658.6
	EWS	11827.4	632.3	12459.7	14237.3
	EWN	11361.7	632.8	11994.5	13766.5
	NSEW	11391.3	632.9	12024.2	13797.7
30	EW	12748.1	632.0	13380.0	15155.4
	NE	11695.6	641.8	12337.4	14094.4
	NS	11421.7	633.3	12055.0	13822.3
	NW	11601.3	633.2	12234.5	13998.8
	SE	12547.9	640.6	13188.5	14954.6
	SW	12436.4	632.7	13069.1	14843.1
	NSW	11780.9	630.4	12411.3	14183.4
	NSE	11849.0	633.1	12482.1	14252.2
	EWS	12534.9	630.7	13165.6	14942.6
	EWN	11973.8	631.1	12604.9	14376.3
	NSEW	12009.4	631.0	12640.4	14413.5

3.3.4 Effect of latitude on building energy performance without daylight integration

Energy performance of buildings in Kolkata, Delhi and Chennai shows influence of latitude as well as the climatic condition of the locations. It is observed that energy consumption of the buildings in Chennai is considerably higher than that of Kolkata and Delhi when daylight is not integrated to control artificial lighting system of the building as shown in figure 3.17 to figure 3.21. The reason of higher energy consumption in Chennai is due to higher cooling energy requirement during the year. It is due to fact that Chennai (13° 4' N, 80° 14' E) is much closer to equator and hence heat gain of the building through north wall is more significant compared to Kolkata (22°33' N, 88°21'E) and Delhi (28° 38' N, 77° 13' E). It is also due to the fact that solar radiation in Chennai is higher than that of Kolkata causing higher heat gain of the building. The effect of huge heat gain through roof and building walls, relative humidity and effect of north wall due to lower latitude, cooling energy requirement in Chennai increases significantly which in turn increase total energy consumption of the building. Although solar radiation and ambient temperature of Delhi is higher than Chennai, but relative humidity in Delhi is much lower than Chennai which reduce the cooling load of the building in Delhi compared to Chennai. Moreover the effect of north wall on heat gain of the building is minimum due to higher latitude of Delhi. Energy consumption in buildings in Kolkata is significantly lower compared to Chennai due to relatively less impact of north wall of the building as well as the solar radiation in Kolkata is comparatively low. But the amount of humidity in Kolkata is very high which increase the cooling load of the building contrary to Delhi where low humidity reduces cooling energy consumption of the building. Window is the thermally weak part in the building envelope. Presence of window and its orientation on building envelope influences building energy consumption. It is found that the presence of window in north orientation reduces building energy consumption in all three locations as the structural heat gain through north surface due to solar radiation is least among all the building surfaces. Impact of north window on energy consumption of the building is higher in comparatively higher latitude. The impact of north window is more prominent with higher WWR of the building in all the study locations compared to window on other directions.

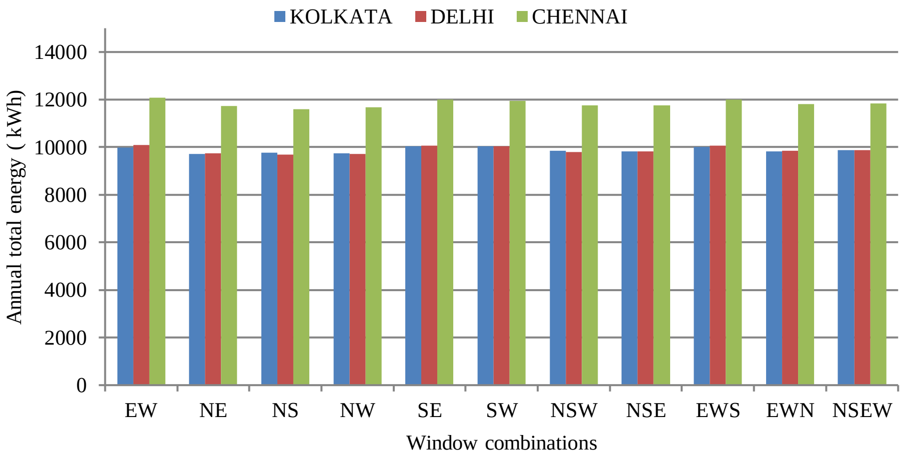

Figure 3.17: Energy consumption of the buildings with 10% WWR

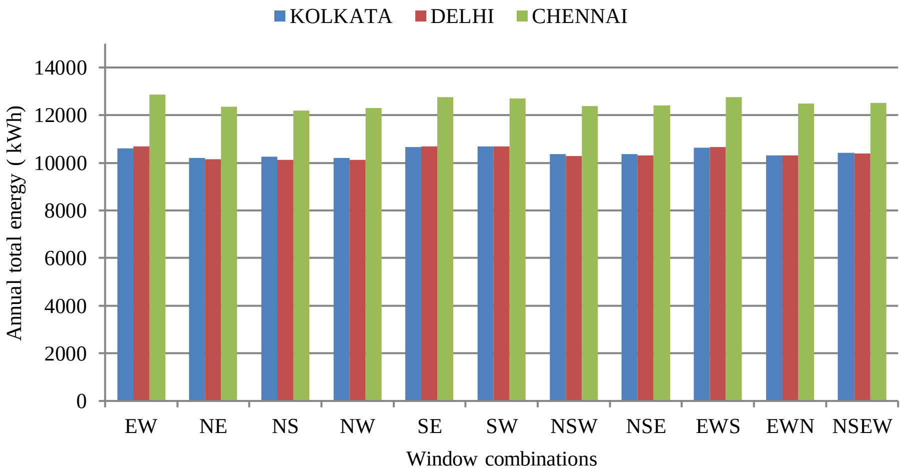

Figure 3.18: Energy consumption of the buildings with 15% WWR

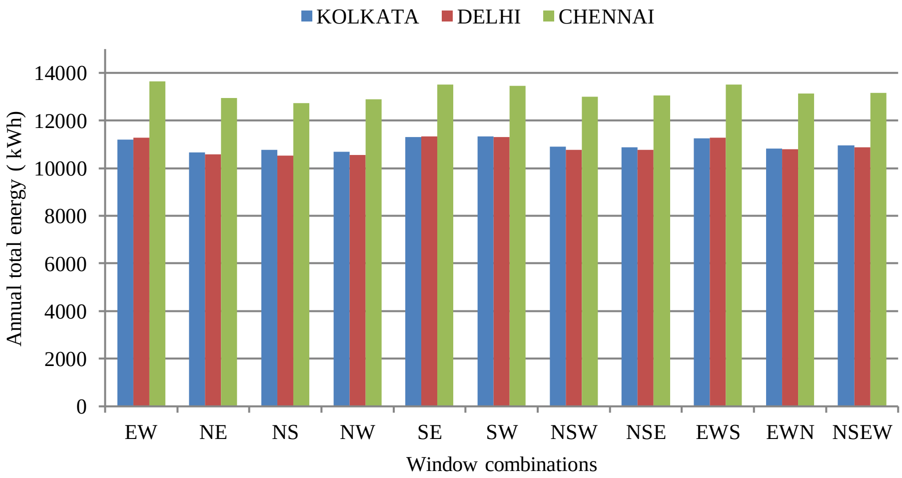

Figure 3.19: Energy consumption of the buildings with 20% WWR

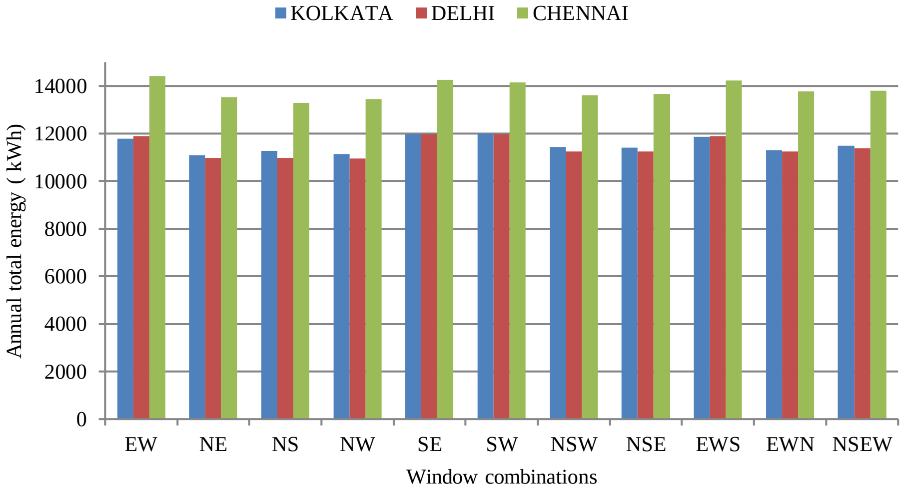

Figure 3.20: Energy consumption of the buildings with 25% WWR

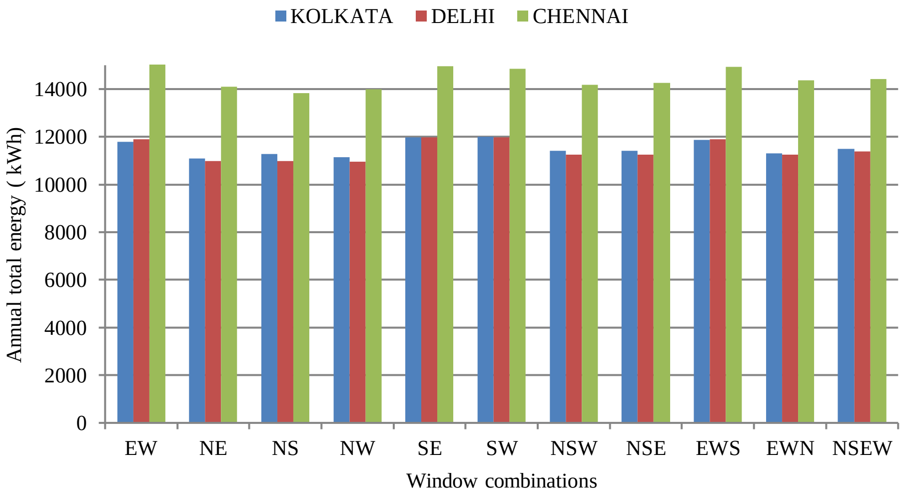

Figure 3.21: Energy consumption of the buildings with 30% WWR

3.3.5 Effect of latitude on building energy performance with daylight integration

Lighting energy consumption of building reduces when daylight through the window combination is integrated to control artificial lighting system of the building. Reduction of lighting energy consumption reduces internal heat gain of the building due to lighting which also reduces cooling load of the building. Reduced lighting energy consumption also reduces total energy consumption of the building in all three study locations as shown in figure 3.22 to figure 3.26. Increasing the window area or WWR increases daylight into the building which reduces lighting energy consumption of the building but it adds heat load into the building which increases the cooling load of the building. Impact of window orientation is noticed from the energy consumption of building with different window combinations. Effect of north window is observed as the solar radiation on north window is comparatively low among the building surface and depends on latitude of the location. Increasing window area in north increase less energy consumption of the building compared to other orientation as observed in the result.

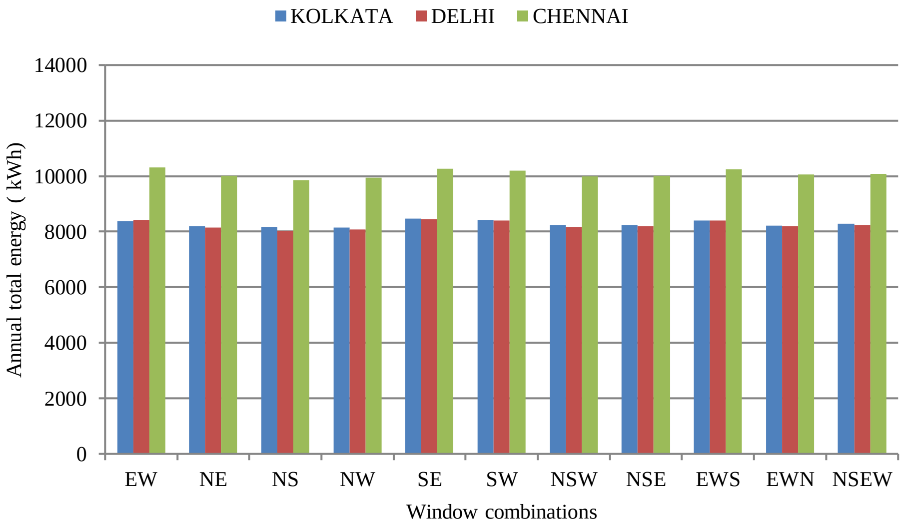

Figure 3.22: Energy consumption of the buildings with 10% WWR with daylight

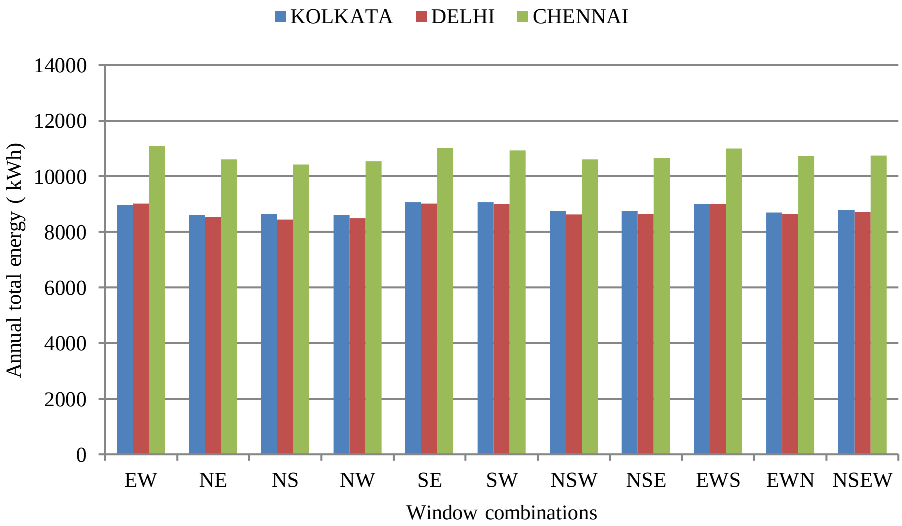

Figure 3.23: Energy consumption of the buildings with 15% WWR with daylight

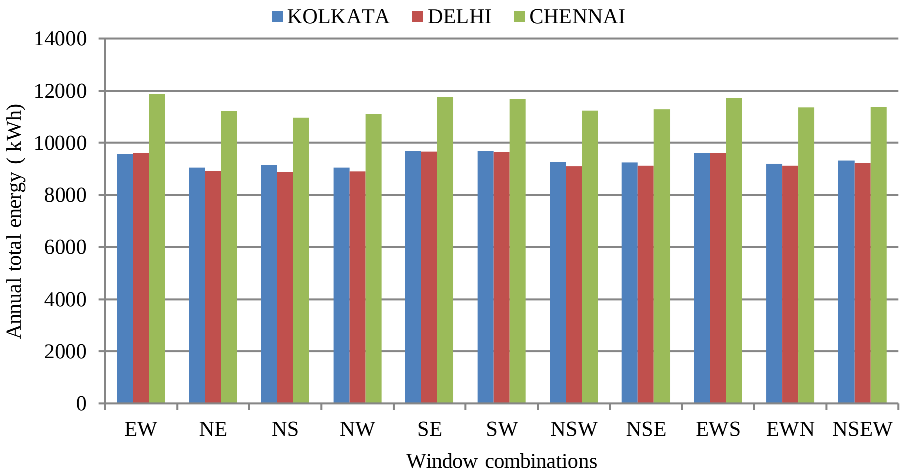

Figure 3.24: Energy consumption of the buildings with 20% WWR with daylight

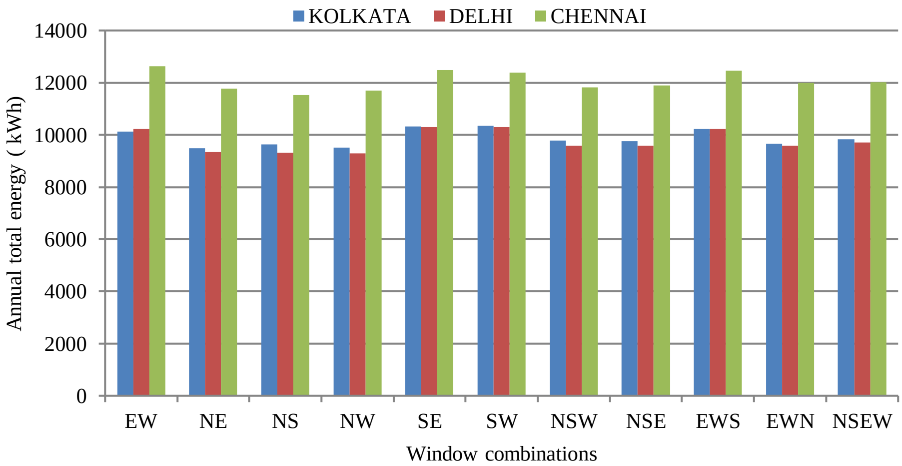

Figure 3.25: Energy consumption of the buildings with 25% WWR with daylight

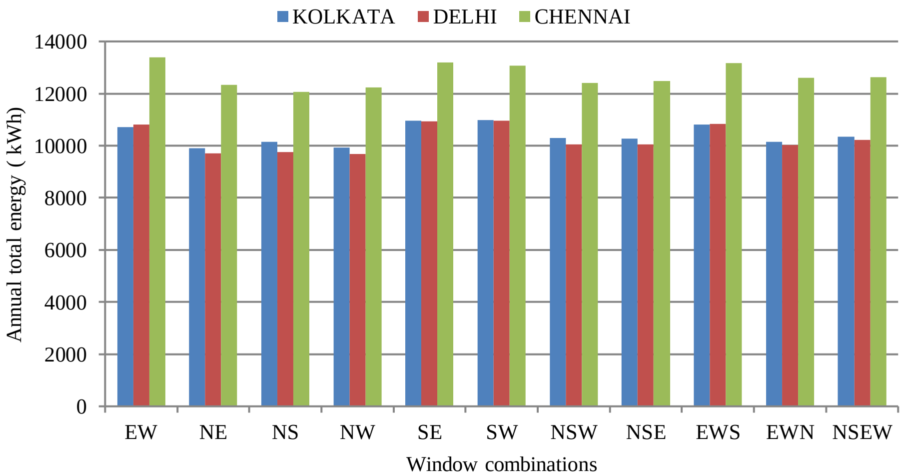

Figure 3.26: Energy consumption of the buildings with 30% WWR with daylight

3.3.6 Determination of optimum window size

In present study optimum use of window glazing area or WWR is investigated for each combination of window in the study locations. In each window combinations optimum value of WWR is calculated so that the total energy consumption of the building do not exceeds total energy consumption of reference building in the study location. Linear regression method is used to evaluate the optimum WWR of the window glazing for all window combinations. Table 3.6 shows the optimum value of WWR for different window combinations as a result of daylight integration into the building in Kolkata, Delhi and Chennai. In Kolkata, optimum value of WWR is maximum with NE and NW combinations. In Delhi, optimum value of WWR is maximum with NW combination where as in Chennai optimum value of WWR is maximum with NS combination. In all three locations, higher value of optimum WWR is possible with NE, NW, NS, EWN, NSW, NSE and NSEW combinations but EW, SE, SW and EWS combination shows comparatively lower value of optimum WWR. From result it is observed that incorporation of window glazing in north wall is beneficial for achieving higher WWR when daylight is integrated into the building.

Table 3.6: Optimum WWR in Kolkata, Delhi and Chennai

Window Combination	Optimum WWR (%)		
	Kolkata	Delhi	Chennai
EW	25	24	20
NE	32	34	26
NS	30	34	29
NW	32	35	27
SE	23	23	21
SW	23	23	22
NSW	28	30	26
NSE	28	30	25
EWS	24	23	21
EWN	30	30	24
NSEW	28	28	24

3.4 Conclusion

Modern commercial buildings uses considerable amount of glazing to allow daylight and to improve aesthetic view. Increasing the glass area causes additional heat load into the building space although it reduces lighting energy consumption of the building. It is desirable to determine optimum window glazing area for different window combinations in the building. From the present study, it is evident that the energy savings can be possible with the integration of daylight into the building. The study shows glazed surface area in a building can be increased without additional energy cost as result of daylight integration. Result of the study identifies the window combinations with the higher and lower optimum WWR. The study specifically provides the optimum WWR for different window combinations in Kolkata, Delhi and Chennai.

4. Energy savings in building and daylighting

4.1 Introduction

The buildings and buildings construction sectors consumes more than one third of the global final energy use **(Mengxue et al, 2019)**. The building sector in India is experiencing an unprecedented growth from the last few years. In India, building sector is responsible for 38% of total annual primary energy consumption and 31% of the total annual electricity consumption **(AEEE, 2017).** Energy demand in India is increasing rapidly with the economic development which results more and more emission into the environment. To meet the ever increasing energy demand, conservation of energy in different sectors is essential. At the same time zero or very low emission alternatives for different sectors are required for sustainable development. Emission due to energy consumption is a big threat to the environment hence a lot of research work is going on to find suitable alternatives to reduce emission due to use of energy in different sectors **(Ahmed et al,2023; Birgit et al, 2015; Paul et al, 2018).** The application of solar architectural strategy reduces the carbon footprint and energy consumption of buildings. Passive strategies such as optimal building orientation, envelope materials and shading devices are useful means to save building energy consumption (**Elistratov et al, 2023)**. Passive solar strategies are helpful to design energy efficient building **(Zakhidov, 2007).** Building geometry and building envelope is one of the suitable areas of research for energy conservation in building sector. Orientation and location of buildings in India has the potential to conserve energy **(Renuka, 2022).** The major electric loads in a building are lighting, air conditioning, and equipments.

Perez-Lombard et al stated that the energy consumption by both residential and commercial buildings in developed countries account for 20-40% of total energy used. Those energies are mainly used for space heating and cooling for residential buildings and lighting for commercial buildings **(Luis et al, 2008).** Halimov et al. studied on reconstruction of windows and other construction materials of building to optimization on supplying energy to rural residential buildings in Uzbekistan **(Halimov et al, 2020).** Building energy consumption is closely related to building envelope material and its thermal and optical properties. In modern buildings, utilization of window glazing is increasing to allow daylight for indoor space as well as for better aesthetic view. Daylighting in buildings has substantial impact on health **(Jeong et al, 2013; Gon et al, 2010)**, productivity and performance of the occupant **(Danny et al, 2003).** Integration of daylighting systems can save lot of lighting energy as reported in many research papers but the glass surface as a window in the building allows lot of heat inside the indoor working space.

Many research work are noticed India to evaluate the benefit of daylight integrations in commercial buildings in India. Daylight integration into Indian building and through window combinations has been studied in three different locations in India. Application of daylight increases energy savings in all three locations **(Biswas et al, 2024).** Application of daylight for energy savings in India have been evaluated by many researchers **(Sudan et al, 2016; Debnath et al, 2016).** Potential of daylighting in reducing lighting load of building in Indian have been evaluated for four different types of windows and for three different climatic conditions of India **(Singh et al, 2010).** Research work on Optimization of daylight performance has been conducted in view of energy savings in Indian climatic conditions **(Kalaimathy et al 2023).** In a study annual energy saving due to rooftop window for different climatic locations in India has studied and considerable savings in energy consumption **(Sudan et al, 2015)**.

Daylightinig and heat gain of the building depends on optical, thermal and geometrical parameter of the window glazing. The increasing window to floor area ratio allows the reduction of annual required heating energy. Inversely, the annual cooling energy requirement increases with increasing the windows to floor area ratio. This is due to the effect of the unwanted solar heat gain into the building space. Larger window area may increase the indoor space temperature to levels higher than the ambient temperature **(Guechchati et al, 2012).** Sujoy Pal et al. developed a mathematical model of one dimensional heat flow into the building space through the window glazing in a tropical climatic condition in India **(Pal et al, 2009).** Aritra et al. measured thermal & daylight performance of evacuated and vacuum glazing in a cold climate zone **(Aritra et al, 2016).** J.O. Aguilar et al also simulated a room in the middle of a multi-storey building with double glazing windows in Mexico to quantify the energy performance of different glass window **(Aguilar et al, 2017).** Kiran et al. mentioned the role of different window glazing materials and their orientation in four different climatic zones in India in terms of energy consumption **(Kiran et al, 2017)**. Singh et al. worked on energy rating of different window glazing materials having different thermal and optical properties for Indian climates on three different types of buildings depending on envelope construction and application of to the wall **(Singh et al, 2009).** Lot of research work have been performed on different improved glazing unit such as double glazing, vacuum glazing, reflective glazing, low-e glazing etc in different climatic conditions. Such high performance glass façades were investigated in tropical climatic zone of Singapore. It is observed that the cooling energy savings with improved glazing for the whole year may goes up to 60% compared to clear float glass **(Bui et al, 2017)**. In a similar study, the influence of different type of insulating glazing compared to clear glass was studied in Amman, Jordon. The study was conducted to evaluate the effect of glass area on energy consumption of a building in different orientation **(Hassouneh et al, 2010).** Andrea et al. worked on the analysis and modelling of window and glazing systems in terms of energy performance in a well insulated residential building. Impact of different kinds of glazing systems, window size (from 16% to 41% of window to floor area ratio), orientation and internal gains on winter and summer energy need and peak loads for the climatic condition of Paris, Milan, Nice and Rome were studied **(Andrea et al, 2011)**. Ramit et al. conducted study on daylight performance of a naturally ventilated building at Mumbai, India and mentioned that the effect of window glazing for daylighting are maximum when the window is placed at south east orientation for the particular location **(Romit et al, 2017)**. Along with orientation, window-to-wall ratio (WWR) is also an important factor for building energy. Increasing WWR of a building allows more heat and daylight inside the working space. As a result of higher heat gain of the indoor space, cooling energy demand of the building increases. Thermal performance of different orientation and window to wall ratio in public rental housing in Hong Kong was evaluated in EnergyPlus simulation software by Siu et al. **(Sui et al. 2017)**. Doris et al. studied on design optimization of perforated solar façades in order to balance daylighting with thermal performance. The study mentioned the way to achieve the annual overall balanced solution between daylighting and thermal performance of perforated solar screen **(Doris et al, 2017)**. Daylight admission and heat gain through the window glazing system of the building depends on optical parameters and thermal parameter of the glass used to construct the window. Besides window to wall ratio, visible transmittance, U-value and solar heat gain coefficient (SHGC) are parameters of the glass responsible for daylighting and heat gain through the window. Louis et al performed a series of correlation among SHGC, U and VT to develop a linear model with a limited number continuous variable for selecting suitable window glazing for the building **(Louis et al, 2017)**. Zakirullin et al. proposed a method to minimize direct solar radiation inside the building using optical filter placed on window glazing of the building. The filter used on the window system provides comfortable daylight into the building space by blocking the direct radiation and transmitting the diffuse radiation without using daylight redistribution devices **(Zakirullin et al, 2019).** Elisa et al. mentioned that application of solar control film on window glazing in moderate climate reduces 60% solar radiation through the window which results decrease in cooling energy demand by 29% and the heating energy increases by 15% **(Elisa et al, 2015).** Integration of daylighting with artificial lighting of the building certainly reduces the lighting energy consumption of the building. In a study in Saudi Arab reveals that the daylighting integration into the building reduce lighting energy up to 71% depending on the types of the window glazing used. It was also observed that total energy consumption of the building reduces up to 15.8% **(Mohammed et al, 2015)**. Li et al. carried out detailed studies on key building parameters affecting the daylighting designs, and found out that daylighting performance in office buildings as well as school buildings where 25% of the total electric lighting energy consumption could be saved with the integration of daylighting **(Li et al et al, 2008).** Bodart et al. developed a calculation model to predict the energy consumption of the building when daylight is linked with artificial lighting system. It is mentioned that daylight could reduce the energy consumption of artificial lighting system by 50 - 80% **(Bodart et al, 2002)**. Li et al. discovered that with the application of high frequency dimming control of daylighting equipment, the artificial lighting energy consumption could be reduced by more than 30% (**Li et al et al, 2006**). Gene et al. investigated daylight performance and users visual appraisal for two green building offices in Malaysia. It is found that both the Office buildings in Malaysia saves 53% and 41% lighting energy as a result of daylight integration **(Gene et al, 2017).**

From the literature survey it is found that a number of study related to daylighting were carried out on window glazing system and most of the work concentrated on the points such as daylight linked lighting system, window orientation, locations and climate conditions, window glazing materials, window to wall ratio (WWR), window aspect ratio, heat gain and cooling and heating load etc. A little attention was paid to the combination of windows for daylighting and its effect on energy consumption of the building. This work focuses on the savings of building energy consumption in Indian context following National Building Code in India 2016 **(NBC, 2016)** and Energy Conservation in Building Code 2017 in India **(ECBC 2017)**. Hence the present work is an attention on energy performance of window combination as daylighting system in a building and potential of daylight in energy saving in India.

4.2 Methodology

In the present study the benefit of integration of daylight in building through different window combinations were investigated and compared with a reference building for energy savings. The location of the present study is Kolkata, India and the results are validated with two different locations Delhi and Chennai. The reference building is modelled according to NBC and ECBC code in India where a single window is placed in south orientation. Lighting cooling and total energy consumption of the reference building is simulated in EnergyPlus building energy simulator. Total energy consumption of the reference building is the sum of annual lighting and cooling energy consumption of the building. This total energy consumption is the benchmark to quantify the energy saving in of the building models under study.

The building models under study consist of eleven number of different window combinations. The building model with windows in east and west wall, it is termed as EW combination. In similar way NE combination (North, East), NS combination (North, South), NW combination (North, West), SE combination (South, East), SW combination (South, West), NSW combination (North, South, West), NSE combination (North, South, East), EWS combination (East, West, South), EWN combinations(East, West, North), NSEW combination (North, South, East, West) were formed. All the building models were simulated for energy performance with five different WWR (10%, 15%, 20%, 25% and 30%). Three different daylight cases are incorporated into the study.

Case 1: Daylight is permitted to enter the building space; however, the artificial lighting system is not regulated in response to the available daylight within the interior space. As a result, the lighting system operates independently of natural illumination. The energy consumption associated with both lighting and cooling has been calculated under these conditions.

Case 2: Daylight is allowed to enter the building space through the window glazing, and the artificial lighting system is automatically controlled based on the available daylight at the reference points (greater than 500 lux). Under these conditions, the energy consumption associated with both lighting and cooling has been calculated.

Case 3: Daylight is permitted to enter the building space through the window glazing in a controlled manner, with the use of external shading devices to minimize excessive heat gain. In addition, the artificial lighting system is automatically regulated based on the available daylight at the reference points (greater than 500 lux).Under these conditions, the energy consumption associated with both lighting and cooling has been calculated.

All building models are simulated with weather data of concern study locations and energy consumptions of the building models are obtained. Energy Savings of the building models compared to reference building is calculated as shown in figure 4.1. In all the cases data of cooling energy, lighting energy and total energy are taken and compared to the energy consumption of the reference building. Energy savings due to distribution of window in different cardinal direction and daylight integration with artificial lighting system were computed in Kolkata (22°33' N, 88°21'E) which is located in worm and humid climatic zone in India **(ECBC 2017).** The results were validated with two more locations Chennai (13° 4' N, 80° 14' E) situated at lower latitude and Delhi (28° 38' N, 77° 13' E) situated at higher latitude compared to Kolkata. Cooling and lighting energy of the building model is influenced by daylight penetration into the building space through the window. It is influenced by the optical and thermal properties of the glazing material used in the window.

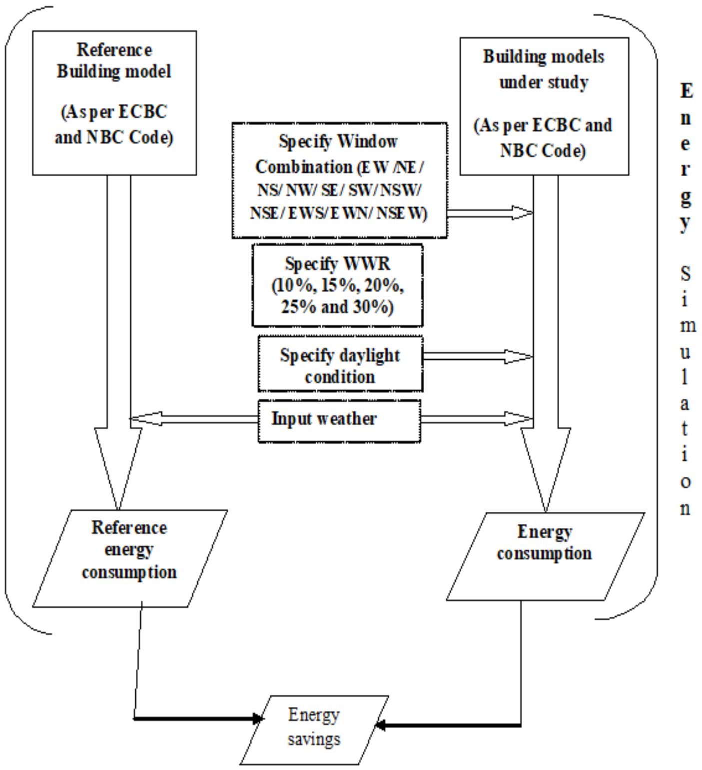

Figure 4.1. Overview of the present work.

4.2.1 Solar radiation on window surface

The solar radiation on window surface plays an important role on daylighting in building. Daylighting has substantial impact on energy consumption of building. Solar beam radiation (I_b) received by any surface is given by

$$I_b = I_{bn}\, cos\theta \qquad (4.1)$$

Here cos θ is given by the following equation **(Duffie and Beckman, 2006)**:

$$\cos\theta = \sin\emptyset(sin\delta\; cos\beta + \cos\delta\cos\gamma\cos\omega\cos\beta) + \cos\varphi\,(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta \qquad (4.2)$$

The amount of global radiation on a surface of a building considering isotropic sky is given by

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r \qquad (4.3)$$

Solar radiation received on a surface considering anisotropic sky is given by **(Duffie and Beckman, 2006)**:

$$I_T = (I_b + I_d A_i)R_b + I_d\,(1 - A_i)\frac{(1+cos\beta)}{2}\left[1 + f\; sin^3\frac{\beta}{2}\right] + I\rho_g\left(\frac{1-cos\beta}{2}\right) \qquad (4.4)$$

Where R_b is tilt factor of beam radiation, R_d is tilt factor of diffusion radiation, R_r is tilt factor of reflected radiation and A_i is anisotropy index which is nearly equal to 1.

$$R_b = \frac{cos\theta}{cos\theta_z} \qquad (4.5)$$

$$R_b = \frac{1+cos\theta}{2} \qquad (4.6)$$

$$R_r = \rho_g\left(\frac{1+cos\theta}{2}\right) \qquad (4.7)$$

In the case of window, β is 90^0 and the equation (4.2) will become

$$cos\theta = sin\emptyset\; cos\delta\; cos\gamma\; cos\omega - cos\emptyset\; sin\partial\; cos\gamma + cos\delta\; sin\gamma\; sin\omega \qquad (4.8)$$

If the window is south oriented then the surface azimuth angle is zero hence the equation (4.8) is transformed into

$$cos\theta = sin\emptyset\; cos\delta\; cos\omega - cos\emptyset\; sin\partial \qquad (4.9)$$

Heat gain due to solar radiation on window surface of building depends on optical and thermal properties of window glazing as well as area of window on the building wall. At morning and afternoon, maximum daylight will enter through east and west windows respectively. From equation (4.8) it is clear that solar radiation on window surface in a particular direction at a given time depends on declination of earth and latitude of the location. . Declination angle of any location for a particular day (N) in year can be found from the following equation **(Duffie and Beckman, 2006)**:

$$\delta \text{ (in degree)} = 23.45 \,\text{Sin}[360(284+N)/365] \qquad (4.10)$$

Daylight through south window in Kolkata is more compared to north window as high beam solar radiation flux on south window. North window receives a very less amount of direct beam solar radiation for very limited days due to its declination and latitude. In Delhi north wall does not receive any beam solar radiation throughout the year. In Chennai, due to lower latitude and declination considerable beam radiation is received for certain period of time in the year on north window. In Chennai solar radiation receives in south window is comparatively less compared to higher latitude location Kolkata and Delhi

Penetration of daylight into the building will depend on the profile angle of sun and angle of incidence of solar radiation on window surface. Angle of incidence of beam solar radiation on south window can be calculated at solar noon for all three locations using the equation (4.9). Calculated angles of incidence of beam radiation on the south window in Chennai, Kolkata and Delhi on 10th May at solar noon are 84.4^0, 74.9^0 and 68.8^0 respectively shown in figure 4.2.

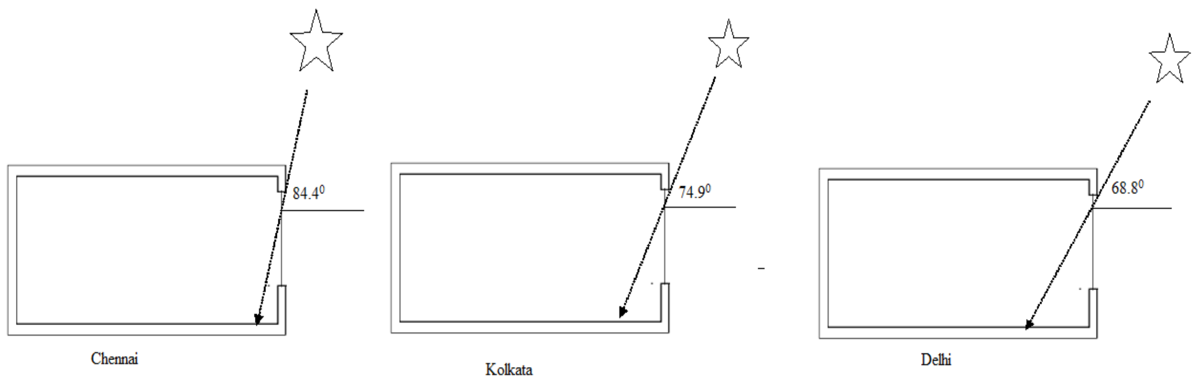

Figure 4.2. Angle of incidence of beam radiation on 10th May in Chennai, Kolkata and Delhi.

4.2.2 Properties of glass sample for window

Optical properties of window glazing are a deciding factor for daylight availability into the building space. The glass material used in window of the building models for the present work was 4 mm clear glass. The experimental study of the spectral transmittance of the glass sample was conducted in UV and Visible wavelength region using a Perkin-Elmer Lambda-35 Spectrophotometer as shown in figure 4.3. Clear glass sample were collected from the market to evaluate the spectral optical parameters. The samples were properly sized into a small piece of 25 mm X 25 mm as shown in figure 4.4. Spectral data from the spectrophotometer was used to calculate solar optical properties according to Indian Standard

(IS 2553, 1990) and British Standard **(BS EN410, 1998)**. Spectral transmittance of clear glass under study as plotted against wavelength is shown in figure 4.5.

Figure 4.3. Perkin-Elmer Lambda-35 Spectrophotometer.

Figure 4.4. Glass sample for the study.

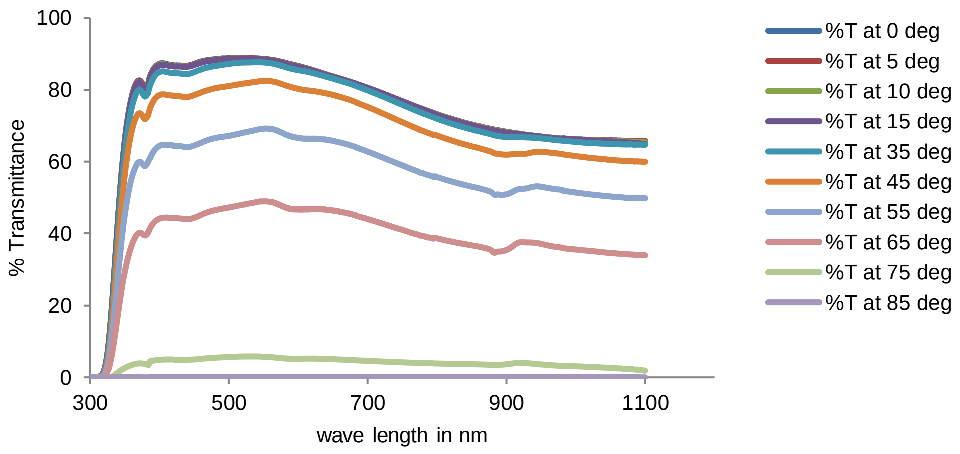

Figure 4.5. Spectral transmittance of clear glass under study.

Optical transmittance and reflectance of the of clear glass can be evaluated from the following equation **(IS 2553, 1990; BS EN410, 1998)**

$$\tau_\lambda = \frac{\sum_{\lambda=380}^{\lambda=780} D_\lambda\, \tau(\lambda) V(\lambda)\, \Delta\lambda}{\sum_{\lambda=380}^{\lambda=780} D_\lambda V(\lambda)\, \Delta\lambda} \qquad (4.11)$$

Where D_λ is the relative spectral distribution of illuminant D_{65}; $\tau(\lambda)$ is the spectral transmittance of the glazing; $V(\lambda)$ is the spectral luminous efficiency for photopic vision defining the standard observer for photometry and $\Delta\lambda$ is the wavelength interval. A software code is developed to determine transmittance of the glass according to the standard. Visible transmittance of the glass sample under study is 87.8% at normal incident of light this value is used into the present simulation study. The U-value and solar heat gain coefficient (SHGC) the glass sample are 5.8 W/m^2K and 0.79 respectively which has been collected from manufacturer data. These optical and thermal data were incorporated into building models under study.

4.2.3 Properties of building materials

The reference building model of 9 m X 9 m X 3 m has been developed for building energy simulation for all three the locations in India **(Singh et al, 2009).** The model was constructed as per the specifications mentioned at National Building Code of India and Energy Conservation Building Code 2017. The walls roof and floor of the building model is constructed with a number of layers of different material suitable for Indian climatic condition and following ECBC 2017 and NBC 2016 code existing in India. The window area 10.8 m^2 (WWR=10%) of 4mm clear glass is placed in the south wall of the reference building. Material used in the building model with specifications and properties are mentioned in table 4.1.

Table 4.1. Properties of construction materials used in the building under study

Components	Layers (from outside to inside)	Thickness (mm)	Conductivity (W/m-K)	Density (kg/m^3)	Specific heat (J/kg-K)
Walls	Cement plaster	13	0.721	1762	840
	Brick	254	0.811	1820	880
	Cement plaster	13	0.721	1762	840
Roof	RCC	135	1.58	2280	880
	Cement plaster	13	0.721	1762	840
Floor	Brick	254	0.811	1820	880
	Concrete	101	1.78	2410	880
	Cement	13	0.721	1762	840

The building models under study are designed with same specification and same materials as reference building. These building models have been studied with five different window to wall ratio (WWR) namely 10%, 15%, 20%, 25% and 30% and three different daylight conditions. The WWR of the building model are calculated following the NBC code of India. The window is made of clear glass with U-value of 5.6 W/m^2K, solar heat gain coefficient (SHGF) of 0.79 and visibl e transmittance (VT) of 87.8%. Glass area was equally distributed to different wall to investigate the impact of combination of window glazing on building energy performance. In all combination the window sill height is fixed to 1m above the floor height complying with the NBC code in India **(Birgit et al, 2016).**

Internal gain of the building from lighting is fixed to 9.5 W/m^2 **(ECBC, 2017)** and constant ventilation with outside air of 0.5 air change per hour **(Singh, 2009)** has been considered. The building model is meant for 10 hours of operation from 08:00 am to 06:00 pm **(Moncef et al, 2005; ECBC, 2017)** and the indoor temperature is controlled to 25^0 C with the help of HVAC system **(Singh, 2009)** . The artificial lighting of the building is linked to delighting to reduce the energy consumption of the building. A continuous dimming control of artificial lightings is so designed based on daylight through window combinations at reference points. The reference point to control lighting system is at 3m and 6m away from the window and at 0.8m above the floor area. Reference point illumination has been taken as 500 LUX to control the artificial lighting system of the building **(Syahrul et al, 2015; Raphaela et al, 2013; Cammarano et al, 2014)**. Dimming of the artificial lights are continuous and linearly from maximum light output to minimum light output as the daylight illuminance increases continuously **(Li et al, 2003; Moncef et al, 2005)**. At minimum dimming level the light output of the artificial lighting is fixed to 30% of its full illumination and further increase in the daylight illuminance will not dim the artificial lighting **(Eric et al, 2014)**. In case 3, daylight is controlled with external shading to the window. Horizontal blind with fixed slat angle of 45^0 is used to controlled daylight into the building space **(Raphaela et al, 2013).** In the blind, slat width is 2.5 cm, slat thickness is 1mm, slat separation is 18.75cm, and front and back side reflectance is 0.8.

4.2.4 Energy simulation of building

A number of simulation tools for building energy simulator such as EnergyPlus, DesignBuilder, DOE2, ECOTECT, TRNSYS, Energy Quest, BSim used to analysis building energy performance. In the present study EnergyPlus has been used as the building energy simulator. EnergyPlus is a whole building energy simulation software which is used to evaluate energy performance in buildings. EnergyPlus was developed by the Department of Energy (DoE), USA. DOE-2 and BLAST programs have been used to develop EnergyPlus building energy software. Building models under investigation has been simulated for the weather condition of Kolkata situated at 22.57^0 N, 88.36^0 E. The results of the simulation study has been validated with results of Delhi situated at 28.7°N, 77.1°E and Chennai 13° N, 80.2° E. Cooling, lighting and total energy consumption of all the building models are calculated from the result to identify the effect of window combinations, window area and daylight integration into the buildings.

4.3 Results and discussion

Cooling, lighting and total energy consumption of reference building is found from the energy simulation of the reference building. It is found that annual cooling energy consumption in reference building in Kolkata, Delhi and Chennai are 8092.5 kWh, 8051.7 kWh and 9895.6 kWh respectively. Annual lighting energy consumption in reference building is 2008.4 kWh in all three locations as there was no lighting control incorporated in the reference buildings during the hours of operation. Total energy consumption of the reference buildings are 10101 kWh, 10060.1 kWh and 11904 kWh in Kolkata, Delhi and Chennai respectively. These annual energy consumptions are considered as reference to calculate energy savings of the buildings with different window combinations, WWR and daylight conditions. All the building models were simulated for the weather condition of Kolkata, Delhi and Chennai. The building models have been simulated for three different cases depending on daylight conditions.

In case 1: The building was simulated without any daylight integration with the artificial lighting system; daylight is allowed to enter into the building space through window.

In case 2: Daylight was integrated with the artificial lighting system to reduce the lighting energy consumption of the building.

In case 3: The daylight was integrated with artificial lighting system of the building in controlled way with external window shading to reduce heat gain and glare into the working space.

4.3.1 Result in Kolkata

4.3.1.1 Annual cooling energy consumption

Case 1: Annual cooling energy of the building models under study varies from 7719.5 - 10624.2 kWh. From the results, it is observed that annual total energy consumption is increasing with increasing WWR in Kolkata as shown in figure 4.6. Cooling energy consumption in NE, NS, NW, NSW, NSE, EWN and NSEW group of window combination is lower compared to SW, SE, EW and EWS combination of window. It is evident that presence of window in north orientation accounts for less cooling energy consumption. Maximum cooling energy consumption is found with the SW combination among all the window combinations.

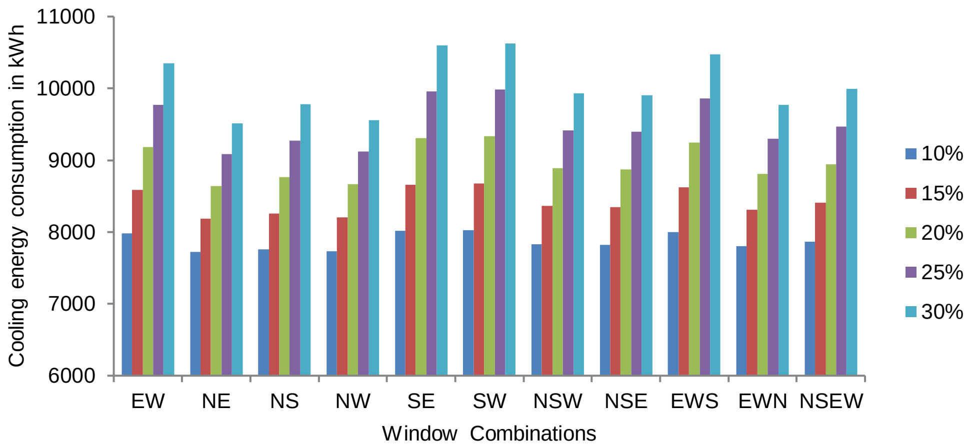

Figure 4.6. Annual cooling energy consumption in Kolkata in case 1.

Case 2: Daylight integration with the artificial lighting system significantly reduces lighting energy consumption of the building as artificial lighting system is controlled based on daylight availability into the building space. Annual cooling energy consumption is reduced compared to case 1 as a result of daylight integration. Figure 4.7 shows annual cooling energy consumption in Kolkata in case 2. Daylight through the window reduces lighting energy consumption and hence reduces internal heat generation of the building reduces. The reduction in heat generation inside the building due to artificial lighting system reduces the annual cooling energy of the building. Result shows the impact of window in north direction is similar as observed in case1. In this case annual cooling energy consumption of the building models under study varies from 7406.7 - 10270.1 kWh.

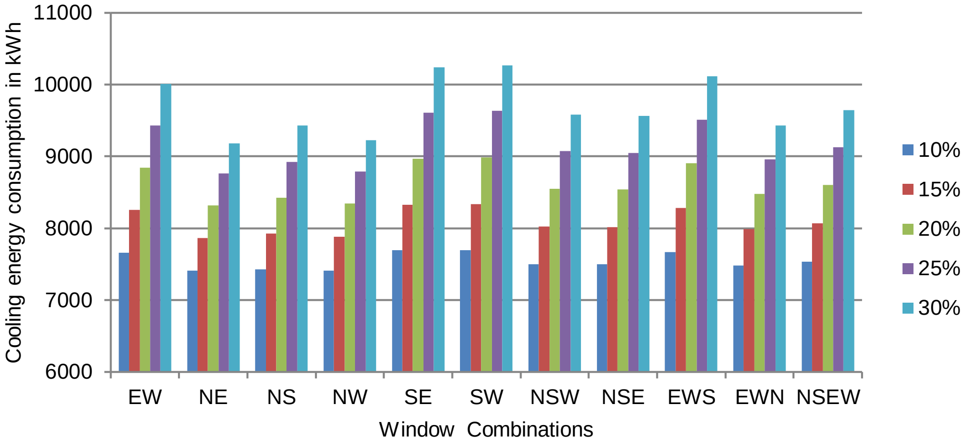

Figure 4.7. Annual cooling energy consumption in Kolkata in case 2.

Case 3: Daylight is integrated into the building in a controlled way with external shading. Controlled daylight further reduces cooling energy consumption of the building compared to previous case. It is found that the increase in cooling energy consumption with increase in WWR in is much lower compared to case 1 and case 2. Cooling energy consumption of different buildings under study varies from 6759.2 - 7098.9 kWh as shown in figure 4.8.

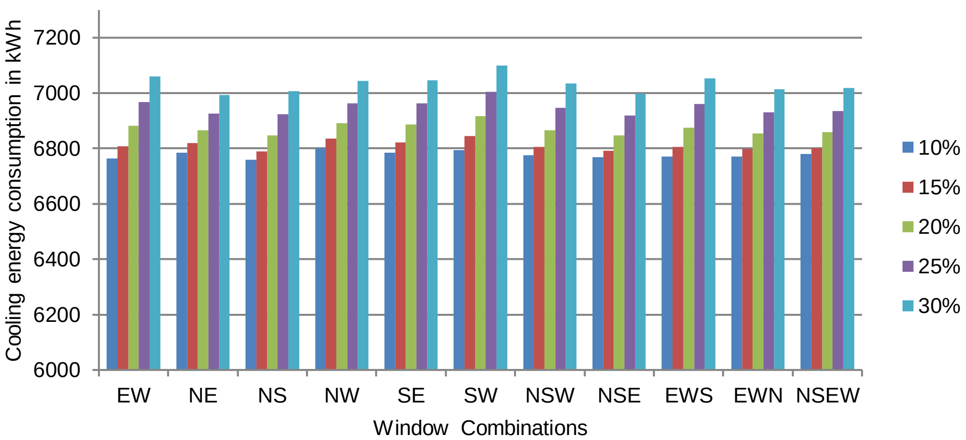

Figure 4.8. Annual cooling energy consumption in Kolkata in case 3.

4.3.1.2 Annual lighting energy consumption

Lighting energy consumption with three different cases is shown in figure 4.9. Annual lighting energy significantly reduced with daylight integration. Annual lighting energy consumption in case 1 is 2008.4 kWh and same for all window combination and WWR as there is no lighting control employed in this case. Lighting energy consumption in case 2 is reduced as a result of daylight integration and varies 700.1 kWh and 777.5 kWh. In case 3, lighting energy consumption for different window combination and WWR lies between 826 kWh and 1452.3 kWh.

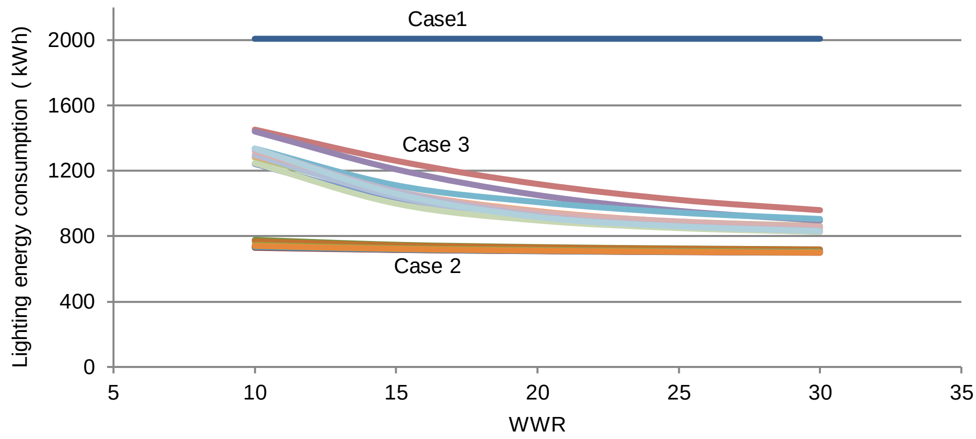

Figure 4.9. Annual Lighting energy in different cases in Kolkata

4.3.1.3 Annual total energy consumption

Case 1: Total energy consumption in case 1 is increasing with increasing WWR for all the window combinations. Similar to annual cooling energy, annual total energy consumption in NE, NS, NW, NSW, NSE, EWN and NSEW group of window combination is lower compared to SW, SE, EW and EWS combination of window. Influence of north window is also present in the total energy consumption of the building. Total energy consumption of the different buildings lies between 9727.9 kWh and 12632.6 kWh as shown in figure 4.10.

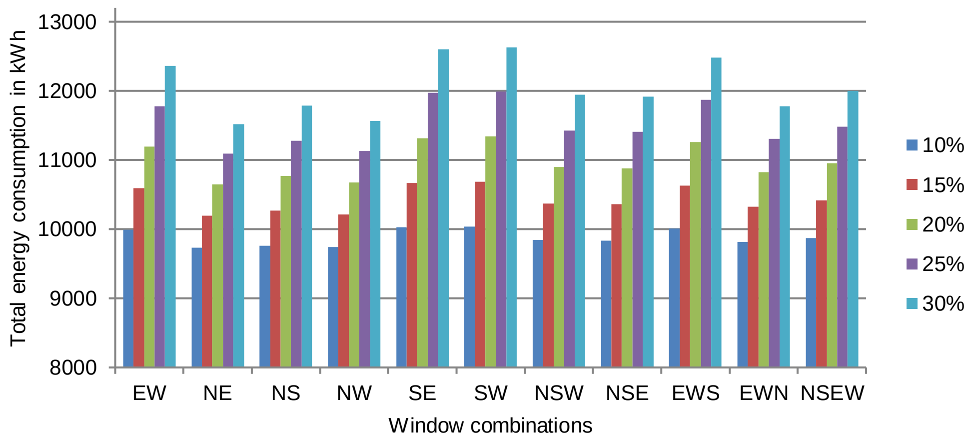

Figure 4.10. Annual total energy consumption in Kolkata in case 1.

Case 2: In this condition total energy consumption is reducing in all combination and in all WWR compared to case 1. Annual total energy consumption varies from 8164.7 -

10974.9 kWh for different window combinations and WWR as shown in figure 4.11. Effect of north window is also present in this case.

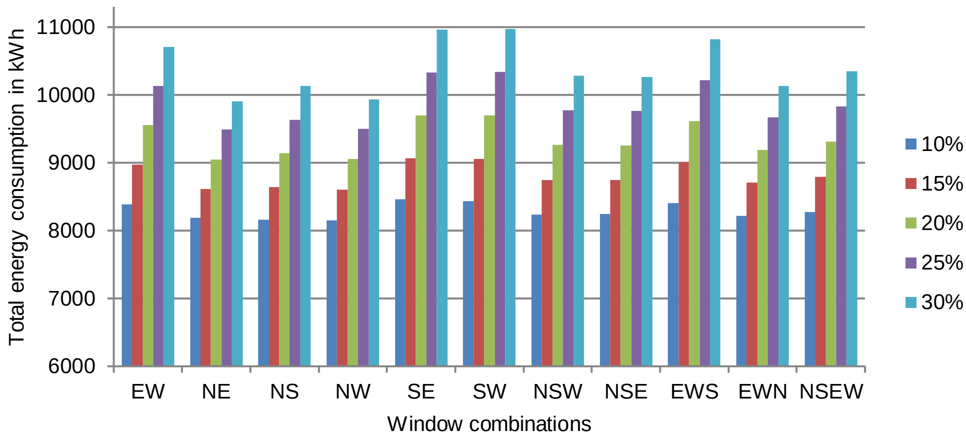

Figure 4.11. Annual total energy consumption in Kolkata in case 2.

Case 3: When daylight is integrated in a controlled way with external shading, total energy consumption decreases with increasing WWR and reaches to a minimum value and further increase in WWR increase the total energy consumption of building with different window combinations. Total energy consumption in this case varies from 7772.9 - 8242.2 kWh for different window combinations and WWR as shown in figure 4.12. Previous effect of north window in this case is not found with controlled daylight. Variation of total energy consumption with WWR in each combination of window is much less compared to case 1 and case 2. Figure 4.13 shows that optimum WWR for the window combinations are around 20%.

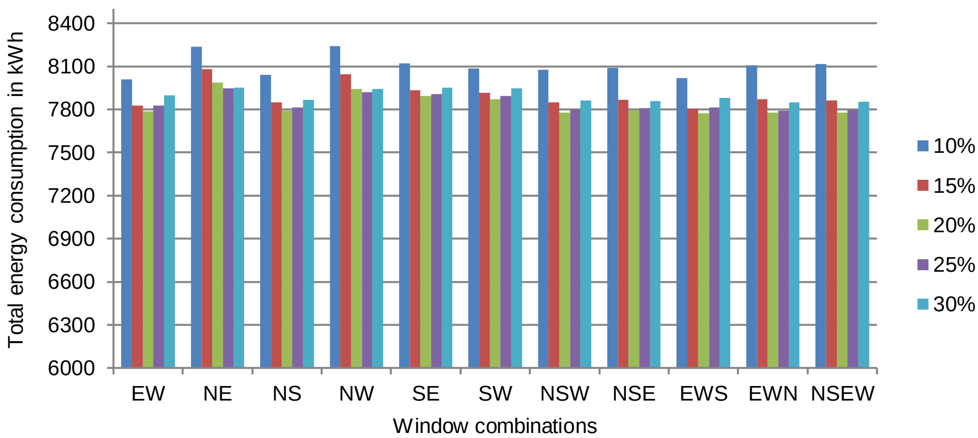

Figure 4.12. Annual total energy consumption in Kolkata in case 3.

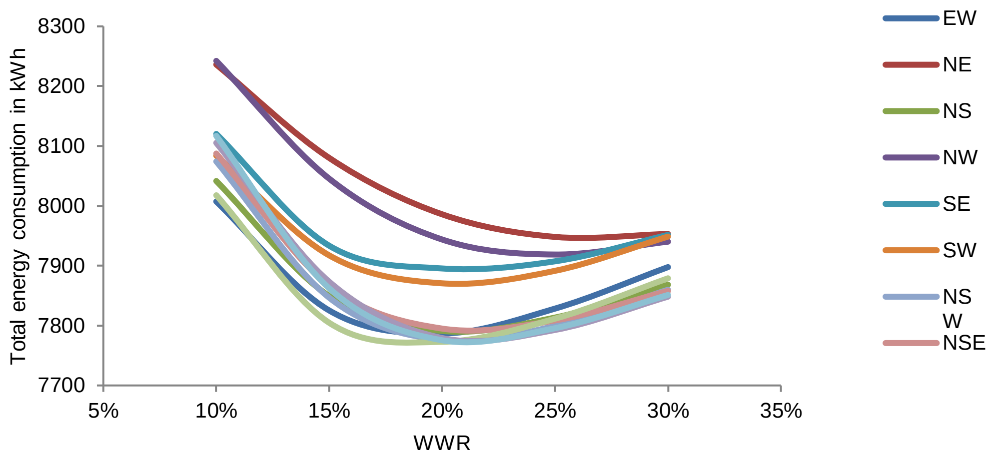

Figure 4.13. Annual total energy consumption in Kolkata in case 1.

4.3.1.4 Annual savings compared to reference building in Kolkata

It is found that distribution of window in different cardinal directions in case 1 is beneficial only for 10% WWR in all window combinations. Increase in WWR beyond 10% saving in total annual energy consumption is negative for all window combinations as shown in figure 4.14. Negative values of savings is actually the energy consumption of the building model is higher compared to the reference building. Result shows that distribution of window in different cardinal direction and increasing WWR beyond reference value may increase annual total energy consumption of the building up to 25%.

As a result of daylight integration through the window in case 2, savings in annual total energy compared to reference building is shown in figure 15. Energy savings in this case increases compared to case 1. It is observed that energy savings in all combinations is decreasing with increase in WWR. When value of WWR exceeds 20%, annual total energy savings is very minimum or negative. Energy savings due to daylight integration in case 2 may reach up to 19.2% compared to reference building.

In case 3, when daylight is integrated in controlled way, all combinations saves energy compared to reference building for all studied values of WWR. In this case, energy savings increases with increasing WWR and reaches to a minimum value and further increase in WWR decreases energy savings compared to reference building as shown in figure 4.16. Total energy savings of different window combinations varies from 18-23%. In all the combinations maximum savings are observed when WWR is around 20% as shown in figure 4.17.

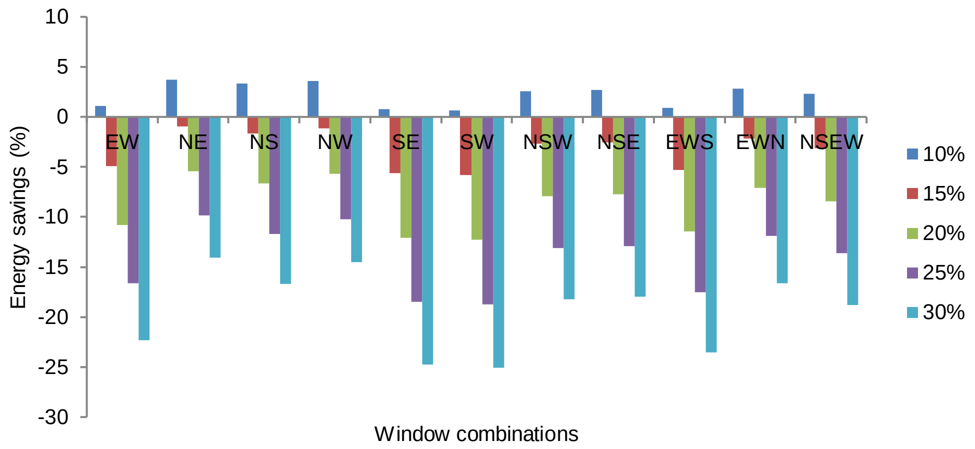

Figure 4.14. Annual total energy savings in Kolkata in case 1.

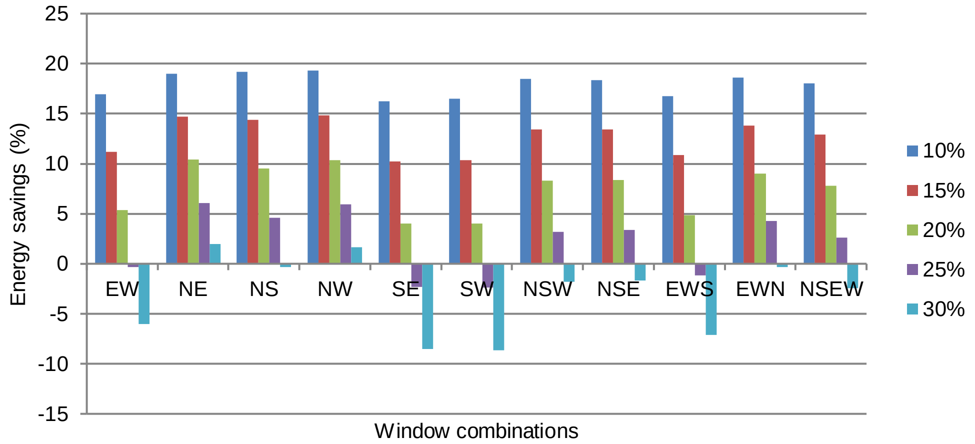

Figure 4.15. Annual total energy savings in Kolkata in case 2.

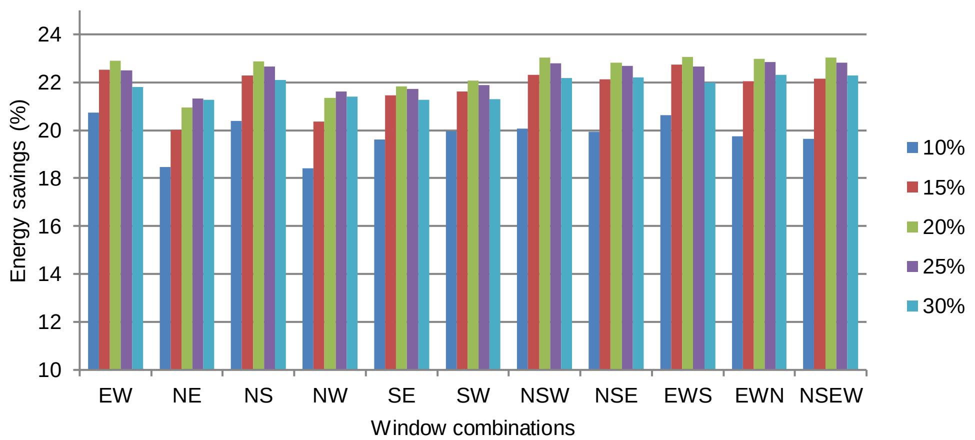

Figure 4.16. Annual total energy savings in Kolkata in case 3.

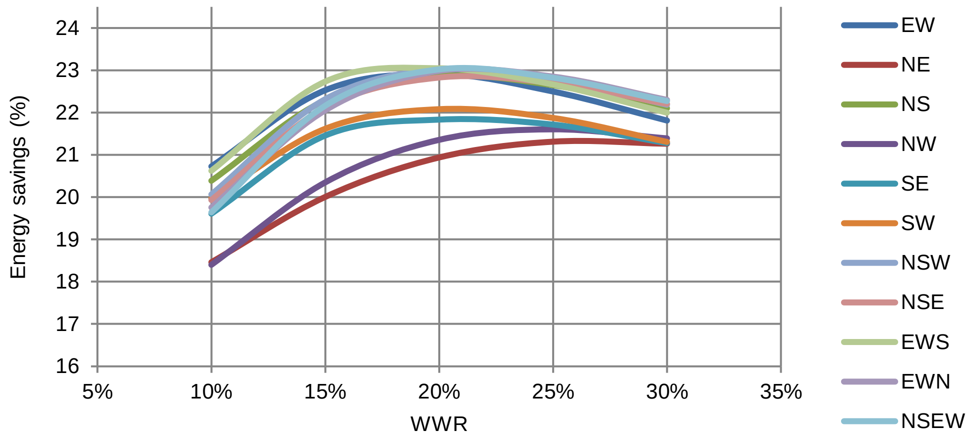

Figure 4.17. Annual total energy savings in Kolkata in case 3.

4.3.2 Result in Delhi

4.3.2.1 Annual cooling energy consumption

Case 1: Annual cooling energy for different window combinations in Delhi varies from 7678.3 - 0635.4 kWh. Energy consumption is increasing with increasing WWR in Delhi as shown in figure 4.18. Similar to Kolkata, cooling energy consumption in NE, NS, NW, NSW, NSE, EWN and NSEW group of window combination is lower compared to SW, SE, EW and EWS combination of window. Presence of window in north orientation has similar effect on cooling energy in Delhi also. Maximum cooling energy consumption is found with the SW combination among all the window combinations.

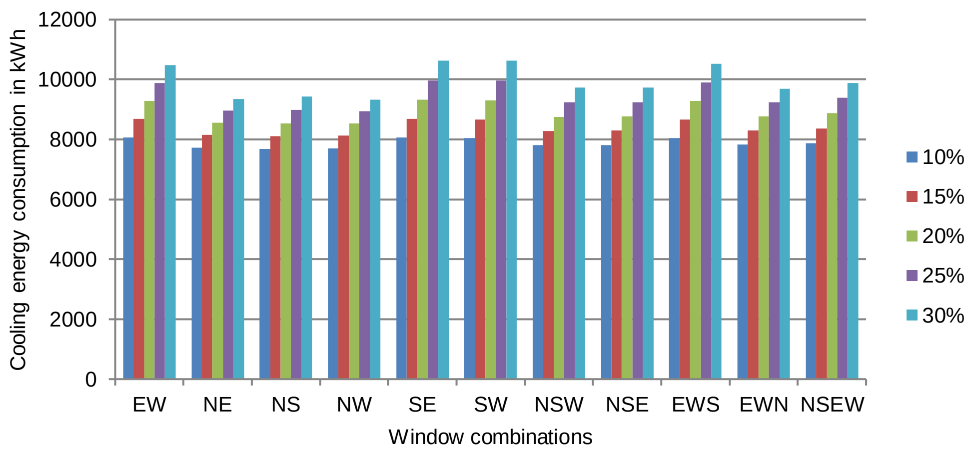

Figure 4.18. Annual cooling energy consumption in Delhi in case 1.

Case 2: Daylight integration in this case reduces annual cooling energy consumption compared to case 1. Similar to case 1, presence of window in north wall of the building accounts for less cooling energy consumption as shown in figure 4.19. Cooling energy consumption of the building models under study varies from 7391.7 - 10314.2 kWh.

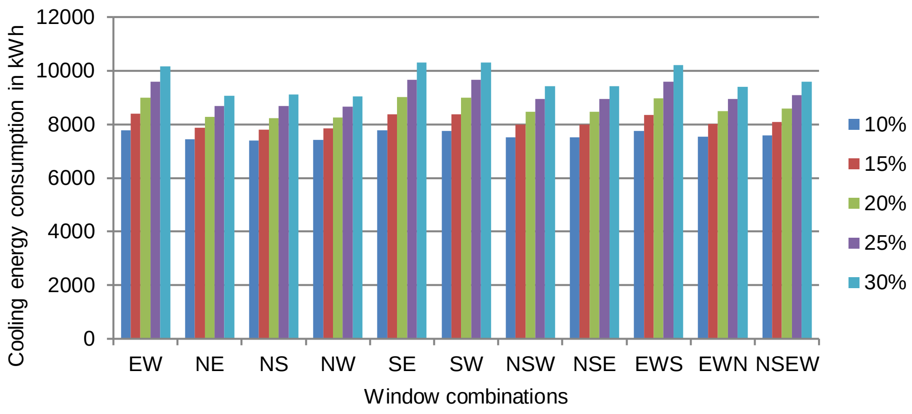

Figure 4.19. Annual cooling energy consumption in Delhi in case 2.

Case 3: Controlled daylight integration further reduces cooling energy consumption of the building compared to previous case 2 as shown in figure 4.20. It is found that the increase in cooling energy consumption with increase in WWR is much lower compared to case 1 and case 2. Cooling energy consumption of different buildings under study varies from 6830.7 - 7125 kWh in Delhi.

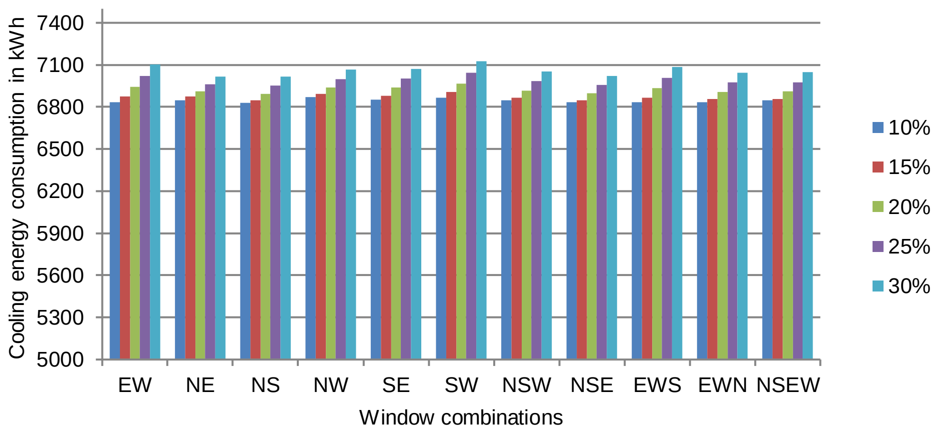

Figure 4.20. Annual cooling consumption energy in Delhi in case 3

4.3.2.2 Annual lighting energy consumption

Lighting energy consumption in Delhi with three different cases is shown in figure 4.21. Lighting energy significantly reduced with daylight integration. Similar to Kolkata, annual lighting energy consumption in case 1 is 2008.4 kWh and same for all window combination and WWR as artificial light is not controlled in this case. Lighting energy consumption in case 2 varies from 632.2 - 645.4 kWh. In case 3, lighting energy consumption for different window combination and WWR lies between 724 kWh and 1098.9 kWh as a result of controlled daylight through window.

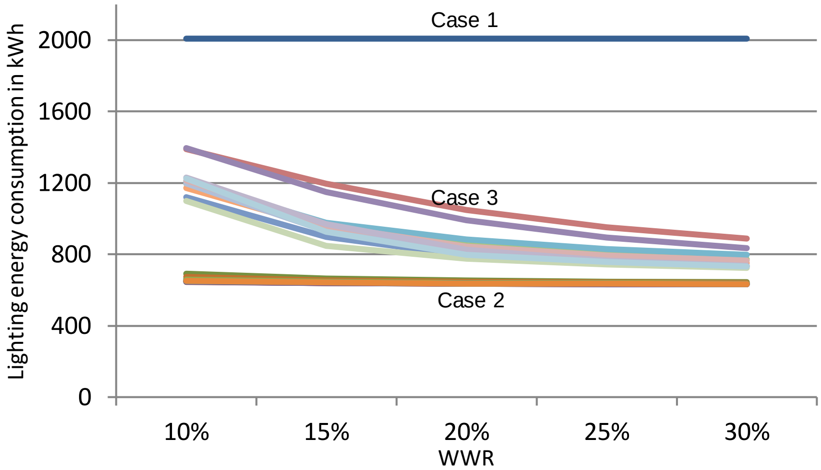

Figure 4.21. Annual lighting energy consumption in different cases in Delhi.

4.3.2.3 Annual total energy consumption

Case 1: In all window combinations total energy consumption in case 1 is increasing with increasing WWR. Similar to annual cooling energy, same group of windows shows less total energy consumption compared to SW, SE, EW and EWS combination of window. Influence of north window is also present in the total energy consumption of the building in this case. Total energy consumption of different buildings lies between 9686.7 kWh and 12643.7 kWh as shown in figure 4.22.

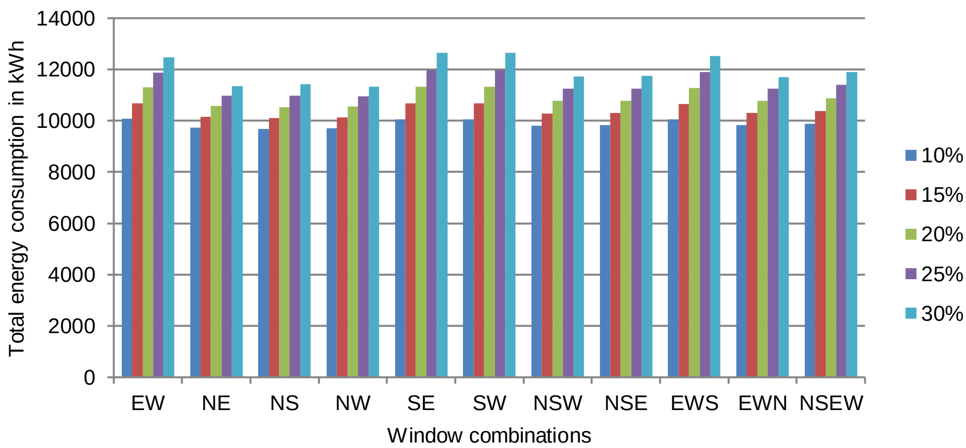

Figure 4.22. Annual total energy consumption in Delhi in case 1

Case 2: In this condition total energy consumption is reducing in all combination and in for all WWR compared to case 1. Annual total energy consumption varies from 8043.8 - 10947.7 kWh for different window combinations and WWR as shown in figure 4.23. Effect of north window is also present in this case.

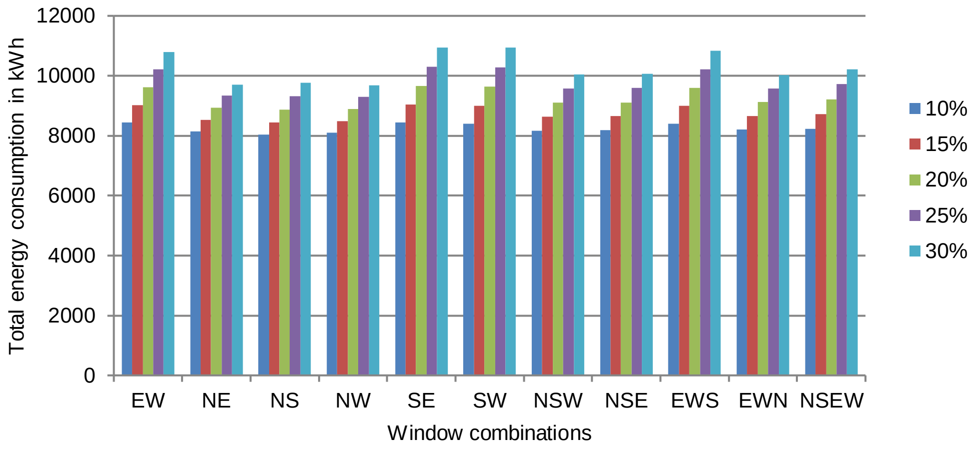

Figure 4.23. Annual total energy consumption in Delhi in case 2

Case 3: When daylight is integrated in a controlled way with external shading, total energy consumption decreases with increasing WWR and reaches to a minimum value and further increase in WWR increase the total energy consumption of building with different window combinations as shown in figure 4.24. Total energy consumption in this case varies from 7705.6 - 8265.2 kWh for different window combinations and WWR. Effect of north window is not found with controlled daylight. Variation of total energy consumption with WWR in each combination of window is much less compared to case 1 and case 2. Figure 4.25 shows that optimum WWR for the window combinations are around 20%.

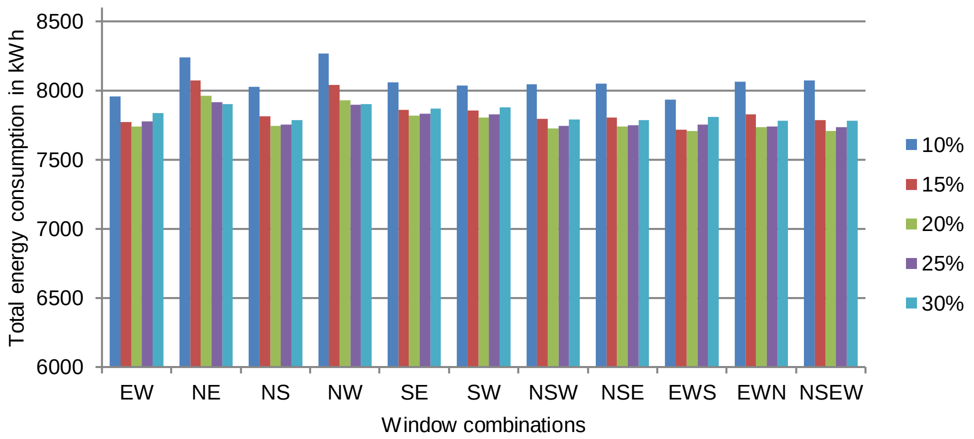

Figure 4.24. Annual total energy consumption in Delhi in case 3.

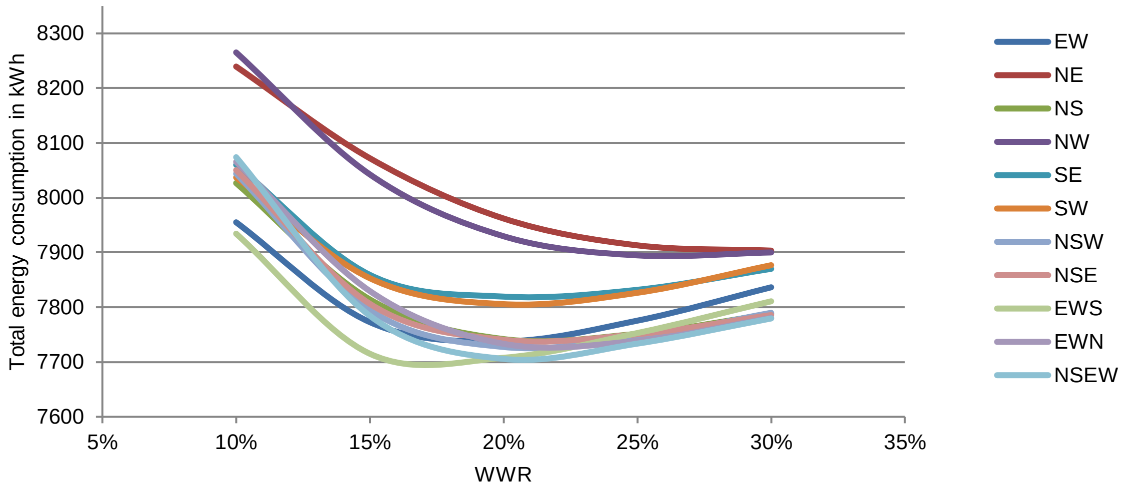

Figure 4.25. Annual cooling energy consumption in Delhi in case 3

4.3.2.4 Annual savings compared to reference building in Delhi

Case 1: It is found that distribution of window in different cardinal directions in case 1 is not beneficial as energy consumption in all the building models is increasing compared to reference building as shown in figure 4.26. Result shows that increasing WWR beyond reference value may increase annual total energy consumption of the building up to 25%.

Case 2: In this case daylight integration through the window increases the annual total energy savings compared to reference building as shown in figure 4.27. It is observed that energy savings in all combinations is decreasing with increase in WWR. When value of WWR exceeds 20%, annual total energy savings is negative in EW, SE, SW, EWN and NSEW combinations. Energy savings due to daylight integration in case 2 may reach up to 20% compared to reference building.

Case 3: In this case all combinations saves considerable energy compared to reference building for all studied values of WWR. Energy savings increases with increasing WWR and reaches to a minimum value and further increase in WWR decreases energy savings compared to reference building as shown in figure 4.28. Total energy savings of varies from 17.8 -23.3% for different window combination and WWR. In all the combinations maximum savings are observed when WWR is around 20% as shown in figure 4.29.

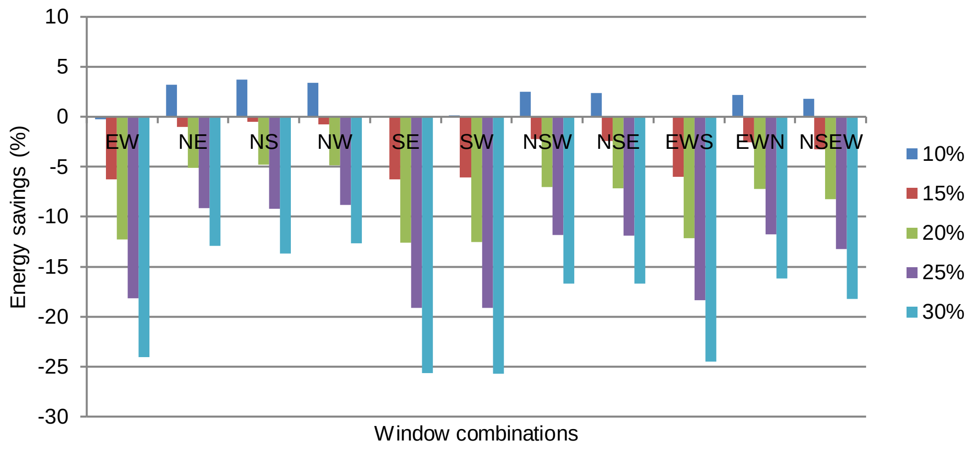

Figure 4.26. Annual total energy savings in Delhi in case 1.

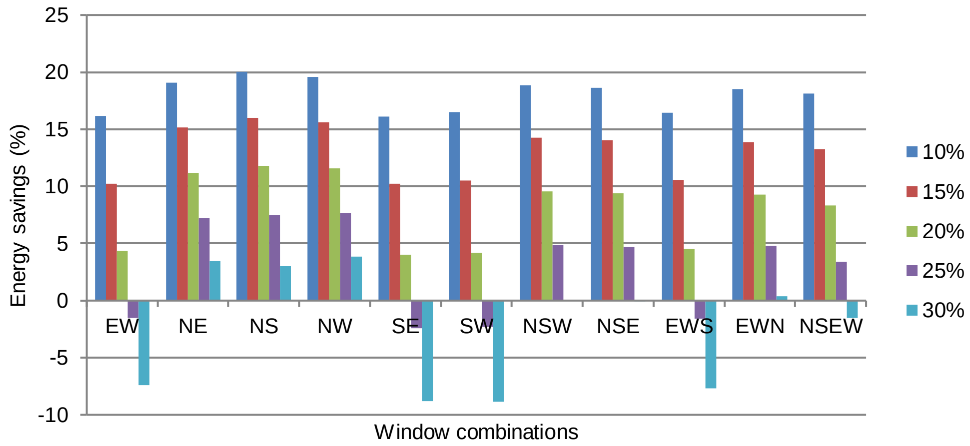

Figure 4.27. Annual total energy savings in Delhi in case 2.

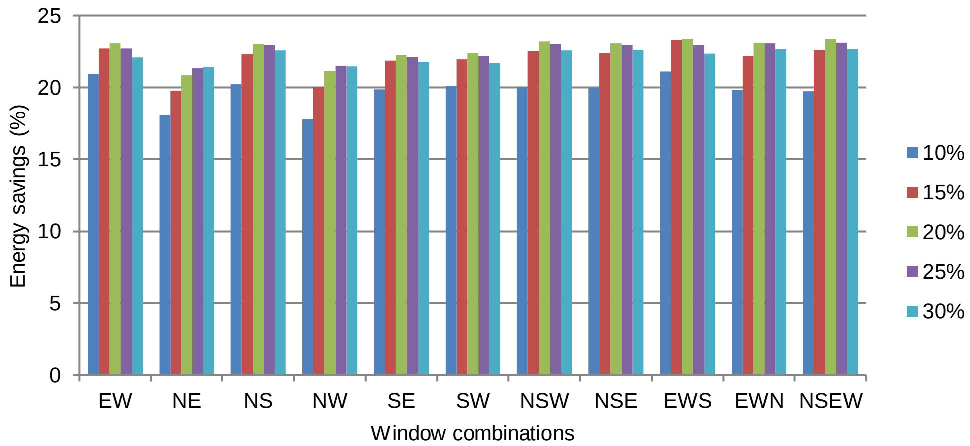

Figure 4.28. Annual total energy savings in Delhi in case 3.

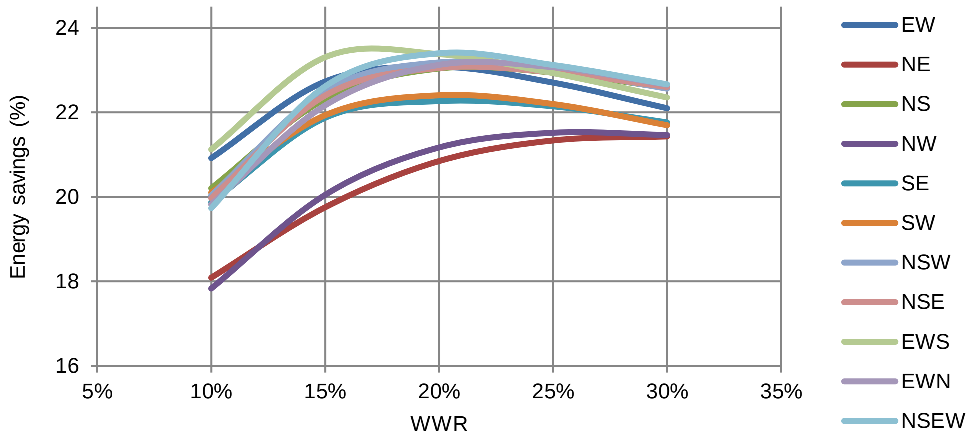

Figure 4.29. Annual total energy savings in Delhi in case 3.

4.3.3 Result in Chennai

4.3.3.1 Annual cooling energy consumption

Case 1: Annual cooling energy in Chennai for different building models under study varies from 9599.7 - 13146.9 kWh. Similar to previous result of Kolkata and Delhi, annual total energy consumption is increasing with increasing WWR in Kolkata as shown in figure 4.30. Presence of North window shows similar effect on cooling energy consumption compared. Maximum cooling energy consumption in Chennai is found with EW window combinations.

Case 2: Daylight integration into the building reduces annual cooling energy consumption compared to case 1. Presence of window in north direction of the building reduces cooling energy consumption as shown in figure 4.31. Annual cooling energy consumption of the building models under study with daylight integration varies from 9203.2 - 12748 kWh.

Case 3: Controlled daylight integration into the building with external shading further reduces cooling energy consumption compared case 2 as shown in figure 4.32. It is found that the impact of WWR on cooling energy consumption is much lower compared to case 1 and case 2. Cooling energy consumption of different buildings under study varies from 8439.6 - 8850.5 kWh in Chennai.

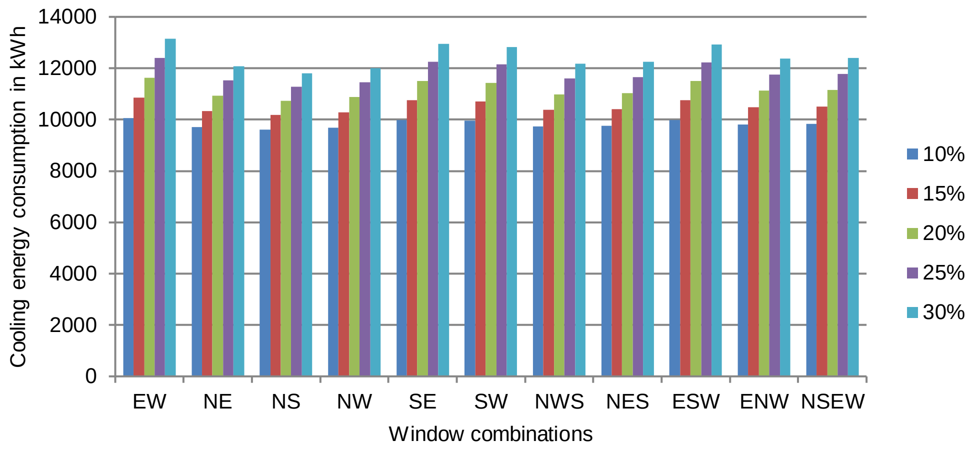

Figure 4.30. Annual cooling energy consumption in Chennai in case 1.

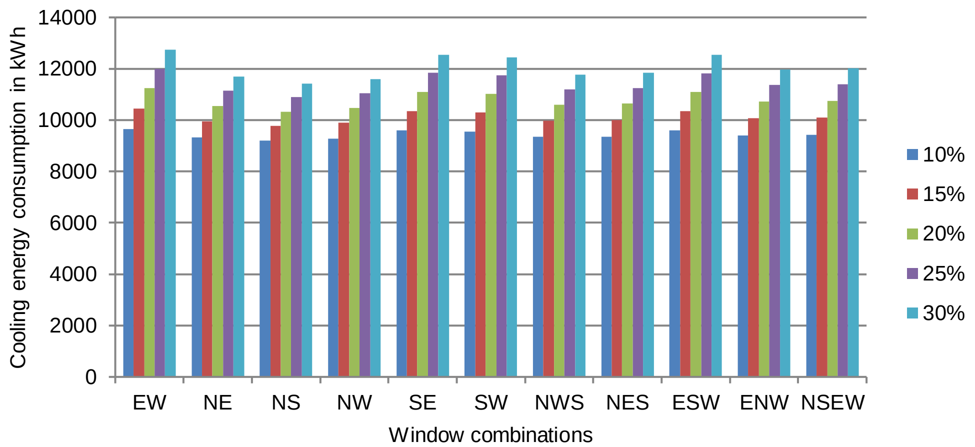

Figure 4.31. Annual cooling energy consumption in Chennai in case 2.

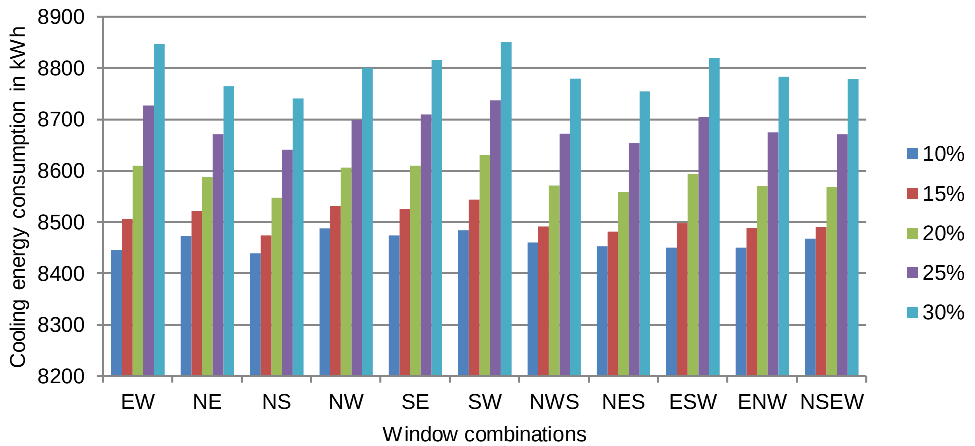

Figure 4.32. Annual cooling energy consumption in Chennai in case 3.

4.3.3.2 Annual lighting energy consumption

Annual lighting energy consumption in Chennai with three different cases follows the similar nature of Kolkata and Delhi as shown in figure 4.33. Annual lighting energy significantly reduced with daylight integration into the building. Annual lighting energy consumption in case 1 is 2008.4 kWh and same for all window combination and WWR as there is no lighting control employed in this case. Annual lighting energy consumption in Chennai varies from 630.4 - 687 kWh and 727.9 - 1345.7 kWh in case 2 and case 3 respectively.

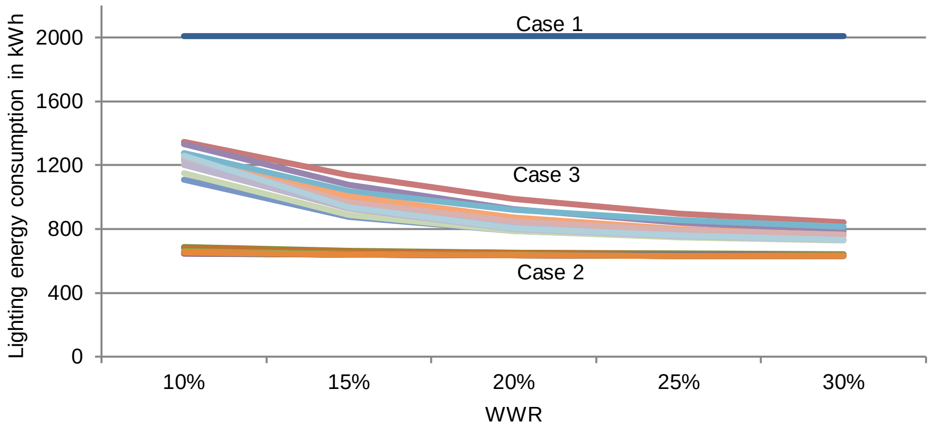

Figure 4.33. Annual lighting energy consumption in Chennai in different cases.

4.3.3.3 Annual total energy consumption

Case 1: Total energy consumption of the different buildings lies between 12632.6 kWh and 15155.3 kWh as shown in figure 4.34. Total energy consumption is increasing with increasing WWR for all the window combinations. Annual total energy consumption in NE, NS, NW, NSW, NSE, EWN and NSEW group of window combination in Chennai is lower compared to SW, SE, EW and EWS combination of window. Influence of north window is also present in the total energy consumption of the building.

Case 2: daylight integration reduces total energy consumption in all combination and in all WWR compared to case 1. Annual total energy consumption in this case varies from 9855.6 - 13380 kWh for different window combinations and WWR as shown in figure 4.35. The combinations containing North window consume less energy compared to other combinations.

Case 3: In this case total energy consumption decreases with increasing WWR and reaches to a minimum value and increase again with increasing WWR in all combinations of window. Total energy consumption in this case varies from 9370 - 9819.9 kWh for different window combinations and WWR as shown in figure 36. Effect of north window in this case is not found with controlled daylight. Figure 4.37 shows that optimum WWR for the window combinations are around 20%.

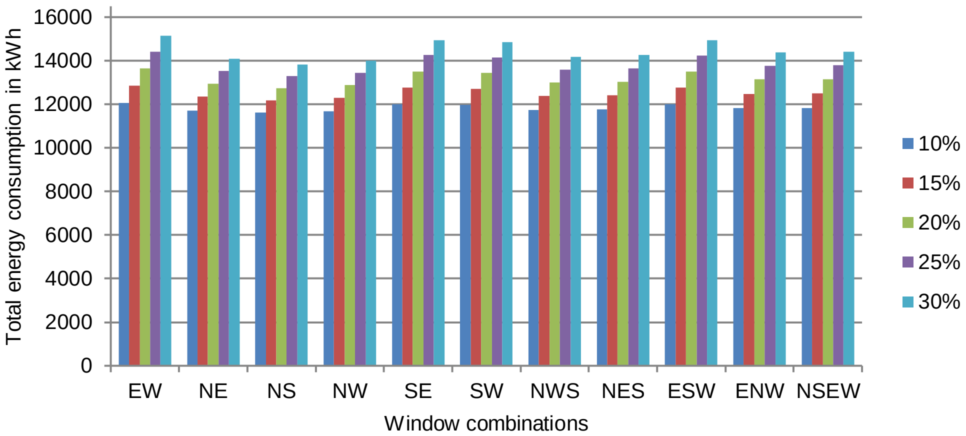

Figure 4.34. Annual total energy consumption in Chennai in case 1.

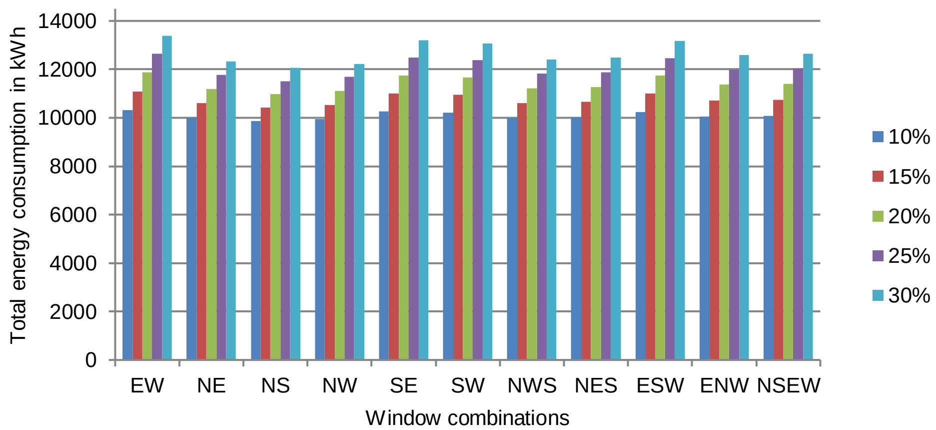

Figure 4.35. Annual total energy consumption in Chennai in case 2.

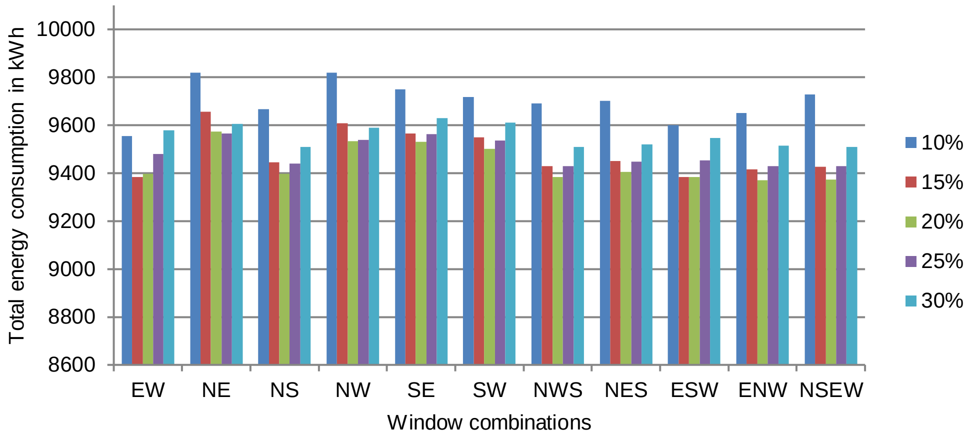

Figure 4.36. Annual total energy consumption in Chennai in case 3.

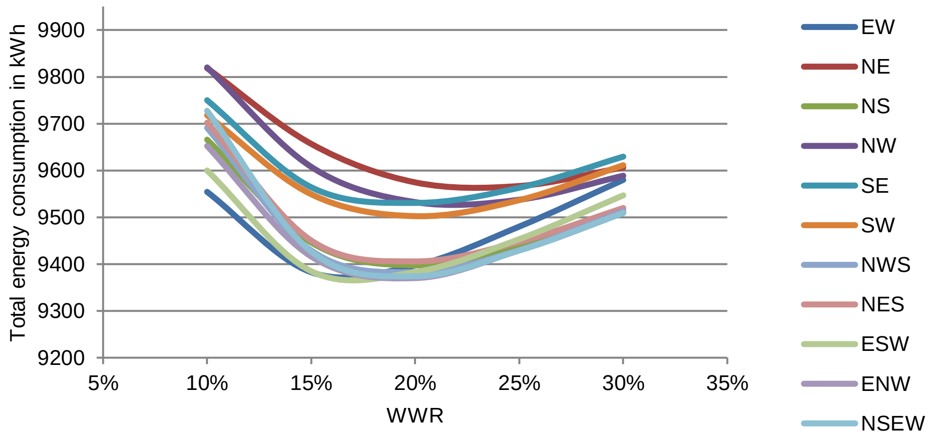

Figure 4.37. Annual total energy consumption in Chennai in case 3.

4.3.3.4 Annual savings compared to reference building

Case 1: It is found that distribution of window in different cardinal directions in this case is not beneficial as very nominal savings is observed for very low value of WWR. Savings in total annual energy consumption is negative for all window combinations as shown in figure 4.38. Result shows that distribution of window in different cardinal direction and increasing WWR beyond reference value may increase annual total energy consumption of the building up to 27%.

Case 2: Daylight integration in case 2, increases the annual total energy savings compared to reference building as shown in figure 4.39. It is observed that energy savings in all combinations is decreasing with increase in WWR. When value of WWR exceeds 20%, annual total energy savings is very minimum or negative for all the window combinations. Energy savings due to daylight integration in lower values of WWR may reach up to 17.2% compared to reference building and loss at higher values of WWR may reach up to 12.3%.

Case 3: When daylight is integrated in controlled way, all combinations saves energy compared to reference building for all studied values of WWR. Similar to Kolkata and Delhi, energy savings increases with increasing WWR and reaches to a minimum value and further increase in WWR decreases energy savings compared to reference building as shown in figure 4.40. Total energy savings of different buildings in this case varies from 17.5 - 21.2%. In all the combinations maximum savings are observed when WWR is around 20% as shown in figure 4.41.

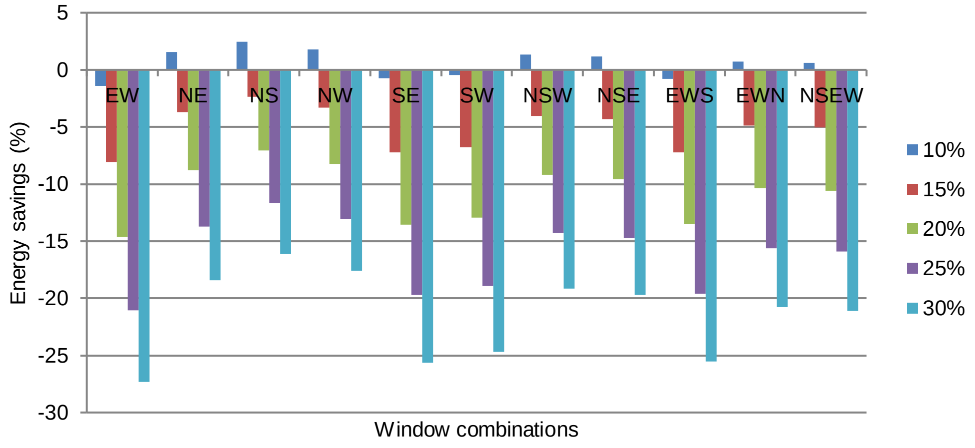

Figure 4.38. Annual total energy savings in Chennai in case 1.

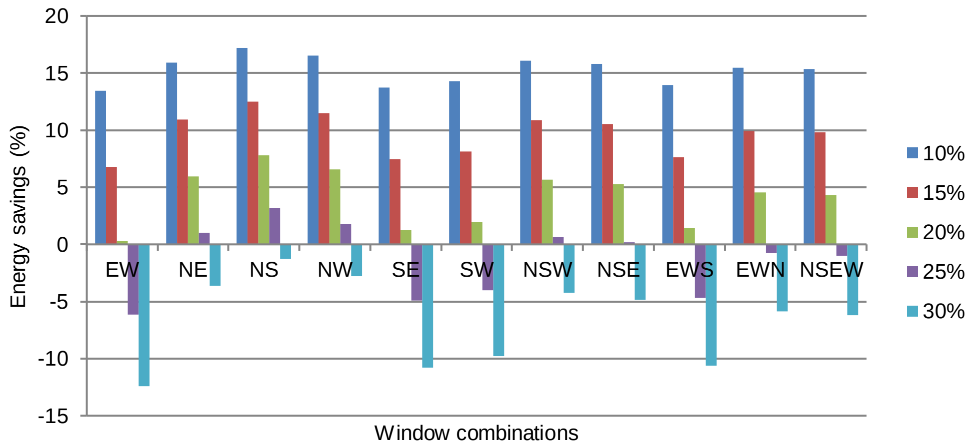

Figure 4.39. Annual total energy savings in Chennai in case 2.

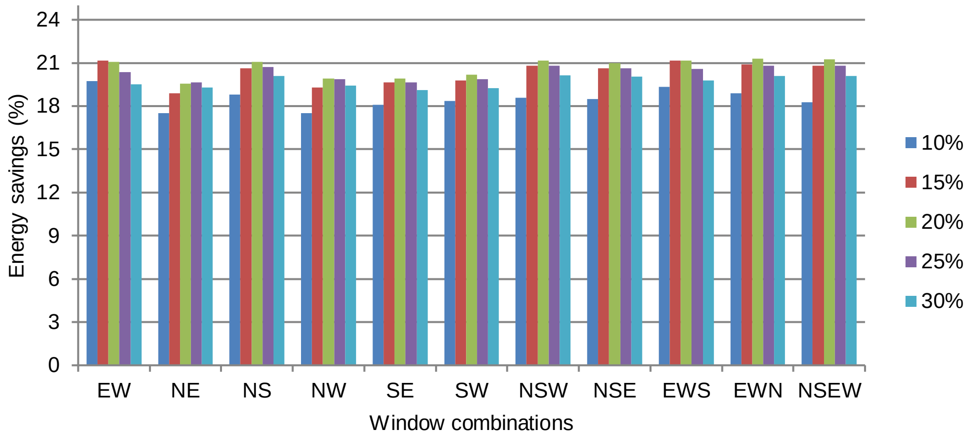

Figure 4.40. Annual total energy savings in Chennai in case 3.

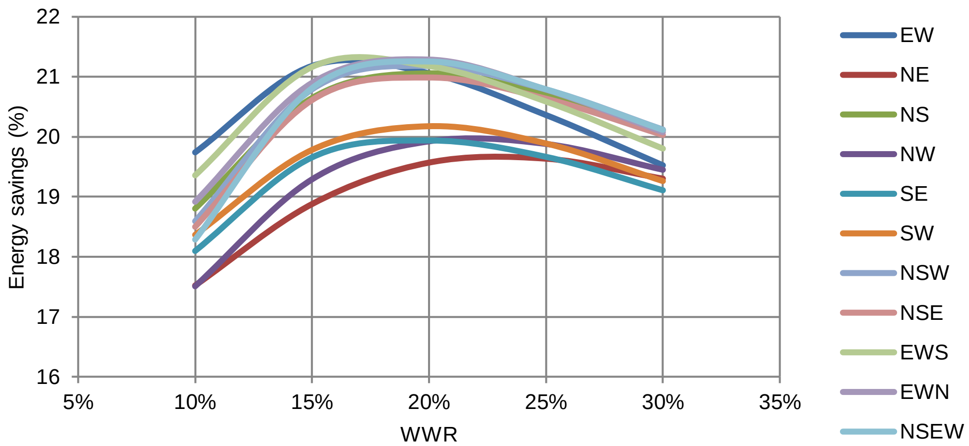

Figure 4.41. Annual total energy savings in Chennai in case 3.

4.3.4 Effect of north window on building energy performance with controlled daylight

In the previous chapter it is observed that latitude of the location and presence of north window in the building has an impact on the energy consumption of the buildings. In this phase of study when daylight is controlled with a fixed shading of slat angle 45^0 and artificial lighting system of the building is controlled according to available daylight in the reference point. The result of the study shows that energy consumption of buildings reduces considerably as a result of controlled daylight integration as shown in figure 4.42 to figure 4.46. Controlling the daylight with external shading reduces excessive heat gain of the building which reduces cooling energy demand of the building. Moreover the controlled daylight minimizes the previous effect of north window in the building energy consumption. Effect of increasing WWR has comparatively less impact on energy consumption of the buildings.

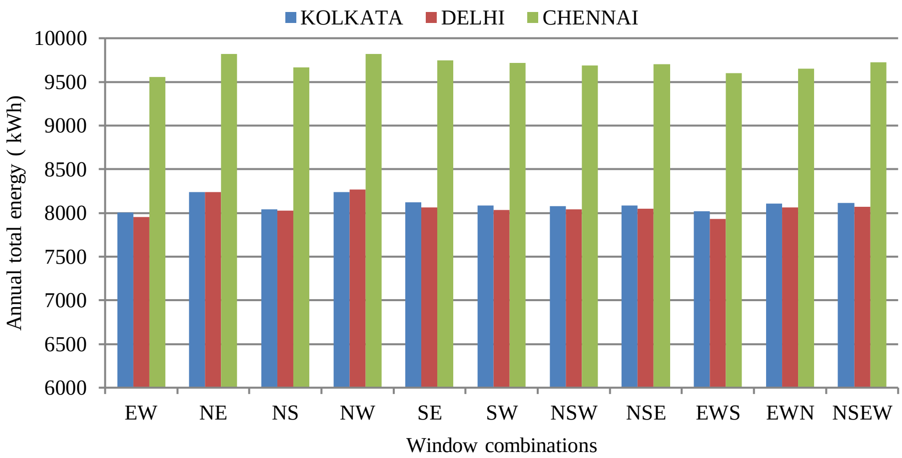

Figure 4.42. Energy consumption of the buildings with 10% WWR with controlled daylight integration

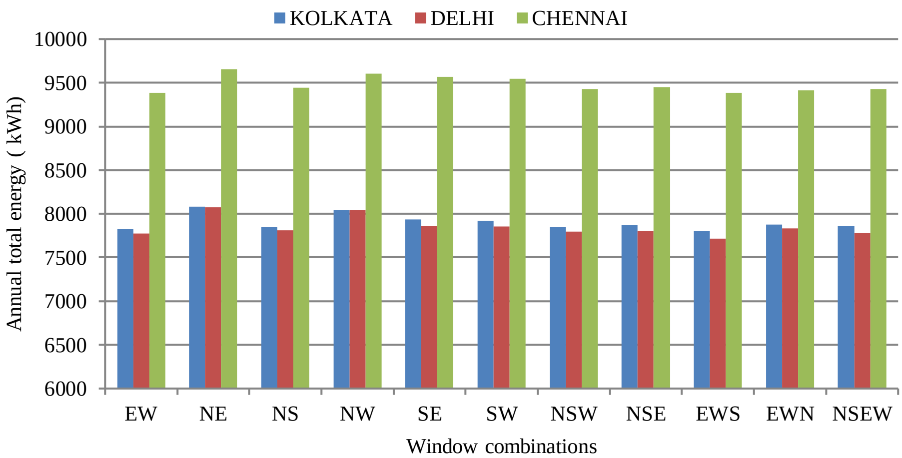

Figure 4.43. Energy consumption of the buildings with 15% WWR with controlled daylight integration

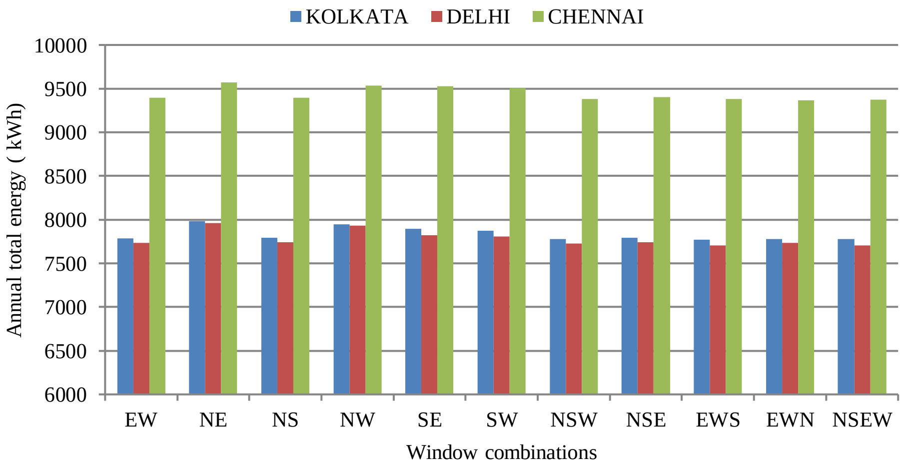

Figure 4.44. Energy consumption of the buildings with 20% WWR with controlled daylight integration

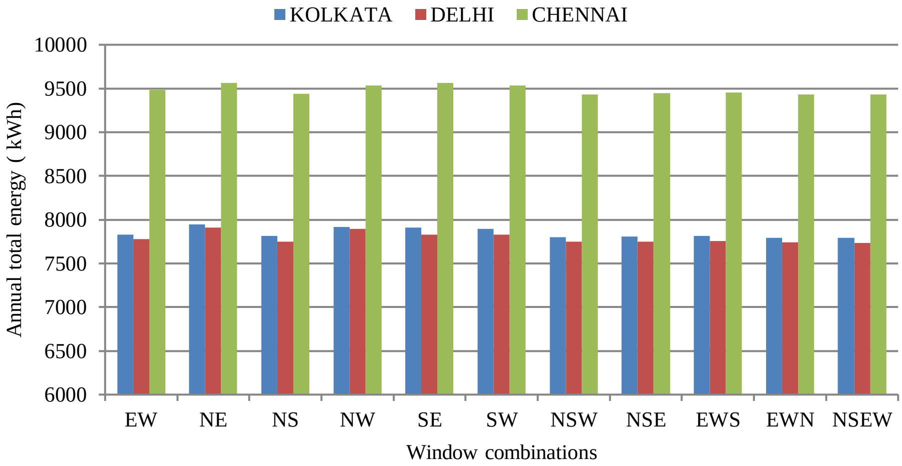

Figure 4.45. Energy consumption of the buildings with 25% WWR with controlled daylight integration

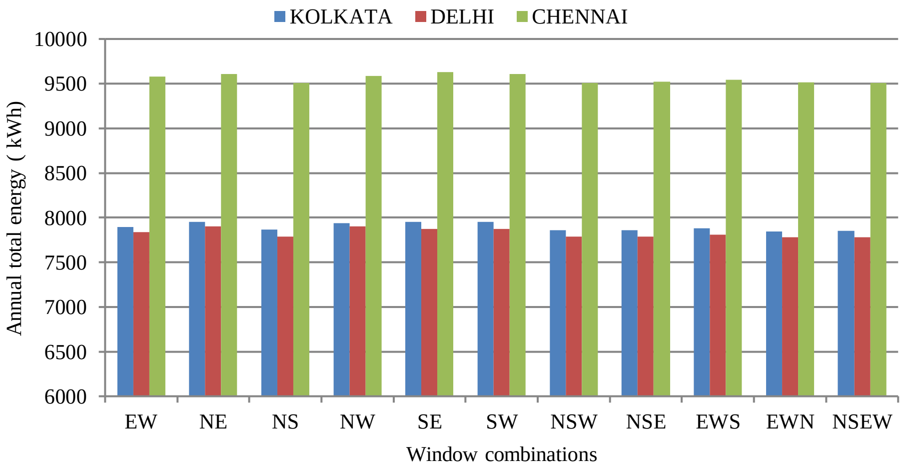

Figure 4.46. Energy consumption of the buildings with 30% WWR with controlled daylight integration

4.4 Conclusion

The present study represents the energy performance of different window combinations with five different WWR (10%, 15%, 20%, 25% and 30%) for the climatic condition of Kolkata, India. Energy savings of the window combinations compared to reference building for three different daylight condition have been quantified. The results of the study reveals that integration of daylight with artificial lighting system (case 2) reduce total energy consumption in all combinations compared to without daylight integration (case 1) into the building. Energy consumption of the building increases significantly when WWR increases. Daylight integration in controlled way (case 3) significantly reduces the total energy consumption with all window combinations compared to case 1 and case 2. Result shows that increasing WWR up to a certain value may lower the total energy consumption when daylight is integrated in controlled way with external shading. The same result has been found in two other locations in higher and lower latitude compared to Kolkata indicates which validate the applicability of controlled daylight into the building with higher WWR.

Energy savings of building with different window combinations compared to the reference building may positive or negative depending on WWR and daylight conditions. Maximum energy savings and loss compared to reference building in all three locations has been shown in table 4.2.

Table 4.2. Energy savings and loss of different building models compared to reference building.

Daylight condition	Location					
	Kolkata		Delhi		Chennai	
	Maximum Energy savings	Maximum Energy loss	Maximum Energy savings	Maximum Energy loss	Maximum Energy savings	Maximum Energy loss
Case 1	3.6%	25.0%	3.7%	25.6%	2.4%	27.3%
Case 2	19.2%	8.6%	19.5%	8.8%	17.2%	12.4%
Case 3	23.0%	0.0%	23.4%	0.0%	21.2%	0.0%

Result of the study shows that increasing glass area or WWR in the building without daylight integration to artificial lighting system increases energy consumption of the building hence potential of energy savings compared to reference building is very less. Considerable amount of energy savings is found with case 2 where daylight is integrated with the artificial lighting of the building but increasing WWR decreases the energy savings and further increase in WWR accounts for the loss of energy compared to reference building in all window combinations. Energy savings with controlled daylight integration in case 3 is quite satisfactory in all window combinations with all five WWR. It is observed from the result that optimum savings in energy consumption is found when WWR is around 20% for all window combinations. Hence integration of daylight in controlled way is one of the effective ways to save energy consumption of the buildings in all three locations.

5 Energy savings in building with controlled daylighting

5.1 Introduction

Building sector is one of the major energy consumers in all over the world. The operations of building sector consume 30% of global final energy consumption and also responsible for 26% global energy related emission into the atmosphere **(IEA, 2022).** The emissions of green house gas due to different human activities are the cause of climate change and global warming. It is reported that building sector emits one third of the total greenhouse gas emissions which leads global warming and climate change **(Danish et al, 2019)**. In the study in UAE, it is observed that global warming is likely to increase the energy used for cooling of buildings by 23.5% if the study location warms by 5.9^{0}C over the next few decades **(Radhi et al, 2009)**. Hence design of sustainable buildings has become a challenging task for all the developing and developed nations in the world. Energy consumption of building is directly influenced by building envelope, geometry, orientation, building materials, location and climatic conditions. Building energy consumption of industrialised countries is responsible for approximately 50% of total carbon dioxide emissions **(Loveday et al, 2002)**. Energy consumption in residential building contributes significantly negative environmental impact related to electricity consumption **(Blom et al, 2011).**

In India, energy demand is increasing due to economic development and rapid urbanization. The building sector in India is experiencing an exceptional growth from the last few years and the sector is responsible for 38% of total annual primary energy consumption and 31% of the total annual electricity consumption (AEEE, 2017). Building parameters such as building geometry, building envelope, orientation and location of buildings has the potential to conserve building energy **(Renuka, et al, 2022)**. Energy Conservation Building Code (ECBC) provides a guideline in to design energy efficient building in different climatic zones in India **(ECBC, 2017)** . Energy saving potential through the implementation of Energy Conservation Building Code (ECBC) and advance Energy Efficiency Measures in different categories of hotels in Jaipur, India has been studied and result shows that significant amount of energy can be saved in the buildings sectors in India **(Chedwal, 2015).** Improvement of thermal properties of building envelope material conserves primary energy consumption in commercial buildings in India **(Bhatnagar et al, 2019).** Window is one of the most thermally weak parts in the building envelope. Energy rating of different window glazing for Indian perspective has been carried out to selecting the best window for a given building in a given climate **(Singh et al, 2009).**

Daylight in building has important role to reduce building energy consumption which in turn reduces emission and environmental impact. To access daylight inside the building working space, modern buildings increases the area of window glazing. Daylight through the window of building reduces lighting energy consumption **(Hosseini et al,2024).** But excessive and uncontrolled daylight increase heat gain of the building especially in tropical region in country like India. This heat gain increases the cooling load of the building which creates negative impact on the environment. Daylightinig and heat gain of the building depends on optical, thermal and geometrical parameter of the window glazing. S. Pal et al. used a mathematical model of one dimensional heat flow into the building space through the window glazing to quantify the heat gain of building in a tropical climatic condition in India **(Pal et al, 2009).** G. Kiran Kumar et al. studied energy consumption of different window glazing materials in four different climatic zones in India **(Kiran et al, 2017).** Aritra et al. measured thermal & daylight performance of evacuated and vacuum glazing in a cold climate zone **(Aritra et al, 2016).** Aguilar et al. studied the impact of double glazing windows in Mexico to quantify the energy performance of different glass window **(Aguilar et al, 2017).**

Application of shading device in window gazing controls the daylight penetration into the building space and reduces excessive heat gain. Application of internal or external shading devices to windows has great impact on thermal performance, energy consumption and associated greenhouse gases emission **(Nikoofard et al, 2014).** Shading performance of a window system in selected cities in USA and China have been carried out and result shows that application of proper shading reduce total building energy consumption up to 37.8% in selected cities in USA and 24.8% in selected cities in China **(Lai et al, 2017).** Similar benefit of shading device is also observed in Qatar **(Touma et al, 2017)** and Indonesia **(Mangkuto et al, 2019)** also.

Window to wall ratio (WWR) and window to floor ratio (WFR) are two parameters which measure the area of window glazing on building envelope to access daylight into the building space. Window glazing not only used to access daylight in to the building but also used to improve the aesthetic view of modern buildings. Introduction of higher glazing area is a common building architectural part in modern building design. Window to floor ratio is an important parameter to assess daylight in to the buildings and an optimal range is 15-24% to controls glare and overheats into the building space **(Vaisi et al, 2019).** Proper selection of window-to-wall ratio (WWR) improves daylight penetration into the building and also conserve significant amount of energy in Indian climatic condition **(Biswas, et al, 2024).** Window-to-wall ratio is an important parameter of consideration to conserve building energy. Increasing WWR of a building allows more heat and daylight inside the working space. As a result of higher heat gain of the indoor space, cooling energy demand of the building increases. Thermal performance of different orientation and window to wall ratio in public rental housing in Hong Kong was evaluated and reported using energy EnergyPlus simulation software **(Fung et al, 2017).** Similar study on WWR is also conducted in Italy and India to find the optimum window surface area in building envelope for minimum overall energy consumption in office building **(Marino et al, 2017; Biswas, et al, 2024**). Studies have been conducted to find optimal window-to-wall ratio in different European climates for office building which consumes minimum sum of the energy use for heating, cooling and lighting **(Goia, 2016).**

Window in the building is one of the important areas of research to conserve building energy consumption for sustainable development. Most of the global energy production comes from fossil fuel burning which leads to an increasing concentration of greenhouse gases in the atmosphere and thus contributes to climate change **(Olonscheck et al, 2011).** It is important to optimize energy consumption in building sector to ensure less amount of emission of toxic gases in to the atmosphere. In the present work, window has been distributed to different building wall to form window combinations. Different window combinations act as means of daylighting into the building space. Daylight through the window glazing has been used to control the artificial lighting system of the building to conserve building energy in India. Daylight integration into the building increases heat gain of the building which results higher cooling energy consumption. External shading is used with different slat angle to control daylight to achieve maximum energy savings in the study locations. All the building models are designed according to ECBC and National Building Code in India **(NBC, 2016).** The benefit of daylight integration for different window combinations and WWR has been studied and reported for newly designed building projects in India

5.1 Methodology

Integration of daylight into building has the potential to save lot of energy consumption. Window plays an important role to integrate daylight into the building. In this study, a building model with a single winnow (WWR=10%) in south direction is considered as reference building in the present study (**Biswas, et al, 2024**). In the present study, window area on the building envelope has been distributed to different cardinal directions to form eleven different window combinations namely EW, NE, NS, NW, SE, SW, NSW, NSE, EWS, EWN and NSEW combination. All the building models were simulated for energy performance with five different WWR (10%, 15%, 20%, 25% and 30%) and six different slat tilt angle (0^0, 15^0, 30^0, 45^0, 60^0 and 75^0) to control daylight into the building space. A continuous dimming control of artificial lightings of the building is incorporated based on daylight through window combinations at reference points. Energy consumption of all building model are investigated using EnergyPlus and energy savings compared to the reference building are calculated. The schematic diagram of the present study is shown in figure 5.1. Daylight integration into the building depends on lot of factors such as available solar radiation on the window surface, orientation of window, window size, optical properties of window glazing material, location of the building etc.

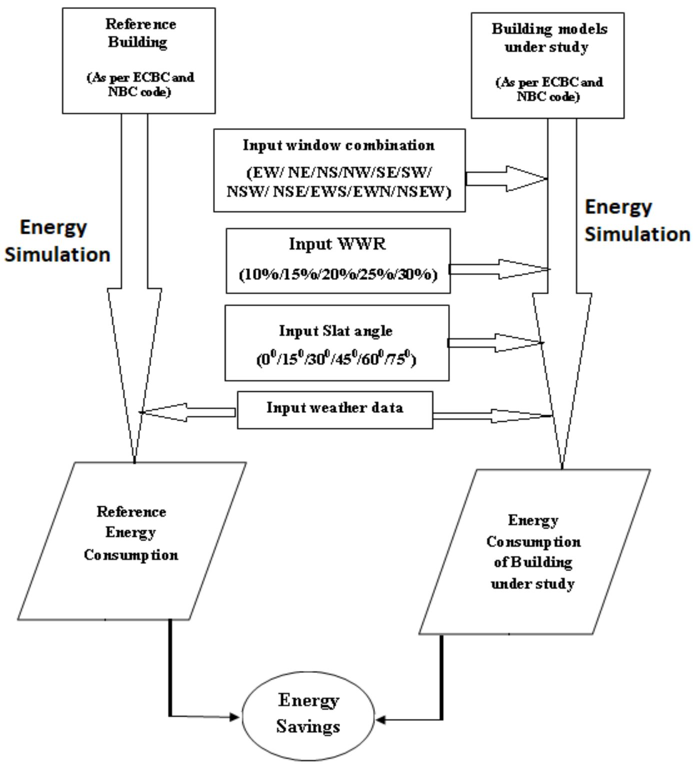

Figure 5.1: Schematic diagram of the study

5.1.1 Solar radiation and heat gain through window

The study is conducted for tropical climate condition hence solar radiation on window pane will contribute significant heat gain into the building. Window glazing system in tropical climate allows daylighting into the building but, the heat gain is also an important factor to take case otherwise cooling energy requirement will increase significantly. Heat gain of a building through window glazing depends on optical and thermal properties of window glazing. Solar radiation received on a surface considering anisotropic sky is given by **(Duffie & Beckman, 2006)**

$$I_T = (I_b + I_d A_i) R_b + I_d (1 - A_i) \frac{(1+cos\beta)}{2} \left[1 + f\, sin^3 \frac{\beta}{2}\right] + I\rho_g \left(\frac{1-cos\beta}{2}\right) \qquad (5.1)$$

Where R_b is tilt factor of beam radiation, R_d is tilt factor of diffusion radiation, R_r is tilt factor of reflected radiation and A_i is anisotropy index which is nearly equal to 1.

$$R_b = \frac{\cos\theta}{\cos\theta_z} \qquad (5.2)$$

$$R_d = \rho_g \frac{(1+\cos\beta)}{2} \qquad (5.3)$$

$$R_r = \rho_g \frac{(1-\cos\beta)}{2} \qquad (5.4)$$

Window is considered as vertical surface hence β is 90^0 and $\cos\theta$ is given by

$$\cos\theta = \sin\varphi \cos\delta \cos\gamma \cos\omega - \cos\varphi \sin\delta \cos\gamma + \cos\delta \sin\gamma \sin\omega \qquad (5.5)$$

$$\theta = cos^{-1}(\sin\varphi \cos\delta \cos\gamma \cos\omega - \cos\varphi \sin\delta \cos\gamma + \cos\delta \sin\gamma \sin\omega) \qquad (5.6)$$

Equation 5.1 through 5.6 is useful to calculate solar radiation received by different building surfaces. Solar radiation received on the window surface allows daylight as well as heat gain of the indoor working space of the building. This heat gain very significant for building energy consumption in tropical climatic condition in India .Heat gain of the building in absence of solar radiation through unit window glazing area is given by

$$\frac{Q}{A} = U(T_0 - T_i) \qquad (5.7)$$

Where Q is the heat flow through the glass window, A is the area of glass window; U is the overall heat transfer coefficient of glass T_0 and T_i are outdoor ambient temperature and indoor working space temperature respectively. When solar radiation falls on the window surface, heat gain through unit window area into the building working space is given by

$$\frac{Q}{A} = U(T_0 - T_i) + \tau I_T + h_i \Delta T \qquad (5.8)$$

Where τ is the transmittance of the glass h_i is the surface heat transfer coefficient of inner side of glass and ΔT is the temperature rice of the glass due to absorption of solar radiation. Absorbed solar radiation by the window glass material is given by

$$\alpha I_T = h_o \Delta T + h_i \Delta T \quad (5.9)$$

$$\frac{Q}{A} = U(T_0 - T_i) + \tau I_T + \frac{\alpha I_T h_i}{h_o + h_i} \quad (5.10)$$

Where h_0 = heat transfer coefficient of outer surface of the glass. Heat gain of the building depends on transmittance and absorbance of the window glass material. Transmittance and absorbance of diffuse solar radiation for the glass is 0.799 and 0.0544 respectively and for beam solar radiation is function of incident angle and given by **(Stephenson, 1965)** the following equations

$$\tau_b = -0.00885 + 2.71235\cos\theta - 0.62062\cos^2\theta - 7.07329\cos^3\theta + 9.75995\cos^4\theta - 3.89922\cos^5\theta \quad (5.11)$$

$$\alpha_b = 0.001154 + 0.77674\cos\theta - 3.94657\cos^2\theta + 8.57881\cos^3\theta - 8.38135\cos^4\theta + 3.01188\cos^5\theta \quad (5.12)$$

Heat gain of the building through window increases cooling energy demand of the building. This heat gain through window can be reduced with the application of external shading device to the window.

5.1.2 Shading device

Heat gain of the building increases when the window of the building receives direct sunlight. It is an adverse effect of daylighting in tropical climate condition. Controlling daylight is necessary to reduce heat gain and consequent cooling energy demand of the building. Many control strategies of daylight is found in literature such as blind, shading, overhang, fin etc. All of the shading devices blocks additional heat gain and glare up to certain extent. Application of overhang with proper dimensions in Indian buildings reduces cooling energy demand **(Shaik et al, 2016).** Heating and cooling energy requirement of building is influenced by orientation of window as well as placement of overhang and fin. Overhang has the potential to reduce cooling energy consumption of buildings in mild and temperate condition **(Idchabani et al, 2017).** In a study in USA, it is found that dynamic overhangs with particular WWR in residential building can save over 45% of the HVAC load **(Krarti,**

2021). Blinds are other shading devices used to protect higher solar radiation on the glazed surfaces of building. The slat angle of the blind with respect to the horizontal can be controlled to regulate daylighting inside building. Slat of the blind blocks the direct sunlight but allow diffuse radiation to penetrate into the building space **(Fathoni et al, 2016)**. Application of different control strategy to regulate slat angle reduces energy consumption of the building **(Lee et al, 2013)**. Controlling the shading device not only reduces energy consumption but also improve thermal and visual comforts of the occupant **(Shen et al, 2014; Oh et al, 2012).** External blind is widely used to control daylighting and heat gain of the building by tilting the slat to different angles. Cut-off control is one of common control strategy for blocking the direct sunlight by calculating the position of sun around the sky and given by the following equation 5.1

$$\beta_{cutt-off} = \sin^{-1}\left(\frac{d}{w}\csc\Omega\right) - \Omega \qquad (5.13)$$

Where '$\beta_{\text{cut-off}}$' is the cut-off angle of the slat, 'd' is the separation between slats, '*w*' is the slat width and 'Ω' is the solar profile angle. This control strategy effectively blocks the direct sunlight penetration into the building space but has some drawbacks **(Luo et al, 2020)**. The main drawback is that it cannot restrict diffuse solar radiation which cause high glare as well as significant heat gain in tropical climate condition. In the present study different slat angle of venetian blind is investigated for optimal energy consumption of the building in tropical climate. Tilt angle of the slat of the shading system is positive when the upper slat surface faces outdoor side whereas negative when upper slat surface is towards indoor side as shown in figure 5.2. Slat tilt angle is 0^0 when the slat is horizontal or fully open and 90^0 when slat is fully closed. Properties of window glazing and shading system used in the study are given in table 5.1.

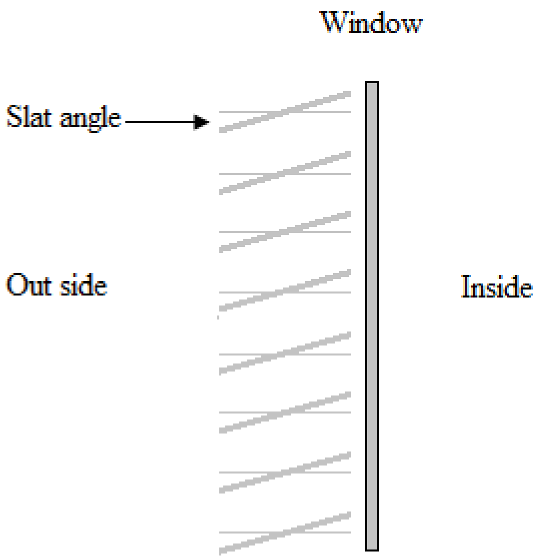

Figure 5.2: Venetian blind for external shading.

Table 5.1. Properties of window glazing and shading device.

Components	Parameter	Specification
Window glazing (Clear glass)	Thickness	4mm
	U- Value	5.6 W/m2K
	Solar Heat Gain Coefficient (SHGF)	0.79
	Visible Transmittance (VT)	87.8%.
	WWR	10%, 15%, 20%, 25% and 30%
Shading (Horizontal Venetian Blind)	Slat tilt angle	0^0, 15^0, 30^0, 45^0, 60^0 and 75^0
	Slat width	2.5 cm
	Slat thickness	1mm
	Slat separation	1. 875cm
	Front side reflectance	0.8
	Back side reflectance	0.8

5.1.3 Distribution of window on building envelope

Total area of the glass window in each building model is distributed equally in different wall for better daylighting. The window is made of clear glass of 4mm thickness. U-value, SHGC and VT of the glass sample are 5.6 W/m^{2}K, 0.83 and 77.8% respectively. Five different window-to-wall-ratios (WWR) namely 10%, 15%, 20%, 25% and 30% are considered for energy evaluation of the building. Total eleven window combinations are formed and each window combination is simulated with five different WWR for energy performance of the building. The dimensions of glass window for all window combinations are shown in table 5.2.

Table 5.2: Specifications of windows in different combination.

Window Combination	WWR (%)	Sill height (m)	Window Height (m)	Width of window (m)	Area of each window (m^2)	Total window area in the building (m^2)
EW, NE, NS, NW, SE, SW	10	1	1.80	3.00	5.40	10.80
	15	1	1.80	4.50	8.10	16.20
	20	1	1.80	6.00	10.80	21.60
	25	1	1.80	7.50	13.50	27.00
	30	1	1.80	9.00	16.20	32.40
NSW, NSE, EWS, EWN	10	1	1.80	2.00	3.60	10.80
	15	1	1.80	3.00	5.40	16.20
	20	1	1.80	4.00	7.20	21.60
	25	1	1.80	5.00	9.00	27.00
	30	1	1.80	6.00	10.80	32.40
NSEW	10	1	1.80	1.50	2.70	10.80
	15	1	1.80	2.25	4.05	16.20
	20	1	1.80	3.00	5.40	21.60
	25	1	1.80	3.75	6.75	27.00
	30	1	1.80	4.50	8.10	32.40

5.2 Result and discussion

5.2.1 Energy consumption in reference building

The reference building is simulated for the weather condition of Kolkata, Delhi and Chennai. Annual Energy consumption for cooling and lighting load is determined from the simulation result. Total annual energy consumption of the reference building is the summation of annual cooling and lighting energy consumption of the building. This energy consumption per unit floor area has been considered as reference energy consumption of the building. Annual total energy consumption per unit floor area of the reference buildings are 120.3 kWh/m^2, 124.2 kWh/m^2 and 147.0 kWh/m^2 in Kolkata, Delhi and Chennai respectively. Energy consumption of reference buildings are considered as benchmark to find the suitable WWR and slat angle of the external shading device for each of the studied window combinations to integrate daylight into the building.

5.2.2 Energy consumption and savings in Kolkata

Daylight through the window is controlled with external shading applied to building models under study. Slat angle of the external shading device are varied to control daylight and heat gain of the building models. Artificial lighting system of the building is controlled according to available daylight into the building spaces. Impact of Controlled daylight on energy consumption of the building is observed. Annual total energy consumption of the building for different window combinations is measured from the study.

Annual energy consumption in Kolkata for all the building models under study with different WWR and slat angle is obtained from the study. From the result annual maximum and minimum energy consumption per unit floor area of the building with each window combinations are determined and shown in figure 5.3. For all the studied window combinations, energy consumption is maximum when WWR is 30% and the slat angle is 0^0 whereas energy consumption is minimum when WWR is 30% and the slat angle is 60^0. Energy consumption in building per unit floor area lies between 94.7 to109.0 kW/m^2 whereas the reference energy consumption in this location is 120.3 kW/m^2. From the result it is clear that energy consumption can be reduced significantly with proper selection of WWR and slat angle of external shading. It is found that the minimum energy consumption of building with two window combinations in Kolkata is slightly higher than the building with three and four window combinations.

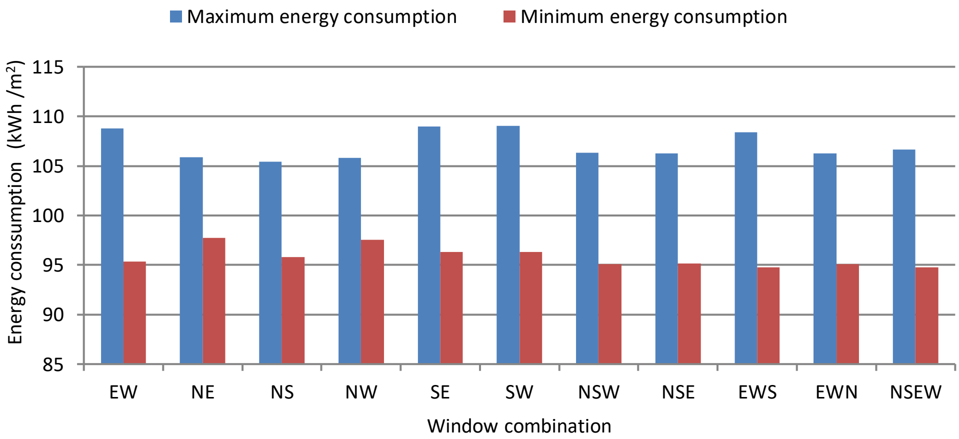

Figure 5.3: Maximum and minimum energy consumption in Kolkata

Energy consumption of the building can be saved with integration of daylight into the building. Artificial lighting system of the building is controlled according to available daylight into the building space which results significant reduction in energy consumption of the building. Daylight in uncontrolled way increases heat gain of the building and results higher cooling energy requirement. Controlled daylight with proper shading strategy significantly reduces heat gain of the building as well as lighting energy consumption of the building. Energy savings due to controlled daylight integration compared to reference building for different WWR and slat angle are shown in figure 5.4 to figure 3.14. Energy savings in Kolkata compared to reference case ranges from 9.3% to 24.0% depending on window combination, WWR and slat angle. In all the window combinations, results shows that lower values of slat angle are desirable when WWR of the building is comparatively smaller to allow more daylight through the window. When WWR is higher, slat opening required to minimize to control daylight and heat gain into the building space for better energy performance. Maximum energy savings in Kolkata is achieved when WWR is 30% and slat angle is 60^0 for all window combinations.

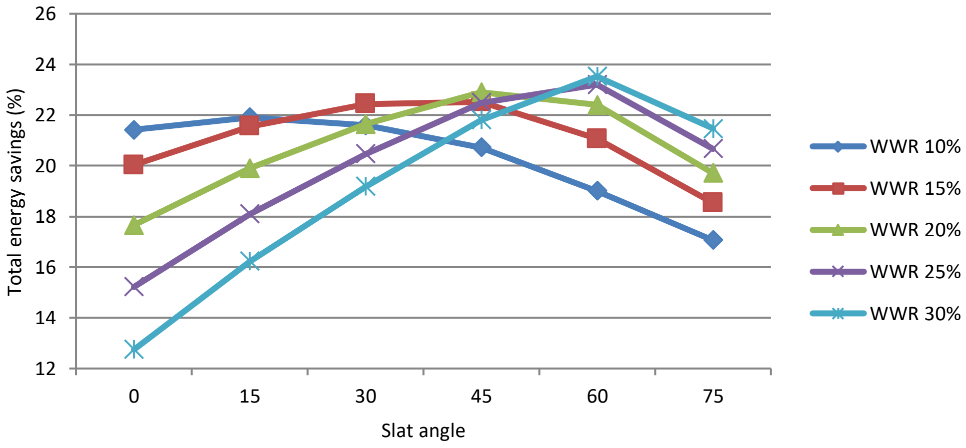

Figure 5.4: Energy savings with EW combination in Kolkata

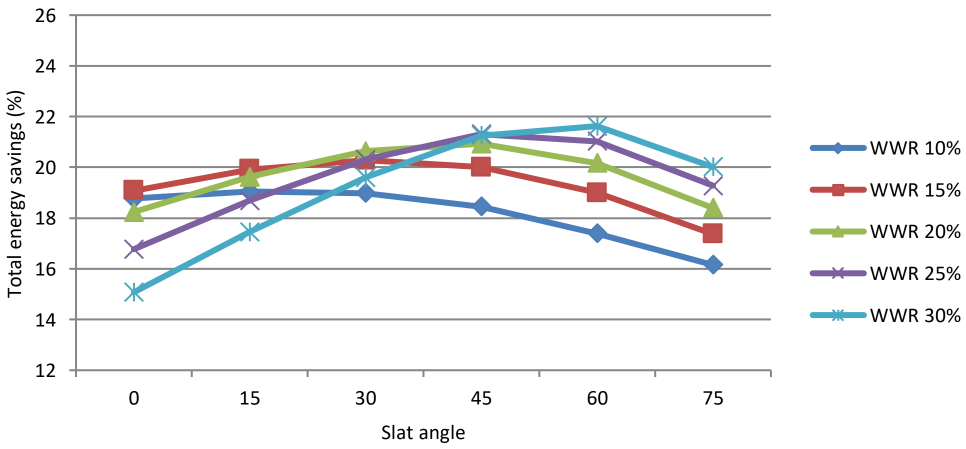

Figure 5.5: Energy savings with NE combination in Kolkata

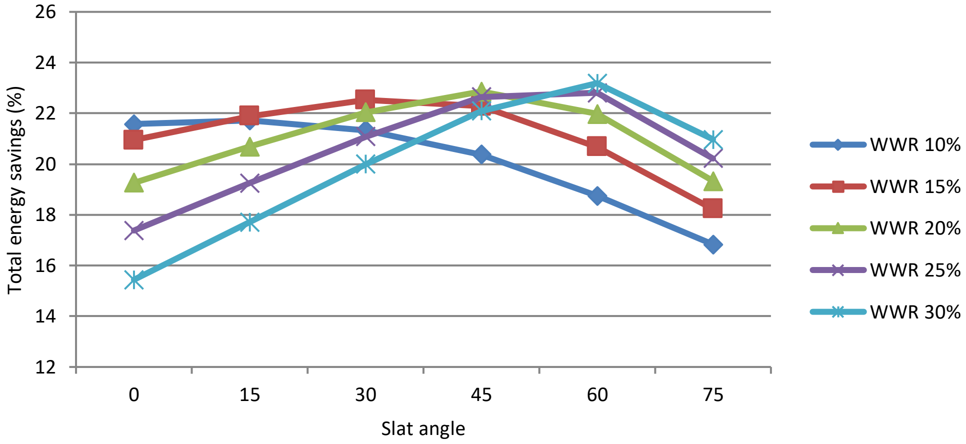

Figure 5.6: Energy savings with NS combination in Kolkata

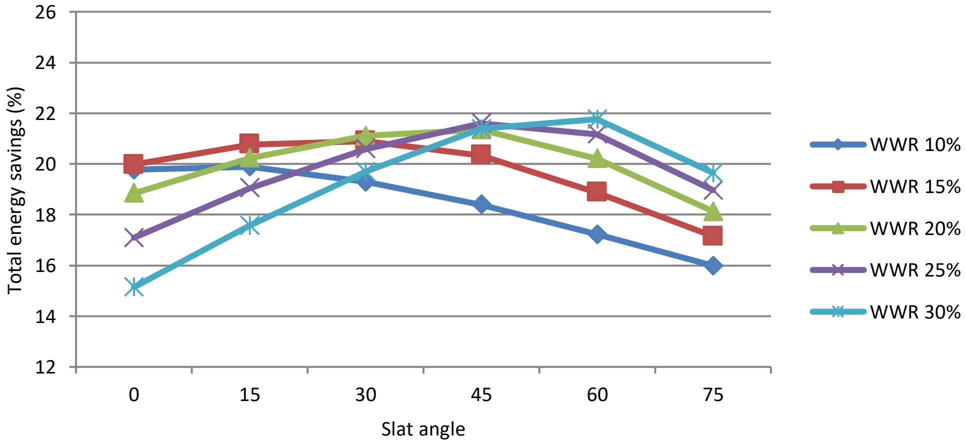

Figure 5.7: Energy savings with NW combination in Kolkata

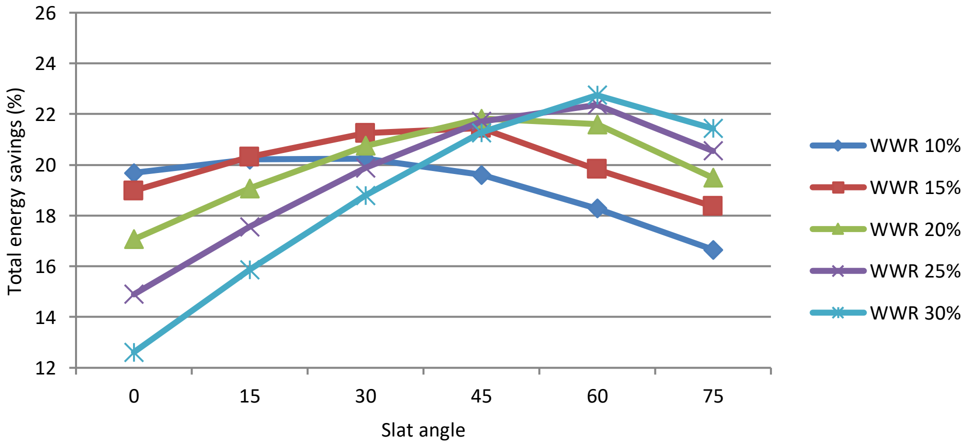

Figure 5.8: Energy savings with SE combination in Kolkata

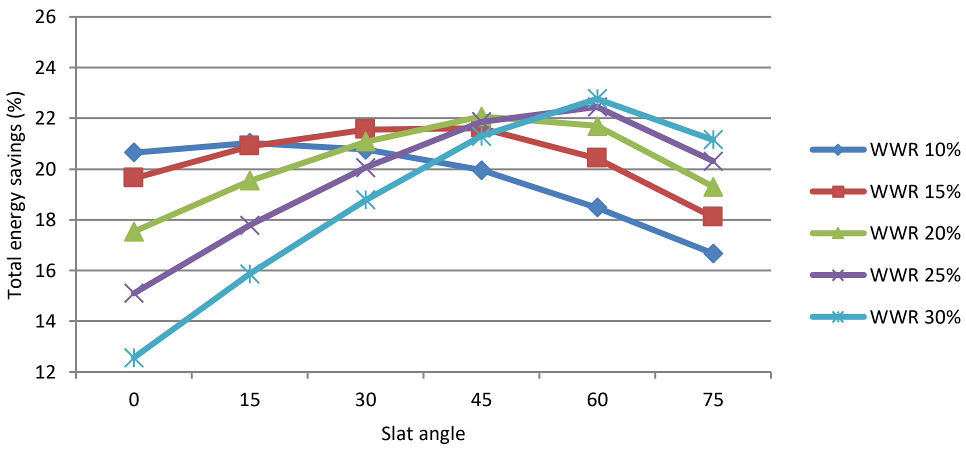

Figure 5.9: Energy savings with SW combination in Kolkata

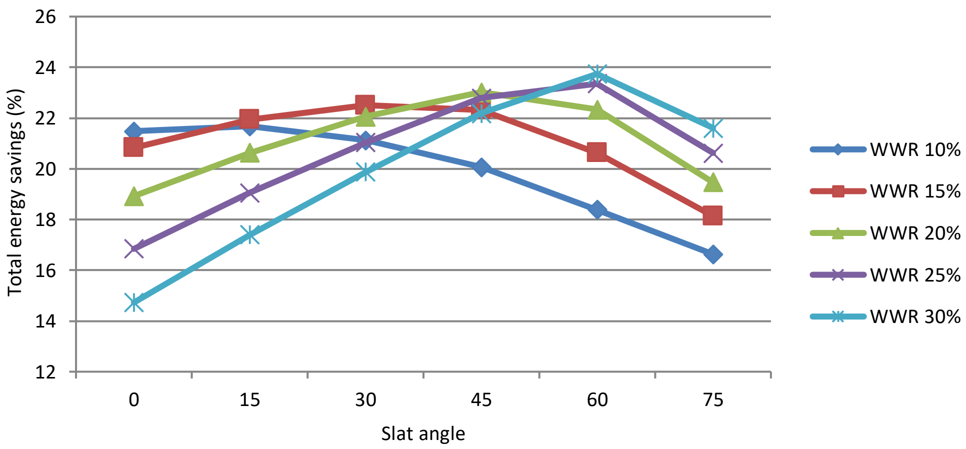

Figure 5.10: Energy savings with NSW combination in Kolkata

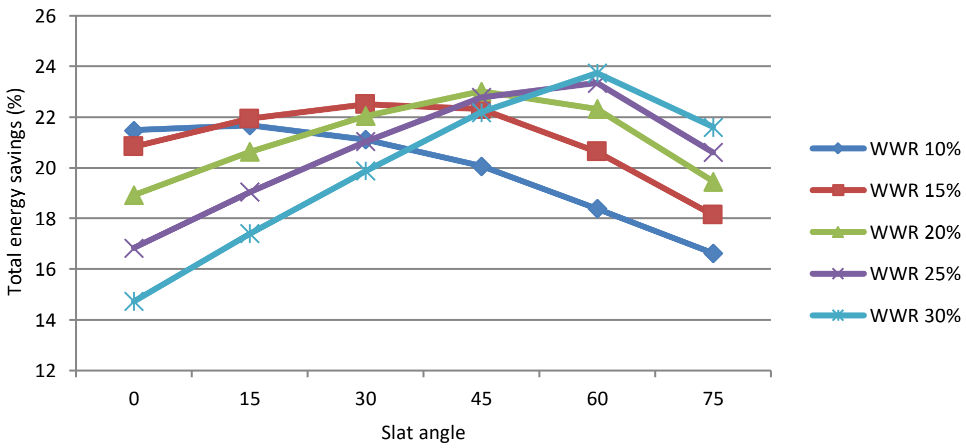

Figure 5.11: Energy savings with NSE combination in Kolkata

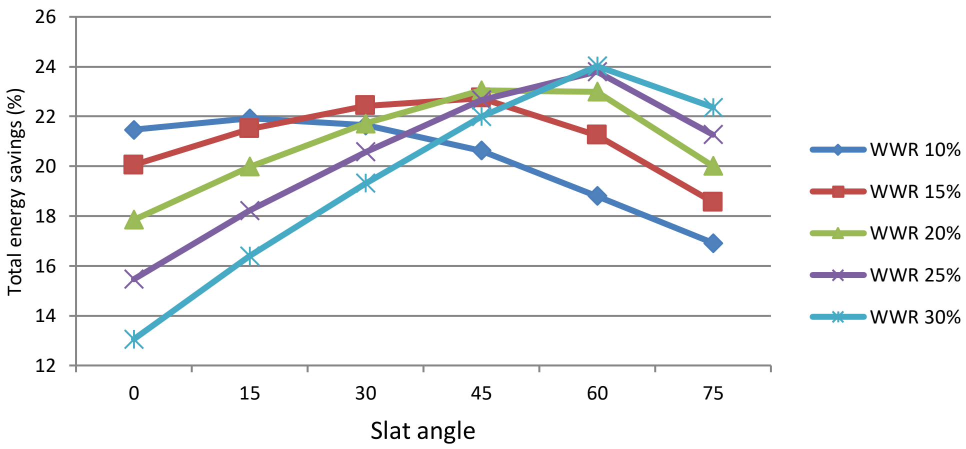

Figure 5.12: Energy savings with EWS combination in Kolkata

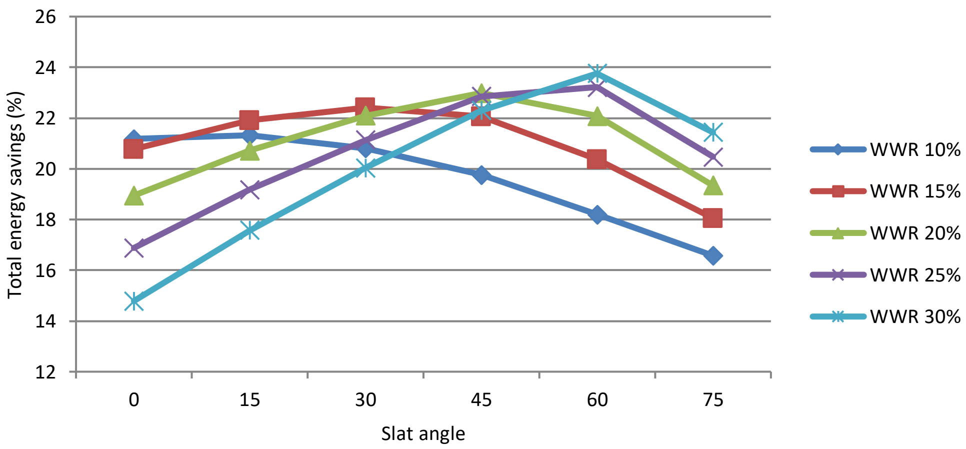

Figure 5.13: Energy savings with EWN combination in Kolkata

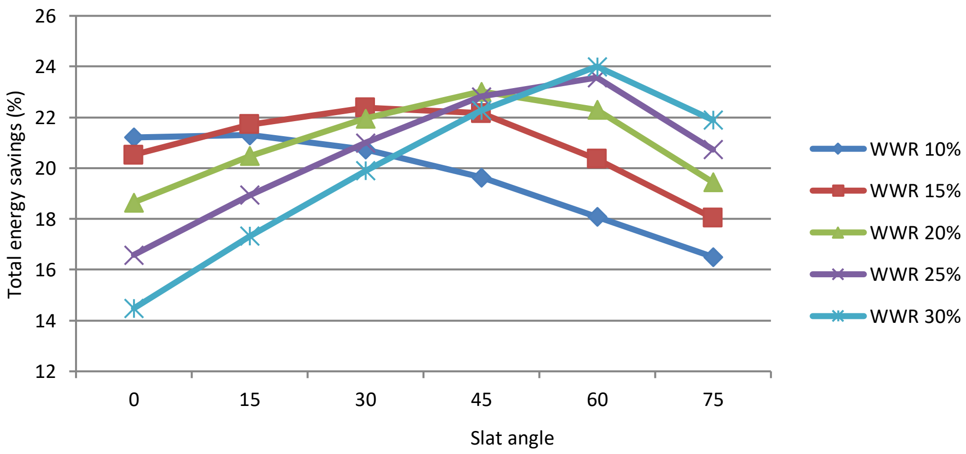

Figure 5.14: Energy savings with NSEW combination in Kolkata

5.2.3 Energy consumption and savings in Delhi

Annual energy consumption per unit floor area for different WWR of the building models and slat angle of the shading device under study in Delhi are also similar to Kolkata. Maximum and minimum energy consumption per unit floor area of the building with different window combinations in Delhi is shown in figure 5.14. Energy consumption per unit floor area in Delhi lies between 93.3 to107.2 kWh/m^2 whereas the reference energy consumption in this location is 124.2 kWh/m^2. Similar to Kolkata, energy consumption is reduced significantly with proper selection of WWR and slat angle of external shading. Energy consumption in the building can be minimized with proper slat angle selection as well as distributing window to more number of walls of the building. Minimum energy consumption of the building with two window combinations in Delhi is slightly higher than the building with three and for window combination.

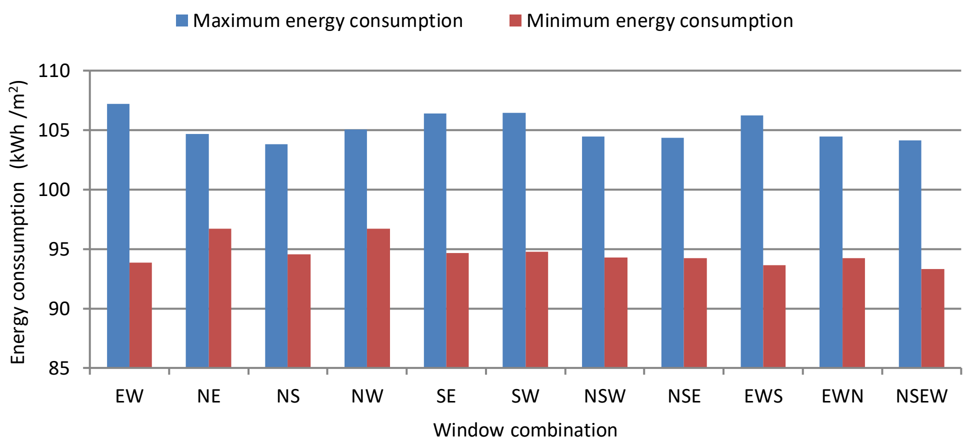

Figure 5.15: Maximum and minimum energy consumption in Delhi

Similar to Kolkata, daylight integration into the building and controlling the artificial lighting according to available daylight into the building space significantly reduces energy consumption of the building in Delhi. Energy savings due to controlled daylight integration compared to reference building for different WWR and slat angle are shown in figure 5.16 to figure 5.26. Energy savings in Delhi compared to reference case ranges from 13.7% to 24.9% depending on window combination, WWR and slat angle. In all the window combinations, lower values of slat angle are desirable with smaller WWR whereas higher slat angle is desirable for larger WWR of the building. Better energy performance of the building with all the window combinations can be achieved with proper control of slat angle. Maximum energy savings in Delhi is also achieved when WWR is 30% and slat angle is 60^0 for all window combinations.

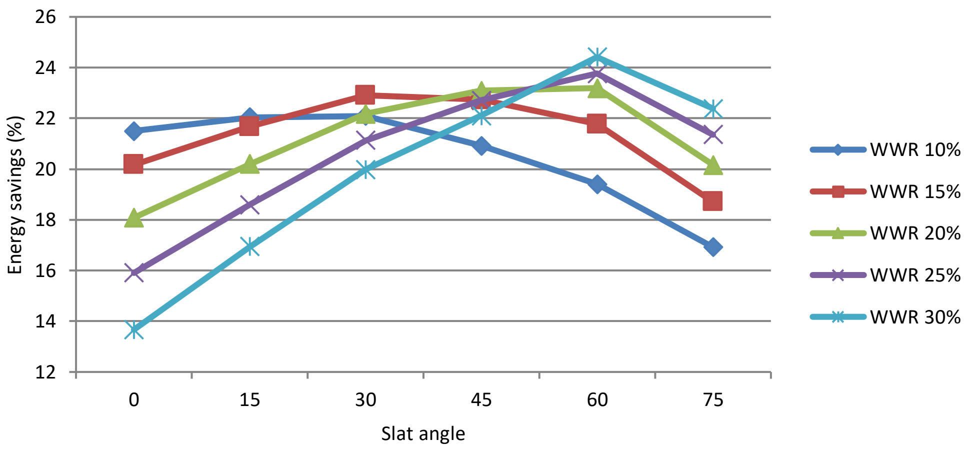

Figure 5.16: Energy savings with EW combination in Delhi

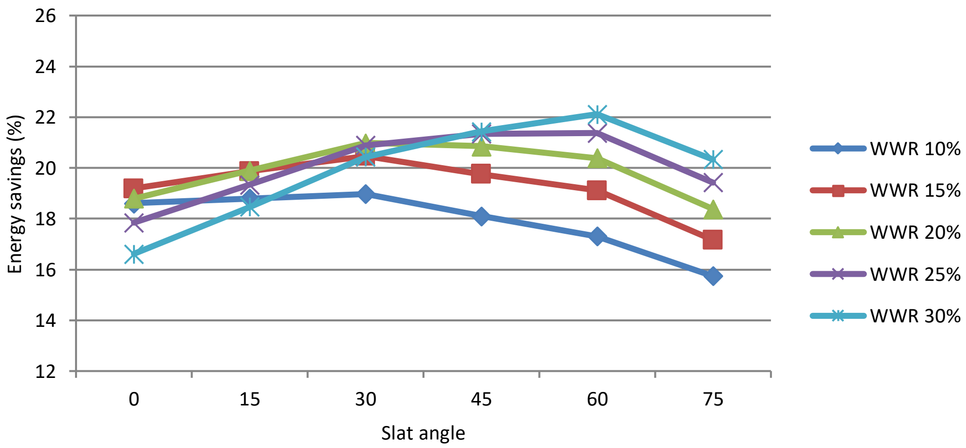

Figure 5.17: Energy savings with NE combination in Delhi

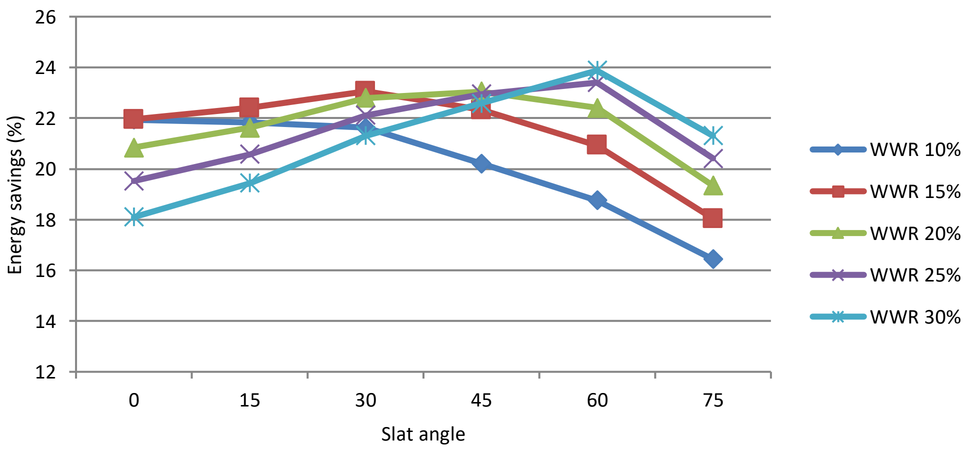

Figure 5.18: Energy savings with NS combination in Delhi

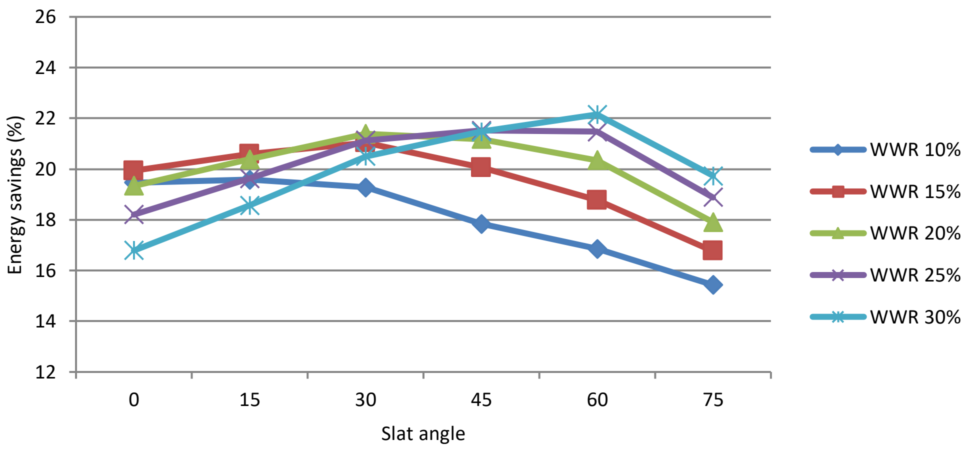

Figure 5.19: Energy savings with NW combination in Delhi

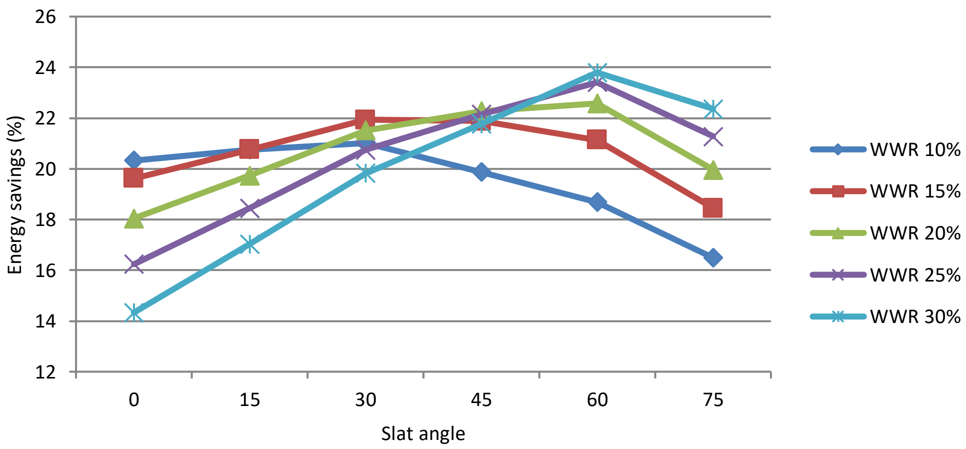

Figure 5.20: Energy savings with SE Combination in Delhi

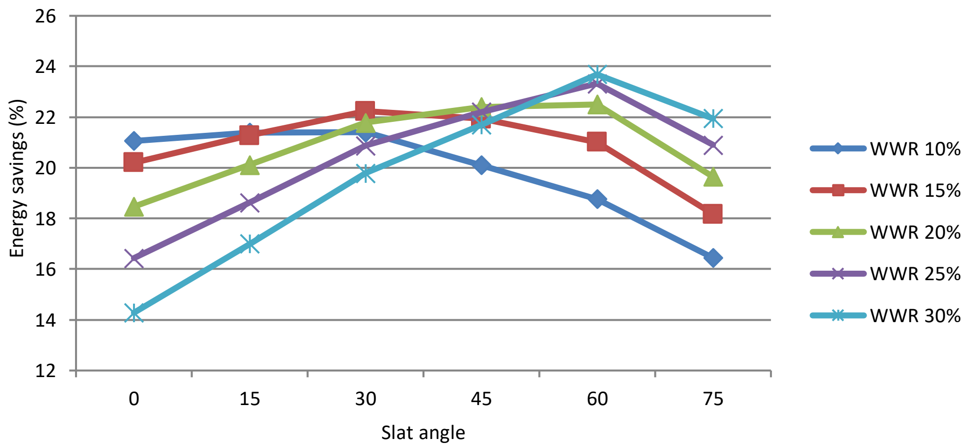

Figure 5.21: Energy savings with SW combination in Delhi

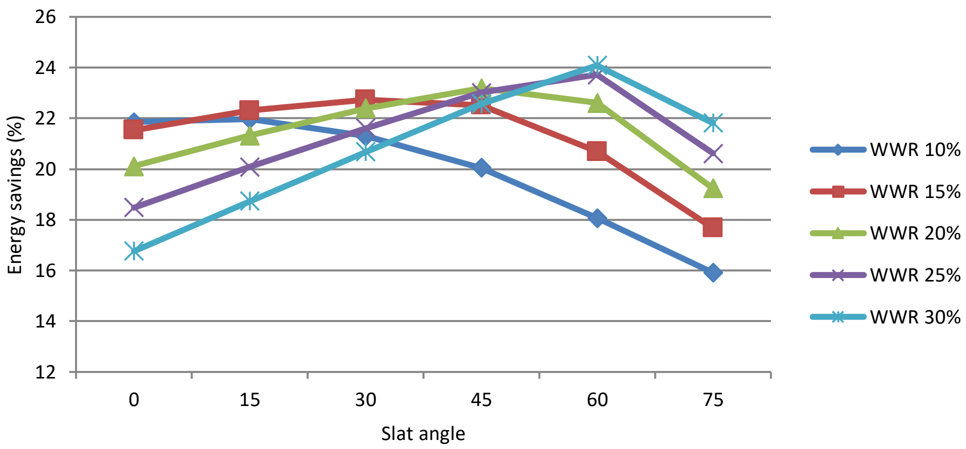

Figure 5.22: Energy savings with NSW combination in Delhi

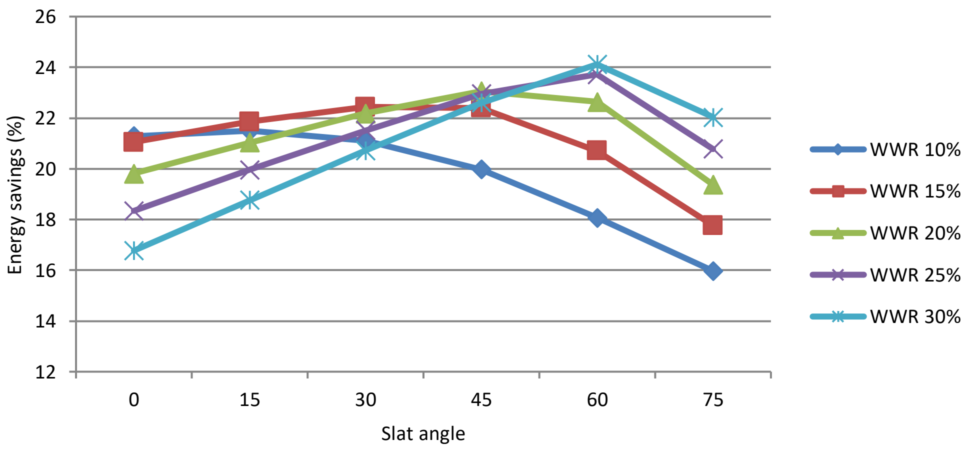

Figure 5.23: Energy savings with NSE combination in Delhi

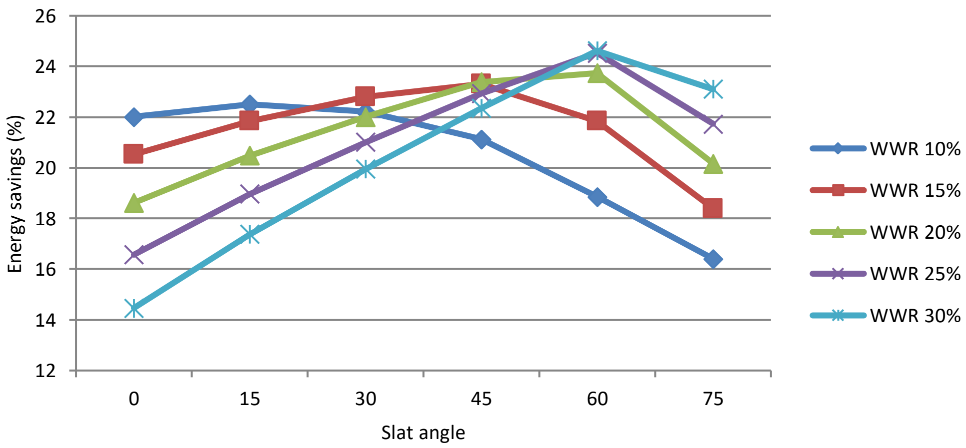

Figure 5.24: Energy savings with EWS combination in Delhi

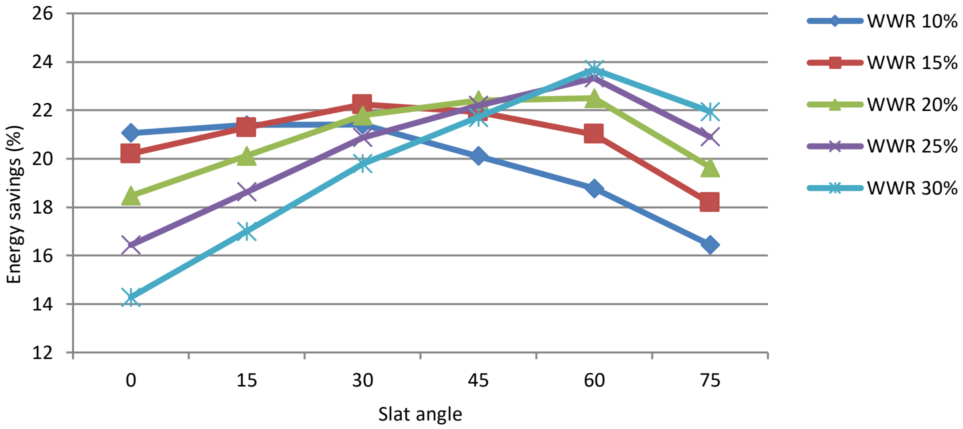

Figure 5.25: Energy savings with EWN combination in Delhi

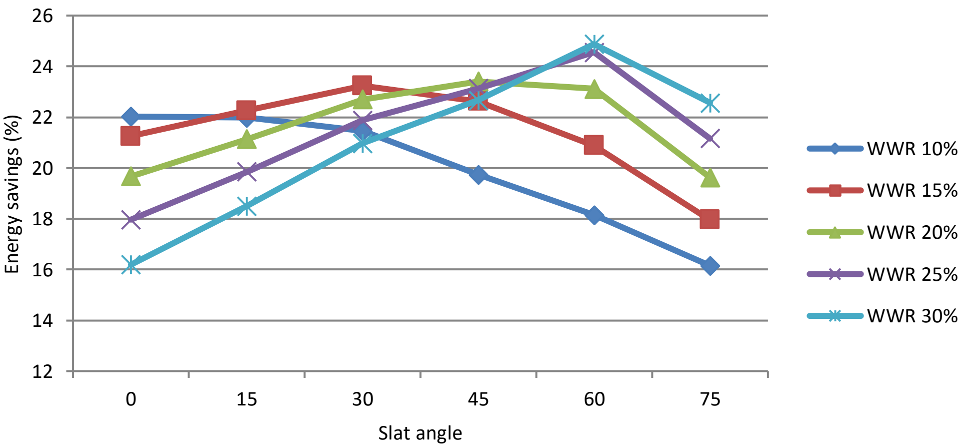

Figure 5.26: Energy savings with NSEW combination in Delhi

5.2.4 Energy consumption and savings in Chennai

Annual energy consumption per square metre of floor area for different WWR of the building models and slat angle of the shading device under study in Chennai are also similar to Kolkata. Maximum and minimum energy consumption per unit floor area of the building with different window combinations in Chennai is shown in figure 5.27. Energy consumption per unit floor area in Chennai lies between 113.7 to 132.9 kWh/m^2 whereas the reference energy consumption in this location is 147.0 kWh/m^2. Similar effect of daylight on energy consumption of the building is observed in Chennai also. Significant amount of energy consumption in the building can be minimized with proper slat angle selection as well as proper distribution of window around the walls of the building. Minimum energy consumption of the building with two window combinations in Chennai is also slightly higher than the building with three and four window combinations.

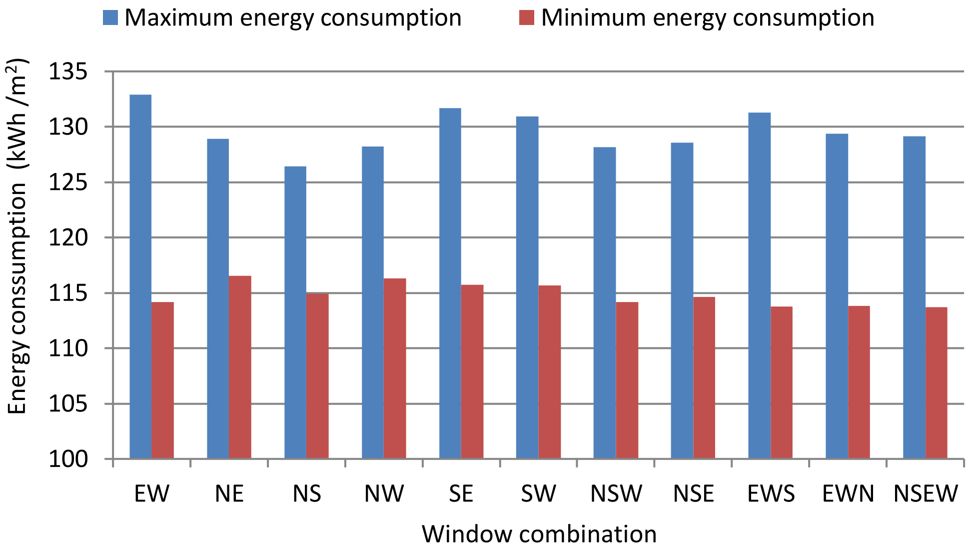

Figure 5.27: Maximum and minimum energy consumption in Chennai

Daylight integration into the building and controlling the artificial lighting according to available daylight into the building space significantly reduces energy consumption of the building in Chennai. Energy savings due to controlled daylight integration compared to reference building for different WWR and slat angle are shown in figure 5.28 to figure 5.38. Energy savings in Chennai compared to reference case ranges from 9.6% to 22.6% depending on window combination, WWR and slat angle. Similar to Kolkata and Delhi, lower values of slat angle are desirable with smaller WWR whereas higher slat angle is desirable for larger WWR of the building in Chennai. Energy performance of the building can be improved with proper selection of slat angle and WWR for all the window combinations. Maximum energy savings in Chennai is found when WWR of the building is 30% and slat angle is 60^0 for all window combination.

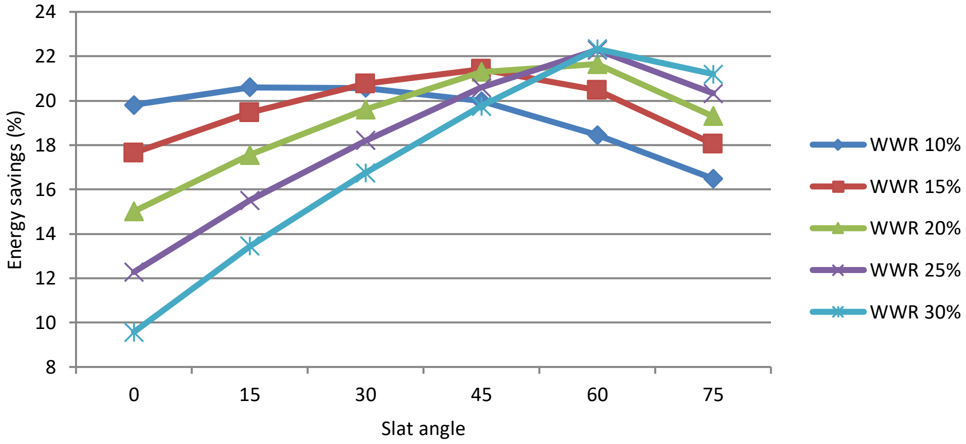

Figure 5.28: Energy savings with EW combination in Chennai

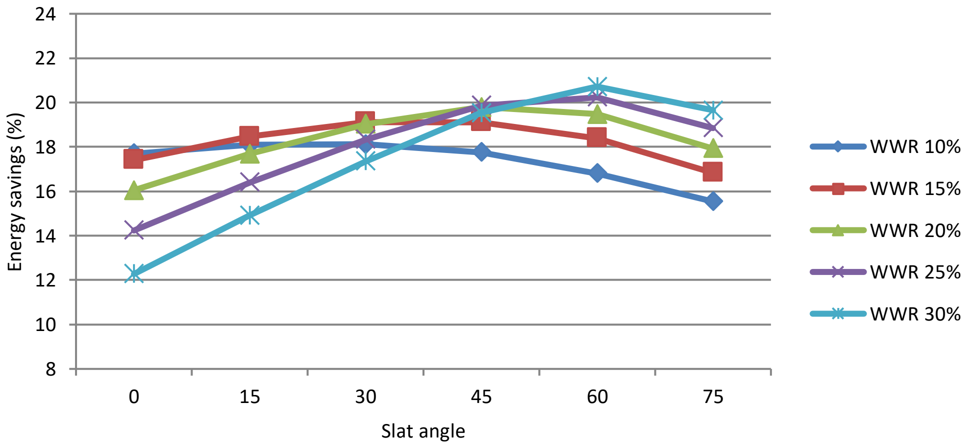

Figure 5.29: Energy savings with NE combination in Chennai

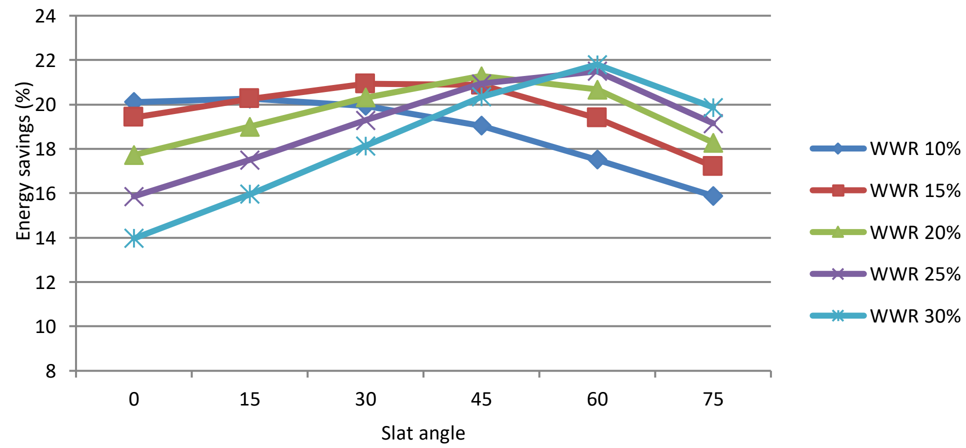

Figure 5.30: Energy savings with NS combination in Chennai

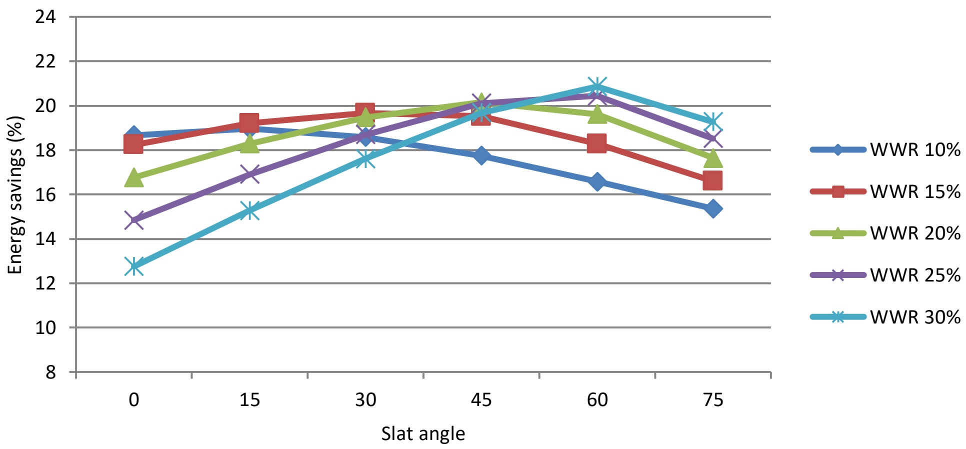

Figure 5.31: Energy savings with NW combination in Chennai

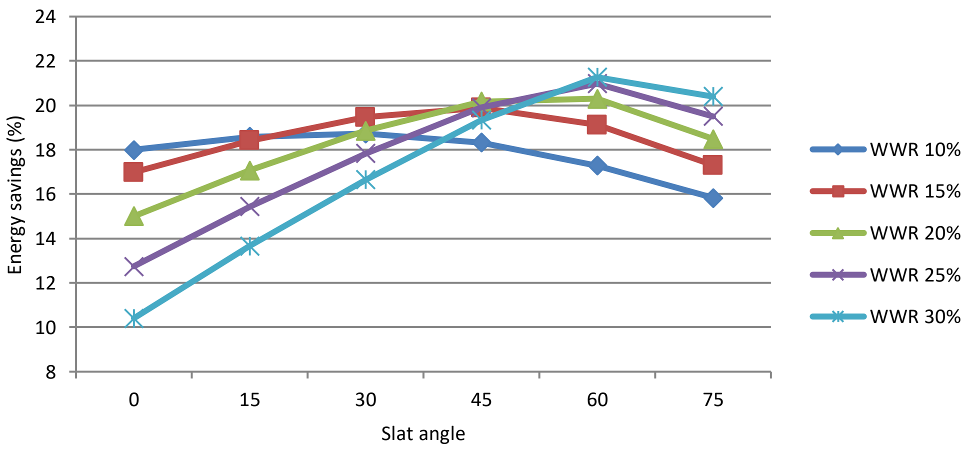

Figure 5.32: Energy savings with SE combination in Chennai

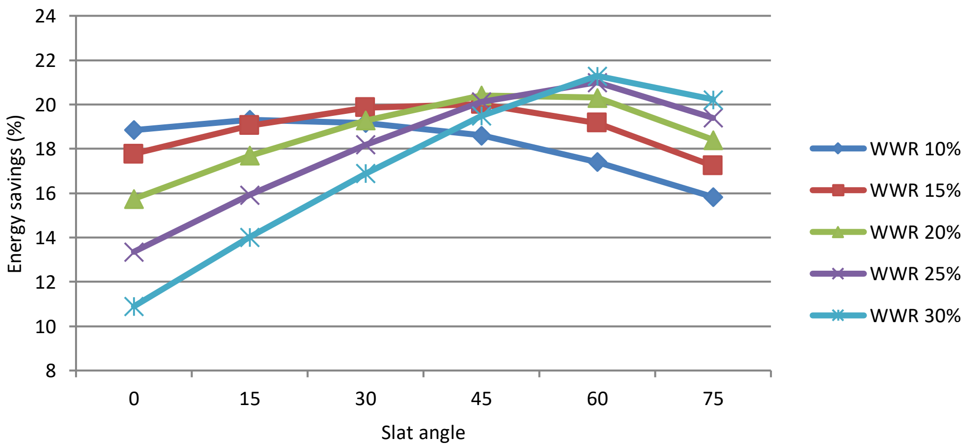

Figure 5.33: Energy savings with SW combination in Chennai

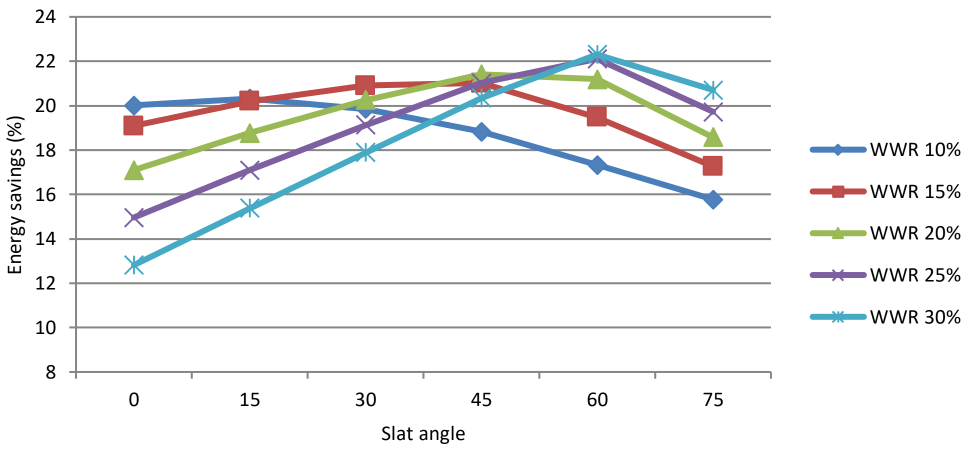

Figure 5.34: Energy savings with NSW combination in Chennai

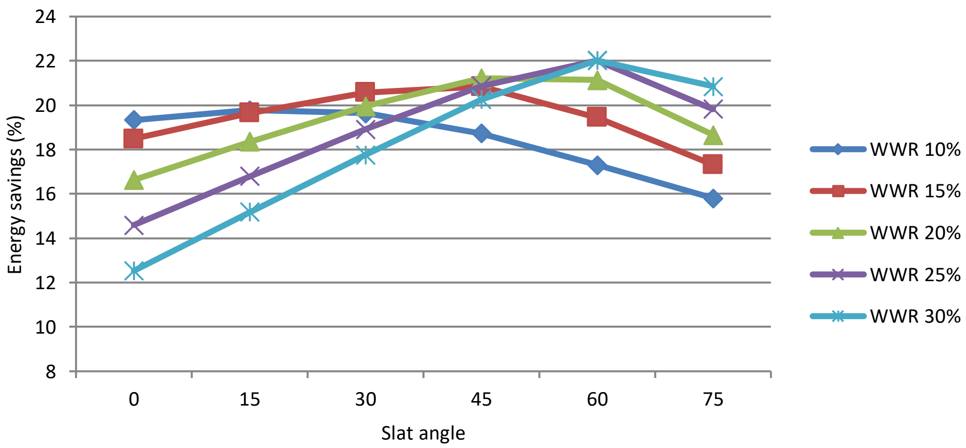

Figure 5.35: Energy savings with NSE combination in Chennai

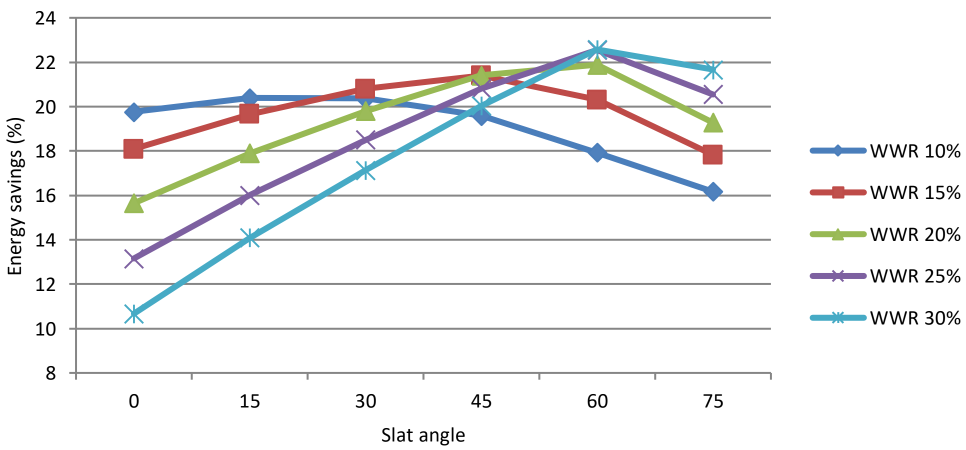

Figure 5.36: Energy savings with EWS combination in Chennai

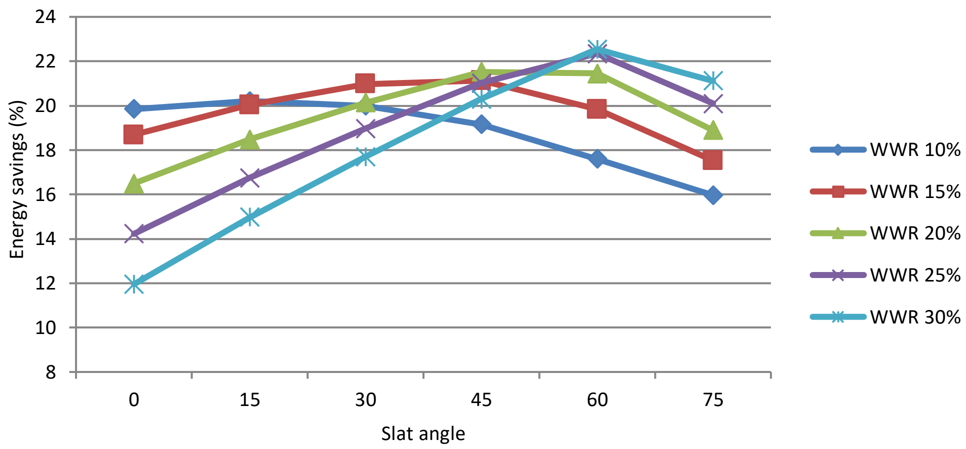

Figure 5.37: Energy savings with EWN combination in Chennai

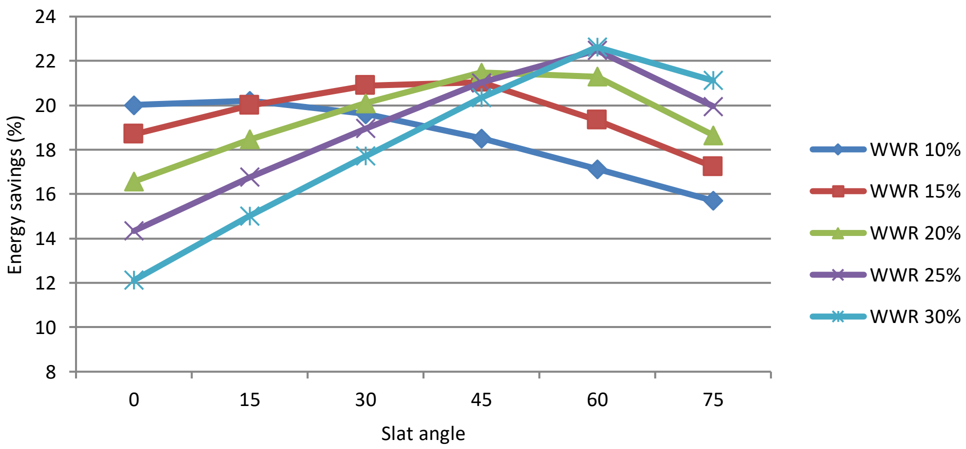

Figure 5.38: Energy savings with NSEW combination in Chennai

5.3 Conclusion

Building sector in India is experiencing rapid growth and hence the energy consumption in this sector is increasing rapidly. A comprehensive guideline for building energy efficiency is essential to prevent excessive growth in energy consumption within the building sector. The key challenge in these days is to design buildings for sustainable development in a longer term and to develop suitable strategies through which building energy use can be optimized. The government of India has developed ECBC code to regulate energy efficiency in new commercial buildings. Government of India has also under taken several energy related program to encourage energy efficiency practices in building sector. This chapter focuses on energy saving opportunity due to daylight integration in buildings following the guidelines of ECBC and NBC in India. Impact of daylight integration in buildings through the different window combination, window-to-wall-ratio (WWR) and different slat angles of the shading device has evaluated in Indian climatic condition and the result of the study has been compared to the reference building to quantify the energy savings in building. Energy savings in Kolkata due to integration of daylight varies from 9.3% to 24.0% depending on combination of window, WWR and the slat angle. Energy savings in Delhi and Chennai are 13.7% to 24.9% and 9.6% to 22.6% respectively. Maximum energy savings for all the three locations are achieved when WWR of the building is 30% and the slat angle is 60^0.

Following the guidelines of the Energy Conservation Building Code (ECBC) and complying with the National Building Code (NBC) can significantly reduce building energy consumption in India, thereby lowering the need for additional electricity generation capacity in the long term. Incorporating daylight integration in buildings, along with adherence to ECBC and NBC standards in new construction projects across India, will serve as a key strategy for achieving energy-efficient and sustainable building design.

6 Long term economic benefit of daylight in building

6.1 Introduction

Energy consumption in building sector is increasing very fast due to rapid urbanization and economic growth. Buildings consume almost 151 EJ of the world's final energy consumption. Almost 30% of the global energy consumption is used for the operation of buildings **(United Nations Environment Programme, 2020)**. Building energy consumption is increasing because of population growth which increases building floor area as well as the demand for energy services. IEA reported that energy demand of the building sector increased around 20% between 2000 and 2017 **(IEA, 2019).** Improvement in Energy efficiency is essential in building sector to decrease global building energy consumption. It is found that the investment in energy efficiency is only $1 for $37 investment in the conventional construction **(IEA, 2021).** It is predicted that generation of electricity in India in 2050 expected to increase eight fold compared to 2005. Total energy production would be more than104EJ in 2050 and 230EJ in 2095 **(Shukla et al, 2013)**. Previous research shows that the primary energy demand in India has grown from about 450 mtoe in 2000 to about 770 mtoe in 2015 and the same is to increase to about 1250 - 1500 mtoe in 2030 **(Sahoo et al., 2016).** Many studies have been conducted to quantify the impact of energy conservation codes around the world. In a study in Hong Kong, energy savings potential of more than 80 existing commercial buildings were investigated and results strongly recommend the implementation of building energy code **(Chan et al, 2005)**. A number of energy efficiency programs has initiated by Bureau of Energy Efficiency (BEE) during eleventh five year plan which have resulted in an avoided capacity generation of 10836 MW during the same period **(Shui et al, 2006)**. It is predicted that cumulative electricity savings in buildings would be around 419,800 GWh by 2050 in Gujarat with ECBC **(ECBC, 2017)** adaption. This saving in electrical energy of building could avoid 134,400 MW of cumulative electricity capacity additions from 2010 to 2050 **(Yu et al., 2017).** Initiatives have been taken by government of India to reduce energy consumption in commercial building for higher energy efficiency. Bureau of Energy Efficiency (BEE) promotes different measures for building energy efficiency. Energy conservation regulation in China predicts 29% energy savings in building sector which strongly suggest adaption of building codes in different part of the world **(Wang et al, 2010).**

Daylighting is an important strategy in modern architecture to replace artificial lighting to reduction of the building energy consumption and visual comfort **(Apian et al, 1998; Chen et al., 2014)**. Building energy simulation tool helps to estimate the potential daylight integration through windows for optimum energy performance of building **(Loutzenhiser et al., 2007).** Potential of energy savings with daylighting in building is found in many research work **(Mohsenin et al, 2015; Motamedi et al, 2017; Gene et al, 2017; Antonis et al, 2017; Badarnah et al, 2016).** In the present study daylight is integrated in building through multiple windows distributed to different building envelope and artificial lighting system is controlled according to daylight into the building space. Window area is distributed to different walls for better daylight integration and external shading with different slat angle is applied to control excessive heat gain into the building. A parametric study of WWR, distribution of glazed surface and slat angle along with lighting control provides a new strategy for building energy savings in the present study. Result of the parametric study is used to find the long term energy savings and economic benefit in commercial building sector in India.

6.2 Methodology

Energy consumption in building sector is increasing in rapid rate due to urbanisation in India. Energy consumption of commercial building is predicted to increase fastest among all building categories. With the economic development of the country, commercial building space with HVAC system is also increasing rapidly. As predicted by many researchers that huge amount of building floor area in India is yet to be constructed. Implementation of suitable energy efficiency strategy can save considerable amount of building energy in India. The present study is conducted to quantify the energy savings opportunity in building with controlled daylight integration through distributed window compared to reference building without daylight integration. The result is used to predict long term energy and economic benefit in commercial building sector in India. Figure 6.1 shows the methodology of the present work.

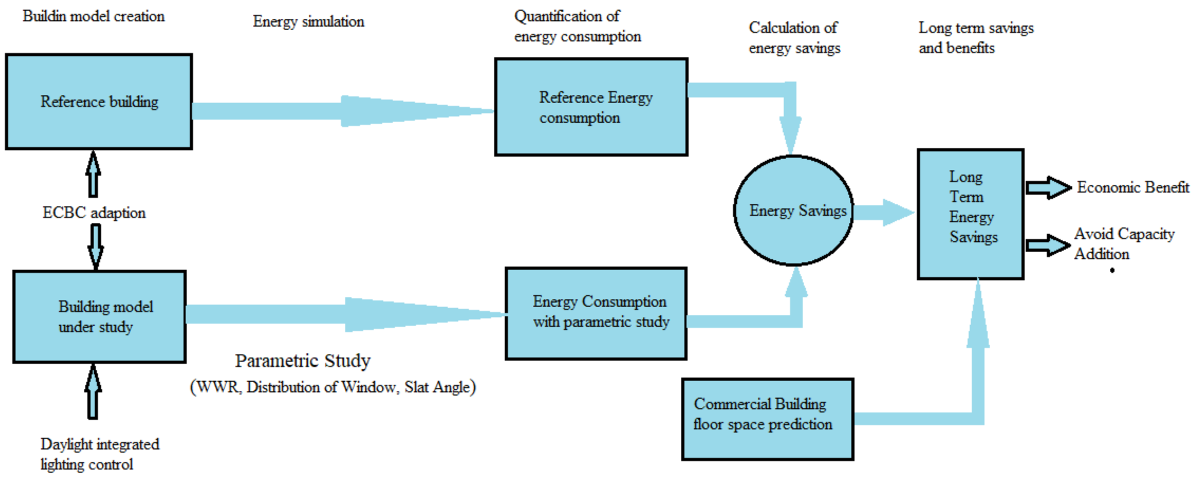

Fig. 6.1. Methodology for estimating long term economic benefits of daylight integration in India.

6.2.1 Building energy code in India

Building codes and standards provide suitable guideline regarding building materials, safety, water efficiency, energy efficiency, thermal comfort, visual comfort etc. Building energy codes deals with energy savings which in turn saves money as well as avoid capacity addition of electric power generation. Adaption of building energy code gives long term economic and environmental benefit. Energy Conservation Act 2001 in India has been introduced by Government of India (GoI) to reduce energy consumption. Bureau of Energy Efficiency (BEE), an autonomous body under Ministry of Power was set up to implement energy efficiency measures in the country. BEE along with United States Agency for International Development (USAID) under its Energy Conservation and Commercialization Project (ECO-II Project) launched the first version of ECBC code in India. To ensure efficient energy utilization in commercial building, Energy Conservation Building Code 2007 (ECBC) has been developed for newly constructed commercial buildings having a connected load of 100 kW or contract demand of 120 kVA or above. A number of energy efficiency measures have been taken by BEE to reduce energy consumption in different area during eleventh five year plan of the country **(Shui et al, 2006).** These initiatives of BEE have resulted in an avoided capacity generation of 10836 MW during the period **(Sahoo et al., 2016).**

6.2.2 Building models

In the present study, all building models have been constructed according to ECBC and NBC code in India for energy performance evaluation in three different locations. All building material and their properties in the present study are considered in accordance with ECBC code and NBC code. Dimensions of the reference building and all other building models under study are 9m X9m X3m **(Singh et al, 2009; Ghosh et al, 2018)**. The reference building has a single window on south wall with 10% window to wall ratio (WWR). No shading device and lighting control has been employed in the reference building. All other buildings have multiple windows to study the impact of distribution of window to different walls. Total eleven window combinations have been consider for the study as shown in table 3.1 in chapter 3. Building envelope materials and their properties are mentioned in table 3.2 in chapter 3. All properties and parameters of window glazing and shading system are given in Table 5.1 in chapter 5. Internal gain of the building from lighting, air changes per hour, operation schedule and other simulation parameters are given in table 6.1.

Table 6.1: simulation parameters of all the building models

Parameter	Description
Cooling set point	25^0 C
Lighting level	9.5 W/m^2
Lighting and HVAC schedule	Week days from 08:00 Hrs to 18:00 hrs
Daylighting control	500 LUX at reference points
Air changes per hour	0.5 ACH
Maximum allowable discomfort glare index	22

6.2.3 Daylight integration strategy

Lighting energy accounts for 20-30% of the total energy consumption in commercial buildings **(Lam et al, 2003)**. Special design strategy is required to minimize lighting energy consumption of the building for the energy efficient operation. Exploration of daylight is an important design strategy in modern building which may replace significant amount of artificial lighting energy consumption of the building. Daylight not only can save energy consumption of the building but also improve the visual comfort of the occupant of the building **(Apian et al, 1998; Chen et al., 2014)**. Many works has been reported lighting energy conservation with the incorporation of daylight based control system in the building

Daylight into the building can be increase with increasing the area of the transparent window on building envelope. Impact of increasing WWR for daylighting in to the building and its impact on energy performance have been studied in many research works **(Mangkuto**

et al, 2016; Ochoa et al., 2012). In the study of daylighting in building, it is observed that evaluating proper WWR is one of the most sensitive parameter to balance between dayligting and energy consumption **(Alex et al, 2018; Shen et al, 2013).** Uncontrolled daylight penetration into the building could cause glare **(Xue et al, 2014)** and excessive heat gain of the building which cause discomfort to the occupant and also increase energy consumption of the building **(Peng et al., 2019)**. Different shading devices are used to control excessive heat gain and visual comfort of building **(Hammad et al, 2010).** Effectiveness of shading device in tropical climatic condition in India has been conducted and result mentions significant energy savings in the building **(Dutta et al, 2017).** In a study, it is found that selection of proper shading device along with artificial lighting control can save 26.1% of total energy consumption of the building within the desired glare index **(Touma et al, 2017)**.

For proper daylighting into the building indoor space, window glazed surface can be distributed into different walls of the building. Higher glazing area in different walls of the building allows higher amount of daylight into the building space. Proper section of slat angle of shading device reduces heat gain through the glazed surface and reduces visual discomfort of the occupant in to the building. In the present study a new strategy to daylight integration in view of energy conservation is used

- The window glazing area (WWR) is distributed equally to different building walls for higher daylighting in to the building and artificial lighting is controlled (continuous dimming control) according to the available daylight at the reference points.
- Balance between heat gains through the higher window area and daylighting is achieved with parametric variation of slat angle of shading device.

Hence the parametric study of WWR, distribution of glazed surface and slat angle along with lighting control provides a new strategy for building energy conservation in the present study.

In this study, window area is distributed equally to different building envelope for optimal use of daylighting. The building models under study consist of eleven number of different window combinations namely EW, NE, NS, NW, SE, SW, NSW, NSE, EWS, EWN and NSEW combination where E stands for east wall and similarly W, N and S stands for west, north and south respectively. A continuous dimming control of artificial lightings is incorporated based on daylight through window combinations at reference points of the building to maintain the illuminance level at 500 LUX at a height of 0.8 m from the floor of the building. At minimum dimming level the light output of the artificial lighting is fixed to

30% of its full illumination. Higher window area increases daylight penetration into the building but it also increases considerable amount heat gain into the working space as India is located at tropical climate region. Daylight into the building reduces lighting energy consumption of the building but increases cooling energy consumption of the building. Hence a balance between daylight penetration and heat gain is essential. Horizontal blind as window shading is used externally to control excessive daylight into the building. Slat angle of the shading device is considered as another parameter to control daylight to achieve balance between lighting and cooling energy consumption of the building. Slat angles are varied from 0^0, to 75^0 in step of 15^0 in the study.

6.2.4 Energy simulation

Whole building energy simulation (BES) models are very effective to determine optimal parameters for energy efficient building design. In the present study, energy consumption of all the building modes is determined in EnergyPlus building energy simulator. Many research works on building energy consumption is carried out on EnergyPlus simulation tool **(Touma et al, 2017)**. EnergyPlus is a whole building energy simulation tool developed by department of energy of USA on the basis of work carried out on DOE-2. EnergyPlus is a widely used simulation tool to determine energy performance of building **(Shabunko et al, 2018; Bernardo et al, 2017)** as well as thermal performance of the building **(Phan et al, 2014)** in different location of the world.

6.2.5 Building floor space prediction

Building sector is growing with the growing economy of India and has lot of opportunity to conserve energy. A limited number of works has been reported so far on long term prediction of building floor space expansion in India. It is projected that commercial floor area is expected to grow around 1.5-2 times by 2028-29, and 2.5-3 times by 2037-38 compared to the commercial floor area of 2017-18 **(India cooling action plan, 2019).** It is also predicted that commercial floor area in India is expected to grow to approximately 2 billion m^2 by 2030 **(Kumar et al., 2018).** Utilization of HVAC system is also increasing rapidly in Indian building for better thermal comfort. It is found that air conditioned commercial floor area was approximately 26% of total commercial floor area in 2017-18 in India. Commercial air-conditioned floor area is predicted to grow approximately 43% and 54% of total commercial floor area in 2027-28 and 2037-38 respectively **(AEEE, 2018).** India Cooling Action Plan of

Ministry of Environment, Forest & Climate Change (2019) also predicted the same data of the commercial air conditioned floor space **(India Cooling Action Plan, 2019).**

6.3 Results and discussion

In the first phase of the study reference energy consumption and energy consumption of all the building models with parametric variation are carried out to quantify the energy saving opportunity with strategic daylight integration into the building. In next phase of the study, future growth of the commercial building floor space area in India is evaluated. Finally, the long term energy savings and economic benefits of daylight integration have been quantified.

6.3.1 Energy savings with daylight integration

6.3.1.1 Reference energy consumption

Reference energy consumption is the basis of the study to quantify the impact of daylight integration into the building. It has been taken as benchmark to determine the energy savings in buildings with distributed window. Annual cooling energy consumption of reference building in Kolkata, Delhi and Chennai are 8092.5 kWh, 8051.7 kWh and 9895.6 kWh respectively. Annual lighting energy consumption is 2008.4 kWh in all three locations. Reference energy consumption per unit floor area in air-conditioned and non air-conditioned commercial buildings in the study locations are shown in table 6.2.

Table 6.2: Reference energy consumption in buildings.

Parameters	Location		
	Kolkata	Delhi	Chennai
Reference energy in air-conditioned building (kWh/m^2)	120.3	124.2	147.0
Reference energy in non air-conditioned building (kWh/m^2)	24.8	24.8	24.8

6.3.1.2 Energy savings in building

In the present study, energy consumption of the 330 building models has been evaluated in EnergyPlus building energy simulator. Energy savings of all the building models has been computed in comparison with the reference energy consumption of the location. Energy savings with SW combination for 60^0 degree slat angle in three different locations has been shown in figure 6.2. It is observed that energy savings for a particular building model increases with increasing WWR with the proposed strategy. Similar result has been obtained for all other combinations.

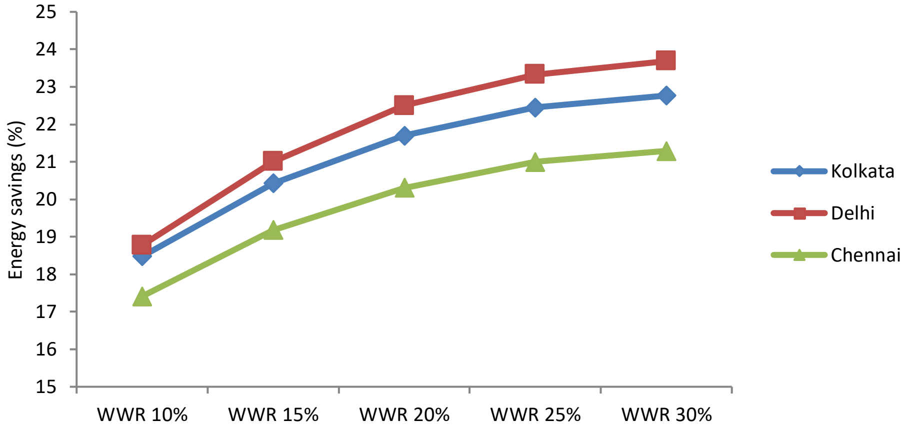

Fig. 6.2. Energy savings the building with of SW combination

Energy consumption per unit air-conditioned commercial floor area of the reference building model in Kolkata, Delhi and Chennai are 120.3 kWh/m^2, 124.2 kWh/m^2 and 147.0 kWh/m^2 respectively whereas the same energy consumption in non air-conditioned commercial building is 24.8 kWh/m^2 in all three locations. Energy savings in all the building models have been determined compared to the energy consumption of the reference building. Maximum energy saving in air-conditioned building for each window combination and WWR has been reported in table 6.3. It is observed that energy saving of air-conditioned building model with each combination of window increases with increasing WWR in all three studied location with proper selection of slat angle. In non air-conditioned building, energy savings increases with increasing WWR. Increasing WWR reduces lighting energy consumption significantly but increase glare index above the comfort level. Optimal energy savings is achieved in non air-conditioned commercial building when WWR is 30% with slat angle 60^0. Average energy savings and annual energy savings per unit floor area in the study locations are shown in table 6.4. Annual energy savings per unit floor area of study locations varies from 26.8 to 30.9 kWh/m^2 in case of air-conditioned building and 12.6 to 13.9 kWh/m^2 in non air-conditioned buildings.

Table 6.3. Maximum energy savings in different building models.

Window combinations	WWR	Kolkata		Delhi		Chennai	
		Maximum savings (%)	Slat Angle	Maximum savings (%)	Slat Angle	Maximum savings (%)	Slat Angle
EW	10%	21.9	15	22.1	30	20.6	15
	15%	22.5	45	22.9	30	21.4	45
	20%	22.9	45	23.2	45	21.6	60
	25%	23.2	60	23.8	45	22.3	60
	30%	23.5	60	24.4	60	22.3	60
NE	10%	19.0	15	19.0	30	18.1	30
	15%	20.3	30	20.5	30	19.1	30
	20%	20.9	45	21.0	30	19.8	45
	25%	21.3	45	21.4	45	20.2	60
	30%	21.6	60	22.1	60	20.7	60
NS	10%	21.7	15	21.9	0	20.3	15
	15%	22.5	45	23.1	30	20.9	30
	20%	22.9	45	23.0	45	21.3	45
	25%	22.8	60	23.4	60	21.5	60
	30%	23.2	60	23.9	60	21.8	60
NW	10%	19.9	15	19.6	15	19.0	15
	15%	20.9	30	21.0	30	19.7	30
	20%	21.3	45	21.4	30	20.2	45
	25%	21.6	45	21.5	45	20.4	60
	30%	21.8	60	22.2	60	20.9	60
SE	10%	20.2	30	21.0	30	18.7	30
	15%	21.5	45	21.9	30	19.9	45
	20%	21.8	45	22.6	60	20.3	60
	25%	22.4	60	23.4	60	21.0	60
	30%	22.7	60	23.8	60	21.3	60
SW	10%	21.0	15	21.4	30	19.3	15
	15%	21.6	45	22.2	30	20.0	45
	20%	22.1	45	22.5	60	20.4	45
	25%	22.4	60	23.3	60	21.0	60
	30%	22.8	60	23.7	60	21.3	60
NSW	10%	21.7	30	22.0	15	20.3	15
	15%	22.5	30	22.7	30	21.0	45
	20%	23.0	45	23.2	45	21.4	45
	25%	23.4	60	23.7	60	22.1	60
	30%	23.7	60	24.1	60	22.3	60
NSE	10%	21.1	15	21.5	15	19.8	15
	15%	22.2	30	22.4	30	20.8	45
	20%	22.8	45	23.1	45	21.2	45
	25%	23.3	60	23.7	60	22.0	60
	30%	23.7	60	24.1	60	22.0	60
EWS	10%	21.9	15	22.5	15	20.4	15
	15%	22.7	45	23.3	45	21.4	45
	20%	23.0	45	23.7	60	21.9	60
	25%	23.8	60	24.5	60	22.5	60
	30%	24.0	60	24.6	60	22.6	60
EWN	10%	21.3	15	21.4	15	20.2	15
	15%	22.4	30	22.6	30	21.1	45
	20%	23.0	45	23.1	45	21.5	45
	25%	23.2	60	23.6	60	22.3	60
	30%	23.8	60	24.1	60	22.5	60
NSEW	10%	21.3	15	22.0	0	20.2	15
	15%	22.4	30	23.2	30	21.0	45
	20%	23.0	45	23.4	45	21.5	45
	25%	23.6	60	24.6	60	22.5	60
	30%	24.0	60	24.9	60	22.6	60

Table 6.4. Reference energy consumption and energy savings of the building models.

Parameters	Location		
	Kolkata	Delhi	Chennai
Average % savings in air conditioned building (%)	22.3	22.7	21.0
Average % savings in non air conditioned building (%)	50.6	56.1	56.2
Annual savings in air-conditioned building (kWh/m^2)	26.8	28.2	30.9
Annual savings in non air-conditioned building (kWh/m^2)	12.6	13.9	13.9

6.3.2 Long term impact of daylighting in commercial buildings in India

Long term benefits of daylighting in buildings can be quantified with the prediction of building floor space in the coming years. With the growth in population and economic development in India, commercial building floor area is increasing. The prediction of commercial building floor area and energy savings per unit floor area is used to predict long term benefits of daylighting in Indian commercial buildings.

6.3.2.1 Growth of commercial floor area in India

Commercial floor space in India is increasing at rapid rate with the economic growth. Use of HVAC system is also increasing for better thermal comfort of the occupant. Cooling energy consumption due to HVAC system is one of the major loads in commercial building in tropical climatic condition. Table 6.5 shows the predicted commercial floor area in India. In this study, commercial floor space in India is predicted based on the building floor space model. Nonlinear regression method based on the available data from the literature survey is used in building floor space model. Long term air-conditioned and non air-conditioned commercial floor space is predicted from the model as shown in figure 6.3.

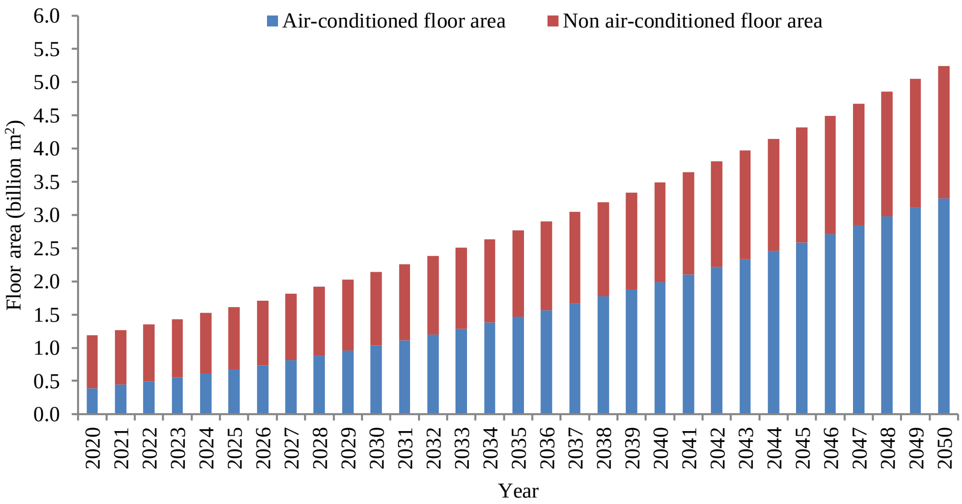

Fig. 6.3. Predicted commercial floor space in Indi

Table 6.5. Predicted commercial floor space in India.

Year	Commercial floor space (billion m^2.)		
	Air-conditioned	Non air-conditioned	Total
2020	0.39	0.80	1.19
2050	3.25	1.99	5.24
2095	12.82	5.24	18.07

6.3.2.2 Long term energy savings and economic benefit

The proposed strategic use of daylight into the building in India can save lot of energy consumption. This savings in electrical energy in Indian commercial building is not only reducing operational cost of building but also reduces emissions related to power generation. Energy savings due to proposed strategy of daylight integration along with result of floor space prediction gives an overall idea of long term energy savings in India. Cumulative savings of electric energy consumption in the air-conditioned commercial buildings in India are more than 565 billion units from 2020 to 2035; the savings is 1799 billion units from 2020 to 2050 and 10511 billion units from 2020 to 2095. This in turn could avoid 9253MW, 18748 MW and 68817 MW of cumulative electricity capacity addition from 2020 to 2035, 2020 to 2050 and 2020 to 2095 respectively.

Present cost per unit electrical energy varies significantly among the category of consumer as well as among the states in India. This is due to differences in subsidy and cross subsidy among the states. Average unit cost for commercial consumer of fifteen utility of eleven major states in India has been calculated as 11.6 INR from electricity tariff & duty of Central Electricity Authority (CEA, 2023). Cumulative savings of energy cost due to adaption of proposed strategy can save around 6562 billion INR up to 2035, 20878 billion INR up to 2050 and the same savings may reach to around 127427 billion INR up to 2095. Avoid capacity addition due to the adoption of this strategy also provide economic benefits. The estimated capital cost of setting up of new coal based thermal power plant is 83.4 million INR /MW in 2021-22 (MoP, 2024). Economic savings due to electric installation capacity avoid is estimated to 786 billion INR, 1593 billion INR and 5849 billion INR up to 2035, 2050 and 2095 respectively. Long term economic benefits of the proposed strategy in India are shown in table 6.6.

Table 6.6. Long term economic benefits of the proposed strategy.

	Long term benefits of the proposed strategy	Period		
		2020 to 2035	2020 to 2050	2020 to 2095
i.	Electrical energy savings in air-conditioned commercial building (billion units)	376.1	1326.0	10511.4
ii.	Electrical energy savings in non air-conditioned commercial building (billion units)	189.6	473.7	2287.0
iii.	**Total units savings in billion units (i+ii)**	**565.7**	**1799.7**	**12798.5**
iv.	Energy cost savings in air-conditioned commercial building (billion INR)	4362.7	15384.0	121932.6
v.	Energy cost savings in non air-conditioned commercial building(billion INR)	2199.3	5494.6	5494.6
vi.	**Total energy cost savings in commercial building billion INR (iv+v)**	**6562.0**	**20878.6**	**127427.2**
vii.	Generation capacity avoid due to air-conditioned commercial building (MW)	6718.2	14856.8	58542.3
viii.	Generation capacity avoid due to non air-conditioned commercial building (MW)	2534.9	3892.0	10275.4
ix.	**Total generation capacity avoid in commercial building in MW (vii+viii)**	**9253.1**	**18748.8**	**68817.8**
x.	Plant installation cost avoid due to in air-conditioned commercial building(billion INR)	571.0	1262.8	4976.1
xi.	Plant installation cost avoid due to in non air-conditioned commercial building (billion INR)	215.5	330.8	873.4
xii.	**Total plant installation cost avoid in commercial building in billion INR (x+xi)**	**786.5**	**1593.7**	**5849.5**

6.4 Conclusion

Building energy consumption is increasing rapidly in all over the world. In India building consumes a significant share of total energy consumption moreover growth of newly constructed building space in India is very high. The proposed strategy to integrate daylight into the building through distributed window saves more than 20% of the building energy in air-conditioned building space and more than 50% in non air-conditioned buildings in India. In longer term, the study shows a significant amount of economic benefits due to savings in building energy consumption and also due to avoid of additional capacity installation. The results of the study strongly recommend the adaption of the proposed study in tropical country like India.

7. Conclusion and Future Scopes

7.1 Conclusions

Modern commercial buildings uses higher amount of glazing area to allow daylight and to improve aesthetic view. Increasing the glass area causes additional heat load into the building space although it reduces lighting energy consumption of the buildings. In country like India, it is desirable to determine optimum window glazing area to balance between energy consumption and heat gain. Result of this study shows that increasing glass area or WWR in the building without daylight linked lighting control system increases energy consumption of the buildings. But energy savings can be possible with the integration of daylight into the building with lower value of WWR. It is observed that energy savings in all building models decreases with increase in WWR. Hence suitable strategy is required for beneficial daylight integration.

Controlled daylight integration changes the pattern of energy consumption. Energy savings with control daylight increases with increasing WWR and maximum savings are observed when WWR is around 20%. Energy savings due to controlled daylight integration reach up to 21.3 to 23.3% in the study locations. Further improvement of energy savings with daylight integration is possible with parametric study of slat angle to control daylighting into the building. Energy savings with control daylight goes up to 22.6% to 24.9% in the locations. It is also observed that higher savings can be achieved with higher WWR with proper slat angle of the shading device which comply with the higher glass area in the modern building architecture. It is also found that distribution of window into different walls improve energy saving in all the study locations.

The building energy savings due to daylight integrations has immense impact on economy, power system and environment. Cumulative savings of electric energy consumption in the commercial buildings in India are more than 565 billion units up to 2035; 1799 billion units up to 2050 and 10511 billion units up to 2095. This energy savings could avoid 9253MW, 18748 MW and 68817 MW of cumulative electricity capacity addition up to 2035, 2050 and 2095 respectively. The economic benefit is also very high at present rate of unit cost. Cumulative savings of energy cost due to adaption of proposed strategy can save around 6562 billion INR up to 2035, 20878 billion INR up to 2050 and around 127427 billion INR up to 2095. The proposed strategy of daylight integration could avoid capacity addition which also results economic benefits. The estimated capital cost savings due to installation capacity avoid is around 786 billion INR, 1593 billion INR and 5849 billion INR up to 2035, 2050 and 2095 respectively. Apart from these benefits, the improved operational energy efficiency of buildings will reduce environmental impact due emissions and the emission intensity of GDP of the country.

7.2 Future Scopes

Based on reported work in this thesis, following future scope of research also exists:

- Establishment of energy savings and carbon emissions model to study sustainable building design.
- Life cycle energy analysis of building can be carried out to assess environmental impact.
- Economic analysis of energy savings with 'time value' of money may be carried out for more realistic way to quantify the economic benefits of daylighting.
- Influence of optical properties of window glazing system on daylighting and energy consumption of building can be studied.

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