STRATEGIES FOR REDUCTION IN ENERGY CONSUMPTION OF RESIDENTIAL MULTISTORIED BUILDINGS: A CASE OF GURUGRAM

Ph.D. Thesis

NEETI

ID: 2015RAR 9038

DEPARTMENT OF ARCHITECTURE AND PLANNING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

May 2019

Strategies for Reduction in Energy Consumption of Residential Multistoried Buildings : A Case of Gurugram

Submitted in

Fulfillment of the requirements for the Degree of

Doctor of Philosophy

by

NEETI

ID: 2015RAR 9038

Under Supervision of

Dr. Ashwani Kumar **Dr. Satish Pipralia**

DEPARTMENT OF ARCHITECTURE AND PLANNING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

May 2019

CERTIFICATE

This is to certify that the thesis entitled "**Strategies for Reduction in Energy Consumption of Residential Multistoried Buildings : A Case of Gurugram**" being submitted by Neeti .(ID: 2015RAR9038) is a bonafide research work carried out under our supervision and guidance in fulfillment of the requirement for the award of the degree of **Doctor of Philosophy** in the Department of Architecture and Planning, Malaviya National Institute of Technology, Jaipur, India. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

Place: Jaipur

Date: 20.5.2019

Dr. Ashwani Kumar
Assistant Professor
Deptt. of Architecture and Planning
MNIT Jaipur

Dr. Satish Pipralia
Associate Professor
Deptt. of Architecture and Planning
MNIT Jaipur

DECLARATION

I, **Neeti**, declare that this thesis titled, "**Strategies for Reduction in Energy Consumption of Residential Multistoried Buildings : A Case of Gurugram"** and the work presented in it, are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this university.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this university or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself, jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Date: 20.5.2019

Neeti

ID: 2015RAR 9038

ACKNOWLEDGEMENT

I would like to take this opportunity to thank Almighty God and acknowledge the contributions of one and all, who have supported me throughout the course of my research in many ways.

To begin with, I am deeply grateful to my thesis supervisors Dr. Ashwani Kumar and Dr. Satish Pipralia, Department of Architecture and Planning, MNIT, Jaipur, for their expertise in the field, inspiring ideas, support and motivation, valuable comments, throughout the process of this long journey, without which it would not have been possible for me to take pride in my work.

I extend my gratitude to, Prof. (Dr.) Jyotirmay Mathur and Prof. (Dr.) Tarush Chandra, MNIT, Jaipur for their highly competent remarks, crits and suggestions which gave me orientation to formulate my research problem.

I am particularly thankful to residents of different housing societies without whose perseverance and active cooperation, this thesis would have not been possible. I acknowledge the experts in the field, officials from town planning offices and secretaries of societies for their support and discussions to have both subjective and objective perspective of the current research topic in the field.

I am specially thankful to Late Dr. P C Jain, IGBC , AECOM; Dr.Mili Majumdar, GRIHA Council; Dr. Sameer Maithel, Greentech Knowledge Solutions; Dr. Vishal Garg, IIIT, Hyderabad; Pierre Jaboyedoff, Indo Swiss Building Energy Efficiency Project; and Vivek Gilani, Fairconditioning for their expert and candid opinions.

I wish to thank all my friends Fuzail, Chandni, Manish, Ankit, Mayank and Ashish for travelling extra mile to pitch in whenever needed.

I am deeply indebted to my hubby Dr. Parveen Kumar, who has shouldered the family responsibility in my absence and remained a great force to help realize my dreams.

Finally I dedicate this thesis to my parents for their unconditional love, blessings and motivation. A special mention to my loving children Kshitiz and Lavanya, who have always taken me as their role model and inspired me to scale new heights in the life.

Ar. Neeti Garg

ABSTRACT

The thesis attempts to underscore the need to reduce energy consumption in existing multistoried residential buildings by retrofitting. Energy use in residential buildings is rising sharply with growing no. of households using air conditioning, indoor living style and higher affordability. A case of the city of Gurugram is taken up for study to prove the posit of bringing energy savings by retrofitting the ubiquitous multistoried group housing for energy efficiency.

The study endeavours to take cross section of multistoried housing by taking up stratified samples from eight group housing schemes across the city, representing a sample population of 4608 flats from public, private and cooperative group housing societies. The study points high variation in energy consumption of users due to high diversity factors in occupancy schedule, HVAC schedule, appliance usage etc. Based on energy consumption, households are classified in three energy use intensity (EUI) categories i.e. Normal EUI case with mean EPI 68.9 kWh/m^2/year, High EUI case with mean EPI 97.4 kWh/m^2/year and Low EUI case with mean EPI 42.7 kWh/m^2/year. An attempt is made to derive schedules of activity, lighting, equipment and HVAC for residential buildings for defining base case for simulation as per ECBC 2017.

Selected design strategies to reduce energy consumption are climate responsive, cost effective, easily achievable and non intruding to users. Parametric runs of energy efficiency measures are conducted to find out optimum values of retrofit parameters. Based on the affordability of users and energy reduction targets, three modules are devised for retrofitting such as Energy Efficient model yielding 25.3% reduction in energy consumption with wall components; Energy Efficient Plus model yielding 54.8% savings with solar PV panels on roof and wall components, Energy efficient Super model yielding 69% savings with roof, wall and other components.

Results of simulations are integrated with life cycle cost analysis to help owners to take informed decision on choosing the retrofit model. The study helps in demand side management of energy by promoting the passive resilience with improvement in thermal comfort and reduced air conditioning operating hours after retrofitting. The study concludes that there is a potential of significant reduction of energy consumption by 60-70% in existing residential multistoried housing in composite climate by retrofitting.

Table of Contents

List of Figures

List of Tables

ABBREVIATIONS

API	Ansal properties and infrastructure
AC	Air conditioning
ASHRAE	American Society of Heating Refrigerating and Air conditioning Engineers
ANOVA	Analysis of Variance
AAC	Autoclaved aerated concrete
ach/hr	Air change/hour
BIS	Bureau of Indian Standards
BHK	Bedroom, Hall and Kitchen
BUA	Built Up Area
BEEP	Building Energy Efficient Project
CLC	Cellular light weight concrete
CO_2	Carbon di oxide
CF	Cooperative group housing scheme
Clo	Clothing insulation
Cv (RSME)	Coefficient root mean square error
DOE	Department of energy
DBT	Outdoor dry bulb temperature in (^{0}C)
DLF	Delhi land and finance
DLF RE	DLF Ridgewood Estate
DHBVN	Dakshini Haryana bijli vitran nigam
DPR	Detailed project report

DU	Dwelling unit
EPF	Envelope Performance Factor
ECBC	Energy Conservation Building Code
EPI	Energy Performance Index
EE	Energy Efficient
EUI	Energy use intensity
ENPER EXIST	Energy performance requirement to existing building
ECM	Energy conserving measures
F	F distribution statistical value
FAR	Floor area ratio
GRIHA	Green Rating for Integrated Habitat Assessment
GRIHA EB	GRIHA for Existing building
GJ	Giga Joule
GHG	Green house gas
GBPN	Global building performance network
Govt.	Government
HVAC	Heating,Ventilating And Air Conditioning
ha	Hectare
HUDA	Haryana Urban Development Authority
HDRUA	Haryana Development And Regulation Of Urban Area Act
HIG	High income group
HSIIDC	Haryana State Industrial And Infrastructure Development Corporation

IEA	International Energy Agency
IGBC	Indian Green Building Council
IT	Information technology
IMAC	India model for adaptive comfort
IPMVP	International Performance Measurement and Verification Protocol
IPCC	International Panel on Climate Chaange
ISO	International Standards Organisation
IT	International Institute of Technology & Management, Murthal
KVA	Kilo Volt Ampere
kWh	Kilo Watt Hour
LED	Light emitting diode
LEED	Leadership in Energy and Environmental Design
LCCA	Life cycle cost analysis
LPD	Lighting Power Density
MBE	Mean Bias Error
Met	Metabolic rate
MNRE	Ministry of Non renewable Energy
MIG	Middle income group
MNC_S	Multi National Companies
m	Meter
MS	Mean square variance
MV	Mechanical Ventilation
n	Sample size

N	Total finite population
NAPCC	National Action Plan on Climate Change
NBC	National Building Code
NV	Naturally ventilated
NCRPB	National Capital Region Planning Board
NE-SW	North east-South west
NW-SE	North west-south east
P	Probability
PSRCUA	Punjab Scheduled Roads And Controlled Urban Area Act
PWD	Public Works Department
PV	Photo voltaic
POE	Post occupancy Evaluation
PGT	Power Grid Township
RH	Relative humidity (%)
sq km	square kilometer
SS	Sum of Square of variance
SRI	Surface reflectance index
SHGC	Solar heat gain coefficient
TERI	The Energy and Resources Institute
TCPO	Town and country planning office
U	Thermal conductance (Watt/ m^2/K)
UNFCCC	United Nations Framework Convention on Climate Change
uPVC	un plasticized poly vinyl chloride

VLT	Visible light transmittance
WWR	Window to wall ratio
WBDG	Whole building Design Guide
XPS	Extruded polystyrene foam
z	Value of standard variate at given confidence level
σ	Standard Deviation

INTRODUCTION

This chapter introduces the research context of energy consumption in existing multistoried residential buildings in a composite climate context. The chapter establishes briefly knowledge gaps in literature review leading to formulation of the research hypothesis. It delineates aims and objectives of the research along with research methodology in the study area context. Finally, this chapter defines the scope of the study along with the limitations of the study. It also provides a brief overview of different chapters of the thesis report.

1.1 Context

Most developing countries have witnessed a major change in the urban landscape in the last 20 years primarily due to demographic and economic growth . With Indian economy moving up the trajectory of growth, urbanization is projected to the tune of 40 % people living in cities and contributing to 75% of India's gross domestic product by 2030[1,2]. Several new initiatives have been launched by the government of India to face challenges posed by the fast rate of urbanization and predicted growth of nearly two-thirds of built fabric yet to be constructed by 2030 [3].The economic growth momentum can be maintained with the structural transformation of existing economy by sustainable approach to resource management. India has committed to reducing carbon emissions by 30% in 2030 over 2005 as a base year in recently held United Nations Climate Change Conference at Paris in 2015[4]. Energy, communication networks and water supply form lifelines of any city [5]. For meeting climate change targets of reducing greenhouse gas emissions by 30% by 2030, energy management in cities holds key to help build a cleaner environment, less pollution and reduced carbon footprint strategy [6]. India has promulgated National Action Plan for Climate Change (NAPCC), advocating the adoption of an inclusive and sustainable development strategy that is sensitive to climate change, with a view to enhancing ecological sustainability. National Missions on Sustainable Habitat and Enhanced energy efficiency as a part of NAPCC has underscored energy efficient and cost-effective strategies for built environment in sustainable habitats, deploy renewable technologies and framework for an approach to sustainability for mitigation of greenhouse gases through its eight national missions.

1.1.1 Energy consumption in existing buildings

Increased energy use in the existing stock of buildings is a serious environmental concern around the world [7]. Incorporating energy efficiency as a prime consideration in the development of existing stock can make a big difference to reduce the total use of energy and carbon emissions [2]. Among the different sectors where energy savings can be realized, the European action plan for energy efficiency of the European Commission has identified the building sector as a top priority [8]. Given, there is an already growing concern for reduced availability of electricity in Indian cities, the thrust is to reduce energy consumption by managing the demand side in existing buildings and also provide unprecedented opportunity to reduce CO_2 emission by 2050 [9]. In 2010 buildings accounted for 48 % (including operational and embodied energy) of total global final energy use, 19% of energy-related GHG emissions (including electricity-related), approximately one-third of black carbon emissions and generate 50% of total waste [10]. There is a dire need to reduce energy consumption to sustain the development without exhausting natural resources or causing ecological damage by climate change within the wider rubric of achieving sustainability goals [11, 12].

Energy is primarily used in buildings for achieving thermal comfort and visual comfort. As per Organization for Economic Co-operation and Development OECD report by UNEP (2013), 25 % of total energy used is in the construction sector of buildings or embodied energy and 75% of the energy is used in operational use such as in HVAC, lighting, equipments and appliances [13]. Buildings nearly consume 75-80% of total energy consumption as operational energy over their life cycle [14]. Therefore, it is imperative to reduce energy consumption in operational energy and enhance environmental quality for a sustainable built environment.

1.1.2 Energy consumption in residential buildings in India

As per the report of the Central Electricity Authority of India (2017), energy use in residential buildings has increased from 80 TWh in 2000 to 260 TWh in 2017 [15]. There is an increased share of energy consumption per capita as actors such as increased appliance ownership and better lifestyle, higher thermal comfort levels and more indoor living as well as higher affordability act as a key driver in rise in electricity consumption [16]. Global Buildings Performance Network GBPN (2014) in its study report titled "Residential Buildings in India: Energy Use Projections and Savings Potentials", has projected scenarios indicating that electricity consumption is predicted to rise by more than eight times by 2050 under the business-as-usual scenario in 2014[1]. Also, the energy consumed in air conditioning is the largest contributor to energy consumption in residential buildings [17].

India, being the third largest importer of crude oil and coal in 2014, fossil fuels contribute to 75% of the current energy production in India [18]. There is a wide gap between high demand and a limited supply of energy, leading to spiralling prices of energy. Additionally, in the absence of energy supply from the grid, the use of diesel generator sets in many residential housing societies as an alternative means of power generation is causing a serious environmental pollution. Thus triple threats of climate change initiatives for restoring global warming, deficits in reserved fossil fuels and the spiralling cost of energy would require the planners to take up sustainable approaches to manage burgeoning demands of energy in our cities [19].

1.1.3 Retrofitting existing residential buildings

By 2050, 70% of the world's population will be living in cities, there is a need to re-engineer systematically existing built environment at various scales (building, neighbourhood, city-region) and domains (energy, water, use of resources) in view of climate change and resource constraints [20]. Eames et al (2013) has further envisaged 'Retrofit 2050 Vision' for three different kind of cities i.e. Smart-Networked City, The Compact City and the Self Reliant Green City; each one varying greatly in terms of indicators for energy , water, waste and resource use, land use, social values, economic growth and urban density (ibid). Seven European countries collaborated in the project 'ENPER-EXIST' for energy performance standardization and regulation [8]. As per the study report of the United Nations' Intergovernmental Panel on Climate Change in its report on "Mitigation of Climate Change", largest energy and carbon savings potential in 2030 can be achieved by retrofitting and renovation of existing buildings [21]. Existing buildings with retrofitting measures have a potential of saving energy up to 20 to 25% [22]. Given, there is an already growing concern for quality and quantity of energy available in cities, the thrust is to reduce energy consumption by managing the demand side in existing buildings and also provide unparalleled opportunity to reduce CO_2 emission by 2050 [9].

Most of the existing residential building stock is characterized by low thermal comfort, poor indoor air quality, poor lighting conditions etc. The retrofitting of existing buildings can lead to significant improvement of the indoor environmental conditions as well as an increase in health and well-being of people [8]. Retrofit of residential buildings usually involves multiple benefits such as reduction in consumption of energy and thus cutting energy and maintenance bills, improving safety, quality, indoor comfort and aesthetic properties, extend lifespan of buildings, as well as boosting market value [23, 24]. Retrofitting of existing built areas have been enunciated as one of the primary smart solutions for area-based development models in smart city mission guidelines so as to achieve the objective of more efficient and livable cities [25].

1.2 Research Problem

The major land use in any city comprises of residential land use as much as 30 -40% of total land use [26]. Nearly 80% of the existing housing stock in India is designed and constructed before 2001, the one-third of which is more than 40 years old [27]. These buildings were designed when there were no energy efficiency codes or sustainability guidelines available and continue to use high energy incessantly. National building codes have been recently revised in 2016 to include sustainability as Part 11 addendum [28]. The focus of the Energy conservation building code ECBC, 2017 is on conditioned buildings, which is also not mandatory in many states [14]. There are no codes for improving existing residential buildings from a sustainability point of view. There are limited studies on energy use in existing housing in India [1]. It is pertinent to study existing framework of national goals and policies within which retrofitting of mixed mode or unconditioned residential buildings can be carried out to achieve objectives of reducing energy consumption and extending benefits to community and nation as a whole.

The model of multistoried group housing societies has evolved as a dominant form of housing typology in last three decades ubiquitously in all metropolitan cities in India due to high land cost, reduced affordability of people to buy homes across all spectrum of income groups and compact city development by authorities. The multistoried group housing schemes support nearly 70% of the households due to higher density in metropolitan cities. As they are managed professionally by facility management companies or resident welfare societies, it is relatively easier to target them to adopt retrofitting of existing apartments in the initial phase to reduce carbon footprint. Benefits of retrofitting existing multistoried residential apartments can reach more no. of households in relatively less time. Besides, these can serve as a role model for the rest of housing societies to emulate.

Recently, guidelines for the design of new residential buildings for energy efficiency have been launched [1, 29]. Energy consumption in residential buildings differs from commercial buildings significantly due to several factors. The occupants tend to use residential buildings in mixed mode operation i.e they like to use spaces naturally ventilated at some hours of operation and have much greater flexibility in controlling window operations, air conditioners and clothing to achieve thermal comfort [30]. However, there is a greater uncertainty in energy consumption in residential buildings due to greater diversity in use patterns of space, occupancy, family structure, time of use of buildings, appliance penetration, personal preferences of cooling set point and indoor living style [31]. Even similar residential buildings in same site context show variation in energy consumption to order of 150-200% [32].

In practice, there is a dearth of data on energy consumption pattern, occupant's behavior and usage pattern, and adaptive opportunities available to them in residential buildings. Therefore, keeping in mind huge stock of existing multistoried residential buildings with their large footprint and continuous consumption of resources incessantly, it is very important to study existing multistoried residential buildings for better understanding and quantification of energy consumption and take corrective actions to reduce energy consumption and hence their carbon footprint.

Energy usage in residential buildings in India are in contrast to developed countries. The living spaces in Indian households are operated in mixed mode ventilation unlike fully air conditioned and extremely airtight houses of Passivhaus homes in Europe [33,34,35]. Most residential units use individual packaged air conditioner systems such as Window air conditioners or split conditioners as opposed to central heating or cooling systems used in developing nations. Lack of thermal insulation in walls and increasingly large use of glass and lack of double or triple glazing units in residential apartments add to more building envelope heat gain and consequently higher cooling load and thus higher energy consumption. Whereas the commercial buildings are designed to fulfil internal loads such as people, lights and equipment, a large percentage of energy is used in residential buildings for space conditioning to meet building envelope load [17]. It is imperative to improve building envelope performance in residential buildings so that building envelope heat gain is minimized for reducing energy consumption. The whole building simulation approach is used to predict energy consumption, thermal comfort and building envelope heat gain by using dynamic building performance simulations. Whereas building simulation models take into account climatic conditions, building geometry, orientation, ground conditions, material properties, occupancy schedule, window opening schedule and ventilation in detail, metabolic activities and clothing patterns etc., still most of the building performance simulation tools do not consider the impact of adaptive opportunities available to occupants. There exists a lot of diversity in how residential buildings are designed and constructed and thus modelling residential buildings for energy consumption pose challenges due to high diversity factors and uncertainty in their input values [36, 37].

There is a lack of awareness among professionals, owners and other stakeholders about the potential of reduction in energy consumption. Many other barriers faced by proponents of retrofits call for cost-effective, easily achievable and non-intruding retrofit measures. There is a need to integrate results of various retrofit strategies from building performance simulation with life-cycle cost analysis so as to arrive at affordable feasible solutions with low payback period. There lies a huge potential of reducing energy consumption by retrofitting of existing multistoried residential buildings with low hanging fruits strategies In view of the large carbon footprint of existing multistoried residential buildings, there is a need to study in depth benchmarks of energy consumption patterns and trends in the study area context and finally suggest cost-effective feasible retrofitting measures for reducing energy consumption.

1.3 Gaps in Research

The literature review is carried out for understanding state of art of contemporary theories and the current knowledge in empirical practices in the field of retrofitting existing housing for energy efficiency. By deriving knowledge from literature review and field studies undertaken, gaps in research in theory and practice were identified to define research questions. Various sources such as peer-reviewed journals, databases for theses, conference proceedings, Handbooks, Building Codes and Standards, e-books and print books from the library have been reviewed. The literature is classified into four domains as listed below:

1.3.1 Energy consumption pattern in residential structure

There are very limited studies available to understand adaptive opportunities and energy consumption pattern of residential apartment buildings with a view to achieve energy efficiency [30]. A study has been undertaken by GBPN in 2014 to develop residential baseline data with the recommendation that the study needs to be expanded with a larger database [1].In another study conducted by BEE (2014) for formulating design guidelines for multistoried residential buildings in composite climate, a sample of four multistoried group housing schemes, having 732 units of built-up area ranging from 80-120 sqm , was analysed in 2009 in NCR of Delhi and predicted average energy use intensity to be 48 kWh/m2/yr. But due to the large time gap of almost nine years from 2009 and change in several factors like changing lifestyle and increased appliance ownership and expected comfort level in cooling, the data is no longer valid.

There is a lack of data on housing built up area, use of construction materials, occupant schedules, appliance ownership and usage pattern etc. [38]. There is a need to develop residential baseline data for better planning and targeted reduction in energy consumption.

1.3.2 Role of National policies, Building codes and rating systems

National Policies play a pivotal role in orienting directions to achieve retrofitting in existing buildings from energy efficiency point of view. In order to achieve a sustainable development path, National Action Plan for Climate Change (NAPCC, 2008), has strategically outlined eight National Missions for achieving key goals on climate change problem mitigation, energy efficiency and natural resource conservation [39].

National Solar mission focuses on harnessing the potential of application of solar energy and research and development in the field. The ambitious National Solar Mission anticipates 20,000 MW to be generated by 2020 through photovoltaic, including rooftop and small plants, [40]. Thus buildings are seen as active participants in energy producing facilities rather than just consumers of electrical energy.

National Mission for Enhanced Energy Efficiency provides a legal mandate via the Energy Conservation Act (2001) through the institutional framework of Bureau of Energy Efficiency (BEE) at all levels of governance to make energy-intensive enterprises namely large industries and facilities work towards reduction in energy through certification of energy savings, creation of affordable energy efficient appliances, and development of fiscal instruments to promote energy efficiency.

National Mission on Sustainable Habitat aims to promote energy efficiency in the residential and commercial sector, management of solid waste and modal shift to public transport. The Energy Conservation Building Code (ECBC), which addresses the design of new and large commercial buildings to optimize their energy demand, will be extended in its application to other building types and incentives provided for retooling existing building stock. It emphasizes that realizing the potential of energy saving requires an integrated design process involving all the stakeholders, with full consideration of opportunities for passively reducing building energy demands in existing and new buildings.

National building code, 2005 has been revised to add Part 11 as Approach to sustainability in 2016 to include various measures for energy efficiency, building performance tracking and monitoring, energy audits and occupant surveys after commissioning and handing over of buildings for three years. Energy audits can be integrated with occupant surveys and interviews for a better picture of energy use pattern and trends in buildings. But this has not been implemented so far under any regulatory framework of states in India.

National Housing Policy 2015 aims at inclusive**,** sustainable and faster housing for all by 2022. Smart city mission guidelines (2015) by Ministry of Urban Development underscores 'retrofitting' (city improvement) of existing areas to make them more efficient and livable. It also targets completion of retrofit projects in a shorter time frame, leading to its replication in another part of the city [25]. The concept of providing assured electric supply is included in core infrastructure elements in a smart city and delineates three smart solutions such as smart meters and management, renewable sources of energy, energy efficient and green buildings [25]. Whereas it is vital to measure energy consumption by end use in different residential apartments so as to gauge energy consumption trends on a real-time monitoring basis, but little work has been done in this direction. Despite multiple policy documents in practice and mission guidelines for larger carbon footprint of residential buildings, there are no developed codes for retrofitting existing residential buildings.

Green building rating systems are used as a tool in the built environment to measure sustainability [41]. Benchmarking facilitates to identify the gaps in the performance of the buildings and facilitates in retrofitting them to achieve sustainability goals by optimizing their functions in line with desired targets and thresholds [42]. No two places which are in different climatic zones and cultural context within the country or different countries are identical and need to be analysed from different sustainability parameters [43].

Energy Conservation Building Code (ECBC), has its focus on commercial or institutional buildings which are air-conditioned. The code has defined occupancy schedules for different building typologies for defining standard case or base case. And it helps designers to ascertain improvement in energy efficiency by comparing EPI of the base case and proposed design by using whole building simulation approach. On similar lines, there is a need to develop baseline data for developing occupancy schedules, lighting schedule, appliance usage schedule so that one can benchmark proposed design or assess energy efficiency improvement for existing multistoried apartment residential buildings over 'As is' case.

Residential building primarily uses mixed mode ventilation i.e. they use both natural ventilation and air conditioning system depending on day use pattern and weather conditions.

There is a high diversity factor in occupancy pattern and user behaviour in residential buildings. Field-based occupant surveys along with thermal mapping of buildings can be integrated with energy use metering to bridge the gap in understanding energy consumption pattern, building performance and user satisfaction in mixed mode operation of buildings. Despite the importance and the largest share of land and net share of high energy consumption, there is no focus on residential buildings in energy conservation building code. Thus there is a need to frame guidelines for occupancy schedules and usage pattern specific to existing huge stock of multistoried apartments.

The housing schemes which have been green rated in the recent past score almost minimal on energy efficiency parameters of rating systems [44]. TZED housing in Bangalore, India awarded Platinum rating by LEED, has the least score on energy efficiency as compared to other parameters of rating scheme. Whereas energy efficiency parameters carry maximum weightage in rating systems in India, but it is hard to score on energy efficiency parameters without taking good measures for improving energy efficiency, Thus near absence of real-life examples of multi-storey group housing schemes having energy efficiency or retrofits in existing housing schemes forms a knowledge gap in building industry.

1.3.3 Design parameters

There is very limited research on parametric values of various design parameter of building performance assessment in residential buildings [1]. ECBC has been a voluntary code applicable for conditioned buildings and local building bye-laws have started incorporating energy efficiency measures as an incentive-based component, but not as a core integral part of building design, particularly in the context of residential buildings. Recently there has been a trend of use of large glass panels even in a residential building across India, irrespective of climatic context, leading to increased use of energy in air conditioning them for achieving thermal comfort. In many countries, the concept of Overall Thermal Transfer Value (OTTV), limiting heat gain to fabric to 35 W/ sqm prevails for better design of buildings and has been part of mandatory building approval rules, whereas, in India, there are no such mandatory provisions in building codes [45]. Thus, there exist knowledge gaps in the parametric analysis for the mixed mode residential building. Developing a detailed understanding of various parameters will lead to developing a roadmap for retrofitting of existing housing by reduction in energy consumption at various levels such as building level and site level thus aggregating to reduced energy consumption at sector level and finally at the city level.

Various passive measures need to be explored for enhanced thermal comfort and reducing air conditioning load of buildings such as insulated walls, airtight envelope, surface finishes of wall and roof, shading by use of solar rooftop solar photovoltaics, green roofs or green facades or solar shading or blinds to cut sun or admit daylight. Various initiatives like solar harvesting, integrated building photovoltaic systems, rooftop solar projects, net metering or smart metering, solar street lighting etc. have come up due to which the role of buildings is changing to energy producing than energy consuming, thus even generating energy plus buildings or net-zero buildings in the process. In the wake of near absence of real-life examples or prototypes of net-zero housing schemes, clarity on a policy of net metering and life-cycle cost analysis thereof, there is a knowledge gap and barrier to implement ambitious schemes of the government.

Therefore the research focuses on field-based occupant surveys in addition to develop a residential baseline data to establish a benchmark of energy consumption standards and bridge the gap extant between their performance and desired levels for mixed mode ventilated multistoried apartments in composite climatic context of the study area.

1.3.4 Benchmarking of energy consumption in mixed mode residential buildings

There is a little research in defining energy performance index for mixed mode buildings in residential buildings particularly in Indian composite climatic context of NCR of Delhi [30, 46]. Energy Conservation Building Code (ECBC, 2007) does not deal with energy intensity use or energy performance index specifically for residential buildings. Other rating systems in India such as GRIHA and IGBC cross-refer to NBC for thermal comfort and have also incorporated ASHRAE 55 and India model for adaptive comfort (IMAC). However, IMAC delineates thermal comfort for mixed mode buildings in general, but not for residential buildings in particular.

The current building rating systems in India are GRIHA, IGBC, BEE and they have developed criteria or credits and star rating systems for different levels of performances achieved by green buildings, but do not directly address parameters for retrofitting existing buildings for energy efficiency per se. A minimum benchmark of EPI of 75 kWh/m2/yr (with 25% improvement over the base case of 100kwh/m2/yr) has been fixed in new residential buildings in hot and dry or composite climate. The improved benchmark prescribed by GRIHA is already higher than average observed data of energy use intensity of current population living in multistoried group housing schemes, implying thereby that without using any energy efficiency measures, all housing schemes will fall under energy efficient category and need no improvement. But this is not the case, thus there is a need for revision of GRIHA benchmarks.

Adaptive opportunities available to residents and high level of diversity in use of buildings by different age groups, lifestyle and awareness of energy consumption accounts calls for more in-depth studies so as to work out energy demand for existing housing as residential buildings are having the largest footprint in any city and consequently have the largest share in energy consumption for meeting thermal comfort. There exists a knowledge gap to understand opportunities of adaptive behaviour and energy consumption with respect to mixed mode residential buildings.

1.3.5 Building performance measurement tools for energy efficiency

Despite a wide range of retrofit technologies widely researched, it is a challenging task to identify the most cost-effective and practically achievable retrofit measures, particularly for residential projects [47]. Tools for assessing building performance measurement include pre-retrofit occupant surveys, energy audits, performance gap modelling from existing standards, building performance simulation modelling by making 'as is' case, calibrating for measurement and verification, quantification of energy savings, life cycle cost analysis (LCCA) for selecting cost-effective technologies.

Findings from occupant surveys can act as a linchpin to develop sustainability key performance indicators for a particular context taking into account people's aspirations and local specific context of the study area. Feedback from occupants can help in evaluating and evolving relevant sustainability indicators [48]. Occupant surveys can best provide candid account of wider variations / diversity found in case of residential buildings in terms of occupant use, occupant age, built environment, psychological comfort and satisfaction; and as well as wide variations in energy use, even within buildings of similar built-up area and building geometry within the same location [49]. There is a need to conduct occupant surveys for assessing thermal comfort, user behaviour and energy consumption pattern so as to enable modelling of existing housing in building performance simulation software in a realistic manner and predict the effect of retrofit measures with more accuracy.

Another tool widely used to assess energy use is Energy audit with the aim to find out measures to save energy or to improve energy efficiency [50]. An energy audit is a key to a systematic approach for decision making in the area of energy management, by quantifying energy use according to discrete functions in the buildings and with the objectives to minimize energy costs, reduce energy wastage without affecting the quality and to minimise environmental effects [51, 52]. Energy mapping can be conducted at community level by adding knowledge of existing energy use intensity of a neighborhood, sensitizing community about comparative energy consumption of different households, introducing concept of benchmarking within communities and competitiveness with other communities (external benchmarking) , identifying energy consumption in community buildings and common services, trend analysis and finally delineating areas of improvement to meet nation action plan of carbon reduction targets [53]. Existing buildings are responsible for a major share of energy consumption as they are generally less efficient than new structures. Energy audits provide an opportunity for policymakers to profitably advance low-carbon objectives. Although world over the major focus is on energy saving products and measures designed for new buildings, in absence of any energy performance criteria for existing buildings, they will continue to consume high energy in near future [1]. WBDG (2016) has cautioned using results of energy calculations from simulation software as factors such as construction quality, occupancy schedules, and maintenance procedures may vary markedly from assumptions contained in the analysis and skew results [54]. Thus energy audits of existing buildings provide a real-life example and provide information on a real-time basis in checking energy consumption. BEEP has conducted energy audit data for 784 households in 2009 [29], but the data is no longer valid in current times due to increased penetration of appliance, increase thermal comfort aspiration and more use of indoor living etc. Thus, there is a gap in the research area as hardly energy audits are conducted for residential buildings.

There exist knowledge gaps or barriers due to the absence of real-time information (energy utility data) of consumers and authorities, quality standards, funding opportunities and trained manpower, knowledge of energy saving opportunities in the implementation of retrofit projects.

Having identified several gaps in the research area, there is a need to study existing residential building stock for assessing its energy performance, benchmarking performance gaps modelling and finally retrofit them for reducing energy consumption to meet targets of reduction in greenhouse gases emission by 2030.

1.4 Aim of the Research

The aim of this study is to formulate strategies for reduction in energy consumption of existing multistoried residential buildings in Gurugram.

1.5 Research Hypothesis

The knowledge gaps in a literature review of the research problem and in real life practical examples led to the formulation of the research aim and hypothesis. With an aim to reduce energy consumption in existing mixed mode multistoried group housing schemes the research hypothesis is defined as:

Energy consumption of existing residential buildings can be reduced significantly by retrofitting buildings for energy efficiency measures.

1.6 Research Questions

The research questions posed by the above-stated problems are as follows:

i. What are the characteristics of existing housing in terms of energy consumption?

ii. What are the factors affecting energy consumption in residential buildings?

iii. What should be the benchmark for energy efficiency in existing housing scenario in composite climate?

iv. What are effective strategies which can be adopted to retrofit existing multistoried residential buildings for reducing energy consumption ?

1.7 Research Objectives

In line with the aim of the thesis and research hypothesis, the various objectives of the study are delineated as follows :

i. To determine factors which affect energy consumption in residential buildings.

ii. To review National policies and initiatives related to energy consumption in existing residential buildings in composite climate.

iii. To assess the energy consumption of existing multistoried residential buildings in the study area.

iv. To formulate strategies for retrofitting existing multistoried residential buildings for reducing energy consumption.

1.8 Scope of the study

The scope of the thesis is limited to undertake energy use assessment of existing multi-storeyed group housing schemes using mixed mode ventilation only in composite climate by taking Gurgram as a case. The boundary conditions of the study area is defined to include multistoried group housing schemes which were constructed before 2010 in the city of Gurugram. The city of Gurugram is a rapidly growing metropolitan city in the National Capital Territory of Delhi, India. The study is limited to assess energy used for thermal comfort and visual comfort only with an aim to reduce energy consumption by retrofitting building envelope and lighting. Only parameters related to improving building envelope with reference to the reduction in energy consumption by passive solar techniques are assessed. Other factors like retrofitting for air conditioning systems and equipments, efficiency in appliances, interventions involving intrusion in interiors or techniques affecting intervention in building bye-laws or factors involving structural interventions are not considered.

1.9 Limitations of the Study

There are limitations in regard to accessibility of data in private housing areas owing to security and privacy requirements. There are limitations of recurring availability of the people and voluntary participation or readily sharing data. There are wide variations in energy use, lifestyles, adaptations and user awareness in recognizing energy conservation practices. Due to the high diversity factor in occupant schedules, the study requires a relatively large sample size to eliminate the effect of any single variables and cross-validate the findings by multiple samples within the same housing. There is a limitation of instrumentation in residential buildings for reason of limited set of instruments and limited accessibility individual homes for data retrieving. Despite limitations, the study hopes to serve as a useful database for analysis and developing national standards, benchmarks and practices for retrofitting to reduce energy consumption.

1.10 Study Area Context

The study area taken up for conducting research is Gurugram in National Capital Region of India of Delhi, located at 28.46° N, 77.02° E at an altitude of 217 m above sea level. It lies in hot arid climate zone having steppe (Bsh) as per Koppen international climate classification and composite climatic zone as per classification of National Building Code, 2016. Gurugram is a satellite town located 32 kilometres south of National Capital Territory of Delhi, is among India's fastest growing urban centres. Gurugram has witnessed rapid urbanization and high population growth (population growth rate of 14.7% p.a. From 2001-2011 and projected growth rate of 8.8 % from 2011-2021, being the highest in National Capital Region of India, Delhi (Revised RP-2021 of NCR). Gurugram is classified as a service town with 81.4 % of the population engaged in the tertiary sector (commercial activities, tourism and related activities), 3.3 % in the secondary sector (industrial activities) and 15.3 %. in primary sector i.e. agriculture and allied activities [55].

The Development Plan for Gurugram catering to a population of 42.5 lacs in 2031 spreads over 338.72 sq km. The city is divided into 118 Sectors with 16021 ha of residential areas, developed on the neighbourhood basis, with an average net residential density of 250 persons per hectare. Gurugram is largely developed through Public-private partnership model giving rise to a boom in housing from 1985-2011. Private colonizers are emerging as major real estate developers and have superseded government developing agency Haryana Urban Development Authority in developing residential sectors. With high residential land use (48.56 % of total land use), Gurugram, largely dominated by multistoried group housing schemes catering to 68.38% of the population, has a huge demand of electricity and there is a limited supply of power [56]. With annual electricity demand increasing at the rate of 17% and supply increasing by 5%, there is a wide gap between demand and supply. Gurugram with yet only 30% of its total plan implemented, serves as an ideal context for alternative approaches and improving the efficiency of existing multi-storeyed residential fabric.

1.11 Significance of Study

Increasing use of air conditioning in multi-storied residential group housing schemes and also increasing use of glass in building facades leading to a high building envelope and consequently high energy use intensity will lead to a higher gap between increasing demand and reduced supply of electricity due to limited resources of fossil reserves. The significance of the study is that there is a high potential to reduce energy consumption by encouraging existing group housing schemes to retrofit their building envelope, thus reducing energy requirement for space cooling and improved thermal comfort in the building - a goal towards achieving low carbon yet comfortable built environment. Additionally, the study will be useful in bridging gaps between the power supply and peak demand of electricity in Gurugram.

The study is instrumental in providing current baseline data of energy consumption pattern and trends in existing multistoried housing in Gurugram. In addition, the study also traces building envelope characteristics of existing multistoried group housing schemes, which is helpful to model “As is” case for dynamic building performance simulation modelling. This study will serve as an exemplar and serve as a reference model for all stakeholders for reducing energy consumption in existing mixed mode multi-storied residential buildings. The findings and methodology of this study can serve a useful dimension to evaluate other group housing schemes in the National Capital Region of Delhi, falling in composite climate zone. People living in these retrofitted residential societies will act as a role model for the society. They may become eventually catalysts in leading sustainability initiatives and promoting other housing societies to take up retrofitting for saving energy and contribute in reducing carbon emissions to fulfil the goal of reduction by 30-35% by 2030.

1.12 Research Methodology

With the aim to formulate strategies for reduction in energy consumption of existing multistoried residential buildings, both qualitative methods and quantitative methods are used in research design and analysis of experiments. To fulfil the objectives of research, two stepped approach is taken. The first step involved a structured literature review of the study area by undertaking an in-depth study of energy efficiency trends and patterns, design parameters, key performance indicators in energy assessment. Due to the lack of existing study on the current topic, the study is more of inductive and exploratory nature. National building codes, international standards, case studies of best practices, challenges and barriers in implementing retrofitting building performance tools are explored. The aim of the research is to gain a holistic and realistic idea of dynamic real-life subjects without controlling subjects or variables. Case study approach has been used to have an understanding of user behavior and energy consumption pattern of real-life subjects in order to arrive at a baseline data of energy consumption of existing residential group housing schemes. Sampling criteria are based on probabilistic stratified sampling so as to include representative cases defined in the scope of the study for different user groups as per their energy use intensity, plan typologies, orientation, floor location, building envelope characteristic like materials and shading etc. Pilot studies were conducted to calculate the sample size.

An extensive database is constructed using a multiple case study for cross-validation and triangulation and also to eliminate the effect of any single variable. The second step involved the study of various research tools such as occupant surveys, energy audits, objective measurements of thermal conditions by data loggers for thermal mapping of sample flats, building performance simulation modelling and life-cycle cost analysis. Inverse modelling technique has been used to identify input parameters for building performance simulation modelling. The primary data is collected using research instruments such as field surveys, questionnaires and thermal instrumentation to understand variables or input parameters required for simulation model and calibration of the same as per International performance measurement and verification protocol standards. Finally, the parametric analysis is run to identify various design parameters to be adopted. Various combination of design parameters are evaluated to understand the reduction in energy consumption for different classes of users with respect to energy use intensity. Statistical tools such as multiple regression analysis and ANOVA have been employed to analyze data so as to predict the energy consumption of different user groups with. Life cycle analysis of different modules is carried out to determine the cost-effective feasibility of retrofit measures by using the net present value method to formulate design strategies for reducing energy consumption in existing housing. The research flowchart can be briefly summarized as the integration of the following steps (Figure 1.1):

i. Structured literature review to understand various factors affecting energy use
ii. Understanding the study area and preparing different architectural drawings, building envelope characteristics, its geometry and functions.
iii. Inverse modelling technique to understand the various parameters/ variables required in the building performance simulation model.
iv. Energy utility bills of different housing schemes as per sampling criteria.
v. Occupant surveys to understand user behavior and energy use pattern so as to form baseline data for calculating energy use intensity of different user groups.
vi. Thermal mapping of selected apartments for one-year duration to determine the occupancy schedule and calibration of simulation model for thermal conditions.
vii. Running building performance simulations to understand the effect of various design parameters and parametric analysis to identify different modules for retrofits.
viii. Data analysis using statistical tools for validation of results and to finally recommend cost-effective and achievable retrofitting measures for building envelope based on life-cycle cost analysis approach.

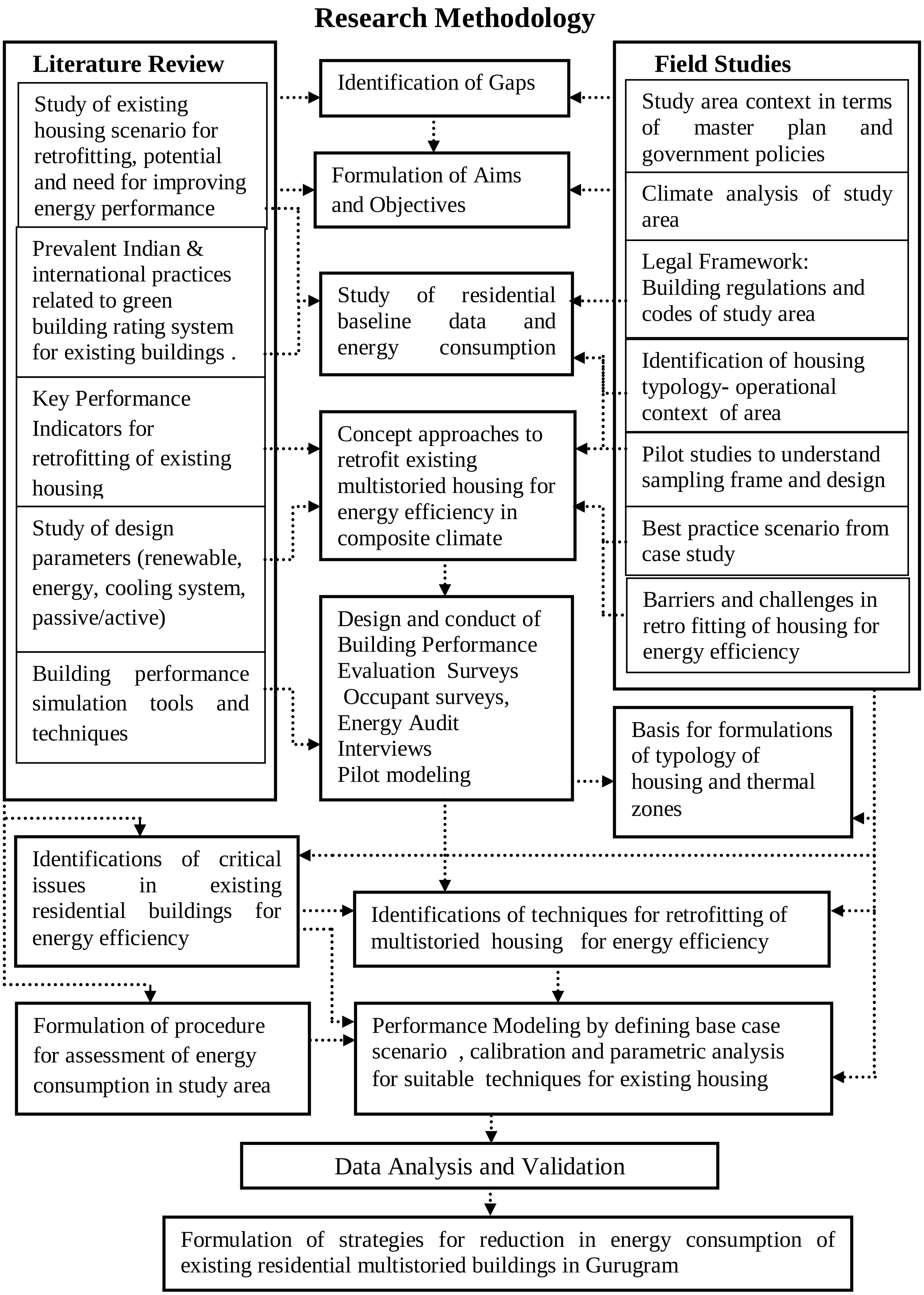


Figure 1.1: Research Framework Flow Chart

1.13 Organization of Thesis

The thesis is divided into six chapters, discussing various stages of research work and are described as follows:

Chapter one: Introduction introduces the problem statement by highlighting the background and context of research, justifying the significance of research and it defines aims and objectives of the research. It also introduces the research methodology adopted along with defining of scope and limitations of the study.

Chapter two: Literature review introduces the theoretical framework of the research problem. This chapter provides state of art of literature review of various research domains in the energy efficiency of multistoried housing societies. Various research outcomes and knowledge gaps in theory and practice are spelt out to evolve the research.

Chapter three: The Context of Gurugram provides an overview of the Gurugram, trends in residential development, its development plan, legislative framework, climatic context, selection criteria of study cases and introduction to characteristics of the sample population.

Chapter four: Research Design and Field Surveys outlines research design, sampling criteria and data collection. It discusses in detail of research instruments like questionnaires, thermal data collection using data loggers, pilot study, building simulation modelling and calibration.

Chapter five: Data analysis provides data analysis and data interpretation in the form of various mathematical models, graphs explaining various simulation results of different retrofitting measures applied to different housing schemes.

Chapter six: Conclusion and Recommendations review key findings in the context of objectives of the study and presents a discussion of results, conclusions and recommendations, the contribution of research to society along with directions for further research. References and various relevant appendices are given at the end.

LITERATURE REVIEW

To define the research problem, a structured literature review of the state of art of contemporary theories, trends and the current knowledge in empirical practices, is taken up in the field of retrofitting existing housing for energy efficiency. Various sources such as peer-reviewed journals from electronic databases (Proquest, Science Direct, JSTOR, Scopus, Web of Science, Emerald, Google Scholar for theses reports), Conference proceedings, Building codes, handbooks and standards, e-books and print books and professional magazines etc. have been reviewed for wider study. The database search using key words from research questions yielded 528 research articles, which were filtered to 216 articles after studying them for relevance to the research area. After in depth study, 89 articles were eliminated due to duplicity of contents. Using snowballing technique and citation analysis to find the most significant works in the field, a total of 172 peer reviewed papers published during period of 1990-2018 are analyzed to synthesize the literature review to gain insight in latest trends, research methodologies, research instruments. Thus literature review attempts to find gaps in theory and practice by collating knowledge from both literature review and empirical studies/ best practices of field. The literature is classified into four domains as listed below:

1. Study of existing scenario for energy use pattern and trends in multi-storied housing for retrofitting
2. Study of design parameters of passive design strategies, HVAC, appliances and renewable energy, key performance indicators for retrofitting of existing housing.
3. Review of national and international policies, building codes and green building rating system for existing buildings and best practices case studies.
4. Building performance assessment tools and techniques to facilitate data collection for establishing baseline data of energy consumption and data analysis, Building performance simulation tools to study input parameters, calibration of model and parametric analysis of design parameters.

2.1 Existing Scenario for retrofitting residential buildings

The built environment in cities contributes to 67% of total energy use [57]. Buildings play a significant role in consuming energy, to the tune of 35% of the total energy use in the building sector [14]. The major land use in any city comprises of residential land use as much as 35 -40% of total land use in large cities and metropolitan cities [26]. 80% of the existing housing stocks in India is designed and constructed before 2001 when there was no code available and awareness to design buildings from sustainable planning principles [27]. National building code in India has been revised recently to include sustainability as Part 11 addendum, but do not address energy efficiency parameters in residential buildings per se [28]. The focus of the Energy Conservation Building Code ECBC, 2017 is on conditioned buildings, which is also not mandatory in many states[14]. Thus, there are no guidelines or codes for designing residential buildings specifically from a sustainability point of view.

There have been very limited studies on understanding built fabric in residential land use. Recently, guidelines for the design of new residential buildings for energy efficiency have been launched by the Bureau of Energy Efficiency, India [1, 29]. As per IEA report (2012), more than 80% of energy efficiency potential in buildings is untapped as compared to other sectors such as industry, transportation and power generation (Figure 2.1).In another report by IPCC(2012), buildings offer the largest potential in curbing CO_2 gas emissions per USD 100 invested in them as compared to other sectors [21].

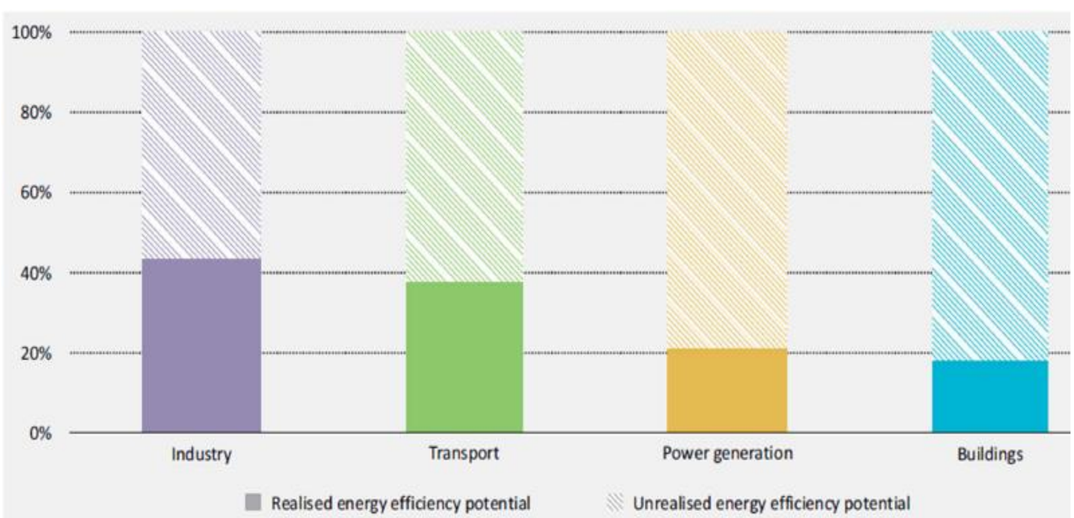


Figure 2.1 Global energy efficiency potential Source: IEA 2015 [72]

Therefore, keeping in mind huge stock of existing residential buildings with their large footprint and continuous consumption of resources incessantly, it is important to understand issues concerning energy consumption in the housing sector and take corrective actions by retrofitting them to reduce energy consumption and enhance the quality of life. In the absence of electricity supply from the grid, the use of diesel generator sets is causing serious environmental pollution. Therefore, it is imperative to reduce energy consumption in operational energy and enhance environmental quality for the sustainable built environment.

2.1.1 Retrofitting Existing Buildings

As per the study report of the United Nations' Intergovernmental Panel on Climate Change in its report on "Mitigation of Climate Change", largest energy and carbon savings potential in 2030 can be achieved by retrofitting and renovation of existing buildings [21]. Given, there is an already growing concern for quality and quantity of energy available in cities, the thrust is to reduce energy consumption by managing the demand side in existing buildings and also provide unprecedented opportunity to reduce CO_2 emission by 2050 [9]. Also added to the fact that by 2050, 70% of the world's population will be living in cities, there is a dire need to re-engineer systematically existing built environment at various scales (building, neighbourhood, city-region) and domains (energy, water, use of resources) in view of climate change and resource constraints [20]. Eames et al (2013) has further envisaged 'Retrofit 2050 Vision' for three different kinds of cities i.e. smart-networked city, the compact city and the self-reliant green city; each one is having variations in terms of indicators for energy, water, waste and resource use, land use, social values, economic growth and urban density. Seven European countries collaborated in the project The ENPER-EXIST for energy performance standardization and regulation [8].

Most of the existing residential building stock is characterized by low thermal comfort, poor indoor air quality and poor lighting conditions [58]. The retrofitting of existing buildings can lead to significant improvement of the indoor environmental conditions as well as increase in productivity and larger economic saving due to enhanced productivity [8].

Retrofit of residential buildings usually involves multiple benefits such as reduction in consumption of energy and hence cutting energy and maintenance bills, improving safety, quality, indoor comfort and aesthetic properties, extend lifespan of buildings, as well as boosting market value [23, 24]. Retrofitting of existing built areas have been enunciated as one of the primary smart solutions for area based development models in smart city mission guidelines so as to achieve the objective of more efficient and livable cities [25].

2.1.2 Existing Residential Buildings Scenario

Residential buildings have significantly higher potential to harness passive low energy techniques to save energy and the current building industry is advancing towards net zero carbon buildings or plus energy buildings with the aim of generating more energy than the building needs [59]. The present study examines the existing residential building stock to develop baseline data for energy consumption, understand their architectural characteristics within socio-cultural and economic context as well as people's aspirations.

Many countries have already plans in place for retrofitting their existing residential buildings like Home Energy Rating System (HERS) in USA and Energy Performance Certificate (EPC) in European countries have been made mandatory while selling or leasing the property. Energy consumption pattern has the most tangible and direct impact on cutting greenhouse gases [60]. In Ireland, the roadmap has been worked out to set different trajectories to build five different levels or scenarios or phases of retrofitting existing stock and future housing stock. The baseline measures include phasing out inefficient lighting and setting minimum standards for boilers, the other scenarios like In the 'Low scenario aim' to improve roof and cavity wall insulation, basic air sealing and air conditioning system controls by 2020 and high energy scenario aim at integrating renewable energy to supply to grid by 2050 by building net positive houses. The Energy Performance of Buildings Directive, EPBD (2003) sets a series of requirements specifically dedicated to existing buildings by ENPER-EXIST project by application of minimum standards, providing general framework for calculating energy use intensity (EUI) and setting targets of EUI and finally energy certification of existing buildings as well as operation and maintenance of HVAC services [8].

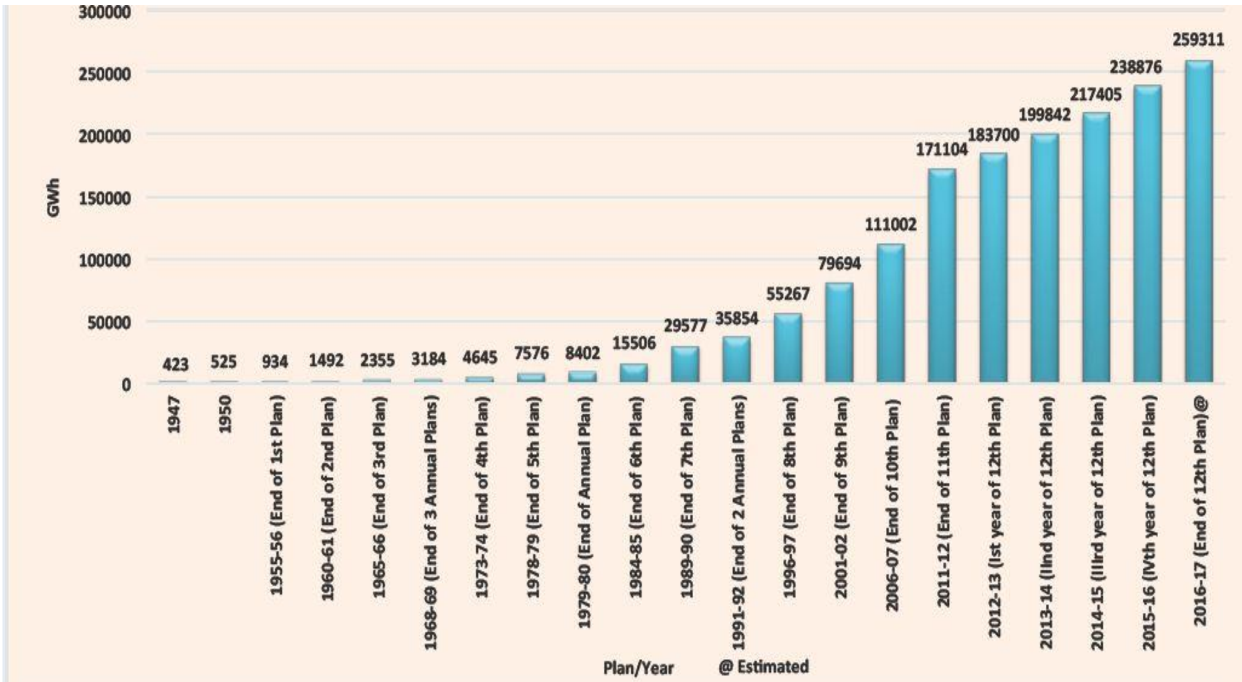


Figure 2.2 Growth of electricity consumption in the domestic sector, India (CEA,2017) [15]

As per the report of the Central Electricity Authority of India (2017), energy use in residential buildings in India has increased from 80 TWh in 2000 to 260 TWh in 2016 (Figure 2.2) [15]. Factors affecting the rise in energy use are urbanization, rising population, indoor living style, high expectation of thermal comfort and higher affordability of people [61]. Over 70 million new urban housing units will be added over the period of next 20 years in India (India Habitat III National Report, 2016). It is estimated that two-thirds of the built-up area is yet to be constructed in the next two decades [63].

It is alarming to note that buildings account for 48% of total global energy use, 19% of energy-related GHG emissions (including electricity-related), approximately one-third of black carbon emissions and generate 50% of total waste. (IPCC 5th Assessment Report, 2014) Of the building sector, commercial building space accounts for 33% and residential buildings account for 67% of energy consumption [18, 64]. The main reason behind the large share of energy consumption in residential buildings in India is due to its largest footprint. Under a business as usual scenario, the growth of the residential building sector at 8-10% annually will lead to a quantum jump in energy consumption. Global Buildings Performance

Network GBPN (2014) in a study report titled "Residential Buildings in India: Energy Use Projections and Savings Potentials", has projected scenarios indicating that electricity consumption is predicted to rise by more than eight times by 2050 under the business-as-usual scenario since 2012 [1]. It further projected that if we use very aggressive measures to reduce energy consumption by adopting ECBC plus compliant building envelopes, a very high-efficiency improvement in air conditioning and equipment, increase in energy consumption can be capped to 1170 kWh per household in 2050. The thrust of energy efficiency measures has so far been on commercial buildings only but residential buildings, which make up 75% of India's market, have been out of the purview of energy efficiency building codes [65]. Residential buildings, which have been placed low on the totem pole so far, offer the highest potential in achieving significant dimension in energy savings by retrofit programs.

In sharp contrast to new residential buildings constructed by developers, where developers are not directly benefitted by adopting energy efficiency practices, owners are directly benefitted due to adopting of renewable energy systems and retrofits of their existing buildings by a reduction in energy bills and subsidies in power tariffs [65]. In addition to resolving the technical issue of energy efficiency, retrofitting of residential blocks/ clusters may be appreciated as an opportunity in a larger framework of an integrated approach to improving neighbourhood, considering urban aesthetics, safety, selection of materials from maintenance viewpoint [66].

2.1.3 Energy consumption pattern and trends in Residential buildings

Energy is primarily used in buildings for achieving thermal comfort and visual comfort. Buildings nearly consume 75-80% of total energy consumption as operational energy over their life cycle [14]. Nearly 25 % of total energy used in the building is in the construction of buildings and 75% of the energy is used in operation of building such as end-use in HVAC, lighting, equipment and appliances [67]. The major share of energy use in multistoried buildings is in air conditioning (38%), followed by water heating (13%), ceiling fans (16%) and artificial lighting 10% of total energy use (Figure 2.3). 23% of the total operational energy use is attributed to process loads in household appliances used by individuals.

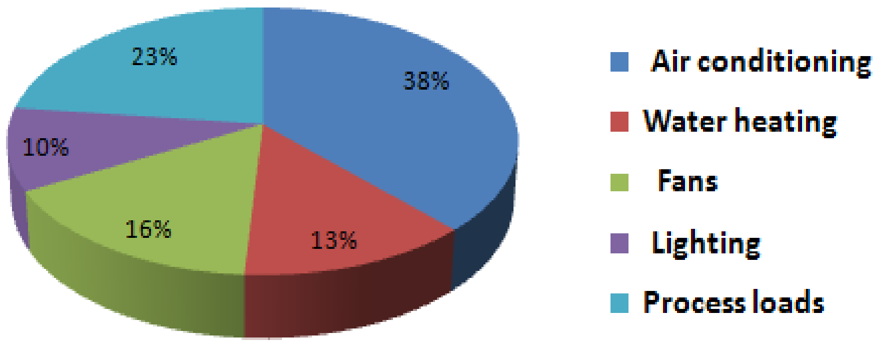


Figure 2.3 Energy consumption breakup by end use, Source UNEP, 2013[67].

In another study by Ganapathy (2016), for the middle-income group villa in Banglore, India, the major share of energy use is in air conditioning (41%), followed by water heating (14%), and artificial lighting 9%of total energy use and 36% in plug loads and appliances. As lighting and plug loads are already being optimised, space cooling or air conditioning emerges out major focus area for energy efficiency [68].

There are very limited studies available to understand adaptive opportunities and energy consumption pattern of residential apartment buildings with a view to achieve energy efficiency [30]. In another study conducted by BEE (2014) for formulating design guidelines for multistoried residential buildings in composite climate, a sample of four multistoried group housing schemes, having 732 units of built-up area ranging from 80-120 sqm , was analysed in 2009 in NCR of Delhi and predicted average energy use intensity to be 48 kWh/m2/yr. But due to the large time gap of almost nine years from hence and change in several factors like changing lifestyle and increased appliance ownership and expected comfort level in cooling, the data is no longer valid. There is a lack of data on housing built up area, use of construction materials, occupant schedules, appliance ownership and usage pattern etc. [38]. There is a need to develop residential baseline data for better planning and targeted reduction in energy consumption.

In another study by GBPN (2014), the survey conducted for all four climate types in India in four cities (n=785), energy consumption in Delhi representing composite climate zone (n=201) was found to be highest (EPI =57 kWh/m^2/ yr) as compared to other cities or climatic zones as shown in Figure 2.4. The large energy use intensity may be attributed to both cooling and heating requirement in composite climate as well as higher affordability due to the higher income level of sample subjects in the National capital of Delhi. The study concluded that it needs to be expanded with a larger database [1].

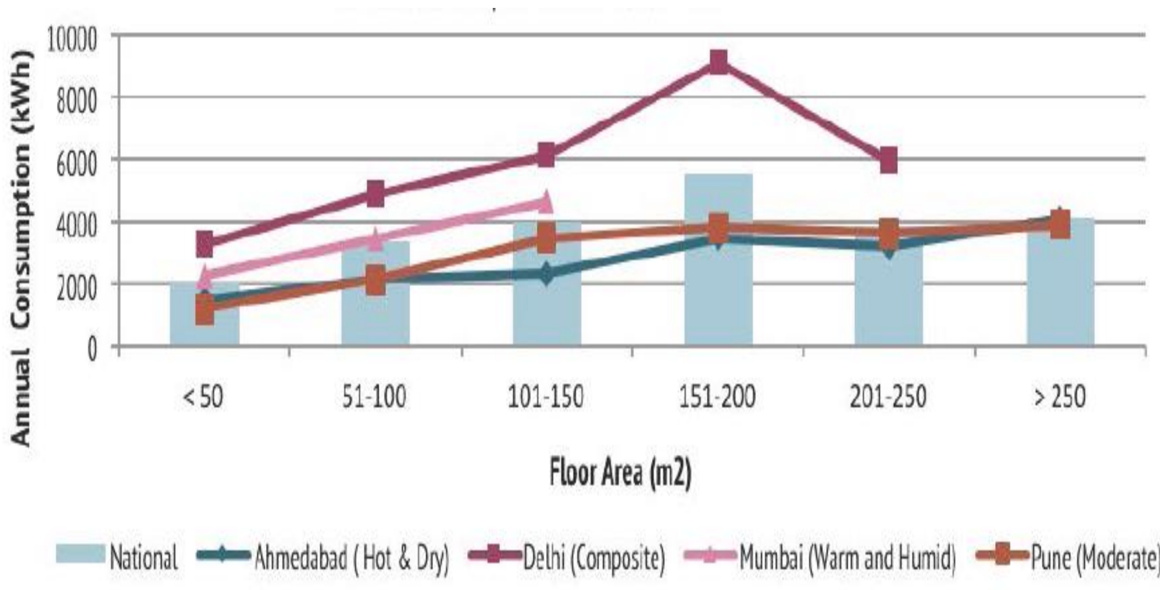


Figure 2.4 Annual energy consumption of different floor area in four cities [1].

Whereas the commercial buildings are designed to fulfil internal loads such as people, lights and equipment, a large percentage of energy is used in residential buildings for space conditioning to meet building envelope load [17]. Space cooling load is increasing sharply as compared to other plug loads/ appliance loads or lighting in residential buildings in developing nations due to change in lifestyle and expected an increase in indoor thermal comfort level. Figure 2.5 traces trends in electricity consumption in different end uses in residential buildings from the year 2000- 2014 [69]. It is possible to reduce cooling load by using passive solar techniques to reduce building envelope heat gain.

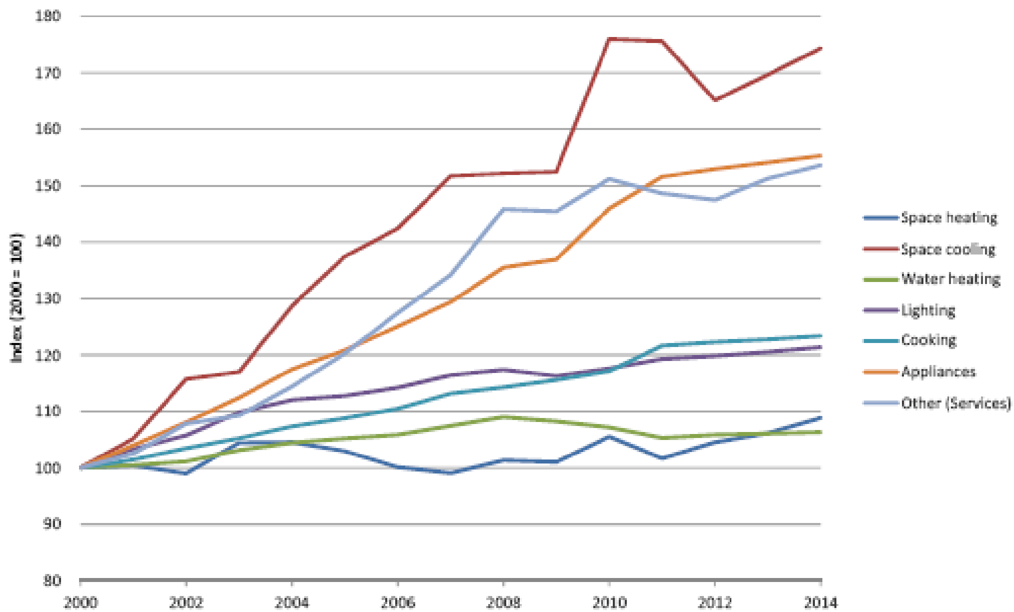


Figure 2.5 Trends of electricity consumption in various end uses in residential buildings from 2000-2014, Source: International Energy Agency, 2015 [69].

Energy consumption in residential buildings differs from commercial buildings significantly due to several factors. The occupants tend to use residential buildings in mixed mode operation i.e they like to use spaces naturally ventilated at some hours of operation and have much greater flexibility in controlling window operations, air conditioners and clothing to achieve thermal comfort [31]. However, there is a greater uncertainty in energy consumption in residential buildings due to greater diversity in use patterns of space, occupancy, family structure, time of use of buildings, appliance penetration, personal preferences of cooling set point and indoor living style [31]. Even similar residential buildings in same site context show variation in energy consumption to order of 150-200% [32]. In addition, there exists a lot of diversity in how residential buildings are designed and constructed and thus modelling of residential buildings for energy consumption pose challenges due to high diversity factors and uncertainty in their input values [36, 37].

Energy usage in residential buildings in India is in contrast to developed countries as due to primarily use of spaces in mixed mode operation unlike extremely airtight houses of Passivhaus homes in Europe [34, 35]. Most residential units use individual packaged air conditioner systems such as window air conditioners or split conditioners as opposed to central heating or cooling systems used in developed nations. Lack of thermal insulation in walls and increasingly large use of glass and lack of double or triple glazing units in residential apartments or villas add to more building envelope heat gain and consequently higher cooling load and thus higher energy consumption.

2.2 Design Parameters

Building envelope optimization is the key tool in the hand of architects and designers to bring energy efficiency in building or increase the thermal performance of the building. Energy is primarily used in building for meeting thermal comfort by cooling or heating and visual comfort by lighting. Given the significant share of buildings in energy consumption to the tune of 40 % of total energy use, building codes such as European Union directives, ASHRAE and ECBC on energy performance have a special focus on passive solar techniques for building envelope optimization to improve energy efficiency.

Passive solar techniques in composite climate entail primarily control of heat flow by the thermal inertia of building envelope (opaque roof and walls), and solar heat gain by transparent fenestrations, regulation of solar radiations access and adequate visual comfort by natural daylighting [70]. Heat regulation through optimizing window design integrated with solar shading devices play a major role in energy demand of buildings and thermal comfort of users. ECBC (2007) has listed detailed thermal comfort objectives and passive solar techniques in buildings for all climatic zones. Passive solar design elements for composite climate are depicted in Table 2.1.

As can be seen, in Table 2.1, designing buildings to perform optimally, is quite a challenging job in a composite climate where diverse seasons alternate from hot and dry to warm and humid as well as cold climatic conditions. In composite climate, in summers, running for eight months a year, the objective is to gain as much shading to ward off the sun and reduce building heat gain factor and increase ventilation in evening hours, but winters involve tapping sun to gain heat indoors, resist heat loss from indoor and have airtightness in the house.

Table 2.1 Thermal objectives and physical manifestation in buildings for Composite Climate

Thermal requirements	Physical Manifestation
Resist heat gain in summer and Resist heat loss in winter	
Decrease exposed surface area	Orientation and shape of the building. Use of trees as wind barriers
Increase thermal resistance	Insulation of building envelope
Increase thermal capacity (Time lag)	Thermal Mass (thicker walls)
Increase buffer spaces	Air locks/ lobbies/ Balconies/ verandahs
Decrease air exchange rate	Smaller window openings, night ventilation
Increase shading	External surfaces protected by overhangs, fins, trees
Increase surface reflectivity.	Pale color, glazed china mosaic tiles, etc
Reduce Solar heat gain	Use glazing with lower SHGC and provide shading for windows, Minimize windows in East and West
Promote heat loss in summer/ monsoon	
Increase air exchange rate (Ventilation during night time)	Courtyards/ wind towers/ arrangement of openings
Ventilation of appliances	Provide exhausts
Increase humidity levels in dry summer	Trees and water ponds for evaporative cooling
Decrease humidity in monsoon	Dehumidifiers/ desiccant cooling

Source: ECBC User Guide 2007 [50].

Boeck et al (2013) in a detailed structured literature review identified five categories of design interventions for improving energy efficiency in existing buildings [71], as listed below:

- Building envelope opaque elements (roof, wall, and flooring)
- Transparent elements such as windows and shading
- HVAC systems
- Lighting
- Appliances

However, the research focus is on reducing energy consumption by passive solar techniques for thermal comfort and lighting for visual comfort. Thus design parameters related to building envelope and lighting are discussed in detail as under.

2.2.1 Building Envelope opaque elements: Roofs and Walls

Whereas in designing new buildings, one can control heat gain or loss by optimizing design parameters like orientation, building layout or geometry, built form and massing, mutual shading and site microclimate to the greater extent for energy efficiency as outlined in Design guidelines for energy efficient multistory residential buildings for hot and composite climates by Bureau of Energy Efficiency [29], there are limitations in altering structural and architectural components in retrofitting existing buildings. There are three important components of building envelope through which heat exchange takes place namely opaque elements i.e. exterior walls and roof; and transparent elements such as windows and skylights.

The important properties of composite wall assembly or roof systems materials are

- Thermal reflectance (depending on the surface texture of the exposed surface layer)
- Thermal conductance (U value responsible for transmittance of heat gain).
- Thermal mass (thermal inertia and capacity as per material bulk and density).

Energy Conservation Building Code of India ECBC 2017 prescribes different values for the above parameters for different climatic zones as depicted in Table 2.2.

ECBC (2017) has delineated two approaches i.e. prescriptive approach including trade-off approach, and the whole building simulation approach [14]. The whole building simulation approach accounts for the complex dynamic relationship of climate, people, occupancy schedule and building envelope geometry and material properties in a detailed manner and uses Energy Performance Index (EPI) as metrics for comparing the simulated case with the base case. ECBC- 2017 is primarily applicable for new conditioned buildings as well as new additions to existing buildings, having a connected load of 100 kW or greater or a contract demand of 120 kVA or greater for commercial buildings. The code has prescribed cool roofs and surface absorption coefficients and SHGC for different WWR in addition to various U values of materials in the prescriptive method. It also discusses Building Envelope trade-off approach to monitor envelope performance factor and provides flexibility to designers to trade off various materials in walls, roofs and glass.

Table 2.2. Prescriptive Building envelope requirements for composite climate for ECBC compliant buildings

Building Type	ECBC	ECBC+	Super ECBC
Max Allowable EPI Ratio			
Hotel (No Star and Star)	1	0.91	0.81
Resort	1	0.88	0.76
Hospital	1	0.85	0.77
Office (Regular Use)	1	0.86	0.78
Roof Assembly Insulation U-factor ($W/m^2.K$)			
All building types, except below	0.33	0.26	0.20
Hospitality > 10,000 m^2 AGA	0.20	0.20	0.20
Wall Assembly Insulation U-factor ($W/m^2.K$)			
All building types, except below	0.40	0.34	0.22
Hospitality > 10,000 m^2 AGA	0.63	0.44	0.22

Source: ECBC, 2017 [14].

There has been extensive research on various thermal insulation levels of the roof, ceilings, floors and especially the walls. Lollini et al (2006) studied optimization of building opaque elements of a detached house on the basis of net present value and the payback rate, considering economic, environmental and energy issues all to be performance measures. Yu et al (2011) also determined the optimum insulation thicknesses of residential roofs and also take into account the impact that both the surface colour and hence the solar radiation absorptance, as well as the insulation materials [73]. Yang et al (2008) consider the individual and simultaneous effects of the exterior wall thermal insulation level and position, the solar radiation absorptance (SRA) of the walls and other design variables in reducing total annual energy consumption in multifamily residential buildings [74]. However as no shoe size fits for all, considering different characteristics of climatic, socio-cultural, housing built form typology, there is a need to work out optimized different thermal properties, surface reflective indices and thermal mass for effective energy efficiency measures in case of retrofitting of residential buildings.

Cool roofs are characterized by reflective coatings on top surface of roofs , having a high emissivity property. They are very effective in reflecting the sun's energy away from roof surface, thus help in reducing thermal gains of building and hence less cooling load of building. Cool roofs can make a good strategy for retrofitting the apartments on the uppermost storey in multistoried buildings. Also use of light colours on building facades are also helpful in warding off the heat in summers as they bounce back the heat at first place and consequently less heat is transmitted through the opaque surface of external wall or roof. As per ECBC 2017, roofs with slopes less than 20^0 shall have an initial solar reflectance of no less than 0.60 and initial emittance no less than 0.75.

Thermal capacity is the measure of the amount of energy required to raise the temperature of a layer of material, it is the product of density multiplied by specific heat and volume of construction layer [75]. Materials with higher density like stone, brick and concrete are having a higher capacity to store heat and hence higher thermal mass. Use of AAC blocks in residential buildings as thermal mass can improve time lag by an additional one hour and can make a big difference to comfort and heating and cooling bills [76]. Reardon et al (2013) in a manual on Australia' s guide to environmentally sustainable homes has suggested the use of high thermal mass for a diurnal range over 10°C [77]. However, it is important to model typical specific housing typology design within a specific climate zone to conclude about thermal mass behavior as appropriate thermal mass level is a function of solar access (glazing type, orientation, area and shading), cool breeze and cool night air access (including mechanical) diffuse and ambient heat gains in summer, nighttime sleeping comfort, and heating/cooling system use and finally seasonal extremes in a climate zone. Gregory et al (2008) carried the comparative analysis of the effect of thermal mass on the thermal performance of various residential constructions systems of Australia and concluded that cavity brick walls and medium thermal mass has pronounced effect on thermal comfort and energy consumption of its inhabitants [78]. Thus, thermal mass with night cooling can be a very effective strategy for composite climates with large diurnal variations. In a composite assembly of construction materials, having the same U value, position of thermal insulation significantly alters thermal gain as it should be placed at the source of ingress of heat to be more effective [75, 79].

In composite climates, apart from thermal insulation and mass effect, shading of walls and roofs plays a vital role in cutting solar radiation and reducing heat gain by building envelope [80]. Shading has been traditionally used as a design element in form of projections over windows, or in modern buildings by movable louvres to ward off the sun and provide flexibility in terms of solar control by designers [81].

Srikonda (2014) has pointed out that buildings in the last decade in India are increasingly using large sizes of glass which increase the demand for mechanical cooling significantly in India's predominantly warm climate [76]. To curb the blatant use of glass and improve the thermal insulation of buildings, the concept of Overall Thermal Transfer Value (OTTV) is evolved, which indicates the average rate of heat transfer into a building through the building envelope or total heat gain per sqm of gross building envelope area. The OTTV of a building is affected by building orientation, the material of walls and roof (U-value), external finish and colour of walls (solar absorptivity), type and area of glass (shading coefficient) and external shading of windows [82]. The concept of OTTV is particularly useful for warm climates like south-east Asian countries [45]. Various countries have put limits on OTTV in the last decade ranging from 45 W/ m^2 for walls and 25-45 W/ m^2 for roofs, 35 W/ m^2 for tower blocks in Hong Kong. Recently launched, GRIHA in its version 2015, a national green building rating agency has defined thresholds for Building Envelope Peak Heat Gain Factor for various climates as per Table 2.3.NBC 2016 part11 has also prescribed Envelope Performance Factor coefficients (EPF) for composite climate as per Table 2.4.

Table 2.3 GRIHA Thresholds for Building Envelope Peak Heat Gain Factor

GRIHA Thresholds for Building Envelope Peak Heat Gain Factor (W/ m^2)	
Climate	Threshold
composite/ Hot and Dry climate	40
for Warm and Humid climate	35
Moderate climate	30

Source: GRIHA V 2015 [83].

Table 2.4 Envelope Performance Factor (EPF) coefficients for composite climate

	24-Hour Occupancy	
	U-factor	SHGC
Mass walls	13.85	
Curtain walls, Other	20.48	
Roofs	24.67	
North windows	-4.56	58.15
Non-North windows	0.68	86.57
Skylights	-294.66	918.77

Source: NBC 2016 Part 11 Approach to Sustainability [28].

Thus the prime purpose of approach to OTTV concept is to limit heat gain by building fabric due to its design and choice of materials. However, there are no such provisions for achieving energy efficiency earmarked in recently amended National Building Code 2016 or Haryana Building Code 2017 (a state building bylaws document).

A well-conceived building envelope harnesses the maximum benefits of passive energy concepts and achieves thermal comfort objectives [84].

"…*Envelopes may soon become even more intelligent dynamic filters by using computer controlled devices for selective shading or movable insulating systems, or by using building materials whose properties change in response to changes in the environment.*" [84,122].

The double skin façade is a relatively recent experiment commanding merit and attention of designers across the world.

Use of double skin facades and lattice screens on buildings also combat solar radiation, yet admitting light and natural ventilation and reduce energy consumption up to 45% in myriad ways [85].Thus double skin facades obviate the use of air conditioning to a greater extent by maintaining higher thermal comfort indoors, channelizes daylight and acts as ventilation subsystem of a building or simply a buffer and minimize air infiltration losses. It is observed that the selection of design parameters should be such that it respects local building bye-laws and non-intruding as well as the cost-effective solution. In that light, use of double skin facades on a larger scale for retrofitting is not feasible from cost-effectiveness [86].

Shading can be provided by a double roof or roof parasol, trellis or pergola or sun breakers in courtyards or atria. Vegetated green roofs and plantation of trees on west sides can considerably control solar gain, thus help to maintain thermal comfort indoor (Lai and Wang, 2011). Detailed understanding of solar chart and shading devices is required to be integrated with building facade design, considering the trade-off between changes in cooling energy requirements in summers and heating energy requirements in winters; aesthetic, functional and social use of space and also to counter improper orientation of buildings in case of existing buildings in different latitudes. Szalay (2008) prescribed various parameters for optimizing energy demand over whole life cycle for residential buildings by considering architectural building envelope characteristics such as ceiling heights, the effect of adjacent walls and the number of storey of the residential buildings and building thermal characteristics [87].

.

2.2.2 Building Envelope transparent elements i.e. fenestrations

Several studies have indicated that maximum flow of heat in buildings is transmitted through transparent elements such as windows and skylights. Consequently, passive design strategies concerning windows have a larger impact on energy and thermal behaviour of buildings [70]. It has further highlighted that window design calls for three specific requirements:

- Provision of adequate visual connection to outdoors and satisfactory level of natural light, avoiding visual comfort detriments (such as glare, etc.).

- Regulation of solar radiation access by solar shading devices, lattice screens curtains and blinds.
- Control of heat flow through components with a low thermal inertia by designing high-performance glass (double glazed units or triple glazed unit, Low SHGC, Low e glass coatings), Low u value frames and window, thermal breaks and air tightness.

Additionally, windows have also to be considered from point of view of safety, mechanical resistance, aesthetics and protection against noise, wind and rain.

Residential windows have a wide range in terms of their material (wood, wood plastic composites (WPC), unplasticized polyvinyl chloride (uPVC), aluminium or steel sections), glass types (single glass, double or triple glazing, low-e etc.), operational mechanism (fixed, casement, pivot, horizontal sliding, top hung or bottom hung), and shades or blinds (fixed, automated, external or internal blinds. ECBC has recommended a maximum of 0.27 SHGC value for WWR ratio less than 40 % in composite, hot and dry, warm and humid climatic zones. Similarly, maximum U value for glazing has been defined as 3.30 W/m^2 for glass and window assembly frame in composite and hot and dry climate. Generally, in residential buildings, windows are kept with clear glass for enabling a view of outside and curtains, shades or blinds are predominantly used to cut off the sun and heat.

Use of curtains, blinds, automated blinds is done extensively as an effective strategy in residential buildings particularly to ward off solar radiations and more importantly glare from the sky and surrounding reflective surfaces [88]. Even if residential buildings are mostly equipped with internal devices, such as drapes, roller shades or Venetian blinds, external shading devices are much more effective in reducing cooling loads and overheating risk, as they intercept and reduce incident solar radiation before it passes through the glass panes, preventing, therefore, greenhouse effect taking place within the house spaces [29].In general, an external shading device (solid or louvred overhangs, side fins, vertical louvres with horizontal or vertical blades, egg-crate louvres, awnings, roller shades, etc.) can be applied just to the window or to a portion or entire facade. In addition, the application of shades also adds an aesthetic value to the renewal of the facade, allowing a new perception of the existing buildings.

Bayne et al (2008) has indicated that in ‘Retrofitting Window systems, improving airtightness (particularly air infiltration) when shut, the operability of the window and lifespan of the system were important design criteria, with key performance indicators being visibility, structural integrity, heat loss/gain regulation’[89].

Bickel (2013) has analyzed in surveys of 12 cities in the USA that approximately half of the window coverings are closed at all times. Between 75% and 84% of coverings remain in the same position throughout the day, depending on the season (summer or winter) and time of week (weekday or weekend). Moreover, between 56% and 71% of households do not adjust any of the covering in their house on a daily basis, depending on the season and time of the week [88].

There is a need to develop baseline data to understand window materials, their base installation, size and no: of windows, type of glass used in windows, window shades and orientations, user behavior of window opening schedule and other environmental factors such as dust, pollution or mosquitoes across the study area in different housing typologies to realistically model them to assess energy efficiency potential.

2.2.3 Best Practices for Building Envelope in Residential Buildings

In design guidelines for constructing new energy efficient multistory residential development by BEE in 2014, it has suggested three packages BEEPS has studied building envelope features to reduce the cooling thermal energy demand and improve thermal comfort and suggested three modules of energy efficiency measures based on simulations carried out on a base case located at Delhi and thermostat set point 26^0 C, WWR 15% and suggested as discussed below

1) Package of Measures I, that can bring about 15%–20% reduction in cooling thermal energy demand: Use of light colours on wall (absorptivity ≤0.4) + window shades with extended overhangs to intercept direct solar radiation on the window + insulated walls (U-value: 0.7 W/m2 .K) + optimised natural ventilation.

2) Package of Measures II, that can bring about 40%–45% reduction in cooling thermal energy demand: Package of Measures I + external movable shutters on windows.

3) Package of Measures III, that can bring about 50%–60% reduction in cooling thermal energy: Package of Measures II + improved wall insulation (U-value: 0.5 W/m2 .K) + use of double glazing in windows + better envelope air-tightness.

For adequate daylighting, BEE (2014) has recommended 10%–15% window-to-wall ratio (WWR) in bedrooms and 30% WWR in living rooms [29]. However, when building blocks in a residential complex are located near to each other, daylighting in bedrooms and living room located on lower floors is substantially reduced. The daylight on the lower floors can be improved by increasing the window area, using light colour with smooth finishes on the wall opposite to the window and using light colour interiors.

For improving, thermal comfort BEE (2014) has recommended design the roof to reduce the cooling thermal energy demand by providing over deck thermal insulation and high reflective surface on roof to minimize heat gain through the roof [29].

In sustainable building design manual, published by TERI, India and Institute Catala de Energia, ICAEN (2004), has suggested to adopt minimum allowable thermophysical properties of building envelope for Gurgaon as recommended for residential buildings by ASHRAE version 90.1-2007- Energy Standard for building except low rise residential Buildings, which is most widely followed/ accepted standard. It prescribes U value 0.048 for roof assembly, 0.151 for mass walls. 0.7 For opaque doors and 1.2 for windows and SHGC to be 0.25, which is a stringent standard than non-residential buildings, underscoring the fact the higher energy consumption takes place in residential buildings [90].

A good example of passive solar techniques in practice is The Passivhaus Homes for both cold climates and warm climate. The Passivhaus certified design engineers have promoted low technology and high-performance measures for energy efficient single family homes and multifamily homes alike, since 1996. The basic five tenets of the Passivhaus concept are:

- All homes should be super thermal insulated.
- Designed with minimum thermal bridges.
- Glazed with well-insulated windows assemblies.
- Good air tightness.
- Ventilation system with highly efficient heat recovery.

The Passivhaus standards were finally packaged to form Passive Housing Planning Package (PHPP) by 1998 and amended in 2007 for both new buildings and renovations in residential buildings. More than 8000 houses have now been built in Germany and elsewhere in central Europe which conforms to the current Passivhaus standard. As per Passivhaus standards, useful energy for space heating is limited to a maximum of 15 kWh/m^2/year and primary energy demand for all energy services (including domestic electricity) is set to a maximum of 120 kWh/m^2/year. Air Tightness in building envelope is such that for thermal comfort, operative room temperatures is set to be minimum 20 ºC in winter.

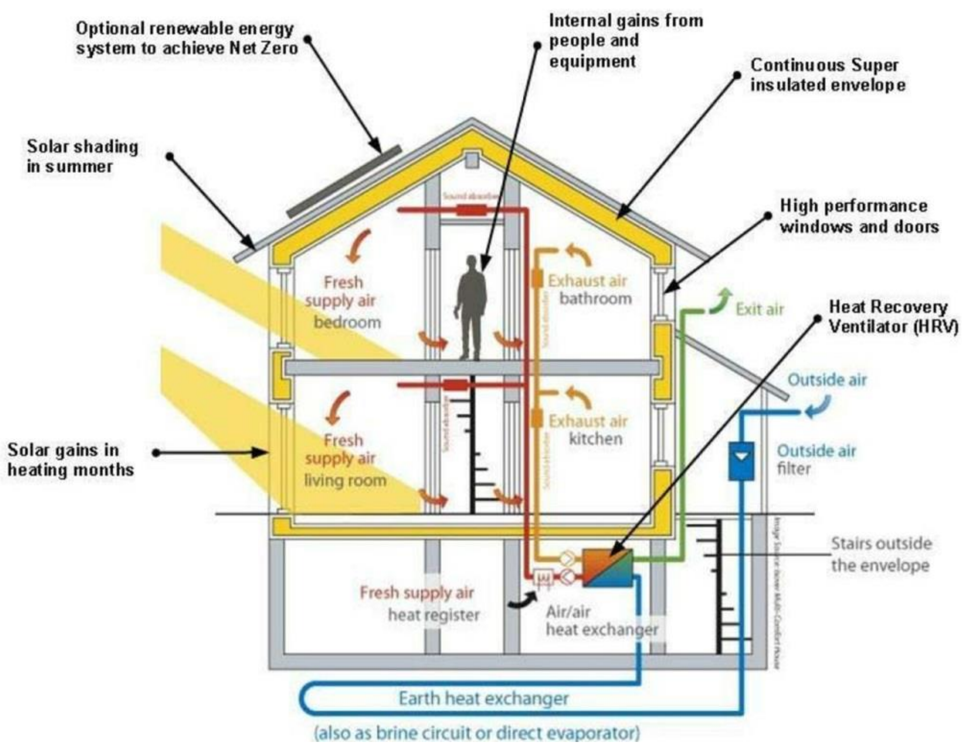


Figure 2.6 Design principles of Passivhaus homes in Europe Source: IEA, 2013[91].

Figure 2.7 Diversity in Passivhaus homes in different climate zones Source: IEA, 2013[91].

Although the Passivhaus standard were framed for the requirements of relatively cold central Europe, they have been amended to also respond to warm European climates. It is possible to achieve adaptive comfort temperature as per standard EN 15251, by using passive cooling strategies, such as window shading and night-time ventilation, leading to literally no energy demand or very low energy demand for air conditioning, for example, Palermo in Sicily. Thus the idea of Passivhaus homes has been successfully executed in both cold climatic zones of Europe as well as hot climates of Southern Europe. There is a great diversity in building styles of Passivhaus homes in Figure 2.7.

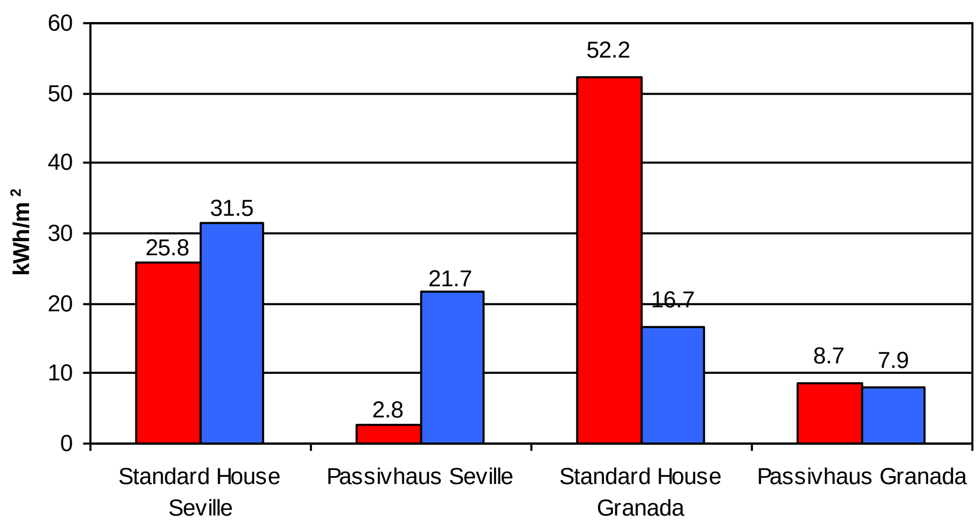


Figure 2.8 Predicted annual heating EPI (Red) and cooling EPI (Blue) for Passivhaus homes Source: IEEA 2013 [92].

The primary energy demand for heating and cooling is limited to maximum of 15 kWh/m2/year in case of passive cooling. However, If cooling is provided by active systems of air conditioning, heating demand is limited to maximum of 15 kWh/m2/year as well as cooling demand is limited to maximum of 15 kWh/m2/year, keeping total primary energy set to maximum of 120 kWh/m2/year . In Passivhaus homes, air conditioning is used only when passive techniques are not able to meet thermal comfort conditions in extreme weather conditions.

The model of Passivhaus homes and standards are precisely standardized product to reduce energy consumption up to 90% of total energy use in buildings and offer relatively standard solutions.The solutions can be integrated into the design of new homes or retrofitting existing model with ease without compromising on aesthetics of houses at a relatively slightly higher cost of 4 - 6% more to build than the conventional home. Thus Passivhaus homes are one of the best exemplars to provide houses supporting low energy and yet comfortable built fabric.

2.2.4 Natural Ventilation

Increasingly buildings are resorting to air conditioning for living and working in building environs, thereby completely foregoing advantages of natural ventilation to improve thermal comfort. Residential buildings, unlike other types of buildings, offer more adaptive controls, window opening controls and urge to have natural ventilation for freshness i.e. quality of air as well as psycho physiological cooling of the body [93]. Ease of availability of air-conditioning in modern times puts it to more frequent use, even when conditions outside are conducive for natural ventilation to provide adequate thermal comfort [46]. Increased use of air conditioning also gives rise to atmospheric pollution by increased use of fossil fuels, global warming and urban heat island effect [94]. For sustainability and reducing carbon footprint, low energy and yet the comfortable maximum advantage of passive design techniques such as natural ventilation should be explored before employing or using the air conditioning system [95]. Issues with running air conditioning in residential buildings, entail extensive energy use, high running cost, poor indoor air quality and integration with building systems and reduced life cycle as well as less responsive to people, sick building syndrome etc. [96].

Residential buildings operate in mixed mode ventilation, dwelling upon natural ventilation means for thermal comfort and fresh air requirements predominantly during early morning hours or evening hours sometimes [1].There lies a huge scope to design thermally comfortable buildings by passive controls and reducing air conditioning hours, when buildings are being used- introducing the concept of passive resilience. The concept of passive resilience translates in terms of reduced air conditioned operative hours at first place or reduced load on the air conditioning system when put to use. ASHRAE standard -2010 specifies that acceptable indoor air speed in warm climates should range from 0.2 to 1.50 m/s and only 0.2 m/s for air-conditioned environments. These ranges specified by ASHRAE do not explicitly address air movement acceptability but focus mainly on overall thermal sensation and comfort. Therefore, the challenge faced in the design of modern apartment buildings is to ensure that the natural ventilation system is effective at providing thermal comfort at appropriate times and to make the natural ventilation "mode" easily accessible to occupants. National building code of India (NBC, 2016) has specified maximum airspeed of 3.04 m/s at temperature for 32^0C and 80 % RH, to provide comfort conditions [28].

Night ventilation or night cooling can dramatically alter thermal comfort for benefit of occupants as the outdoor temperature in evenings is pleasant in summers as compared to indoor thermal conditions. Use of lattice screens on buildings can play important role in cutting sun and facilitating wind movement. A suitable provision in window design should also be made to accommodate evaporative cooler so as to use them in very harsh months of summers when external conditions are extreme. There are various ventilation strategies to induce venturi effect or stack effect through double-height volumes or atriums, shafts, solar chimneys, wind towers, night ventilation or their combinations.

Infiltration is a phenomenon of both providing natural air ventilation as well as medium of heat loss or gains through various form of joints such as cracks, the opening of doors. Faulty constructions and gaps in doors and windows or improper packing of package terminal air conditioners generally used in residential building cause infiltration losses in air-conditioned apartments.

As per ECBC, Air leakage for door and windows should not be more than 2.0 l/ sec m^2. ICAEN (2004) has suggested two methods for calculating infiltration, first by air leakage rate or effective air leakage area calculated from predicted air flow rate in whole building case [90]. Second method is known as Crack method: which calculates the infiltration rate by relating it to the difference between inside and outside wind pressure and the cross-sectional area of open cracks and joints. Air leakage is possible through opaque elements such as cracks or construction joints. Air leakage can also lead to condensation in structures in air-conditioned buildings and cause rotting of insulation or other structural materials or finishes Air-tightness of the building can be controlled by proper detailing of joints, sealing of windows and doors by the appropriate section of window type selection and quality (ICAEN, 2004). However residential buildings need greater attention in regard to air tightness as they are mixed mode buildings and have more adaptive controls. Thus tight sealing of windows is not really desirable also from viewpoint of air conditioning as there are no provisions of fresh air supply in package terminal units, largely employed in residential apartments. However, ECBC has identified several key areas where air tightness should be kept in mind such as joints around fenestrations, openings of utility services or ducts or plenums, site built doors and windows, expansion joints or construction joints.

There is a need to work out standards or norms for mixed-mode buildings, where supplementary air conditioning is used for discomfort hours unmet by passive solar design techniques. Mixed-mode buildings can reduce carbon footprint, reduce energy consumption and running cost, at the same time help in maintaining indoor air quality. Indian households are known for relatively greater adaptive behaviour for thermal comfort as compared to narrow limits or tolerances in developed nations [97]. There lies a challenge to strike a balance between dichotomies of design imperatives for air conditioning and natural ventilation systems in building design in mixed mode buildings, but it certainly offers a cleaner, fresh, green and natural way of living. As per the study conducted by Thomas[1] et al (2014), one should use natural ventilation to a larger extent and operate the apartment in "free running mode" during times when the outside dry bulb temperatures lie within comfort band [46].

2.2.5 Sustainable materials

Selection and use of materials is very intrinsic to retrofitting existing buildings. Generally the existing building stock is comprised of buildings with single pane glass, inadequate insulation and significant amounts of unmanaged air leakage [98]. It is imperative to draw an inventory of all available materials and technologies for energy efficiency including renewable solar photovoltaic panels for environmentally friendly and sustainable retrofit practices [99].

"Sustainable design practices in retrofitting calls for use and selection of appropriate materials, which enhance thermal performance, energy efficiency, indoor air quality and resource efficiency and aesthetically pleasing for exterior surface finishes" [100].

Other important factors in selecting materials are climatic, strength, durability, cost-effective, fire resistance, environment-friendly and local availability. Use of recycled synthetic materials (using technical nutrients as per using the cradle to cradle approach), such as aluminium composite sheets, high-pressure laminates etc. can lead to sustainable practices [101]. There is a need to develop an ecologically intelligent design by innovating at all levels – products, buildings and communities for sustainability [102]. To face huge challenge of affordable retrofitting of existing residential huge stock needs innovative practices by developing selective interventions such as reflective indoor coatings, high reflectance and durable outdoor coating, Phase Change Materials (PCM), thermal insulation materials etc. at acceptable investment (cost-effective solution with lowest payback period) and minimal disruption of building use [103].

Use of new innovative reflecting–cum-insulating material (R-I) such as composite assembly of expanded polystyrene with sawdust and aluminium sheet (r=0.8); either over or under the roof slab can significantly reduce cooling load and reduce energy consumption and the cost of operation [104].Green roofs can help provide both thermal insulation, reduce urban heat island effect, can provide for ecological features by substituting hard paved area with the ground cover or grasses and provide pleasing appearance [28].

National Building Code Part 11 (2016) has taken life cycle assessment-based approach to select materials for sustainability. Various criteria to select materials include embodied energy, resource reuse and upgradation of existing components, recycled content, reusable or recyclable, biodegradable and plentiful in nature, indigenous or locally available, rapidly renewable material and materials compliant with clean air and clean water, materials having low ozone depletion process in their manufacturing [28].

Haryana building code (2017) has incorporated sustainable materials such as panels, hollow slabs, hollow blocks with less consumption of water, Fly ash bricks, portland pozzolana cement for recycled content, AAC blocks and CLC panels (Cellular Lightweight Concrete) for ensuring thermal comfort and reducing load on air conditioning energy requirement, compressed soil earth blocks for walls for better thermal insulation [105].

Various green building rating organizations such as GRIHA Council has published product catalogue on their website to help choose sustainable materials and technologies by stakeholders , ranging from adhesives, wall and roof materials, SRI coatings, fenestrations, glazing, lighting equipments, ceiling fans, chillers, controls and sensors, interior materials, solar photovoltaic panels along with other site development products such as rainwater harvesting paving, organic waste composters and paving materials. GRIHA has laid down criteria for sustainable materials such as criteria 13 and 14 for ECBC compliant material, criterion 15 for use of flyash, criterion 16 for efficient construction technologies criterion 17 for low energy materials, criterion 27 for thermal insulation. IGBC has stressed use of materials with recycled content and at least 50% of all wood-based materials (by cost) to be Rapidly renewable wood and or certified wood by Forest Stewardship Council (FSC) or Programme for the Endorsement for Forest Certification (PEFC) or equivalent. It has further mandated at least 25% of the total building materials (by cost), used in the buildings or campus, are manufactured within a distance of 400 km. For a rating of existing multi-dwelling communities residential societies, IGBC has focused on CFC free appliances, efficient lighting fixtures , solar power for street & common area lighting ,energy metering and solar water heating systems.

Haryana Renewable Energy Development Agency has incorporated several items such as AAC blocks, RC jali, flyash bricks, XPS foam, heat-resistant tiles for roof insulation, uPVC windows, double glazing, solar water heating systems etc. In Haryana PWD Schedule of rates 1988 to guide stakeholders to specify the materials and prepare estimate and find out additional cost due to high performance and energy efficient materials [106].

TZED housing scheme, Banglore (Zero energy development),developed by Biodiversity Conservation India Limited, was the first residential project to be awarded platinum rating by IGBC, India in 2009 [107].This project comprises of 95 homes built over five acres site consists of five-storeyed apartments and villas and is designed on the principles of the sustainable built environment. Use of alternative materials and technologies such as soil stabilised blocks, and laterite blocks for external walls , reinforced cement filler slabs help in reducing carbon emission through energy savings by better thermal insulation, reduction on resource consumption and embodied energies. Also, sky gardens or green roofs contributing to the thermal comfort of the dwellings have been designed using lightweight mulch and coir pith instead of heavier soil, and are irrigated via a drip method. Rubberwood, a non-forest timber, is used for door shutters, thus using eco-friendly materials.

Autoclaved aerated concrete (AAC), also known as autoclaved cellular concrete (ACC), is an immensely popular material for walls in recent years as it is lightweight and have good thermal insulation, fire and mould-resistance properties. AAC products include blocks, wall panels, floor and roof panels, cladding (facade) panels and lintels. Similarly, preformed Structural Insulated Panels (SIPs), made of a foam insulation core bonded between two structural facings, are being frequently deployed for exterior walls.

Renewable energy building envelope options include the use of Building Integrated Photovoltaic (BIPV) system. It consists of integrating photovoltaic modules into the building envelope, such as the roof or the façade and are instrumental in savings in materials and electricity costs, reduce the use of fossil fuels and emission of ozone depleting gases, and add architectural interest to the building. They can be used interfaced with the available utility grid, or as an off-grid systems.

There is an ongoing research in different parts of the world in innovative materials such as phase change materials, engineering material at nanoscale to form superinsulators such as aerogels [86], the full-scale application of which has been demonstrated in Lumenhaus, 2005 zero energy solar house prototype. However such materials potential is yet to be explored in the field for testing and commercial production.

2.2.6 Landscaping

Site climate plays important role in controlling outdoor temperature and thermal comfort conditions. Usually, buildings located in dense core areas characterized by hard paved areas experience less congenial ambient air conditions as compared to buildings located in low density suburbs or surrounded by lush green areas. Outside temperature is influenced by tree cover, ground cover, wind pattern and topography of the site. In a field study and simulation analysis it was found that trees have been able to control undesirable hot winds in summers [108]. On the western boundary, deciduous trees can be planted to cut harsh sun and glare and at the same time to admit sun in winter when it is needed. Trees which attain height 12-

15 m can be very instrumental in providing shade as well sun in summers and winters respectively, should be planted at 10-15 m away from the buildings. It is further pointed out in the field study in residential buildings in Delhi that the net effect of various landscaping elements has a potential to decrease ambient air temperature by 2 -3 ^{0} C in summers. Thus the reduction in outdoor temperature can result in less cooling/ heating load significantly. Bansal (2004) has suggested that a simple shrub or green creeper can alter outside temperature conditions in simple houses due to evapotranspiration effects of vegetation [109].

Ground conditions, its reflective quotient, permeability, soil temperature, paved areas or green cover (dry or irrigated with sprinklers) can create ambient conditions conducive to indoors. On the other hand, residential areas having high density and large paved areas due to parking lots or roads are known to attain a relatively higher ambient temperature, causing urban heat island effect, which in turn forces air conditioning systems to use more energy to cool spaces and reject excess heat back to outdoors, leading to even higher temperature of outdoors and discomfort conditions. In high-density cities, vegetation can prevent overheating in street canyons, decrease solar radiation absorption by shading, increase evaporative cooling by trees and ground cover [110].Urban Heat Island (UHI) phenomenon has a two-fold disadvantage, firstly by an increase in fossil fuel consumption and leading to atmospheric pollution and secondly adding to the global warming effect. Effect of shading by trees or man-made features outdoors can also lead to increased walkability index, less dependence on indoor areas (particularly in residential areas in evenings, when children play or residents take to walk for socialization) in addition to regulating temperature by cutting solar radiations, produce cooling of wind in shaded areas [111].

Although tree cover and other landscaping elements have a pronounced effect on site microclimate, but, ironically, most frequently used energy simulation softwares do not consider effect of trees or ground temperature and they treat trees as temporary or not fixed elements having their full growth right from start of the project and more skewed philosophy of designers to think of life only indoors [112]. A combination of both green roofs and green walls leads to the highest mitigation of temperatures inside the buildings in multistoried buildings and outdoor streets as well. In a study and works by Ken Yeang (2013) on 'Eco

Architecture' Green roofs and green walls are found to create areas of mitigated temperatures in both block level and also in the whole city scale [113]. Especially for hot climates, they bring temperatures down to more "human-friendly" levels coupled with substantial energy saving and at the same time are aesthetically pleasing too by breaking the monotony of ubiquitous multistoried concrete jungles of housing.

2.2.7 Heating, Ventilation and Air Conditioning Systems

Electricity consumption in air conditioning contributes to nearly 60 % of total electric energy consumption in multistoried residential buildings in composite climate [29]. In the composite and hot-dry climates, where outdoor conditions are very harsh with temperatures soaring up to 45 ^{0} C and with urban heat island effect, increased use of air conditioning is characterized by longer duration in the year from mid-March to mid-October. The use of room air-conditioners is increasing rapidly in multi-storey residential buildings. The annual sale of room air-conditioners in India has trebled over the past five years. Analysis of time-series data (2006–2013) from one of the residential complexes in Delhi indicates that electricity consumption for space cooling is more than double in air conditioning as compared to evaporative cooling systems (BEE, 2014).The electricity consumption in the space-cooling system primarily depends upon the building fabric heat gain factor, infiltration losses, lighting loads, the rate of air change, ambient air temperature, cooling set-point temperature and energy efficiency ratio of the mechanical equipment used [29].

Active air conditioning systems should be used after taking full advantages of passive cooling systems. Unlike commercial or institutional buildings, residential buildings use air conditioning systems intermittently in the daytime, also make use of natural ventilation for some time, especially in morning hours and also from the month of October to March. Thus residential buildings essentially use mixed mode systems. NBC (2016) defines adaptive thermal comfort model for mixed mode buildings as per the following equation:

$T_o = 0.28 \times T_{mmo} + 17.87^0$

$T_{o=}$ Indoor operative temperature in ^{0}C to be taken as the thermal neutral temperature

T_{mmo} = Mean monthly outdoor temperature in ^{0}C

Thermal comfort band for 90 %acceptability range for the India specific adaptive models for mixed-mode buildings is defined as ±3.46°C [28].

It is very important to have fresh air supply in air-conditioned spaces to maintain good indoor air quality, failing which many energy efficient buildings tend to acquire sick building syndrome (Chandra, 2004). The minimum fresh air required in a mechanically ventilated or air-conditioned spaces should be as per norms recommended in NBC 2016 (Part 8: Building services, Section 1: Lighting and Natural ventilation, subsection 5: Ventilation), the relevant sections of which are reproduced in Table 2.5.

GRIHA has prescribed the use of indoor air quality standards for non-air-conditioned buildings as well as residential buildings with operable windows. For the purpose of the design of mechanical equipment for conditioned spaces, NBC 2016 prescribes ventilation rate to be 2.5 l/s per person or 0.3 $l/s/m^2$ on area basis of different rooms in residential dwelling units. The occupancy density for residential is defined as two persons for the living room and one-bedroom units, with one additional person for each additional bedroom [28].

Table 2.5 Recommended air changes rate for various spaces

Sr. No	Applications	Air change per hour
1	Living Rooms	3-6
2	Bedrooms	2-4
3	Kitchens	8-12
4	Toilets	6-10
5	Assembly Rooms	4-8

Source: NBC, 2016 [28].

Use of hoods with forced suction (chimney) above cookstove and other exhaust fans in the kitchen is must for extracting heat, the spread of kitchen fumes to other living areas, maintaining freshness of air [29]. Adequate natural ventilation should be provided in the kitchen to provide thermal comfort.

Predominantly packaged terminal units, like window air conditioners or split air conditioners are used in existing residential buildings in multistoried housing. Bureau of Energy Efficiency (BEE) has prescribed star rating for unitary air conditioning system. However, in new residential buildings, use of variable refrigerant volume (VRV) is replacing unitary systems of air conditioning. When using packaged terminal units, like window air conditioners or split air conditioners, use of five star rated by BEE is desirable for energy efficiency. Depending on the usage of the air-conditioners, the energy saving (with five star over one star) during the year is expected to range from 200 to 700 kWh per year, resulting in 10-15% savings in electricity consumed in space cooling [29]. The EER for the air-conditioner is defined as the ratio of output cooling power (watt) to the input electrical energy (watt). The maximum and minimum limits of Energy efficiency ratio (EER) of unitary and split air conditioners defined by BEE (2014) is as per Table 2.6.

Table 2.6 Energy efficiency Ratio of Unitary and Split Air conditioners (up to 3TR)

Split Air conditioners			**Unitary (Window) Air conditioners**		
	Energy-efficiency ratio (watt/watt)			**Energy-efficiency ratio (watt/watt)**	
Star level	**Minimum**	**Maximum**	**Star level**	**Minimum**	**Maximum**
1 star *	2.70	2.89	1 star *	2.50	2.69
2 star **	2.90	3.09	2 star **	2.70	2.89
3 star ***	3.10	3.29	3 star ***	2.90	3.09
4 star ****	3.30	3.49	4 star ****	3.10	3.29
5 star *****	3.50	—	5 star *****	3.30	—

Source: BEE, 2014 [29].

In the context of retrofitting the homes, several measures like low hanging fruits can be taken up first by minimizing building fabric heat gain by improving airtightness or reducing infiltration losses, replacing the glass with double glazing unit or using solar control films to reduce unwanted heat gain in the buildings. Particularly in mixed mode buildings, one should allow natural ventilation to serve most parts of the building. Air conditioning should be used only during peak design conditions in summers or areas when excessive heat builds up.

2.2.8 Lighting

Lighting constitutes a key component of energy consumption in buildings for providing visual comfort in indoor spaces. Residential sector contributes to 21% of the total electricity consumption in India [116].With the latest advancements in lighting technologies, controls and knowledge on integrating daylighting, it is possible to reduce energy consumption in lighting, even below set benchmarks in Building Codes. ECBC (2007) has prescribed interior lighting requirements in terms of lighting power density (LPD) to be 7.5 W/ m^2 for multifamily residential building types in (Building Area Method) or 11.8 W/ $m^2$for guest rooms in a hotel or living quarters in the dormitory by (space function method). For exterior lighting, the code has limited LPD to 13W/ $m^2$of building entrance canopy or 90Wper linear metre of entrance door width in case of no canopy and for building facades 2 W/ m^2 of vertical facade area.

Reduction in energy use in lighting can be win-win situation for all stakeholders as it comes at a relatively lower initial cost and easily achievable target, having low payback period, reducing peak load for utilities to handle [117].It can be accomplished by working out size and distribution of windows so as to maximise daylight and minimise solar heat gain; using light finishes in interiors, using task lighting to supplement light at work /counter/ desk level, using energy efficient luminaires like LED lights, selecting lamps with high luminous efficacy, use of light sensors as per occupants in circulation areas and daylight sensors, lighting controls such as dimmers, solar-powered street lighting etc. A good lighting design also helps in reducing cooling demand energy due to heat emitted from lighting fixtures.

Whereas conventional daylighting design components can provide adequate daylight upto 5m of the window and is good enough for residential buildings [118].There is a hyped global fascination to provide large unobstructed glass in all modern buildings, even in residential buildings that thermal discomfort is more than visual comfort. Visual discomfort due to glare by the additional brightness of large windows is a concern.

An energy efficient approach to lighting design calls for lower lighting power density (LPD) than ECBC standard, yet at the same time maintaining illumination level for the specified task as per NBC 2016. Lower range of illumination levels are to be explored in residential buildings This can be achieved by two-fold approach: Firstly by proper utilization of daylight from proper distribution of windows, lighter finishes of room surfaces, control glare by window coverings or shading; secondly by use of efficient luminaries, lighting distribution, colour rendering index, lighting controls and following maintenance schedule for cleaning of luminaries.

Daylight integration calls for appropriate window design, its size and distribution, the decision of the type of glass, internal finishes colours, shading devices to cut off glare and heat to maintain average daylight factor. There is a possibility that due to glare from the windows, one has to keep the internal blinds closed for the most part of the day, nullifying the daylight based savings and in turn increase energy consumption (due to artificial lighting being kept on during daytime and also due additional cooling load from the heat of lights).

In design guidelines for constructing new energy efficient multistory residential development [29], BEE has prescribed window-to-wall ratio (WWR) 10%–15% in bedrooms and 30%in living rooms. However, in dense multistoried housing developments, daylight penetration on lower floors is reduced considerably, particularly when building blocks are located near to each other. Remedial measures to increase daylight factor should be taken up by increasing the window area, using light walls colour on interiors as well as the exterior for enhancing external reflection component. Currently, window sizes in residential multistoried buildings are generally the same on all floors and orientations, thus leading to either too bright or poorly lit interiors. GRIHA has mandated Minimum of 25% of the living area should meet an adequate level of daylight (daylight factors) as prescribed in SP 41 Handbook of functional requirements of buildings. For residential buildings, GRIHA has fixed threshold of 100 lux daylight to be met over the total living area for at least 50% of total annual analysis hours (annual analysis hours from 8:00 am to 6:00 pm each day).

Choice of lighting fixtures with higher luminous efficacy and appropriate light distribution is the most effective means of energy saving in lighting. However other factors such as power consumption and likely lifespan of different lamps govern their choice. For residential buildings, lighting lamps options range from, tubular fluorescent lamps (T5 tube lights with electronic ballast)as a linear source, Compact fluorescent lamps CFLs as a point source, light emitting diodes LEDs, both point and linear source. Use of BEE labelled star rated lights can reduce power consumption by 10-15 %.GRIHA has mandated artificial lighting design to fall within limits (lower and higher range limits) as recommended space/task specific lighting levels as per NBC 2005 and to meet a minimum uniformity ratio of 0.4 [119].

Daylight integration and use of light coloured finishes in common services areas is important for reducing overall electric consumption as they consume about 16% of the total annual electricity consumption of the residential complex [29]. Use of star rated LEDs and TFL having high colour rendering index are more suitable for indoor lighting. Typical recommended values for daylight in common areas are given in Table 2.7.

Table 2.7 Typical recommended values for daylight in common areas

Type of space	Illuminance level required (lux) l	Minimum daylight factor based on New Delhi climate data (%)
Corridors, lobbies, circulation areas	50–100	0.3–0.5
Staircases	100–150	0.7–1.0

Source: BEE, 2014 [29].

To reduce wastage of energy used in lighting, lighting controls play a major role. Several choices such as automatic controls switch off or light dimmers, motion detector sensors based on occupancy for common areas such as corridors, staircases in multi-dwelling units or individual rooms, photocell type daylight sensors, timer switches for external lighting are available. Separate light controls to switch on or off a small group of lights such as accent or decorative lighting should be provided. Smart Building automation systems essentially control lighting centrally in common areas by integrating with daylight and are an integral part of energy saving measures [29].

2.2.9 Appliances

Residential building energy demand is influenced largely by the extent of the use of household electrical appliances [120]. Change in income level and affordability increased the availability of appliances is responsible for the increased use of electrical appliances in households [121].Apart from air conditioning and lighting, 33% of total electrical energy is used in plug loads or appliances in residential buildings with 19% in kitchen appliances and 14% in entertainment [122].

The Bureau of Energy Efficiency (BEE) launched the Standards and Labelling (S&L) Programme by rating systems electrical appliances in May 2006 under the National Mission for Enhanced Energy Efficiency (NMEEE), with aim of operational cost-saving potential of equipment/appliances. Star rating system assigns stars from one to five; five stars being the most energy efficient. Use of star rated equipments for ceiling fans, water heating, lighting or other electric appliances used in domestic buildings can reduce energy consumption significantly. For four products (frost-free refrigerators, room air conditioners (ACs), fluorescent tube lights and distribution transformers) labels have been made mandatory [116].

Ceiling fans are widely used to bring thermal comfort. The star rating of ceiling fans is based on the 'service value,' which is defined as the air delivery in m^3/min divided by the electrical power input to the fan in watts, with higher service values rated as a higher star rating [29]. Use of five star rated 1200 mm sweep ceiling fan can produce energy savings from 12 kWh/year to 75 kWh/year.

Use of five Star rated electric water heaters (Stationary storage-type) of capacity 15 litres, (both vertical and horizontal type) can reduce standing losses up to 25% as compared to one-star heaters. The star rating of the electric water heater is based on the grade of standing loss (kWh/24 h/45 °C), indicating loss of energy from the tank [29].

Other appliances used in households are Frost-free refrigerators, washing machines, microwave ovens, dishwashers, Water purifiers, kitchen mixers/ blenders, Color televisions , music systems , Laptop/notebook computers exercise equipment, electric iron, other small appliances such as chargers, mosquito repellers or electronic items etc. in addition to equipment used in common service areas such as lifts, and electrical pumps for water supply and equipments for horticulture, distribution transformers [116]. In a study of small housing complex (3 towers, G+7 floors, 90 flats) in New Delhi by BEE (2014) , it was found that electricity consumed for common services such as lifts (62% of common area energy), lighting of common areas(21% of common area energy) and pumping water to overhead tanks(17% of common area energy)was 72,000 kWh/year, or around 16% of the total annual electricity consumption of the complex. Use of regenerative brakes in lifts, the gearless system of lifts with Variable Frequency Drives (VFD) in lift motors and other water pumping motors use much less energy [29]. The use of LED lights in lifts, light coloured finishes in lift interiors, automated controls for light and ventilation of lift cars is recommended to reduce the energy consumption of lifts in standby mode i.e. when lifts are not running as in residential buildings, lifts are in standby mode for most times.

Energy consumption in electrical appliances is a function of energy use pattern, household income level, people's attitude, behaviours and use of advance technology in appliances. In a survey of 684 households to understand the lighting energy consumption Jaipur city, In energy consumption for lighting, it is understood that the per capita energy consumption for lighting is increasing along with increase in income group, i.e., just 48.90 kWh for the lowest income groups, and it is increased to 167.59 kWh for the higher income group of Rs. 120,000-150,000 which shows that income decides the quantity of energy consumption at the household level [123].

Table 2.8 National average of Appliances in residential households, 2014

Appliance type	Average	Appliance type	Average	Appliance type	Average
Tube lights	8.0	Refrigerator	1.0	Electric Kettle	0.1
CFL/Bulbs	8.8	Water Pump	0.3	Fans	3.3
Television	1.6	Microwave Oven	0.8	Grinder	0.5
Washing M/c	0.9	Toaster	0.5	Laptop	1.2
Geyser	1.5	AC	1.6	Air Cooler	0.1

Source: GBPN, 2014 [1].

There are very limited studies on a number of appliances used in residential buildings, their power rating and operational patterns [1]. In a study by GBPN(2014) on 785 samples of residential apartments drawn from four metropolitan cities : Ahmedabad, Pune, Delhi, and Mumbai, 2 bhk and 3 bhk units consist of 80% of sample size; Delhi has the highest average of appliance penetration per household and 12.6 CFLs per household the highest AC average at 2.4. Increase in energy consumption in appliances is largest as compared to other end uses in the last decade [124]. Highest energy consumption in Delhi can be explained due to the composite climate; where both heating and cooling are required as well as higher income levels and higher appliance penetration [125].

As per interim report of the Low Carbon Committee [126] of the Planning Commission 15-20% of total electricity consumption can be saved by more efficient lighting and appliances for instance use of LED in television sets, Ceilings fans with light-weight brushless DC (BLDC) motors against use of induction motors etc., Electronically controlled refrigerators and variable speed compressors in air conditioners etc. . In a background paper by World Bank (2008) on India: Strategies for Low Carbon Growth, various tables provide duration of use of various electrical appliances, power rating and energy consumption in residential buildings in India, but data need to be upgraded in view of changed lifestyle currently and more penetration of equipment and their increased efficiency [127].

Although architects have no direct control over the use of domestic appliances in residential buildings, for energy modelling of existing buildings parameters such as number of appliances, plug loads due to appliances, and their usage pattern need to be worked out realistically as they form significant energy guzzlers.

2.2.10 Renewable energy integration systems

Use of Solar water heating systems has been already made mandatory in institutional, commercial and large residential complexes. Net Zero Buildings or nearly Net Zero Energy buildings (NZEBs) have been a target for new buildings as well as retrofitting existing buildings by 2050 in net-zero buildings all over the world. Various initiatives like solar harvesting, integrated building photovoltaic systems, rooftop solar projects , net metering or smart metering and solar street lighting etc. have come up due to which the role of buildings is changing to energy-producing from that of energy consuming, thus even generating energy plus buildings or net-zero buildings in the process.

Availability of good annual global solar irradiation (more than 1700 kWh/ m^2) in a composite climate of Delhi and its surroundings, can ensure optimum use of solar photovoltaic and solar water heating systems in multi-dwelling units [29]. In multi-storey residential buildings, the available roof area for harnessing solar energy per flat decreases from about13–18 m^2 roof area per flat for a 4-storey building to 2–3 m^2 roof area per flat for a 24-storey building [29].Building facades can be used to integrate photovoltaic panels in its fenestrations. In the rooftop photovoltaic system, one can choose from an array of systems such as Stand-alone (off-grid) solar PV system with dedicated loads or grid-connected solar PV system with net metering or Hybrid system (system with grid backup power).

As per recommendations by BEE(2014), "For multi-storey residential buildings, up to 12 storeys, community solar water heating systems on the roof (assuming utilization of 60% of the roof area) can meet around 70% of the annual electricity requirement for heating water. Beyond 12 storeys, there are diminishing returns due to lower energy replacement, increased complexity in distribution and heat losses. Unlike individual and low-rise housing where the roof area is sufficient to install both solar water heating and solar PV systems, in most of the multi-storey residential buildings only one of the technologies can be used due to the limitations in the roof area. The choice of the technology should be based on the priority of the requirements and a cost-benefit analysis." Therefore the use of building integrated photovoltaics (BIPV) is recommended to be integrated with existing building facades so as to harness maximum potential of solar energy to meet building energy requirements [128].

GRIHA (2015) has made mandatory the requirement of on-site/off-site renewable energy system installation to offset a part of the annual energy consumption of internal artificial lighting and HVAC systems Table 2.9, Mandatory requirements of criteria 9.1.1 must be met through on-site renewable energy system or in case one uses off-site renewable energy system , then 100% building energy should be met to score full 7 points from offsite renewable energy [119].

Table 2.9 Onsite/ Offsite renewable energy points for meeting annual energy consumption

Residential Buildings (onsite renewable) Part of annual energy met	Points	Residential Buildings (off site renewable) Part of annual energy met	Points
5%	1	100 %	7
10%	2		
15%	4		
20%	5		
25%	7		

Source: GRIHA, 2015 [119].

In the wake of near absence of real-life examples or prototypes of net-zero multi-dwelling housing schemes, clarity on a policy of net metering and life-cycle cost analysis thereof, there is a knowledge gap and barrier to implementing ambitious schemes of the government in India.

2.2.11 Key performance indicators

For sustainable development and sustainable urbanization, sustainability indicators play a major role to measure or benchmark performance of a project at the city level, neighbourhood level or building level [129]. It is well said that what cannot be measured, cannot be managed. Indicators are defined as a specific, observable and measurable characteristic to reflect the progress of process or impact of an action for achieving a specific outcome [130]. Characteristics of good indicators include validity, reliability, precision and measurable [131]. Indicators along with their metrics can help define various parameters of energy efficiency and they help you in understanding where you are, which way you are going and how far you are from the target [130]. Various researchers and international agencies have attempted to create an inventory of indicators showing a wide range of key performance indicators for benchmarking the projects or rating systems for projects ranging in scale from neighbourhoods to cities and metropolitan regions. In developing countries particularly, sustainability indicators must take into account local climatic context, prioritise local needs and should lead to programs and policies to deliver at various levels by developing mechanisms and potential technological solutions [32].

For achieving sustainability goals, benchmarking is used as a tool in buildings to measure design variables or energy efficiency [133].Sustainability benchmarking is a most commonly used tool across the world to assess the performance of a particular built fabric from sustainability parameters and improvise projects to meet continually rising higher thresholds of sustainability [134].Benchmarking facilitates to identify the gaps in the performance of the buildings and facilitates in retrofitting them to achieve sustainability goals by optimizing their functions in line with desired targets and thresholds [42]. No two places which are in different climatic zones and cultural context within the country or different countries are identical and need to be analysed from different sustainability parameters [43].

There is no room for universal indicators and indices in view of varying standards of adaptive thermal comfort, lighting and indoor air quality for different building typologies and for different climatic zones as well as socio-cultural factors. Various sustainability indicators applicable to existing buildings by different green building rating systems have been analysed in section 3.4, but there is a need to develop key performance indicators for benchmarking sustainability and enhancing performance for retrofitting existing housing stock consuming higher resources. Energy efficiency is recognised to play a pivotal role in achieving sustainability goals by taking into account resources limitations.

Sustainability indicators are useful to quantify building performance, target setting and prepare a roadmap for delineating strategies for taking corrective steps to address problems and achieve target benchmarks [135]. Building performance simulation tools are widely used to understanding complex dynamic interaction systems of buildings and design high-performance buildings by applying the highest levels of design, construction, operation and maintenance principles [136]. The US Department of Energy (DOE US 2014) has listed 416 building software tools along with a brief description of salient feature of each tool including expertise required. Most codes and standards refer to the whole building performance simulation for evaluating various indicators and comparing effects of various parameters for making rational choices of appropriate building fabric and program in order to achieve sustainability [137].

National Housing Bank, India developed an IT-based toolkit for energy-efficient residential buildings, known as 'EnEFF: ResBuild India' in collaboration with The Energy Resources Institute (TERI), Fraunhofer Institute for Building Physics (IBP), Germany and KfW Development Bank (KfW), Germany. It gathers information on various parameters such as weather or climate zone, housing unit type break up of conditioned and unconditional floor plate, total exposed and unexposed wall and roof area, window wall ratio, solar heat gain coefficient factor of type of glass used and local shading devices, orientation and thermal conductance (U value) of materials used in apartments, building services such as lighting power density, coefficient of performance of air conditioning systems installed and solar water heater and campus lighting. US residential energy consumption survey has listed indicators for tracking as shown in Table 2.10. It has underscored demographical characteristics by taking in account number of occupants, annual income and energy payment method , Construction characteristics in terms of floor area of units and year of construction, Ownership type, housing unit typology, Energy usage pattern by fuel type and end use, and finally energy usage in appliances and electronics.

Table 2.10 Various Parameters for US Residential Energy Consumption Survey

Demographics	**Construction Characteristics**	**Region & Metropolitan & Climate**	**Energy**	**End-uses**	**Appliances & Electronics**
Number of occupants	Year of construction	Urban vs. Rural	Energy by fuel type	Space heating	Count,
Annual income	Floor area	Housing unit typology	Energy by end-use	Space cooling	age
Relation to the poverty line		Ownership type		Water heating	usage
Energy payment method				lighting	size

Source: Dulac and Dean (2014).International Energy Agency (2014) [138].

There is a need to develop a baseline for existing residential societies in group housing, situated in the National Capital Region of Delhi. POE surveys can provide value feedback on the design quality, functional aspects and thermal comfort. There is a need for objective and rigorous performance evaluation technique to provide systematic and easy to understand structure for measurement, evaluation and continuous improvement of buildings [150]. A pilot questionnaire survey and simulation of modelling of test case can help to determine sample size and finally develop a set of indicators for assessing energy consumption for a specific case of retrofitting existing residential buildings in composite climate. Comparison of various benchmarks achieved in the simulation output against design intent can be helpful in formulating strategies for high performing buildings in the near future [139]. Selection of a well-designed existing residential complex for developing the best case scenario, its POE surveys and then building performance simulation modelling and finally its analysis, can serve as a blueprint for setting achievable targets in various indicators of sustainability. Thus analysis of baseline data of exemplars on the extreme side of the scale will help in understanding the concept of threshold values of the indicator and also help in bridging the gaps and fixing targets for retrofitting.

Various Key Performance Indicators (KPI) which are useful in building scenario are as per performance functions to be conducted by employing energy. Energy is primarily used for thermal comfort and visual comfort. Various KPIs for energy used in thermal comfort are discomfort hours or unmet hours, Energy performance Index, design cooling load, peak cooling demand and building heat gain factor. For energy used in visual comfort, various KPIs are lighting power density and illuminance level.

2.3 National Policies, Building codes and Green Building Rating Systems

At the policy level, various efforts to reduce energy consumption can be discerned in form of National policies and acts, National Building Codes and standards and current green building rating or labelling schemes available in the country. There is a vast repository of green building rating systems across the globe and building software tools for evaluating in addition to building codes for different nations for guiding principles, addressing energy efficiency, renewable energy and sustainability in buildings. Criterion Planners (2014) in its report on Global Survey of Urban Sustainability Rating Tools, have listed 63 rating systems prevalent across the globe, with major players among them are BREEAM, LEED, CASBEE, GREEN STAR and HK-BEAM, SB TOOL, ARCHITECTURE 2030, ONE PLANET [140]. Residential buildings constitute major share in building typologies in any city and consume high energy. There are no energy efficiency codes specifically for new as well as existing residential buildings in India unlike developed nations, where they have been implemented as a key driver for reducing energy consumption. (Figure 2.9).

.

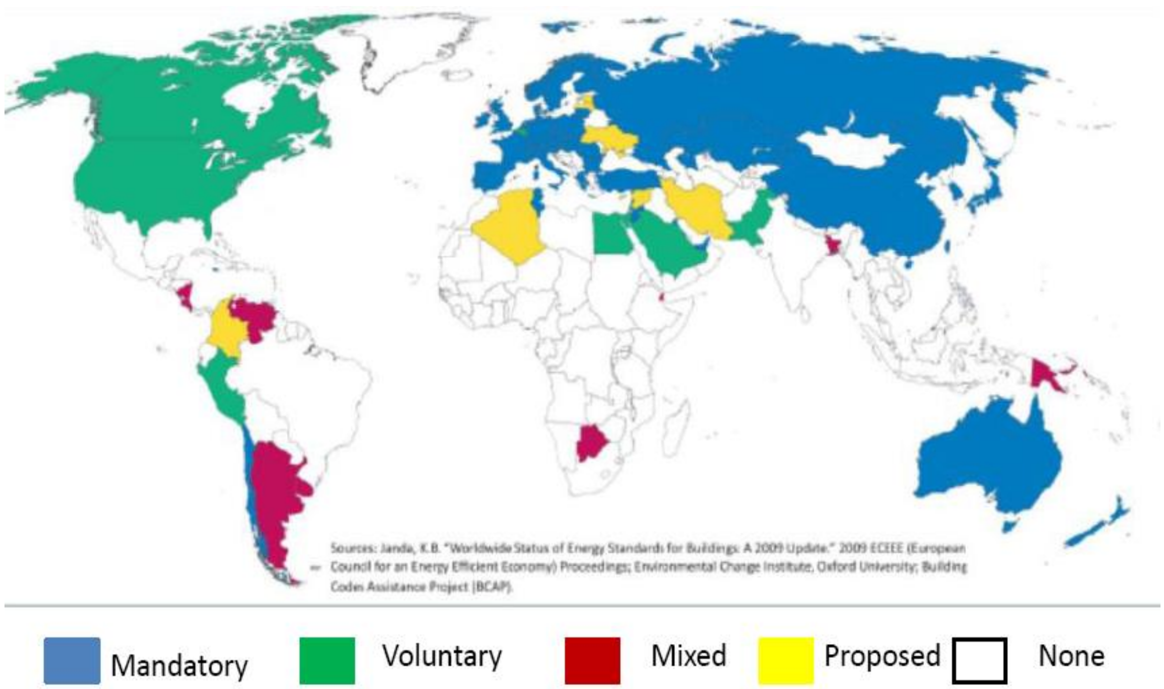


Figure 2.9 Energy codes for residential buildings in the world
Source: IEA 2013 [69].

In India, Energy conservation building code is in practice since 2007, framed under energy conservation act, 2001 and has been recently revised in 2017. It is being adopted increasingly by many states as an integral part of building bye-laws and is applicable to conditioned commercial buildings having a connected load of 100 kW or more. The current building rating systems in India are GRIHA, IGBC, BEE and they have developed criteria or credits and star rating systems for different levels of performances achieved by green buildings overarching various environmental sustainability parameters. To minimize negative impacts on the environment due to increased use of energy, various national agencies and state level urban local bodies are adopting higher thresholds of building performance gradually. Recently GRIHA- national green building rating agency, has revised point systems more sternly, giving higher points of reward to better performance target levels. Use of the 'whole building performance simulation' as a tool is a common practice to benchmark various key performance indicators at building levels such as energy performance index or energy use intensity or at building systems level such as lighting power density. Commonly used sustainability rating systems in India are discussed in the following section along with relevant sections for existing buildings for energy efficiency.

2.3.1 National policies and initiatives to achieve energy efficiency

In addition to various codes and green building rating systems, Govt. of India is taking up several initiatives by launching several policies and National missions to conserve energy and provide incentives to design and construct green buildings by means of subsidies in electric tariff, tax breaks, incentives in additional FAR to developers for making energy efficient green rated buildings and awards to architects. Various states in the country have voluntarily followed footsteps of national policies.

However, for all building typologies, where green buildings are being designed, not much attention has been paid to design and retrofit of residential buildings and therefore merit serious research and efforts to the largest share of land use in any city. Various electricity authorities have offered subsidies in electric tariff to users for using solar water heating systems or solar photovoltaic systems and it can be a booster for people to retrofit existing housing as financial benefits accrue directly to users [1].Property tax rebates are on the cards to adopt the green building practices for all building types. The Govt. of Haryana has recently revised all its building bye-laws and applied uniform building bye-laws titled 'Haryana Building Code 2017' across all development agencies such as HUDA, HSIIDC Housing board, town and country planning department. Use of solar water heating systems is mandatory in all building types having plot area more than 300 sqm [105]. Additional FAR for all building types except plotted residential buildings has been offered for installing solar photovoltaic plants Table 2.11 (A) and executing GRIHA rated green buildings Table 2.11 (B).

Table 2.11 (A) Incentives for installing a solar photovoltaic power plant

Generating power in respect of total connected load of building from the solar photovoltaic power plant	15-25%	26-50%	51-75%	76-100%
Additional FAR for all buildings (except plotted residential)	5%	10%	15%	20%

Table 2.11 (B) Incentives for implementing GRIHA rated green building

GRIHA Rating	1 star	2 Star	3 Star	4 Star	5 Star
Additional FAR for all buildings (e xcept plotted residential)	5%	10%	15%	20%	25%

Source: Haryana Building Code 2017 [105].

Similarly, another city NOIDA in NCR of Delhi announced an additional 5% FAR free of cost in 2015 to developers promoting green buildings or constructing green building certified by IGBC, GRIHA or LEED. Consequently, NOIDA has seen a spurt in the construction of green-rated real estate projects and townships. Various state governments have committed to construct all government buildings to be green buildings and retrofit their existing buildings. Thus the provision of additional FAR has bolstered the development of green cities, without requiring any financial outflow from government coffers. The Ministry of Urban Development is promoting all municipal administration departments of the state governments to implement ECBC and include revisions as per National building code for sustainability in their building by-laws [25]. To encourage increasing use of energy efficient materials, various state and central govt. construction agencies such as Public work departments (PWD) have also published a schedule of rates of various energy efficient materials such as AAC blocks, thermal insulation etc. and empanelled suppliers of energy efficient materials. Various Govt. agencies such as Building material Technology promotion council BMTPC , HUDCO, research organizations such as CBRI , Roorkee etc are engaged in research and promotion of innovative eco-friendly and high performance building materials and construction systems to save energy. With the increased supply of energy efficient materials and technologies leading to the decline in prices thereof, the payback period has decreased from seven years to two and a half year at the best and the incremental costs of retrofitting existing structures has dipped to 7-8% in 2015 from 16-17% of total cost of project in 2000 , thus providing congenial environment for promoting green building initiatives. In India, Bureau of Energy Efficiency and several state governments have taken steps to promote various Energy Service Companies (ESCOs) on lines of business models in western countries. These ESCOs provide technical expertise as well as incur financial investment in the project. The client and the ESCO enter into an energy performance contract and the investment is recovered by the ESCO from the project's savings. The central cooperative group housings in Dwarka, New Delhi have benefitted under Indo German partnership, Deutsche GIZ India in installing rooftop solar power plant without any capital investment [141].

In developed countries like the USA, policy tools for retrofit entail five key parameters such as the establishment of National benchmarks/goals for reduction in energy, incentive schemes, utility-funded energy efficiency programs, market development schemes, training and education programs [142]. Although rating systems in the USA are not mandatory, but has adopted Home Energy Rating System *(*HERS) index developed by Residential Energy Services Network (RESNET) as a national standard by ANSI American national standard institute in 2014 [143].

The HERS index is a measurement of home's energy efficiency. A certified RESNET rater conducts energy audit of home and evaluates its performance against the reference home. Certification is based on an energy audit that includes recommendations for improving the building. Financial assistance is also provided to undertake comprehensive efficiency retrofits. Lower the HERS index, more efficient is the house (Figure 2.10) A home with HERS index score of 70 is 30 % more energy efficient than RESNET reference home.

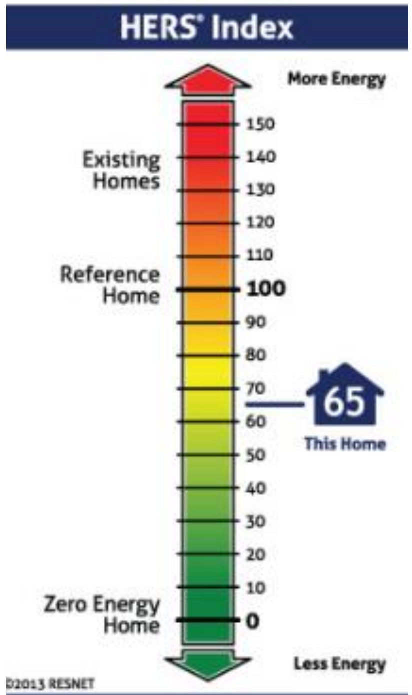


Figure 2.10 HERS index developed by RESNET in USA for energy efficiency of homes (RESNET, 2018) [143].

European countries have implemented various measures to retrofit existing houses and install smart meters and undertake carbon mapping at neighbourhood level or community level to monitor energy consumption compulsorily by 2019 and completely retrofit existing housing by 2030 to reduce greenhouse gas emission [144]. Energy performance certificate is required in the European Union whenever a residential property is being sold, acquired or rented out [145]. An EPC card carries out detailed information about a property's energy use with a rating from A (most efficient) to G (least efficient) and typical energy costs with recommendations to reduce energy use (Figure 2.11).

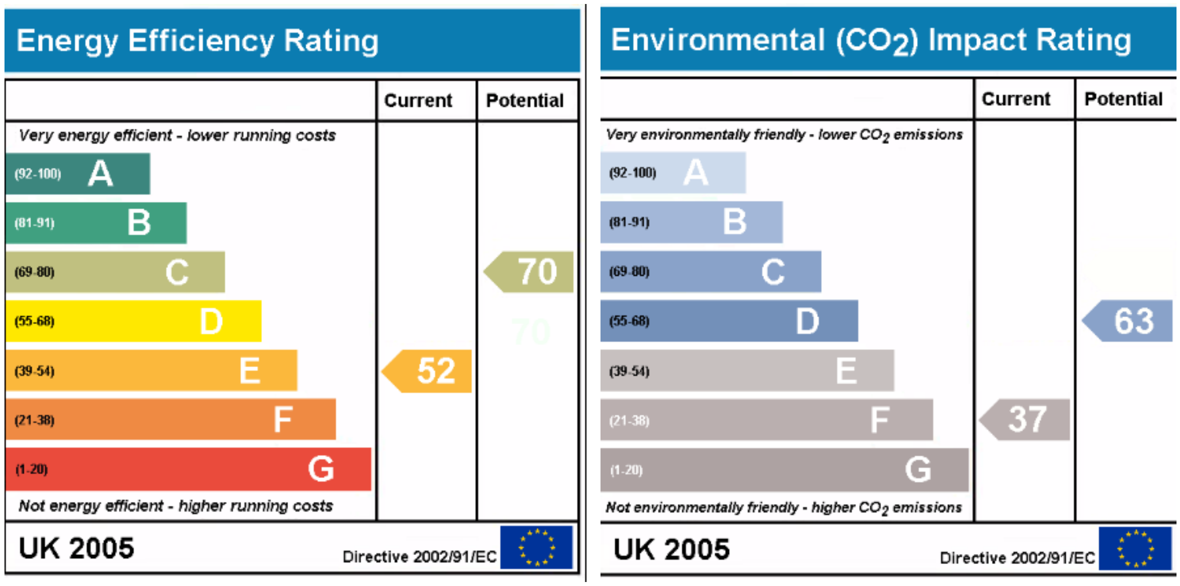


Figure 2.11 Energy performance certificate showing energy efficiency for housing in the UK [145].

In addition to financial funding, property taxes on single-family to four-family dwellings are exempted up to the amount that the improvements would increase the value of the home or by use of energy efficient equipment. Energy efficiency goals are reviewed every three years and upgraded, if necessary. There are specific provisions for residential buildings, taking into account their diversity and special needs. A scorecard based point systems are awarded to evaluate regulatory policy/measures with respect to national goals, revisions in building codes and labelling schemes, financial instruments such as incentives or taxation mechanism, economic instruments such as funding of retrofit schemes or market instruments, capacity building by training and education, establishment of one-stop shops and finally net result of all schemes in form of monitored results of achieved EPI/ capita or total electricity consumption.

The Govt. of India has emphasized for sustainable development of habitats in its Eleventh Five Year Plan as outlined in National Urban Housing and Habitat Policy 2007. It calls for inclusive, faster and sustainable housing for all by 2022, incorporating utilization of solar technologies, green technologies/energy preserving gadgets [146]. Also the Government has brought on grid net metering policy under the National solar mission to allow buildings and grids as active participants in energy production and consumption cycle. Thus various national and state policies play a pivotal role in shaping the cities clean and green by adopting energy efficiency measures. However it is paradoxical to note that not much attention is paid to frame energy efficiency codes specifically for new as well as existing residential buildings in India unlike developed nations, where they have been recognized as a key area of concern and continuously reviewed to monitor the progress.

2.3.2 National building code (NBC) 2016, Part 11 Approach to Sustainability

National Building code has been recently revised in 2016 to add sustainability as a major focus of new developments. It underscores design parameters to be implemented above benchmarking standards given in the code, develop a deeper understanding of the performance of building as per climate zone, function, context and imbibe from traditional wisdom concepts of sustainability. It further emphasizes building long-term scenario by identifying optimum levels and take decision making process of measurable level for making judicious choices over the life cycle of the project [28]. It also further focuses on balancing building envelope by eco-friendly materials and high technology end solutions, reduced embodied and operational energy. It also provides guidelines for integrated design approach, building orientation, shading, thermal massing, reduced footprint and reduced volume, building form, natural ventilation, optimum daylighting, building service life with life cycle analysis approach to be followed optionally. Section 13.4 of NBC, Building performance Tracking (Measurement and Verification) clearly spells out techniques of building performance assessment subsequent to commissioning and handover stage of building to the owner [28].

For renovation or addition and/or alteration to an existing building, part 11 of the National Building Code applies partially to such parts of the building. Building owners have been provided flexibility to be optional to get an existing building or part thereof evaluated for sustainability, but there is no specifically developed code or guidelines for retrofitting existing residential buildings in particular.

2.3.3 Energy Conservation Building Code (ECBC)

The Energy Conservation Building Code ECBC (2017), launched by Bureau of energy efficiency in 2007 under the Energy Conservation Act, 2001, provides significant parameters to reduce energy consumption for building envelope, electrical and mechanical equipment, lighting and service hot water heating for various climate zones of the country. The code is applicable to building complexes having a connected load of 100 kW or greater or a contract demand of 120 kVA or greater and is applicable to conditioned commercial buildings. It has categorised buildings in three categories; ECBC Compliant Building as mandatory for all buildings, ECBC plus Building, ECBC Super Building as voluntary standards for higher order of energy efficiency [114]. Although the code does not apply to residential buildings/ multifamily dwelling units, but it demonstrates an approach to energy efficiency by taking two approaches. The first approach comprises of prescriptive approach setting benchmarks for individual components and option of trade-off between sub-components and the second approach consists of 'Whole building simulation approach' considering EPI and unmet hours showing the total performance of the system by end use. Based on the EPI of whole building simulation approach, Bureau of Energy Efficiency (BEE), awards star rating to energy-efficient green buildings, thus also recognizes exemplary buildings [14].

2.3.4 GRIHA (Green Rating for Integrated Habitat Assessment)

GRIHA, designed as National Green Building Rating System and developed by the Ministry of New and Renewable Energy (MNRE) and The Energy & Resource Institute (TERI), was launched in 2007. It has undergone major revisions in 2015 to reflect the current scenario in green buildings and revised its benchmarks for meeting sustainability goals better. It integrates all relevant Indian codes and standards such as National Building Code, Energy Conservation Building Code, environmental policies of India (MoEF).

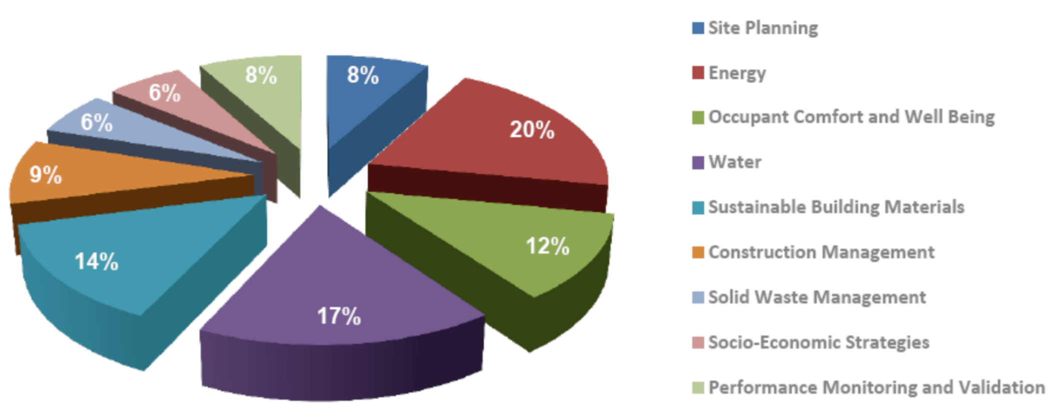


Figure 2.12 Pointwise breakup of various parameters in GRIHA Version, 2015.
Source: GRIHA Version 2015(2016) [119].

The GRIHA Version 2015 (2016) has listed 31 criteria in 9 categories as shown in figure 2.12 with the addition of two new subcategories namely Socio-Economic Strategies with 6% weight age; and Performance Monitoring and Validation with 8% weightage [119]. The parameters such as Criteria 12 Indoor air quality has been added to ensure healthy living conditions and entails monitoring of CO_2, temperature and relative humidity at the occupied spaces as per national standards. GRIHA has also defined EPI benchmarks for residential buildings/ Hostels as 70 kWh/m^2/year for composite/ warm and humid/ hot and dry climates and 50 kWh/m^2/year for moderate climates Also in order to achieve higher threshold a new concept of non-linear point distribution has been introduced as shown energy efficiency in Table 2.12.

Table 2.12 Non-linear point distribution for rewarding sustainability measures

Reduction from EPI Benchmark	GRIHA V 2015	GRIHA V3
10%	2	2
20%	3	2
30%	5	4
40%	7	6
50%	10	8

Source: GRIHA Version 2015 (2016) [119].

GRIHA Existing Building (2017) has been launched in 2017 for unlocking the potential of energy saving in existing buildings. GRIHA EB is applicable to all buildings having built up area more than 2500 sqm to optimize operation and maintenance O & M practices [147]. There are maximum points for energy efficiency covered under criteria 5 and 6 out of all twelve criteria, carrying 35% weightage as shown in Figure 2.13. Maximum points are awarded for percentage improvement in energy consumption over the base case i.e. 20 points are assigned for showing savings of 15% in energy consumption and implementation of O & M of simple energy efficiency measures. Criterion 6 promotes the use of renewable energy technologies and power generation on site and maximum of 15 points are awarded for offsetting 25% of annual total energy consumption by renewable energy generation in residential buildings [147].

However, GRIHA benchmarks of EPI have been observed to be quite high than most existing housing surveys/ baseline studies' EPI. So it would be relatively easier to show energy savings by developers without investing in any energy efficiency measure and obtain green building rating certificate. There is a need to revise the GRIHA benchmark as per realistic values.

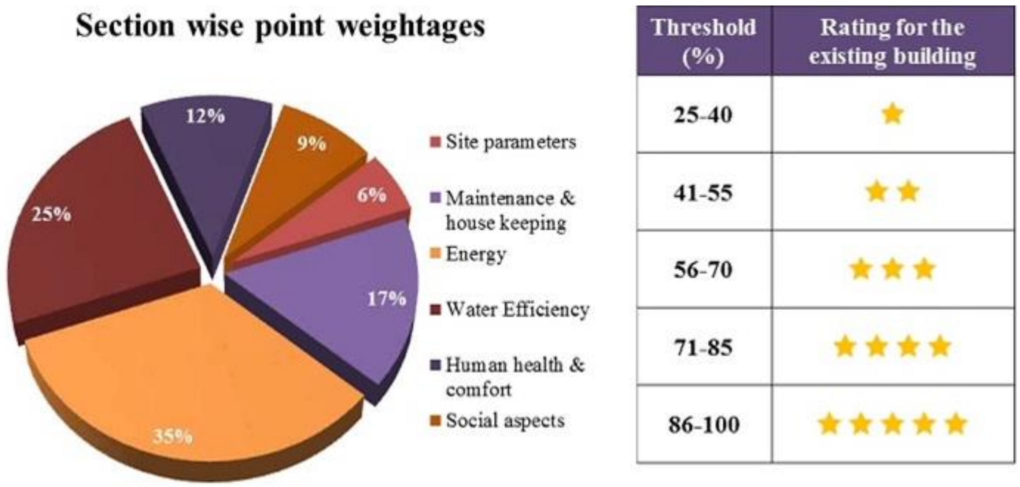


Figure 2.13 Point Weightage of different criteria in GRIHA Existing buildings [147].

Table 2.13 Points for a reduction in energy consumption in GRIHA EB, 2017

Criterion 5 (% Reduction in Energy Consumption in existing buildings		
SN	Residential Buildings	Points
1	3	2
2	6	5
3	9	8
4	12	11
5	15	15

Source: GRIHA EB, 2017 [147].

Table 2.14 Points for offsetting annual energy consumption by renewable energy GRIHA Existing Buildings

Criterion 6 (% Reduction in Annual Energy Consumption by renewable energy		
SN	Residential Buildings	Points
1	5	3
2	10	5
3	15	7
4	20	10
5	25	15

Source: GRIHA EB, 2017 [147].

2.3.5 IGBC Green Residential Societies Rating System

IGBC Green Residential Societies rating system 2015, has been recently launched in 2015, addressing existing multi-dwelling communities [148]. Indian Green Building Council (IGBC) is a voluntary rating system, developed on lines of an international rating system, LEED ((Leadership in Energy and Environmental Design) for existing building developed by the US Green Building Council. The credits / points allocated to different aspects of energy conservation in existing green residential societies rating scheme are shown in Table 2.15.

IGBC has also developed a special rating system for existing buildings 'Green Existing Building O&M Rating System' in 2013 addressing sustainability parameters and benchmarking for existing buildings. For reducing carbon footprint, it has defined performance-based benchmarks for EPI, use of onsite and offsite renewable energy and energy metering. For health and comfort, it mandates occupant surveys to be conducted every 6 months after commissioning and handing over buildings and monitoring for fresh air ventilation, CO_2 comfortable thermal environment at 26 ± 2^0 C and 30-70% RH.

Table 2.15 Credits for Energy conservation in Existing Multi-Dwelling Societies IGBC.

Energy Conservation 22 points		
EC Credit 1	CFC Free Appliances	3
EE Credit 2	Efficient Lighting Fixtures: 25, 50, 75, 95%	4
EE Credit 3	EC Credit 3 Solar power for street & Common Area Lighting: 20, 30 ……. 80%	7
EE Credit 4	Energy metering	2
EC Credit 5	Solar Water Heating Systems: 20, 30. …… 70%	6
Innovative Practices 14 points		
IP Credit 1.6	Day-Light / Motion Sensors in common areas	1

Source: IGBC Green Residential Societies rating system (2015). [148].

2.3.6 Eco housing, Pune

Eco housing has been developed by Pune Municipal Corporation as a special rating system for its new housing designs addressing sustainability parameters and benchmarking for existing buildings [149]. For reducing carbon footprint, it is a voluntary rating system and is based on 1000 point system. Energy conservation and management has been defined in detail and given the highest subscore of 240 points and will lead to environmental performance based benchmarks for the housing sector and their quantification. Power factor of 0.9 and more is kept under mandatory provisions, aiming to limit the line losses maximum by 10% in electrical distribution system. Similarly the integration of passive solar design techniques for thermal comfort are also kept under mandatory provisions. Among non mandatory provisions, use of renewable energy for common area and street lighting, renewable energy for meeting electricity demand, daylight harvesting, use of solar water heaters have been awarded points, but are voluntary in nature.

2.3.7 Overview of different Rating Systems

There have been major revisions and new categories introduced both within ECBC, IGBC and GRIHA in 2015, pushing the sustainability boundaries and setting thresholds to higher levels and encourage better practices in sustainability. IGBC has come up exclusively with rating systems for existing buildings O and M as well as for existing multifamily dwelling units. There is a major thrust on environmental parameters such as energy in both rating systems. There is a great variation between baseline and top line value of all rating systems. Buildings with a five-star rating in GRIHA and platinum rated in IGBC and BEE five stars rated are quite different in performance levels. Star rating systems of BEE focuses on energy consumption only and rely on ECBC as a tool to assess the performance of conditioned buildings, with its focus primarily for commercial and institutional buildings. The other rating systems such as IGBC and GRIHA focus on holistic measurement of different sustainability parameters, with energy as one component only.

Another major difference is the baseline case for both rating systems followed by base case modelling in ECBC and IGBC, whereas GRIHA prescribes absolute benchmarks for comparing proposed case and is easily understood. For example, the base case of EPI is kept at 70 $kWh/m^2/year$ for residential buildings for three climate zones (composite, warm and humid, and hot & dry climates). But GRIHA has more focus on passive building design, by promoting low carbon architecture as compared to high-performance building design to save energy in air conditioning in IGBC. GRIHA LD has a focus on both qualitative aspects as well as self-sufficiency in energy, water and waste. Renewable energy also finds more attention in GRIHA and addendum to NBC, part 11 for sustainability as compared to IGBC practices [150].

Although energy efficiency has been given the highest priority in all rating systems, but due to absence of energy codes suitable for residential buildings or high capital cost of energy efficiency measures, it is even possible to get platinum certification by IGBC or LEED without investing for achieving energy efficiency as can be seen in TZED housing (Zero Energy Development Project) developed in Bangalore in 2009 – a first platinum-rated LEED housing in the country.

Figure 2.14 TZED housing in Bangalore - first platinum-rated LEED housing in the country Source: En3, 2016 Case study: BCIL TZED homes. [44].

In another project Ansal Esencia launched in 2017– a five star GRIHA rated housing in Gurugram, the major thrust for reducing energy consumption is by BEE rated geysers and air conditioners and solar-powered street light instead of any improvement in building envelope for energy efficiency [151]. However, the GRIHA takes into account passive solar design building techniques, renewable energy, and occupant surveys in large housing complexes. IGBC has set guidelines for a rating of existing multifamily dwelling units. ECBC does not consider existing residential buildings. No single rating system addresses the core issues of retrofitting in residential buildings and hence there is a need to develop benchmarks for energy saving measures for existing multifamily multistoried residential apartments. The summary, overview of different rating systems and their focus area are presented in Table 2.16.

Table 2.16 Overview of different Rating Systems for Energy Efficiency

SN	Rating System	Area of Application	Type of buildings	Focus Area
1	BEE	New Construction and Existing buildings	Commercial	Reduction in EPI(operational Energy) Energy Efficiency 100 % weightage
				Base case modelled as per ECBC 2017
				Popular for Govt. Projects and institutional buildings. Referred to as Model Rating System
2	GRIHA	New Construction and Existing buildings	Residential/ Commercial	Energy Efficiency 35% weightage for existing buildings
				The absolute benchmark for EPI base case
				Focus on Passive design strategies, Low Carbon architecture, Less Embodied energy,
				Popular for Govt. Projects and Private Developers for all type of buildings.
3	IGBC	New Construction and Existing buildings	Residential/ Commercial	Energy Efficiency 30% weightage
				Focus on building design to save energy in conditioned buildings, Base case modelled as per ECBC 2017.
				Thrust on Occupant Surveys, Operation and Maintenance in energy savings
				Popular with Private Developers for Residential and Commercial buildings
4	Eco Housing	New construction and Existing Buildings	Residential in Pune	Energy Efficiency 24% weightage Absolute benchmarks for EPI
				Passive Solar Techniques mandatory, Focus on use of Renewable Energy Popular with Private Developers for Residential in Pune Municipal Corporation.

Source: Author

2.4 Building performance assessment tools for energy efficiency

Selection of retrofitting measures needs a deep understanding and systematic analysis of existing buildings. The various steps involved in the retrofit range include delineating the problem, mapping users aspirations, selecting the most cost-effective retrofit technologies from design parameters and its optimisation, implementation of strategies for achieving low energy and yet acceptable indoor thermal comfort and indoor air quality. Despite a wide range of retrofit technologies widely researched, it is challenging task to identify the most cost-effective, practically feasible and non-intruding retrofit measures, particularly for residential projects in climatic context [47]. Tools for assessing building performance measurement include pre-retrofit occupant surveys and making baseline data, energy audits, performance gap modelling from existing standards, building performance simulation modelling by making base model or as is case , calibrating for measurement and verification, quantification of energy savings, life cycle cost analysis (LCCA) for selecting cost-effective technologies. The following sections discusses various tools in detail as under.

2.4.1 Pre Retrofit Occupant Surveys

In order to understand characteristics of existing residential buildings within domains of sustainability framework, findings from occupant surveys act as a vital resource to form baseline data of energy consumption pattern for a particular context taking in account people's aspirations and local specific context of the study area. Post-occupancy evaluation studies carried out under normal daily life routine of subjects, with their entire psycho-behavioural, environmental and social context, can serve as feedback and feedforward loop to continually evaluate and evolve relevant sustainability indicators [48]. Post-occupancy evaluation surveys are more helpful in addressing sustainability issues as they can best provide candid account of wider variations or high diversity factor found in case of residential buildings in terms of occupant occupancy pattern and their concerns, occupant background in terms of age, family structure and income level etc. , architectural features of building envelope, window opening schedules, use of appliances , user expectations of indoor thermal comfort and satisfaction and as well as wide variations in energy use, even within buildings of similar built-up area and building geometry within the same location

[149]. Findings from POE surveys can be useful to bridge the performance gaps as invariably buildings are not found to perform as expected and enable the use of realistic parameters to produce realistic models for sustainability [152, 153, 154, 155]. As outlined in National Building Code of India 2016: Part 11, Approach to sustainability, it is required to conduct occupant surveys annually for first three years of building operation for obtaining feedback from users subsequent to commissioning and handover stage of building to the owner [28]. Field-based occupant surveys can play a vital role to establish sustainability indicators, benchmark their performance against national standards or rating systems and find out how much gap is extant between their performance and desired levels for mixed mode ventilation multistoried apartments in National Capital Region of Delhi. Occupant surveys can thus be used to develop building baseline data for window operating schedule, occupancy schedule, equipment usage schedule, air conditioning use schedules, lighting fixtures operating schedules in addition to types of various materials used in windows, star rating of air conditioners, power consumption of appliances and lighting fixtures, fans etc and their controls. This data is a necessary to input for a better understanding of building operational problems and the main concerns of occupants and provides significant inputs for modelling in building performance software. Inverse modelling technique has been used to know the input parameters required for building performance simulation modelling. A better understanding of input variables helped elicit the information from the sample subjects in the form of field-based research instruments such as questionnaires and instrumentation for thermal mapping.

2.4.2 Energy Audit

As per Energy conservation act 2001, “Energy audit is defined as "the verification, monitoring and analysis of the use of energy including submission of a technical report containing recommendations for improving energy efficiency with cost-benefit analysis and an action plan to reduce energy consumption". An energy audit is a tool to understand how energy is used and to find out measures to save energy or to improve energy efficiency [50]. Thus energy audit is the key to a systematic approach for decision making in the area of energy management with the objectives to minimize energy costs, reduce energy wastage without affecting the quality and to minimise environmental effects [51].

Energy audits for retrofitting projects have been mandated by several countries and serve as a useful tool for long-term building renovation planning. Energy audit directly benefits housing owners to reduce energy cost as well as reducing carbon footprint [52]. As energy audits provide information on a real-time basis, thus can help in demand side management. Energy mapping can be conducted at community level by adding knowledge of existing energy use intensity of a neighborhood, sensitizing community about comparative energy consumption of different households, introducing concept of benchmarking within communities and competitiveness with other communities (external benchmarking), identifying energy consumption in community buildings and common services and trend analysis [53]. An energy audit is also helpful in performance monitoring and labelling systems for buildings or societies or green building rating systems such as GRIHA LD or IGBC existing multi-dwelling housing societies. In the UK, energy use mapping has been carried for 1300 households in five low carbon communities for improving the energy efficiency of their housing stock by displaying estimates of energy use and carbon emissions before and after community action. Assessment of incremental packages of energy-saving measures and finding the potential for large-scale refurbishment in the local area enabled funding by National Green Deal program of UK by offering up-front loans for energy savings [53]. Thus energy mapping helps people or owners to have awareness about energy efficient measures and serves as good platform for reducing demand supply management, fixed energy consumption, variable energy consumption, peak time period, seasonal variations etc. and for even effective tool in changing attitude and behavioral pattern of people in energy use [156].

WBDG (2016) has cautioned that energy calculations from simulation software cannot precisely predict actual energy consumption. Factors such as construction quality, occupancy schedules, and maintenance procedures may vary markedly from assumptions contained in the analysis and skew results. Thus energy audits of existing buildings are really important in the understanding of energy consumption of different design typologies or variation in different design parameters [54].

Different levels of energy audits are conducted depending upon the purpose of an energy audit. ASHRAE has identified four levels of energy use analysis such as Benchmarking level audit, Walkthrough audit, Detailed/General energy audit, and Investment Grade Audit.

Benchmarking level comprises of preliminary Whole Building Energy Use (WBEU) analysis based on the analysis of the energy bills and comparison of the performances of the buildings to those of similar buildings. Walkthrough audit involves preliminary analysis to identify not only simple, low-cost improvements, a list of energy conservation measures et al and based on a visual survey of the study of installed equipment and operating data and electricity bills. Several energy audit software such as EMAT or ETAP have been used in residential energy audits for an efficient and economical way of conducting an energy audit and reduce costs for all phases of the audit [157].

BEE (2014) in framing design guidelines for new multi-storey residential buildings in composite and hot-dry climates, carried out energy audit for the one-year duration for 732residential units from four residential complexes in Delhi–NCR in 2009. The selected residential complexes were multi-storey apartment buildings of 3 to 15 storeys, with a built-up area of individual flats ranging from 80 m^2 to 130 m^2. However, this energy consumption data cannot be taken as a basis for present study due to time gap of almost seven years and increase in EPI due to changing lifestyle and increased appliance ownership and expected comfort level in cooling. Also the approach 'one-size-fits-all' is not appropriate and has to account for differences in different places and income groups. Energy audits can be integrated with on-site measurements, occupant surveys and interviews. Data analysis of energy audits and occupant surveys can serve as a most effective tool in understanding variations in user behaviour, building envelope parameters occupational schedules equipment operating schedules, appliance ownership, seasonal variations and age of the home etc.

National Building Code in part 11 Approach to sustainability has emphasized on monitoring of technical and energy performance after occupancy by energy metering for energy consumption end use in lighting (Exterior and Interior),air conditioning, domestic water heating, renewable energy systems, water pumping, elevator and plug loads separately by using Energy Management and Control systems (EMCS) [28].

Energy audits assume a significant role as the target of achieving energy savings in buildings till date remains a small fraction of the overall potential of the building sector. The success of building energy efficiency standards lies in collecting real-time information, identifying benchmarking levels and setting thresholds for different climatic types. Energy audits can also lead to conceiving of net-zero buildings or nearly net zero concepts or even next level i.e energy plus residential clusters.

2.4.3 Performance Gap Modeling

Sustainability indicators for each of the dimensions of the existing housing study area are to be compared with base case developed using maximum and minimum threshold values of sustainability indicators. The maximum value of a particular sustainability indicator is derived from the best case scenario and worst value is determined from the worst case scenario [135]. Mapping of standardised indicator values is undertaken on the radar showing hypothetical best case scenario and proposed case or 'as is' case as shown in Figure 2.15 The distance between the two values indicates the gap in the performance of a particular project. It also reflects that which areas are needing more attention and which areas of interventions need special attention or no attention.

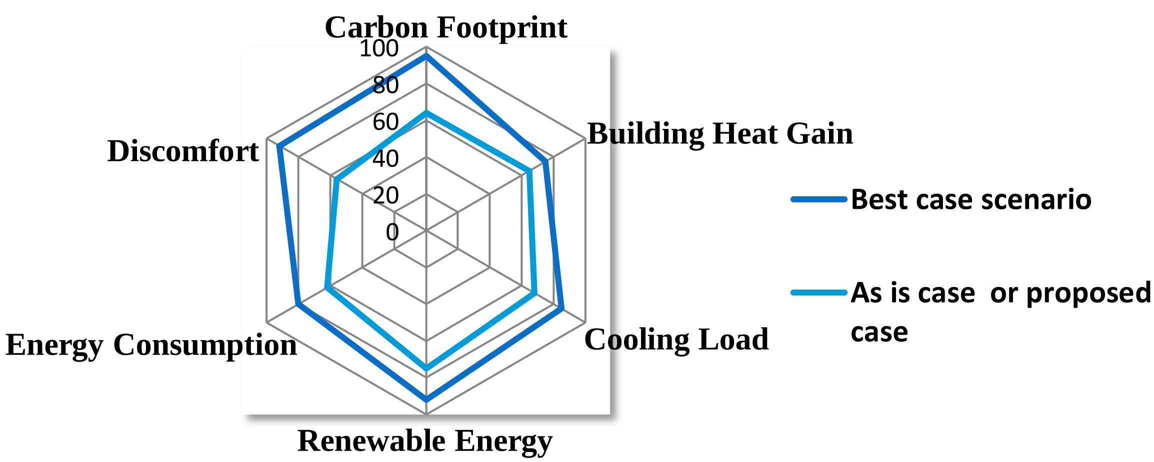


Figure 2.15 Benchmarking Urban Sustainability
Source: Author

2.4.4 Life cycle cost analysis

The main goal of Life Cycle Cost Analysis is to determine cost optimal solution out of different alternatives and hence optimization of retrofit measures. One can check whether retrofits for energy efficiency in existing buildings is more cost-effective than investing in renewable energy in nearly net zero or net zero residential buildings. There are various methods such as payback method (capital budgeting method), Net Present Value, Internal Rate of returns. Capital budgeting method is the most commonly used in which the financial viability of several energy-saving design options by only using the simple payback period method. Net Present Value method is the most reliable method to calculate the payback period. It takes into account discount rate (interest value) of money as well as inflation to account for the realistic value of savings. Various authors have researched on life-cycle cost analysis of energy retrofits and have included demolition cost, replacement and installation cost, annual maintenance cost [47, 73,158,159,160,161,162].

Life cycle energy analysis accounts for all energy inputs to a building in its life cycle while carbon footprint accounts for embodied energy and operational energy [163,164,165,166,167]. In a study on five Belgian houses, building performance tools such as simulation and net present value method is employed to suggest roof insulation, better performing glazing and efficient heating system and floor insulation [168]. Maleki 2009 demonstrated energy savings between 10% and 30% of pre-retrofit energy use by window retrofits and heating equipment retrofits using payback method Residential buildings possess many characteristics which can complicate the application of LCCA methods, such as the diversity in use, human behavior, adaptive opportunities, other uncertainties [169]. Existing Database needed to analyze life-cycle cost analysis for retrofitting buildings using modern materials/technologies have limitations in terms of available data of cost input parameters and life expectancy of different material/ systems.

2.4.5 Building modelling and simulation

Building performance dynamic simulation is the most reliable way to predict energy consumption and other key performance indicators. Building performance models take into account the complex interaction of different factors such as external heat gain through envelope as per weather file, site geometry, orientation, building materials, activity pattern, clothing and occupancy schedule, hot water, lighting, air conditioning systems used.

Currently, building performance simulation models compute carbon footprint, life-cycle cost analysis in addition to generate reports to check compliance with norms of green building rating systems. It is through computational building performance simulation that we can study various constructs of energy consumption with dynamic boundary conditions (complex and transient conditions of thermal heat transfer of building envelope) in a realistic way. The Whole building performance simulation is the major tool prescribed in energy codes ECBC 2017 for comparing effects of sometimes conflicting passive energy-conserving techniques including thermal loads, thermal mass and natural ventilation in composite climate for making rational choices of appropriate building envelope for reducing energy consumption.

ECBC 2017 has prescribed a list of software for the whole building performance simulation and daylighting analysis. There are a number of tools available in the profession for simulating building performance to facilitate early decision, detailed design wizard for taking a decision, parametric analysis of design parameters. The US DOE (Department of Energy) has listed building software tools for simulation [137]. Various software for building performance in mixed mode residential buildings are compared in Table 2.17.

Table 2.17 Comparative overview of Building Performance Simulation Tools

SN	**Parameter**	**IESVE**	**Design-builder**	**eQuest**	**Autodesk Green BS**	**Energy plus**	**Transys**	**Econirman**
1	Graphical representation of output	●	●	●	●	X	●	●
2	Short learning curve period	X	●	●	●	X	X	●
3	Graphical representation of input	●	●	●	●	X	X	X
4	Creation of comparative reports	●	●	●	●	X	●	X
5	Quality control of simulation	●	●	●	X	●	X	X
6	Allowing default values	●	●	●	●	X	●	●
7	High model resolution	X	●	●	●	X	●	X
8	Allow Renewable Energy system	X	●	X	●	●	●	X
9	Allow energy cost +LCCA	●	●	●	●	●	●	●

● Included

X Not included

Source: Attia, S.(2010), ECBC (2017) [170,14].

Designbuilder software version 5.01.024 has been chosen for building performance simulation modelling for the reason of enabling modelling in mixed mode operation of residential buildings and a very user-friendly graphic interface of building modelling. The software uses energy plus DOE simulation engine for design algorithms. It can provide outputs in short frame of time and one can model at the early design stage or detailed model in the final design stage, which can be-be helpful in modelling different alternatives and comparing building performance indicators at any stage [171].

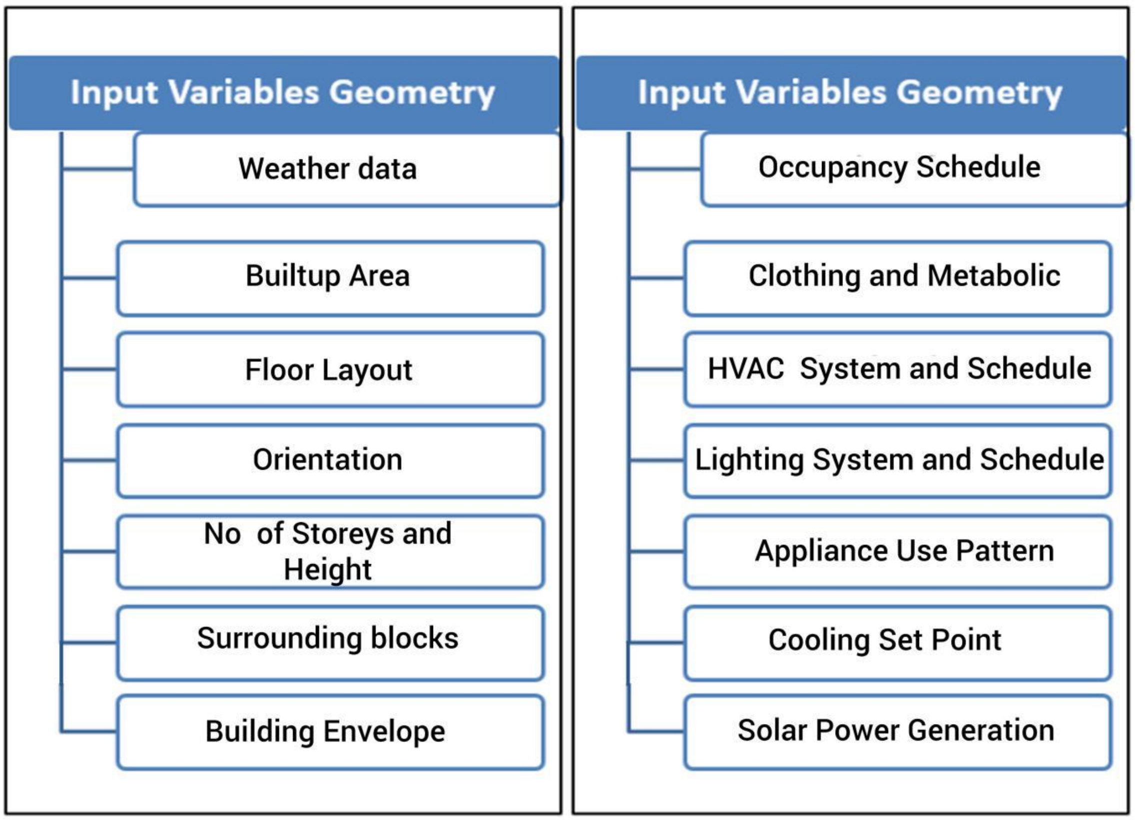


Figure 2.16 Design input variables in Designbuilder software [171].

There are two types of inputs variables The first type relates to Weather data, Building floor area, geometry, orientation, building envelope details, No of storeys and surrounding blocks, ground conditions etc. The second type takes into account input variables related to use of building such as occupancy pattern, clothing, metabolic, activity pattern, HVAC schedule, lighting schedule, appliance use pattern and cooling set point (Figure 2.16). The analysis can be run for daily, monthly, hourly basis for all 8,760 hours in the year.

In the case of existing buildings, as is model is developed to from a baseline model which behaves like monitored known performance of existing building. Calibration of the model is done to match internal temperatures of zone level and energy consumption at the monthly level. Finally, the calibrated model is simulated for gauging the effect of various Energy conserving measures (ECMs) and to evaluate the effects of each design parameter. The International Performance Measurement and Verification Protocol (IPMVP) provides an option D for calibration of the simulation model on the basis of energy consumption [172]. The mean bias error (MBE) and the coefficient of variation of the root mean squared error Cv(RMSE) are calculated for simulation data and observed measured data to determine 'best fit' between calibrated energy model and utility data. The values of the coefficient of variation of the root-mean-squared error Cv(RSME) is used to gauge the validity of the model. The lower the Cv(RSME), better is the best fit relationship between the simulated model and real-time data. Permissible Range of MBE and Cv(RMSE) in IPMVP and ASHRAE are as per shown in Table 2.18

Table 2.18 Permissible Range of MBE and Cv(RMSE) in IPMVP and ASHRAE

Calibration basis	INDEX	IPMVP (%)	ASHRAE 14 2002 (%)
Monthly	MBE monthly (%) CV(RMSE monthly)	±5 15	±5 15
Hourly	MBE hourly (%) Cv(RMSE hourly)	±10 30	- -

Source: IPMVP 2012 [172].

High variations in the simulated model and monitored data account for uncertainty in the building performance model as no model can replicate actual monitored data. The model is best used for comparative analysis of different indicators such as EPI or zone operative temperature. There are a lot of variables in the real world due to variables like Climate or weather conditions of a particular year, site landscape, green cover, surrounding trees, occupancy pattern of people, building activity pattern etc. The model may be seen as a probabilistic model than the absolute deterministic model.

2.5 Knowledge Gaps in research

The literature review carried out for understanding state of art of contemporary theories and the best empirical practices for bringing energy efficiency in existing housing yielded to define the knowledge gaps, which needs to be addressed. Despite the largest footprint of residential buildings and the highest share of energy consumption, there is no focus on the existing stock of residential buildings. The major knowledge gaps are summarised as under:

- There are very limited studies available to understand adaptive opportunities and energy consumption pattern of residential apartment buildings with a view to achieve energy efficiency. A study has been undertaken GBPN in 2014 to develop residential data but recommended that it needs to be expanded with the larger database. There is a large time gap of baseline studies conducted by BEE since 2009. The average EPI arrived in these studies are no longer valid due to several factors like changing lifestyle and increased appliance ownership and expected comfort level in cooling.

- There is a lack of data on housing built up area, construction materials used, occupant schedules, appliance ownership and usage pattern etc. There is a need to develop residential baseline data for targeted reduction in energy consumption.

- Whereas it is vital to measure energy consumption by end use in different residential apartments so as to gauge energy consumption trends on a real-time monitoring basis, but little work has been done in this direction. Despite multiple policy documents in practice and mission guidelines and the largest carbon footprint of residential buildings, there are no codes developed for retrofitting existing residential buildings.

- Energy Conservation Building Code (ECBC), has its focus on commercial or institutional buildings which are air-conditioned. The code has defined occupancy schedules for different building typologies for defining standard case or base case. And it helps designers to ascertain improvement in energy efficiency by comparing EPI of the base case and proposed design by using a whole building simulation approach. On similar lines, there is a need to develop baseline data for developing occupancy schedules, lighting schedule, appliance usage schedule to enable benchmarking of proposed energy efficiency improvement model over 'As is' case.

- There is a little research in defining energy performance index for mixed mode buildings in residential buildings. Energy Conservation Building Code (ECBC, 2007) does not deal with energy performance index specifically for residential buildings. Other rating systems in India such as GRIHA and IGBC cross-refer to NBC for thermal comfort and have also incorporated ASHRAE 55 and India model for adaptive comfort [14]. However, IMAC delineates thermal comfort for mixed mode buildings in general, but not for residential buildings in particular.

- The current building rating systems in India are GRIHA, IGBC, BEE and they have developed criteria or credits and star rating systems for different levels of performances achieved by green buildings, but do not directly address parameters for retrofitting existing buildings for energy efficiency per se. A minimum benchmark of EPI of 75 kWh/m^2/yr (with 25% improvement over the base case of 100kwh/m^2/yr) has been fixed in new residential buildings in hot and dry or composite climate [46]. The improved benchmark prescribed by GRIHA is already higher than average observed data of energy use intensity of current population living in multistoried group housing schemes, implying thereby that without using any energy efficiency measures, all housing schemes will fall under energy efficient category and need no improvement. But this is not the case, thus there is a need in the revision of GRIHA benchmarks.

- Residential building primarily uses mixed mode ventilation i.e. they use both natural ventilation and air conditioning system depending on day use pattern and weather conditions. There is a high diversity factor in occupancy pattern and user behaviour in residential buildings. Field-based occupant surveys along with thermal mapping of buildings can be integrated with energy use metering to bridge the gap in understanding energy consumption pattern, building performance and user satisfaction in mixed mode operation of buildings. Despite National building code, 2016 emphasizing on building performance tracking and monitoring, energy audits and occupant surveys, occupant surveys have not been conducted so far under any regulatory framework of states in India.

- The housing schemes which have been green rated in the recent past score almost minimal on energy efficiency parameters of rating systems. TZED housing in Bangalore, India awarded Platinum rating by LEED, has the least score on energy efficiency as compared to other parameters of rating scheme [44]. Another project awarded five Star rating by GRIHA again does not dwell on Whereas energy efficiency parameters carry maximum weightage in rating systems in India, but it is hard to score on energy efficiency parameters without taking good measures for improving energy efficiency, Thus near absence of real-life examples of multi-storey group housing schemes having energy efficiency or retrofits in existing housing schemes forms a knowledge gap in building industry.
- There is a very limited research on parametric values of various design parameters of building performance assessment in residential buildings [1]. Recently there has been a trend of use of large glass panels even in residential building across India, irrespective of climatic context, leading to increased use of energy in air conditioning them for achieving thermal comfort. In many countries, the concept of Overall Thermal Transfer Value (OTTV), limiting heat gain to fabric to 35 W/ sqm prevails for better design of buildings and has been part of mandatory building approval rules, whereas, in India, there are no such mandatory provisions in building codes [55]. There exists knowledge gaps on parametric analysis for the mixed mode residential building. Developing a detailed understanding of various parameters will lead to developing a roadmap for retrofitting of existing housing by a reduction in energy.
- Adaptive opportunities available to residents and high level of diversity in use of buildings by different age groups, lifestyle and awareness of energy consumption accounts calls for more in-depth studies so as to work out energy demand for existing housing as residential buildings are having the largest footprint in any city and consequently have the largest share in energy consumption for meeting thermal comfort. There exists a knowledge gap to understand opportunities of adaptive behaviour and energy consumption with respect to mixed mode residential buildings.

- Various initiatives like solar harvesting, integrated building photovoltaic systems, rooftop solar projects, net metering or smart metering, solar street lighting etc. have come up due to which the role of buildings is changing to energy producing than energy consuming, thus even generating energy plus buildings or net-zero buildings in the process. In the wake of near absence of real-life examples or prototypes of net-zero multi-storey group housing schemes, clarity on a policy of net metering and life-cycle cost analysis thereof, there is a knowledge gap and barrier to implementing ambitious schemes of the government.
- Despite a wide range of retrofit technologies widely researched, it is challenging task to identify the most cost-effective climatic specific, non-intruding and practically achievable retrofit measures, particularly for residential projects [47]. Results for assessing building performance measurement should be integrated with life-cycle cost analysis (LCCA) for selecting the cost-effective technologies.
- WBDG (2016) has cautioned using results of energy calculations from simulation software as factors such as construction quality, occupancy schedules, and maintenance procedures may vary markedly from assumptions contained in the analysis and skew results. Thus energy audits of existing buildings provide a real-life example and provide information on a real-time basis in checking energy consumption [54].

There exist knowledge gaps or barriers due to the absence of real-time information (energy utility data) of consumers and authorities, quality standards, funding opportunities and trained manpower, knowledge of energy saving opportunities in the implementation of retrofit projects.

2.6 Conceptual framework for Retrofitting

Having conducted state of art of literature review and study of best practices, a conceptual framework model is prepared to conduct the research. It was analysed that the retrofitting measures to be taken can be classified in two or more than two scenarios. Immediate efforts can be undertaken for the easily achievable results i.e. with low hanging fruits. The other scenario can be built up using high up hanging fruit, but needing time and investment, which can be done in a phased manner. Remeasuring building performance after retrofitting can lead to better understanding of the subject and further innovations as indicators are a means to achieve the objectives and are not an end in themselves. Thus the conceptual framework model identified for working out indicators for assessing energy efficiency of existing residential multistoried buildings, shall involve the following steps

a) Assess existing residential building from electricity utility bills
b) Conduct occupant surveys to establish energy usage pattern and the indicators which are relatively important
c) Developing residential baseline data for assessing the current performance of residential buildings or complexes. It may include standardized plan typologies, construction specifications, building envelope parameters, operational schedules, plug loads, energy data
d) Analysis of thermal mapping by data loggers to validate occupancy pattern of users and calibration of the model.
e) Building performance simulation modelling, Preparation of templates, occupancy schedules, calibration of the building model in sync with baseline data
f) Study effect of various selected design parameters on key performance indicators
g) Scenario building and identifying retrofitting measures,
h) Integration with a Lifecycle cost analysis to recommend the most feasible scenarios.

2.7 Summary

This chapter attempts to provide a state of art of literature review and theoretical framework to define a research problem and develop research methodology. The literature review summarises findings from different research areas to establish design parameters, key performance indicators, benchmarks in existing residential building and finally building performance assessment tools. Inverse modelling technique is used to understand various input parameters required for building performance simulation model. In view of rather limited studies on the energy consumption pattern of existing housing and high potential of reducing energy consumption, the subject area merits attention and further research.

THE CONTEXT OF GURUGRAM

3.1 Introduction

This chapter provides an overview of the Gurugram, its development plan, legislative framework and trends in residential development, introduction to characteristics of the sample population. The chapter explains how Gurugram provides an ideal context for study to prove the research hypothesis. It discusses in detail the selection criteria of study cases, overview and characteristics of different multistoried housing schemes chosen for case study. This chapter further presents a climatic analysis of Gurugram based on weather data and outlines climate-specific design interventions appropriate for retrofitting of existing housing.

3.2 City Profile

The research study has been carried in context of the city of Gurugram- in National Capital Region of India of Delhi, located at 28.46° N, 77.02° E at an altitude of 217 m above sea level. Gurugram is a satellite town located 32 kilometres south of National Capital Territory of Delhi, bound by Delhi on North, Faridabad to east and Rajasthan on south and Rewari on west boundary. The city is linked strategically with National Highway NH8 from Delhi to Jaipur, Northern and Southern peripheral Kundli Manesar expressway with a metro link to Delhi and close proximity to the domestic and international airport of New Delhi.

Figure 3.1 Location map of Gurugram (Source: property.magicbricks.com, 2016) [173].

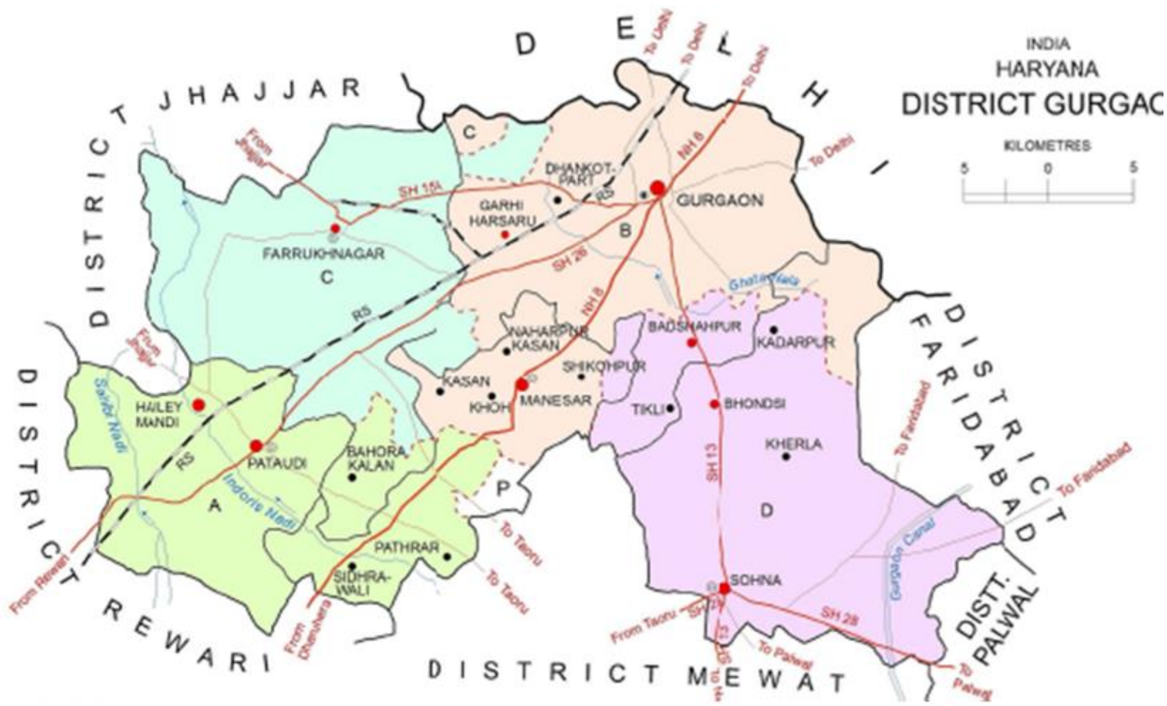


Figure 3.2 Boundary of Gurugram Source: Census 2011 [55].

The city of Gurugram, one among India's fastest growing urban centres is also known as Millennium city – a hub of information technology (IT) sectors, multinational companies, industries, thus fuelling demand for residential areas. The city's strategic connectivity, quality of real estate developments coupled with proactive government policies have helped it to grow faster than any other competing suburbs of Delhi. Gurugram is the second largest township in Haryana, having a population of 9,77,387 [55]. The city has witnessed rapid urbanization and high population growth (population growth rate of 14.7% p.a. From 2001-2011 and projected growth rate of 8.8 % from 2011-2021), being the highest in the National Capital Region of India, Delhi [174]. It lies in hot arid climate zone having steppe (Bsh) as per Koppen international climate classification and composite climatic zone as per classification of National Building Code, 2016 [28].

As per the District Census Handbook (2011), the literacy rate in Gurugram is highest in Haryana state (84.7 %) and the share of the workers to the total population (Work Participation Rate) in 2011 was 36% [175]. Gurugram is classified as Service town as a major share of the total working population (81.4 %) is engaged in tertiary sector (commercial activities, tourism and related activities), only 3.3 % of the working population is engaged in the secondary sector (industrial activities) and 15.3% population is engaged in the primary sector (agriculture and allied activities) [55].

The Development Plan for Gurugram catering to a population of 42.5 lacs in 2031 spread over 338.72 sq km [176]. The city is divided into 118 Sectors with 16021 ha of residential areas, developed on the neighbourhood basis average net residential density of 250 persons per hectare (Figure 3.3). The city is planned by town and country planning office (TCPO) and developed in its initial phase by Haryana Urban Development Authority (HUDA). Due to its strategic connectivity and proximity to National Capital, the city developed on public-private partnership model (PPP) as a priority destination for upcoming multinational companies during liberalization period from 1990, giving a quantum boost to rapid growth in real estate in terms of the residential, commercial and retail hub, fuelling the growth of residential development. With the advent of the private developers in residential buildings from 1981 onwards, the city gained momentum in terms of growth of the residential development.

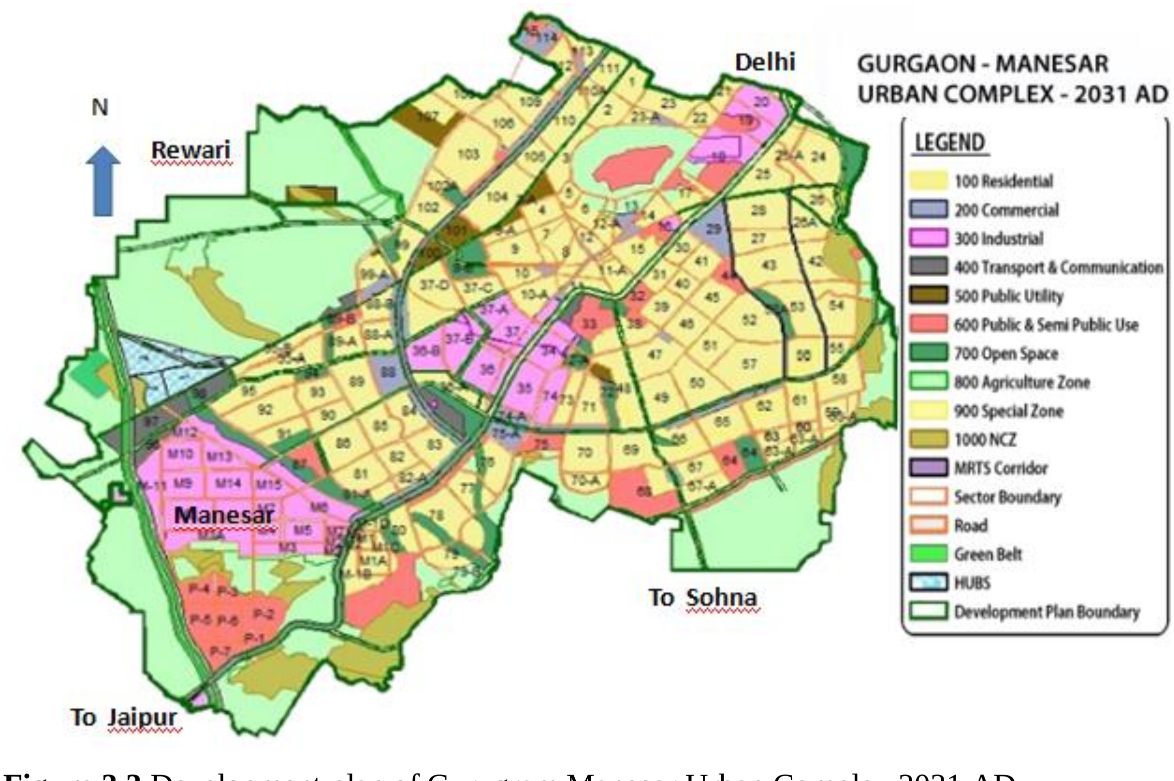


Figure 3.3 Development plan of Gurugram Manesar Urban Complex 2031 AD
Source: TCPO Gurugram [176].

As per land use plan of development plan of Gurugram, the residential land use constitutes 48.56% of total land use, implying a relatively high residential land use as compared to residential land use delineated as 35-40% of total land in large cities, metropolitan cities and megacities in Urban and Regional Development Plans Formulation & Implementation Guidelines [26].

Table 3.1 Landuse distribution of Development plan of Gurugram -2031

S. No.	Land use	Area (ha)	% area
1	Residential	16021	48.56
2	Commercial	1616	4.89
3	Industrial	4613	13.98
4	Transport and Communication	4428	13.42
5	Public Utilities	608	1.84
6	Public and semi public	2027	6.14
7	Open spaces	2928	8.87
8	Special zone	114	0.34
9	Defense land	633	1.91
	Total land	32988	100

Source: TCPO, Gurugram [176].

The city of Gurugram primarily consists of four parts: Gurugram town, area developed by HUDA, area developed by private developers and urban villages (Figure 3.4). The major development of residential areas is carried out by HUDA through public group housing schemes, cooperative group housing societies and plotted development, the private builder housing consists of plotted development in licensed colonies, villas, floors and group housing schemes. From the last two decades i.e. 2000-2018, development through public-private partnership model has given rise to a boom in housing from 1985-2015.

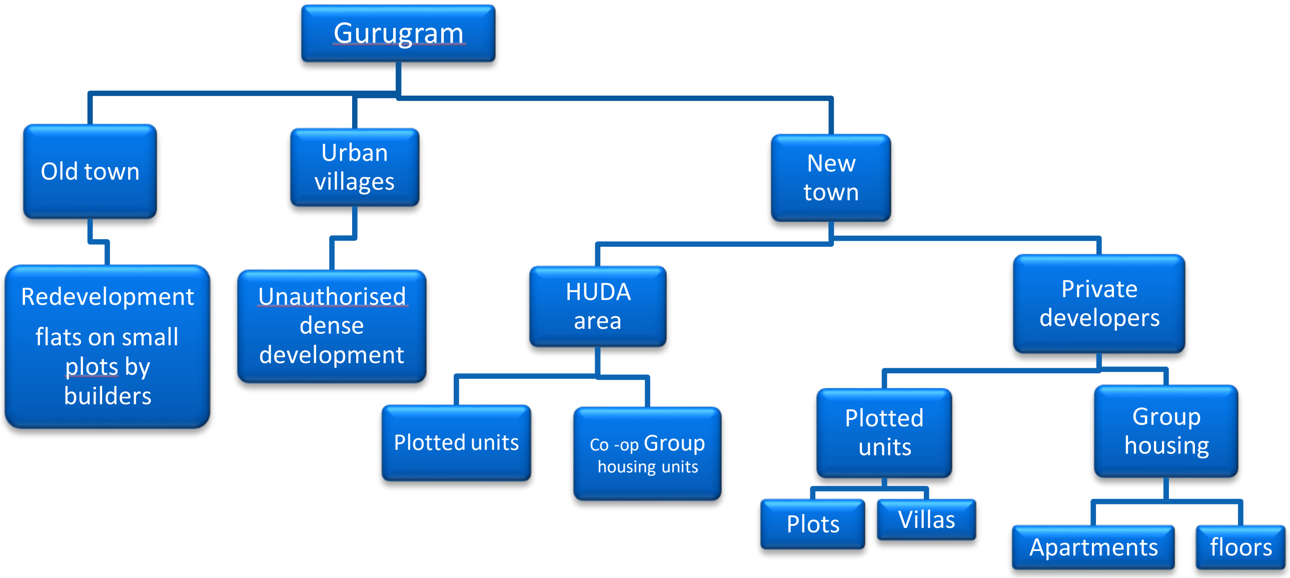


Figure 3.4 Gurugram Urban Area Profile

The colonizers' share has grown from 0% in 1985 to 54% in a time period of 30 years and is likely to increase sharply now. Private developers are emerging as major developing bodies and have superseded HUDA. Due to high land prices in Gurugram and less affordability of people to invest in plotted units, multistoried group housing schemes has emerged as popular choice among users. The share of multistoried flats have gone up to 68.43% of total no of dwelling units developed in 2015 from 44.28% of total no of dwelling units in 1999 as illustrated in Table 3.2.

Table 3.2 Residential Area Development by the Agencies (1985-1999) and (2000-2015)

Type	Net Area developed (ha) 1985-1999	No of dwelling units	% share of total units	No of dwelling units	Net Area developed (ha) 2000-2015	No of dwelling units	% share of total units
Total area	2044	98368	100	92368	3748	233330	100
Plotted units	1636	54808	55.72	41808	2455	73650	45.26
Multistoried flats	408	43560	44.28	50560	1293	159680	68.43

Source: TCPO Gurugram [176].

The Group housing norms in Haryana are governed by Haryana Development and Regulation of Urban Areas Act (HDRUA), 1975, Punjab Scheduled Roads and controlled urban area act (PSRCUA) Act, 1963. As per HDRUA, 1975, the minimum site area for private developers is fixed at 10 acres (40480 sqm). (Table 3.3) Sites for cooperative group housing schemes are floated for a minimum of site area of 0.5 acres (2024 sqm) or more. The key building bye-laws governing the existing housing stock capped maximum floor area ratio (FAR) 1.75 and ground coverage 35 % of site area with nos. of dwelling units fixed at a residential density of 250 persons per acre.

Table 3.3 Acts Governing Residential Development in Gurugram

Acts/ Features	**Objective**	**Area of**	**Functions**
PSRCUA' 63	Prevent haphazard & unauthorized Development along scheduled Roads & in controlled areas	Jurisdiction of the entire state of Haryana	Declaration of the controlled area Preparation of development plan Development. of private colonies Building controls and regulations Zoning regulations
Haryana Housing board act 1971	To provide housing	Haryana	Disposal of land tenements to diff. Income groups, particularly low-income groups and economically weaker section
HRDUA, 1975	Regulation use of land promote planned development in the private sector	Urban area in Haryana	License to private developers for residential development Approval or conciliation of licenses Conditions for licenses.
HUDA 1977	Undertake urban development in Haryana	Urban areas in Haryana	Development of public sector housing External Development of land in private colonies Plotted sector development Disposal of land & buildings
NCRPB, 1985	Planned Development of NCR	National Capital Region	Development Plan in Regional context Affordable housing policy
Haryana Aptt. Ownership Act,1983	Best use of existing and new structures, increase housing stock	Haryana	Parameters for floor wise registration Development of floors and villas Rules for construction of floors

Source: TCPO Haryana [174,179,180].

3. 3 Climatic Context

3.3.1 Climatic Features

The city of Gurugram falls in hot arid climate zone having steppe (Bsh) as per Koppen climate classification or composite climate zone as defined in National building code 2016 of India (Figure 3.5) [28]. The composite climate is characterized by alternating seasons of hot and dry summers and winter conditions interspersed by a brief spell of warm and humid climate in monsoon months. The year is broadly divided into four seasons, viz. Spring, summer, monsoon and winter. The winter starts late in November and continues to the beginning of March. The summer is from March till the end of June. The period from July to mid-September is the south-west monsoon season. Mid-September to end of November constitutes the post-monsoon or the transition period.

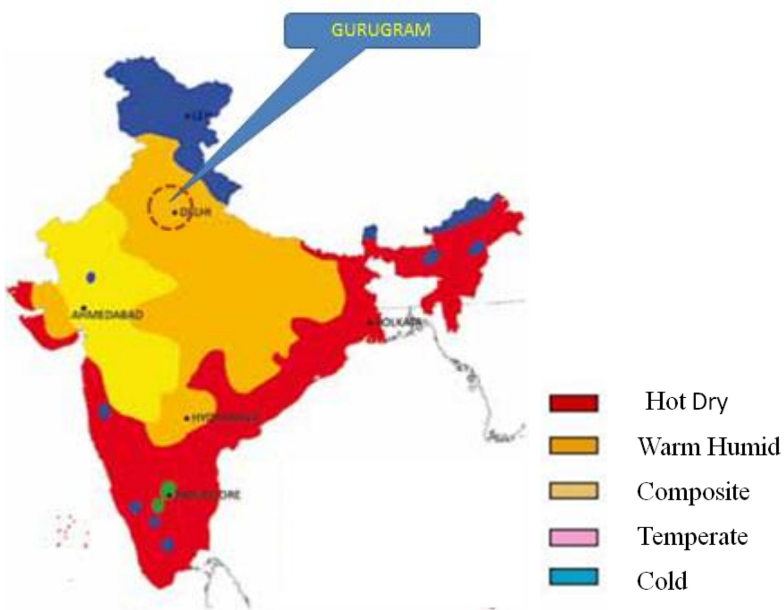


Figure 3.5 Climatic Zone Map of India, National Building Code, 2016 [28]

The various features of the climate of Gurugram are

i. Temp Range from 45^{0}C in summers to 6^0 C in winters,

ii. Annual Diurnal Range of Temp: 6.5 K,

iii. Annual Mean Range of Temp: 24.6 K

iv. RH 20-50% in dry months, 50-90% in wet months

v. Annual rainfall: 553 mm with nearly 77% of the rain from July to September

vi. Solar radiations are generally high throughout the year. Average global radiation is of the order of 5.38 kWh/m^2d with the minimum mean global radiations 3.77 kWh/m^2d

vii. The sky is overcast with mean cloud cover 58%-60% in monsoons, clear in winter with mean cloud cover 25% -48% and frequently hazy in summer (mean cloud cover 20%-35%).

viii. Strong winds prevail during monsoons from the south-east and dry cold winds from the north-east. In summers, the winds are hot and dusty.

ix. The direction of the wind is predominantly from North West to South East and average wind speed is 1.4 m/s.

For selecting weather file in building simulation software, the base data for Delhi (28.70° N, 77.10°E) as described in Table 3.4 is adopted for Gurugram (28.46° N, 77.02° E) as a reference file for its proximity to Delhi and similar weather conditions.

Table 3.4 Climatic data of Delhi: air temperature, wind speed, RH, sunshine hour

	Spring			Summers			Monsoons				Winter		
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
DBT $_{Av}$ ^{0}C	14.0	16.5	21.9	28.2	31.8	33.2	31.3	29.9	29.3	25.3	19.5	14.7	24.65
DBT $_{Min}$ ^{0}C	6	13.4	17.9	24.0	24.2	28.5	26.9	26	27.5	21.7	15.4	12.0	20.72
DBT $_{Max}$ ^{0}C	16.41	20	25.8	32.	36.7	37.8	35.5	32.5	30.7	28.4	23.5	16.4	28
RH $_{Av}$ %	72	70.5	53.7	35.9	48.6	52.8	63.9	72.5	67.3	63.1	58.1	65.0	60.3
RH $_{Max}$ %	49.71	50.8	39.1	29.7	30.2	28.2	44.6	58.4	49.2	48.4	46.8	54.8	44.1
Rainfall mm	20.9	21	14.5	10.7	14.1	66.3	198.4	206.5	130.3	20.8	3.9	8.8	716.
Wind speed m/s	1.3	1.4	1.7	2.3	2	1.8	1.6	1.3	1.4	1	0.6	0.6	1.4
Av monthly Shining hours	213.9	218	238.7	216	263	198	167.4	167.6	219	269.7	246	217	2634

Source: https://energyplus.net/weather [177]

3.3.2 Thermal Comfort and Design parameters

There is a direct relationship between thermal comfort and climatic conditions as per ASHRAE 55-2004 for defining thermal comfort band. The plot of thermal comfort band for 80% acceptability of people superimposed on climatic data reflects that for most of the months, mean monthly outdoor temperature is outside the temperature range of thermal comfort band (Figure 3.6). There is a high diurnal range of temperature with high depression between wet bulb temperature and dry bulb temperature indicating dry air from April to June and high humidity from July to September.

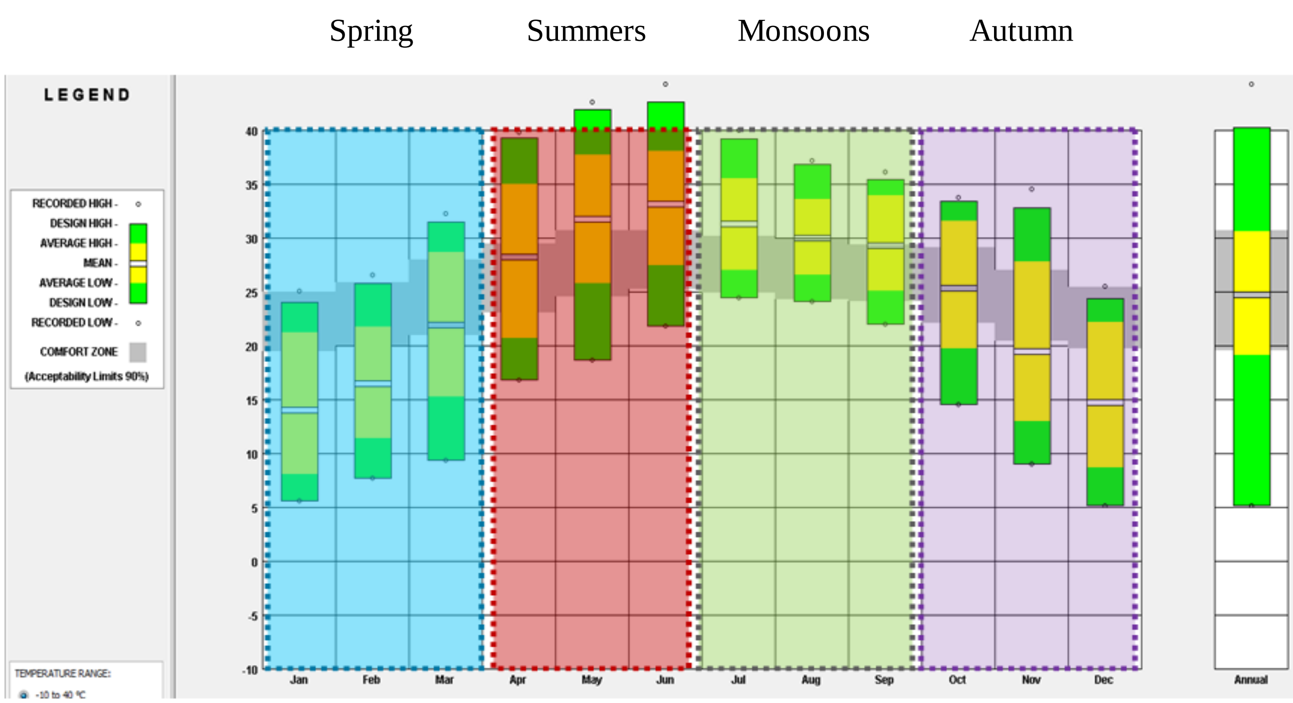


Figure 3.6 Monthly temperature range for Delhi & Adaptive comfort band for 80 % of acceptability, Source: Climate Consultant 6.1 [178].

The comfort potential zones are plotted on psychrometric charts as per adaptive thermal comfort model ASHRAE 55-2004 to understand a wider range of temperature and humidity conditions within comfort potential zone in Figure 3.7, showing that most of the times of the year, climatic conditions are not conducive for thermal comfort [178].

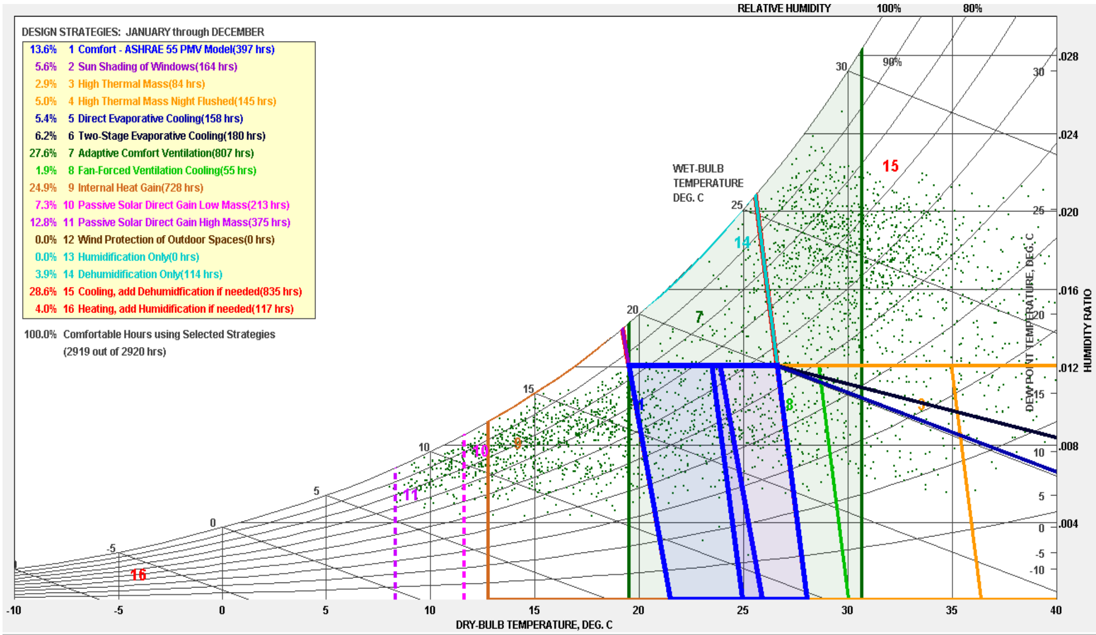


Figure 3.7 Psychrometric chart showing comfort hours by using design strategies ASHRAE 55-2004 from 5 pm to midnight for the entire year, Source: Climate Consultant 6.1 [178].

To achieve the thermal objective for climate responsive design, the design strategies with their physical manifestations as suggested in ECBC 2007 are listed below for reference

Table 3.5 Climate Responsive Design Strategies

Objective	Physical manifestation
1) Resist heat gain in summer and Resist heat loss in winter	
Decrease exposed surface area	Orientation and shape of the building. Use of trees as wind barriers
Increase thermal resistance	Roof insulation and wall insulation
Increase thermal capacity (Time lag)	Thicker walls
Increase buffer spaces	Airlocks/ Balconies
Decrease air exchange rate	Weather stripping
Increase shading	Building to be protected by overhangs, fins and trees
Increase surface reflectivity	Pale colour, glazed china, mosaic tiles, etc
2) Promote heat loss in summer/ monsoon	
Ventilation of appliances	Provide exhausts
Increase air exchange rate (Ventilation)	Courtyards/ wind towers/ openings
Increase humidity levels in dry summer	Evaporative cooling through landscaping
Decrease humidity in monsoon	Dehumidifiers/ desiccant cooling

Source: Nayak and Prajapat, 2006 in ECBC 2007 [50].

3.4 Selection Criteria for Study Area

3.4.1 Selection of Multistoried Group Housing Schemes

With high residential land use (48.56 % of total land use), Gurugram is largely dominated by multistoried group housing schemes catering to 68.38% of the population. The share of land in multistoried group housing society is nearly 34% of the total land area under residential land use in Gurugram, but due to higher density in group housing, it caters to 68.38% of the population as illustrated in Table 3.6.

Table 3.6 Net area under each category and population served in Gurugram, 2011

Types of Housing	**Area under each category (acres)**	**% distribution under each category**	**Population served**	**% population Served**
Plotted	6063	65.49	456601	31.62
Group Housing	3195	34.51	986983	68.38

Source: TCPO Gurugram 2011[176].

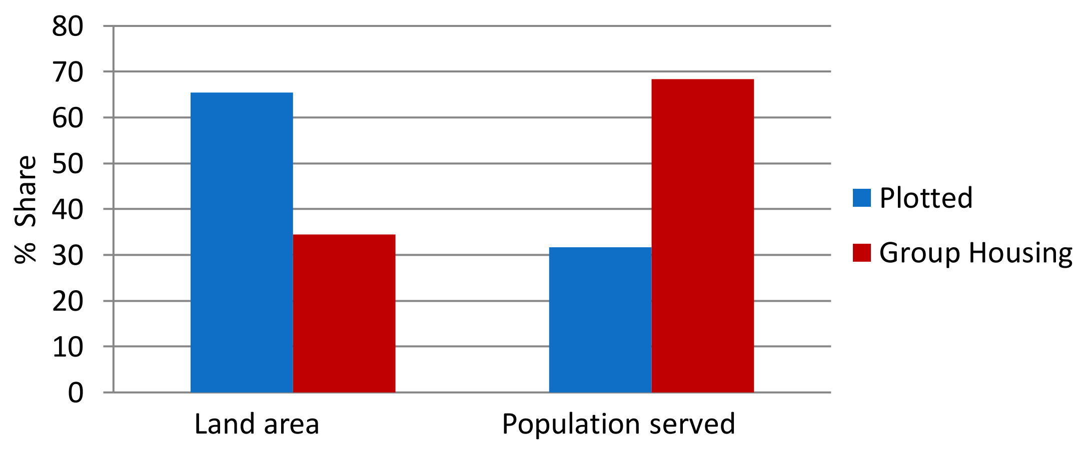


Figure 3.8 Distribution of Land and population served in plotted housing & Group Housing

The existing housing stock is typically characterized by multistoried group housing schemes in Gurugram, designed and constructed before 2010 i.e. year of implementation of Energy Conservation Building Code ECBC 2007 [90]. Gurugram, the Millennium city – a hub of, multinational companies and IT sector, is typically characterized by the presence of high-end multistoried group housing schemes. The decade from 1980's onwards has shown maximum growth in terms of residential spread with the land values skyrocketing with people opting for group housing schemes villas and floors. Mid rise and high rise apartments accommodate the vast majority of dwellings and constitute 70% of total housing supply.No of ready to move flats by 2010 was 95000 [63].

Gurugram has an overall annual energy consumption of 3988 million kWh (mu) including residential, commercial and industrial from Sector 1-57 in Gurugram. With a share of 1874 mu in buildings, the share of residential buildings is 1285 mu (68.57%) and the commercial sector is 589 mu (31.43%). As per DPR Smart Grid Project DHBVN (2016), the annual electricity demand is increasing by 17% whereas the supply of electricity is increasing by 5 %, leading to a wide gap between demand and supply of electricity in Gurugram [181].

In the wake of huge demand for electricity and limited supply of power, many residential units are run on 100% captive power on diesel, causing environmental pollution [56]. Highest energy consumption and high carbon footprint of multistoried housing make them strong candidate for retrofits. Also, the group housing societies are maintained professionally by facility management companies rather than individual plot owners, so it is practically possible to implement retrofitting. Gurugram with yet only 30% of its total plan implemented serves as an ideal context for alternative approaches and improving the efficiency of existing multistoried residential fabric. Thus the city of Gurugram is chosen as a case to constitute a sample universe for conducting the research and analyzing data to fulfil aims and objectives of the research.

3.4.2 Selection of Cases of Group Housing Society for detailed survey

For undertaking a detailed survey of the assessment of energy consumption in Gurugram, various housing schemes having different built up area and WWR , have been selected to have a wider cross-section of housing schemes in the city. The housing societies are developed predominantly by private developers, having 69% share in total no of societies, followed by 22% share of cooperative group housing societies and remaining 9% by public sector housing schemes. The sampling has been done on a probabilistic stratified basis so as to represent housing schemes from each type of multistoried group housing societies i.e. public sector housing, cooperative group housing schemes and private developer group housing schemes. The housing schemes are selected for diversity and for eliminating the effect of any single variable as per following criteria.

i) A proportional sample of housing typology in existing housing scheme as per sample population in the city of Gurugram. The housing scheme should have been built and designed before 2010 i.e. the year of implementation of Energy Conservation Building Code ECBC 2007 in the state.

ii) At least two samples from each housing typology so as to eliminate the effect of any single variable and allow comparison and validation of data by a triangulation method.

iii) Only one block chosen from each housing scheme so as to understand energy performance index at building level for detailed energy analysis modelling and also considering constraints time and instrumentation.

iv) Housing schemes are selected to represent the uniform spatial distribution of different housing schemes in the study area built before 2010.

v) Housing schemes have been selected to represent diversity taking into account diversity by choosing housing sizes of various sizes in terms of land area and as well as no of dwelling units,

vi) At least one representative sample of the major players in private developers in Gurugram in a sample of private developers group housing schemes.

vii) The samples represent various plan typologies (geometry, size and orientation) and wall to window ratio to study the effect of architectural design parameters through building performance modelling and monitored data.

As per the above selection criteria, eight housing schemes were chosen as a case for the detailed study of the assessment of energy consumption in existing housing as per the objectives of the research. Figure 3.9 shows the distribution of different group housing schemes as per study criteria i.e. housing schemes built before 2010.

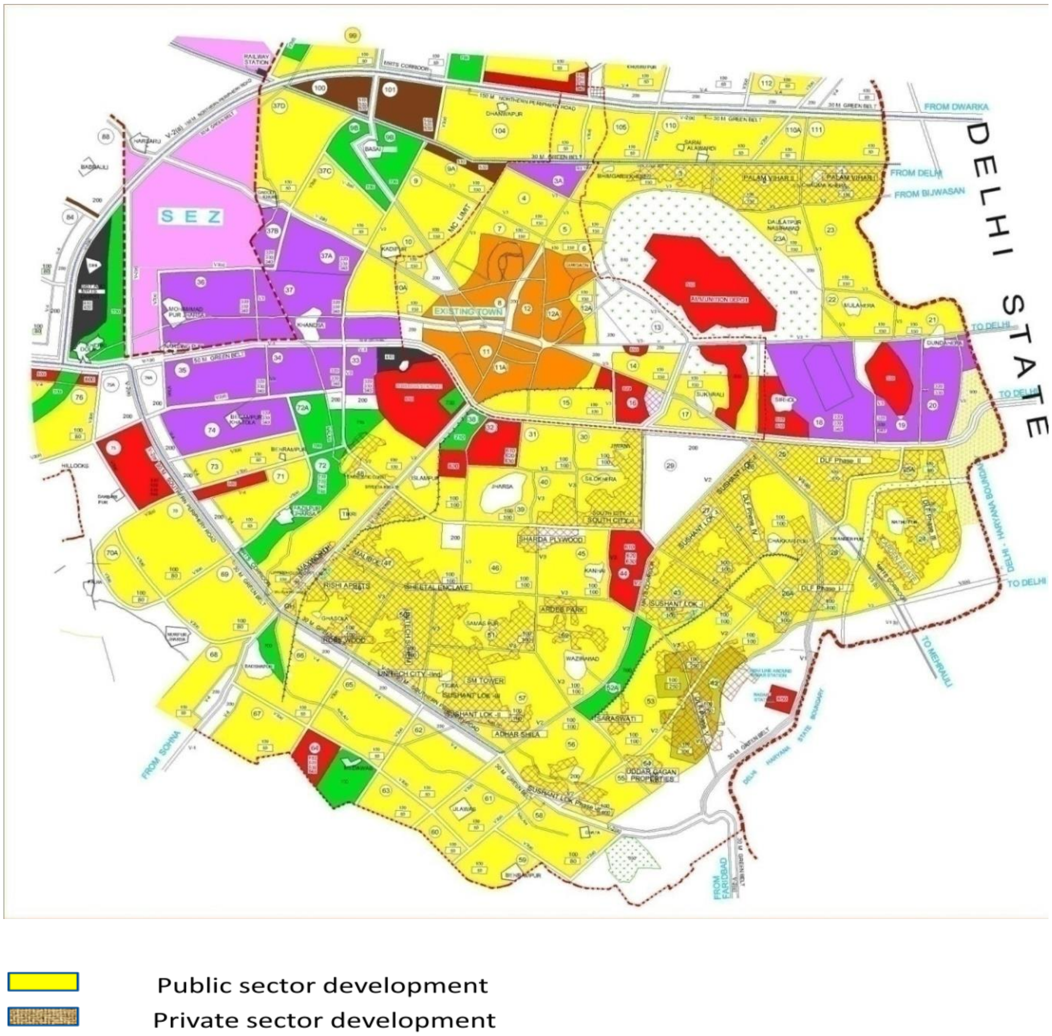


Figure 3.9 Distribution of the sample population in the study area of Gurugram built before 2010, Source: Kumar P 2016 [182].

The private colonizers involved in the residential development activities are limited to few that are controlling the bulk of the land in the urban area of Gurugram. The major players in private developers who have developed residential societies are M/s DLF (Qutub Enclave) & ANSAL API (Palam Vihar) in 1980 's followed by Unitech Ltd, Uppal housing scheme and Orchid petals infrastructure in 2000 as can be seen in Figure 3.10. In the initial phase of development, the private developers DLF developed a major chunk of land near Delhi Border and later area around Gurugram-Sohna road emerged as a favourite place of development by private developers like Unitech and other private players. The development by public sector agencies are sporadic and interspersed within various sectors. Sector 56 emerged as a hub of cooperative group housing societies for development of MIG and HIG category of population. Based on the above selection criteria, the various housing schemes selected as a case are listed in Table 3.7.

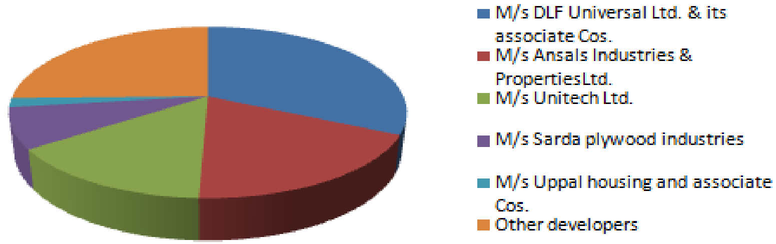


Figure 3.10 Distribution of Residential development by Private developers in Gurugram.

Table 3.7 Detail of housing schemes selected for detailed survey of energy consumption

SN	Name of Housing Society	Location	Site Area (acre)	Type	No of dwelling units
1	DLF Ridgewood estate (DLF RE)	Sector 27	13.5	Private Developer	724
2	Ansal API Sushant Estate ANS SE)	Sector 52	10.0	Private Developer	864
3	Unitech Fresco (UN FRS)	Sector 50	16.9	Private Developer	830
4	Orchid Petals (OPID)	Sector 49	37	Private Developer	1300
5	Antriksh Srishti CGHS (A SR)	Sector 56	1.03	Cooperative Group Housing (CGHS)	48
6	Hextax Commune CGHS (HXT)	Sector 43	1.5	Cooperative Group Housing (CGHS)	107
7	HSIIDC Apartments (HSIIDC)	Sector 31	6.87	Public Sector Housing	385
8	Power Grid Township (PGT)	Sector 43	7.02	Public Sector Housing	350
Total units					4608

Thus sampling frame is drawn from different typologies of housing which are constructed before 2010 i.e. Public housing, Cooperative group housing scheme (CGHS), Private developer housing. The various flats in different plan form (linear, slab type or tower block) and occupancy (2 BHK or 3BHK) are studied. Further flats with variations in orientation and floor location and using different strategies WWR, Shading and materials have been taken up. For energy consumption survey, a minimum of two cases from each category in societies are chosen for cross-validation. Figure 3.11 shows the spatial distribution of various samples chosen in Gurugram based on the above selection criteria.

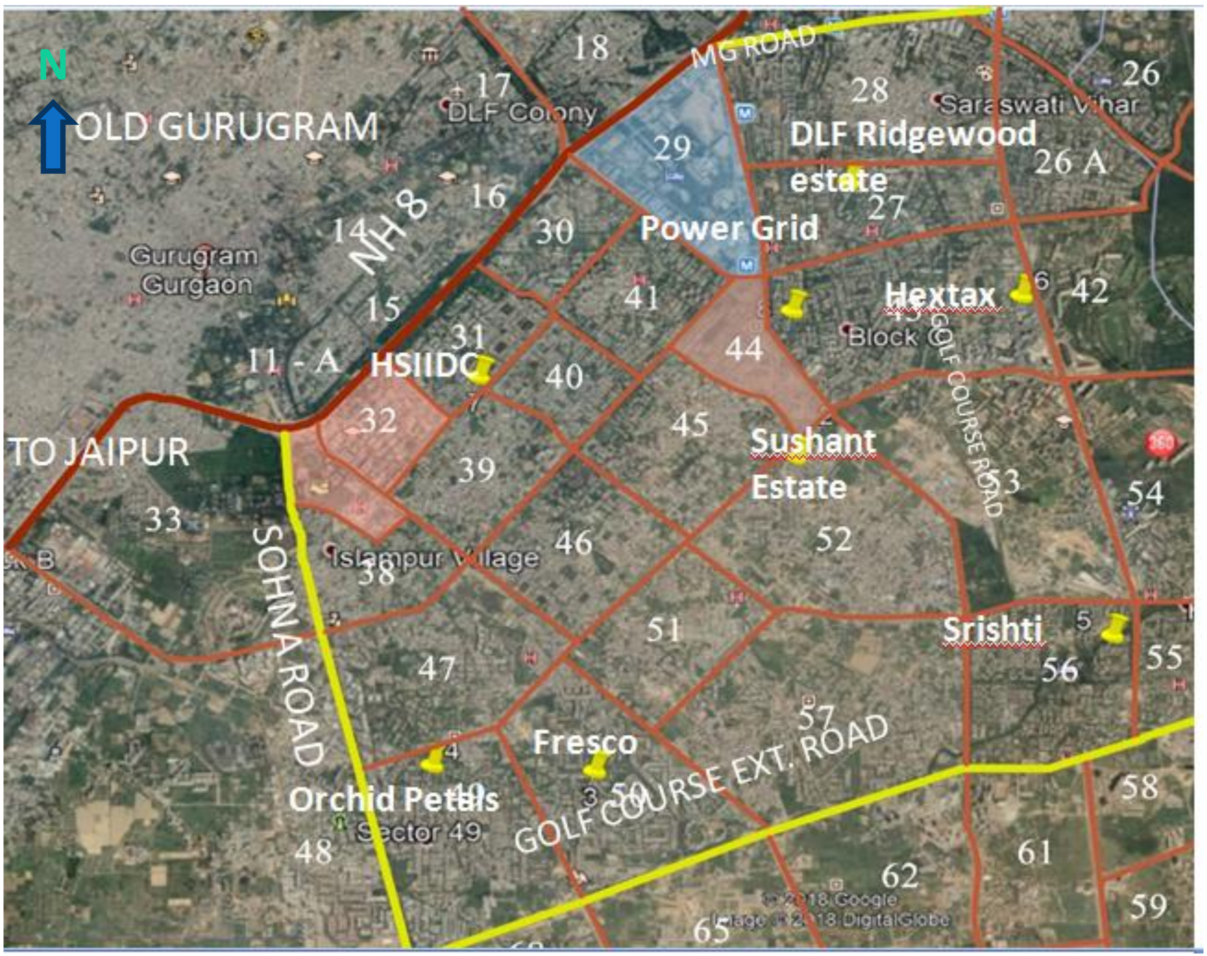


Figure 3.11 Distribution of Case study areas of Residential development in Gurugram, Source: Google Maps 2017 [183].

.

3.4.3 Selection of study parameters

To meet the objectives of the research, selection of study parameters is done with the aim to reduce energy consumption in existing multistoried residential buildings. Selection of design parameters entails choosing the factors which are responsible for the reduction of building heat gain and thus reduce cooling demand, using energy efficiently and harnessing renewable energy. In the context of retrofitting existing housing, design interventions should be climate responsive which are suitable for composite climate context, cost-effective, easily achievable and non-intruding to users. The design interventions should not violate existing building regulations and without causing an impact on the structural components of existing buildings.

The list of various parameters selected are as follows :

i) Building Envelope wall components

   a) Surface Reflectance Walls
   b) Thermal Resistance Walls
   c) Solar heat gain coefficient for transparent surfaces

ii) Building Envelope Roof components

   a) Surface Reflectance roofs
   b) Thermal Resistance roofs

iii) Other components

   a) Exterior Shading
   b) Air Tightness
   c) Rooftop solar photovoltaics
   d) Grasscrete paver blocks
   e) LED internal lighting

3.5 Overview of Housing Schemes as a case for detailed energy analysis

Based on sampling criteria and selection of design parameters, eight housing schemes are chosen for primary data collection. The housing schemes are chosen are of various scales in terms of site area and no of dwelling units as per details are given in Table 3.7. The following sections present an overview of the different housing schemes chosen.

3.5.1 DLF Ridgewood Estate, Phase IV, Sector 27, Gurugram

The DLF Ridgewood Estate Apartments is one of the first private developer housing developed by M/s DLF, the largest player in private housing in Gurugram. The housing is strategically located near MG Road in DLF Phase IV, Sec 27, Gurugram. It is one of the largest housing projects by DLF and completed in 2002. There is a very high occupancy rate as much as 90% of total flats are occupied.

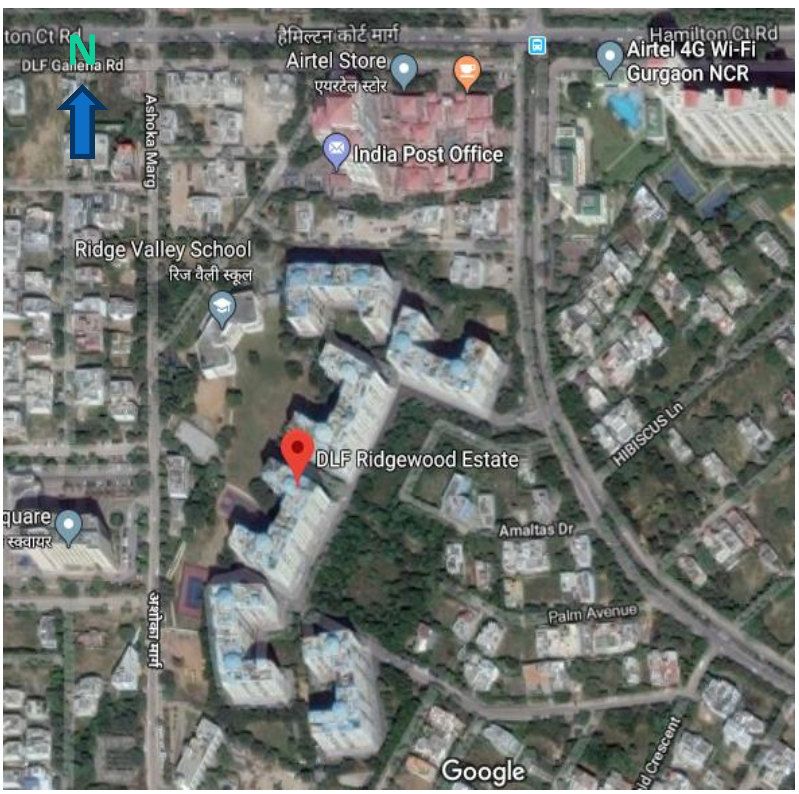


Figure 3.12 Google image showing the layout of DLF Ridgewood in Gurugram [183].

The society is spread in 13.51 acres, having 724 units with a mix of 3 BHK and 4 BHK dwelling units. The site is surrounded by low rise plotted development (Figure 3.12).

Figure 3.13 Site plan of DLF Ridgewood Apartments in Gurugram

Figure 3.14 View of DLF Ridgewood Apartments in Gurugram

The project is designed by Architect Hafeez Contractor. There are six towers in all which are 15 storied in height with stilt and basement reserved for parking. The site is irregular in shape and has resulted in a different orientation of towers. Two of the towers are oriented NW-SE and the rest of towers are oriented along NE-SW axis. Figure 3.14 depicts the architectural character of the apartments, showing light-coloured facades and shallow balconies.

Figure 3.15 Detail of cluster and unit plan in DLF Ridgewood Apartments in Gurugram

Two dwelling unit are arranged back to back, reducing the exposed area of flat considerably. Each tower consists of six dwelling units with a set of three units arranged around two central cores of lifts and stairs present at each corner junction of the C shape. The distance between towers is 30 m. The plan is linear and rectangular in shape, with a long corridor leading to individual bedrooms. The individual units are having a super area of plan ranging from 121 sqm to 168 sqm, with built-up area ranging from 107 sqm to 126 sqm representing most common flat size available in Gurugram.

The building envelope consists of burnt brick walls with cement plaster on both sides with RCC roof finished with tile terracing. The Window to Wall ratio is 13.64% with windows having 6mm thick clear glass. Some of the windows are shaded with balconies 1.2 m wide. The society uses a mixed mode of ventilation using split and window air conditioners. The society is maintained by Cushman & Wakefield Prop. Mgmt. Services and provides electricity bills to each individual unit.

3.5.2 Ansal API Sushant Estate, Sector 52, Gurugram

The Ansal API Sushant Estate is developed by private developer M/s Ansal API developers, the second largest player in integrated townships and group housing schemes in Gurugram. The site is located strategically on Wazirabad Road at the intersection of Vikas Marg and CRPF Marg in Sector 52, Gurugram and surrounded by multistoried group housing schemes such as Aardee city, Palm grove heights. The project was completed in 2005 with a high occupancy rate of 85% of total flats as occupied.

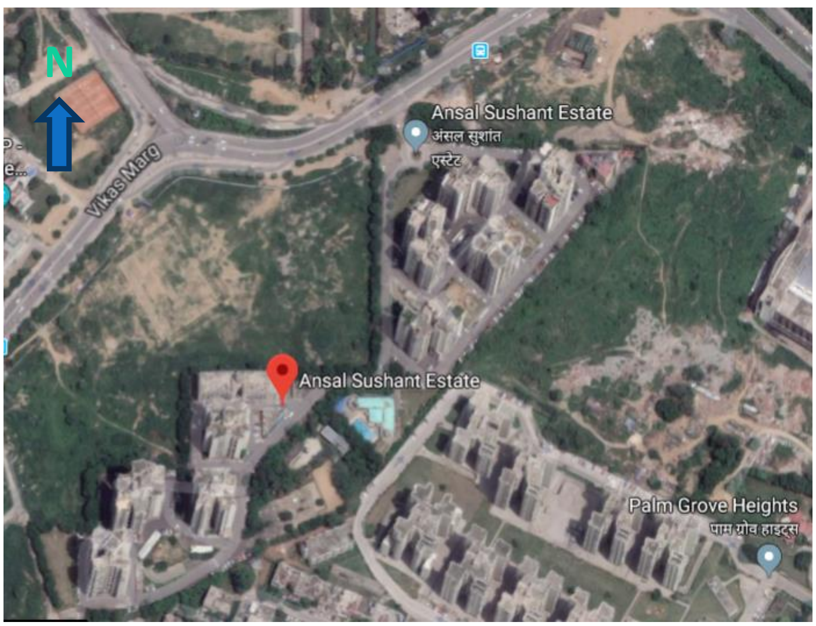


Figure 3.16 Google image showing the layout of Ansal API Sushant Estate in Gurugram [183].

The society is spread in 10.0 acres, having 864 units with a mix of studio apartments, 1 BHK, 2BHK, 3 BHK and 4 BHK apartments. There are nine towers in all which are 16 storied in height with stilt and basement reserved for parking (Figure 3.17).

Figure 3.17 Site plan of Ansal API Estate, Sector 52, Gurugram

Figure 3.18 View of API Sushant Estate Apartments in Gurugram

The site is fragmented in two parts due to highly irregular site shape and has resulted in two types of the orientation of towers. Four towers are oriented NS and five towers are aligned along NW-SE axis. Figure 3.18 depicts the architectural character of the apartments, showing light colour painted facades and shallow balconies.

Figure 3.19 Detail of cluster and unit plan of API Sushant Estate Apartments, Sector 52, Gurugram

There are a variety of arrangements in a dwelling unit with a relatively larger surface area of flat exposed to outside. There are two types of tower, one the typical tower with four units arranged around central core lifts and stairs. The other tower has six units arranged around the core placed at the common intersection of L shape form. Each tower consists of four 2 BHK units and two 3BHK dwelling units. The distance between towers varies from 12 m to 25 m. The plan is linear and rectangular in shape, with a short corridor leading to individual bedrooms. The individual units are having a super area of plan ranging from 120 sqm to 160 sqm, with built-up area ranging from 94 sqm to 119sqm representing most common flat size available in Gurugram.

The building envelope consists of burnt brick walls with cement plaster and light coloured paint on both sides with RCC roof finished with tile terracing. The Window to Wall ratio is 19.2 % with windows shaded with balconies 1.2 m wide. All towers are operated on the mixed mode of ventilation using split and window units for air conditioning.

3.5.3 Unitech Fresco, Sector 50, Gurugram

The Unitech Fresco is developed by India's leading real estate developer M/s Unitech Limited. The site is located on the main Golf course extension road as a part of elite Nirvana Country integrated township in Sector 50, Gurugram and surrounded by low rise villas and floors in the township. The site is in close proximity to The Medanta Medicity, IT office buildings on Sohna Road. The project was completed in 2006 with a high occupancy rate of 80% of total flats as occupied.

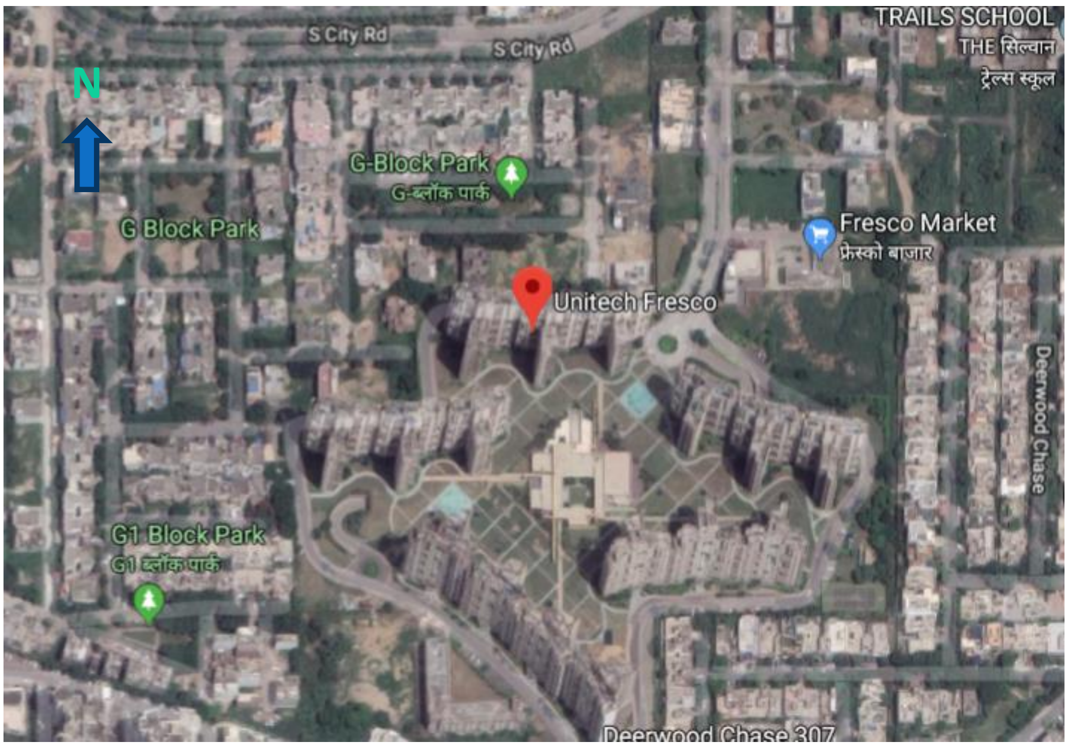


Figure 3.20 Google image showing the layout of Unitech Fresco, Sector 50, Gurugram [183].

The society is spread over 16.9 acres, having 830 units of 3 BHK apartments. These units have three variants: 3 BHK with 2 toilets, 3 BHK with 3 toilets and 3BHK with servant room apartments. There are sixteen towers and 15-18 storeys in height with stilt and basement reserved for parking. (Figure 3.21). Fresco comprises of 2 & 3 bedroom apartments ranging from 1336 sq. ft. to 1877 sq. ft.

Figure 3.21 Site plan of Unitech Fresco, Sector 50, Gurugram

Figure 3.22 View of Unitech Fresco Apartments in Gurugram

The site is largely rectangular in shape resulting in placement of the tower on the outer perimeter with a central large green chunk of land and club in the middle. Most of the towers

(66%) are oriented NS and remaining towers are aligned along NE SW. Each tower is T shaped, serving three dwelling units on each floor. Figure 3.22 depicts the architectural character of the apartments, showing light colour painted facades and deep balconies.

Figure 3.23 Detail of cluster and unit plan of Unitech Fresco Apartments, Sector 50, Gurugram

Each tower is having a central core of lifts and staircases at common intersection of T shape with three apartments placed around it, leading to quite a large surface area exposed to the sun. Each unit faces a large central green court and club building. The distance between towers varies from 12 m and they are arranged linearly to give an effect of long continuous slab structures. In the unit plan, the arrangement is very simple with all three bedrooms facing the drawing hall instead of a narrow corridor. The individual units are having a super area of plan ranging from 141 sqm to 161 sqm, with built-up area ranging from 98.5 sqm to 120 sqm having large carpet area available for users. The building envelope consists of burnt brick walls with cement plaster and light coloured paint on both sides with RCC roof finished with tile terracing. The Window to Wall ratio is 14.08 % with windows shaded with balconies 1.2 m wide. All towers are operated on the mixed mode of ventilation using split and window units for air conditioning.

3.5.4 Orchid Petals, Sector 49, Gurugram

The Orchid Petals is developed by a private developer M/s Orchid Infrastructure Developers. The case study is chosen for a case representing other private developer's category. The site is located in sector 49, Gurugram and is easily accessible from the main Sohna Road. The site is surrounded by large multistoried developments including group housing schemes, IT parks, shopping malls, cooperative group housing schemes etc. The project was completed in 2001 with one of the highest occupancy rates of 96% of total flats as occupied.

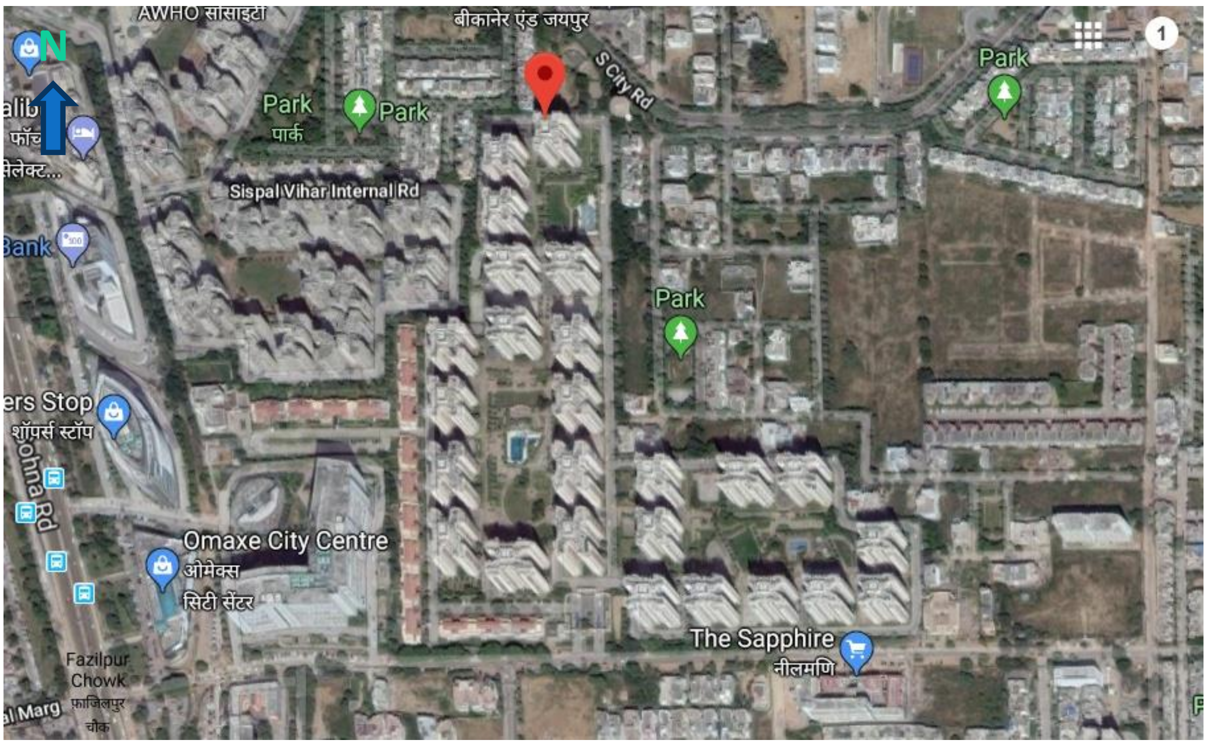


Figure 3.24 Google image showing the layout of Orchid Petals, Sector 49, Gurugram [183]

The society is one of the largest group housing schemes spread over 37 acres, having 1300 units. The society offers primarily 3 BHK apartments and a very few 4 BHK apartments. The three-bedroom apartments have two variants 3 BHK and the other 3BHK with study room. There are twenty-five towers and 14 storeys in height with stilt and basement reserved for parking (Figure 3.25).

Figure 3.25 Site plan of Orchid Petals, Sector 49, Gurugram

Figure 3.26 View of Orchid Petals Apartments, Sector 49 in Gurugram

The site is rectangular in shape with towers arranged in three clusters around central green courts. Most of the towers (60%) are oriented in a way that their predominant windows face east or west and in 40% dwelling units, windows face north or south. The geometry of the tower is a typical stand-alone point type tower with four dwelling units arranged around the central core of services on each floor. Figure 3.26 depicts the architectural character of the apartments, showing light colour painted facades and up to 1.8 m deep balconies.

Figure 3.27 Detail of cluster and unit plan of Orchid Apartments, Sector 49, Gurugram

Each tower is planned in such a way that it gets exposed to solar radiations in three directions, resulting in a large surface area exposed to the sun. The unit is planned in such a manner that there are multiple vertical projections of rooms leading to mutual shading of adjacent surfaces and windows of the rooms. The distance between adjacent towers is 15 m. The individual units are having a super area of plan ranging from 160 sqm to 251 sqm, with built-up area ranging from 120 sqm to 180 sqm having large carpet area available for users. The building envelope consists of burnt brick walls with cement plaster and light coloured paint on both sides with RCC roof finished with tile terracing. The Window to Wall ratio is 11.7 % with windows shaded with balconies. All towers are operated on the mixed mode of ventilation using split and window units for air conditioning.

3.5.5 Antriksh Srishti CGHS, Sector 56, Gurugram

The Antriksh Srishti CGHS represents cooperative group housing scheme developed by a The Antriksh Group society. The site is located in sector 56 - a hub of cooperative group housing schemes in Gurugram. The site is surrounded by large multistoried developments group housing schemes and easily accessible from Golf Course Road and metro station of Sector 55-56. The project was completed in 2009 with 100% occupancy rate.

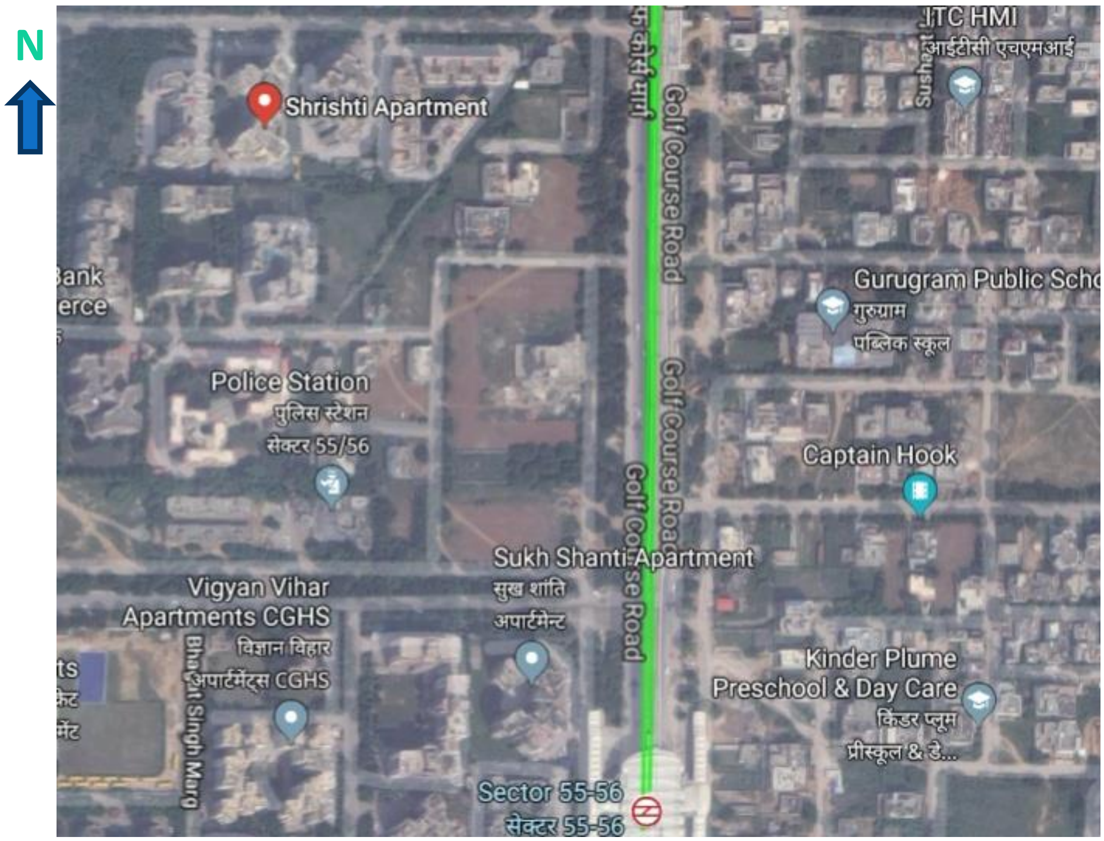


Figure 3.28 Google image showing the layout of Antriksh Srishti Sector 56, Gurugram [183].

The society is a typical cooperative group housing society having an area of 1.03 acres accommodating 48 units. The society offers primarily 3 BHK apartments and a very few 4 BHK apartments. The three-bedroom apartments have two variants 3 BHK and the other 3BHK with study room. There are three towers and 8 storeys in height with stilt reserved for parking. The towers are oriented NW-SE, leading to windows facing NE or SW.

Figure 3.29 View of the Antriksh Srishti Apartments, Sector 56, Gurugram

The site is rectangular in shape with towers arranged at an angle to the site around central green courts. The geometry of tower is typical point type tower with two dwelling units arranged around lifts and staircase on each floor. Figure 3.29 depicts the architectural character of the apartments, showing light colour painted facades and 1.2 m deep balconies.

Figure 3.30 Detail of cluster and unit plan of The Antriksh Srishti Apartments, Sector 56, Gurugram

Each tower is planned in such a way that it gets exposed to solar radiations in three directions, resulting in a large surface area exposed to the sun. The unit is planned in such a manner that there is almost a continuous balcony on one edge of the dwelling unit. The distance between adjacent towers is 9 m. The individual units are having a super area of plan ranging from 120 sqm, with built-up area ranging from 90 sqm. The building envelope consists of burnt brick walls with cement plaster and dark coloured paint on both sides with RCC roof finished with tile terracing. The Window to Wall ratio is 17.2 % with windows shaded with balconies. All towers are operated on the mixed mode of ventilation using split and window units for air conditioning

3.5.6 Hextax Commune CGHS, Sector 43, Gurugram

The Hextax Commune CGHS represents cooperative group housing scheme developed by a Group society floated by Income Tax employees. The site is located in sector 43, Gurugram and is surrounded by large multistoried developments group housing schemes. The site is easily accessible from Golf Course Road. The project was completed in 2008 with 100% occupancy rate.

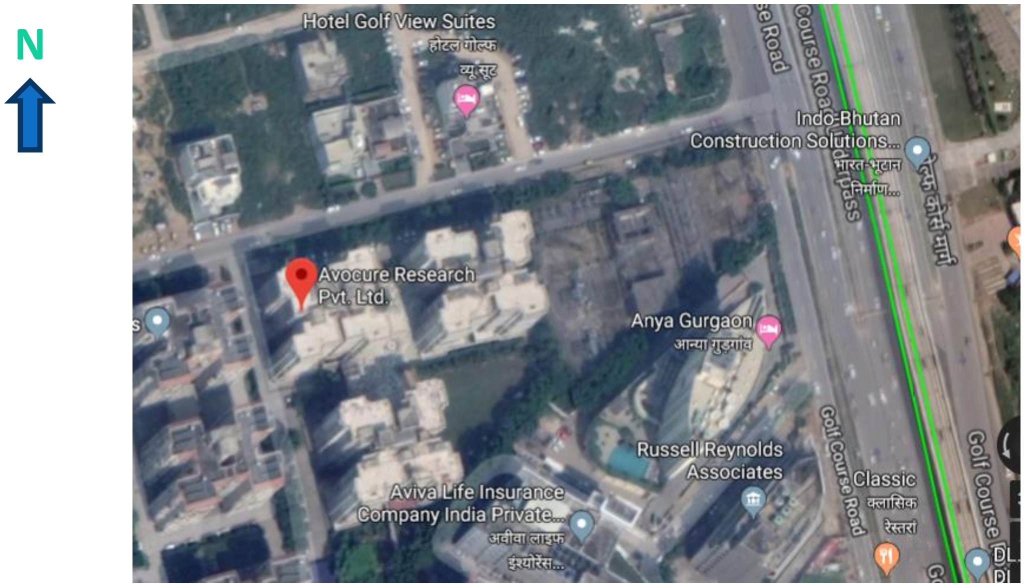


Figure 3.31 Google image of the layout of Hextax Apartments, Sector 43,Gurugram [183].

The society is a typical cooperative group housing society having an area of 1.5 acres accommodating 107units. The society offers primarily 3 BHK apartments and 4 BHK apartments. There are three towers and 12 storeys in height with stilt reserved for parking. The towers are oriented NS, leading to windows facing E or W.

Figure 3.32 View of Hextax Apartments, Sector 43, Gurugram

The site is rectangular in shape with towers arranged at an angle to the site around central green courts. The geometry of tower is typical point type tower with four dwelling units arranged around lifts and staircase on each floor. Figure 3.32 depicts the architectural character of the apartments, showing light colour painted facades and 1.8 m deep balconies.

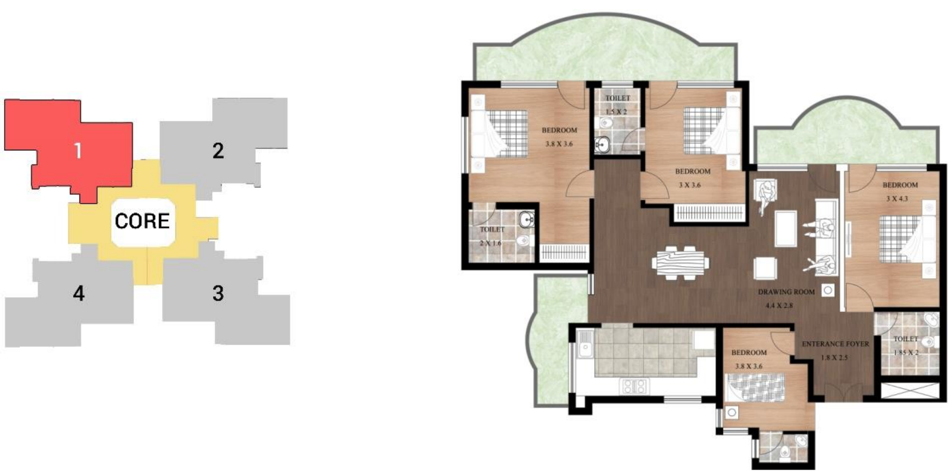


Figure 3.33 Detail of cluster and unit plan of the Hextax Apartments, Sector 43, Gurugram

The unit is planned in such a manner that there are large and deep balconies on two faces of the dwelling unit. The distance between adjacent towers is 16 m. The individual units are having a super area of plan ranging from 165-198 sqm, with built-up area ranging from 120-160 sqm. The building envelope consists of burnt brick walls with cement plaster and dark coloured paint on both sides with RCC roof finished with tile terracing. The Window to Wall ratio is 16 % with windows shaded with balconies. All towers are operated on the mixed mode of ventilation using split and window units for air conditioning.

3.5.6 HSIIDC Apartments, Sector 31, Gurugram

The HSIIDC apartments Society represents public housing scheme developed by a State Government for accommodating staff and officials of Haryana State Industrial and Infrastructural Development Corporation. The site is located in sector 31, Gurugram with easy proximity to National Highway NH -8 and is surrounded by another public sector group housing scheme. The project was completed in 1999 with 100% occupancy rate.

Figure 3.34 Google image of the layout of HSIIDC Apartments, Sector 31, Gurugram [183]

The society is typical public sector housing having an area of 6.87 acres accommodating 385units. The society offers primarily 3 BHK apartments and 4 BHK apartments. There are eleven towers and nine storeys in height with stilt reserved for parking. The towers are oriented NS, leading to windows facing E or W.

Figure 3.35 View of HSIIDC Apartments, Sector 31, Gurugram

The site is rectangular in shape with towers arranged at an angle to the site around central green courts. The geometry of tower is typical point type tower with four dwelling units arranged around lifts and staircase on each floor. Figure 3.35 depicts the architectural character of the apartments, showing light colour painted facades and 1.2 m deep balconies.

Figure 3.36 Detail of cluster and unit plan of the HSIIDC Apartments, Sector 31, Gurugram

The unit is planned in such a manner that there are large and deep balconies on two faces of the dwelling unit. The distance between adjacent towers is 12 m. The individual units are having a super area of plan ranging from 82-126 sqm, with built-up area ranging from 68-96 sqm. The building envelope consists of burnt brick walls with cement plaster and dark coloured paint on both sides with RCC roof finished with tile terracing. The Window to Wall ratio is 13.5 % with windows shaded with balconies.All towers are operated on the mixed mode of ventilation using split and window units for air conditioning

3.5.8 Power Grid, Sector 43, Gurugram

The Power Grid apartments in Sector 43 represents another case of public housing scheme developed by the public sector undertaking Power Grid Corporation. The site is accessible from the Golf Course road and strategically close to District Centre of Gurugram i.e. Sector 29 with near proximity to Metro Station on Mehrauli-Gurugram Road. The site is surrounded by a no of multistoried cooperative group housing schemes such as Navyug apartment, Surabhi apartments, AWHO apartments, Sanskriti apartments and Sujjan Vihar. The project was completed in 2009 with 100% occupancy rate.

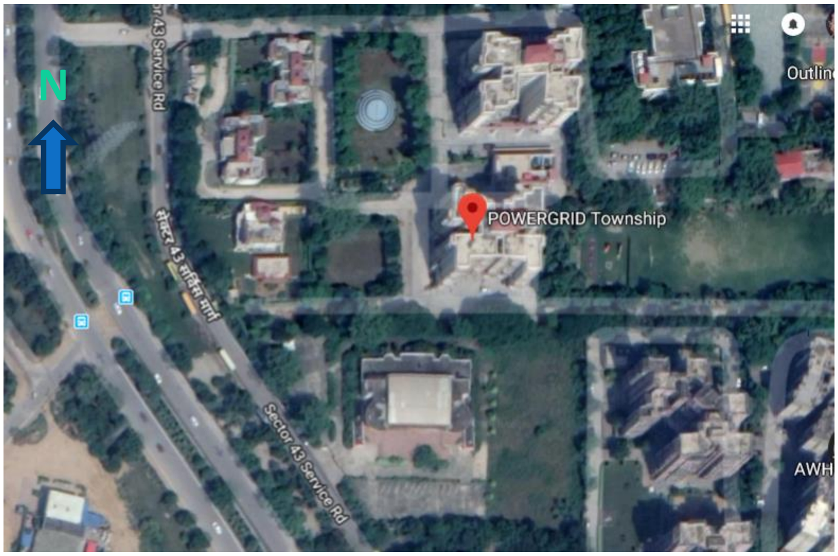


Figure 3.37 Google image of Power Grid Apartments, Sector 43, Gurugram [183]

The society is typical public sector housing having an area of 7.02 acres accommodating 350 units. The society offers a rich mix of 2 BHK, 3 BHK and 4 BHK apartments. There are ten towers and nine storeys in height with stilt reserved for parking. The towers are oriented NS, leading to windows facing E or W. The site is rectangular in shape with towers along cardinal directions with a large green court at one end of the township.

Figure 3.38 View of Power Grid Apartments, Sector 43, Gurugram

The towers are typical point blocks with four dwelling units arranged around lifts and staircase on each floor. The facades are self-shaded due to offset geometry (Figure 3.38) and have a balcony with a mean projection of 1.8 m.

Figure 3.39 Detail of cluster and unit plan of Power Grid Apartments, Sector 43, Gurugram

The unit is planned in such a manner that there are large and deep balconies on two faces of the dwelling unit. The distance between adjacent towers is 12 m. The individual units are having a super area of plan ranging from 92-163 sqm, with built-up area ranging from 75-132 sqm. The building envelope consists of plastered brick masonry finished with light coloured paint on both sides and RCC roof finished with tile terracing. The windows are relatively large with WWR of 17.5 % with shading from balconies and vertical sides/offsets in the geometry of tower. All towers are operated on the mixed mode of ventilation using split and window units for air conditioning.

3.6 Comparative Summary of Cases

By comparing the various cases chosen for a case study, it is observed that most muti-storeyed towers in group housing schemes are 9-15 floors with four flat opening on each floor from the central core of lifts and services. The towers are invariably pointed blocks with walls having windows on three sides and exposed to solar radiations. All towers are operated on the mixed mode of ventilation using split and window units for air conditioning. The various features of different case study areas are summarized in Table 3.8.

Table 3.8 Comparative Summary of Various Study Area

1	Name of Developer	UN FRS	DLF RE	OPID	HXT	HSIIDC	PGT	ANS SE	A SR
2	Site Area (Acs)	16.9	13.51	37	1.5	6.87	7.02	10.0	1.0
3	Number of towers	16	12	25	3	11	10	9	3
4	Number of flats	830	724	1300	107	385	350	864	48
5	Number of floors	15-18	15	14	10	9	9	16	8
6	Flats on 1 floor	3	4	4	4	4	4	4	4
7	Orientation NS EW	66% 34%	NW SE	40 60	NS	NE-SW	NS	NS	NW SE
8	Geometry	Tower	Slab	Tower	Tower	Tower	Tower	Tower	Tower
9	Dist bet two towers	25m	30 m	15m	16m	12m	12m	12m	9m
10	Built up area DU (sqm)	141	121-48	91-257	165-198	82-126	125	120-160	120
11	Electricity Agency	Freedom	RWA	RWA	DHBVN	DHBVN	DHBV N	RWA	RWA
12	Occupancy	80%	90%	96%	100%	100%	100%	85%	100%
13	WWR %	14.08	13.64	11.7	16	13.5	17.5	19.2	17.2
14	Wall material	Bk. Masonry	Bk. Masonry	Bk. Masonry	Bk. Masonry	Bk. Masonry	Bk. Mason	Bk. Masonry	Bk. Masonry
15	Roof finish	Tile terr	Tile terr	Tile terr	Tile terr	Tile terr	Tile	Tile terr	Tile terr
16	Glass type	Single	Single	Single	Single	Single	Single	Single	Single
17	HVAC Type	Split	Split	Split	Split	Split	Split	Split	Split
18	Projection Factor	0.45	0.27	0.30	0.4-0.6	0.4	0.5	0.4	0.32
19	Balcony (m)	1.2	1.2	1.2	1.8	1.2	1.2	1.2	1.2
20	Year of construction	2006	2002	2001	2008	1999	2009	2005	2009

3.7 Summary

This chapter introduces the city of Gurugram, delineating its urban area profile, land use character, development plan along with various legislative acts applicable to the development of the housing sector in Gurugram. It describes the climatic context of the city in relation to thermal comfort band as per adaptive thermal comfort model of ASHRAE 55-2004 and provides climatic responsive design strategies along with their physical manifestations. The chapter attempts to establish selection criteria of multistoried group housing as a study context, selection of study parameters to carry research and further selection criteria of different cases for taking up detailed survey. Finally, a comparative overview of different cases representing eight housing schemes. Ranging from, the public sector, private developer and cooperative group housing schemes is undertaken with respect to architectural geometry, shading devices, occupancy and building envelope characteristics. The collected details of different housing schemes form important input for preparing a base case in building energy simulation software.

4.1 Introduction

This chapter deliberates on various aspects of research design and tools employed for conducting research. Some of the aspects of research design such as selection criteria of study parameters and selection of samples for conducting surveys have been introduced in the previous chapter. This chapter delineates research design by defining sampling size, sampling design, research instruments such as the design of different types of questionnaire, surveys to understand building envelope characteristics, energy consumption pattern, instrumentation and experimental design for thermal mapping of existing multistoried group housing schemes. This chapter further discusses issues related to the conductance of questionnaire design, pilot testing and building performance assessment tools such as energy audits, building performance simulation modelling and life-cycle cost analysis.

4.2 Research approach and methodology

There are rather limited studies and availability of data on energy consumption pattern of existing multi-storeyed housing as evident from the literature review [1]. There is hardly any focus on energy efficiency in existing residential buildings due to the absence of any codes or standards, despite having the largest footprint and significant carbon footprint in terms of operational energy consumed in the residential sector.

Both quantitative and qualitative approaches have been adopted in order to understand baseline data of energy consumption and factors affecting variations in energy consumption in addition to building envelope characteristics. To resolve complexities in energy consumption pattern in different users and finally establish a benchmark for baseline datum for multistoried group housing, multiple case studies have been employed to understand the pattern in variations in energy use in different types of housing schemes such as public sector, cooperative group housing schemes and private developer apartments.

Findings from the literature review presented in chapter 2 of the study form the basis for research approach and methodology in line with the objectives of the research, which are summarised in Table 4.1

Table 4.1 Research Design approach based on Literature Review

SN	Objectives	Literature Review Parameters	Outcomes
1	Factors affecting energy consumption	Energy Use patterns & trends in multistoried housing Design parameters Building Envelope, Renewable energy	Design Parameters for retrofitting of existing housing, Key Performance Indicators
2	National policies & initiatives in energy efficiency	National policies, Building Codes, GBRS for existing buildings, Best practices case studies Drivers and Challenges	Choice of design strategies, Benchmark for existing housing, Cost effective strategies, Non intruding as per building byelaws, Three type of models based on ECBC
3	Assessment of energy consumption baseline	Sampling Design , Instrumentation. Energy Audits , Occupant Surveys Building performance evaluation tools	Research instruments Benchmark for energy use in study area Design of Questionnaire to form energy use pattern Thermal data modelling Inverse Modelling
4	Design strategies for retrofit	Research Methodologies Building Performance Simulation Statistical tools Life cycle cost analysis	Selection of Software Inverse Modeling Calibration Standards Design Simulations Design strategies Data Analysis

For data validation, multiple case studies have been employed so as to have a better understanding of various cross-section of society, rather than just one sample as required in a stratified sampling of different classes of samples. Multiple case study also eliminates chances of error due to any specific variable data and also provide a larger dataset to analyse [184]. Thus in all, eight case studies have been chosen representing a wider cross-section. The dataset so obtained is helpful in facilitating the triangulation of data from questionnaire surveys for generalizing the findings with higher accuracy and confidence.

Research design consists of the inductive and exploratory genre. The research design comprises of literature review, selection of study areas, sampling design based on framing of questionnaires and instrumentation, pilot study, sampling size and probabilistic stratified sampling and selection of research tools (Table 4.2). Energy consumption data for different group housing societies are collected from electricity utility bills. Two types of questionnaires are floated to understand user electricity consumption pattern, family composition, occupancy schedule, lighting schedule, appliance ownership, time and duration of use, window opening schedule, air conditioning schedule as well as building envelope characteristics of different housing societies.

A test simulation has been run in building simulation software Designbuilder to understand various attributes of each input variable and accordingly questionnaires were framed to extract information required as input variables in the software model. Thermal mapping of different apartments was conducted by using data loggers to establish temperature and humidity conditions.

Table 4.2 Details of Field surveys for research

Objective: To assess the energy performance of existing multistoried housing			
SN	Activity	Field Survey	Sample Size
1	Field Survey 1	Questionnaire Form I	67 societies
		Building Envelope Characteristics	
2	Field Survey 2	Questionnaire Form II	400 households from 8 societies
		Energy Consumption Pattern	
3	Field Survey 3	Electricity utility bills	
4	Field Survey 4	Thermal Mapping Instrumentation using data loggers	3 households for one year

The model is calibrated to energy use index or EPI from observed data and re-simulated several times after applying energy efficiency improvements in various input variables such as building envelope, shading and air tightness etc. The whole set of data both observed and simulated data are combined to form discrete smaller clusters so as to represent a set of different conditions. For instance, extreme values of energy consumption, very high and low with intermediate clusters of mean energy use intensity, medium high and medium-low and their attributes. From the data set, the probability distribution of such clusters or different parameters can be ascertained to minimise estimate or mean values currently being adopted. Thus the main steps involved in research methodology are

a) Selection of study area, selection of cases and establishing study parameters, Collection of base maps and preparing architectural drawings of each case.

b) Sampling Design, design of instrumentation and questionnaire.

c) Conducting Pilot surveys and test simulations to understand inputs required for whole building simulations.

d) Administering questionnaires, data collection

e) Thermal mapping of apartments continuously by instruments for a year.

f) Constructing baseline data taking in accounting for variations stochastic nature of occupants and building specifications using questionnaire.

g) Data analysis to establish a range of parameters of energy consumption patterns stratification of flats in different groups as per low, medium, high and extremely high energy usage trends and establishing a benchmark for data.

h) Selection of energy conserving measures for retrofitting in existing residential buildings

i) Simulating building model using building performance software and running parametric tests of different variables to yield optimum results.

j) Calculating Energy Performance Index (EPI) for different probability distributions /classes of buildings and other allied parameters such as reduction in discomfort hours, reduction in cooling load etc.

k) Data analysis using Analysis of Variance (ANOVA) to understand the variation in the mean of different EPIs achieved due to different energy conservation measures

l) Using sensitivity analysis to find the most significant architectural parameters or variables to affect EPI and to predict EPI using Multiple Regression Analysis by finding the relationship between EPI and architectural parameters for different use intensities.

m) Reduction in EPIs after applying retrofit measures in building simulations to assign a range of modules such as EE, EE plus or EE super having different sets of retrofit measures for making informed decisions as per cost-effective feasibility of retrofit measures by using net present value method to understand payback period and life cycle benefit.

4.3 Sampling Criteria for Selection of Cases

4.3.1 Selection of Parameters

The Quasi-experimental approach has been used to study the effect of selected design parameters using building performance dynamic simulations. The scope of the study is limited to only group housing schemes in Gurugram. Selection of sampling parameters entails choosing the case studies which are representative of different typologies of housing, for instance, public housing (institutional), Cooperative housing schemes (CGHS) and private developer housing. Another important criteria for selecting cases is building envelope characteristics primarily Window to Wall Ratio (WWR) and Projection factor for shading windows. Based on the pilot survey, the significant study parameters for thermal mapping of flats entails selection of three different types of energy usage pattern i.e. Low Energy Use Intensity (EUI), Normal Energy Use Intensity, and High Energy Use Intensity. Based on plan typology of tower type and slab type and product mix (2 BHK units and 3 BHK units), samples were selected for conducting questionnaire form II as defined in Table 4.2. Further different apartments have been chosen in same building having different orientations and location on the floor.

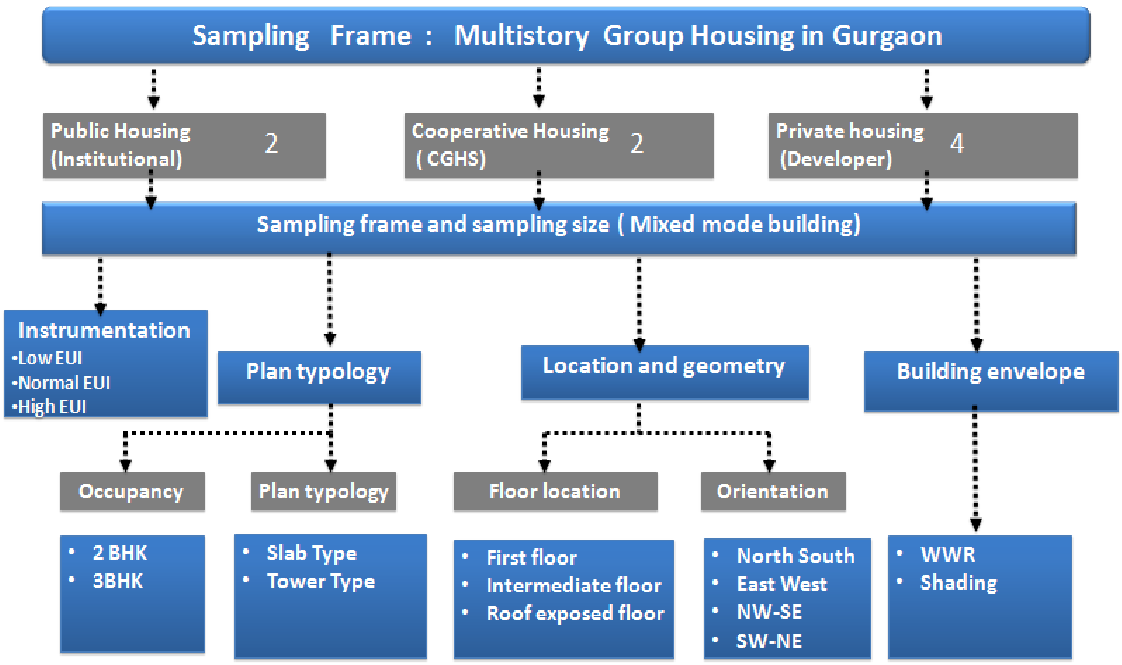


Figure 4.1 Study Parameters for Choosing Sample

4.3.2 Selection of Case Study areas

Based on sampling criteria defined in the previous section, an attempt has been made to take multiple representatives of each class so as to have a wider cross-section of study area and subjects. Multiple case study approach has been used to eliminate chances of error due to any specific variable data and also provide a larger dataset to analyze as well as validate the findings of data by a triangulation method. Thus for Questionnaire 1 as defined in Table 4.2, 67 housing societies have been studied taking at least two examples from each residential sector of Gurugram so as to define benchmark data of building envelope characteristics in the study area. For a detailed qualitative survey of energy consumption pattern in questionnaire II, the study of eight existing multistoried group housing societies has been undertaken for the entire year of 2016-17, taking 400 samples. For thermal mapping of flats, three flats in different housing societies have been chosen as per different use intensity owing to limited instrumentation available and accessibility of flats for allowing to install data loggers for the entire year.

Table 4.3 Detail of housing schemes selected for Survey II (Questionnaire II)

SN	Name of Housing Society	Location	Site Area (acre)	Type	No of dwelling units	No of samples taken
1	DLF Ridgewood estate (DLF RE)	Sector 27	13.5	Private Developer	724	52
2	Ansal API Sushant Estate (ANS SE)	Sector 52	10.0	Private Developer	864	75
3	Unitech Fresco (UNFRS)	Sector 50	16.9	Private Developer	830	75
4	Orchid Petals (OPID)	Sector 49	37	Private Developer	1300	114
5	Antriksh Srishti CGHS (A SR)	Sector 56	1.03	Cooperative Group Housing	48	12
6	Hextax Commune CGHS (HXT)	Sector 43	1.5	Cooperative Group Housing	107	24
7	HSIIDC Apartments (HSIIDC)	Sector 31	6.87	Public Sector Housing	385	24
8	Power Grid Township (PGT)	Sector 43	7.02	Public Sector Housing	350	24
Total units					4608	400

All of the samples in Table 4.3 use mixed mode of ventilation that is both air conditioning as well as natural ventilation for some part of the day and some months. Detailed selection criterion, the outline of various study areas chosen and their characteristics are described in Section 3.5.1to 3.5.8 the previous chapter 3 of the report.

DLF Ridgewood Estate

Ansal API Sushant Estate

Unitech Fresco

Orchid Petals

Antriksh Srishti CGHS

Hextax Commune CGHS

HSIIDC Apartments

Power Grid Township

Figure 4.2 Overview of Different cases for detailed study as per Table 4.2

4.4 Sampling Frame and Sample Size

4.4.1 Sampling Technique

The type of sampling technique used is probabilistic stratified sampling so as to take into account proportionate samples from each category as defined in sampling frame as per Figure 4.1 so as to represent subjects under case study from different strata such as different builder representation of housing from major developer share in Gurugram, public sector and cooperative group housing scheme. Within these societies, samples are again selected on basis of their floor location such as the First floor, intermediate floors and roof exposed top floors as well as different orientations. The sampling criteria have been explained in detailed in section 3.4.2 of chapter 3.

4.4.2 Sample Population and Sample Size

The sample population consists of a universe of all existing multistoried group housing schemes using mixed mode ventilation only in the city of Gurugram ; representing composite climatic context. The boundary conditions of the study area is defined to include multistoried group housing schemes which were constructed before 2010.

Gurugram, designated as a high potential zone by Haryana State Government and having a high-income level of its denizens is typically characterized by the presence of high-end multistoried group housing schemes. The decade from 1980's onwards has shown maximum growth in terms of residential spread with the land values skyrocketing with people opting for group housing schemes. Mid rise and high rise apartments accommodate the vast majority of dwellings and constitute 70% of the total housing supply. The number of ready to move flats by 2010 was 95,000 [63].

Thus the entire population of flats which is under scrutiny for the purpose of this research constitutes 95000 flats, out of which 80 % are occupied. Thus the target population works out to be 95,000*0.8 =76,000 flats housing nearly housing a population of 3, 80,000 by taking the size of 5 persons per household.

Sampling distribution of various statistic parameters such as mean or variance in EPI of the samples collected can be assumed close to normal distribution of population if the sample size is correctly derived. This implies that mean of a sampling distribution can be referred to as the mean of the population. Sample size can be calculated by finding out proportions of a particular attribute as best estimator of population proportion [184].

N = 76,000 (Total finite population of occupied flats)

e = Margin of error in % (taken as ±5 % error around EPI)

z = z score for confidence level (1.96 for 95% confidence level)

p = Expected proportion of population assumed to be

50% for most variable value in multiple attributes (0.5)

$$n = \frac{\mathbf{z^2. p. (1 - p)}}{\mathbf{e^2}}$$

$n = (1.96)^2 * 0.5*(1-0.5) / (0.05)^2$

n = 3.8416 * 0, 25 / 0.0025

n = 384.16

$$n_{adjusted} = \frac{\mathbf{n}}{\mathbf{1 + [(n - 1) / N]}}$$

n adjusted = 384/ [1+(383/76,000)]

= 384/1.005 = 382

Thus the sample size works out to be 382

There is another method of calculating sample size with the aid of online calculators and ready to use indices to arrive at sample size. In Table 4.4, It can be seen that sample size for a population size of 1, 00,000 works out to be 383 by taking margin of the error at 5% of EPI value and at a confidence level of 95%. It can be further seen that the there is an insignificant change in sample size when the sample population size increases to 10 lacs.

Table 4.4 Sample Size for given population size, confidence level & margin of error

	Confidence level = 95%			Confidence level = 99%		
	Margin of error			Margin of error		
Population size	5%	2,5%	1%	5%	2,5%	1%
100	80	94	99	87	96	99
500	217	377	475	285	421	485
1.000	278	606	906	399	727	943
10.000	370	1.332	4.899	622	2.098	6.239
100.000	383	1.513	8.762	659	2.585	14.227
500.000	384	1.532	9.423	663	2.640	16.055
1.000.000	384	1.534	9.512	663	2.647	16.317

Source: www.research-advisors.com/tools/SampleSize.htm [185]

It can be inferred from Table 4.4 that the sample size of 384 is large enough to account for all probabilities of the proportion of any attribute in data and sampling distribution and value of statistic parameter i.e. mean and variance in the sample can be taken for entire sample population with high reliability.

However, 400 samples are collected for analysis of questionnaires from eight different societies based on a stratified sampling of no of flats in each society.

For thermal mapping, 12 data loggers are used by taking a sample of three flats representing different types of energy usage intensity i.e. Low EUI, Normal EUI, and High EUI.

4.5 Data Collection

A pilot survey has been conducted to ascertain sample size by understanding variance in responses of samples. Finally, the sample size is calculated as defined in the previous section. The primary data is collected using research instruments such as field surveys, questionnaires and thermal instrumentation to understand variables or input parameters required for simulation model and calibration of the same as per International performance measurement and verification protocol standards. Permissions were obtained from respective Resident Welfare Association (RWA) to conduct a questionnaire survey. Respondents were pre-informed, about the intent and outcomes of the research and consent of their voluntary participation was obtained. Respondents were assured about the anonymity and confidentiality of their responses.

4.5.1 Field Survey I: Building Envelope Characteristics

To understand Building Envelope characteristics of sample housing schemes so as to form input variables for building simulations and understand the relationship between energy consumption residential group housing societies and building envelope, a detailed survey was taken to form baseline data of existing housing schemes. Various housing schemes are chosen from each residential sectors having group housing societies designed and constructed within a period of 1985-2010.

The large sample size was taken to assess different variables in building geometry and materials used, by taking at least two housing societies from each sector. The city development plan of Gurugram shows the distribution of various housing schemes as sample data.

Figure 4.3 Panel of different housing schemes as samples in Gurugram showing the diversity of materials, shading devices, Wall to Window Ratio

There are a total of 210 group housing societies constructed in Gurugram within a period of 1985-2010, with no: of flats constructed 95000. Thus a total of 67 housing schemes, representing 29148 flats. were studied as a sample data (Table 4.5 and Figure 4.3) showing the diversity of materials, shading devices, wall to window ratio. The sample consists of 9% share of public sector housing (6 samples), 22% sample of Cooperative group housing Societies (15 samples) and rest 69% data from private developers (46 samples) (Figure 4.4).

Table 4.5 List of selected Group housing schemes in the sample in the study area of Gurugram for Building Envelope Characteristics.

SN	Sector	Name of housing Society as Sample
1	1,2,15, 21, 22	Mittal Cosmos Executive Apartment, Bestech Park View Residency, CGHS Rail Vihar Apartments, Mittal Surya Vihar, Alpha Gurgaon One 22, Maxworth Premier Urban, Ambience Creations
2	26A, 27, 28, 30,31, 39,	DLF Ridgewood Estate, Hamilton, Essel Tower, Windsor, Rose Apts., Beverly Park, Laburnum Apts. Unitech world spa south, Unitech Uniworld city, CGHS HEWO apartments, HSIIDC Apartments, Milan CGHS; The Palm
3	41,42,43, 45,47	Central Park I, Aralias, PWO Housing Complex, Navyug Apts. , Maple Heights, HB Galaxy, Lord Krishna CGHS, Hamlin Apts., Army Welfare Housing, Power Grid Township, Hextax Commune. Unitech Greenwood City, CGHS Doordarshan Apartments; CGHS Airport Apartments BNB Imperia Tower
4	49, 50, 51, 52,	Vatika City, Omaxe the Nile, Sispal Vihar, Eros Wembley Estate, Orchid petals, The Close North, Unitech Fresco, Abhinandan CGHS, Arzoo CGHS, Ansal API Sushant Estate
5	53, 54, 55, 56, 57	Vipul Belmonte, Carlton Estate, Vipul Orchid Gardens, Dlf the Belaire, CGHS Aravali Homes; Sagavi Apartment, PragatiApartment; Kendriya Vihar, Rail Vihar, Smriti Apartment, CGHS, , Kanchanjanga Tower, Guru Gram Haryana, , Antriksh Srishti Apartment, The Lions, Alaknanda Apartment, Sahyog Apartment; BPTP Freedom Park Life, IRWO Classic Rail Vihar .

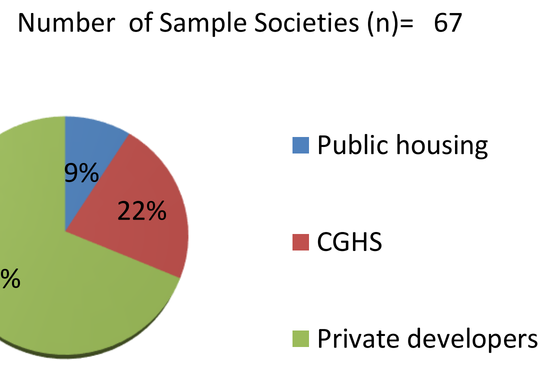


Figure 4.4 Percentage distribution of public sector housing, Cooperative group housing Societies and private developers in Gurugram.

The questionnaire is designed to gain insight in building design parameters of existing building. It consists of four sections having 25 questions as defined below:

i) Section 1 having 10 questions pertaining to
Housing characteristics covering Information of the housing society, site area, no of flats, stilt parking, shape of the tower, area of the dwelling unit.

ii) Section 2 having 4 questions pertaining to
Opaque construction covering Wall and roof covering, wall construction, roof construction, the colour of the finish on walls, roof finishing.

iii) Section 3 having 6 questions pertaining to
Fenestrations for understanding, WWR, window material, type of glass, type of window, openable % v/s fixed window, external doors.

iv) Section 4 having 5 questions pertaining to
Shading characteristics covering internal shading devices, exterior shading devices, size of projections, size of the balcony.

4.5.2 Field Survey II :Energy Consumption Pattern Questionnaire

4.5.2.1 Design of Questionnaire

The primary objectives of the second questionnaire in the field survey is to firstly understand energy consumption usage pattern of existing multi-storeyed group housing in the study area , secondly form baseline data for occupancy schedule , HVAC schedule, lighting schedule as prescribed by ECBC 2017 for defining base case in energy simulation models for other building typology and lastly to gauge people's awareness and attitude towards retrofitting for understanding non-intrusive design parameters as well as affordability of people. All the data so collected forms input variables for preparing base model building simulations and also decide design parameters to be employed in retrofitting of existing housing schemes. Eight housing schemes are chosen for in-depth qualitative assessment of energy consumption pattern from residential sectors having group housing societies designed and constructed within a period of 1985-2010. Housing schemes chosen as a case represent a proportional sample of housing typology with at least two samples from each housing typology so as to eliminate the effect of any single variable and allow comparison of data and validation by a triangulation method. Various housing societies selected for sample survey along with their site area and no of units and type are listed in Table 4.2.

A test survey was conducted in the field to understand the responses, ambiguity in statements of questions and gauge respondents' reaction in terms of understanding the question statement or difficulty to answer or even order of questions. As a consequence, some of the questions have been rephrased for better understanding. Use of ordinal scales was made to gauge qualitative responses. Some indirect questions were added to validate responses of previous questions in order to ascertain responsiveness of subjects. Some of the answers are redefined for ease of respondents.

Inverse modelling technique has been used to identify input parameters for building performance simulation modelling. Inverse modelling technique entails determining parameters from causal factors or effects that are responsible for causing effect [197]. An Inverse modelling solution maps the causal effects to establish factors responsible for them [198]. The building performance simulation models to establish baseline model are data driven models where a large no of input variables are required to be fed in the model. A test simulation model is generated to identify parameters/ input variables influencing the results in the model . This data is a necessary to input for a better understanding of building energy performance concerns A better understanding of input variables from inverse modelling technique helps in eliciting the information from the sample subjects in the form of field-based research instruments such as questionnaires and instrumentation for thermal mapping. As a result, occupant surveys are conducted to develop building baseline data for window operating schedule, occupancy schedule, equipment usage schedule, air conditioning use schedules, lighting fixtures operating schedules in addition to types of various materials used in windows, star rating of air conditioners, power consumption of appliances and lighting fixtures, fans etc and their controls. A few questions have been added in line with requirements of simulation software model as input variables like the amount of time spent in different areas of the apartment as per modelling requirement or rating of thermal comfort of respondents on ASHRAE Scale.

The questionnaire consists of four sections having 41 questions in all (Appendix B).

i) Section 1: Household Characteristics covering background information of the occupants, area of dwelling, the age of housing and connected electric load.

ii) Section 2: Electricity Consumption pattern covering Occupancy schedule, schedule of cooling and heating, cooling set point temperature, usage and type of appliances, lighting and fans, and electricity consumption.

iii) Section 3: Environmental characteristics such as thermal conditions, visual comfort, lighting controls, and ventilation.

iv) Section 4: Retrofitting characteristics covering renovation trends, attitude towards renovation, affordability of users to invest initial capital in retrofitting. The questionnaire ended with an open-ended section for comments/ observations/ suggestions of respondents.

For eliciting proper responses from respondents, use of a standardized scale of measurement (5 points Likert scale) such as to rank response of importance of renovation in different objectives, the scale used is not important, slightly important, important, very important, and essential. Questions like how satisfied you are on daylighting in your house, 5 point scale from very dissatisfied to very satisfied have been used. For acceptance of thermal environment, two-point nominal scales are used in form of two responses only whether acceptable or not acceptable.

Different sampling techniques are used to widen database and collect samples. Both offline and online forms were designed for questionnaire with the help of Google Docs. Direct surveys were conducted from friends/ acquaintances residing in societies and by contacting resident welfare associations (RWAs), taking their permission and contacting residents by lead provided by the RWAs. Real Estate Agents operating in these societies were conducted to provide contact details of residents. Offline forms are used to contact residents in society, parks or local convenience shopping market. Snowballing technique is used to increase the database by getting lead from friends/relatives or students of architecture or real estate agents or getting lead from the mailing list of facility management offices. Online questionnaire survey form was mailed to residents of the housing scheme. Residents participated enthusiastically in questionnaire surveys with a response rate of over 25% which is considered a very high response rate in online questionnaire responses. All the responses, whether offline or online were fed in Google docs responses so as to generate an automated response summary from Google Docs. A total of 400 samples as transverse surveys are collected representing 4608 samples throughout the year 2016-17. The spatial distribution of samples collected at the city level is shown in Figure 4.5.

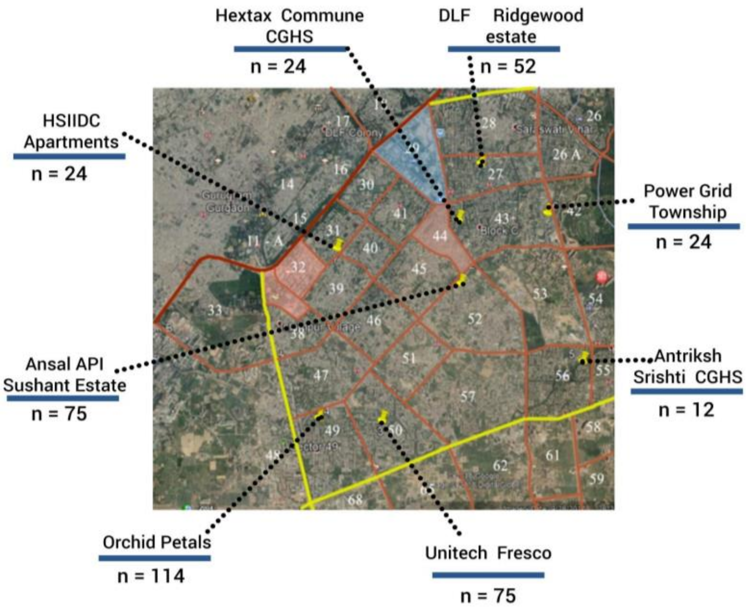


Figure 4.5 Spatial distribution of samples of different housing schemes as a case [183]

4.5.3 Field Survey III: Electrical Energy Utility Bills

Electric energy utility bills are collected for all the flats in a single tower in eight housing societies chosen as sample. While taking utility bills, electricity units for common lighting services and maintenance charges have not been considered. Public sector housing units have a direct connection from Dakshini Haryana Bijli Vitran Nigam (DHBVN), a state government agency responsible for the supply of electricity. In some cooperative housing societies, there is bulk electricity metering for all tower, from where electricity consumed by each consumer is billed to residents by Resident Welfare Association (RWA) or facility management agency of the respective society.

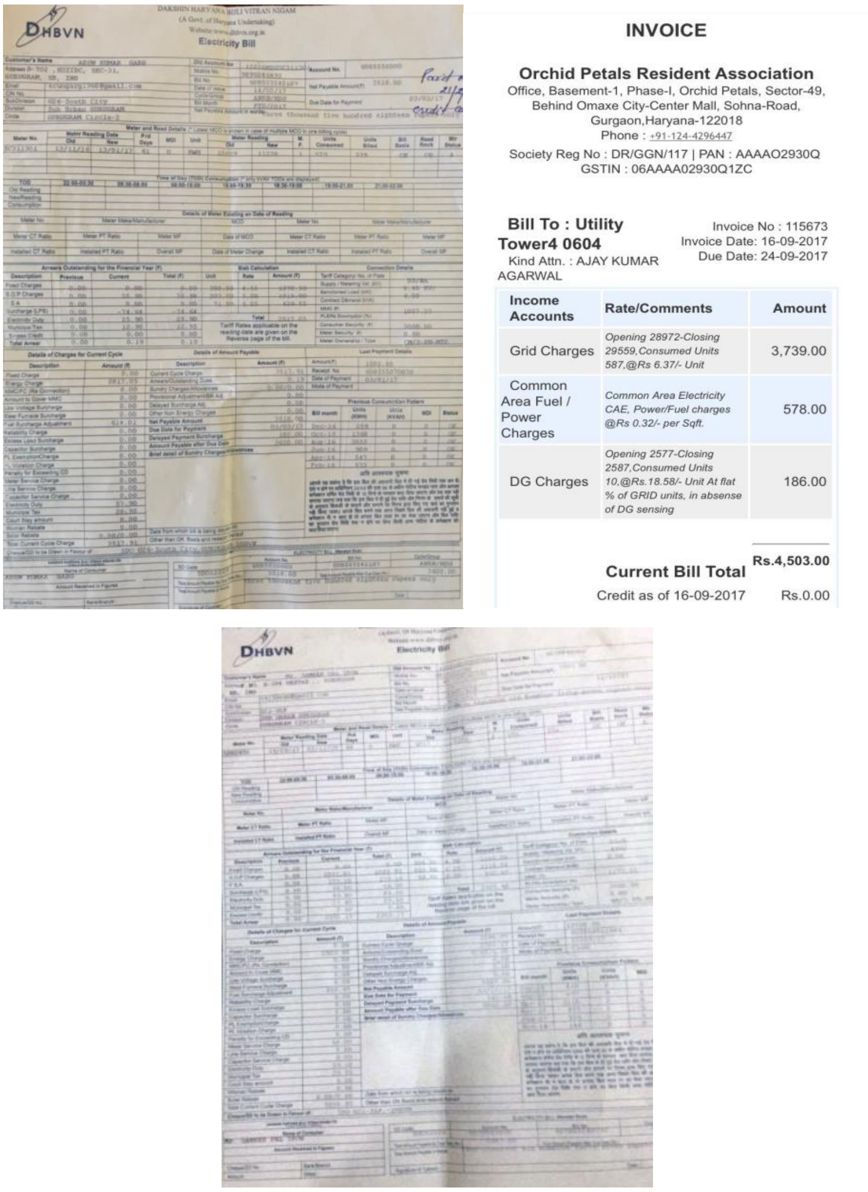


Figure 4.6 Electricity Utility Bills of sample housing schemes

Table 4.6 Detail of Electricity Utility bills of a typical tower.

Annual Electricity Consumption Survey Chart, (NOV.2016 - OCT. 2017)

.No	Floor	Flat No	FLAT A	BLOCK A												
			SQ.FT	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Total
1		A/1	2150	870	976	765	1023	578	976	1432	1876	1211	1760	1660	1123	14250
2		A/2	1875	615	689	540	723	408	689	1012	1325	855	1243	1173	793	10065
3		A/3	1677	291	264	168	182	83	114	135	144	941	1108	846	464	4740
4	Ground	A/4	2282	261	237	150	163	75	102	121	129	843	993	758	416	4248
5		A/5	2150	688	772	605	809	457	772	1133	1484	958	1392	1313	888	11271
6		A/6	1875	467	524	411	549	310	524	769	1007	650	945	891	603	7650
7		A/7	1975	221	201	128	138	63	87	103	109	715	842	643	352	3602
8	1	A/8	2282	771	865	678	906	512	865	1269	1662	1073	1560	1471	995	12627
9		A/9	2150	523	587	460	615	348	587	861	1128	728	1058	998	675	8568
10		A/10	1875	248	225	143	155	71	97	115	122	801	943	720	395	4035
11		A/11	1975	863	969	759	1015	574	969	1421	1862	1202	1747	1647	1115	14143
12	2	A/12	2282	586	657	515	689	389	657	964	1263	816	1185	1118	756	9595
13		A/13	2150	656	736	577	772	436	736	1080	1415	913	1327	1252	847	10747
14		A/14	1875	422	473	371	496	280	473	694	910	587	853	805	545	6909
15		A/15	1975	381	427	335	448	253	427	627	821	530	770	727	492	6238
16	3	A/16	2282	735	824	646	864	488	824	1210	1585	1023	1487	1402	949	12037
17		A/17	2150	499	559	439	586	331	559	821	1075	694	1009	952	644	8168
18		A/18	1875	384	384	384	384	384	384	384	384	384	384	384	384	4608
19		A/19	1975	757	849	666	890	503	849	1246	1632	1054	1531	1444	977	12398
20	4	A/20	2282	545	612	479	641	362	612	897	1176	759	1103	1040	704	8930
21		A/21	2150	356	400	313	419	237	400	587	769	496	721	680	460	5838
22		A/22	1875	169	153	97	105	48	66	78	83	546	643	491	269	2748
23		A/23	1975	1114	1249	979	1309	740	1249	1833	2401	1550	2253	2125	1437	18239
24	5	A/24	2282	131	147	115	154	87	147	216	283	182	265	250	169	2146
25		A/25	2150	364	409	320	428	242	409	600	786	507	737	695	470	5967
26		A/26	1875	434	512	652	320	423	454	554	311	558	657	502	654	6031
27		A/27	1875	678	761	597	798	451	761	1117	1463	944	1372	1294	876	11112
28	6	A/28	2282	303	340	267	357	202	340	499	654	422	614	579	392	4969
29		A/29	2150	846	949	744	995	562	949	1393	1825	1178	1712	1614	1092	13859
30		A/30	1875	574	644	505	675	381	644	945	1238	799	1162	1096	741	9404
31		A/31	1875	281	315	247	331	187	315	463	606	391	569	537	363	4605
32	7	A/32	2282	840	942	739	988	558	942	1383	1811	1169	1699	1603	1084	13758
33		A/33	2150	259	291	228	305	172	291	426	558	360	524	494	334	4242
34		A/34	1875	500	561	439	588	332	561	823	1078	696	1011	954	645	8188
35		A/35	1875													
36	8	A/36	2282	426	478	375	501	283	478	702	919	593	862	813	550	6980
37		A/37	2150	515	577	453	605	342	577	847	1110	716	1041	982	664	8429
38		A/38	1875	371	416	326	436	246	416	610	799	516	750	707	479	6072
39		A/39	1975	242	272	213	285	161	272	399	523	337	490	462	313	3969
40	9	A/40	2282													
41		A/41	2150	757	850	666	890	503	850	1246	1633	1054	1532	1445	977	12403
42		A/42	1875	89	100	78	105	59	100	147	192	124	180	170	115	1459
43		A/43	1875													
44	10	A/44	2282	248	278	218	291	165	278	408	534	345	501	473	320	4059
45		A/45	2150	461	518	406	542	306	518	759	995	642	933	880	595	7555
46		A/46	2282	206	231	181	243	137	231	340	445	287	417	394	266	3378
47		A/47	1875	297	334	261	350	198	334	489	641	414	602	567	384	4871
48	11	A/48	2282	575	645	506	677	382	645	947	1241	801	1164	1098	743	9424
49		A/49	2150	191	215	168	225	127	215	315	412	266	387	365	247	3133
50		A/50	1875													0
51		A/51	1975	571	641	502	672	379	641	940	1232	795	1155	1090	737	9355
52	12	A/52	2282													0
53		A/53	2150	176	198	155	207	117	198	290	380	245	356	336	227	2885
54		A/54	1875	340	381	299	400	226	381	559	733	473	687	648	439	5566
55		A/55	1875	290	325	255	341	193	325	477	625	403	586	553	374	4747
56	13	A/56	2282	332	373	292	391	221	373	547	717	463	673	634	429	5445
57		A/57	2150	350	393	308	412	233	393	576	755	487	708	668	452	5735

With the aim of developing energy conservation measures and arrive at a clear understanding of patterns of energy use and user behaviour, utility electric data of 400 flats is collected for assessing energy consumption to understand consumption pattern month wise (Table 4.6 and Figure 4.6) and find out what are the factors responsible variations in energy use intensity. It is interesting to note that there is a high variation in EPI. It varies from 33 kWh/m^2/yr to 128.5 kWh/ m^2/yr. There are several variables affecting energy use such as number of members in the family, usage pattern in daytime or evening time as people work in multi-national companies, cooling set point temperature preferences, appliance penetration, energy efficient gadgets, use of artificial lighting, use of heaters in winters etc. There are large variations in electricity consumption within different months depending on occupancy pattern, people not living in the house during vacations or otherwise, the energy required for cooling and heating etc. Some of the residential units are not occupied or are sparingly used by guests or caretakers only. Data obtained from such flats are treated as outliers case in statistical data and hence not included while calculating statistic parameters such as mean and standard deviation of EPI.

Finally, the data of individual flats is collected for the entire year 2016-17 to arrive at electricity consumption baseline data and classify the users in three classes i.e. Low energy intensity use (EUI), Normal energy intensity use and High energy intensity use.

4.5.4 Field Survey IV: Thermal mapping for indoor environmental parameters

Thermal conditions of indoors are monitored using data loggers of onset computers, U.S.A. as per international protocols as defined in 'Performance Measurement Protocols for Commercial Buildings: Best Practices Guide by ASHRAE'[186]. Data loggers are used for obtaining three parameters i.e. temperature, relative humidity and lighting level in indoors as shown in Figure 4.7 [187].

Figure 4.7 Data logger U-12 by Onset Computers

Three flats are selected as a sample case for thermal mapping of environmental parameters with four data loggers installed in each 3 BHK flat (Table 4.7). Thus in all, twelve data loggers are employed in three flats only, due to the availability of limited numbers of data loggers and accessibility constraints to private nature of housing units. The flats are selected on basis of energy consumption use i.e Low energy intensity use (EUI), Normal energy intensity use and High energy intensity use. Further all flats are located on intermediate floors and facing same orientation so as to eliminate the effect of other variables such as roof exposed floor or effect of solar radiations on flats. Further, an attempt is made to include flat from each category of developer i.e. Public sector, Cooperative sector, Private developer housing.

Table 4.7 Details of flats for thermal mapping by data loggers

SN	Name of Housing Society	Type	Size	Floor	Orientation	Energy Use Intensity
1	Orchid Petals (OPID) , Sec 39,	Private Developer	3BHK	6	NS	Low
2	HSIIDC Apartments (HSIIDC) , Sec 31	Public Sector Housing	3BHK	5	NS	Normal
3	Hextax Commune CGHS (HXT) , Sector 43	Cooperative Group Housing	3BHK	4	NS	High

Data loggers are launched through a laptop using software Hoboware to start recording of temperature, relative humidity and lighting levels [187]. The thermal mapping for three flats is conducted for the entire year of May 2017- April 2018 to provide continuous data on an hourly basis. Data loggers offer the scope of calibration in temperature conditions.

Each data logger is calibrated from readings of handheld thermo hygrometers. The difference of maximum 0.4^0C was noticed between readings, which is well within tolerance limits prescribed by the manufacturer. Each data logger is mounted at height of 1.2 m above the finished floor level of the apartment and at a distance of 1.0 m away from the window in all three bedrooms and living room (Figure 4.8).

Figure 4.8 Location of data logger in different rooms

The data can be exported in spreadsheets as well as plotted for the desired period. Usually, each flat is monitored once each month to ensure that they are in place and working order and as well as retrieve data. Various parameters for a range of measurement, accuracy and response time of data loggers are presented in Table 4.8.

Table 4.8 Range of data loggers U-12 for measuring Temperature, RH and Lighting [187]

SN	Parameter	Temperature	Relative humidity	Lighting
1	Measurement Range	-20°C to 70° C	5% to 95% RH	0-32000 Lumens/m^2
2	Accuracy	±0.4° @25° C	±2.5% RH from 10 % to 90% RH	For indoor measurements
3	Resolution	0.03°	0.03% RH	12 bit
4	Response time	6 Minutes to 90 % in air flow of 1m/s	1 Minute to 90 % in air flow of 1m/s	Instantaneous

4.5.5 Discussion with experts in the field

Participation in different training programs, hands-on workshops on building simulation modeling, national and international conferences, the opinion of several experts in the field is obtained to form construct of realistic issues in the research area. The external inputs so obtained helped in strengthening of problem statement, identification of issues in retrofitting of existing housing, selection of design parameters and finally helping in forming occupancy schedule from database in primary field survey on the lines of ECBC 2017. Acquiring soft skills in early stages of the research helped to frame design questionnaire for inputs required in building simulation model. The interaction with researchers and experts in the field yielded in fine-tuning statistical skills to conduct statistical analysis in data analysis and recommendations. The list of various training programs, workshops, and conferences attended to understand the depth of the subject can be referred in Appendix.

4.6 Reliability and validity of the data

Reliability and validity of data collection methods are important steps in research design. Taking more than two techniques, often referred as triangulation of data is considered the best way to establish reliability as well as internal validity of data collection. Thus, multiple tools and techniques have been used in the following ways:

i) Sample design and Sample size worked out for the reliability of data
ii) Multiple case studies to eliminate the effect of any single variable and allow comparison of data and validation by a triangulation method.
iii) Minimum of two housing schemes from each sector for building envelope characteristics study.
iv) Indirect questions in the questionnaire to validate responses of the respondents and multiple questions for measuring energy consumption pattern.
v) Electrical energy bills data to validate responses from the questionnaire for detailed survey of energy consumption.
vi) Calibration of data loggers to give accurate temperature conditions.
vii) Thermal mapping by data loggers to validate response from the questionnaire
viii) Statistical tools such as ANOVA and other tests to compare variation in data collected.
ix) Calibration of building simulation model for reliability and validation of the model

4.7 Summary

This chapter deliberates on systematic approach in various steps of research design such as delineating various steps of research in fulfilling the objectives of the research i.e. assessment energy performance of existing multistoried housing. Selection criteria of study parameters and selection of cases for undertaking a detailed survey are established to choose samples. It describes sampling size and sampling design for ensuring a wider cross-section of society to help generalize the findings. Data collection method include research instruments for both qualitative and quantitative data such as questionnaires for assessing building envelope characteristics and energy consumption pattern, electricity utility bills and thermal mapping to measure environmental parameters required for calibration of building a simulation model. Further, the chapter prescribes procedures to conduct field surveys, pilot surveys, scales of measurement and ethical considerations adopted in carrying the research.

5.1 Introduction

Energy consumption of existing multistoried residential buildings depends on several design parameters, user behaviour and preferences in energy use. There is a great variation in energy usage pattern in residential buildings unlike other typology of buildings such as commercial and institutional buildings. This chapter provides data analysis of energy consumption to construct baseline data of energy performance index in existing housing and occupancy schedules for residential buildings on parallel lines of ECBC 2017 for other residential buildings. Further, it analyzes various dependent variables which would affect energy consumption pattern as well as form basis for input of building performance simulation model to calibrate the model. Finally retrofitting measures are applied to building simulation model to predict savings in energy. Statistical tools have been applied to establish a relationship between building envelope characteristics and energy consumption pattern. Analysis of variance between simulated results of energy savings is done to understand variations in predicted EPI and hence generalize the findings. Finally, Lifecycle cost analysis is carried out to form three modules to offer choices to help users in making decisions as per affordability of users and payback period of investments done in retrofits.

5.2 Methodology

Three types of primary surveys are conducted as defined in Table 4.1 of the previous section. Responses from the two questionnaires are entered in Google Docs to auto-generate the response summary which can be retrieved in spreadsheets as well as graphical bar diagrams or pie charts. Based on findings of Questionnaire II, occupancy schedules, window opening schedule, HVAC, schedules, lighting schedules are defined so as to form input for building performance schedule. A test model is generated in Design builder version 5.01.024 to test run the inputs and reports so as to check the validity of input data. A total of 48 test iterations of the model are run by changing different variables such as creation of virtual partitions in thermal zones and ground temperature, reflectivity of ground and modelling surrounding buildings in the model. Finally different models for mean energy performance index of different use intensities such as Low, Medium and High and as well as for thermal data mapping are prepared so as to construct the 'As is' model as close to real life context using mixed mode of ventilation. Different parameters such as Energy Performance Index, building heat gain factor, cooling load and discomfort hours are recorded from each simulation so as to derive the relationship between them and design parameters for retrofitting as dependent variables. This also helped in cross-validating the findings from each retrofit as well as in the enhanced understanding of reasons in variations in different parameters. Multiple indicators are also helpful in the internal validation of findings. The findings are discussed in the next chapter in context of finding of other researchers for external validation

5.3 Field Survey I: Building Envelope Characteristics

The sample of 67 societies is evaluated for making baseline data of Building Envelope Characteristics of existing multistoried residential buildings in Gurugram, taking the representation of at least two sample from each residential sector. The questionnaire is designed to address various design parameters such as geometry, construction of opaque and transparent surfaces and lastly shading devices and the type of ventilation system. There is a rich mix of societies having site area ranging from 0.5 acres to acres in size with the mean density of units as 50 dwelling units per acre. The questionnaire is divided into four sections viz. geometry, opaque construction, transparent construction and shading elements

5.3.1 Geometry of apartments

5.3.1.1 Built-up Area of the dwelling unit

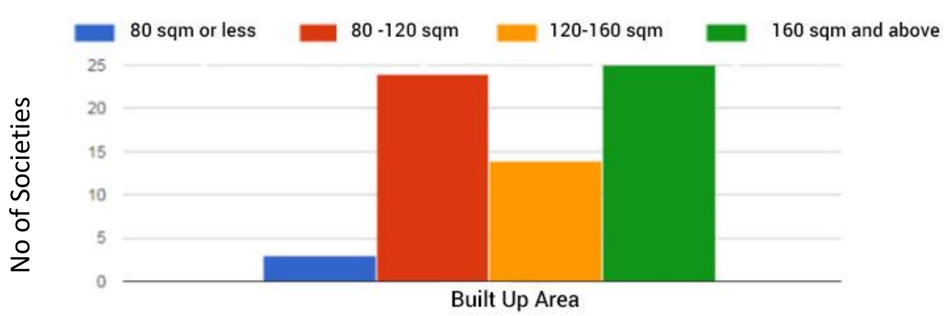


Figure 5.1 Distribution of flats as per area of the flats.

In the geometry of apartments, the built-up area of dwelling units constitutes one of the major factors in determining energy consumption or EPI. The residential flats are quite large in size.

37.8% of the total flats in sample constitute largest size category i.e. 160 sqm and above built-up area with 3 BHK and study room or 4 BHK units, closely followed by 21.21% of flats of built-up area in a range of 120-160 sqm, thus together making 59.01% of flats forming a class of 120 sqm and above category. The flats of area 80-120 sqm having 2 BHK -3BHK constitute 36.3% of total flats. The flats with 80 sqm or less size (2BHK or studio apartments) constitute only 4.5% share of total flats.

5.3.1.2 Provision of Stilts

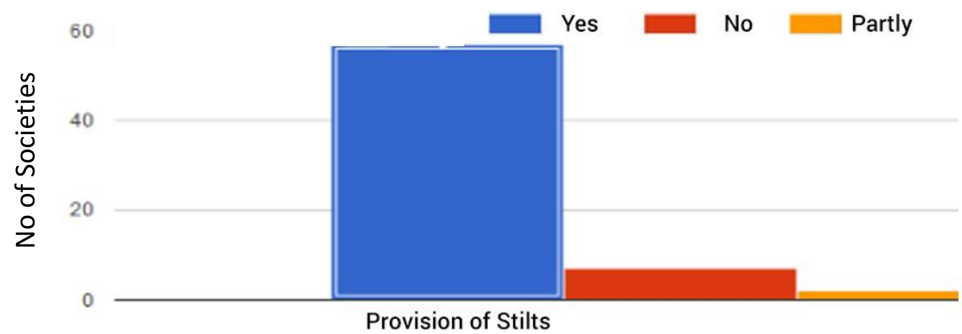
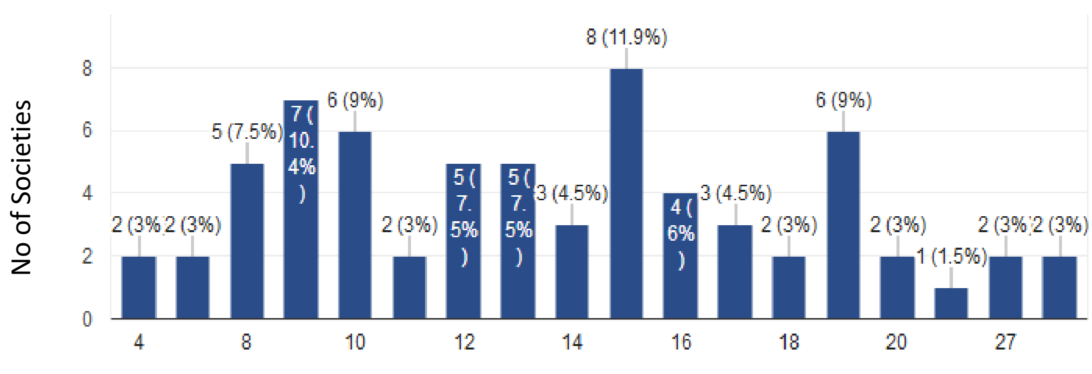


Figure 5.2 Distribution of societies for the provision of Stilts.

Most of the societies have stilts for parking, thus having no floors in contact with the ground, implying that residential units on the first floor of such units can transmit heat with surrounding air through the base floor. 86 % of the total societies in the sample have the provision of stilt for parking, whereas, in 14% societies, there are flats constructed on ground floor fully or partially.

5.3.1.3 No of stories



No of Storeys
Figure 5.3 Distribution of societies for no of stories.

No of storeys in existing group housing range from 4 to 29 with 54.5% schemes falling between the class of 8-15 storeys. The average no of storeys is 15 with the mode also being 15, indicating that the most schemes are 15 storeys in height. The schemes which have more than 15 stories constitute 31.8% share of the total housing schemes. The schemes upto 8 stories in height constitute 13.7% share of the total housing schemes.

5.3.1.4 Geometry of Tower

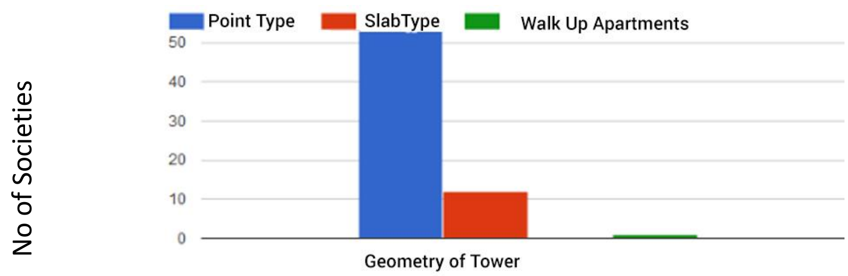


Figure 5.4 Distribution of societies for the geometry of towers.

The most common form of the residential built typology is point tower blocks (80.3%) with four dwelling units on each floor, served by a central core of services and staircase/ lift lobby. Thus in most cases, in the tower type flats, walls are exposed to three sides for thermal transmittance. Since there are four flats symmetrically placed, windows generally face all orientations. The other class is slab type apartments, the flats are conjoined on at least one side, making two sides exposed to solar radiations for thermal heat gain or loss. There are a very few flats with slab type (18.7%) of total flats.

5.3.1.5 Distance between two blocks

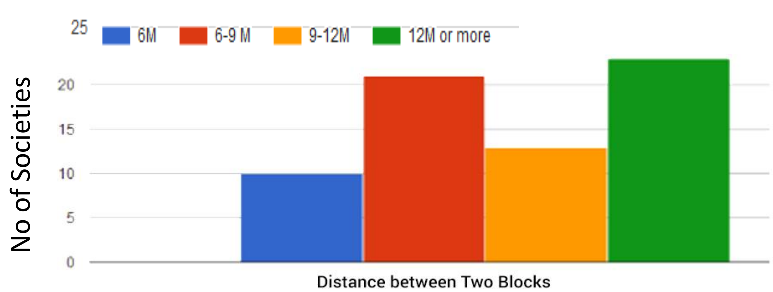


Figure 5.5 Distribution of flats as per distance between two blocks.

The distance between towers plays important role in mutual shading of blocks, reducing the thermal gain of the blocks in summers. 46.96% of towers have distance from less than 6 m to 9 m between two towers, thus considerable shading is due to less distance between the towers.19.69% of all the towers have distance ranging from 9m to 12 m between towers. 33.35 % of towers have distance more than 12 m between towers.

5.3.2 Opaque Construction Characteristics

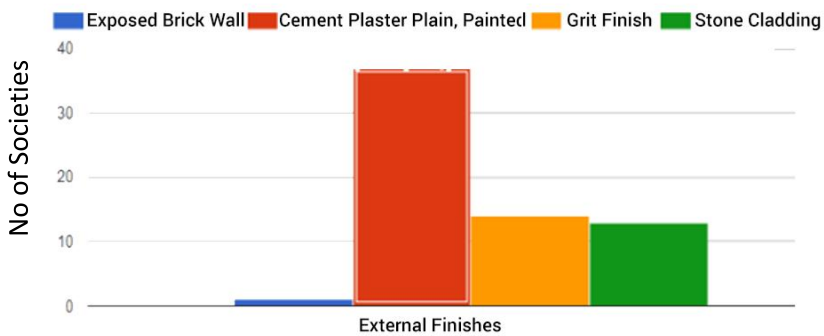


Figure 5.6 Distribution of flats as per external finishing of towers

All the flats are constructed with 230 mm thick burnt brick masonry with plaster on inside face. 56.1% of flats are finished with exterior cement based paints, followed by 21.2% of flats finished in grit finish (Figure 5.6). 19.7% of flats are finished with stone cladding on the external face with only 3% of flats are finished in the exposed brick face. Mean thermal transmittance U value for wall assembly in flats is 2.51. Roof Assembly consists of reinforced cement concrete (RCC) slab of thickness varying from 125-150 mm insulated with brick Coba or mud phuska and finished with brick tile terracing. Mean thermal transmittance U value for roof assembly in flats is 2.6.

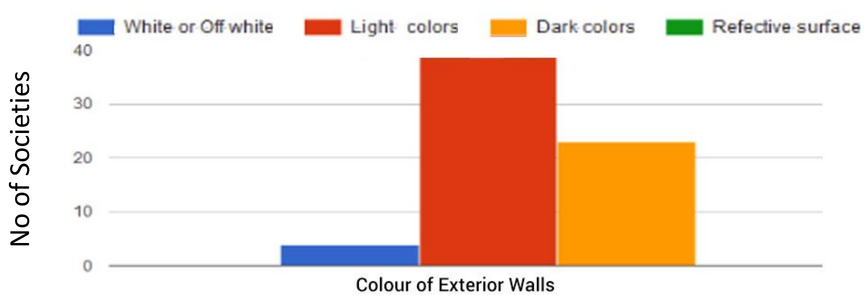


Figure 5.7 Distribution of flats as per the colour of the exterior walls

The surface reflectance of the exterior side of building envelope plays important role in reducing or absorbing thermal heat. 59.09 % of towers have light colour finish with medium reflectivity 0.5, 6.11 % of towers have a white surface with high reflectivity 0.7 and above. 34.8% of towers have dark colour finish with low reflectivity 0.3 or less. Mean surface reflectivity of walls is 0.45, with a standard deviation of 0.115 and the mode being 0.5. The surface reflectivity of the roof is 0.45 for all cases.

5.3.3 Transparent Construction Characteristics

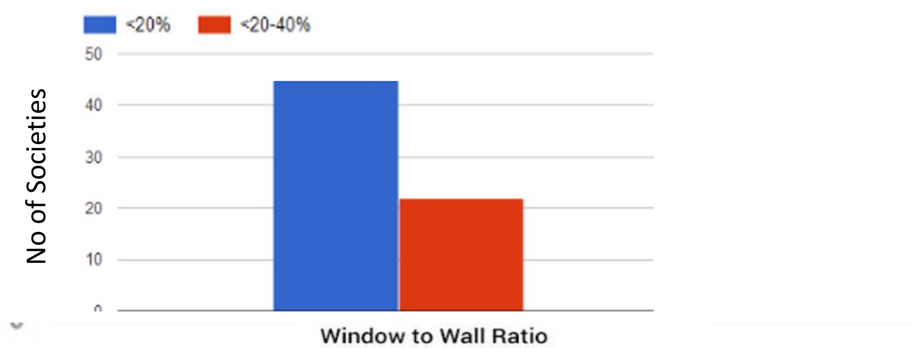


Figure 5.8 Distribution of flats as per WWR

The window to wall ratio (WWR) defined as window area as a percentage of total wall area constitutes a major source of heat ingress due to its being transparent to solar radiations. 68.18 % of flats have WWR less than 20 %,31.82% of flats have WWR between 20-40%. There is an increasing trend of large size glass windows in recent constructions having WWR upto 45%.The properties and colour of the glass is an important factor in controlling solar heat gain. 95% of flats have a single plain glass of thickness 4mm to 5 mm with SHGC of value 0.85. Very few flats (5%) have windows fitted with tinted glass or reflective glass with SHGC of 0.47. External doors to balconies from living spaces have a remarkable variation with 44 % of flats having a glass door to the balcony. 36% of flats have an opaque wooden door, followed by 20 % of flats having a partly glazed door.

Another important parameter for heat gain or loss through the window is window material. 56 % of towers have a wooden frame with less than 25% operable windows. 44 % of towers have aluminium windows with 50% operable windows (Figure 5.9).Thermal transmittance (U value) for wooden frames in windows is 3.3 $W/m^2/K$ whereas U value for aluminum frames in windows is 6.1 $W/m^2/K$.

Figure 5.9 Distribution of flats as per material used in the window frame

5.3.4 Shading of windows

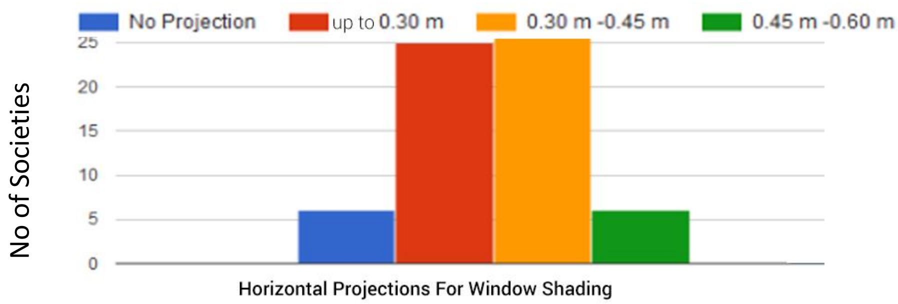


Figure 5.10 Distribution of flats for horizontal projections as shading over windows

Shading is a useful tool with designers to ward off solar radiations and direct heat through windows and walls. Shading consists of horizontal projection as sunshades, balconies, vertical projection or combination of both to form box type projection. In 77.27 % of flats, horizontal projection range upto 0.45 m depth from the face of the wall, in 11.09% of flats, projection are beyond 0.45 m and upto 0.6 m deep and a few flats (11.64%) have windows with no projections.

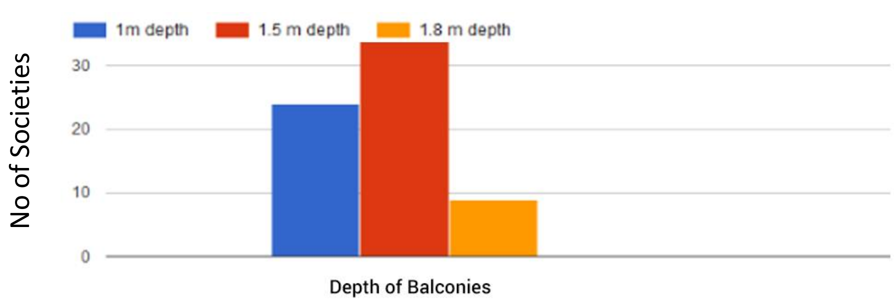


Figure 5.11 Distribution of flats as per depth of balcony

Balconies are an integral part of the architectural character of apartments in Gurugram and also serve to shade windows and exposed walls. 51 % of towers have a balcony with the depth of 1.2m, providing adequate shadingto windows and 13 % of flats have a 1.8 m depth of balcony. 36 % of towers have a balcony with a shallow depth upto 1.0 m from the face of the wall. The shading devices range from balconies, recessed window types or fins like projections from the face of the wall to form box structure or movable retractable awnings. Figure 5.11 shows the distribution of flats having different shading devices, showing 79.1% of windows are having a balcony as a shading device and 14.9% windows are recessed type upto 0.45 m depth. The value of the projection factor as an indicator of the effectiveness of the shading element ranges from 0.45 to 0.66.

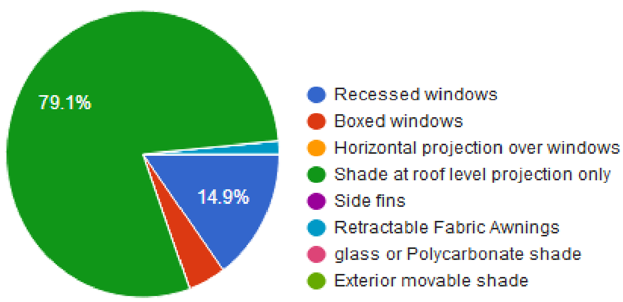


Figure 5.12 Distribution of windows as per types of shading devices used.

5.4 Field Survey II: Energy Consumption Assessment

The primary objectives of the second questionnaire are to establish baseline data for energy consumption usage pattern, occupancy schedule, HVAC schedule, lighting schedule to form input for building performance model and as well as to gauge people's responses towards retrofitting for understanding non-intrusive design strategies for retrofitting and affordability of people.A total of 400 samples as transverse surveys are collected for energy use assessment by residents representing 4608 samples throughout the year 2016-17. Eight housing schemes are chosen as a case for the detailed survey through questionnaire and electricity utility bills, the location of housing societies collected at the city level is shown in Figure 4.6 in the previous chapter. Samples have been drawn to represent group housing societies designed and constructed within a period of 1985-2010 developed by all major private developers, public sector and cooperative group housing schemes as defined in Table 4.5 of the previous chapter.

The questionnaire is divided into four sections viz. Household characteristics, Electricity Consumption pattern and schedules, Thermal and visual environment, Retrofitting Characteristics.

5.4.1 Household Characteristics

From a sample survey of 400 flats, the information related to apartment size, location, the age of housing connected electrical load, window opening schedule is assessed. Private developers constitute the largest share (68.35%) of total samples, followed by 23.46% share of cooperative group housing and 8.19% of the public sector (Figure 5.13). 61% of the sample population is employed in the service sector with 18% of people engaged in business activities and rest are involved in other activities.(Figure 5.14).

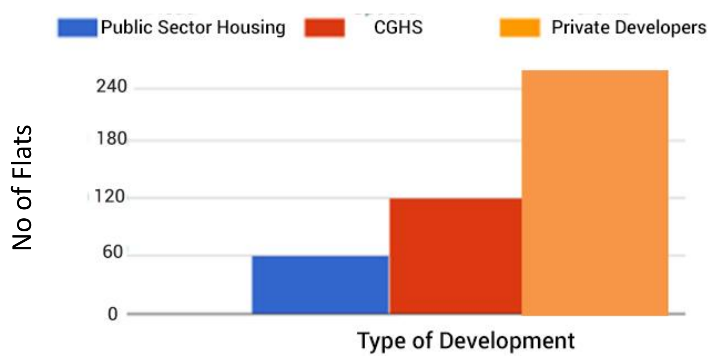


Figure 5.13 Distribution of flats as per type of developers

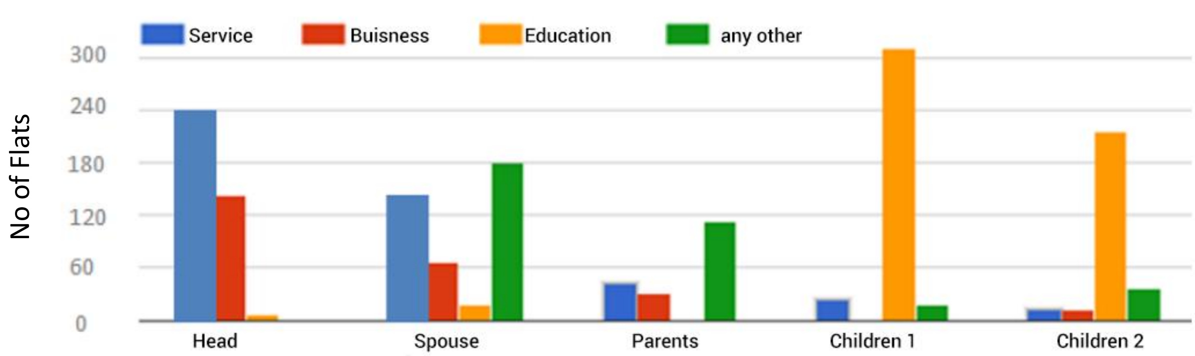


Figure 5.14 Activity profile of the residents

The most commonly available flats with respect to number of bedrooms in a flat is 3 BHK (51.4 %), followed by 4 BHK units (32.8%) and 2 BHK units being only 15.8% share of total population (Figure 5.15). Most of the survey responses are from flats on intermediate floors 76% with 14.4% sample from Stilt floor or first floor and 9.6 % samples from the top floor which are roof exposed (Figure 5.16).

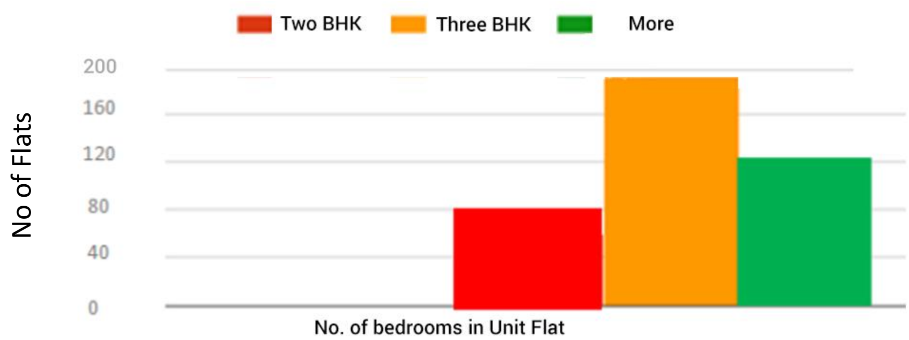


Figure 5.15 Type of flats with respect to no of bedrooms

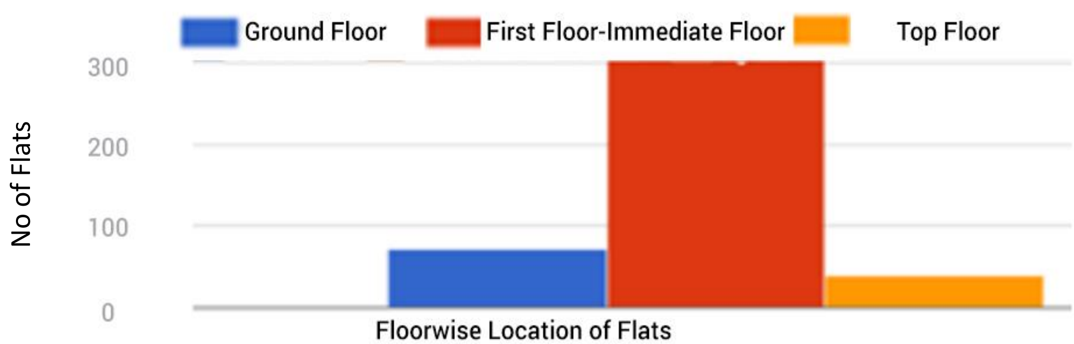


Figure 5.16 Location of flats in the sample

5.4.2 Electricity Consumption Pattern

In this sections, questions related to electricity consumption pattern are addressed by understanding electricity bills, occupancy schedule, capacity of air conditioners, cooling set point. Duration of air conditioning operating hours, the star rating of air conditioners and heaters, duration of heaters, geysers, refrigerator capacity and star rating, duration and use of lighting fixtures, duration of use of ceiling fans and other electrical equipments/ appliances with their quantity, no of hours used per day and per week. The largest no of air conditioners (74.5%) are of 1.5 TR rating (Figure 5.17) or18000 BTU/hr or 5275.5 watts with energy efficiency ratio EER for one to three-star rating with a range of 2.2 to 2.7. In 28 % of apartments, living rooms have no air conditioners.

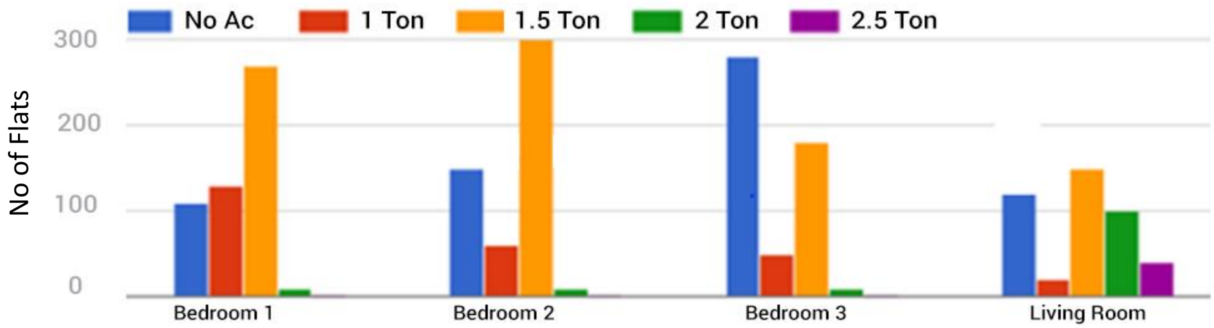


Figure 5.17 Capacity of air conditioners in different spaces

There is a wide variation in lighting use in homes. Some even use artificial light in the daytime with windows covered with drapery or opaque blinds. Figure 5.18 shows the maximum use of artificial lighting in 75% of flats for 16 hours and above in bedroom 1. 60% of flats use lighting for 16 hours and above in bedroom 2 with gradual reduction of lighting in bedroom 3. In 80% of flats, duration of use of lighting in kitchens is nearly 10 hours per day.

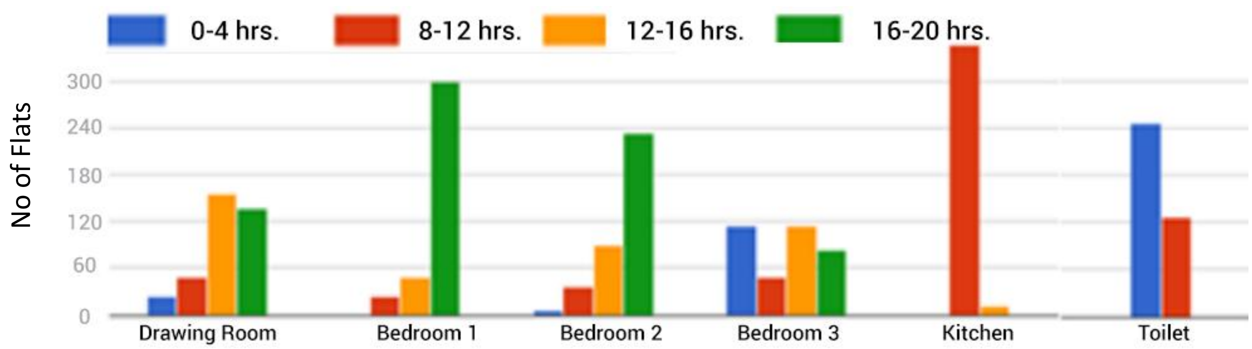


Figure 5.18 Duration of use of lighting in different spaces

Based on the data collected in this section, activity schedules are formed for different spaces such as master bedroom, children bedroom, guest bedroom (if any), living room, kitchen and toilets by considering data true for 70% and above flats as standardized data. Figure 5.19 defines activity schedule for children bedroom showing data on an hourly basis for occupancy pattern, lighting, task lighting, ceiling fan, equipment (laptop usage), HVAC cooling, heating, window opening for spring and summers, Window shade schedule for summers and winters for weekdays in Figure 5.19 (a). Similar data has been prepared for the weekend for all spaces Figure 5.19 (b). Separate schedules have been formed for different energy usage intensity (EUI) patterns such as Low EUI, Medium EUI and High EUI. The model will be used for all societies as a template in building simulation model as a standard for both base case and proposed case to compare different energy performance index of different retrofitting strategies for energy efficiency Figure 5.19 (b).

Children Bedroom

WEEKDAY	0-1	1_2	2_3	3_4	4_5	5_6	6_7	7_8	8_9	9_10	10_11	11_12	12_13	13_14	14_15	15_16	16_17	17_18	18_19	19_20	20_21	21_22	22_23	23_24
OCCUPANCY	1	1	1	1	1	1	1								1	1			1	1	0.7	0.7	1	1
LIGHTING						1	1								1	1			1	1	0.5	1	0.5	
EQUIPMENT (LAPTOP)															0.7	0.7					0.5	0.5		
HVAC COOLING SUMMER	1	1	1	1											1	1					0.7	0.7	1	1
CEILING FAN MISC. SUMMER	1	1	1	1	1	1	1								1	1					0.7	0.7	1	1
HVAC HEATING WINTERS	1																						0.5	0.5
WINDOW OPENING SCHEDULE EVERYDAY (SUMMER)						1	1	1												1				
WINDOW OPENING SCHEDULE EVERYDAY (SPRING)	1	1	1	1	1	0.5	1	1	1	1	1				0.5	0.5	0.5	0.5	1	1	0.5	0.5	0.5	0.5
TASK LIGHT																					0.5	1	0.5	
WINDOW SHADE WINTER	1	1	1	1	1	1	1											1	1	1	1	1	1	1
WINDOW SHADE SUMMER	1	1	1	1	1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 5.19(a) Weekday Schedule for Children Bedroom

Children Bedroom

WEEKEND																								
OCCUPANCY	1	1	1	1	1	1	1	1	1	0.5				0.5	0.5	1					1	1	1	1
LIGHTING								1	1												1	1	0.5	
EQUIPMENT (LAPTOP)										0.7			0.7	0.7	0.7	0.7				0.5	0.5	0.5		
HVAC COOLING SUMMER	1	1	1	1	1				1	0.5				0.5	0.5	1					1	1	1	1
CEILING FAN MISC. SUMMER	1	1	1	1	1	1	1	1	1	0.5				0.5	0.5	1					1	1	1	1
HVAC HEATING WINTERS	1																						0.5	0.5
WINDOW OPENING SCHEDULE EVERYDAY (SUMMER)						1	1	1												1				
WINDOW OPENING SCHEDULE EVERYDAY (SPRING)	1	1	1	1	1	0.5	1	1	1	1	1				0.5	0.5	0.5	0.5	1	1	0.5	0.5	0.5	0.5
TASK LIGHT																					0.5	1	0.5	
WINDOW SHADE WINTER	1	1	1	1	1	1												1	1	1	1	1	1	1
WINDOW SHADE SUMMER	1	1	1	1	1				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 5.19 (b) Weekend Schedule for Children Bedroom

5.4.3 Thermal and visual environment

Thermal comfort sensation of respondents is gauged on seven-point standard ASHRAE scale with the voting of respondents from cold (-3), cool (-2), slightly cool (-1), Neutral (0), slightly warm(+1), Warm (+2), Hot (+3). 43.2% of respondents reported their homes to be thermally neutral, whereas 34.7% of respondents found them slightly warm, 16.6% of homes reported slightly cool, thereby implying 94.5 % respondents in thermal comfort band (Figure 5.20).

Responses to satisfaction of daylighting and thermal comfort are measured on a five-point Likert scale with a ranking from 'Very dissatisfied' to 'Very satisfied'.84.3% respondents reported their home to be satisfied and above on scale with respect to daylighting. For controlling excessive daylight and glare, most commonly adopted tool is to use window blinds or shades on windows. Most of the homes do not use artificial light in daytime for most months of the year.

47.2% of respondents were satisfied and above on scale with respect to the thermal environment of their homes. There is a need to improve the thermal environment of homes without using air conditioning or improving passive resilience hours using natural ventilation at best to advantage of improved ventilation and fresh air.34% of respondents expressed their desire to have more air movement. 89% of the respondents opined saving of electricity within their households important, very important or essential by means of reducing air conditioning cooling demand or air-conditioned hours to meet thermal comfort requirement.

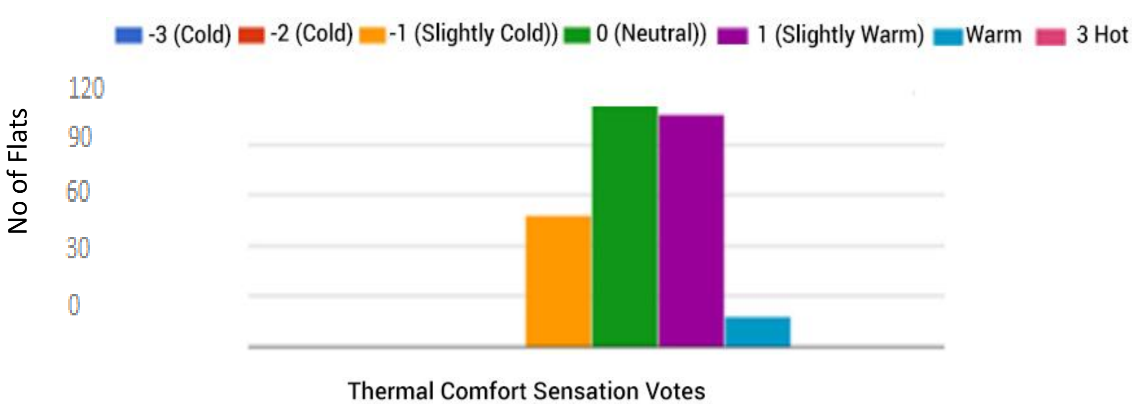


Figure 5.20 Thermal comfort sensation in sample flats

5.4.4 Retrofitting Characteristics

Invariably every household had carried out retrofitting in their homes last five years. The various retrofit measures range from refitting kitchen/ bathrooms, rewiring of additional points/ faulty electrical points, interior fittings and painting or installing air conditioners/ heaters to improve thermal comfort. Most people neither replaced or added door/ windows or airtight the joints around windows, nor they added or deleted rooms. Only 11.5% of respondents had an understanding of the importance of retrofitting from energy efficient viewpoint.

A question was posed to users in the questionnaire to know people's perception and issues on five points Likert scale graded from not important to essential. Figure 5.21 shows peoples' perception by related to reduce energy consumption save the environment, improving the external appearance of the house, improving lighting and ventilation, reducing heat gain in summers, reducing maintenance of exterior facades, exploring renewable rooftop solar energy and finally saving the environment. 67.2 % of respondents favoured retrofitting for reducing energy consumption as essential and very important. Nearly 72 % of respondents gave high importance or more to save the environment.

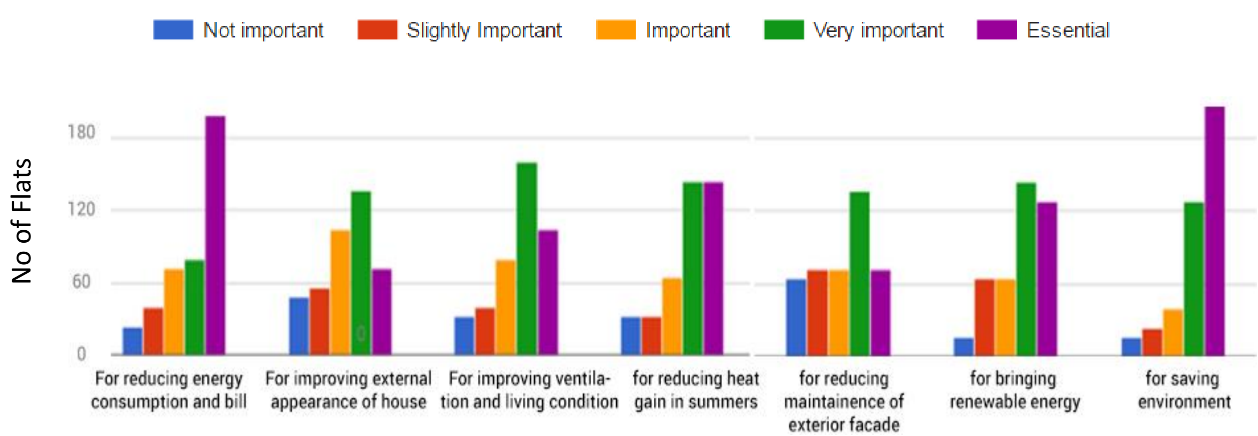


Figure 5.21 Analysis of importance attached to different factors for retrofitting

In the question to assess the affordability of users to pool in for investing in retrofitting for energy efficiency of existing housing, A total of 76.8% (41% users to spend less than INR 1.0 lacs and 35.8% users to spend from INR 1.0 lacs to 2.0 lacs) respondents show willingness to spend upto INR 2.0 lacs per flat (Figure 5.22).

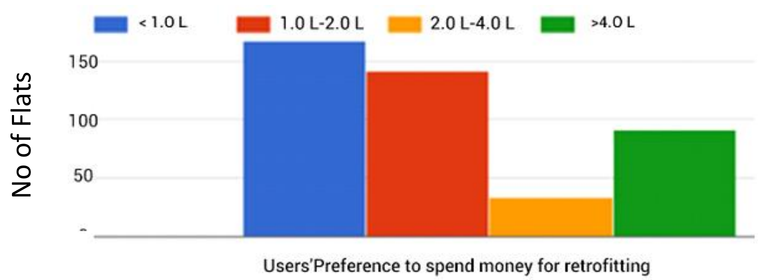


Figure 5.22 Affordability of users to invest in retrofitting for energy efficiency

5.5 Survey III: Baseline Energy performance Index

For understanding baseline data for Energy performance Index, utility bills of flats were collected for the entire year in 2016-17 and 2017-18 from the subjects of the sample in eight housing societies. Also, electricity bills of all residents of two – four towers were collected from central facility management or direct residents in some cases. There is 300 % variation in annual electricity consumption within different residents of the same tower (Figure 5.23). The graph shows variation in total electricity usage of different consumers in the same tower with a range from 4200kWh to 14000 kWh for a flat in the built-up area of 108.2 sqm. Thus energy performance index varied within the same tower from 33 kWh/m^2/yr to 128.5 kWh/m^2/yr.

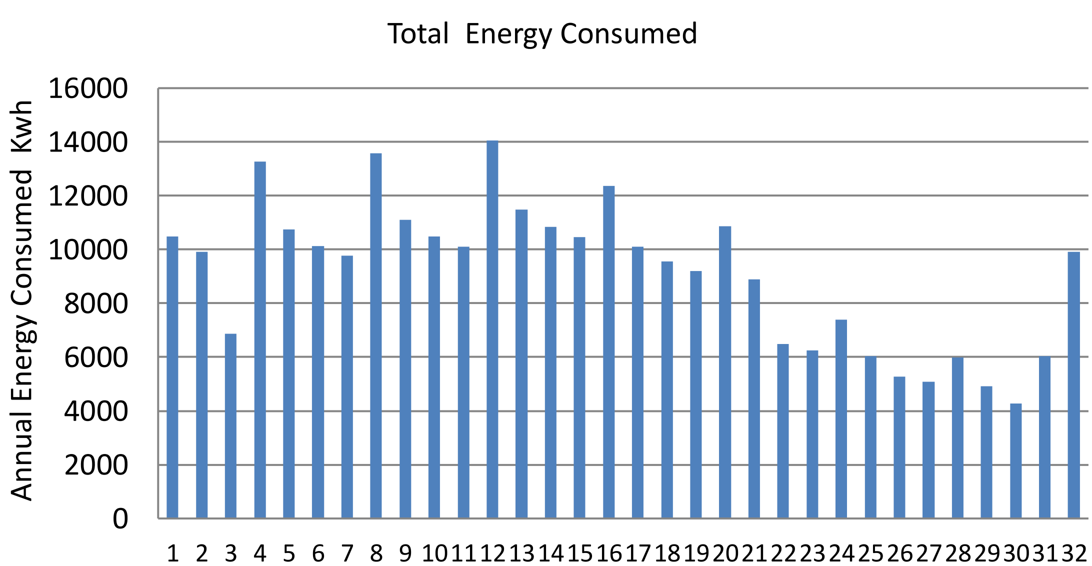


Figure 5.23 Annual electricity consumption of different residents of a tower.

Analysis of electricity consumption on monthly basis shows a high degree of variation of electricity consumption by different consumers within same tower of society as well as monthly variation of an individual consumer over different months due to climatic considerations, user lifestyles and occupancy schedules. The graph in Figure 5.24 shows electricity consumption data of one tower having 60 flats, presenting variation in electricity usage in different months of the year by an individual consumer and high variations among different consumers.

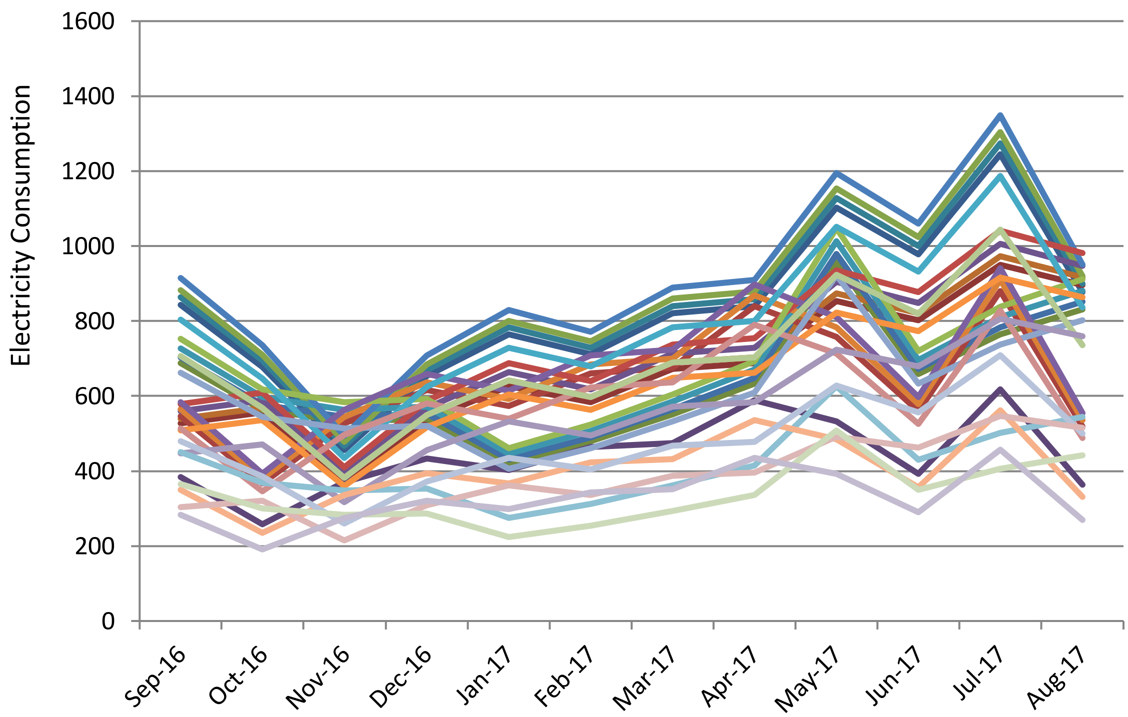


Figure 5.24 Monthly electricity consumption of different residents within the one tower in Orchid Petals.

Energy variations are due to high diversity factors as evident from outputs of analysis of questionnaire in previous sections. Thus various factors governing the use of electricity can be attributed to family structure and number of family members, occupation profile, time of operation (working couples),usage pattern such as the use of appliance and duration of usage, user preferences such as cooling set point temperature, use of heating in winters, efficiency equipment such as star rating of equipment, the frequency of use of artificial lighting.

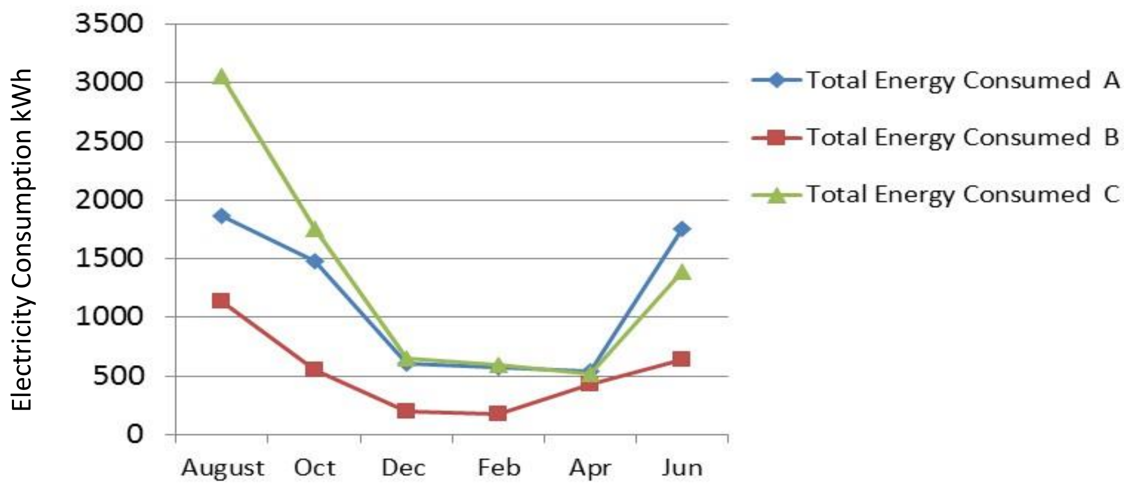


Figure 5.25 Bimonthly electricity consumption of three residents (A,B and C) within the same tower

Based on data of energy bills of all the samples, users/households are put in 3 categories Low energy intensity, Normal energy intensity, High energy intensity. The graph in Figure 5.25 shows variation in the month wise electricity usage of three different consumers in the same tower. Mean EPI of all samples is 68.9 kWh/m^2/year, Low case EPI 42.7kWh/m^2/year, Base case (normal energy use is 68.9,the high case is 97.4).

Table 5.1 Measure of central tendency of EPI of all samples

Parameter	**Low case (z score -1.5 to -1)**	**Normal Case (z score ±1)**	**High case (z score +1 to 1.5)**
Mean EPI	42.7	68.9	97.4
Standard deviation	8.89	15.4	11.8
Maximum	48.7	89.3	128.5
Minimum	33 .4	48.7	89.3
% of flats	14.45	68.11	17.44

Table 5.1 shows a measure of central tendency of EPI of all samples and % of each category of flats based on energy usage of all samples in data. The lower range of normal energy intensity is analyzed as 48.7kWh/m^2/year by taking z score deviation within ±1 of distribution

of data around the central mean value of all samples. For the purpose of retrofitting, mean EPI benchmark i.e. 68.9 kWh/m^2/year is a way higher than actual EPI of nearly 21.6% of the population with the implication that a significant no of residents may not be prepared to invest in retrofitting for energy efficiency at the collective level. Hence it becomes imperative to classify the consumers in three distinct classes i.e. residents of Low energy use intensity, Normal energy use intensity and High energy use intensity. Based on above information, three different models for each of eight housing schemes have been prepared depending on energy use intensity i.e. Low, Normal and High for assessing savings in energy consumption by applying different retrofit measures.

5.6 Survey IV: Thermal mapping for indoor environmental parameters

Thermal mapping of three flats is conducted for the entire year of May 2017- April 2018 to obtain continuous data of three parameters for indoors namely Temperature, Relative Humidity and Lighting level on a time interval of one hour using data loggers. The flats are selected by taking one sample from each category of the developer as well as on basis of energy consumption use i.e. low energy intensity use (EUI), normal energy intensity use and high energy intensity use as per table 4.7 in the previous chapter.

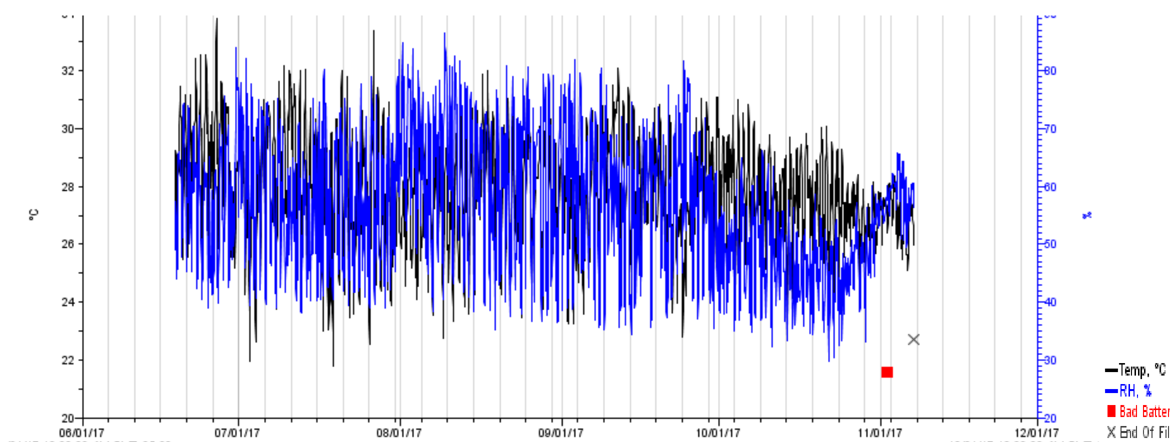
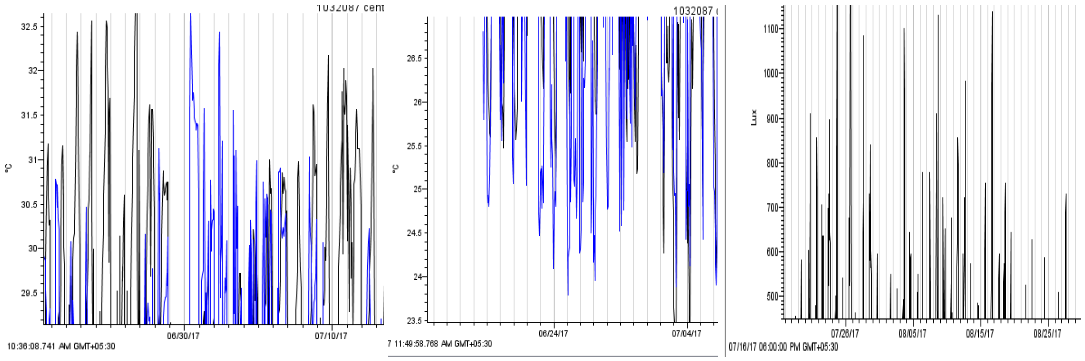


Figure 5.26 Plot obtained from data loggers for temperature and RH in Orchid Petals



Plot A   Plot B   Plot C

Figure 5.27 Blow up of the plot in Figure 5.26 for one-day peaks in temperature in the daytime, the temperature during air conditioning operative hours and glare in lighting.

The data output from data loggers is obtained in both spread sheets as well as plots. Figure 5.24 shows variation in Temp and RH from 18.6.17 to 7.11.2017 of the master bedroom in a flat on 6th floor having low energy use intensity located in private developer society Orchid Petals Infrastructure Limited. Plot A shows blow up of 18.6.17 to 17.8.17 (upper peaks) showing max temp reached in the daytime and sometimes evening hours.Plot B shows blow up of 18.6.17 to 17.8.17 (lower peaks) showing times of air conditioner operation. Plot C shows lighting levels in the master bedroom18.6.17 to 17.8.17 showing excessive glare.

Table 5.2 Typical spreadsheet export from data logger for one day

	Plot Title: 1032087 Orchid Petal	Master Bedroom		
SN	Date Time, GMT+05:	Temp, Â°C	RH, % (LGR	Intensity,
1	6/18/2017 17:00	28.99	54.032	516.4
2	6/18/2017 18:00	27.431	48.99	232.6
3	6/18/2017 19:00	28.369	53.468	11.8
4	6/18/2017 20:00	28.642	54.713	11.8
5	6/18/2017 21:00	29.04	55.373	11.8
6	6/18/2017 22:00	29.24	57.487	11.8
7	6/18/2017 23:00	29.09	54.745	19.7
8	6/19/2017 0:00	26.94	45.015	11.8
9	6/19/2017 1:00	26.451	44.241	11.8
10	6/19/2017 2:00	26.231	44.671	11.8
11	6/19/2017 3:00	25.963	44.021	11.8
12	6/19/2017 4:00	25.768	45.589	11.8
13	6/19/2017 5:00	25.647	45.574	11.8
14	6/19/2017 6:00	25.598	49.331	11.8
15	6/19/2017 7:00	26.818	56.845	11.8
16	6/19/2017 8:00	27.751	62.184	43.4
17	6/19/2017 9:00	28.171	64.408	122.2
18	6/19/2017 10:00	28.369	65.513	82.8
19	6/19/2017 11:00	28.543	65.818	193.2
20	6/19/2017 12:00	29.04	64.768	216.8
21	6/19/2017 13:00	29.29	66.038	256.2
22	6/19/2017 14:00	29.59	64.675	350.8
23	6/19/2017 15:00	30.142	64.398	445.4
24	6/19/2017 16:00	31.001	62.771	579.5
25	6/19/2017 17:00	31.459	61.877	603.1
26	6/19/2017 18:00	31.179	62.8	201

Table 5.2 shows values of air temp, relative humidity and lighting level in the room in the masterbedroom in Orchid Petals flat for a single day i.e. on 18.6.17; 5:00 pm to19.6.17; 6:00

pm. The values are an indicator of operation of air conditioning use, heat gain in the building, use of lighting fixtures, lighting level in daytime and glare in the master bedroom. It clearly shows the duration of air conditioner operation from 12 midnight to 7:00 am a daytime temp reaches very high 31.45 ^{0}C and high RH 62.77%, there is excess daylight 603 lux, showing excessive glare and indicator of heat gain as well.

Similarly the data from two other flats, one flat in public sector (HSIIDC apartments) located on 5th floor and having Normal EUI and the another flat from cooperative group housing society (Hextax apartments CGHS) located on 4th floor and having high EUI is analyzed. Thus the data retrieved from data loggers of three flats are used in calibrating the simulation model accurately and validating responses of users in questionnaire design in previous section and energy use data.

5.7 Building simulation modelling and analysis

5.7.1 Approach to Building Simulation and Methodology

Inverse modelling technique has been used to understand input data required for building performance modelling for energy simulations for detailed design wizard. Building simulation software ‘Designbuilder’ version 5.01.024, has been employed for simulation of existing building for mixed mode ventilation of case study models. Selection of Designbuilder software is based on its ability to simulate for both natural ventilation and air conditioning as well as choices of parameters for internal blinds and model complex geometry of buildings withthe interactive graphic interface. The software is based on Energy plus DOE simulation engine for design algorithms and has been included in the approved list of software for whole building performance as Appendix E defined in ECBC 2017[14]. The software also generates output summary which is in line with requirements of the research as well as it gives a parametric analysis of design parameters by multiple iterations of simulations. A test model was created in the early stage so as to understand data required for generating base case and calculate predicted energy consumption and other related parameters. Figure 5.28 shows various steps involved in preparing building simulation model as per geometry, climate and activity schedules, calibrate the same for ‘As is’ case and then run simulations for obtaining results leading to comparative evaluation of different retrofit measures.

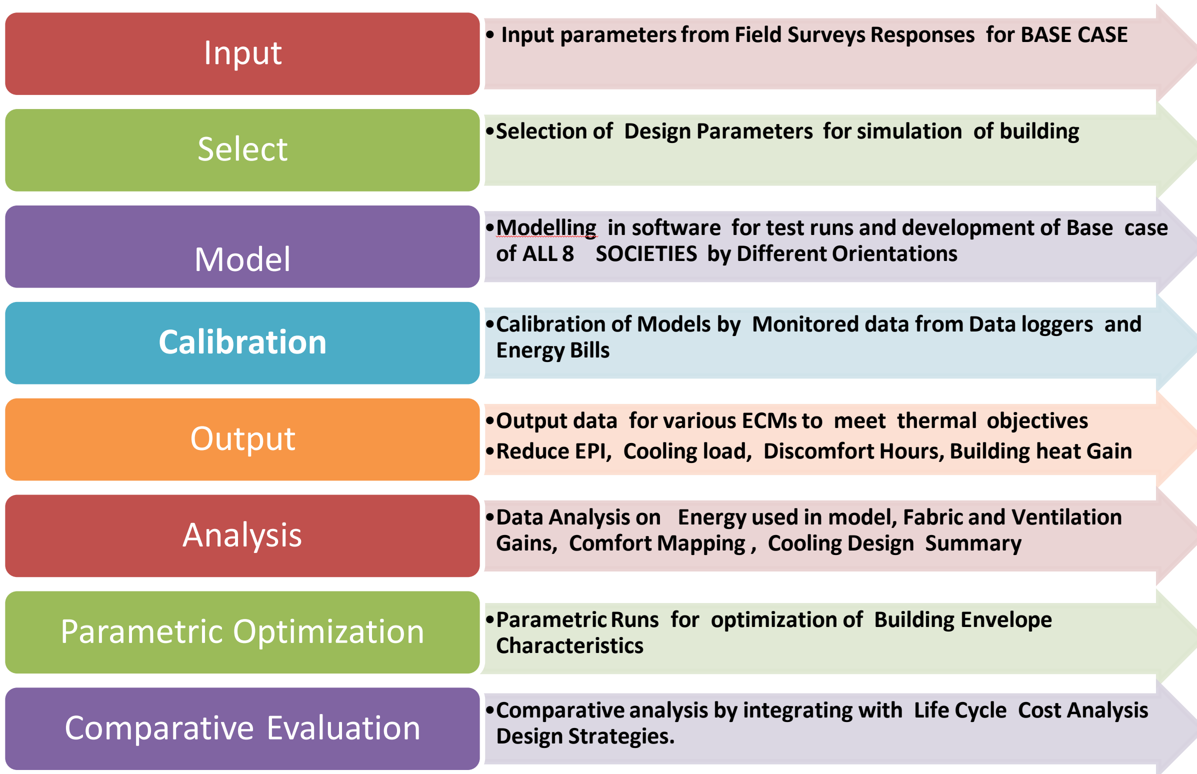


Figure 5.28 Flow chart for building simulation modelling and data analysis.

Field surveys are designed and conducted to elicit the information required to prepare baseline data and design templates for 'As is' case Templates are standardized for Occupancy and activity schedules, opaque construction, window openings and shading devices, lighting schedule, equipment schedule plug loads and HVAC schedules are prepared for base case for low energy use intensity , normal energy use intensity and high energy use intensity as per pattern defined in ECBC 2017 so as to compare 'As is' case with different retrofit models of all eight societies in the case study. Figure 5.29 shows the creation of various templates for input variables such as building envelope construction templates for opaque and transparent elements and input variables for usage occupancy and usage pattern, clothing and metabolism (activity), window opening and shading schedules, types of lighting systems, appliances, HVAC systems and renewable energy.

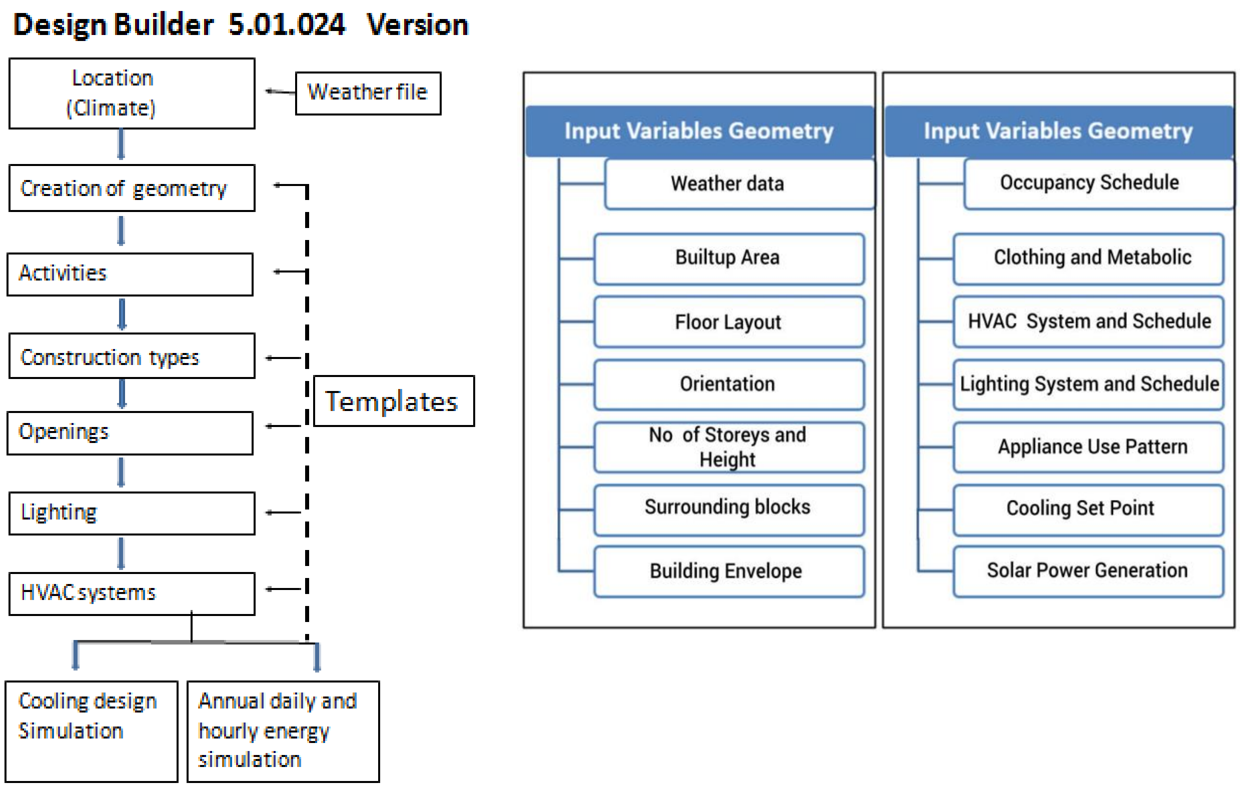


Figure 5.29 Design of templates for 'As is' case for input variables in Designbuilder

5.7.2 Input variables for modelling

There are two types of input variables required in building simulation model as per geometry and usage pattern of residents. In order to model geometry, the architectural drawings are prepared for all cases including plan configuration, height of each storey, orientation, position and size of surrounding blocks in addition to building envelope features such as type, size and position of windows, % operable windows, walling and floor materials, finishes and their colors, details of terraces, shading devices based on data analysis of field surveys of both questionnaires, typical input variables of geometry and input variables for usage are defined. Different input variables for geometry for transparent and opaque construction, internal partitions, types of thermal zones, HVAC system are defined in Table 5.3. Detailed activity schedules of 24 x 7 are prepared for each thermal zone separately for weekday and weekends in the floor describing occupancy schedule, lighting schedule, task lighting schedule equipment schedule (plug loads), cooling and heating schedule, cooling set point temperature, ceiling fan schedule, window opening schedule for different seasons in year, windows shade (internal roller blinds or curtains) schedule for summers and winters are prepared as described in Figure 5.19.

Table 5.3 Input Variables for Geometry for 'As is' Case

Head	Subhead	Detail
Opaque Construction	Walls	The outermost layer of 12 m Cement Plaster outside finished with paint +230 mm thick Burnt Brick masonry in Cement Mortar +15 mm cement plaster on inside face of the wall.
	Flat Roof	The outermost layer of 40 mm brick tile terracing + 70 mm thick thermal insulation mud phuska+ 115 mm RCC structural slab + 6 mm cement plaster on the ceiling (underside of the roof)
Internal Partitions		115 mm burnt brick masonry in Cement Mortar finished with 12 mm plaster on both faces
Floors	Intermediate floor	40 mm thick ceramic tiles or stone flooring on 75 mm thick Cement Concrete screed on RCC structural slab
Transparent Construction	Glass	Single glazing 4 mm thick clear glass
	Layout	Windows sizes and position modelled as per geometry,
Thermal Zones		Master Bedroom, children bedroom, guest bedroom, living room, kitchen, toilets, circulation area/lobby.
HVAC		Mechanical and natural ventilation, no heating,

Different templates for all input variables as per usage (schedules based on 24 x 7 hourly basis) have been prepared so as to assign them on geometric models for different energy usage intensity (EUI) patterns such as Low EUI case, Medium EUI case and High EUI case. Each of these models thus prepared is simulated by applying different selected design parameters for retrofitting to derive output results (Figure 5.30).Thus for the purpose of detailed design analysis, firstly 'As is' case is prepared for each of eight group housing case, calibrated for energy usage and operative temperature and then is simulated for different cardinal directions, resulting in all 38 cases. Mean Energy Performance Index (EPI) is calculated based on EPI of the output of each model to form eight 'Base Case' for different societies. Each of the base cases is simulated for three different energy use intensity cases such as Low EUI, Normal EUI and High EUI, which in turn is simulated for ten retrofit parameters, thus resulting in 264 cases as per figure 5.30.

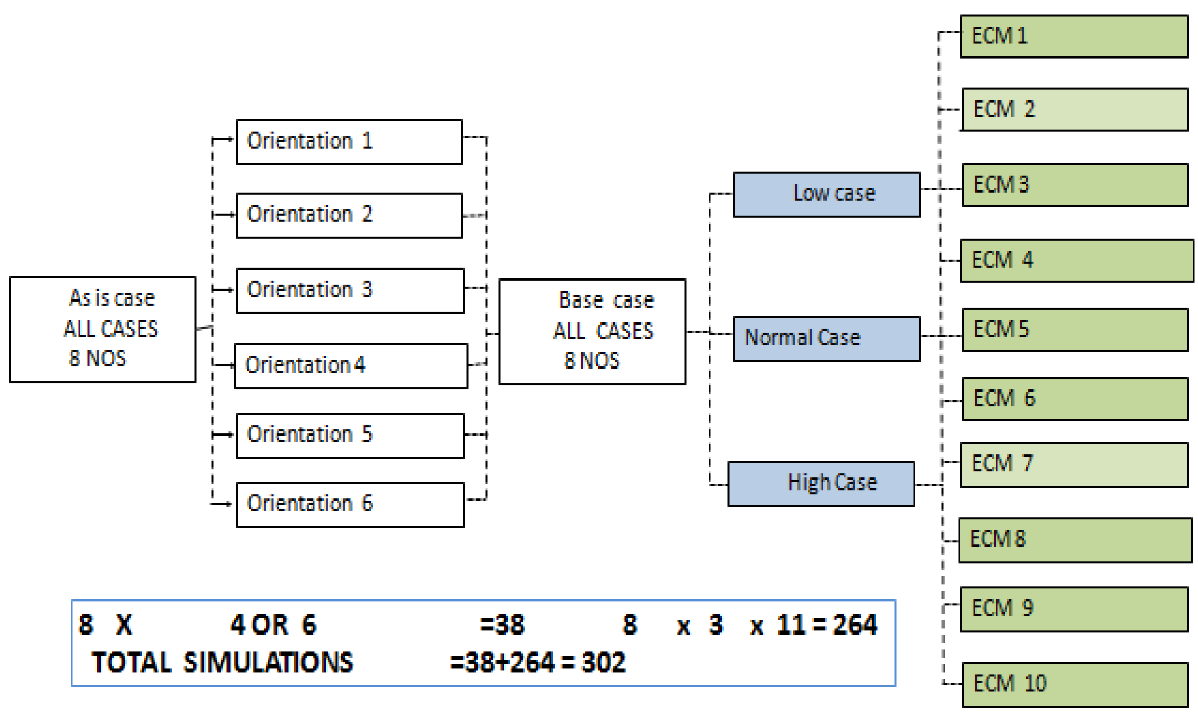


Figure 5.30 Approach to simulation as per input variables usage.

5.7.3 Building Geometry Modeling

All eight cases taken up for detailed design wizard are modelled as per their existing geometry, no of stories and orientation for mixed mode ventilation as per template assigned to the different thermal zone. Figure 5.31 shows Designbuilder model of one of the societies, Antriksh Srishti a cooperative group housing society having Stilt+8 storeys building showing various rooms, windows, balconies modelled as components. Three floors are modelled as per building envelope heat gain i.e. First floor, Intermediate floor and top floor which is roof exposed floor (Figure 5.32). As per standard practice of simulation to reduce simulation time, intermediate floors are modelled only once and multiplied by zone multiplier (in this case six, making total no of floors Eight).Floor to floor Height of each storey is taken as per existing 3.15 m. The building is T shaped in Geometry, having three blocks; each block having two apartments at each floor. Thus for ease of simulation and making model simpler, only one tower is taken up for simulation and other parts of the building are modelled as a component in order to account for the effect of shading and heat reflectivity of building blocks (Figure 5.33). The ground conditions of the base model are modelled as a mix of paved area and green ground cover.

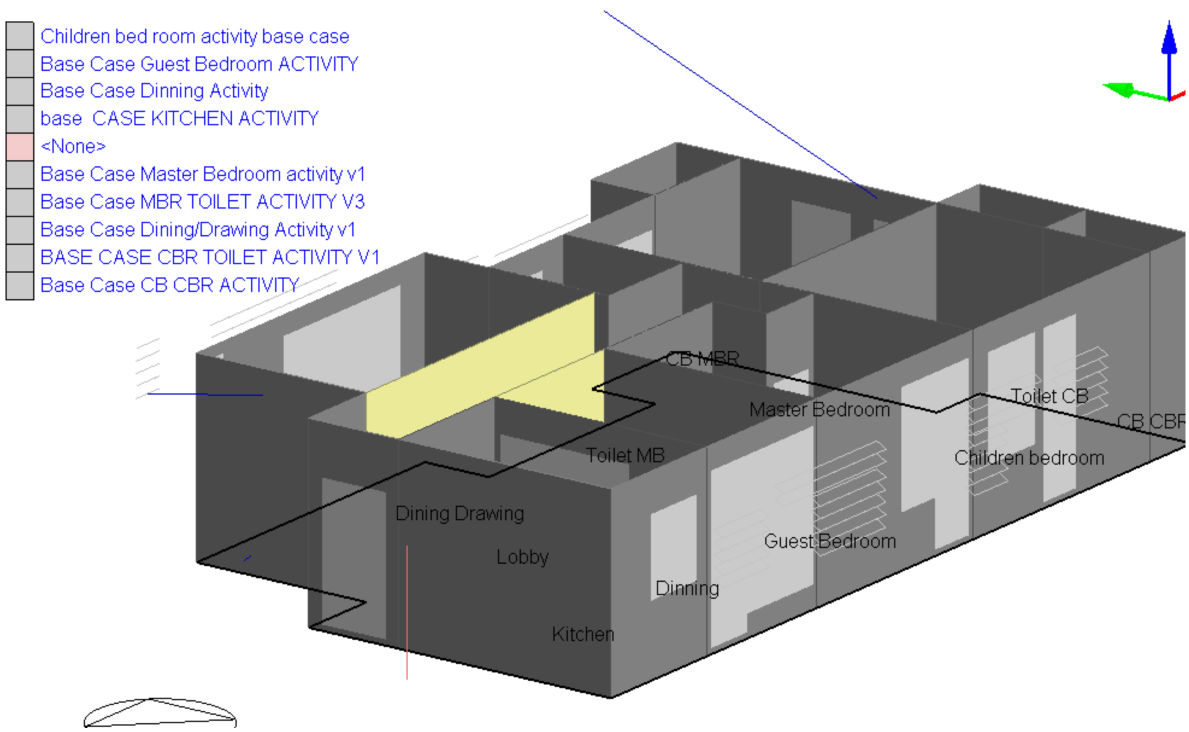
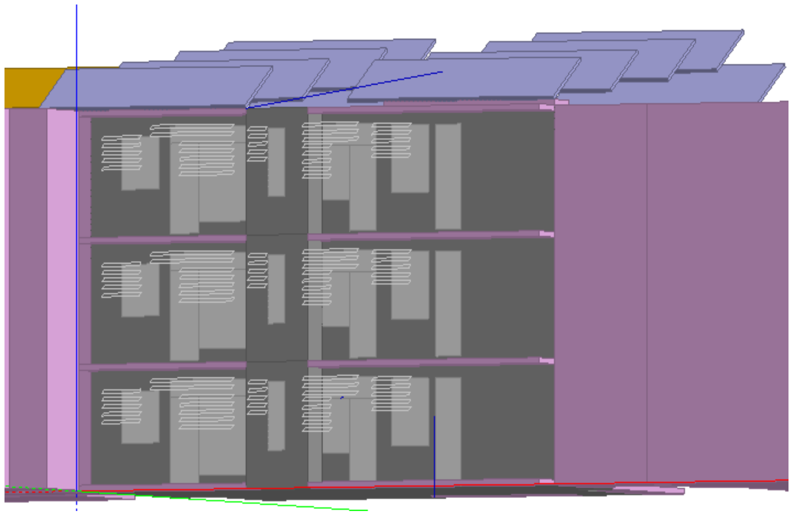


Figure 5.31 Design builder model of one of the floors of Antriksh Srishti - CGHS Society.



Building Area

	Area [m2]
Total Building Area	783.22
Net Conditioned Building Area	550.96
Unconditioned Building Area	232.26

(a) (b)

Figure 5.32 a) Zone Multiplier for intermediate floors for simplification of the model. b) Screenshot of Building area statement showing the actual area of 8 storeys.

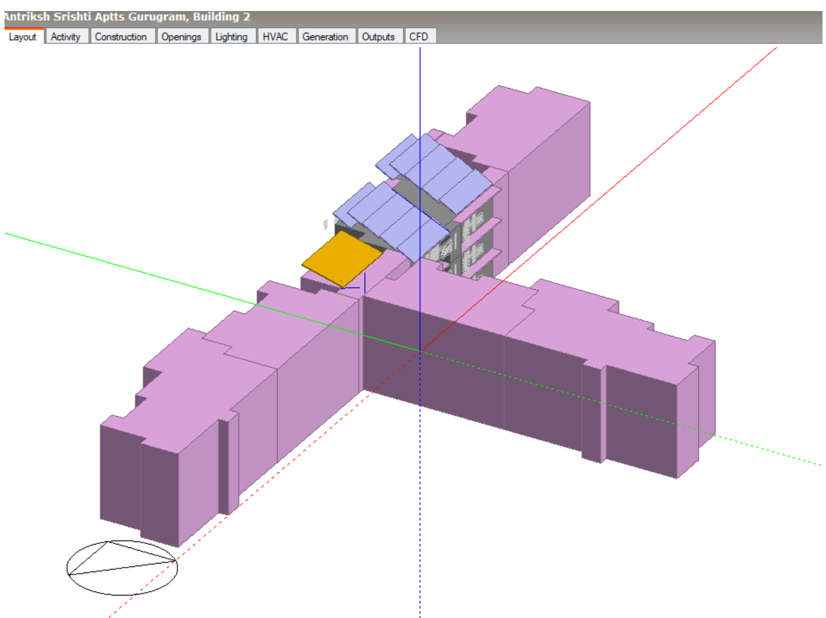
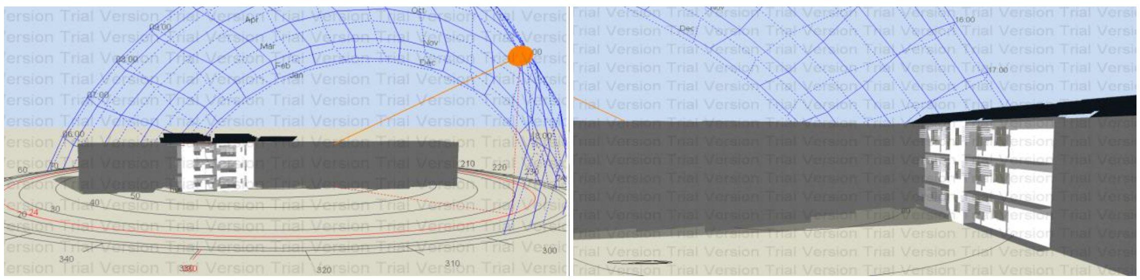


Figure 5.33 Model of T shaped Antriksh Society, showing other towers modelled as component model for taking in effect of shading and heat reflectance.

Figure 5.34 illustrates Designbuilder visual rendering of sun path diagram at two different critical days in the same model, showing the effect of surrounding buildings/ blocks modelled as a component block. It is clear that the simulation model accounts for shadows and shades due to mutual surfaces or surface geometry such as balconies etc to calculate heat load of buildings.



21 June, 17:00hrs 22 Dec, 11:00hrs

Figure 5.34 Designbuilder visual rendering showing shadow pattern affecting heat loads as per shading due to surrounding blocks.

5.7.4 Assigning input variables of usage

As a result of data analysis of field surveys of questionnaire responses, input schedules for usage are formed for different thermal zones. Mapping of usage is first plotted on spreadsheets to examine the close interaction between different activity schedules defined on an hourly basis on parallel lines of ECBC 2017 [14]. Figure 5.35 defines activity schedule of occupancy pattern, lighting, task lighting, ceiling fan, equipment (laptop usage), HVAC cooling, heating, window opening for spring and summers, window shade schedule for summers and winters for weekdays for various thermal zones. The same is modelled as operational schedules in Designbuilder (Figure 5.36) similar data is prepared for the weekend for all spaces. Templates are prepared for Low EUI, Normal EUI, and High EUI.

MASTER BED ROOM

WEEKDAY	0-1	1_2	2_3	3_4	4_5	5_6	6_7	7_8	8_9	9_10	10_11	11_12	12_13	13_14	14_15	15_16	16_17	17_18	18_19	19_20	20_21	21_22	22_23	23_24
OCCUPANCY	1	1	1	1	1	1										1							1	1
LIGHTING																							0.5	
EQUIPMENT (LED TV)																0.7							1	
HVAC COOLING SUMMER	1	1	1	1												1							1	1
CEILING FAN MISC. SUMMER	1	1	1	1	1	1										1							1	1
HVAC HEATING WINTERS	1																						0.5	0.5
WINDOW OPENING SCHEDULE EVERYDAY (SUMMER)						1	1	1												1	1	1		
WINDOW OPENING SCHEDULE EVERYDAY (SPRING)	1	1	1	1	1	1	1	1	1	1	1				0.5	1	0.5	0.5	1	1	1	1	1	1
TASK LIGHT																								
WINDOW SHADE WINTER	1	1	1	1	1	1												1	1	1	1	1	1	1
WINDOW SHADE SUMMER	1	1	1	1	1				1	1	1	1	1	1	1	1	1	1	1		1	1	1	1
WEEKEND																								
OCCUPANCY	1	1	1	1	1	1	1	1	1						0.5	1						1	1	1
LIGHTING								1	1													1	0.5	
EQUIPMENT (LED TV)									1						0.7	0.7						0.5		
HVAC COOLING SUMMER	1	1	1	1					1						0.5	1						0.5	1	1
CEILING FAN MISC. SUMMER	1	1	1	1	1	1	1	1	1						1	1						1	1	1
HVAC HEATING WINTERS	1																						0.5	0.5
WINDOW OPENING SCHEDULE EVERYDAY (SUMMER)						1	1	1												1	1			
WINDOW OPENING SCHEDULE EVERYDAY (SPRING)	1	1	1	1	1	1	1	1	1	1	1				0.5	1	0.5	0.5	1	1	1	1	1	1
TASK LIGHT																								
WINDOW SHADE WINTER	1	1	1	1	1	1												1	1	1	1	1	1	1
WINDOW SHADE SUMMER	1	1	1	1	1				1	1	1	1	1	1	1	1	1	1	1		1	1	1	1

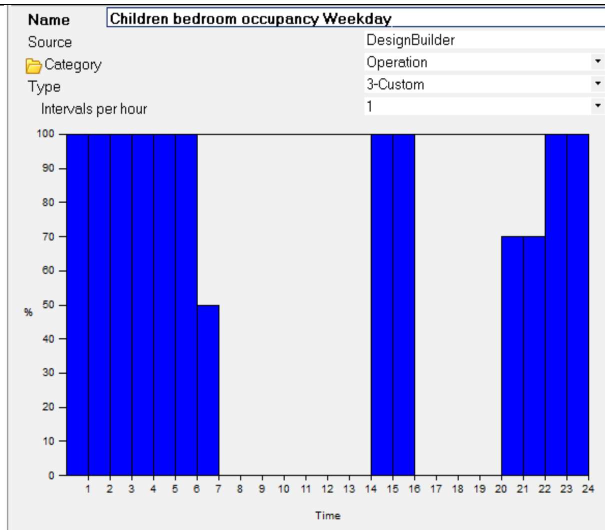
(a)

DRAWING ROOM

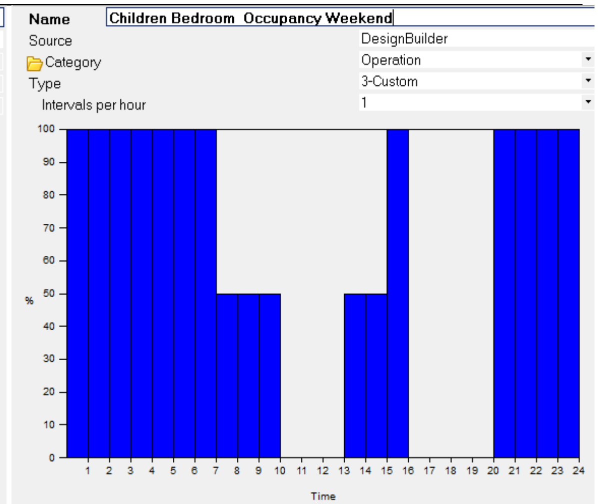
WEEKDAY	0-1	1_2	2_3	3_4	4_5	5_6	6_7	7_8	8_9	9_10	10_11	11_12	12_13	13_14	14_15	15_16	16_17	17_18	18_19	19_20	20_21	21_22	22_23	23_24
OCCUPANCY									1	0.5				0.5	1				0.5	1	1			
LIGHTING						0.5	1	1										0.5	0.5	1	1			
EQUIPMENT (LED TV)									1						1						1			
HVAC COOLING SUMMER														0.5	0.5					0.5	1			
CEILING FAN MISC. SUMMER									1	0.5				1	1				1	1	1			
WINDOW OPENING SCHEDULE EVERYDAY (SUMMER)	1	1	1	1	1	1	1	1														1	1	1
WINDOW OPENING SCHEDULE EVERYDAY (SPRING)	1	1	1	1	1	1	1	1	1	1	1				0.5	1	0.5	0.5	1	1	1	1	1	1
WINDOW SHADE WINTER	1	1	1	1	1	1												1	1	1	1	1	1	1
WINDOW SHADE SUMMER	1	1	1	1	1				1	1	1	1	1	1	1	1	1	1	1		1	1	1	1
WEEKEND																								
OCCUPANCY										0.5	0.5	0.5	0.5	0.5						0.5	0.5	0.5		
LIGHTING																				0.5	0.5	0.5		
EQUIPMENT (LED TV)											0.5	0.5	0.5	0.5						0.5	0.5	0.5		
HVAC COOLING SUMMER											0.5	0.5	0.5	0.5						0.5	0.5	0.5		
CEILING FAN MISC. SUMMER										0.5	0.5	0.5	0.5	0.5						0.5	0.5	0.5		
WINDOW OPENING SCHEDULE EVERYDAY (SUMMER)	1	1	1	1	1	1	1	1															1	1
WINDOW OPENING SCHEDULE EVERYDAY (SPRING)	1	1	1	1	1	1	1	1	1	1	1				0.5	1	0.5	0.5	1	1	1	1	1	1
WINDOW SHADE WINTER	1	1	1	1	1	1												1	1	1	1	1	1	1
WINDOW SHADE SUMMER	1	1	1	1	1				1	1	1	1	1	1	1	1	1	1	1		1	1	1	1

(b)

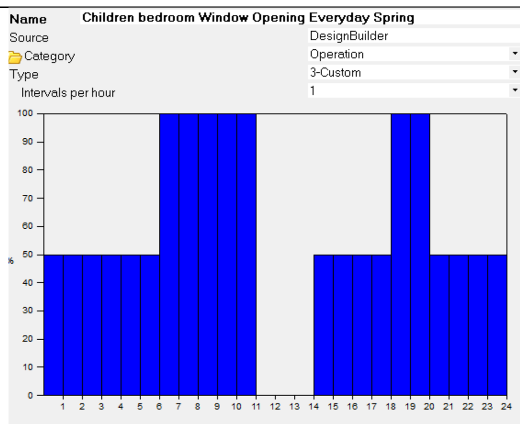
Figure 5.35 Activity Schedules for (a) Master Bedroom (b) Drawing Room



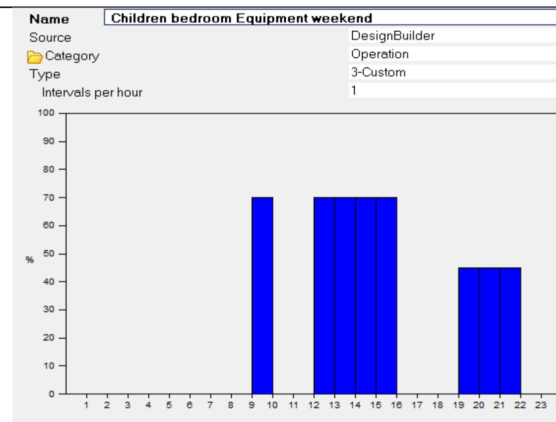
Occupancy Weekday



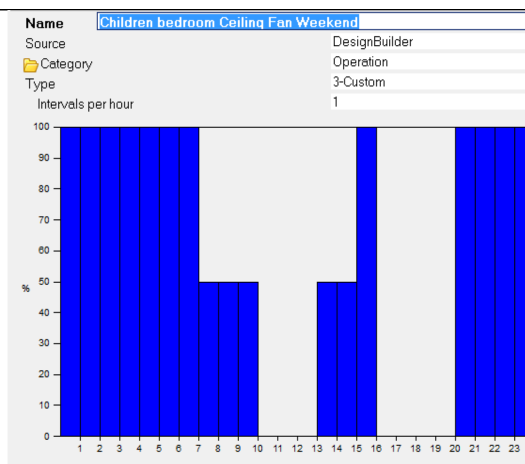
Occupancy Weekend



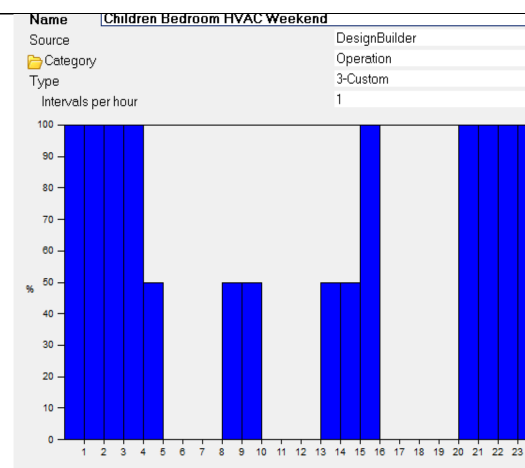
Window Opening Everyday Spring



Equipment Weekend

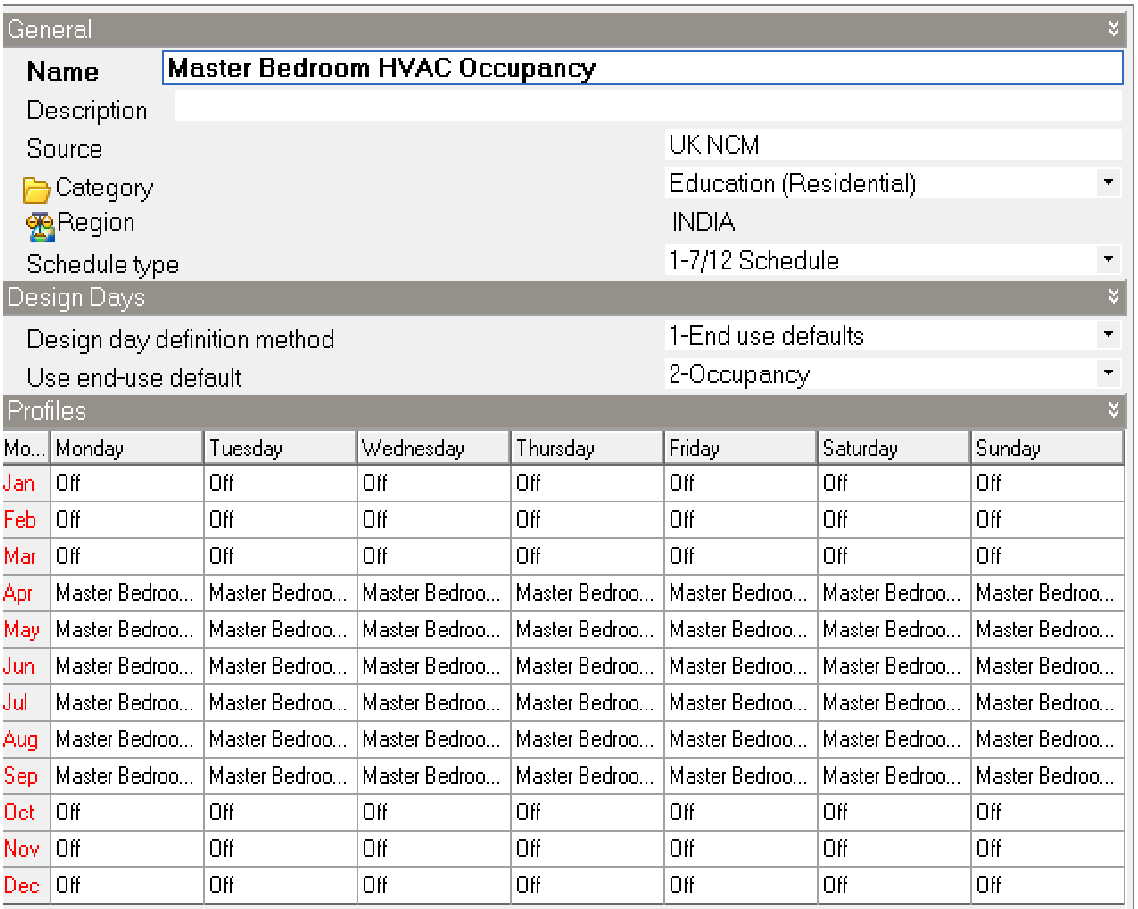


Ceiling Fan Weekend



HVAC Weekend

Figure 5.36 Modeling Schedules in Designbuilder for Children Bedroom



Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	Off	Off	Off	Off	Off	Off	Off
Feb	Off	Off	Off	Off	Off	Off	Off
Mar	Off	Off	Off	Off	Off	Off	Off
Apr	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...
May	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...
Jun	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...
Jul	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...
Aug	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...
Sep	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...	Master Bedroo...
Oct	Off	Off	Off	Off	Off	Off	Off
Nov	Off	Off	Off	Off	Off	Off	Off
Dec	Off	Off	Off	Off	Off	Off	Off

Figure 5.37 Schedules in Designbuilder for master bedroom HVAC operation**.**

Detailed Schedules are prepared for occupancy pattern. A total of 21 holidays have been included in the year including summer break and winter vacation. Schedules are prepared for window opening, window shading, and general lighting, task lighting, ceiling fan, equipment HVAC cooling as a template for each hour of the day and each week in the year format. (Figure 5.35). A similar exercise is carried out for preparing and assigning templates for low EUI and high EUI cases (Figure 5.38). Figure 5.39 shows assigning of HVAC templates for mixed mode ventilation such as window opening schedule for natural ventilation and HVAC cooling schedule when cooling required for children bedroom in normal EUI.

Case	Space	Category	Directory	Template
Base Case Templates DB Inputs	Children Bedroom	Activity template	Residential Spaces	Children bed room Activity base case 1
		Openings	Early design	Base case Children BR Glazing and Shade 1
		Lighting	System	Base case ligting T5 16 floursent
		HVAC	Project	Base Case CBR AC no Fresh Air
	Drawing Room	Activity template	General	Base Case Dining/Drawing Activity v1
		Lighting	System	Base Case Lighting T5 16 Flours Drawing v1
		Openings	Early design	Base case Glazing and Shade 1 DRAWING
		HVAC	Project	Base Case Drawing AC no Fresh Air v2
	Master Bedroom	Activity template	Residential Spaces	Base Case Master Bedroom activity v1
		Openings	Early design	Base Case MBR GLAZING & SHADE
		Lighting	System	Base Case T5 Flourscent Master Bedroom
		HVAC	Project	Base Case HVAC split no fresh air MBR
	Guest Bedroom	Activity template	Residential Spaces	Base Case Guest Bedroom ACTIVITY
		Openings	Early design	Base Case GBR GLAZING & SHADE
		Lighting	System	Base Case T5 Flourscent Guest Bedroom
		HVAC	Project	Base Case HVAC split no fresh air Guest BR
	KITCHEN	Activity template	Residential Spaces	Base Case KITCHEN ACTIVITY
		Openings	Early design	Base Case KITCHEN GLAZING & SHADE
		Lighting	System	Base Case Lighting KITCHEN
		HVAC	Project	Base Case KIT NATVENT
	MBR Toilet	Activity template	Residential Spaces	Base Case MBR Toilet Activity V1
		Openings	Early design	Base Case MBR TOILET GLAZING & SHADE
		Lighting	System	Base Case Lighting MBR Toilet V1
		HVAC	Project	Base Case Toilet NATVENT MBR
	GBR Toilet	Activity template	Residential Spaces	Base Case GBR Toilet Activity
		Openings	Early design	Base Case GBR TOILET GLAZING & SHADE
		Lighting	System	Base Case Lighting GBR Toilet
		HVAC	Project	Base Case Toilet NATVENT GBR V1
	Dining	Activity template	Residential Spaces	Base Case Dining Activity v1
		Lighting	System	Base Case Lighting dining
		HVAC	Project	Base Case Dining HVAC
High Occupancy Case	Children Bedroom	Construction	Early design	Final base case wall & roof
		Activity template	General	High Children Bed Room Activity Base Case 1
		Openings	Early design	High Children Bed Room Activity Base Case 1
		Lighting	System	High Case T5 Floursent Children Br
		HVAC	Project	High Case Children Bedroom AC no Fresh Air
	Drawing	Activity template	General	High Case Drawing Activity
		Lighting	System	High Case Drawing Lighting T5 Flourscent
		Openings	Early design	High Case Drawing Glazing and Shade
		HVAC	Project	High Case Drawing AC no Fresh Air Split
	Guest Bedroom	Activity template	Residential Spaces	High Case Guest Bedroom Activity
		Openings	Early design	High Case Guest Bedroom Glazing & Shade
		Lighting	System	High Case Guest Bedroom T5 Lighting
		HVAC	Project	High Case HVAC GBR split no fresh air
Low Occupancy Case	Children Bedroom	Activity template	General	Low Case Children Bedroom Activity
		Openings	Early design	Low Case Children Bedroom Glazing
		Lighting	System	Low Case Children Bedroom T5 Florscent
		HVAC	Project	Low Case Children BR HVAC No Fresh Air
	Drawing	Activity template	General	Low Case Drawing Activity
		Lighting	System	Low Case Drawing Lighting T5 Flourscent
		Openings	Early design	Low Case Drawing Glazing & Shade
		HVAC	Project	Low Case Drawing Room HVAC Cooling
	Guest Bedroom	Activity template	Generic	None
		Openings	Early design	Low Case Guest BEdroom GLazing N ShADE
		Lighting	Generic	None
		HVAC	Generic	None
	Dinning	Activity template	General	Low Base Case Dinning Activity
		Lighting	System	Low Case Drawing Lighting T5 Flourscent
		Openings	Early design	Low Case Glazing & Shade Dinning
		HVAC	Project	Low Case Drawing Room HVAC Cooling

Figure 5.38 Templates for low case EUI, base case EUI, high case EUI

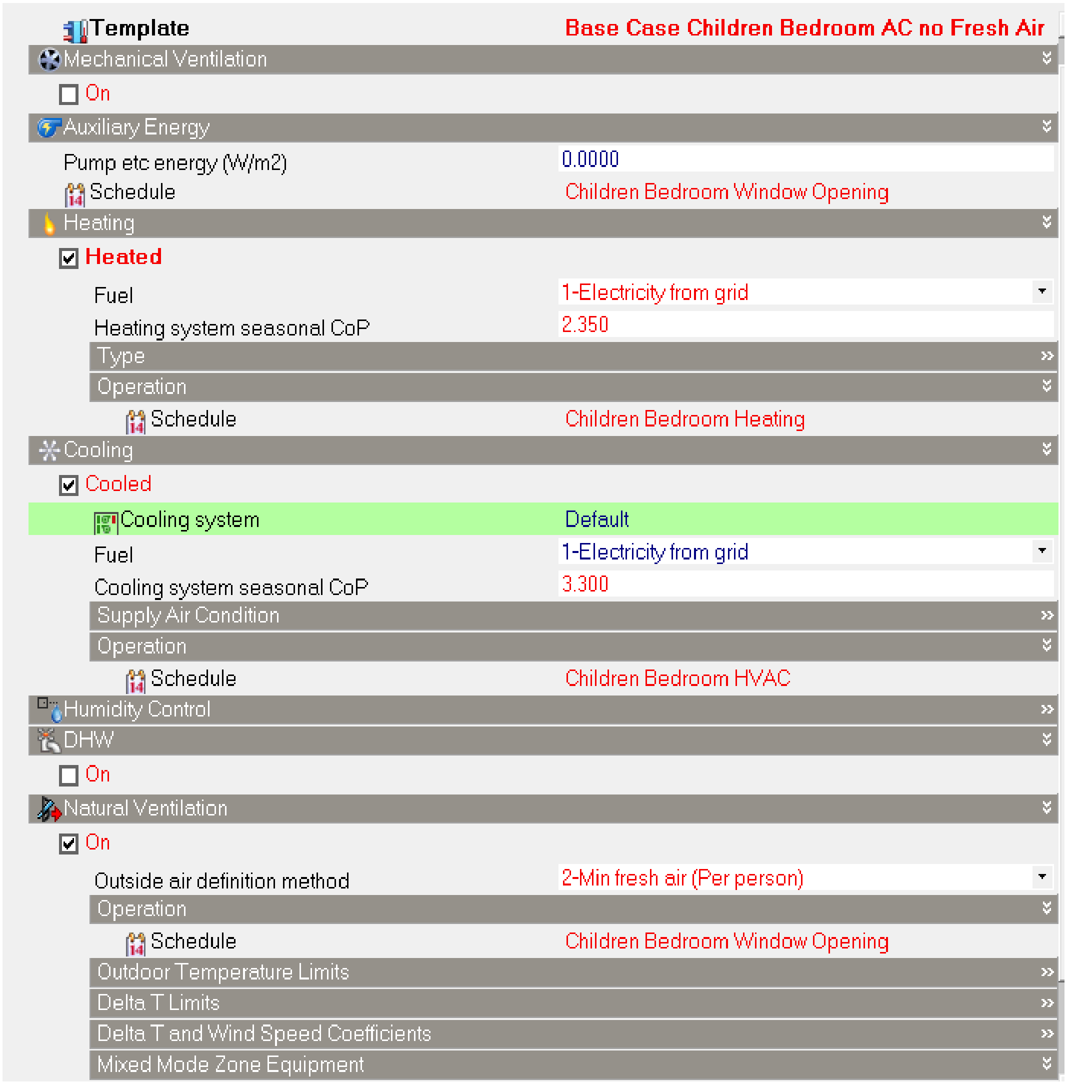


Figure 5.39 Assigning Templates to different thermal zones such as HVAC template for children bedroom

5.7.5 Calibration of the Model and Validation

First of all, the building performance model is simulated for the hourly analysis of all 8,760 hours in the year. From electricity bills, electric energy data of all eight cases, the simulated EPI is compared with actual EPI and checked as per applicable criteria: option D of whole building simulation defined in the International Performance Measurement and Verification Protocol (IPMVP) for calibration of simulation model on the basis of energy consumption [172].The simulation of building model is reiterated several times in a stepped manner by making minor changes such as surface reflectance of walls, roof, base ground reflectivity, the creation of virtual partition in kitchen and dining spaces so as to get closer values of electricity consumption at the monthly level. The mean bias error (MBE) and the coefficient of variation of the root mean squared error Cv(RMSE) are calculated for simulation data and observed measured data(2016-17) to determine 'best fit' between calibrated energy model and utility data. The percentage MBE and C_V(RMSE) error specified in the IPMVP on monthly basis is ± 5% and 15 % respectively for energy consumption (Figure 5.40). For calibrating the model for air temperature at the zone level, percentage MBE and C_V(RMSE) error are taken as ± 10% and 30 % respectively. Calibration of the models finally done to match internal temperatures at the zone level (master bedroom as this is the most occupied zone in a residential apartment). Table 5.4 shows percentage MBE and C_V(RMSE) error before and after calibration of the model, thus validating the model.

Table 5.4 Percentage MBE and C_VRMSE error before and after calibration of the model

	Permissible range of IPMVP	Prior to calibration	Calibrated model
For energy Consumption On a Monthly basis			
MBE (%)	±5%	15.29%	4.73 %
C_V RMSE	15	18.37	12.82
For zone temperature On an hourly basis			
MBE (%)	±10 %n	14.76%	7.24 %
C_V RMSE	30	21.45	17.32

There is a high variation in the simulated model and monitored data in unconditioned time due to a higher order of uncertainty in building envelope as no model can replicate actual monitored data. Figure 5.40 & 5.41 shows the superposition of simulated operative temperature v/s actual operative temperature retrieved from data loggers installed in Orchid Petals both for conditioned hours in weekend in HSIIDC apartments as well as unconditioned hours during holidays in Orchid Petals. The model is best used for comparative analysis of different indicators such as EPI or zone operative temperature. There are a lot of variables in the real world due to variables like weather conditions of a particular year, site landscape, green cover, surrounding trees, occupancy pattern of people, building activity pattern etc. The model may be seen as a probabilistic model than the absolute deterministic model.

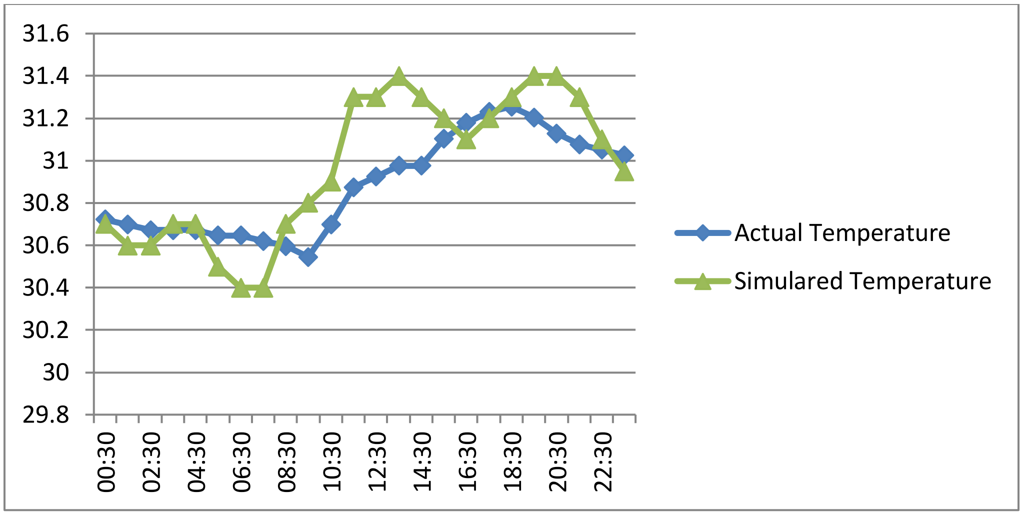


Figure 5.40 Superposition of simulated operative temperature v/s actual operative temperature during unconditioned hours for Orchid Petals apartments.

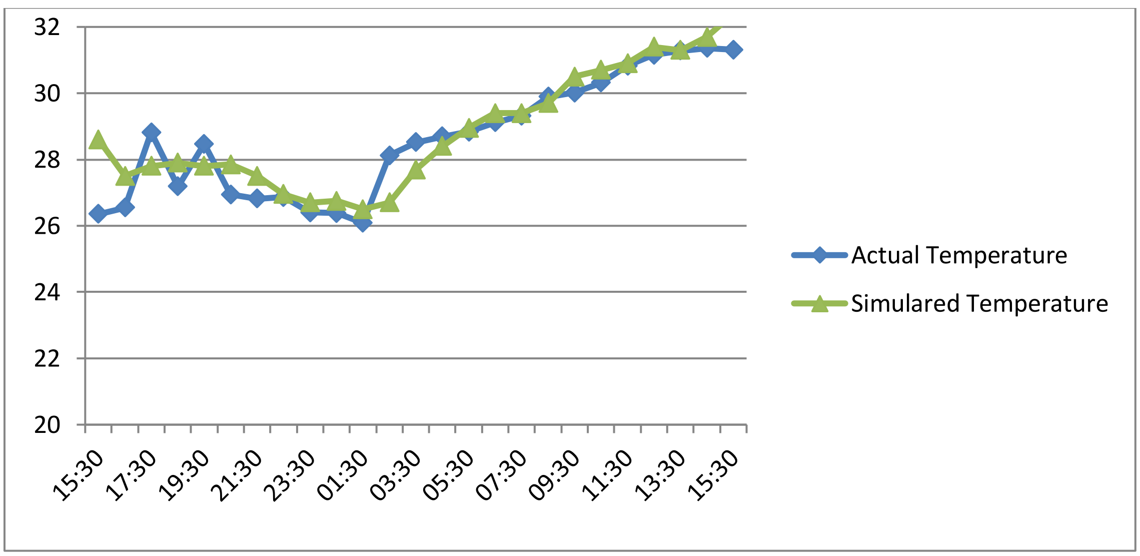
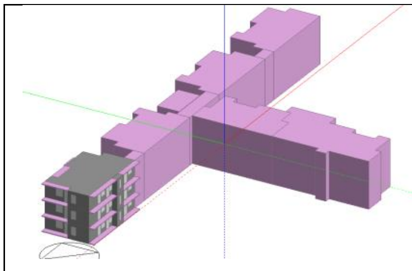


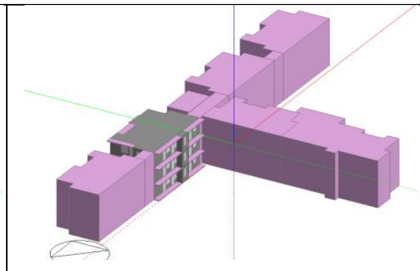
Figure 5.41 Superposition of simulated operative temperature v/s actual temperature during for HSIIDC apartments.

5.7.6 Preparation of Base case

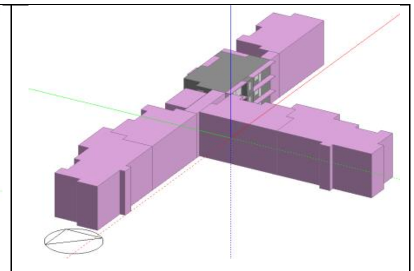
After the models are calibrated, they are simulated by rotating them as per site conditions. For different orientations of the model, EPI is recorded for each of the cases as per orientation. Finally, the mean EPI is taken to form the base case of building simulation model by taking an average of EPI of all directions Figure 5.42.



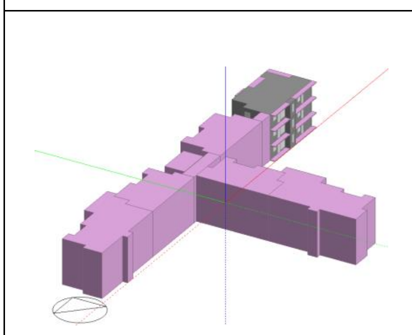
NW SE Left external



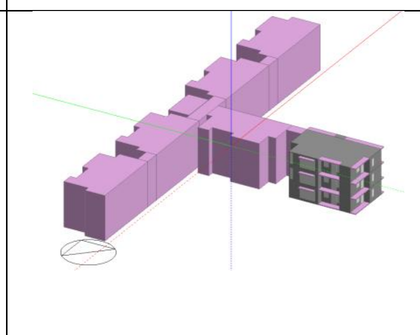
NW SE Left Internal



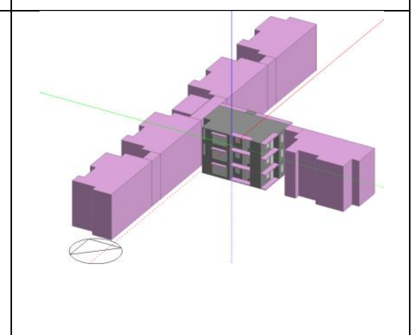
NW SE Right Internal



NW SE Right external



NW SE Third external



NW SE Third Internal

Antriksh Srishti Apartments						
	Gross Wall Area [m2]	1293.33	indow Opening Area [m	220.11	WWR %	17.02
Sr. N	Orientaion	EPI(kWh/m2)	HVAC COOLING(kwh)	Lighting(kwh)	Equipments(kwh	Total Energy
1	NW-SE (Right Internal)Base Case	85.29	57414.08	1848.63	9058.79	68454.54
2	NW-SE (Right External)	87.98	59647.66	1848.63	9058.79	70707.27
3	NW-SE (LEft Internal)	80.98	54025.6	1848.63	9058.79	65085.2
4	NW-SE (LEft External)	85.66	57789.68	1848.63	9058.79	68849.29
5	NW-SE (Third External)	86.03	58081.76	1848.63	9058.79	69141.37
6	NW-SE (Third Internal)	78.84	52307.98	1848.63	9058.79	63367.58
	Average	84.13	56544.46	1848.63	9058.79	

Figure 5.42 Mean EPI of all orientations for preparing base case Model

5.7.7 Selection of Design Strategies for retrofitting to reduce EPI.

Based on the outcomes of the literature review, selection criteria for design strategies for retrofitting entail choosing the factors which are responsible for the reduction of building heat gain and thus reduce cooling demand, using energy efficiently and harnessing renewable energy. In the context of retrofitting existing housing, design interventions should be climate responsive which are suitable for composite climate context, cost-effective and easily achievable. While implementing retrofitting, design strategies should be such that the retrofit measures should be non-intruding to users, implying that one should be able to implement retrofitting from outside the apartment, without intervening with interiors and privacy of users. The design interventions should not violate existing building regulations and without causing an impact on the structural components of existing buildings. Thus various energy conserving measures (ECMs) for reducing cooling load and energy consumption are classified on basis of wall elements, roof elements, other advance elements as well as a simple tool like lighting and landscaping. Table 5.5 shows a list of various ECMs applied to study the reduction in energy consumption (EPI), cooling load, building heat gain factor and discomfort hours.

Table 5.5 List of Various ECMs for retrofitting existing group housing schemes

SN	Description	Retrofitting Measure	Type
1	Simulated	'As is'	
2	ECM 01	Thermal insulation Wall	Wall Elements
3	ECM 02	Surface Reflectance Walls	
4	ECM 03	Sun control film on Glass	
5	ECM 04	Roof Top Solar Photo voltaics	Roof Elements
6	ECM 05	Roof Insulation	
7	ECM 06	Cool roof	
8	ECM 07	Exterior Window Shading	Building Elements, Lighting, Landscaping
9	ECM 08	Airtight Construction	
10	ECM 09	Lighting	
11	ECM 10	Site Microclimate	

A test model is run for understanding optimum value for each of the design parameters as listed above by conducting parametric runs in the building simulation software. There are some conflicting design parameters which negate the effect of other design parameters for instance shading and cool roof do not really impact comfort hours significantly as in composite climate, these design strategies work counterproductive in winters. The parametric analysis serves as a fundamental tool to understand which design parameters are more effective in reducing energy consumption than others and also reject the design parameters which do not bring much improvement in the system [188].

Table 5.6 List of Various ECMs for retrofitting existing group housing schemes

SN	Description	Design Parameter	Base Case	Proposed Case
1	ECM 01	Thermal insulation Wall (U value)	2.501	0.507 Base case +50 mm thick XPS extruded polystyrene + cement plaster render on outside face
2	ECM 02	Surface Reflectance Walls	0.6	0.85 White/ light pale color exterior finish
3	ECM 03	Solar heat gain Windows(SHGC)	0.8	0.3 (Sun control film on glass)
4	ECM 04	Solar PV Panels	Nil	RTSPV panels
5	ECM 05	Thermal Insulation Roof (U value)	2.561	0.401 (Base case +75 mm XPS extruded polystyrene + 50 mm concrete screed finished with tile terrace
6	ECM 06	Cool roof (Surface reflectivity)	0.4	0.8 Broken chine tiles mosaic or High SRI paints smooth texture
7	ECM 07	Exterior Window Shading	1.2 m balcony With no blinds	External Blinds Blade Depth 0.2 m @ 0.2m c/c at 30^0 upto ht.1.0 m from top of window @ 1.2 m away from face of the window
8	ECM 08	Airtightness	0.5 ach^{-1}	0.25 ach^{-1} Air tightness around windows
9	ECM 09	Lighting	T5 16 dia fluorescent tubelight	LED
10	ECM 10	Site Microclimate Ground Cover	Grey paved ground	Grasscrete paver blocks with 60% voids Surface reflectance 0.15

Parametric design runs for various building envelope design parameters such as thermal insulation of walls, roof insulation, external shading of windows exhibit a linear relationship with energy consumption. There is an inbuilt mechanism in the Designbuilder software to run the parametric analysis for finding optimum values of design parameter under study through iterations of several simulations resulting in a plot/region in Pareto curve which provides the optimized value of design parameters. Table 5.6 lists optimized values of design parameters analyzed from the parametric analysis. A brief description of a proposed case of various design strategies is detailed below

5.8 Retrofitting strategies for reducing energy consumption

5.8.1 Strategies for Wall elements

5.8.1.1 ECM 01 Thermal Insulation

Exterior walls have the largest contribution in heat transfer through building skin by virtue of their largest surface area and exposure to solar radiations. It is proposed as ECM 01 to retrofit exterior walls with exterior insulation 50 mm thick XPS (extruded polystyrene) protected by cement plaster render on outside face. Figure 5.43 shows the construction details of layers of wall assembly and U value of the proposed wall.

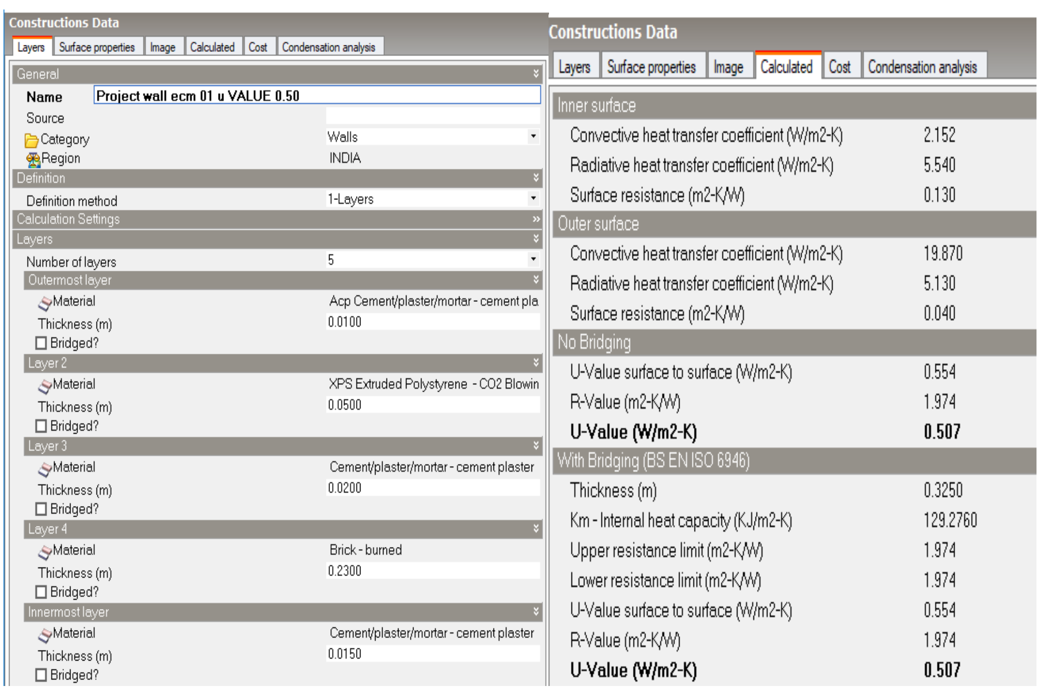


Figure 5.43 Construction details of proposed Wall assembly and its U value

5.8.1.2 ECM 02 Surface Reflectance Walls

It entails providing lighter surface finishes to exterior wall with high surface reflective index (SRI) paint. Reflectance can help ward off heat at first interface with solar radiations at a nominal cost. Figure 5.44 shows a screenshot of graphic details of wall assembly and its surface reflectance modelled data. Building heat gain due to walls can be seen in a Heat balance plot in Fabric and Ventilation Gains summary plotted for the sub-hourly basis for 15th May of the year Figure 5.45. Due to ECM 02, building heat gain is reduced from 11.59 kW to 9.45 kW, resulting in 6.68 % reduction in heat gain.

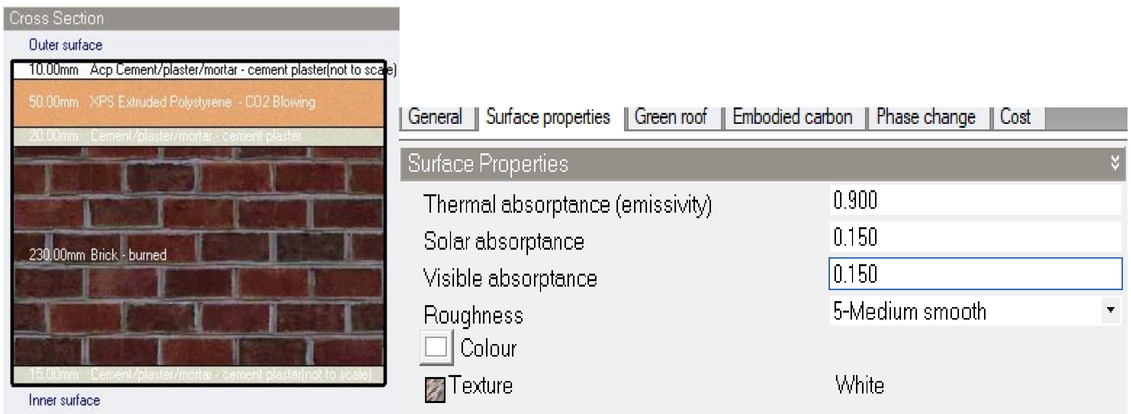
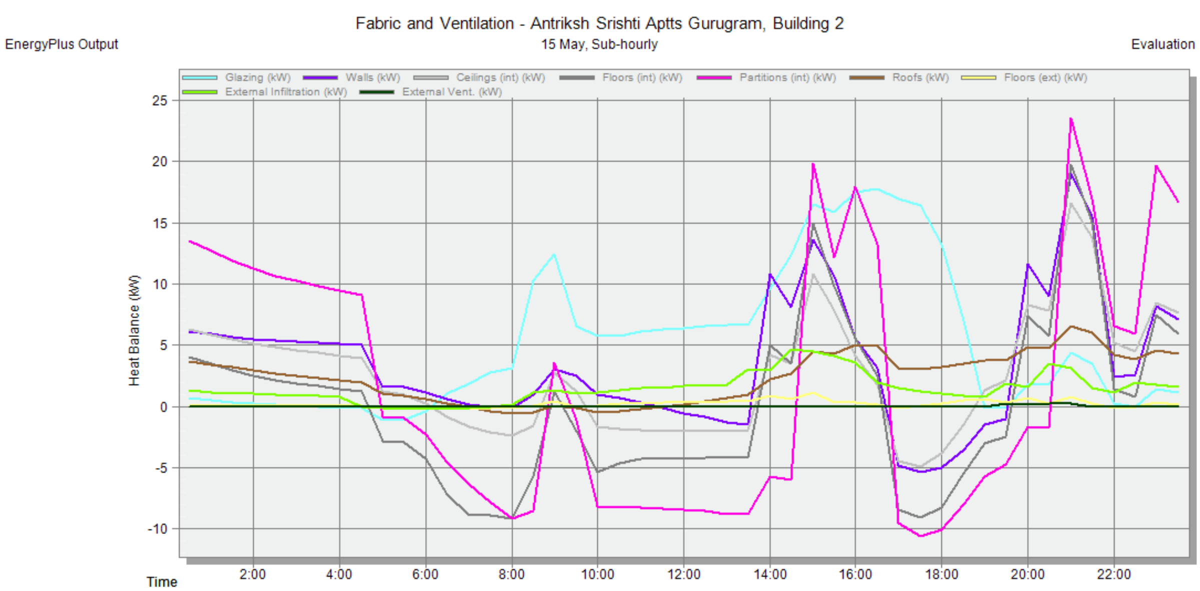


Figure 5.44 Surface reflectance modelled data of wall assembly

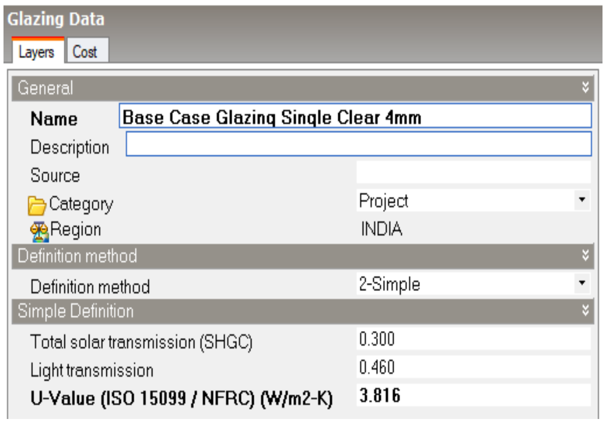


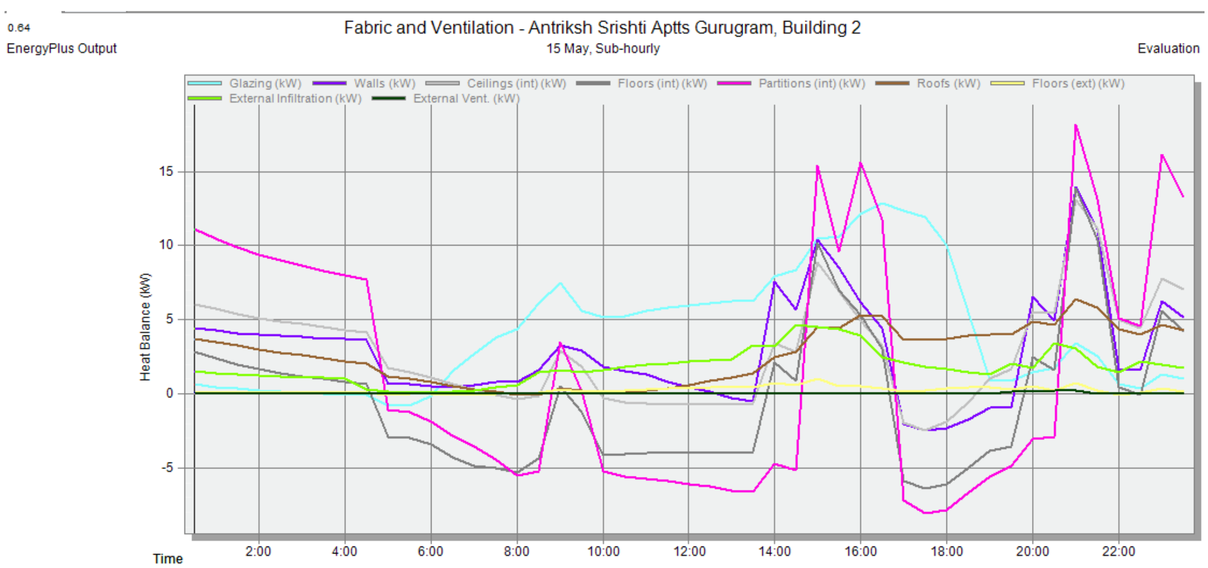
	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Glazing (kW)	0.24	-0.10	-0.39	3.10	5.77	6.42	9.61	17.47	13.29	1.75	0.22
Walls (kW)	5.53	5.10	1.19	-0.09	0.98	-0.55	10.84	5.62	-4.98	11.59	2.44
Ceilings (int) (kW)	5.11	4.17	0.21	-2.38	-1.62	-2.03	4.19	4.11	-3.81	8.33	5.25
Floors (int) (kW)	2.49	1.44	-4.25	-9.17	-5.35	-4.24	5.06	5.57	-8.28	7.38	1.39
Partitions (int) (kW)	11.24	9.47	-2.30	-9.13	-8.19	-8.47	-5.72	18.00	-10.02	-1.66	6.53
Roofs (kW)	2.94	2.12	0.60	-0.55	-0.44	0.19	2.24	5.07	3.21	4.90	4.22
Floors (ext) (kW)	0.07	0.05	-0.11	-0.10	0.06	0.34	0.85	0.31	0.28	0.66	-0.14
External Infiltration (kW)	1.02	0.79	-0.21	0.17	1.15	1.66	2.99	3.59	1.03	1.64	1.19
External Vent. (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00

Figure 5.45 Fabric and ventilation gain summary on the sub-hourly basis for 15th May

5.8.1.3 ECM 03 Solar Heat Gain Windows

As seen from the literature review and simulation analysis, maximum heat gain occurs through transparent surfaces by way of direct solar radiations. In ECM 03, Windows are retrofitted with inexpensive sun control solar film so as to reduce solar heat gain coefficient (SHGC). The base case consists of glazing type as single glass 4 mm thick with SHGC 0.8, Visible Light Transmittance 0.85.The proposed case of retrofitted windows with solar control film reduces SHGC to 0.3 and VLT to 0.46, which is well within permissible limits. With this ECM 03, building heat gain is reduced from 17.54 kW to 12.12 kW, resulting in 30.9 % reduction in heat gain and consequently, EPI is also reduced by 20.71% (Figure 5.46).





	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Glazing (kW)	0.26	-0.05	-0.14	4.34	5.16	5.99	7.89	12.12	10.01	1.49	0.64
Walls (kW)	3.98	3.68	0.49	0.83	1.85	0.42	7.59	6.20	-2.32	6.52	1.61
Ceilings (int) (kW)	5.13	4.32	1.09	-0.37	-0.26	-0.73	3.40	4.96	-1.87	5.55	4.99
Floors (int) (kW)	1.66	0.84	-3.43	-5.29	-4.13	-3.96	2.09	5.29	-6.12	2.50	0.44
Partitions (int) (kW)	9.37	7.97	-1.86	-5.52	-5.24	-6.10	-4.70	15.65	-7.81	-3.03	5.09
Roofs (kW)	3.02	2.20	0.80	-0.05	0.01	0.61	2.47	5.29	3.73	4.88	4.33
Floors (ext) (kW)	0.10	0.07	-0.02	-0.00	0.14	0.39	0.76	0.54	0.34	0.50	-0.04
External Infiltration (kW)	1.24	1.01	0.10	0.62	1.63	2.17	3.23	3.91	1.67	1.78	1.49
External Vent. (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00

Figure 5.46 Modeled data of glass and heat balance plot due to ECM 03.

5.8.2 Strategies for Roof Elements

5.8.2.1 ECM 04 Solar PV Panels

Roofs can be effectively utilized for generation of power through rooftop solar photovoltaic panels. Rooftop solar photovoltaics are mandatory for new constructions as per new building bye-laws of Haryana Building Code 2017. Under the National Solar Mission, the government is promoting group housing societies to install rooftop solar panels with financial incentives. Solar panels are modelled in Designbuilder as component and provide shade to the roof to help to curb direct solar radiations. Figure 5.47 illustrates PV characteristics assigned to different Solar PVs in one of the projects installed with ten nos. of PV panels of each 12 sqm, producing 6811 kWh of energy per year.

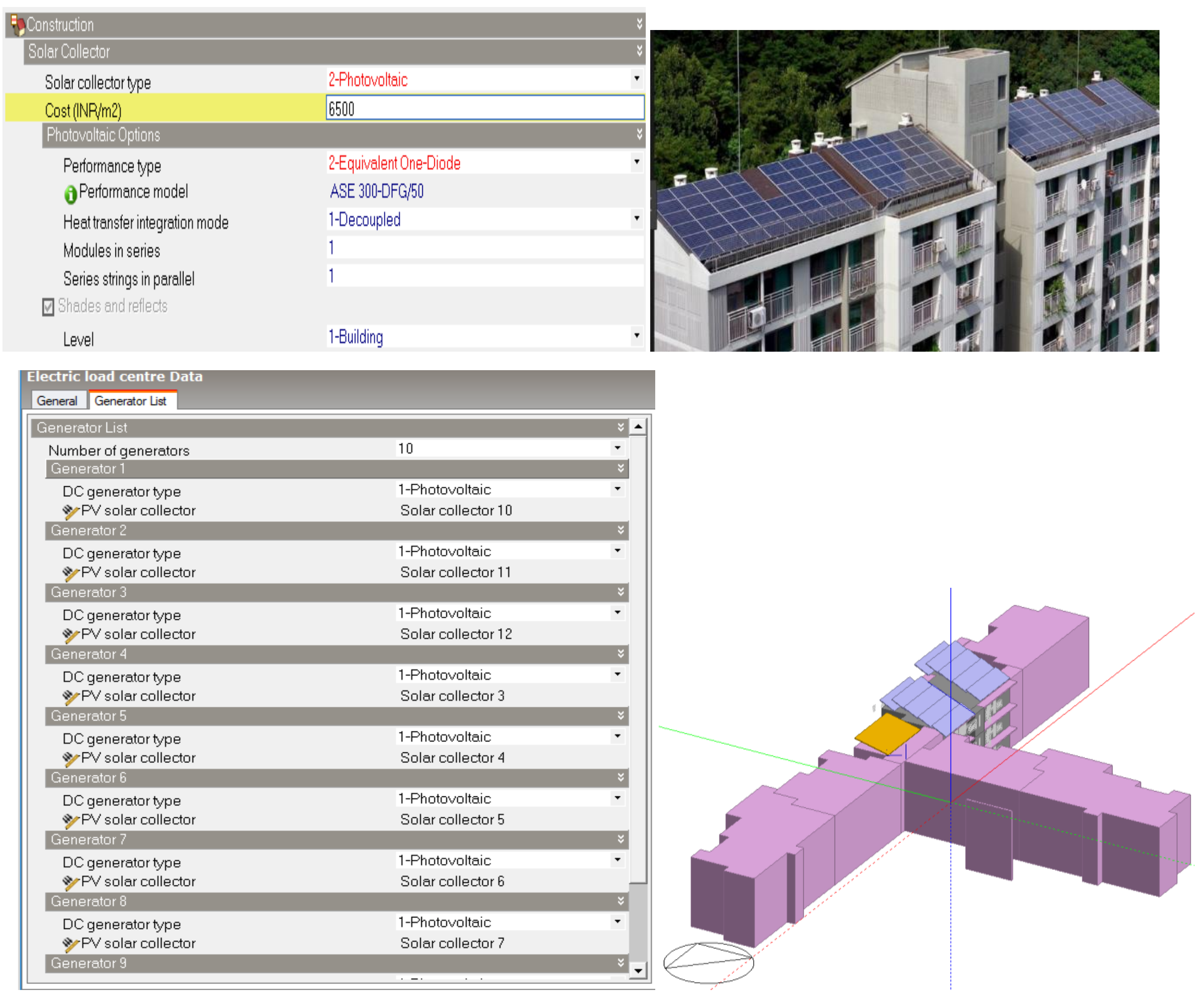


Fig 5.47 ECM 04 Model of Rooftop Solar PV with its characteristics

5.8.2.2 ECM 05 Thermal Insulation Roof:

Thermal insulation of the roof can provide additional resistance to heat transmittance due to conductance. In proposed case, there of is retrofitted with an overdeck insulation layer of 75mm thick extruded polystyrene (XPS) laid with 50 mm thick concrete screed finished with tile terracing, reducing thermal conductance to 0.401 (Figure 5.48). There is a considerable reduction in heat gain from 5.07kW to 0.84kW, resulting in 83.4% reduction in heat gain through the roof and consequently, EPI is also reduced by 37.28% (Figure 5.49).

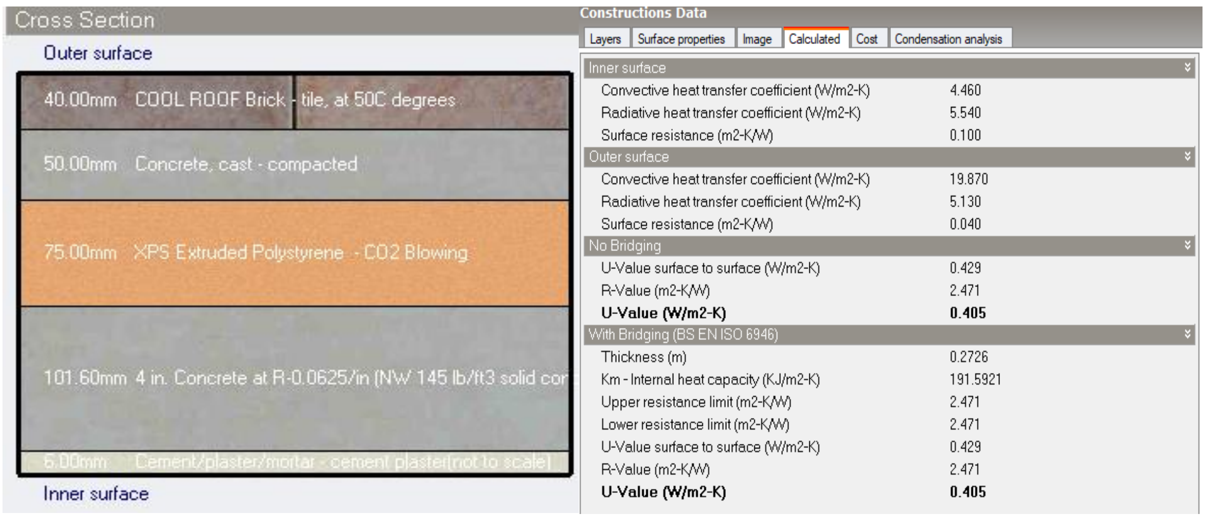
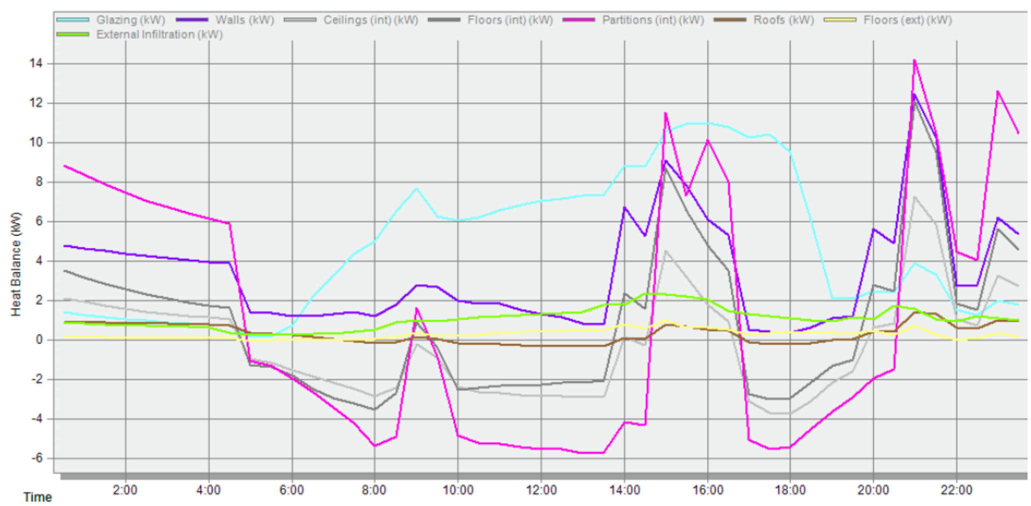


Figure 5.48 ECM 05 Thermal insulation roof assembly layers and its U value

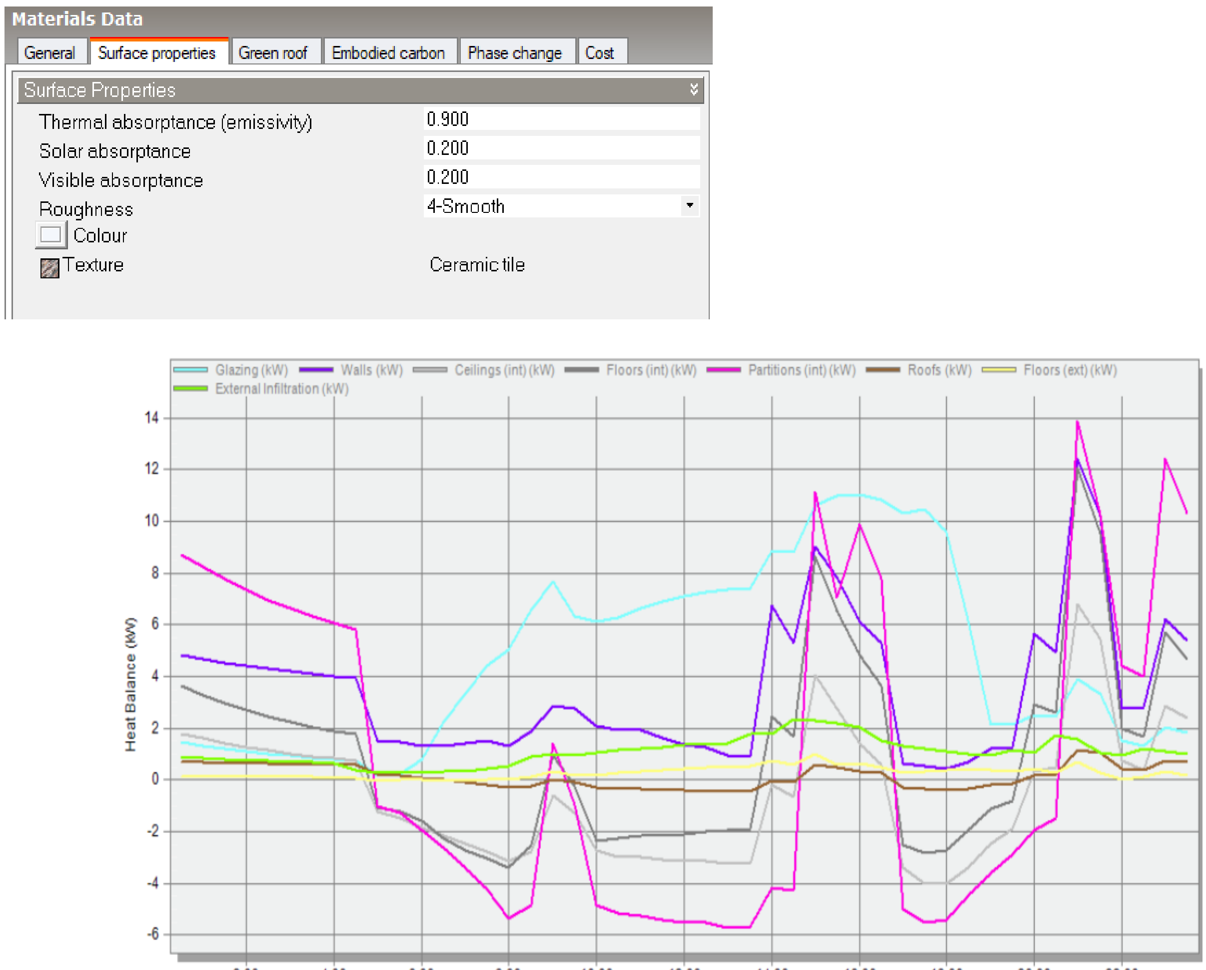


Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Glazing (kW)	1.06	0.75	0.71	4.98	6.04	7.03	8.82	10.97	9.51	2.45	1.49
Walls (kW)	4.36	3.96	1.21	1.19	1.98	1.27	6.73	6.11	0.33	5.63	2.71
Ceilings (int) (kW)	1.57	1.12	-1.57	-2.85	-2.40	-2.85	0.14	1.76	-3.75	0.64	1.06
Floors (int) (kW)	2.56	1.74	-1.81	-3.57	-2.55	-2.30	2.34	4.78	-2.96	2.75	1.84
Partitions (int) (kW)	7.44	6.14	-1.98	-5.41	-4.86	-5.55	-4.17	10.17	-5.47	-1.97	4.47
Roofs (kW)	0.84	0.76	0.22	-0.16	-0.18	-0.31	0.08	0.50	-0.23	0.38	0.61

Figure 5.49 Reduction in building heat gain due to thermal insulation of the roof

5.8.2.3 ECM 06 Cool Roof:

Cool roofs have been recognized as a cost-effective means of reflecting heat or solar radiations. Roofs can be finished with high surface reflective index paint or finished with broken china tiles mosaic flooring to reflect heat. In the proposed case, the surface reflective property has been modelled as 0.8 against base case reflectance of 0.4. Heat gain through the roof is further reduced to 0.64 kW. Figure 5.50 depicts properties of the cool roof as modelled in Designbuilder software and building heat gain due to cool roof



	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Glazing (kW)	1.10	0.79	0.77	5.04	6.09	7.10	8.86	11.01	9.57	2.50	1.54
Walls (kW)	4.40	4.01	1.30	1.28	2.08	1.38	6.72	6.11	0.43	5.66	2.78
Ceilings (int) (kW)	1.27	0.82	-1.85	-3.16	-2.71	-3.17	-0.22	1.39	-4.03	0.31	0.75
Floors (int) (kW)	2.69	1.88	-1.61	-3.38	-2.36	-2.10	2.44	4.83	-2.75	2.90	1.99
Partitions (int) (kW)	7.34	6.06	-1.93	-5.39	-4.83	-5.51	-4.16	9.92	-5.42	-1.93	4.42
Roofs (kW)	0.64	0.57	0.08	-0.29	-0.29	-0.42	-0.06	0.32	-0.39	0.17	0.40
Floors (ext) (kW)	0.11	0.09	-0.00	0.02	0.18	0.42	0.76	0.62	0.36	0.45	-0.00
External Infiltration (kW)	0.76	0.65	0.26	0.53	1.04	1.33	1.78	2.02	1.12	1.06	0.93

Figure 5.50 Properties of Cool roof and Building heat gain plot

5.8.3 Other Strategies for Retrofitting

5.8.3.1 ECM 07 Exterior Window Shading

It is proposed to have exterior blinds/ louvres to shade windows or improve projection factor of windows. Figure 5.51 shows a typical section of the proposed ECM, showing louvres of height 1.0 m with a blade depth of 0.2 m, vertical spacing @ 0.2m c/c at angle $30^{0.}$ The louvres are placed touching the balcony end at distance of @ 1.2 m away from the face of windows, Figure 5.51. Figure 5.52 depicts heat balance plot showing a reductionin building heat gain by 13.77% through glazing due to proposed shading by external blinds.

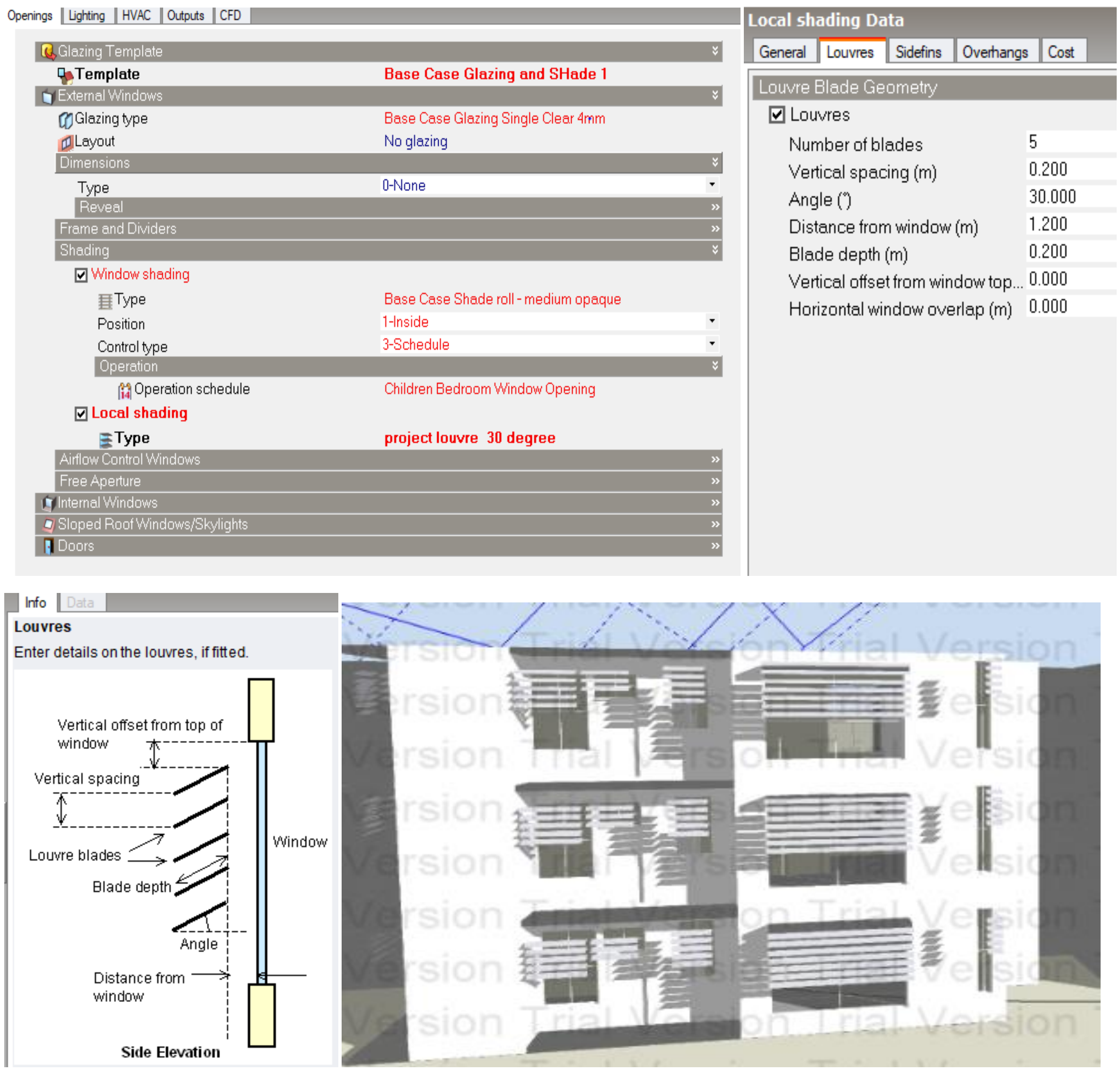


Figure 5.51 ECM 07 Details of exterior window Shading

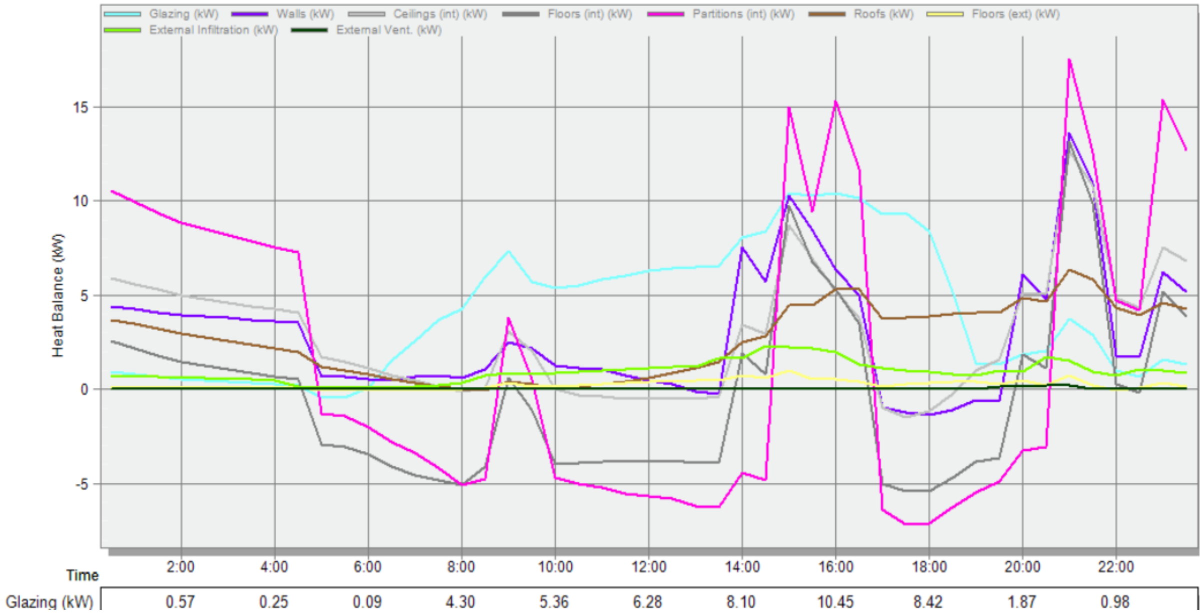


Figure 5.52 Heat balance plot of windows with exterior window shading.

5.8.3.2 ECM 08 Airtight Construction

Airtight construction is a prerequisite for air-conditioned spaces so as to avoid heating or cooling losses due to infiltration. It is proposed to seal all windows and doors joints with sealants so as to achieve air changes 0.25 ach/ hr as against base case of 0.5 ach/hr (Figure 5.53). Reduction in heat gain through convective infiltration losses by nearly 1.92 kW over the Base case heat gain of 3.91 kW.

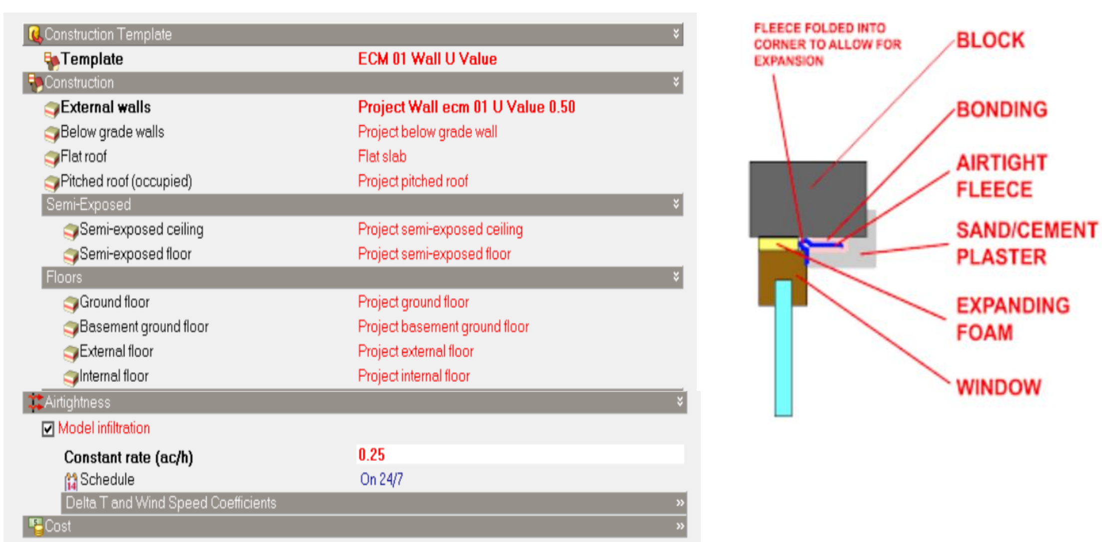
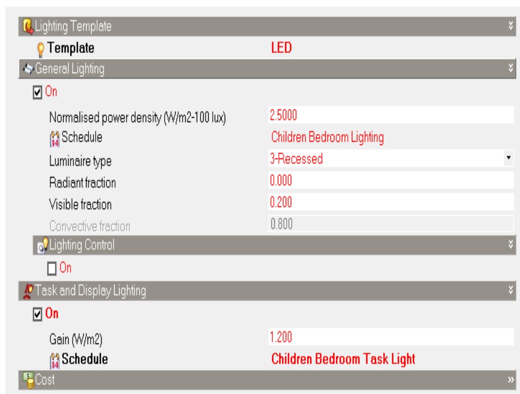


Figure 5.53 Air tightness details in the proposed case

5.8.3.3 ECM 09 Lighting

Energy is consumed directly in artificial lighting for visual comfort as well as in combating internal heat gain due to artificial lighting luminaires. Efficient lighting like Light Emitting Diode (LED), not only lighting power density is decreased, but also there is much less heat gain due to lighting. Base case has been modelled as ubiquitous T5 16 mm diameter fluorescenttriphosphor tube light, whereas the proposed case is modelled as LED. Figure 5.54 shows proposed case as LED with gains at 1.2 W/ m^2 and contribution of various elements in internal heat gain summary.



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ı (kWh)	150.33	137.98	156.78	146.96	151.10	152.64	151.10	156.38	147.35	151.10	151.50	150.72
Task Lighting (kWh)	1.18	1.07	1.18	1.15	1.18	1.15	1.18	1.18	1.15	1.18	1.15	1.18
General Lighting (kWh)	14.95	13.71	15.47	14.54	14.95	15.06	14.95	15.44	14.56	14.95	15.03	14.98
Miscellaneous (kWh)	14.19	13.96	75.57	71.46	73.57	73.46	73.57	75.02	72.01	73.57	29.51	15.21
Process (kWh)	17.82	16.09	17.82	17.24	17.82	17.24	17.82	17.82	17.24	17.82	17.24	17.82
Catering Gains (kWh)	6.96	6.29	6.96	6.74	6.96	6.74	6.96	6.96	6.74	6.96	6.74	6.96
Computer + Equip (kWh)	12.34	11.37	12.92	12.02	12.34	12.60	12.34	12.69	12.25	12.34	12.37	12.57
Occupancy (kWh)	82.80	71.98	115.90	57.54	48.28	43.93	49.15	53.50	53.39	75.99	119.63	81.49

Figure 5.54 LED lighting and internal heat gain summary

5.8.3.4 ECM 10 Site Microclimate Ground Cover

Ground conditions modulate site microclimate and contribute to heat gain of buildings due to the reflection of heat from the ground to buildings. By altering ground conditions, one can reduce heat gain in buildings by soft scape and save electrical energy due to less urban heat island effect at relatively low capital investment. The proposed case is taken as grasscrete paver blocks with 60% voids filled with grass against the base case of concrete pavement. There is a reduction in ambient air temperature due to less urban heat island effect and absorption of solar radiations by green softscape elements. Figure 5.55 shows site details modelled as grasscrete paver module green blocks with 60% voids, having 85% absorption of solar radiations. Heat balance in fabric and ventilation gains plot shows the nominal share of heat gain due to external floors (Figure 5.56)

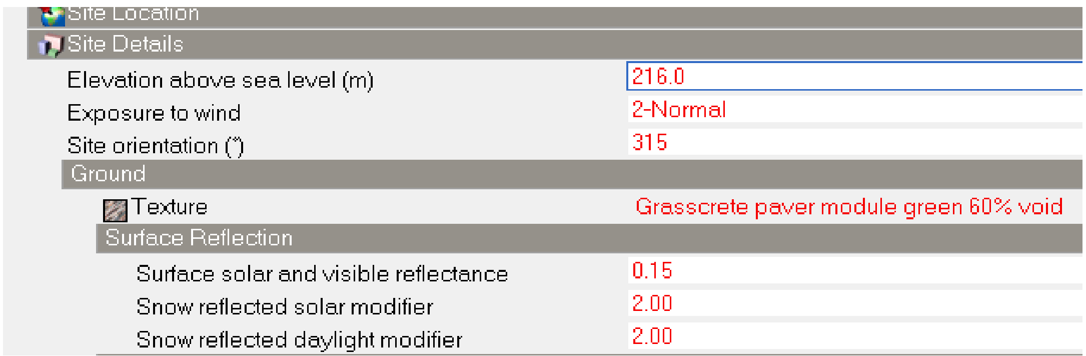
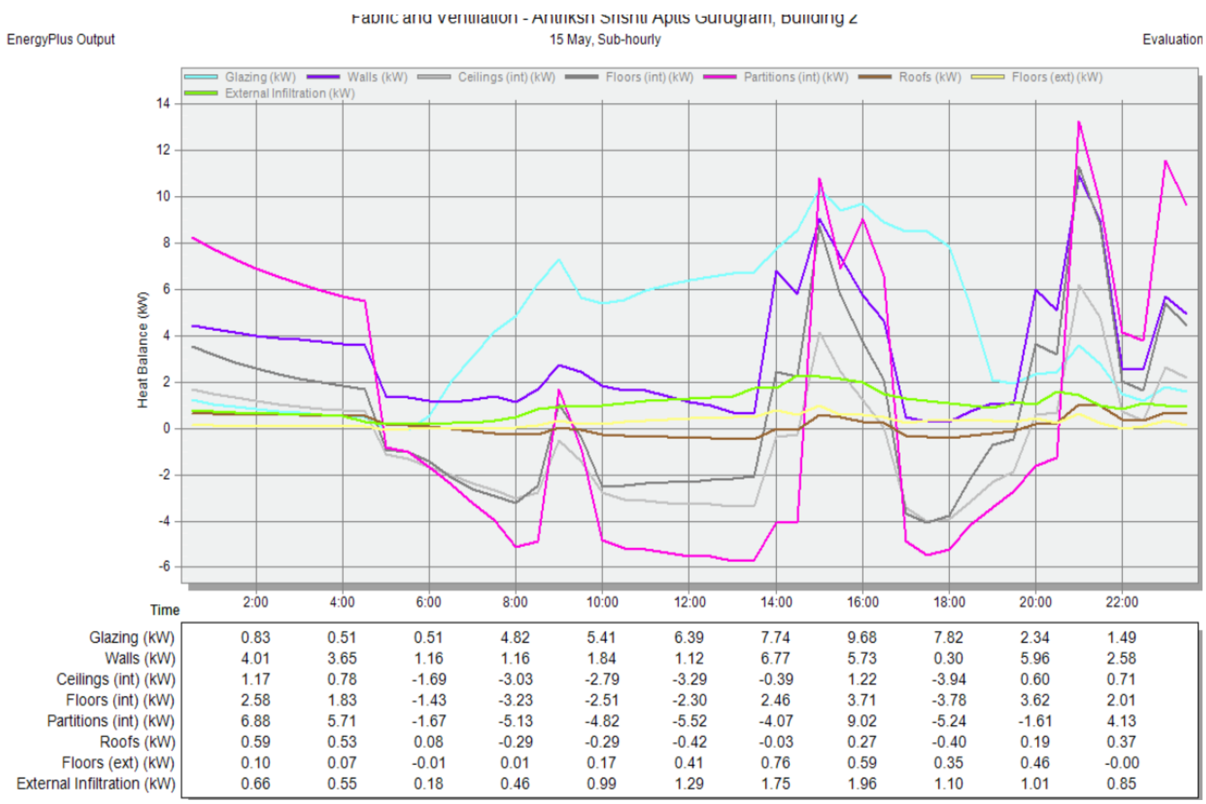


Figure 5.55 Site details showing ground conditions and its reflection



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Glazing (kW)	0.83	0.51	0.51	4.82	5.41	6.39	7.74	9.68	7.82	2.34	1.49
Walls (kW)	4.01	3.65	1.16	1.16	1.84	1.12	6.77	5.73	0.30	5.96	2.58
Ceilings (int) (kW)	1.17	0.78	-1.69	-3.03	-2.79	-3.29	-0.39	1.22	-3.94	0.60	0.71
Floors (int) (kW)	2.58	1.83	-1.43	-3.23	-2.51	-2.30	2.46	3.71	-3.78	3.62	2.01
Partitions (int) (kW)	6.88	5.71	-1.67	-5.13	-4.82	-5.52	-4.07	9.02	-5.24	-1.61	4.13
Roofs (kW)	0.59	0.53	0.08	-0.29	-0.29	-0.42	-0.03	0.27	-0.40	0.19	0.37
Floors (ext) (kW)	0.10	0.07	-0.01	0.01	0.17	0.41	0.76	0.59	0.35	0.46	-0.00
External Infiltration (kW)	0.66	0.55	0.18	0.46	0.99	1.29	1.75	1.96	1.10	1.01	0.85

Figure 5.56 Share of heat gain due to external floors in fabric and ventilation gains plot

5.9 Comparative Overview of Different Strategies

After calibration of a model of 'As is'case, the base case is simulated on an hourly basis for each of ten energy-conserving measure in the proposed case as per Table 5.6 for all eight housing societies for three cases such as Low energy use intensity, normal energy use intensity, and high energy use intensity. The output summary generated from (8 x 3x 11= 264 simulations) is analyzed for energy performance index, design cooling load, building heat gainand discomfort hours.

The graph (Figure 5.57) shows a comparative reduction in EPI due to different ECMs, by taking base case indexed as EPI at 100 kWh/ m^2/yr. It is observed that ECM 01 Thermal insulation walls, ECM 02 Reflective walls, ECM 03 Solar film on windows, ECM 04 Solar PV Panels, ECM 10 Site microclimate are the most effective strategies to reduce EPI.

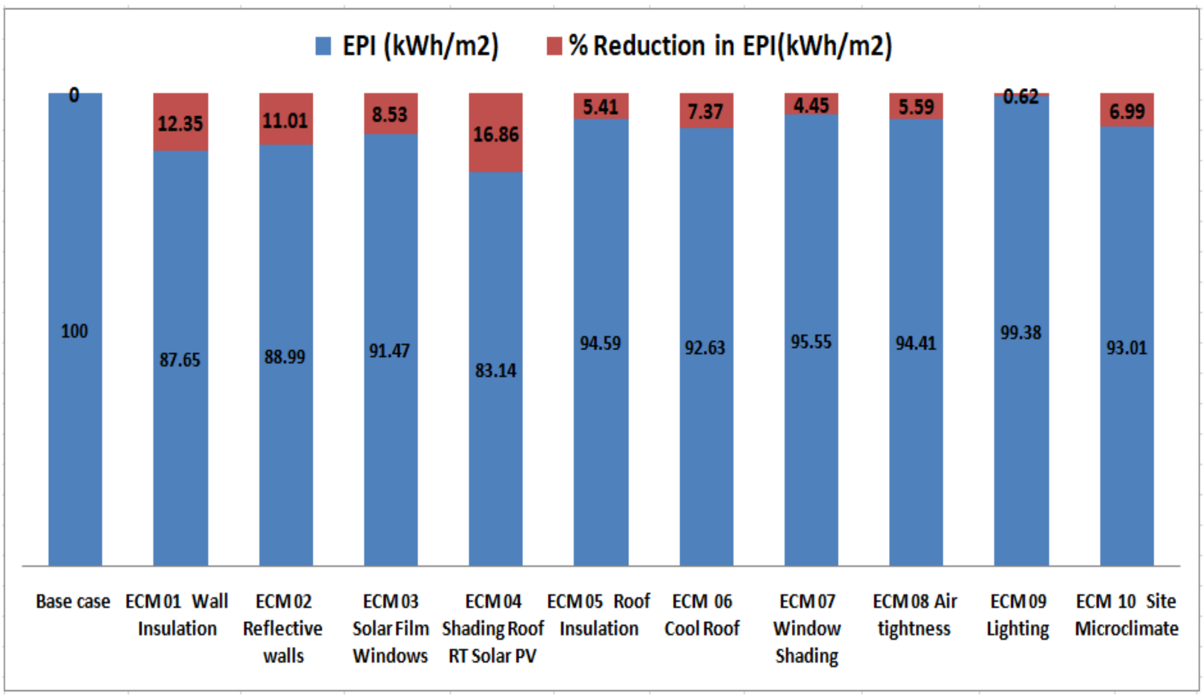


Figure 5.57 Comparison of individual retrofit ECMs on energy consumption

The table 5.7 shows the final summary of all retrofit ECMs for normal energy use intensity in another case study Ansal API Sushant Estate in city Gurugram addressing breakup of the enduse of energy in HVAC, Lighting and equipment and EPI, % reduction in EPI by each progressive retrofit measure simulated. The major share of energy consumption is in HVAC i.e. cooling the space for thermal comfort, followed by equipment loads and nominal share in lighting. There is a great potential for reducing cooling load by improving building envelope to reduce heat gain primarily as can be seen finally reduction in cooling load from 74014.3 kW to 26399.87 kW, (% reduction in cooling load by 64.33 %). By replacing base case lighting by LED lighting, there is a reduction in heat load and hence reduction in cooling load. There is a room for more reduction in energy consumption by improving the efficiency of HVAC mechanical system and energy efficient equipments but have not been discussed here because they are outside scope of this research work.

Table 5.7 Output Summary for end use breakup of energy consumption due to different retrofit measures (Ansal API Sushant Estate, Gurugram)

Sr. No.	Nomenclature	EPI kWh/ m2/ yr)	HVAC Cooling (kwh)	Lighting (kwh)	Equipments (kwh)	Total Energy (kwh)	Reduction EPI (kWh/m2)	% Reduction EPI
1	BASE CASE	65.85	74014.3	2715.29	13215.86	91017.12	-	-
2	ECM 01 Wall Insulation	57.72	60893.66	2715.29	13215.86	77365.52	8.13	12.35
3	ECM 02 Reflectivity walls	55.22	57544.43	2715.29	13215.86	74016.28	10.63	16.14
4	ECM 03 Solar Film Windows	48.42	48423.39	2715.29	13215.86	64895.25	17.43	26.47
5	ECM 04 Solar PV Panels	45.14	44031.37	2715.29	13215.86	60503.23	20.71	31.45
6	ECM 05 Roof Insulation	41.38	38984.4	2715.29	13215.86	55456.26	24.47	37.16
7	ECM 06 Cool Roof	40.58	37922.9	2715.29	13215.86	54394.76	25.27	38.38
8	ECM 07 Ext. Window Shading	39.04	35854.24	2715.29	13215.86	52326.1	26.81	40.71
9	ECM 08 Air Tightness	35.34	30895.87	2715.29	13215.86	47367.72	30.51	46.33
10	ECM 09 Lighting	34.91	30944.44	2087.81	13215.86	46788.82	30.94	46.99
11	ECM 10 Site Microclimate	31.52	26399.87	2087.81	13215.86	42244.25	34.33	52.13
12	Net Addition of RTSPV	20.6	26399.87	2087.81	13215.86	27613.59	45.25	68.72

Table 5.8 shows final summary of all retrofit ECMs for normal energy use intensity in another case study Ansal API Sushant Estate in city, Gurugram addressing % reduction in EPI, design cooling load per floor area (W/m^2), Time not comfortable based on ASHRAE, Heat gain due to windows and opaque surface by each progressive retrofit measure simulated. It can be seen from the data that different architectural retrofit measures lead to significant reduction in design cooling load, improvement in comfort hours and reduction in building heat gain in addition to the primary objective of reduction in energy consumption.

Table 5.8 Output Summary for EPI and other design parameters due to different retrofit measures (Ansal API Sushant Estate, Gurugram)

Sr. No.	**ECM**	**EPI kWh/ m2/ yr)**	**% Reduction EPI**	**Design Cooling Load Per Floor Area (W/m2)**	**Time Not Comfort Based on Simple ASHRAE**	**Window Heat Addition [GJ]**	**Opaque Surface Conduction and Other Heat Addition [GJ]**	**Total ofOpaque Surface Conduction + Window Heat [GJ]**
1	BASE CASE	65.85	0	125.2	625.5	35.052	15.925	50.977
2	ECM 01 Wall Insulation	57.72	12.35	106.4	459.5	35.998	0.001	35.999
3	ECM 02 Reflectivity walls	55.22	16.14	101.3	506	36.724	0.001	36.725
4	ECM 03 Solar Film Windows	48.42	26.47	83.1	614	20.369	0.001	20.37
5	ECM 04 Solar PV Panels	45.14	31.45	76.8	781	21.316	0.001	21.317
6	ECM 05 Roof Insulation	41.38	37.16	67.7	633	21.743	0.001	21.744
7	ECM 06 Cool Roof	40.58	38.38	66	670	21.984	0.001	21.985
8	ECM 07 Ext. Window Shading	39.04	40.71	59.8	708	21.041	0.003	21.044
9	ECM 08 Air Tightness	35.34	46.33	54.1	580	21.228	0.001	21.229
10	ECM 09 Lighting	34.91	46.99	54	582	21.25	0.001	21.251
11	ECM 10 Site Microclimate	31.52	52.13	48.7	584	20.338	0.001	20.339
12	Net Addition of RTSPV	20.6	68.72	48.7	584	20.338	0.001	20.339

Table 5.9 shows reduction in energy consumption of all eight cases under study insample space for normal energy use intensity (EUI) by applying different retrofit energy conserving measures (ECMs) progressively applied. It is observed that there is a variation of EPI in eight cases with Srishti apartments showing a spike in the graph (Figure 5.58). It can be reasoned that Srishti apartments have less built-up area per apartment and no of stories also being less (S+8) and also the apartments are linear in nature with long walls exposed to solar radiations and poor orientation. As Energy Performance Index (EPI) is metrics for assessing energy consumption per annum per square meters of built-up area, the flats smaller in area and having less no of floors will tend to show higher EPI as compared to taller building blocks and flats with large built-up area, but there is no significant difference in the absolute energy consumption of flats in the simulated model.

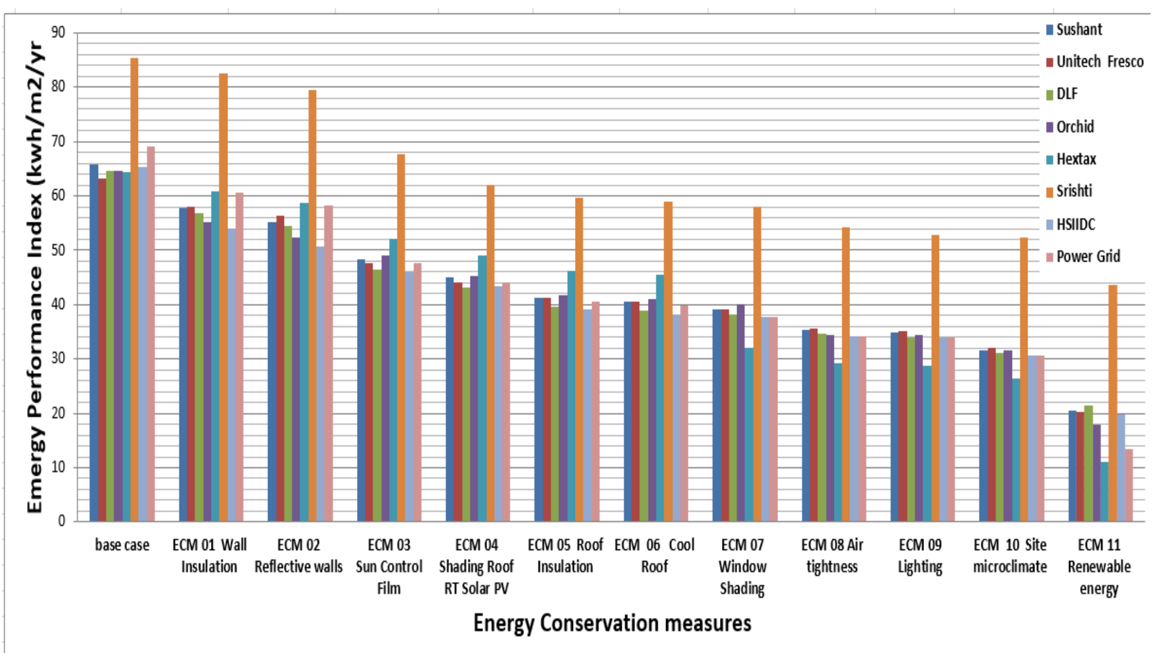
Table 5.9 Reduction in EPI of all cases in Sample for Normal EUI by retrofitting ECMs

Sr. No.	Retrofit ECM	Sushant	Unitech Fresco	DLF	Orchid	Hextax	Srishti	HSIIDC	Power Grid
1	Base case	65.85	63.2	64.59	64.69	64.37	85.29	65.27	69.18
2	ECM 01	57.72	57.97	56.77	55.2	60.83	82.45	53.98	60.7
3	ECM 02	55.22	56.27	54.42	52.27	58.67	79.59	50.81	58.19
4	ECM 03	48.42	47.74	46.44	49.04	52.22	67.63	45.9	47.74
5	ECM 04	45.14	44.11	43.07	45.27	48.97	62.04	43.37	44.21
6	ECM 05	41.38	41.28	39.58	41.84	46.21	59.64	39.05	40.59
7	ECM 06	40.58	40.57	38.8	41.04	45.5	59.04	38.11	39.81
8	ECM 07	39.04	39.1	38.11	40.2	32	58.01	37.7	37.7
9	ECM 08	35.34	35.58	34.58	34.48	29.12	54.29	34.24	34.15
10	ECM 09	34.91	35.17	34.06	34.32	28.87	52.89	33.89	33.84
11	ECM 10	31.52	31.96	31.21	31.48	26.49	52.31	30.76	30.54
12	Net Addition of RTSPV	20.6	20.22	21.35	18.01	11.05	43.62	19.75	13.37

The graph (Figure 5.58) shows comparative EPI of all cases for normal EUI with actual EPI as base case and simulated EPI after applying retrofit ECMs progressively. Various ECMs are classified into three categories as represented by different horizontal colored bands at the bottom of graph as defined below:

i) Energy Efficient Retrofit Model (represented by horizontal yellow band) leading upto 25.32% reduction in EPI consisting of wall components ECMs 01 by retrofitting walls for thermal insulation, ECM 02 improving surface reflectivity and ECM 03 Solar control films on windows to reduce solar heat gain.

ii) Energy Efficient Plus Retrofit Model (represented by horizontal blue band) leading upto 54.81 % reduction in EPI, consisting of wall components and roof components: ECMs 04 by installing solar PV panels on rooftop, ECM 05 by improving the thermal insulation of roof and ECM 06 Cool roofs by improving surface reflectivity in addition to ECM 01 to 03.



Energy Efficient 25.32 % Reduction

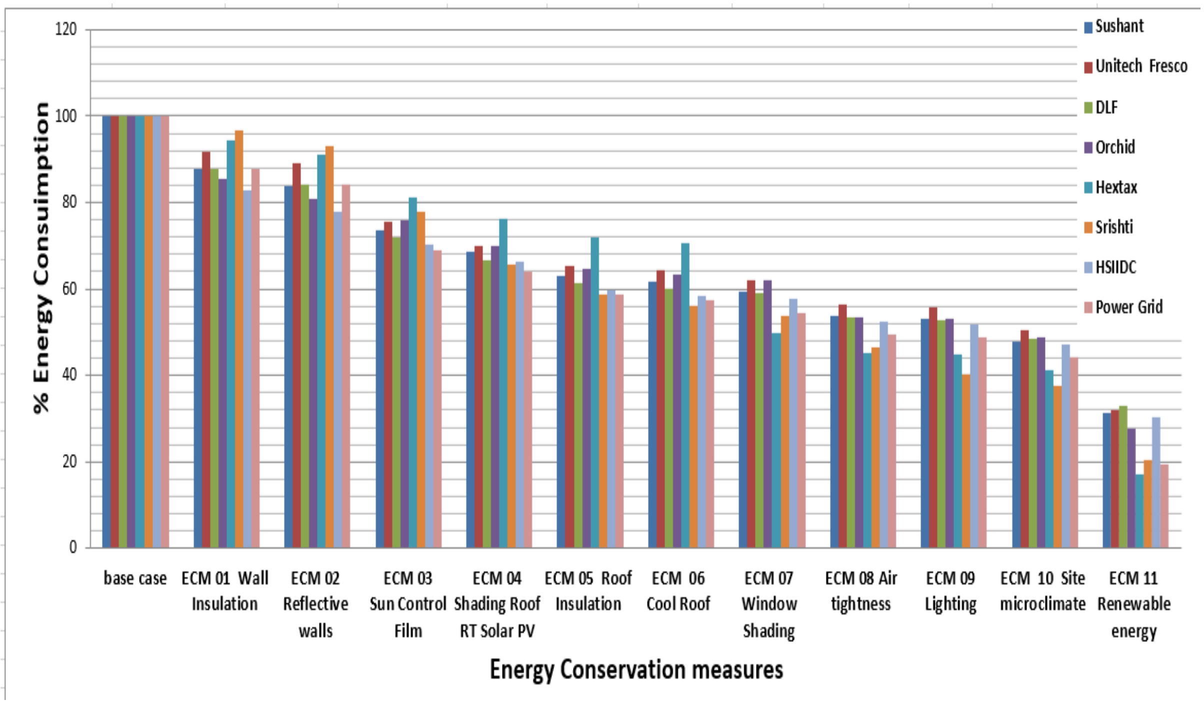
Energy Efficient Plus up to 54.81 % reduction

Energy Efficient Super up to 69.04 % reduction

Figure 5.58 Reduction in energy consumption (EPI) by applying retrofit ECMs of all eight cases in the sample for normal EUI.

iii) Energy Efficient Super Retrofit Model (represented by horizontal green band) leading upto 69.04% reduction in EPI, consisting of other components, ECMs 07 by external window shading, ECM 08 by improving airtightness, ECM 09 by LED lighting, ECM 10 by paving with grasscrete blocks, in addition to wall and roof components ECM 01 to 06.

The graph (Figure 5.59) shows comparative EPI of all cases for normal EUI with normalized EPI taking the base case as EPI of 100 kWh/m^2/year and simulated EPI after applying retrofit ECMs progressively. It is seen that all eight cases show a similar trend in reduction in energy consumption in progressive retrofit energy-saving measures. One can achieve upto 69.04 % saving in energy consumption by applying all retrofit ECMs.



Energy Efficient 25.32% Reduction

Energy Efficient Plus up to 54.81 % reduction

Energy Efficient Super up to 69.04 % reduction

Figure 5.59 Reduction in Normalized energy consumption (EPI) by applying retrofit ECMs of all eight cases in the sample for normal EUI

The graph in Figure5.60 shows a reduction in energy consumption based on the mean of all cases in the sample (Normal Case) through different ECMs progressively applied.Mean EPI of the base case of all sample withoutretrofit measures is 67.81 kWh/m^2/yr. After applying Energy efficient retrofit (from ECM 01- ECM 03), mean EPI of all cases for normal EUI is 50.64 kWh/m^2/yr. For energy efficient plus retrofit measures, mean EPI of all cases is 30.64 kWh/m^2/yr and finally after retrofitting all ECMs, mean EPI for energy efficient super retrofits of all samplesis 20.99 kWh/m^2/yr, leading to a maximum of 69.04% saving for normal EUI.

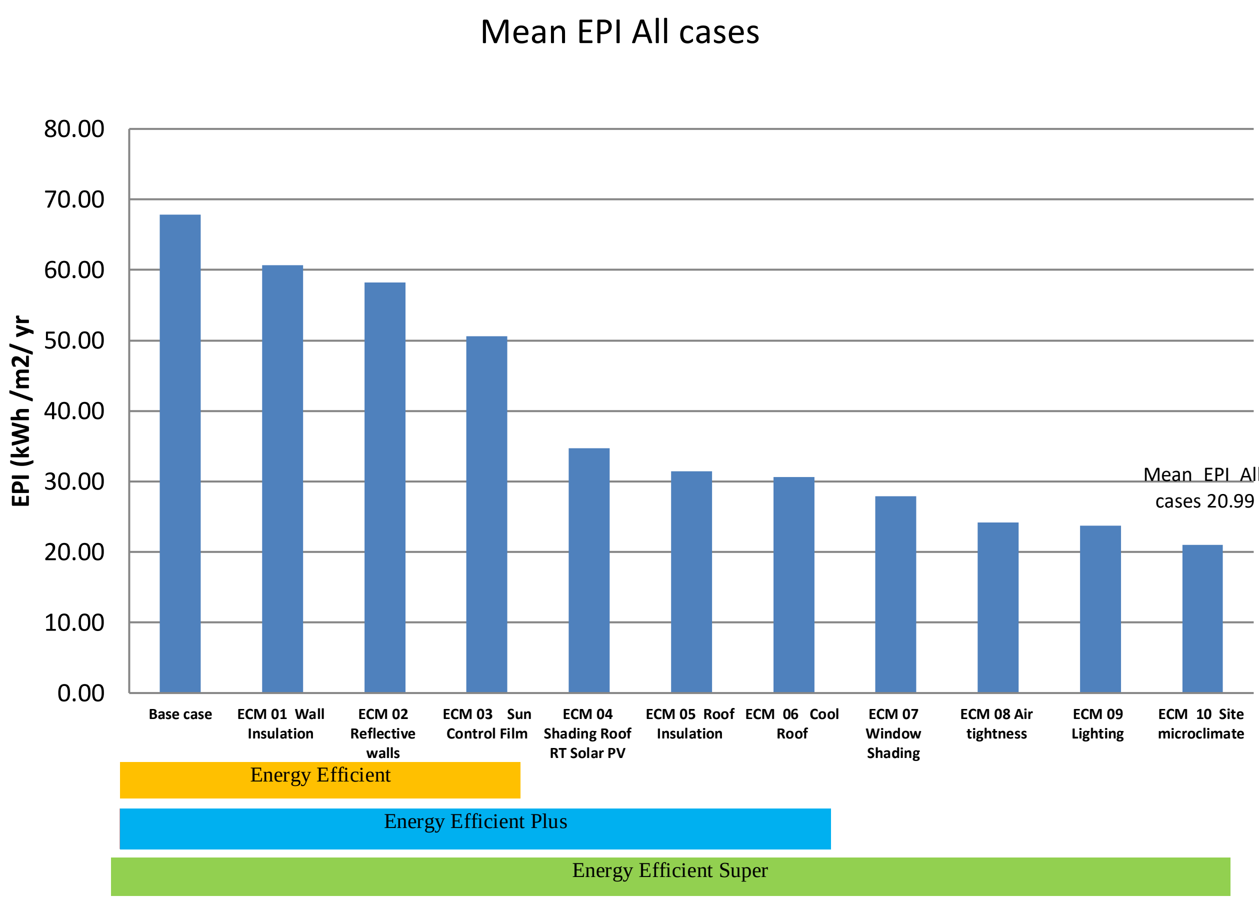


Figure 5.60 Mean EPI of all samples due to retrofitting ECMs for normal EUI.

Trendline analysis of the peaks of the curve of the graph of total annual energy use isan indicator of the comparativecontribution ofvarious energy conserving retrofit measures in the end-use breakup of energy use. Figure 5.61 reflects detailed breakup of end energy use for one of case study i.e. Ansal API Sushant Estate, Gurugram. There is no change in energy use in plug loads due to equipment. Lighting loads are reduced slightly in ECM 08 of lighting retrofitting by LED. The gradient of the curve in the plot reflects that ECM 03 i.e. solar control film on windows is the most effective ECM to reduce total annual energy use in residential buildings followed by ECM 01 i.e. thermal insulation of walls. Thus the premise of energy efficient model deals with ECM 01- ECM 03, reducing mean energy use by 25.32%. The next higher gradient fall is governed by ECM 05 i.e. thermal insulation of the roof and ECM 08 i.e. airtightness of windows.

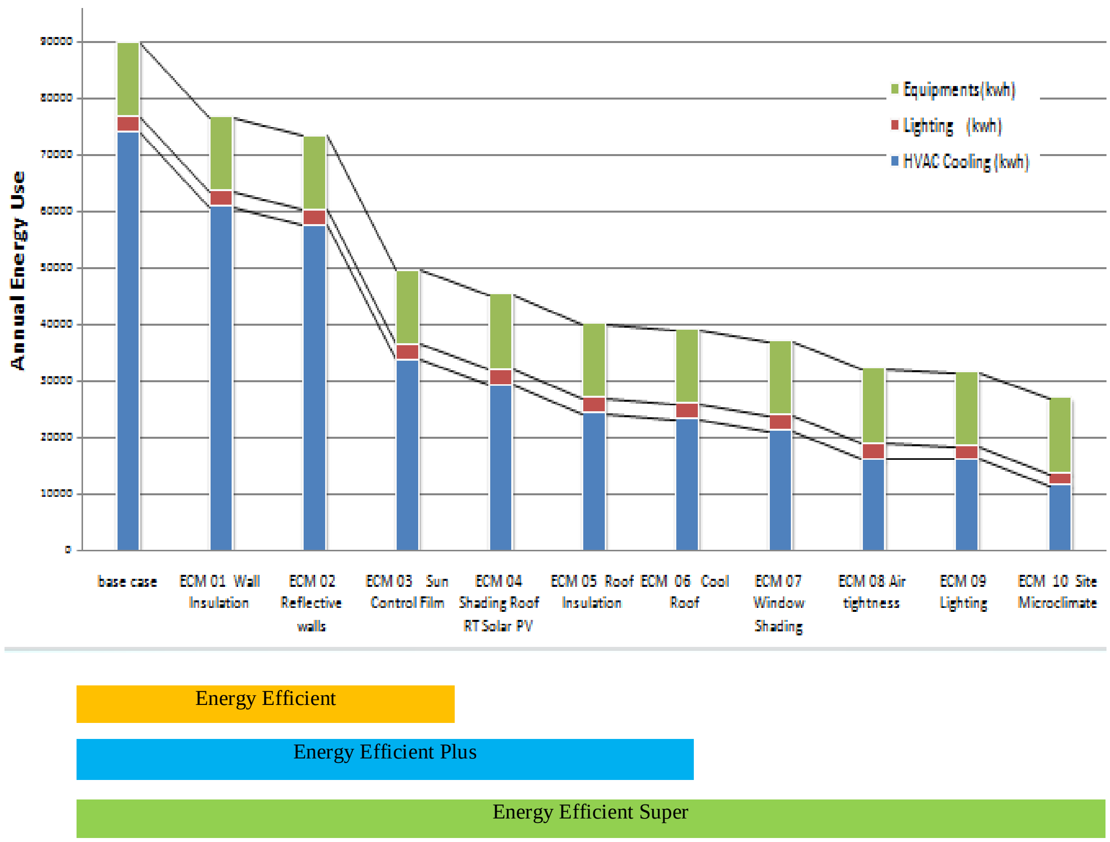


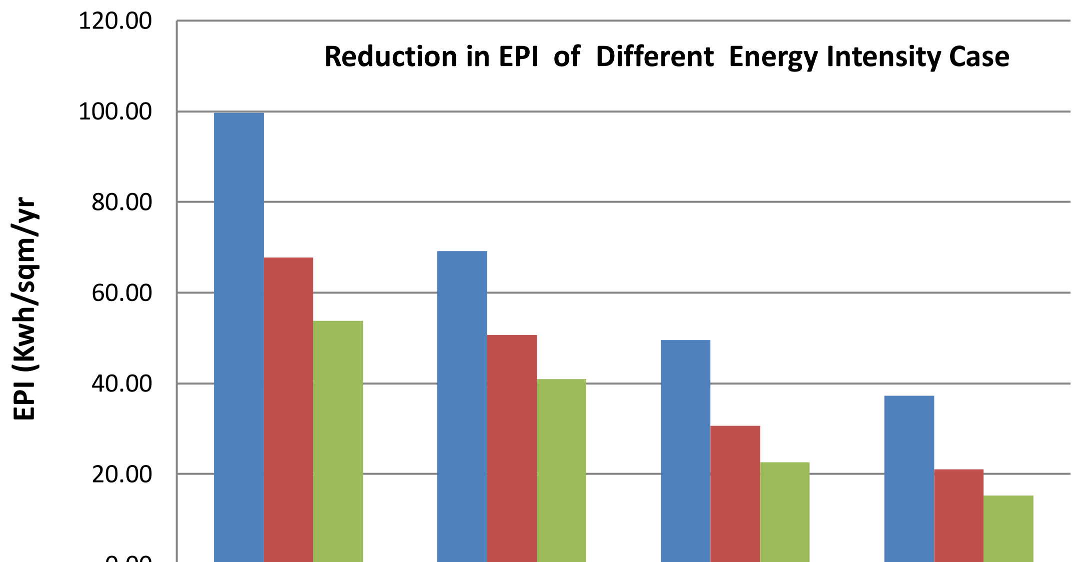
Figure 5.61 Trend line analysis of peak in total energy use due to different ECMs for Ansal API Sushant Estate, Gurugram.

A similar analysis of energy savings is done for low energy use intensity (EUI) and high energy use intensity (EUI). Three different retrofit models are proposed depending on different combinations of retrofit measures such as wall components (ECM 01-ECM 03), roof components (ECM 04- ECM 06) and other components (ECM07-ECM 10). Three modules are devised for retrofittingproviding choices to users depending on capital cost investments and energy reduction targets (Figure 5.62).

i) Normal Energy Use Intensity Case: Energy Efficient (EE)model leading upto 25.32% reduction in EPI, Energy Efficient Plus (EE plus) model leading upto54.81% reduction in EPI, and Energy Efficient Super (EE Super) model leading upto69.04% reduction in EPI.

ii) Low Energy Use Intensity Case: In EE model, reduction in EPI up to23.9 %, in EE plus model reduction in EPI up to 57.9% and in EE super model, reduction in EPI upto 71.7% is feasible.

iii) High Energy Use Intensity Case: In EE model, reduction in EPI up to 30.6 %, in EE plus model reduction in EPI up to 50.3% and in EE super model, reduction in EPI upto 62.6 % is feasible.



	Base case	EE	EE plus	EE Super
High Case EPI	99.72	69.20	49.61	37.31
Normal case EPI	67.81	50.64	30.64	21
Low Case EPI	53.73	40.89	22.57	15.21

Figure 5.62 Comparative reduction in EPI of a different energy intensity use case for EE, EE plus and EE super models.

5.10 Other Key Performance Indicators of different Strategies.

5.10.1 Design Cooling load Analysis

Other related design parameters are analyzed to corroborate the main objectives of research i.e. reduction in energy consumption. Design cooling load refers to the requirement of cooling per unit of built-up area. By designing an energy-efficient building envelope, there is demand-side management by reducing cooling requirements. Unlike energy use intensity, design cooling load is factor specific to building heat gain, internal gain and independent of user behavior and energy use intensity of a user. Figure 5.63 plots design cooling load (W/ $m^{2)}$ for Zone level (Master bedroom) for summer design day (15th May) for different retrofit energy saving measures and the results are in line with plots of energy performance index (EPI). Comparison of design cooling load of various ECMs reveals that ECM 01 Thermal insulation of walls, ECM 03 Solar control films on windows, ECM 05 roof insulation, ECM 08 airtightness are most effective in reducing cooling load of existing housing and hence energy consumption accordingly.

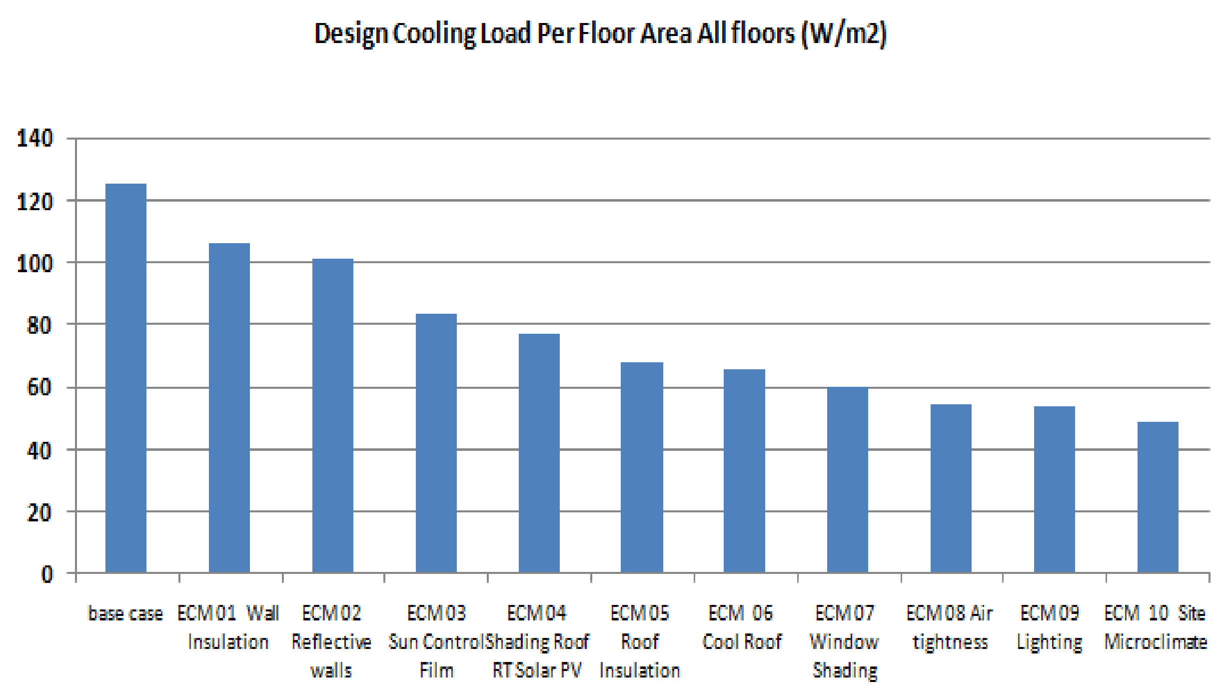


Figure 5.63 Design cooling load for zone level (Master bedroom) for summer design day (15th May) for different retrofit energy-saving measures.

5.10.2 Discomfort hours analysis

Energy is used in buildings mainly for meeting thermal comfort in buildings. Discomfort hours are hours key performance indicator of building performance and are calculated using operative temperature data and relative humidity at zone level based on comfort potential zone defined in ASHRAE Standard 55-2004 for occupied hours, clothing and metabolism defined in activity for that respective zone. The Designbuilder software generates a summary of data at the zone level. Figure 5.64 shows a comparison of discomfort hours based on ASHRAE Standard 55-2004 for all clothing (summers and winters) for each of retrofit energy conserving measures. The plot shows more discomfort hours in some ECMs related to roof components, solar control films on windows and window external shading asthese reduce solar gain in winters, thereby increasing discomfort hours in winters more than gain in comfort hours in summers. For mild winters in this climate, it is rather easier to heat the spaces in winters with radiant heaters/ oil dehumidifiers with much less energy for the relatively short duration of winters rather than higher cooling load in predominant summers prevailing for eight months a year. Hence the primary focus of the research is to reduce energy use in cooling by reducing heat gain of the building and hence the cooling load of buildings.

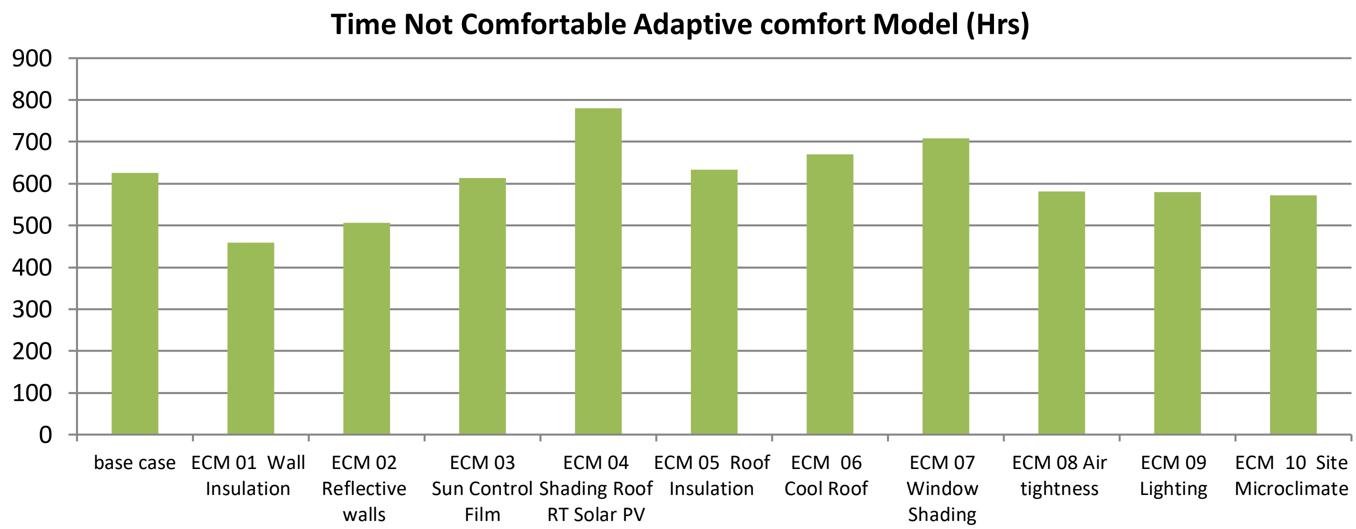


Figure 5.64 Comparison of discomfort hours of various ECMs at zone level

5.10.3 Building heat gain analysis

The primary objective of the energy-efficient building envelope is to limit heat gain by building fabric due to its design and choice of materials. The Designbuilder software calculates building heat gain from radiations through windows and thermal transmittance of heat through opaque construction walls and roofs separately. Building heat gain factor is an important indicator of envelope performance and is independent of energy use intensity or user behavior. GRIHA in its version 2015 has defined thresholds for building envelope peak heat gain factor to 40 W/ m^2 for composite and hot & dry climates. In NBC 2016, envelope performance factors (EPF) has been defined for walls, roofs and windows for all climatic zones of India (Table 2.4). The detailed summary outputs of simulations in Table 5.8 show windows heat addition, opaque surfaces heat addition due to conduction and total heat gain by windows and opaque construction. By retrofitting existing housing for thermal insulation of walls (U value 0.404), building heat gain due to thermal conductance through walls is reduced significantly. The other most effective instrument in reducing building heat gain is the use of solar control films on windows, reducing heat gain load to 40% (Figure 5.65).

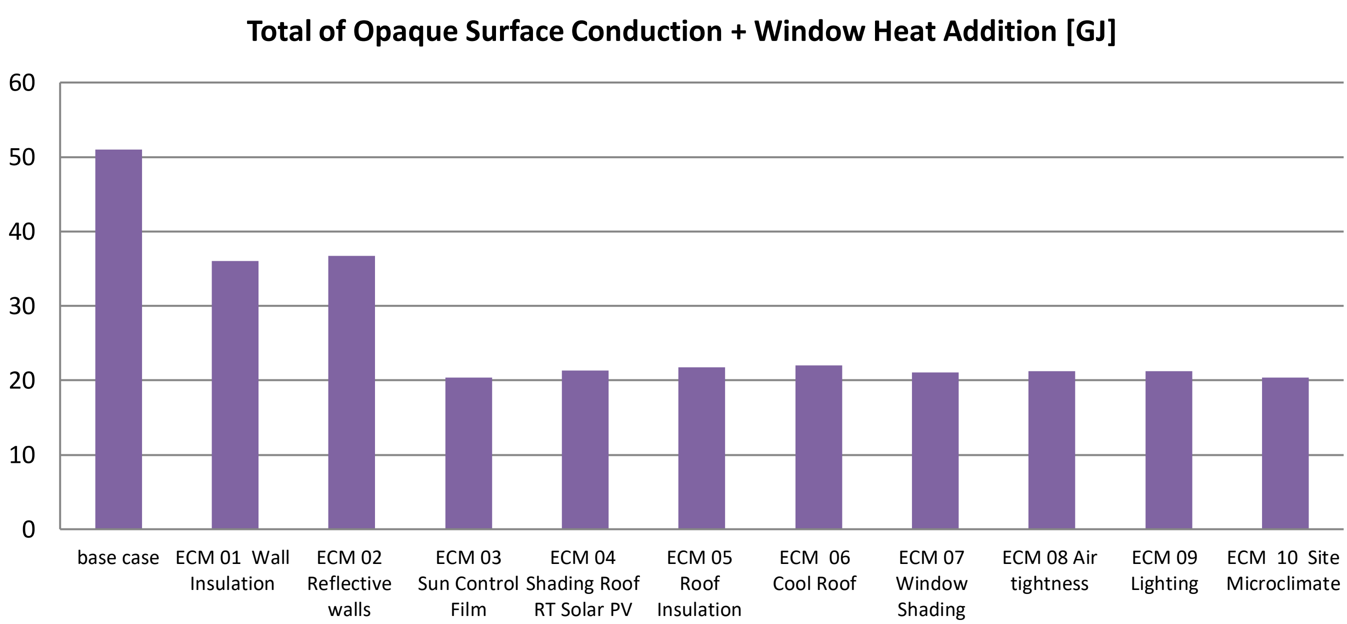


Figure 5.65 Reduction in building heat gain due to transparent and opaque construction

5.11 Analysis of Energy Performance Index of All Samples

There are eight group housing societies consisting of two public sector housing, two cooperative group housing schemes and four private developer housing schemes, representing 4608 flats, to understand energy consumption in residential buildings. Energy performance index (EPI) of all societies is analyzed for different retrofitting energy conserving measures. To understand variation in EPI of all cases, whether the difference in EPI is significantly different or they represent the population of existing group housing societies in the city of Gurugram. Table 5.10 shows descriptive statistics of reduction in energy consumption by progressive retrofit measures in all societies in the sample from the base case indexed at 100.

Table 5.10 Descriptive statistics of variation in % reduction of EPI in all cases in the sample after applying retrofitting ECMs progressively.

% EPI after applying Retrofitting Energy measures of different housing societies for Normal EUI										
Sr. No.	Model		Sushant	Unitech Fresco	DLF	Orchid	Hextax	Srishti	HSIIDC	Power Grid
1	BASE	Base case	100	100	100	100	100	100	100	100
2	EE	ECM 01	87.65	91.72	87.89	85.33	94.50	96.67	82.70	87.74
3		ECM 02	83.86	89.03	84.25	80.80	91.14	93.09	77.85	84.11
4		ECM 03	73.53	75.54	71.90	75.81	81.12	77.81	70.32	69.01
5	EE Plus	ECM 04	68.55	69.79	66.68	69.98	76.08	65.62	66.45	63.91
6		ECM 05	62.84	65.32	61.28	64.68	71.79	58.66	59.83	58.67
7		ECM 06	61.62	64.19	60.07	63.44	70.69	55.99	58.39	57.55
8	EE Super	ECM 07	59.29	61.87	59.00	62.14	49.71	53.79	57.76	54.50
9		ECM 08	53.67	56.30	53.54	53.30	45.24	46.56	52.46	49.36
10		ECM 09	53.01	55.65	52.73	53.05	44.85	40.32	51.92	48.92
11		ECM 10	47.87	50.57	48.32	48.66	41.15	37.64	47.13	44.15
		RE	31.28	31.99	33.05	27.84	17.17	20.34	30.26	19.33

For a generalization of findings, statistical tool ANOVA (Analysis of variance) is used to find whether the data set of different samples represent the same set of the population or not. It is used to test the hypothesis whether significant energy savings in existing group housing societies can be brought by proposed retrofitting measures. Results of ANOVA analysis are presented in Table 5.11. The null hypothesis is that mean EPI reduction of several populations are equal. If the computed value of F ratio is less than the critical value of F from tables for a given degree of freedom at given level of confidence, the null hypothesis is accepted, failing which alternate hypothesis is accepted.

Table 5.11 ANOVA Summary for EPI of different retrofit measures for normal EUI

Anova: Single Factor	(Mean of population EPI)					
Objective :	To test the null hypothesis that the means (EPI) of several populations (different housing societies) are all equal H0:μ1=μ2=μ3=μ4=μ5=μ6=μ7=μ8 H1: At least one of the means is different					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Sushant	12	783.17	65.26	357.23		
Unitech Fresco	12	811.98	67.66	367.01		
DLF	12	778.73	64.89	347.71		
Orchid	12	785.04	65.42	360.50		
Hextax	12	783.44	65.29	647.81		
Srishti	12	746.49	62.21	638.80		
HSIIDC	12	755.06	62.92	332.69		
Power Grid	12	737.24	61.44	472.96		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	350.99	7	50.142	0.114	0.047	2.115
Within Groups	38771.72	88	440.588			
Total	39122.71	95				
Conclusion: If F<F crit, we accept the null hypothesis CASE F=0.1138< 2.115 Therefore the Null hypothesis that the mean of all populations are equal. Thus **Findings of these samples can be generalized to a larger population in Gurugram**						

The calculated F value is 0.1138, which is less than F crit i.e.2.115 (for the degree of freedom (v1=7, v2=88 at 95% confidence level). Therefore the null hypothesis that the mean of all populations are equal is accepted and the difference in EPI is insignificant i.e. due to chance.The null hypothesis of no difference between sample means is verified statistically. Since all these samples are taken from diverse sampling criteria, different WWR, orientation, no of stories, built up area, shading projection and different developers like DLF, Ansal, Unitech and other developers, but showing similar results in terms of % reduction, therefore it can be concluded that findings based on these samples can be generalized to a larger population of existing housing in Gurugram with high level of confidence.

5.12 Predicting energy consumption and % savings in energy

From a sample of eight housing societies, each of them representing diversity in terms of built-up area, shading projection, windows to wall ratio, an attempt is made to establish a relationship between energy consumption and building characteristics of existing housing.With the confidence gained by proving the null hypothesis, findings based on these samples are generalised to the larger population of existing housings in Gurugram. Statistical analysis is used to predict the energy consumption of different user groups with the tool of multiple regression analysis using multiple variables. There are two major variables in existing group housing schemes namely built up area of the building and wall to window ratio, which have a profound effect on the energy consumption of buildings. Multiple regression is carried out for different models to predict energy consumption for three classes i.e. Low Energy Use Intensity (EUI), Normal Energy Use Intensity and High Energy Use Intensity and is governed by the following equation:

i) $\textit{Predicted Base EPI}_{NOR} = 86.44+0.48\ WWR-0.02A$,

ii) $\textit{Predicted Base EPI}_{LOW} = 67.07+0.59\ WWR-0.015A$

iii) $\textit{Predicted Base EPI}_{HIGH} = 106.+0.7\ WWR-0.015A$

WWR =Wall to Window Ratio

A = Built-up area of the tower (No of flats x built up area of each flat).

Results of multiple regression between Energy consumption as the dependent variable and WWR and Built up area of the tower are presented in Table 5.12.

Table 5.12 Summary Output of Multiple Regression between EPI, WWR and BUA for Normal EUI

SUMMARY OUTPUT OF MULTIPLE REGRESSION						
Regression Statistics						
Multiple R	0.848					
R Square	0.720					
Adjusted R Square	0.608					
Standard Error	4.560					
Observations	8					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	2	266.92	133.462	6.4174	0.0416	
Residual	5	103.98	20.79697			
Total	7	370.9088				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	86.442	10.642	8.122	0.00046	59.085	113.799
Built up Area of tower	-0.020	0.006	-3.388	0.01950	-0.035	-0.005
WWR	0.481	0.463	1.040	0.03996	0.208	0.971

For Normal EUI, Coefficient of Correlation between EPI and other two variables is 0.84, indicating a strong relationship between predicted dependent variable EPI and independent variables WWR and built-up area of the tower. The high value of Coefficient of determination or (R^{2}=0.72) in the regression model implies that 72% of the variation in predicted EPI is explained by the two variables WWR and built-up area of the tower. For coefficients of slope for WWR (0.481) indicates that for every unit increase in WWR %, energy consumption is increased by 0.481kWh/m^2/yr, reflecting the high contribution of WWR in building performance. There is an inverse relationship between the area of tower and energy performance, indicating that smaller BUA, the more EPI and vice versa. For a confidence interval of 95%, lower and upper limits for probable distribution of coefficient of slope for WWR range from 0.208 to 0.971 and for an intercept on x-axis range from 59.08 to 113.79. A high value of intercept i.e. 86.44 kWh/m2/yr is an indicator of high significance attached to the fixed benchmark of EPI. As per Table 5.12, the p-value is less than 0.05 signifying that there is a strong relationship between dependent and two independent variables. Figure 5.66 depicts the relationship of EPI with two variables WWR (High positive slope for WWR) and built up area of flat (low negative slope w.r.t built-up area of the tower).

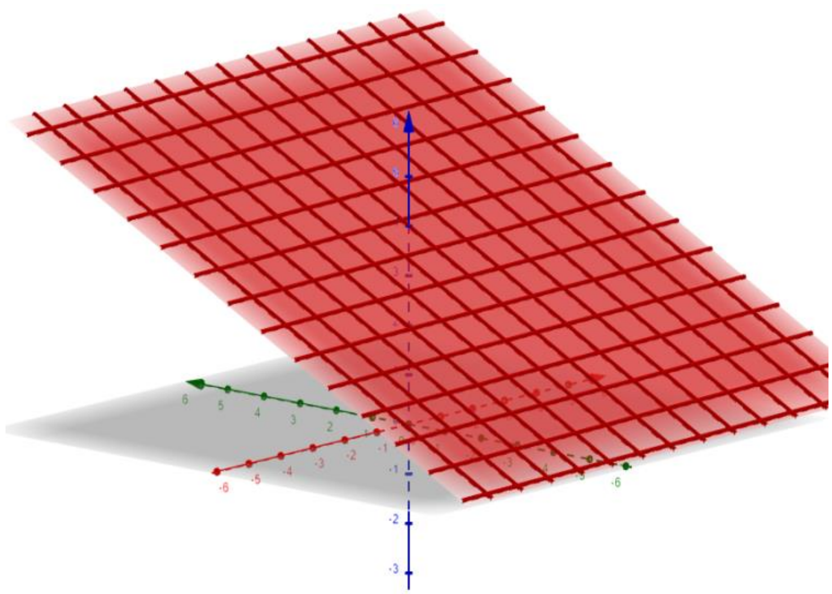


Figure 5.66 Multiple regression plot between predicted variable EPI and independent variables WWR and BUA.

With the help of projections of energy savings in each case and choosing modules of different retrofits, one can evaluate % saving in energy as well as payback period for each module. This will help users/ owners/ facility managers of respective group housing societies to take informed decisions to select retrofit modules for implementation.

5.13 Life Cycle Cost Analysis

Life cycle cost analysis of each of these three cases i.e. low energy use intensity (EUI) , normal energy use intensity and high energy use intensity for three modules, Energy Efficient (EE), Energy Efficient plus (EE plus) and Energy Efficient Super (EE super) model is carried out to determine the cost-effective feasibility of retrofit measures. Net present value method is used to calculate payback period and life cycle benefit over 15 years of retrofitting. It is observed that for normal energy use intensity by investing INR 250,000.00 per household, the payback period is calculated at 12 years for both models in Energy Efficient plus and Energy Efficient Super retrofit model.(Table 5.13).

Table 5.13 Life cycle cost analysis for normal EUI for EE super model

NORMAL Energy Use Intensity EE SUPER MODEL					
Built up Area of each flat (sqm)		1382.1	Discount Rate	10%	
Total energy base case (kwh)		91011.285	Inflation	3%	
Cost of total energy base case		728090.28	NPVF	(1+0.03)^n-1/(1+0.1)^n	
Energy saving (kWh)		64696.101			
Cost of energy savings (INR)		517568.808	(n is number of years)		
		Total income from saving	NPV Factor	Net present value (INR)	Cumulative NPV (INR)
Initial Capital investment = 250000*16					-4000000
No of Years	1	517568.81	0.91	470517.10	-3529482.90
	2	517568.81	0.85	440575.10	-3088907.80
	3	517568.81	0.80	412538.50	-2676369.30
	4	517568.81	0.75	386286.05	-2290083.24
	5	517568.81	0.70	361704.21	-1928379.03
	6	517568.81	0.65	338686.67	-1589692.36
	7	517568.81	0.61	317133.88	-1272558.47
	8	517568.81	0.57	296952.64	-975605.84
	9	517568.81	0.54	278055.65	-697550.18
	10	517568.81	0.50	260361.20	-437188.98
	11	517568.81	0.47	243792.76	-193396.22
	12	517568.81	0.44	228278.68	34882.45
	13	517568.81	0.41	213751.85	248634.30
	14	517568.81	0.39	200149.46	448783.77
	15	517568.81	0.36	187412.68	636196.44
				Life cycle benefit	636196
				Payback period	12 years

The main goal of life cycle cost analysis is to determine cost optimal solution out of different alternatives and hence optimization of retrofit measures. Thus life-cycle cost analysis for all three cases of energy intensity use will provide users to help take decisions and choose from the proposed three models of retrofitting for energy efficiency (EE, EE plus or EE super) (Table 5.14). Cost of various design retrofitting measures have been worked out as per Haryana Schedule of Rates with latest ceiling premiums 2018 and market rates. The discount rate and inflation rate has been accounted from trading sites and International Monetary Fund. The cost of electricity is taken as per the prevailing unit purchase rate @ Rs. 8/- unit. However, the increase in the cost of electricity units in future and higher electricity cost due to generator sets, depreciation of plant and machinery has not been accounted for.

Table 5.14 Life Cycle Cost Analysis for all models for different energy use intensity

Case	Initial Investment per flat (INR)	Total investment in tower	Energy Savings (Kwh)	Payback Period (Years)	Life Cycle Benefit (INR)
High EUI					
EE Model	1,62,250	25,96,000	42181.69	12	426788
EE Plus Model	2,04,000	32,65,000	69257.63	9	1698038
EE Super Model	2,50,000	40,00,000	86256.86	8	2181265
Normal EUI					
EE Model	1,62,250	25,96,000	23730.65	24	122161
EE Plus Model	2,04,000	32,65,000	51372.65	12	416423
EE Super Model	2,50,000	40,00,000	64696.10	12	636196
Low EUI					
EE Model	1,62,250	25,96,000	17746.16	25	14723
EE Plus Model	2,04,000	32,65,000	43066.23	16	54808
EE Super Model	2,50,000	40,00,000	53238.49	16	103947

With the help of projections of energy savings in each energy use intensity case and choosing modules of different retrofits, one can evaluate % saving in energy as well as payback period for each module. This will help users/ owners/facility managersof respective group housing societies to take informed decisions to select retrofit modules for implementation. The mean payback period of all cases works out to be 15 years.

People with low energy intensity may not find energy efficient model retrofitting feasible from payback period of view, but will definitely relish more thermally comfortable place to live in. Eventually the persons of other use intensity may use air conditioning for lesser duration than business as usual scenario due to more comfortable building envelope and or may use less energy for cooling, thereby leading to concept of passive resilience due to reduced cooling load and as well reduced operational hours of air conditioning as compared to the current context.

An excel based algorithm is prepared finally to map the energy consumption of any multistoried residential property by integrating results from regression equation for different category users along with energy reduction savings or calculate the payback period. This tool can be helpful for a common man to rate one's apartment with respect to existing energy efficiency level and assess the potential of different modules EE, EE plus or EE super with respect to their payback period.

5.14 Summary

This chapter analyzes data obtained in field surveys of questionnaires and electricity utility bills to form baseline data for building envelope characteristics and energy performance index of existing group housing societies. Based on data of energy bills of all the samples, users/ households are put in 3 categories low energy use intensity, normal energy use intensity, high energy use intensity. Mean EPI of all samples with Normal EUI is 68.9 kWh/m^2/year, for Low EUI case, EPI is 42.7 kWh/m^2/year and for High EUI case, EPI is 97.4 kWh/m^2/year,

Based on outcomes of data collection and analysis of sample group housing schemes, an attempt has been made to devise schedules of occupancy, activity, lighting schedule, equipment and HVAC for residential buildings and are prepared on the lines of ECBC 2017.

All eight group housing societies are modelled in Designbuilder and simulated for all three energy use intensity cases to form the base case. The models are further simulated for ten retrofit energy conserving measures to predict savings upto 69.04% savings in energy use in Energy efficient Super model, upto 54.81 savings % in Energy Efficient Plus model and upto 25.32% reduction in EPI by retrofitting for Energy Efficient (EE) model. Other design indicators such as design cooling load, discomfort hours and building heat gain are also analyzed which are in line with EPI trend line analysis.

Analysis of variance is carried out to prove the hypothesis that mean of all populations are equal is accepted and the difference in EPI is insignificant i.e. due to chance. Since all these samples are taken from diverse sampling criteria, but showing similar results in terms of % reduction in EPI, therefore it can be concluded that findings based on these samples can be generalized to the larger population of existing housings in Gurugram with a high level of confidence.

Multiple regression is carried out to predict energy consumption of the basecase of all energy use intensity cases. With the help of simulation data, it is easier to predict energy savings of each of three modules proposed in retrofitting i.e. Energy efficient (EE), Energy efficient plus (EE plus) and Energy efficient Super (EE Super) Model. Life cycle cost analysis of the proposed models for each energy use intensity cases will help users/ owners/facility managers of respective group housing societies to take informed decisions to select retrofit modules for implementation.

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This chapter presents key findings in the context of objectives of study framed in chapter one of the report and discusses the results in the light of scholarly work in the field. Based on the discussion of findings, recommendations are framed to form strategies for reduction in energy consumption of existing multistoried residential buildings. It also outlines the major contributions of the research to society along with directions for further research.

6.2 Approach to fulfil research objectives

In view of the large carbon footprint of existing multistoried residential buildings, there is a need to study in depth benchmarks of energy consumption pattern and trends in study area context and finally suggest appropriate retrofitting measures for reducing energy consumption. A case of the city of Gurugram is taken up for the study to prove the point that the energy consumption of existing residential buildings can be reduced significantly by retrofitting buildings for energy efficiency measures. The aim of this study is to formulate strategies for reduction in energy consumption of existing multistoried residential buildings using mixed mode of ventilation in composite climatic context of Gurugram. A structured literature review is undertaken for understanding the state of art of energy efficiency trends and patterns, design parameters, key performance indicators in an energy assessment, regulatory framework and policies, international standards, case studies of best practices, challenges and barriers in implementing retrofitting and building performance tools. Due to the lack of existing study on the current topic, the study is more of inductive and exploratory nature.

Primary data is collected for energy consumption pattern from the occupant survey by conducting questionnaires, energy consumption utility bills, instrumentation for thermal data of apartments and field survey for building envelope characteristics by personal observation, discussions with experts and urban local bodies. Inverse modeling technique is used to design the questionnaire to understand energy consumption pattern in detail so as to form input for building performance dynamic simulations.

The samples are drawn from eight multistoried group housing schemes across the city, representing a sample population of 4608 flats, selecting two samples from public housing, two samples of cooperative group housing and four samples from private developers housing. Based on sample size criteria, a total of 400 surveys are conducted using a questionnaire to understand their energy consumption pattern in detail. A comparative study of different housing schemes representing diversity in terms of orientation, wall to window ratio, number of stories, floor area and type of window projection, location on different floors, occupant profiles was undertaken to understand variation in energy consumption.

Based on literature review and practices, three modules of retrofits are suggested such as Energy Efficient, Energy Efficient Plus and Energy Efficient Super model. Life cycle cost approach has been used to understand the cost-effectiveness of retrofit measures in all different modules. The details of the fulfilment of various objectives discussed in section 1.7 of chapter 1 are described as under:

6.2.1 To determine factors which affect energy consumption in residential buildings

A structured literature review is undertaken for understanding the state of art and knowledge gaps in energy efficiency trends and patterns in residential building use, design parameters governing heat gain of the buildings, key performance indicators in energy use and assessment. Findings of different study reports are reviewed to find end-use energy breakup and types of loads as compared to other building types and similar residential buildings in India and global context. Various design parameters governing energy consumption in residential buildings are building envelope, sustainable materials, lighting, HVAC systems, appliance usage pattern, Site microclimate, landscaping, renewable energy systems are discussed in detail to bring out key performance indicators of energy use in residential buildings and select design parameters which are climate responsive to composite climate context, cost-effective, easily achievable. A conceptual framework model based on a study of design interventions, the design of questionnaires to understand diversity and variations in energy use and instrumentation is prepared to conduct the research.

6.2.2 To review National policies related to energy consumption in existing residential buildings in composite climate

Various efforts to reduce energy consumption are collated from National policies and acts, National Building Code and standards of current green building rating or labelling schemes. Review of national policies and other schemes is presented in chapter 2 and 3 delineating various aspects related to energy use in buildings. Key parameters and design metrics are discussed in detail for energy efficiency measures in NBC Part 11 approach to sustainability, regulatory framework for housing in Haryana Building Code 2017, incentive schemes of FAR, benchmarks and criteria for energy efficiency in green building rating systems such as GRIHA, IGBC , Eco housing etc., international practices such as HERS index in USA and Energy performance certificate in European Union. Also, the government has launched several initiatives to allow buildings and grids as active participants in energy production and consumption cycle by implementing on grid net metering policy under the National solar mission.

There are green building rating systems for existing buildings energy operation and maintenance (EBOM), but there are no specifically developed code or guidelines for retrofitting existing residential buildings to reduce energy consumption.

In addition case study of best practices in the existing residential buildings is undertaken to know real life application and performance of energy efficiency measures and also ascertain drivers and barriers in energy efficiency retrofits. Strategies for reducing energy consumption entails selection of design interventions which do not violate existing building regulations and cause no impact on structural components of existing buildings. While implementing retrofitting, design strategies should be such that the retrofit measures should be cost-effective, non-intruding to users, implying that one should be able to implement retrofitting from outside the apartment, without intervening with interiors and privacy of users.

In view of rather limited studies on the energy consumption pattern of existing housing and high potential of reducing energy consumption, the outcomes from literature review of national policies, building codes and green building rating systems are instrumental in establishing design parameters, key performance indicators, benchmarks in existing residential building and finally building performance assessment tools. Inverse modelling technique has been used to understand various input parameters required for building performance simulation model.

6.2.3 To assess the energy consumption of existing multistoried residential buildings in the study area

In order to assess the energy consumption of existing multistoried residential buildings in Gurugram, research framework is designed for collecting primary data through field surveys of samples drawn from different types of housing as detailed in chapter 4 of the study. A wide survey of 67 housing societies is undertaken to understand building envelope characteristics to form a database of housing characteristics. Eight housing schemes, representing 4608 samples from public, cooperative and private group housing societies are chosen as a case for undertaking a detailed survey of diversity in energy usage pattern through questionnaire and electricity utility bills for the year 2016-17. A total of 400 samples as transverse surveys are analyzed for energy use assessment of residents as detailed in chapter 5 of this report.

There is high diversity in energy usage in terms of occupancy schedule, HVAC schedule, cooling set point temperature preferences, appliance penetration, energy efficient gadgets, use of artificial lighting etc. Based on data of energy bills of all the samples, users/households are classified into three categories i.e. Low energy use intensity (EUI), Normal energy use intensity, High energy use intensity. Thus Mean EPI of all samples for normal EUI is 68.9 kWh/m^2/year with a range from 33.4 kWh/m^2/year to 128.5 kWh/m^2/year. Mean EPI of Low case EUI is benchmarked at 42.7 kWh/m^2/year, and for the high case, EUI is 97.4 kWh/m^2/year. The lower and upper limits of normal energy use intensity are benchmarked as 48.7 kWh/m^2/year and 89.3 kWh/m^2/year respectively by taking z score deviation within ±1 of distribution of data around the central mean value of all samples.

A test pilot run is conducted for building performance simulation model in Designbuilder version 5. 01.024. Inverse modelling technique is used to design the questionnaire to understand energy consumption pattern in detail so as to model input variables for building performance dynamic simulations. Thermal mapping of indoor environmental conditions is conducted for three flats throughout the year to calibrate the building performance model.

6.2.4 To formulate strategies for reduction in energy consumption of existing multistoried residential buildings in Gurugram

Having identified key issues in energy usage pattern from field surveys and established energy use benchmarks from analysis of electricity bills in existing group housing, an attempt has been made to devise schedules of occupancy, activity schedule, lighting schedule, equipment schedule and HVAC schedule for residential buildings on the lines of ECBC 2017.

Building performance simulation models of all case studies in sample subjects are generated in simulation software Designbuilder and are calibrated for mean energy performance index of different energy use intensities such as Low, Medium and High EUI with reference to findings from thermal data mapping so as to construct the base case as close to real life context using mixed mode of ventilation. The building performance models of all cases are simulated to understand the effect of various retrofit measures or design interventions derived from literature review and field surveys.

A test model is run for understanding optimum value for each of the design parameters as listed above by conducting parametric runs in the building simulation software. The parametric analysis serves as a fundamental tool to understand optimum values of design parameters and are also useful to find out which design parameters are more effective in reducing energy consumption than others and help in rejecting the design parameters which do not bring much improvement in the system.

Results of simulation outputs are analyzed and presented in chapter 5 of the report. Design interventions are classified as wall components in energy efficient model; wall components and roof components in Energy Efficient Plus model and wall components, roof components and other components in Energy efficient Super model. Based on the mean of Energy performance index (EPI) of all samples, predicted energy savings are projected for all three models i.e. Energy Efficient (EE) model, Energy Efficient Plus model and Energy efficient

Super model. Analysis of variance for mean percentage reduction in EPI is carried to prove the research hypothesis that energy consumption of existing residential buildings can be reduced significantly by retrofitting buildings for energy efficiency measures.

In addition to Energy Performance Index, the other important constructs of efficient building envelope such as building heat gain factor, cooling load and discomfort hours are analyzed from each simulation so as to validate the findings internally to promote the concept of passive resilience by retrofitting buildings thermally comfortable through reduced building heat gain and reduced operating hours of air conditioning and also a significant reduction in cooling load.

Multiple regression is carried out to predict energy consumption of base case on the dependent variables i.e. window to wall ratio (WWR) and built-up area of the tower for all three cases of energy intensity use (EUI) i.e. low EUI, normal EUI and high EUI. Based on the outcomes of the study, an excel based algorithm is prepared finally to project energy savings for all three models EE, EE plus and EE Super Model.

Life cycle cost analysis of the proposed models for each energy use intensity cases is carried out by using net present value method to find out life cycle benefit and a payback period of capital investments in retrofitting for all energy intensity use cases and for all the three modules of energy efficiency. Comparative overview of life cycle cost analysis will help users or owners or facility managers of respective group housing societies to take informed choices as per affordability of users and payback period.

6.3 Summary of the Work done

The key findings and the results of the study are summed up in this section to have an overview of the work done in the field. In the wake of very limited studies conducted already in this field and absence of focus on energy conservation building codes for residential buildings and high diversity in energy consumption, the findings of the research help in plugging the knowledge gaps. Multiple case study approach is used for a wider cross section of the society and help in eliminating the effect of a single variable as well as internal validation of the results. The findings are discussed in the context of other researchers' work for external validation of the thesis. The findings may be seen in the context of the study area context, scope and limitations of the thesis as defined in the section from 1.8 to section 1.10 in chapter 1 of the report. Major Key findings and discussion of findings are listed as under:

6.3.1 Study area context

Due to its strategic connectivity and proximity to National Capital, the city of Gurugram is developed on public-private partnership model (PPP) as priority destination since 1990. The city has a relatively higher share of residential land use i.e. 48.56% of total land use as per the development plan of Gurugram Manesar Urban Complex 2031; as compared to residential land use delineated as 35-40% of total land in large cities, metropolitan cities and megacities in Urban and Regional Development Plans Formulation & Implementation Guidelines (URDPFI), 2014 [26]. The city of Gurugram is largely dominated by multistoried group housing schemes catering to 68.38% of the population. The share of land in multistoried group housing society is nearly 34% of the total land area under residential land use in Gurugram, but due to higher density in group housing, it caters to 68.38% of the population.

6.3.2 Existing housing composition

The existing housing stock taken up for retrofitting in Gurugram is typically characterized by multistoried group housing schemes designed and constructed before 2010 i.e. year of implementation of Energy Conservation Building Code ECBC 2007. Mid rise and high rise apartments accommodate the vast majority of dwellings and constitute 70% of the total housing supply. Total no. of ready to move flats designed and constructed by the year 2010 is 95,000 [63]. The housing societies are developed predominantly by private developers, having 68.35 % share in total no of societies, followed by 23.46% share of cooperative group housing societies and remaining 8.19% by public sector housing schemes. Gurugram, designated as a high potential zone for urban development in Haryana has a high-income level of its denizens and is typically characterized by the presence of high-end multistoried group housing schemes.

6.3.3 Energy use share of residential buildings

Gurugram has an overall annual energy consumption of 3988 million kWh (mu) including residential, commercial and industrial from sectors 1-57 in Gurugram. With a share of 1874 mu in buildings, the share of residential buildings is 1285 mu (68.57%) and the commercial sector is 589 mu (31.43%). As per DPR Smart Grid Project DHBVN (2016), the annual electricity demand is increasing by 17% whereas the supply of electricity is increasing by 5 %, leading to a wide gap between demand and supply of electricity in Gurugram [181]. In the wake of huge demand for electricity and a limited supply of power, many residential societies are run on 100% captive power on diesel, causing environmental pollution.

6.3.4 Occupants' background

Nearly 70 % of households live in private developers societies. 61% of the sample population is employed in the service sector with 18% of people engaged in business activities and rest are involved in other activities. The most commonly available flats with respect to no. of bedrooms in a flat is 3 BHK unit (51.4 %), followed by 4 BHK units (32.8%) and 2 BHK units being only 15.8% share of total population.

6.3.5 Architectural profile of group housing schemes

Built up area of dwelling units and the height of flats constitute one of the major factors in determining energy consumption or EPI. The residential flats are quite large in size, with 59.01% of the total flats (3BHK and above) having built up area 120 sqm and above, followed by 21.21% of flats having area ranging from 120-160 sqm,36.3% of flats having area ranging from 80-120 sqm and rest of flats 4.5% with 80 sqm or less in area.

Most of the housing societies (54.5%) have 8-15 storeys with mean number of storeys as 15 and mode as 15 storeys. The schemes which have more than 15 stories constitute 31.8% share of the total housing schemes. 86 % of the total group housing societies have the provision of stilts for parking.

6.3.6 Building Envelope Characteristics

The most common form of the residential built typology is point tower blocks (80.3%) with four dwelling units on each floor, served by a central core of services and staircase or lift lobby, thus having walls and fenestrations in all orientations. Only 18.7% of total flats have slab type configuration.

The distance between towers plays important role in mutual shading of blocks, reducing the thermal gain of the blocks in summers. 46.96% of towers have distance ranging from 6 m to 9 m between two towers, thus considerable shading is due to less distance between the towers. 19.69% of all the towers have distance ranging from 9m to 12 m between towers. 33.35 % of towers have distance more than 12 m between towers.

All the flats are constructed with 230 mm thick burnt brick masonry with plaster on inside face. 56.1% of flats are finished with exterior cement based paints, followed by 21.2% of flats finished in grit finish and 19.7% of flats are finished with stone cladding on the external face with only 3% of flats are finished in the exposed brick face. Mean thermal transmittance U value for wall assembly in flats is 2.51 W/ m^2/K. Roof Assembly consists of reinforced cement concrete (RCC) slab of thickness varying from 125-150 mm insulated with brick coba or mud phuska and finished with brick tile terracing. Mean thermal transmittance U value for roof assembly in flats is 2.6 W/ m^2/K.

68.18 % of flats have Wall to Window Ratio (WWR) less than 20%, 31.82%. of flats have WWR between 20-40%, 95% of flats have a single plain glass of thickness 4mm to 5 mm with SHGC of value 0.85 with only 5% of flats have windows fitted with tinted glass or reflective glass having 0.47 solar heat gain coefficient, 56 % of flats have windows with a wooden frame and less than 25% of window area is operable. 44 % of the flats have aluminium windows with 50% operable window.

Balconies are an integral part of the architectural character of apartments in Gurugram and also serve to shade windows and exposed walls. 51 % of towers have a balcony with the depth of 1.2 m and 13 % of flats have a 1.8 m depth of balcony. 36 % of towers have a balcony with a shallow depth up to 1.0 m from the face of the wall. 79.1% of windows are having a balcony as a shading device and 14.9% windows are recessed type up to 0.45 m depth. The value of the projection factor as an indicator of the effectiveness of shading element ranges from 0.45 to 0.66.

6.3.7 Energy consumption usage pattern and schedules

There is a high diversity factor in occupancy pattern, duration of use, user preferences cooling set point, appliance usage and equipment efficiency and energy consumption user behavior in residential buildings. Occupants in study area context of flats constructed between 1985-2010, use mixed mode of ventilation, primarily relying on windows or split air conditioners of rating 1.5 TR or 18000 BTU/hr in 74.5% of flats with one to three-star rating with a range of EER from 2.2 to 2.7. In 28 % of apartments, living rooms have no air conditioners.

Based on the data collected in this section, activity schedules are formed for different spaces such as master bedroom, children bedroom, guest bedroom (if any), living room, kitchen and toilets by considering data true for 70% and above flats as standardized data. Separate schedules have been formed for different energy usage intensity (EUI) patterns such as Low EUI, Medium EUI and High EUI. The templates formed are used building simulation software to the model base case and proposed case to evaluate outputs of different retrofitting strategies for energy efficiency.

6.3.8 Thermal and visual environment

Thermal comfort sensation response of occupants gauged on seven point standard ASHRAE scale reveal that 43.2% of respondents reported their homes to be thermally neutral, whereas 34.7% of respondents found them slightly warm, 16.6% of homes reported slightly cool, thereby implying 94.5 % respondents in thermal comfort band. 47.2% of respondents have reported satisfaction with their thermal environment on five points Likert scale with respect to the thermal environment of their homes. 34% of respondents expressed their desire to have more air movement. 84.3% respondents reported their home to be satisfied and above on scale with respect to daylighting. For controlling excessive daylight and glare, most commonly used measure is to use window blinds or shades on windows.

6.3.9 Retrofitting behaviour and attitude

67.2 % of respondents favoured retrofitting for reducing energy consumption as essential and very important on a five points Likert scale. Nearly 72 % of respondents agreed to assign high importance or more to save the environment by retrofitting the flats for energy efficiency. In terms of affordability or willingness of users to pool in funds for investing in retrofitting for energy efficiency of existing housing, 76.8% of users responded shows willingness to spend up to INR 2.0 lac per flat.

6.3.10 Baseline Energy performance Index

There is 150 to 300 % variation in annual electricity consumption within different residents of the same tower, which can be attributed to high diversity factors as discussed in the previous section. Energy performance index calculated from electricity bills of samples is in range of 33 kWh/m^2/yr to 128.5 kWh/m^2/yr. Based on data of energy bills of all the samples, households are put in 3 categories: Low energy use intensity (EUI), Normal energy use intensity, High energy use intensity. Mean EPI of all samples for normal EUI is 68.9 kWh/m^2/year with lower range of EPI as 48.7 kWh/m^2/year and upper range as 89.3 kWh/m^2/year and standard deviation of 15.4. The lower range of normal energy intensity is analyzed as 48.7 kWh/m^2/year by taking z score deviation within ±1 of distribution of data around the central mean value of all samples. Mean EPI of Low EUI case is 42.7 kWh/m^2/year with lower and upper limits from 33.4 to 48.6 kWh/m^2/year. In High EUI case, mean EPI is 97.4 kWh/m^2/year with lower and upper bounds between 89.4 kWh/m^2/year and 128.5 kWh/m^2/year. Occupancy schedule and templates for all three case viz. Low use case, Normal use case and High use case are prepared.

6.3.11 Parametric runs for design parameters

For retrofitting existing housing, design interventions selected are climate responsive, cost-effective, easily achievable, and non-intruding to users and in line with existing building regulations. Thus various energy conserving measures (ECMs) for reducing cooling load and energy consumption are classified on basis of Wall Elements, Roof Elements, Other Advance Elements as well as a simple tool like lighting and landscaping. Parametric runs are simulated in Designbuilder software to find out optimum values of retrofit measures so as to reduce energy consumption building heat gain and cooling demand. Eight housing societies with three cases of different energy intensity use (EUI) are modelled for ten design interventions. Several iterations are done by varying values of design parameters to analyze percentage improvement in EPI for each successive incremental addition. Based on results of the parametric analysis in the composite climatic context of Gurugram, for wall assembly, U value is taken as 0.507 W/ m^2/K with a surface reflectivity of 0.85 and windows mounted with solar control film on glass with SHGC 0.3. ; Roof assembly with U value 0.401 W/ m^2/K and surface reflectivity of 0.8 and shaded by rooftop solar photo voltaic panels. Other parametric runs include the design of exterior blinds for shading windows giving best results at blade depth 0.2 m@ 0.2m c/c at an angle of 30° and hung up to 1.0 m below from ceiling of the balcony. LED Lighting has been modelled so as to reduce lighting power density and heat gains due to lighting fixtures. Parametric analysis is done for various ground cover conditions to finally the optimized value of grasscrete paver blocks with 60% voids and surface reflectance 0.15 so as to subdue urban heat island effect.

6.4 Key Findings and Discussion

6.4.1 Retrofit Models for reducing energy consumption

Three modules are devised for retrofitting based on the affordable capacity of users and energy reduction targets such as

i) Energy Efficient Retrofit Model: consisting of wall assembly ECMs only with ECM 01 by retrofitting walls for thermal insulation, ECM 02 improving surface reflectivity and ECM 03 Solar control films on windows

ii) Energy Efficient Plus Retrofit Model: consisting of roof assembly and wall assembly components: ECMs 04 by installing Solar PV Panels on the rooftop, ECM 05 by improving the thermal insulation of roof and ECM 06 Cool roofs by improving surface reflectivity in addition to ECMs 01 to 03 of Wall elements.

iii) Energy Efficient Super Retrofit Model: consisting of Other components, roof assembly and wall assembly components: ECMs 07 by external window shading, ECM 08 by improving airtightness, ECM 09 by LED lighting, ECM 10 by paving with grasscrete blocks. In addition to ECMs 01 to 06.

The base case after calibration of the model is simulated on an hourly basis for each of ten energy conserving measures in the proposed case for all eight housing societies for three cases such as Low energy use intensity, Normal energy use intensity, and High energy use intensity. Energy savings by applying retrofit measures of EE, EE plus and EE super model are defined as under

i) Normal Energy Use Intensity Case: Energy Efficient (EE) Model leading up to 25.32% reduction in EPI, Energy Efficient Plus (EE plus) Model leading up to 54.81% reduction in EPI, and Energy Efficient Super (EE Super) Model leading up to 69.04% reduction in EPI.

ii) Low Energy Use Intensity Case: In EE model, reduction in EPI up to 23.9 %, in EE plus model reduction in EPI up to 57.9% and in EE Super model, reduction in EPI up to 71.7% is feasible.

iii) High Energy Use Intensity Case: In EE model, reduction in EPI up to 30.6 %, in EE plus model reduction in EPI up to 50.3% and in EE Super model, reduction in EPI up to 62.6 % is feasible.

Analysis of Variance (ANOVA) is conducted to understand the variation in the mean of different EPI s achieved due to different energy conservation measures applied on eight different sample housing societies. Comparative results of net reduction in energy saving by applying all energy conserving measures indicate the % reduction of energy consumption in eight societies is very close to each other i.e. within a range from 61.44% to 65.26% . The Null hypothesis is accepted, concluding there is no difference in mean of results obtained in eight different samples, giving confidence in predicting the effect of different ECMs, leading to a generalization of findings and validation thereof.

Results of percentage savings in energy consumption is analyzed in the context of findings of other researchers in the field. Studies by Global Buildings Performance Network conducted by CEPT University, Ahmedabad in its report titled “Residential Buildings in India: Energy Use Projections and Savings Potentials demonstrated 27% savings in energy use with modest efforts, 44% savings in aggressive measures and up to 57% energy use reduction in very aggressive scenario as compared to business as usual scenario in the base year 2012 [1]. In another study by BEEP (2014) to develop design guidelines for constructing new energy efficient multistory residential development in composite climate, reduction up to 60% in cooling thermal energy demand over base case of 2009 by better design of building envelope only, without considering effect of site microclimate, lighting and renewable energy [29]. The present study by author demonstrated 15-25% savings in energy by installing rooftop solar PV panels for 60% of roof area, thereby leading up to 69.04% for normal energy use intensity case.

Green building rating systems such as GRIHA (2015) has reserved 10 points for 50% reduction in energy consumption from EPI benchmark of 70 kWh/m^2/year for residential buildings in composite climate and 15 points for 50% reduction in annual energy consumption by renewable energy in existing buildings [119].

Similar empirical findings in Passivhaus homes for new homes or retrofitting existing models has been able to achieve reduction in energy consumption up to 90% of total energy use in buildings, serving as one of the best exemplars to provide low energy and comfortable houses [92]. Other researchers Vishal Garg et al (2013) have reported similar findings 57.4% savings in the retrofit model for net-zero energy design for a house in the composite climatic context of Ahmedabad [194]. Similar studies by Jankovic (2017), Samuelson (2016), Itagaki (2015) Trigaux (2014), Gupta (2014),Ganesan(2014), Roaf (2013), Trubiano(2013) have reported similar behaviour in energy consumption in residential buildings [33,36,53, 86, 192,193,195].

6.4.2 Predicting Energy Consumption and percentage savings in energy

Statistical Analysis is used to predict the energy consumption of different user groups with the tool of multiple regression analysis. The sensitivity analysis of different factors affecting the energy consumption is carried out to find that there are two main factors, which have a profound effect on the energy consumption of buildings in existing group housing schemes namely; built-up area of the building and window to wall ratio. Multiple regression is carried out for different models to predict energy consumption for three classes i.e. Low Energy Use Intensity (EUI), Normal Energy Use Intensity and High Energy Use Intensity and is governed by the following equation:

i) *Predicted Base EPI* $_{NOR}$ *=86.44+0.48 WWR - 0.02A*

ii) *Predicted Base EPI* $_{LOW}$ *=67.07+0.59 WWR - 0.015A*

iii) *Predicted Base EPI* $_{HIGH}$ *= 106.+0.7 WWR - 0.015A*

WWR =Wall to Window Ratio; A = Built up area of the tower.

Estimation of predicted energy consumption of different use intensities is helpful in developing tools of an energy audit of apartments or energy use mapping at neighbourhood level or city level. The tool can be used for rating the apartment against reference home like HERS index in the USA or Energy performance certificate (EPC) in European Union along with a choice of a package of retrofits to improve its energy efficiency. Benchmarking existing home against reference homes can be instrumental in performance monitoring of homes.

6.4.3 Life Cycle Cost Analysis

Life cycle cost analysis of each of these three cases for three modules is carried out to determine the cost-effectiveness of retrofit measures by using net present value method to understand payback period and life cycle benefit over 15 years of retrofitting. It is observed that by investing INR 250,000.00 per household, the payback period is calculated at 12 years for both models in Energy Efficient plus and Energy Efficient Super retrofit model. With the help of projections of energy savings in each energy use intensity case and choosing modules of different retrofits, one can evaluate percentage savings in energy as well as payback period for each of module. This will help users, owners, facility managers of respective group housing societies to take informed decisions to select retrofit modules for implementation. The mean payback period of all cases of energy use intensity and all suggested energy efficiency modules is 15 years.

6.5 Strategies to Reduce Energy Consumption

Strategies to reduce energy consumption in existing multistoried group housing schemes call for an integrated approach to combine outputs of building performance simulation analysis and life-cycle cost analysis. Based on the parametric analysis of design parameters and the building performance simulations, the proposed strategies to reduce the energy consumption in existing multistoried housing stock in Gurugram are listed as under:

- The building envelope components for retrofitting are to be selected in line with existing building byelaws, as per climatic context, practically feasible, easily achievable non-intruding and less initial capital cost so that users/ facility managers can easily adopt them.

- Design interventions have been classified as Wall components, Roof components, Other components as per following details :

  i) Wall Components: Effective strategies for reducing energy consumption recommended are ones with low pay back period and reduce building heat gain factor such as wall assembly having U value 0.507 W/ m^2/K with exterior thermal insulation of 50 mm thickness extruded polystyrene (XPS) on outside face of existing walls, finished with cement plaster on exterior, Use of light colors with surface reflectivity of 0.85 and windows mounted with solar control film on glass with SHGC 0.3.

  ii) Roof Components : Use of Solar photovoltaics PV panels on 60% or more roof area is an effective strategy as a part of the Roof assembly, bringing 15-25% savings in energy by the generation of electricity and also a significant factor in reducing the building heat gain load. Other components of roof assembly include thermal insulation of Roof with U value 0.4 W/ m^2/K, 75 mm thick extruded polystyrene (XPS) over deck insulation and cool roof finished with high SRI paint or china mosaic tiles with surface reflectivity 0.8.

iii) Other components : Other components include installation of exterior blinds for shading windows giving best results at blade depth 0.2 m@ 0.2m c/c at an angle of 30^0 and hung up to 1.0 m below from ceiling of balcony, use of LED Lighting to reduce lighting power density and heat gains due to lighting fixtures, and finally altering site microclimate with grasscrete paver blocks with 60% voids and surface reflectance 0.15 so as to subdue urban heat island effect.

- The concept of three modules for retrofitting measures is suggested by the combination of different design interventions so as to form Energy Efficient Model, Energy Efficient Plus Model, Energy Efficient Super Model.
  i) Energy Efficient Model: consisting of wall assembly components leading to a reduction in energy consumption from 23.9% to 30.6%, depending on energy use intensity.
  ii) Energy Efficient Plus Retrofit Model: consisting of roof assembly and wall assembly components; leading to a reduction in energy consumption from 50.3% to 57.9%, depending on energy use intensity.
  iii) Energy Efficient Super Retrofit Model: consisting of other components, roof assembly and wall assembly, leading to a reduction in energy consumption from 62.6% to 71.7%, depending on energy use intensity.

- From Life cycle cost analysis of design interventions for retrofitting, energy efficiency plus model and energy efficient super model are desirable for all energy intensity use as by investing INR 200,000 to 2,50,000 per household, the payback period is calculated at 12 years. However low energy intensity user have longer payback period of 16 years, but are compensated by additional thermal comfort hours.

6.6 Conclusions

Residential buildings in Gurugram are predominantly multistoried group housing schemes and having the largest footprint in land use and are operated in mixed mode ventilation condition. Consequently, they have the largest share in energy consumption. Energy is primarily used in residential buildings for space conditioning to meet building envelope load in contrast to other building typologies, where internal loads such as people, lights and equipment constitute heat load of the building. Space cooling load is increasing sharply as compared to other plug loads/ appliance loads or lighting in residential buildings due to change in lifestyle and expectations of users, in indoor thermal comfort level.

There has been sharp increase in energy performance index from 48 kWH/ m^2/yr from 2009 [29] to 68.9 kWH/ m^2/yr in 2018. There is a greater diversity in energy consumption in residential buildings due to high variation in usage patterns of space, occupancy, family structure, time of use of buildings, appliance penetration, personal preferences of cooling set point and energy usage behaviour. Keeping a greater diversity factor in mind, it is proposed to classify the users in three categories, Normal energy intensity use, Low energy intensity use and High energy intensity use.

Further, the EPI of existing multi-storeyed residential group housing schemes in composite climate context of Gurugram city is lower than EPI benchmark of GRIHA i.e. 70 kWh/ m^2/yr without adopting any energy efficiency measures. Thus a wider study of occupant surveys and thermal data mapping is required to be undertaken to establish the realistic benchmark for energy efficient housing. A lower benchmark of EPI for energy efficient housing model will have far reaching impact to prompt developers and builders to adopt measures for reducing consumption. There should be different benchmark for EPI for retrofitting existing group housing schemes, keeping in mind the barriers or constraints posed by existing building fabric, practically non disruptive, non-intruding and easily achievable solutions.

The concept of retrofitting existing multi-storeyed group housing, having a high carbon footprint should be promoted on parallel concepts practiced elsewhere in the world like HERS index in USA and Energy performance certificate in European countries, while leasing out or selling the property. This will ensure a huge reduction in energy consumption or demand side management of energy management in existing housing and thus lower the carbon footprint by enforcing retrofitting at least for tenant occupied properties or transfer of the property.

The study has concluded that all three classes from energy use intensity point of view can adopt any of the models namely Energy Efficient Retrofit Model, Energy Efficient Plus Retrofit Model, Energy Efficient Super Retrofit Model. There is a significant energy reduction in in Energy Efficient Retrofit Model, ranging from 23.9 - 30.6% depending upon different classes of energy usage. A higher proportion of people classified under Normal energy use intensity and High energy use intensity are benefitted by significant reduction in energy use (ranging from 54.81% to 69.04%) from retrofitting of their respective units / tower by adopting Energy Efficient Plus Retrofit Model and Energy Efficient Super Retrofit Model. The suggested retrofitting interventions have been designed to keep within low initial capital cost and affordability limits of users/ owners of flats, thus making them feasible, cost effective and easily achievable goal.

Retrofitting existing buildings with energy conserving measures is instrumental to reduce widening gap between demand and supply of electricity in Gurugram. Further, retrofitting the existing stock also brings additional thermal comfort hours (12% of occupied hours) due to which it can lead to reduction in air conditioning hours or reduction in cooling demand due to reduction in building heat gain by 60% over 'As is' case through building envelope, thus leading to improved passive resilience in the buildings.

In absence of codes for retrofitting existing residential buildings in India, Rating of existing residential buildings by energy performance index by estimating predicted energy consumption of different use intensities is helpful in assigning points or index against reference home or energy use mapping at neighbourhood level or city level. It can be instrumental in benchmarking of existing house/ flats/ towers in a housing society as well as quantifying the performance gap so as to help users to take informed decision about type of retrofitting model to be adopted to retrofit their homes.

6.7 Contributions of the research

In the context of growing energy demand in residential buildings, both due to its large footprint and increasing air conditioning requirements for restoring thermal comfort, the findings of this study are an important milestone.

- There is a potential of significant reduction of 60- 70% in energy consumption by adopting simple retrofit measures in building envelope, site microclimate and harnessing renewable energy through rooftop solar photovoltaic panels, without changing air conditioning systems and equipments, appliance efficiency, interior interventions or techniques affecting intervention in building byelaws. The study will be useful in bridging gaps between the power supply and peak demand for electricity in Gurugram.
- The research endeavours to establish EPI benchmark of existing multistoried housing by conducting wide surveys of occupants and measuring environmental conditions of various rooms for a full year and validating study by testing findings on eight housing societies in Gurugram. The research findings serve as a useful dimension in existing literature for baseline energy consumption for all mixed mode ventilated group housing projects in the study area context.
- The study traces building envelope characteristics of existing multistoried group housing schemes to serve as a template for all stakeholders for referring to occupancy schedules, lighting schedule, HVAC schedule etc. which is helpful to prepare ‘As is’ case for dynamic building performance simulation modelling.
- The research promotes the concept of passive resilience by making building more thermally comfortable with less dependence on air conditioning systems, reduction in building heat gain factor and cooling load of buildings-leading to meet the challenge of demand-side management of energy.
- Integrating life cycle cost analysis with predicted energy performance index (EPI) can be helpful for retrofit professionals to advice owners and create awareness to undertake retrofitting for energy efficiency. This will trigger the retrofitting of

existing housing for reducing energy consumption, generate employment and boost the economy.

- A software-based application to ‘Rate my house to save energy’ of existing multistoried housing is developed to help owners to easily understand and take an informed decision in selecting Energy Efficient Model, Energy Efficient Plus Model and Energy Efficient Super retrofit model with payback period and energy savings. This can be of direct application in the field and has a strong potential to turn in a business model.
- People living in these retrofitted residential societies will act as a role model for the society. They may become potential drivers in leading sustainability initiatives and promoting other housing societies to take up retrofitting for saving energy and contribute to reducing carbon emissions to fulfil the goal of reduction by 30-35% by 2030.
- The findings of this study can be instrumental in developing policy recommendations for retrofitting for reducing energy consumption in existing housing. The findings and methodology of this study can serve as a useful tool to other group housing schemes in the National Capital Region of Delhi in the composite climate to reduce energy consumption.

Despite the limitations of the study in regard to accessibility of data in private housing areas owing to security and privacy requirements, limited availability of instrumentation and limited accessibility of individual homes for data retrieving, the study hopes to serve as a useful database for developing National standards, benchmarks and practices for retrofitting to reduce energy consumption. This study has contributed in extending the literature by adding a dimension of integrating life cycle cost analysis with the results of building performance simulations to predict cost effective retrofit measures for existing multistoried group housing in Gurugram and promoting the concept of passive resilience – a step towards a low carbon and comfortable environment.

6.8 Recommendations

There are no existing codes of energy efficiency for retrofitting residential buildings in India. Although green building rating systems GRIHA and IGBC have published rating system for existing building from operation and maintenance (EBOM) point of view, but they do not address directly retrofitting measures for energy efficiency. To reduce energy consumption in existing group housing schemes, the following recommendations are delineated as under:

- There is a need to undertake wider studies of energy consumption assessment of multi-storeyed residential buildings to form baseline data of energy consumption with larger sample size as there is a high variation in energy consumption due to high diversity in factors like family structure, energy usage pattern, time of operation, appliance usage and their efficiency and cooling set point temperature, and a wide range of adaptive opportunities and occupancy schedules in residential buildings as contrasted to other typology of buildings.
- There should be specific code for retrofitting for energy efficiency in existing residential buildings to address the increasing use of energy primarily due to their large footprint, the largest share in energy consumption, increasing use of energy in air conditioning systems and more time spent in indoor. With the energy demand projected to eight times by 2050 as business as usual scenario in residential buildings, building codes for retrofitting of residential buildings are even more pertinent for demand-side management as well as in bridging the increasing gap between demand and supply of electricity.
- Whereas it is easy to design buildings with energy efficient envelope design, there are limited choices of energy efficiency measures of building envelope in existing buildings. As the study has proven that there is a significant potential of saving in energy consumption by 60-70% by adopting simple design parameters, codes on retrofitting for energy efficiency should focus on detailed analysis of building envelope design parameters along with life-cycle cost analysis and carbon footprint.
- Occupant surveys form an important part of the study to understand energy use pattern as wide variation in the range of EPI is primarily due to occupancy pattern

and energy use intensity of residents. A mechanism should be evolved to collect energy use data and energy usage pattern with urban local bodies or electricity authorities so as to have an institutional collection of data due to limited availability of data or poor quality of data.

- There should be more studies for energy mapping supported by smart metering to give real-time monitored data for the enhanced understanding of occupant activity and end-use consumption of energy in HVAC, lighting and appliances. The data from surveys can be used to predict accurate modelling of the occupancy schedule for different user groups on the line of ECBC 2017.
- The concept of passive resilience of homes should be promoted by designing better building envelope, shading devices and limiting building heat gain factor so as to have 15-20% more thermally comfortable hours leading to less operating hours of air conditioners or using less energy in space cooling due to reduced cooling load compared to the base case.
- An IT based software toolkit should be developed to map the energy consumption of any multistoried residential property in different modules for design parameters along with the capital cost investment and payback period. This toolkit can be instrumental for a common man to rate one's apartment with respect to existing energy efficiency level and assess the potential of different modules EE, EE plus or EE super model. This will help in creating awareness amongst residents to be conscious of energy use index as well as carbon mapping of societies at neighbourhood level or city level
- National and state building codes should offer incentives to act as drivers for developers or owners to retrofit their societies for energy efficiency by awarding benefit of additional FAR or rebate in property tax or stamp duty in line with current practice of new housing scheme proposals, as there is a huge potential of energy saving in existing housing stock. This will render proposals viable under self-finance scheme and reap maximum benefits to existing users by reduced electricity bills.
- A robust mechanism of market-based fiscal instruments should be evolved by the government to certify Energy Service Companies (ESCOs) to offer technical

expertise as well as incur financial investment in retrofitting the existing housing and installing rooftop solar power plant and retrofitting the project. With rating of projects and performance monitoring of the project, the investment can be recovered by ESCOs from project's savings over the life cycle of the project.

- Real life examples of energy efficient model retrofit projects should be initiated in public, private or cooperative group housing scheme so as to act as a role model for others to emulate. They could serve to increase public awareness, act as multiplier effect in tapping the potential of energy saving and promote best practices in the field, research and development on retrieved energy use data from these buildings.
- Training and capacity building of various stakeholders i.e. professional engineers and architects, contractors and product manufacturers can act as a driver for bringing awareness in the field and help in the proper implementation of the retrofit measures in its earnest manner.

6.9 Directions for future research

Due to lack of focus on the retrofitting the existing residential buildings hitherto and significant potential of reduction in energy consumption by adopting simple retrofit programs, the research field warrants attention of professionals. The following research paths are identified to develop the relatively young world of retrofits of existing multistoried residential buildings further:

- Multistoried residential buildings are ubiquitous in all metropolitan towns due to paucity of land as well as reduced affordability of owners. There is a need of extensive study of retrofit measures for different typologies of multistoried residential buildings in different sub climatic zones within composite climate so as to develop both generic and specific set of retrofitting design guidelines to reduce energy consumption as well as bridge the gap between demand and supply of electricity.
- There is a high diversity factor or wide variation in energy use pattern among different households. Also, there are adaptive opportunities with users in residential buildings, there is a need to work out thermal comfort standards for residential

buildings as they command special attention due to different activity schedule in contrast to other building typologies. Energy is used primarily to restore thermal comfort owing to building envelope heat gain, implying that an extensive research is required to be carried out in the field of developing thermal comfort standards for residential building.

- There is a need for research on extending the concept of overall thermal transfer value (OTTV) for limiting building heat gain factor for residential buildings by detailed study of building envelope characteristics of existing buildings, trends in upcoming built form typology, window to wall ratio and character and design parameters of efficient building envelope design.

- Baseline data for Energy performance index for existing residential buildings should be worked out by collating data for different climatic zones at National level so as to prepare benchmarks for EPI of existing residential group housing societies or prepare project 'Rate your home' against reference homes in the country.

- Real-time measurements of indoor environment by thermal mapping in empirical work of post retrofitted model housing scheme can be useful value addition in the field to gain understanding of dynamic behavior of heat gain and effect of retrofit measures.

- Life cycle cost analysis, carbon footprint analysis and embodied energy of different retrofit strategies need to work out design strategies which are climate responsive, cost-effective, environmentally sound and less embodied energy. It is possible to achieve the target of Nearly Net Zero Buildings (NNZB) in existing residential buildings with integrated design of retrofit approach by adopting other energy efficiency measures in HVAC, Equipment efficiency, Building automation and controls, BIPV etc.

REFERENCES

1. GBPN. 2014. Residential Buildings in India: Energy Use Projections and Savings Potentials. Global building performance network. Available at www.gbpn.org. <accessed 12.2.2016>

2. Ahluwalia, I. J., Munjee, N., Mor, N., Vijayanunni, M., Mankad, S., Lall, R., Sankaran, H., Ramanathan ,Mathur, O.P. , Srivastava, P. K. 2011. *Report on Indian Urban Infrastructure and Services*, MoUD, Govt of India. Available at http://www.vision realization .com /Resources /Organizational/Benchmarking.pdf <accessed on 13.04.2016>

3. UNFCC, 2015. Technical Report: India's Intended Nationally Determined Contribution: Working Towards Climate Justice , Available at http://www4. unfccc.int/ submissions/INDC/Published%20Documents /India/1/ INDIA %20INDC %0TO%20UNFCCC.pdf. <Retrieved on Feb 2017>

4. UNFCC 2015, United Nations Climate Change Conference, or COP 21 , 2015, Paris

5. IBM,2013. Intelligent Energy Management in cities, How to transform the urban energy chain"Available at https://www.capgemini.com/.../intelligent-energy-management-in-cities-how-to transf.. <accessed 12.8.2016>

6. ICLEI , 2009,– Local Governments for Sustainability, Sustainable Urban Energy Planning , A handbook for cities and town in developing countries. UN-HABITAT and UNEP publications

7. Pearce, D. 2006. "Is the construction sector sustainable?: Definitions and Reflections." Building Research & Information. Vol 34, No 3, pp 201-207.

8. Xavier ,L., Peter, W., Vandaele ,L.2007. "Roadmap for energy efficiency measures /policies inthe existing building sector, Applying the EPBD to improve the Energy Performance Requirements to Existing Buildings."ENPER-EXIST, Belgian Building Research Institute .

9. Architecture 2030. 2014. Roadmap To Zero Emissions, The Built Environment in a Global Transformation to Zero Emission. New Mexico ,USA. Available at http://architecture2030.org /files/roadmap_web.p df <accessed on 16.9.2015>

10. IPCC 5th Assessment Report, 2014. Intergovernmental Panel on Climate Change, Available at ww.ipcc.ch/.../publications_ ipcc_fifth_ assessment_report _wg3_repor... <Retrieved on 10.5.2016>

11. WCED. 1987 Our Common Future. World Commission on Environment and Development. Brundtland Commission. Oxford University Press. ISBN 019282080X

12. Hammer, S., Chaoui, L. K., Robert, A. and Plouin, M.2011. "Cities and Green Growth: A Conceptual Framework", OECD Regional Development Working Papers 2011/08, OECD

Publishing. Available at http://dx.doi.org/ 10.1787/ 5kg0tflmzx34-en <Accessed 15.3.2016>

13. UNEP2013. "Sustainable building and construction". Industry and Environment. Vol 26, No 2.

14. ECBC 2017. Energy Conservation Building Code User Guide. Bureau of Energy Efficiency. New Delhi.

15. Central Electricity Authority. 2017. Growth of Electricity sector in India from 1947 to 2017. Ministry of Power,New Delhi

16. Paula,C. 2014. "Sustainable Habitat for developing Societies." 30th International PLEA Conference,Ahmedabad, India, pp. 1-2.

17. Autodesk 2016 Measuring Energy Building Use Sustainability Workshop , Available at https://sustainabilityworkshop.autodesk.com/buildings/measuring-building-energy-use , <Retrieved 23.5.2017>

18. EIA, 2016, International Energy Outlook 2016, With Projections to 2040, U.S. Energy Information Administration, Available at www.eia.gov/forecasts/ieo <Retrieved 23.5.2017>

19. Walliser G B , Shrivastava P & Sulkowski A, 2016., *Using Proactive Legal Strategies for Corporate Environmental Sustainability*, 6 Mich. J. Envtl. & Admin. L. 1 Available at: http://repository.law.umich. edu/mjeal/vol6/iss1/1

20. Eames, M. , Dixon, T. , May ,T. and Hunt, M. 2013 "City futures: exploring urban retrofit andsustainable transitions". Building Research & Information, 41:5, 504-516, Available at http://www.tandfonline.com/doi/pdf/10.1080/09613218.2013.805063<accessed on 21.4.2016>

21. IPCC Fourth Assessment Report2013. "Climate Change 2007: Mitigation of Climate Change", Working Group III Report "Mitigation of Climate Change", Chapter 6. Available www.ipcc.ch/.../publications_ipcc_fourth_assessment_report_wg3_report <accessed on 10.3.2016>

22. TERI. 2013. *Roadmap for Incorporating Energy Efficiency Retrofits in Existing Buildings*. N.Delhi. Available at cbs.teriin.org/pdf/Energy_Efficiency_Retrofits_in_Existing_Buildings.pdfm <accessed on 17.5.2017>

23. Martinaitis, V., Kazakevičius, E. and Vitkauskas, A. 2007. "A two-factor method for appraising building renovation and energy efficiency improvement projects." Energy Policy, 351, pp. 192–201. doi:10.1016/j.enpol.2005.11.003

24. Užšilaitytė, L. and Martinaitis, V. 2010. "Search for optimal solution of public building renovation in terms of life cycle". Journal of Environmental Engineering and Landscape Management, 182, pp. 102–110. doi:10.3846/jeelm.2010.

25. MoUd. 2015. , Smart Cities, Mission Statement & Guidelines, Paper for India: Strategies for Low Carbon Growth. Ministry of Urban Development Government of India, Delhi.

26. URDPFI. 2014, Urban and Regional Development Plans Formulation & Implementation Guidelines, 2014, Volume 1. Ministry of Urban Development, India. N.Delhi..

27. JLL 2014. On Point - JLL India Affordable Housing in India, An inclusive approach tosheltering the bottom of the pyramid , Jones Lang Lasalle , <www.jll.co.in/india/en gb/.../Indias-Stock-of-Commercial-Real-Estate_Jun2014.pdf> accessed 22.8.2016.

28. BIS, 2016. National Building Code of India 2016 .Bureau of Indian Standards. New Delhi.

29. BEE,2014. Design Guidelines For Energy-Efficient Multi-Storey Residential Buildings Composite and Hot-Dry Climates. Bureau of Energy Efficiency. New Delhi.

30. Indraganti, M. 2014, "Adaptive use of natural ventilation for thermal comfort in Indian Apartments", Build. Environ. 45 6 1490e1507.

31. Marshall, E. Steinberger,J. K. Dupont,V. Foxon, T. J. 2016. Combining energy efficiency measure approaches and occupancy patterns in building modelling in the UK residential context, Energy and Buildings.

32. Kolter, J. Zico. J., Ferreira Jr. 2011."A large-scale study on predicting and contextualizing residential building energy usage." Proceedings of the Twenty-Fifth AAAI Conference on Artificial Intelligence, 7-11 August 2011, San Francisco, California

33. Samuelson H. ,Claussnitzer S., Goyal A., Chen Y. 2016. Parametric energy simulation in early design: High -rise residential buildings in urban contexts. Building and Environment 1012016 19-31

34. Sun, L., Huang, Y., Liu, S., Chen, Y., Yao, L. and Kashyap, A. 2017 A completive survey study on the feasibility and adaptation of EVs in Beijing, China. Applied Energy, 187. pp. 128-139. ISSN 03062619 Available from: http://eprints.uwe.ac.uk/31192

35. Pits A, 2017 Passive House and Low Energy Buildings: Barriers and Opportunities for Future Development within UK Practice, Centre for Urban Design, Architecture and Sustainability, University of Huddersfield, UK

36. Itagaki, Y. Yamaguchi, Y. Shimoda, Y.2015. Analysis Of Factors Creating Variety In ResidentialEnergy Demand Based On Measured Electricity Consumption, Proceedings of International building performance simulation, 2015, Hyderabad,India.

37. Jain, N., Lala, C. R. Chopra ,M. González, A. P. R. Natarajan, S. 2015. Impacts of Uncertainty In Energy Modelling Widely Used In Aggressive Energy Efficiency Regulations, Proceedings of International building performance simulation, 2015,Hyderabad, India.

38. Roychowdhury A. 2017. Green Sense: Sustainability Guidelines in Built Environment, New Delhi

39. NAPCC. 2008. National Action Plan on Climate Change 2008. "National Mission on Sustainable Habitat".Ministry of Urban Development, Government of India.

40. Zia, H., Sharma, C.,2015. Green growth and buildings sector in India. The Energy and Resources Institute, New Delhi.

41. Bantanur, S., Mukherjee, M.,Shankar ,R.2012. "Benchmarking - as a tool for sustainable buildings". National Conference on Energy Efficient Design of Buildings: Seeking Cost Effective Solutions, 6-10th February 2012. Murthal, India.

42. Grayson, R. 2010. Social, developmental & organizational psychology applied to camp. National Crime Prevention Council, Singapore.

43. Reed, R., Bilos, A., Wilkinson,S. and Schulte, K .W. 2009. "International Comparison of Sustainable Rating Tools." Journal of Sustainable Real Estate, Vol 1 no: 1,pp 1-22

44. En3, 2016 Case study BCIL tzed homes, Engineering Environment Energy, A carbon neutral company en3/ admin/ case studies/ BCIL Tzed homes- Case Study.pdf accessed 13.8.2017

45. Hui, S. C. M., 1997. Overall thermall transfer value OTTV: how to improve its control in Hong Kong,

46. Thomas P. C. , Venkatesan A, Thomas L E 2014, Effective natural ventilation in modern apartment buildings. PLEA 2014. 30th International PLEA Conference ,Ahmedabad, India, p 75

47. Ma Z, Cooper P, Daly D, Ledo L, 2012, Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings* .Volume 55, 2012, Pages 889-902

48. Kumar, P.2014. "Evaluation of thermal comfort of Naturally Ventilated University Students'Accommodation on basis of Adaptive Thermal Comfort Model and Occupant Survey in Composite Climate." International Journal of Architecture, Engineering and Construction, Vol. 3 no: 4, 2014 pp 298-316.

49. Preiser, W. F.E. 1995 ."Post occupancy evaluation: how to make buildings work better", Facilities, Vol. 13: 11, pp.19 – 28

50. BEE. 2007. ECBC User Guide 2007. Bureau of Energy Efficiency. New Delhi.

51. Thumann, A. ,2009, Handbook of Energy Audits, The Fairmont Press, Inc. Inc., GA

52. Tallinn 2001, Energy Audit Guide for Buildings, Finnish Ministry of the Environment.

53. Gupta R & Gregg M, 2014, A quiet revolution: Mapping energy use in low carbon communities, Proceedings of International Conference PLEA, 2014, Ahmedabad, India.

54. WBDG 2016,Measuring performance of suystainable buildings Available at www. wbdg.org/resources/measuring-performance-sustainable, Accessed 12.8.2017

55. Census Organization of India 2011, Gurgaon- Census of India, Available at censusindia.gov.in/2011census//dchb /DCHB.../ 0618_PART_A_DCHB_GURGAON.pdf Accessed 10.3.2016

56. Cushman and Wakefield. 2015. Growth in population to lead to housing demand. Available at www.cushmanwakefield.co.in /en. ../ growth-in- population-to-lead-to-housing- demand accessed 21.8.16

57. Lombard, L.P., Ortiz, J. and Pout, C. 2008. "A review on buildings energy consumption information". Energy and buildings, 403, pp.394-398.

58. Spentzoue E, Cook M, Emmitt S. 2013. *Enhancing Indoor Comfort In Existing Apartment Buildings In Athens Using Natural Ventilation* Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France.

59. Kluttig ,H .E. , Erhorn, H. and Reiß , J.2015. "Plus energy – a new energy performance standard in Germany for both residential and non-residential buildings." Advances in Building Energy Research, 9:1, 73-88, DOI:10.1080/17512549.2014.923328.

60. SEAI 2014. "Residential Energy Roadmap to 2050." Sustainable Energy Authority of Ireland.

61. BEE 2016, Design Guidelines For Energy-Efficient Multi-Storey Residential Buildings Warm and Humid Climates. Bureau of Energy Efficiency. New Delhi.

62. India Habitat III National report, 2016, Ministry of Housing and Urban Poverty Alleviation , Government of India, New Delhi .

63. McKinsey Global Institute. 2016. Report on Building India, 2016 Available at www.mckinsey.com/. ../building_ India transforming_ the _nations_ logistics_infrastruct.

64. CSO, 2015, Energy Statistics for 2013-14, Central Statistics Office, India, New Delhi

65. GBPN 2013 Achieving scale in energy-efficient buildings in India: A view from the construction and real estate sector, Technical report by Global Buildings Performance Networks, India

66. Raslanas, S ., Alchimovienė, J. and Banaitienė, N. 2011. "Residential Areas with Apartment Houses: Analysis of the Condition of Buildings, Planning Issues, Retrofit Strategies and Scenarios." International Journal of Strategic Property Management, Vol. 15:2, pp 152 172, DOI: 10.3846/1648715X.2011.586531 < accessed 22.4.2016>

67. UNEP 2013. United Nations Environmental Program Year Book 2013: Emerging Issues In Our Global Environment

68. Ganapathy G. 2016. Energy Efficient Residential Buildings, International Conference on Building Design by Indo Swiss Building Energy Efficiency Project BEEP, Nov 2016, N. Delhi.

69. IEA , 2015, Where to start: Understanding building energy use. International Energy Agency , USA. Available at https://www.iea.org. Accessed <2.4.2016>

70. Carletti c, Sciurpi F and Pierangioli L. 2014. The Energy Upgrading of Existing Buildings: Window and Shading Device Typologies for Energy Efficiency Refurbishment. Sustainability 2014, 6, 5354-5377; doi:10.3390/su6085354

71. Boeck, A. Audenaert A, Mesmaeker L2013. Improving the energy performance of residential buildings: a literature review, FaculteitEconomie En Bedrijfswetenschappen , Hubrussel , Brussels, Belgium,

72. IEA , 2015, Where to start: Energy Efficiency potential in buildings . . International Energy Agency , USA. Available at https://www.iea.org. Accessed <2.4.2016>

73. Yu J, Yang C, Tian L, Liao D. 2009b. Evaluation on energy and thermal performance for residential envelopes in hot summer and cold winter zone of China. Applied Energy 2009b;86:1970-85.

74. Yu J, Yang C, Tian L. Low-energy envelope design of residential building in hot summer and cold winter zone in China. Energy and Buildings 2008;40:1536–46.

75. MoEFCC, 2010, Environmental Impact Assessment Guidance Manual - Building, Construction, Townships and Area Development Projects, Ministry of Environment & Forests, Climate Change, Government Of India, New Delhi.

76. Srikonda R, 2014, Initiatives in Climate Responsive and Energy Efficient Architecture in India, Working Paper No. 16102014 001

77. Reardon C, McGee C, Milne G, 2013, Your Home , Australia' s guide to environmentally sustainable homes Available at /sites/prod.yourhome.gov. au/files/pdf/YOURHOME2PassiveDesign9ThermalMass 4 Dec13.pdf accessed Sep. 2016

78. Gregory K ,Moghtaderi B ,Sugo H, Page A, 2008. Effect of thermal mass on the thermal performance of various Australian residential constructions systems, Energy and Buildings Volume 40, Issue 4, 2008, Pages 459–465

79. Pushplata, A. Naphade, A. Sharma, P.S.Chani,2013, P.Garg. Green Building Retrofit for the Library of Indian Institute of Technology Roorkee, Journal of the Institute of Engineers India, Series A, , Volume 94 Issue 1, pp 35-42

80. Ruiz MC, Romero E. Energy saving in the conventional design of a Spanish house using thermal simulation. Energy and Buildings 2011;43:3226–35.

81. Pushplata, Mohd. Arif Kamal, Nazamuddin, 2009, Climatic Control Strategies in Traditional Built Form- Lucknow Context, Architecture + Design, A Journal Of Indian Architecture Vol. XXVI No 2 February 2009 pp 70- 78

82. University oF Hongkong. 2012.Energy and Use of Energy- Calculation and Application of OTTV and U-value. Community Project Workshop

83. GRIHA LD 2015 2015 . GRIHA Large developments 2015 , GRIHA Council. New Delhi Available at http://www.grihaindia.org/index.php? option=com_content& view=article &id=78&t=library, <accessed 10.2.2016>

84. Prowler D. and Kelbaugh D., 1990. "Building Envelopes", Solar Heat Technologies: Fundamentals and Applications, Massachusetts Institute of Technology, USA

85. Akhgari P, 2014, Building performance analysis for double skin residential buildings, Unpublished thesis Project,

86. Trubiano F. 2013. Design and Construction of High-Performance Homes: Building Envelopes, Renewable Energy and Integrated Practice .Routledgepublishers , London and New York.

87. Szalay Z. 2008. Modelling building stock geometry for energy, emission and mass calculations. Building research & Information ;366:557–7

88. Bicke S Phan E- Christie G S 2013 Residential Windows and Window A detailed view of the installed Base and user behaviour covering Building Technologies Office Office of Energy Efficiency and Renewable Energy , U.S. Department of Energy

89. Bayne K,; Allan T,; Baker K , 2008 Design Criteria for Retrofit Windows and New Walls Final Draft. A report prepared for Beacon Pathway Limited.Beacon Pathway Limited and the Foundation for Research, Science and Technology.

90. TERI , 2004, Sustainable Building Design Manual- Volume I and Volume II , ICAEN & TERI ISBN 9788179930533

91. Johansson T B 2013 . Energy and the Challenges of Sustainability – OSCE, 21st OSCE Economic And Environmental Forum, 4-5 February 2013, Vienna Available at https://www.osce.org/eea/99192?down

92. Tanasiev V, Dinca C, Vidu R, Mihai M I 2017, Passive House Analysis in Terms of Energy Performance, Energy and Buildings 144:74-86.

93. Szokolay, S. 2004. Introduction to Architectural Science : the Basis of Sustainable Design. Architectural Press, Oxford

94. Indraganti.M. 2010. Thermal comfort in naturally ventilated apartments in summer: Findings from a field study in Hyderabad, India, *Applied Energy*. 87 3.

95. Ford, B. 2002 The Architecture of Cooling Without Air Conditioning, SAMSA 2002 Lecture Notes

96. Seppänen, O. and Fisk, J. 2002 Association of ventilation system type with SBS symptoms in office workers, Indoor Air 2002; 12

97. Thomas L, 2014, Shifting the norm - towards effective mixed mode buildings

98. Anis W. 2015. Retrofit of Building Enclosures for Energy Efficiency, Wiss, Janney, Elstner& Associates, Inc. apartment buildings, PLEA 2014 proceedings

99. Serghides D.K. andKatafygiotou M.C. 2013. The role of materials in the energy efficient retrofitting of traditional Buildings, Materials and processes for energy: communicating current research and technological developments A. Méndez-Vilas, Ed.

100. Gillem M.L., 2014, Aesthetic Opportunities, Whole building Design Guide, Available at https://www.wbdg.org/resources/aestheticopportunities.php. accessed October, 2016.

101. McDonough, W. Braungart M. 2013. The Upcycle: Beyond Sustainability – Designing For Abundance. North Point Press

102. McDonough, W. Braungart M. 2002. Cradle To Cradle®: Remaking The Way We Make Things. North Point Press

103. Bax L, 20 Cruxent J, Komornicki J, 2014. Innovative Chemistry for Energy Efficiency of Buildings in Smart Cities, Advanced Materials for Energy Efficient Buildings, European commission.

104. Sakhare V V., Raut S.P., Mandavgane S.A., Ralegaonkar R.V. 2014. Development of sustainable retrofitting material for energy conservation of existing buildings. International journal of civil engineering

105. HBC, 2017, Haryana Building Code, Haryana .

106. HPWD, 2010, New items inducted in Haryana PWD Schedule of rates, 1988 2nd Edition Haryana Govt. Public works department notification.

107. Architecture & Development , 2016. Case Study III: TZED homes in Bangalore by BCIL, Energy efficiency and high environmental quality buildings in India. Available at http://www.archidev.org/spip.php?rubrique318

108. Hanley,D. P., Kuhn, G, 2003 Trees against the Wind, A Pacific Northwest Extension Publication

109. Bansal N.K., Hauser, G., Minke. G. 1994, 'Passive Building Design',. A Handbook of Natural Climatic Control, Elsevier Science BV, London.

110. Duarte D.H.S., Shinzato P, Gusson C.D.S., Alves C.A.2015. The impact of vegetation on urban microclimate to counterbalance built density in a subtropical changing climate,,

Urban Climate, Cooling Heat Islands, Volume 14, Part 2, December 2015, Pages 224–239

111. Parolek D, 2012. Missing Middle Housing: Responding to the Demand for Walkable Urban Living. Opticos Design, Inc. accessed 12.6, 2016.

112. Schindler D, Bauhus Jürgen, Mayer Helmut, 2011, Wind effects on trees, European Journal of Forest Research, 2011, Volume 131, Number 1, p 159

113. Hart S, 2011. Ecoarchitecture: The Work of Ken Yeang, Wiley Publications. ISBN: 978-0-470-72140-7

114. Zhao M ,Hartwig M. K, Antretter F, Parameters influencing the energy performance of residential buildings in different Chinese climate zones. Energy and Buildings Volume 96, 1 June 2015, Pages 64–75.

115. EPA.2011. Indoor Air Facts No. 4 revised Sick Building Syndrome. Research and Development Md-56 U S Environment Protection Agency

116. India energy. 2014. India Energy Security Scenarios, 2047 User Guide: Residential Lighting and Appliances. Available at www.indiaenergy.gov.in/docs/Residential-Lighting_Appliances-documentation.pdf accessed 8.10.2016

117. Halim M A, Azlan H , Faisal M. H 2017, Lighting Retrofit Scheme Economic Evaluation. Available at https://www.semanticscholar.org/ paper/Lighting-Retrofit

118. Hansen , V, Kennedy, R., Sanders, P , Varendorff, A,. 2012. Daylighting performance of subtropical multi-residential towers : Simulations tools for design decisions PLEA2012 - 28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture Lima, Perú 7-9 November 2012.

119. GRIHA Version 2015 2016 . GRIHA Council. New Delhi Available at http://www.grihaindia.org/index.php? <Retrieved 10.2.2016>

120. CSE 2014 Energy and buildings, Technical report, Centre of Science and environment, N.Delhi.

121. Can S, Letschert V,McNeil M, Zhou N, and Sathaye J, 2009, , Residential and Transport Energy Use in India: Past Trend and Future Outlook, Lawrence Berkeley National Laboratory, USA.

122. DOE.2014. Issues in International Energy Consumption Analysis: Electricity Usage in India's Housing Sector U.S. Energy Information Administration.

123. Kumar N, Devadas V ,2016 A Household-based analysis of domestic energy consumption for lighting in Jaipur City, International Journal Of Built Environment And Sustainability, Faculty of Built Environment, UniversitiTeknologi Malaysia, 126-133, Available at http://www.ijbes.utm.my IJBES 32/2016

124. DOE.2015. Drivers of U.S. Household Energy Consumption, 1980-2009, U.S. Energy Information Administration

125. Bhatt, S. M., Rajkumar, N., Jothibasu, S., Sudirkumar, R., Pandian, G., & Nair, K. 2005. Commercial and residential building energy labeling. Journal of Scientific & Industrial Research, 30-34

126. LCC. 2011. Interim Report of the Expert Group on Low Carbon Strategies for Inclusive Growth. Planning Commission, Government of India.

127. Worldbank 2008. Residential consumption of electricity in india : Documentation of data and methodology, Background Paper, India: Strategies for Low Carbon Growth.

128. Evola G., Margani, G. 2016 .Renovation of apartment blocks with BIPV: Energy and economic evaluation in temperate climate, Energy and Buildings 130 2016 794–810.

129. Soares, A., Ribeiro ,A. 2011. "Application of urban sustainability indicators to the city of Coimbra, Evaluation of urban sustainability data and regulations". *Proceedings of VCT, Lisbon, Portugal*, 11-13 October 2011.

130. Shen, L .Y., Ochoa, J. J ., Shah, M .N., Zhang ,X .2011. "The application of urban sustainability indicators – A comparison between various practices." Habitat International, Vol. 35,Issue 1, pp 17–29.

131. Heink, U., Kowarik, I. 2010. "What are indicators ?" On the definition of indicators in ecology and environmental planning, Ecological Indicators, Volume 10, Issue 3, pp 584 593.

132. Chaudhary, A., Ambuj.,Sagar, A.D. and Mathur, A.2012. "Innovating for energy efficiency: a perspective from India. Innovation and Development." Special Issue: Sustainability oriented innovation systems in China and India, Vol.2:1 pp 45-66

133. Bantanur, S., Mukherjee, M.,Shankar ,R.2012. " Benchmarking - as a tool for sustainable buildings". National Conference on Energy Efficient Design of Buildings: Seeking Cost Effective Solutions, 6-10th February 2012. Murthal, India

134. Sharma, N., Langebro,J., Khan, S. H.2010. Sustainability Benchmarking – The Case of Thule. Masters project Masters program n"Sustainable Business Leadership, School of Economics and Management, Lund University.

135. Balachandra, P. and Reddy, B. S. 2013. Benchmarking Bangalore City for sustainability—An indicator-based approach. Available at cistup.iisc.ernet.in/ presentations/Research%20project/CIST035.pdf <accessed 10.2.2016>

136. Hensen, J.L. 2002. "Simulation for performance based building and systems design: some issues and solution directions". Proceedings of 6th International Conference on Design and Decision Support Systems in Architecture and Urban Planning .Vol. 2, No. 002, pp. 186-199.

137. DOE US 2014 Department of Energy Building Tools Directory http://www.eere.energy.gov/ buildings /tools _directory/ 2009. Ministry of Power.New Delhi, India.

138. Dulac, J., Dean, B. 2014 International Energy Agency , USA. Available at https://www.iea.org /media/ training/.../A.8_Tracking_progress.pdf. Accessed <2.4.2016>

139. Grierson, D. and Moultrie, C.M. 2011. "Architectural design principles and processes for sustainability: Towards a typology of sustainable building design." Design Principles and Practices, pp.623-634.

140. Criterion Planners .2014. "A Global Survey of Urban Sustainability Rating Tools". GRI Cons & Real Estate. Available at crit.com/wp-content/.../ criterion_planners_ sustainability_ratings _tool.pdf .<Accessed 5.5.2016>

141. India Energy Analysis, 2018, First solar RTPV IN Dwarka CGHS. Available at ,https://indiaenergyanalysis. wordpress.com/2018/0

142. CEAC, 2016, Energy Efficiency Metrics and Targets Options Report, Clean Energy Advisory Council, Deartment of Public Service , New York State of Opportunity.

143. RESNET, 2018, Home Energy Audits and Ratings , Residential Energy Services Network, http://www.resnet.us/

144. Department of energy and climate change, 2014, UK National Energy Efficiency Action Plan, Available at https://ec.europa.eu/energy/sites/ener/files/.../2014_neeap_united-kingdom.

145. Energy performance certificate n.d. https://www.gov.uk/buy-sell-your-home/energy-performance-certificates

146. Ministry of Housing & Urban Poverty Alleviation, 2007. National Urban Housing and Habitat Policy. 2007April, Government of India. New Delhi

147. GRIHA EB 2018GRIHA for Existing Buildings,.grihaindia.org. GRIHA EB manual.pdf.

148. IGBC2015. "IGBC Green Residential Societies rating system". Available at https://igbc.in/igbc/redirectHtml.htm?red Val=showResourcesnosign#about-content<accessed 10.2.2016>

149. PMC. 2010. Eco housing for Pune Municipal Corporation , building a better tomorrow Available at http://www.ecohousing.in/Eco- Housing-for-PMC.php , <Retrieved May2017>

150. Kumar, P.2014. "Building Performance Assessment and Evaluation of Existing Buildings for Energy Efficiency: Case Study of Students' Accommodation in a University Campus". Tekton Vol.1, Issue 1. pp 76-95

151. Green buildings in India. 2013. Available at https://greenbuildingsindia.wordpress .com/2013/08/22/ansal-esencia

152. Menezes, A.C., Cripps, A., Bouchlaghem ,D., Buswell, R. 2012. "Predicted vs. actual energy "http://www.sciencedirect.com/science/article/pii/ S0306261911007811" performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap ." Applied Energy, Vol. 97, Pages 355–364.

153. Hassanain, M.A. 2012. "Post-Occupancy Evaluation". Available at MA Hassanain open courseware.kfupm.edu.s<accessed 15.3.2016>.

154. Vischer, J.2002. "Post-occupancy evaluation: A multifaceted tool for building improvement. Learning from Our Buildings: a state-of-the-practice summary of post occupancy evaluation". National Academies Press, pp.23-34.

155. Leaman, A. Bordass, B. 2003. "Post-occupancy evaluation". in Presentation at Gaia Research Sustainable Construction Continuing Professional Development Seminars, Gaia Group, Edinburgh, Scotland.

156. Latvia. 2009. Case study 20: Building energy audits project, Latvia , Contextualising behavioural change in energy programs involving intermediaries and policymaking organizations working towards changing behaviour ; Available at www.energy change. info

157. Singh M, Singh G and Singh H, Energy Audit: A Case Study To Reduce Lighting Cost , Asian Journal of Computer Science and Information Technology, 2012, PP 119-122

158. Morrissey J, Horne RE. Life cycle cost implications of energy efficiency measures in new residential buildings. Energy and Buildings 2011;43:915-24.

159. Fesanghary M, Asadi S, Geem ZW. Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm. Building and Environment 2012;49:245-250.

160. Ihm P, Krarti M. Bhandari M, Design optimization of energy efficient residential buildings in Tunisia. Building and Environment 2012;58:81-90. USA Building Simulation Conference. Atlanta, GA, September 10-12, 2014

161. Kapsalaki M, Leal V, Santamouris M. A methodology for economic efficient design of Net Zero Energy Buildings. Energy and Buildings 2012;55:765-78.

162. Ucar A, Balo F. Determination of the energy savings and the optimum insulation thickness in the four different insulated exterior walls. Renewable Energy 2010;35: 88-94.

163. Audenaert A, De Boeck L, Roelants K. Economic analysis of the profitability of energy-saving architectural measures for the achievement of the EPB-standard. Energy 2010;35:2965-71.

164. Jaber S, Ajib S. Optimum, technical and energy efficiency design of residential building in Mediterranean region. Energy and Buildings 2011a;43:1829-34.

165. Jaber S, Ajib S. Thermal and economic windows design for different climate zones. Energy and Buildings 2011b;43:3208–15.

166. Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast. Energy and Buildings 2013;56:189-203.

167. Marszal AJ, Heiselberg P. Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark. Energy 2011;36:5600-9.

168. Tanasa C, Sabau C, Stoian D Dan D, Stoian V. 2014. Study on the life cycle cost of energy efficient residential buildings . Conference proceeding published in *Advances in Environmental Technology and Biotechnology*

169. Maleki A, 2009, Life-Cycle Cost Evaluation of Building Envelope Energy Retrofits, Unpublished thesis, Department of Civil Engineering. University of Toronto

170. Attia S ,Hensen L.M. , Beltrán L & Herde. 2012. Selection criteria for building performance simulation tools: contrasting architects' and engineers' needs, Journal of Building Performance Simulation. Vol. 5, Issue 3.

171. Designbuilder. N.d.. https://www.designbuilder.co.uk/

172. IPMVP.2007. Concept and Options for Determining Energy and Water Savings. Efficiency Valuation organization – IPMVP Available at www.ipmvp.org accessed 12.10.14

173. State of the Real Estate Market– National Capital Region Part 1 Gurgaon. property.magicbricks.com, 2016

174. NCR Planning Board,2005, Regional Plan 2021, Ministry of Housing and Urban Affairs, Government of India, N. Delhi.

175. Census India 2011, District Census Handbook Gurgaon available at http://censusindia.gov. in/2011census/ dchb/DCHB_ Haryana.html.

176. TCPO Haryana, 2012, Final Development Plan Gurugram 2031, Available at https://tcpharyana.gov.in/ Development_Plan. htm

177. Weather data WMO Region 2, India New Delhi 421820. Available at https://energyplus.net/ weather

178. Climate consultants 6.1 n.s. Weather Data of Delhi

179. TCPO Haryana n.d. Functions and Policies Town & Country Planning Department, Haryana, https://tcpharyana. gov.in /FunctionAndPolicy.html

180. HUDA, n.d. 2018, https://www.hsvphry.org.in

181. DHBVN 2016, DPR OF Smart Grid Project in Gurgaon Sector 1 -57, www.dhbvn.org,in/ new/ smartgrid projects/ DPR Gurgaon Sec 1 -57 pdf

182. Kumar P, 2016, Revisiting Public Private Partnership In Urban Residential Sector in Gurgaon,, CreateSpace , ISBN-13: 978-1537119946

183. Google maps .2017. https://www.google.com/maps

184. Kothari C R, Gaurav G, 2018, Research Methodology. New Age International Publishers. ISBN -978-93-86649-225

185. Research Advisors. n.d. Sample Size Table . www.research-advisors.com/tools/SampleSize.htm

186. ASHRAE 2012.Performance Measurement Protocols for Commercial Buildings: Best Practices Guide. Atlanta, United States. ISBN -978-1-936504-343

187. Onset 2012.Onset Hobo Data Loggers. Available at<http://www.onsetcomp.com/ products/ dataloggers /u12-006>

188. Pratt K B , Bosworth D E. 2011, A Method For The Design And Analysis Of Parametric Building Energy Models, Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November

189 Pushplata , Monalisa, 2009, Energy Sensitized Architecture in India, Journal of Indian Building Congress, Jan 2009,Vol.XVI, No. 01, pp 156-162

190 Pushplata, Tejo Vihas, P.Gupta, S. Dave , 2007, Design Considerations for Building Integrated Photo Voltaics, The Journal of the Indian Institute of Architects, Vol. 72, Issue 04, April 2007.

191 Sharma A, Dhote K, Tiwari R, 2003, Climatic responsive energy efficient passive techniques in buildings, IE Journal

192 Jankovic L., 2017, Designing Zero Carbon Buildings Using Dynamic Simulation Methods, Routledge, ISBN

193 Roaf S,2013, Ecohouse, A design guide, Routledge,USA ISBN 9780415526777.

194 Garg V, Bhatia A, Rakllapalli H, Gandhi J,Arumugam R,Tetali S, 2013.Net zero Energy Design for a house in Ahmedabad. Unpublished Project Report.

195. Trigaux D, Leuven K, 2014, Optimization for Passive Design of Large Scale Housing Projects for Energy And Thermal Comfort in a Hot and Humid Climate, 30th International PLEA Conference, Ahmedabad, India.

196 Ganesan K, 2014, Baseline Scenario of Energy Consumption of Urban Multi-storey Residential Buildings in India.

197. Zhang Y, Neil Z, Dong B, Augenbroe G, 2015, Comparisons of inverse modeling approaches for predicting building energy performance, Building and Environment, Volume 86, April 2015, Pages 177-190

198 Bass A,1997, An Inverse Model To Predict and Evaluate the Energy Performance of Large Commercial and Institutional Buildings, IBPSA Conference Proceedings.

APPENDICES

List of Appendices

APPENDIX 1

BUILDING ENVELOPE CHARACTERISTICS

To understand Residential Apartments Geometry and construction parameters for Baseline Data Modeling

* Required

1. **Name of Housing Society**

2. **Site Area**

3. **No of flats/ units in site**

4. **No of stories/ floors in one tower**

5. **Ground floor Stilt**
Mark only one oval per row.

	Yes	No	Partly
Status	◯	◯	◯

6. **Shape of the tower**
Mark only one oval per row.

	Point type	Slab type	Singly loaded corridoer linear	Walk up apartments	floors	Cluster type
Type	◯	◯	◯	◯	◯	◯

7. **Distance between Two blocks**
Mark only one oval per row.

	6M	6-9 M	9-12M	12M or more
Distance	◯	◯	◯	◯

8. **Area of dwelling units**
Mark only one oval per row.

	80 sqm or less	80-120 sqm	120-160 sqm	160 sqm and above
Area	◯	◯	◯	◯

9. **Construction Wall materials**

Mark only one oval.

- Brick wall 230 mm thick
- AAC Concrete blocks
- Fly ash bricks
- Concrete walls
- Prefab Conc insulated walls
- Cavity walls in brick
- Brick or concrtete thick mass walls
- Integrated Wall insulation
- Other: ____________________

10. **Exterior finishing of walls**

Mark only one oval per row.

	Exposed brick wall	Cement plaster plain , painted	Grit finish	Stone cladding
Finish	◯	◯	◯	◯

11. **Color of exterior walls**

Mark only one oval per row.

	White or Off white	Light vcolors	Dark colors	Refective surface
color	◯	◯	◯	◯

12. **Construction Roof and finishing**

Mark only one oval.

- RCC slab with mud phuska and brick tile terracing
- Thermal insulation of XPS or EPS or other material
- Heat resistant tiles
- High SRI paints
- Green roof / Terrace garden
- Double roof shaded

13. **Window Area as percentage of total Wall area (WWR)**

Mark only one oval per row.

	<20%	<20-40%	<40-60%	<60% or more
WWR	◯	◯	◯	◯

14. **Window frame material**

Mark only one oval per row.

	Aluminum	PVC	Steel	Wood
Material	◯	◯	◯	◯

15. **Glass color**
Mark only one oval per row.

	Bronze	Green	light blue	Dark blue	Plain (no colr)	Reflective
color	⬭	⬭	⬭	⬭	⬭	⬭

16. **Type of glass**
Mark only one oval per row.

	Single plain glass	Double glazing unit	Reflective glass film coated	Tinted glass
Type	⬭	⬭	⬭	⬭

17. **Window type**
Mark only one oval per row.

	Fixed	25% operable	50% operable	75% operable
Type	⬭	⬭	⬭	⬭

18. **External doors**
Mark only one oval per row.

	glass	opaque (solid wood or other materials	partly glass and partly opaque
Type	⬭	⬭	⬭

19. **Internal shading on windows**
Mark only one oval per row.

	No curtains	Single layer curtains	Dual Curtains (Light and Dark)	Chic or screens	Vertical blinds	Roller blinds
Type	⬭	⬭	⬭	⬭	⬭	⬭

20. **Projection of External Shading on window**
Mark only one oval per row.

	No Projection	0 to 0.30 m	0.30 m -0.45 m	0.45 m -0.60 m	0.6m - 0.75 m	0.75m-0.9m
Row 1	⬭	⬭	⬭	⬭	⬭	⬭

21. **Exterior shading on windows** *
Mark only one oval.

- ⬭ Recessed windows
- ⬭ Boxed windows
- ⬭ Horizontal projection over windows
- ⬭ Shade at roof level projection only
- ⬭ Side fins
- ⬭ Retractable Fabric Awnings
- ⬭ glass or Polycarbonate shade
- ⬭ Exterior movable shade
- ⬭ Pergola wooden or concrete
- ⬭ Louvres / Blinds

22. **Balcony size**

Mark only one oval per row.

	1m depth	1.5 m depth	1.8 m depth	2.0 m depth	More	None
Size	◯	◯	◯	◯	◯	◯

23. **HVAC Type**

Mark only one oval.

◯ Package terminals (Window AC / Split Ac)

◯ Centralized AC System

◯ VRF Varioous Refriferant Flow System

◯ Other: ____________________

24. **Comments / Any other features**

____

APPENDIX 2

Energy Consumption Survey of Residential Apartments

Questionnaire 2017-18

Dear Sir/ Madam ,

I introduce myself as Architect Neeti Garg, research scholar, currently pursuing PhD in Department of Architecture and Planning in Malviya National Institute of Technology, Jaipur.

You are requested to fill up the questionnaire online to devise "Strategies for reducing energy consumption of existing residential multistoried apartments by renovating / retrofitting them", which will lead to saving in electricity bill , reduced energy consumption , and also for sustainable environment in wake of India's recent climate change goals to reduce carbon emissions.... It may take 10-12 minutes.

Please note: All survey responses will remain confidential and will be used for academic purpose only.

* Required

1. **Email address** *

2. **Name of Housing Scheme** *

3. **SECTOR** *

4. **BLOCK/ POCKET/FLAT NO** *

5. **TYPE**
Mark only one oval per row.

	Government (Public Sector)	Cooperative Society (CGHS)	Private Developer
Type	◯	◯	◯

6. **Area of dwelling unit (sqm)**
Mark only one oval per row.

	<80	80-120	120-160	160-200	>200
Area	◯	◯	◯	◯	◯

7. **No of Bed rooms**
Mark only one oval per row.

	One BHK	Two BHK	Three BHK	More
Size	◯	◯	◯	◯

8. **TENTATIVE AGE OF HOUSING**
Mark only one oval per row.

	<10 YEARS	10-15 YEARS	More
Age	⬭	⬭	⬭

SECTION 1 : HOUSE HOLD CHARACTERISTICS

Please note: All survey responses will remain confidential. Participants will remain anonymous .

Participation Identification Code

9. **Date** *

Example: December 15, 2012

10. **Family structure**
Mark only one oval per row.

	1	2	3	4
Childrens	⬭	⬭	⬭	⬭
Adults	⬭	⬭	⬭	⬭
Elder People	⬭	⬭	⬭	⬭

Occupation

11. **Please use code 1 for Service 2 for Business 3 for Education 4 for any other**
Mark only one oval per row.

	service	business	education	any other
Head	⬭	⬭	⬭	⬭
Spouse	⬭	⬭	⬭	⬭
Parents	⬭	⬭	⬭	⬭
Children 1	⬭	⬭	⬭	⬭
Children 2	⬭	⬭	⬭	⬭

12. **Location of Flat/apartment** *
Mark only one oval per row.

	Ground floor	First floor- intermediate floor	Top floor
Location	⬭	⬭	⬭

13. **Duration (Timings) of Opening Windows**
Mark only one oval per row.

	6:00-10:00	10:00-14:00	14:00-18:00	18:00-22:00	22:00-2:00	2:00-6:00
Summers(Mar-Jun)	⬭	⬭	⬭	⬭	⬭	⬭
Summers(Jul-Nov)	⬭	⬭	⬭	⬭	⬭	⬭
Winters(Dec-Jan-Feb)	⬭	⬭	⬭	⬭	⬭	⬭

14. **Connected Electrical Load (pls refer elec. bill)** *

Mark only one oval per row.

	2-5 kw	5-10 kw	10-15 kw	>15 kw
Load	⬭	⬭	⬭	⬭

SECTION 2 : ELECTRICITY CONSUMPTION PATTERN

Electricity Bill Consumption

Please write total no of units of electricity consumed on average basis per month

15. **Average Electric bill consumption(Summer months)**

____

16. **Average Electric bill consumption(Winter months)**

____

17. **How much time do you spend in your house at the following times of day?**

Mark only one oval per row.

	No of hours in a day	No of days in a week	No of weeks in a year not occupied
Drawing Room	⬭	⬭	⬭
Bed Room 1	⬭	⬭	⬭
Bed Room 2	⬭	⬭	⬭
Bed Room 3	⬭	⬭	⬭
Kitchen	⬭	⬭	⬭

18. **Capacity (tonnage) of ac** *

Mark only one oval per row.

	No AC	1 ton	1.5 ton	2 ton	2.5 ton	Inverter AC
Bedroom 1	⬭	⬭	⬭	⬭	⬭	⬭
Bedroom2	⬭	⬭	⬭	⬭	⬭	⬭
Bedroom 3	⬭	⬭	⬭	⬭	⬭	⬭
Living Room	⬭	⬭	⬭	⬭	⬭	⬭

19. **Ac Set point Temperature Degree Celsius** *

Mark only one oval per row.

	18-20	21-23	24-26	27 -28
April -May-June	⬭	⬭	⬭	⬭
July- August	⬭	⬭	⬭	⬭
September-October	⬭	⬭	⬭	⬭

Duration of AC operating (hours)

20. **April-May-June**
Mark only one oval per row.

	Bedroom 1	Bedroom 2	Bedroom 3	more
6:00-10:00				
10:00-14:00				
14:00-18:00				
18:00-22:00				
22:00-6:00				

21. **July - August**
Mark only one oval per row.

	1	2	3	more
6:00-10:00				
10:00-14:00				
14:00-18:00				
18:00-22:00				
22:00-6:00				

22. **September-October**
Mark only one oval per row.

	1	2	3	more
6:00-10:00				
10:00-14:00				
14:00-18:00				
18:00-22:00				
22:00-6:00				

Duration of heater operating (hours)

23. **Dec-Jan-Feb**
Mark only one oval per row.

	1	2	3	more	none
6:00-10:00					
10:00-14:00					
14:00-18:00					
18:00-22:00					
22:00-6:00					

Star rating of ACs/ heaters

24. **AC** *

Mark only one oval per row.

	5 star	4 Star	3 Star	2 Star	I star	No star	No AC
Bedroom 2							
Living room							
Bedroom 1							
Bedroom 3							

25. **Heaters** *

Mark only one oval per row.

	S star	4 star	3 Star	2 Star	1 Star	No star	No heater
Bedroom 1							
Bedroom2							
Bedroom 3							
Living room							

Months of geyser operation

26. **Starting month** *

Mark only one oval per row.

	January	February	March	October	November	December
Starting month						
Ending month						

27. **Type of geysers**

Mark only one oval per row.

	Electric	Gas
Toilet 1		
Toilet2		
Toilet 3		
Kitchen		

28. **Duration of geyser operating hours**

Mark only one oval per row.

	One Hour	2 hours	3 hours	4 hours	More
Toilet 1					
Toilet 2					
Toilet 3					
Kitchen					

29. **Star rating of geyser** *

Mark only one oval per row.

	5 Star	4 Star	3 Star	2 Star	One Star	No Star	No geyser
Toilet 1							
Toilet 2							
Toilet 3							
Kitchen							

30. **Capacity of Refrigerator in Litres**

31. **Star rating of Refrigerator** *

Mark only one oval per row.

	5 star	4 star	3 star	2 star	1 star	no star
Rating						

32. **Inverter capacity**

33. **Other Electrical Equipments**

Check all that apply.

	Quantity	No of hours used in a day	No of days used in week
LCD TV			
Laptop			
Washing machine			
Dish washer			
Microwave			
Iron			

34. **No's of Lighting /Fixtures**

Mark only one oval per row.

	LED	CFL	TL	Ceiling Fans
Drawing room				
Bed room 1				
Bed room 2				
Bed room 3				
Kitchen				
Toilets				

35. **Duration of use of Lighting Fixtures** *
Mark only one oval per row.

	0-4 hrs	8-12 hrs	12-16hrs	16-20hrs
Drawing room	◯	◯	◯	◯
Bed room 1	◯	◯	◯	◯
Bed room 2	◯	◯	◯	◯
Bed room 3	◯	◯	◯	◯
Kitchen	◯	◯	◯	◯
Toilets	◯	◯	◯	◯

36. **Duration of use of fan** *
Mark only one oval per row.

	0-4 hrs	4-8 hrs	8-12 hrs	12-16hrs	16-20hrs
Drawing room	◯	◯	◯	◯	◯
Bed room 1	◯	◯	◯	◯	◯
Bed room 2	◯	◯	◯	◯	◯
Bed room 3	◯	◯	◯	◯	◯
Kitchen	◯	◯	◯	◯	◯
Toilets	◯	◯	◯	◯	◯

SECTION 3 ENVIRONMENTAL CHARACTERISTICS

37. **Please rate your thermal comfort sensation in your house** *
Mark only one oval per row.

	-3 (Cold)	-2 (Cool)	-1(Slightly Cool	0(Neutral)	1 Slightly Warm	Warm	3 Hot
Row 1	◯	◯	◯	◯	◯	◯	◯

38. **I would like Air movement** *
Mark only one oval per row.

	More Air Movement	No change	Less Air movement
Air movement	◯	◯	◯

39. **How Satisfied are you with daylighting in your house** *
Mark only one oval.

	1	2	3	4	5	
Very dissasified	◯	◯	◯	◯	◯	Very Satisfied

40. **How Satisfied are you with thermal comfort in your house** *
Mark only one oval.

	1	2	3	4	5	
Very dissasified	◯	◯	◯	◯	◯	Very Satisfied

41. **Which of the following controls do you have over the lighting in your house?** *

Mark only one oval.

- Light switch
- Light dimmer
- Window blinds or shades
- Desk light
- Any other

42. **How important is it for you to save electricity within your house/flat?** *

Mark only one oval.

	1	2	3	4	5	
Not important						Essential

SECTION 4: RETROFITTING CHARACTERISTICS

43. **What renovations / repairs have been undertaken in your house in last five years?**

Mark only one oval per row.

	Yes	No
Refitting Kitchen / bathrooms		
Rewiring in the house		
Changing / Adding windows and doors		
Space Remodelling (Interior) painting		
Adding/ deleting room		
Solar energy systems		
Improve appearance of home (exterior)		
Installing Air conditioners/ heaters		
Improve openness in the home for health		

44. **How important you think renovating / retrofitting your house would be in achieving following aspects of your house?** *

Mark only one oval per row.

	Not important	Slightly Important	Important	Very important	Essential
For reducing energy consumption and bill	⬭	⬭	⬭	⬭	⬭
For improving external appearance of house	⬭	⬭	⬭	⬭	⬭
For improving ventilation and living conditions	⬭	⬭	⬭	⬭	⬭
For reducing heat gain in summers	⬭	⬭	⬭	⬭	⬭
For reducing maintenance of exterior façade	⬭	⬭	⬭	⬭	⬭
For bringing renewable energy	⬭	⬭	⬭	⬭	⬭
For saving enviroment	⬭	⬭	⬭	⬭	⬭

45. **How much you can afford to spend to improve your housing condition (INR)** *

Mark only one oval per row.

	< Rs.1.0 L	I.0 L- 2.0 L	2-0 L-4.0 L	> 4.0 L
Amount in INR lacs	⬭	⬭	⬭	⬭

46. **Do you have any comments about improving energy efficiency of your housing which have not been covered so far ?**

____

____

____

____

____

Thank you for taking the time to complete this survey.

In case of difficulty, please contact 9996312901

Program Version:**EnergyPlus, Version 8.5.0-c87e61b44b, YMD=2018.06.30 00:32** Table of Contents

Tabular Output Report in Format: **HTML**

Building: **Building**

Environment: **DLF (01-01:31-12) ** New Delhi Delhi IND ISHRAE WMO#=421820**

Simulation Timestamp: **2018-06-30 00:32:53**

Report: **Annual Building Utility Performance Summary** Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

Values gathered over 8760.00 hours

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	67920.25	47.17	55.53
Net Site Energy	67920.25	47.17	55.53
Total Source Energy	110131.68	76.48	90.04
Net Source Energy	110131.68	76.48	90.04

Site to Source Energy Conversion Factors

	Site=>Source Conversion Factor
Electricity	3.167
Natural Gas	1.084
District Cooling	1.056
District Heating	3.613
Steam	0.250
Gasoline	1.050
Diesel	1.050
Coal	1.050
Fuel Oil #1	1.050
Fuel Oil #2	1.050
Propane	1.050
Other Fuel 1	1.000
Other Fuel 2	1.000

Building Area

	Area [m2]
Total Building Area	1439.94
Net Conditioned Building Area	1223.18
Unconditioned Building Area	216.75

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00
Cooling	0.00	0.00	0.00	49835.10	0.00	0.00
Interior Lighting	2144.81	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	15387.50	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	552.84	8.66
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	17532.31	0.00	0.00	49835.10	552.84	8.66

End Uses By Subcategory

Report: **Input Verification and Results Summary** Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

General

	Value
Program Version and Build	EnergyPlus, Version 8.5.0-c87e61b44b, YMD=2018.06.30 00:32
RunPeriod	DLF (01-01:31-12)
Weather File	New Delhi Delhi IND ISHRAE WMO#=421820
Latitude [deg]	28.58
Longitude [deg]	77.20
Elevation [m]	216.00
Time Zone	5.50
North Axis Angle [deg]	135.00
Rotation for Appendix G [deg]	0.00
Hours Simulated [hrs]	8760.00

ENVELOPE

Window-Wall Ratio

	Total	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Gross Wall Area [m2]	2671.96	475.97	860.01	475.97	860.01
Above Ground Wall Area [m2]	2671.96	475.97	860.01	475.97	860.01
Window Opening Area [m2]	299.46	5.77	0.00	5.79	287.90
Gross Window-Wall Ratio [%]	11.21	1.21	0.00	1.22	33.48
Above Ground Window-Wall Ratio [%]	11.21	1.21	0.00	1.22	33.48

Conditioned Window-Wall Ratio

	Total	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Gross Wall Area [m2]	2264.29	446.58	481.73	475.97	860.01
Above Ground Wall Area [m2]	2264.29	446.58	481.73	475.97	860.01
Window Opening Area [m2]	299.46	5.77	0.00	5.79	287.90
Gross Window-Wall Ratio [%]	13.23	1.29	0.00	1.22	33.48
Above Ground Window-Wall Ratio [%]	13.23	1.29	0.00	1.22	33.48

Skylight-Roof Ratio

	Total
Gross Roof Area [m2]	110.58
Skylight Area [m2]	0.00
Skylight-Roof Ratio [%]	0.00

PERFORMANCE

Zone Summary

	Area [m2]	Conditioned (Y/N)	Part of Total Floor Area (Y/N)	Volume [m3]	Multipliers	Gross Wall Area [m2]	Window Glass Area [m2]	Lighting [W/m2]	People [m2 per person]	Plug and Process [W/m2]
137538	2.51	Yes	Yes	8.14	14.00	13.65	0.42	2.5000	2.71	8.0000
137545	13.61	Yes	Yes	44.23	14.00	21.68	3.46	2.5000	6.99	9.2000
137555	0.70	No	Yes	2.28	14.00	13.69	0.00	0.0000		0.0000
137562	10.03	Yes	Yes	32.60	14.00	11.43	3.52	3.6000	5.12	9.0000
137572	10.63	No	Yes	34.56	14.00	11.79	0.00	0.0000		0.0000
137586	2.95	Yes	Yes	9.59	14.00	9.94	0.27	2.5000	3.10	15.0000
137595	1.11	No	Yes	3.59	14.00	0.00	0.00	0.0000		0.0000
137602	1.11	No	Yes	3.59	14.00	0.00	0.00	0.0000		0.0000

137609	9.90	Yes	Yes	32.18	14.00	11.30	3.52	2.5000	5.05	9.2000
137618	2.67	Yes	Yes	8.68	14.00	9.82	0.27	2.5000	2.82	15.0000
137626	6.98	Yes	Yes	22.70	14.00	7.35	2.06	2.5000	7.11	73.0000
137633	7.20	Yes	Yes	23.40	14.00	7.35	0.00	2.5000	1.83	1.0000
137641	20.59	Yes	Yes	66.93	14.00	49.01	3.33	2.5000	5.35	4.2000
139218	2.51	Yes	Yes	8.14	1.00	13.65	0.42	2.5000	2.71	8.0000
139225	13.61	Yes	Yes	44.23	1.00	21.68	3.46	2.5000	6.99	9.2000
139235	0.70	No	Yes	2.28	1.00	13.69	0.00	0.0000		0.0000
139242	10.03	Yes	Yes	32.60	1.00	11.43	3.52	3.6000	5.12	9.0000
139252	10.63	No	Yes	34.56	1.00	11.79	0.00	0.0000		0.0000
139266	2.95	Yes	Yes	9.59	1.00	9.94	0.27	2.5000	3.10	15.0000
139275	1.11	No	Yes	3.59	1.00	0.00	0.00	0.0000		0.0000
139282	1.11	No	Yes	3.59	1.00	0.00	0.00	0.0000		0.0000
139289	9.90	Yes	Yes	32.18	1.00	11.30	3.52	2.5000	5.05	9.2000
139298	2.67	Yes	Yes	8.68	1.00	9.82	0.27	2.5000	2.82	15.0000
139306	6.98	Yes	Yes	22.70	1.00	7.35	2.06	2.5000	7.11	73.0000
139313	7.20	Yes	Yes	23.40	1.00	7.35	0.00	2.5000	1.83	1.0000
139321	20.59	Yes	Yes	66.93	1.00	49.01	3.33	2.5000	5.35	4.2000
139403	2.51	Yes	Yes	8.39	1.00	13.65	0.42	2.5000	2.71	8.0000
139410	13.61	Yes	Yes	45.59	1.00	21.68	3.46	2.5000	6.99	9.2000
139420	0.70	No	Yes	2.35	1.00	13.69	0.00	0.0000		0.0000
139427	10.03	Yes	Yes	33.61	1.00	11.43	3.52	3.6000	5.12	9.0000
139437	10.63	No	Yes	35.63	1.00	11.79	0.00	0.0000		0.0000
139451	2.95	Yes	Yes	9.89	1.00	9.94	0.27	2.5000	3.10	15.0000
139460	1.11	No	Yes	3.70	1.00	0.00	0.00	0.0000		0.0000
139467	1.11	No	Yes	3.70	1.00	0.00	0.00	0.0000		0.0000
139474	9.90	Yes	Yes	33.17	1.00	11.30	3.52	2.5000	5.05	9.2000
139483	2.67	Yes	Yes	8.95	1.00	9.82	0.27	2.5000	2.82	15.0000
139491	6.98	Yes	Yes	23.40	1.00	7.35	2.06	2.5000	7.11	73.0000
139498	7.20	Yes	Yes	24.12	1.00	7.35	0.00	2.5000	1.83	1.0000
139506	20.59	Yes	Yes	68.99	1.00	49.01	3.33	2.5000	5.35	4.2000
Total	1439.94			4688.79		2671.96	269.45	2.2463	5.16	11.2733
Conditioned Total	1223.18			3982.99		2264.29	269.45	2.6443	4.38	13.2710
Unconditioned Total	216.75			705.80		407.67	0.00	0.0000		0.0000
Not Part of Total	0.00			0.00		0.00	0.00			

Report: **Demand End Use Components Summary**

Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

End Uses

	Electricity [W]	Natural Gas [W]	Propane [W]	District Cooling [W]	District Heating [W]	Water [m3/s]
Time of Peak	02-MAR-08:30	-	-	16-JUN-14:30	10-JAN-07:30	01-JAN-07:30
Heating	0.00	0.00	0.00	0.00	0.00	0.00
Cooling	0.00	0.00	0.00	60426.50	0.00	0.00
Interior Lighting	917.78	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	6373.16	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	3810.96	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	7290.94	0.00	0.00	60426.50	3810.96	0.00

End Uses By Subcategory

	ELECTRIC EQUIPMENT#139403#02	10.02	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139410#05	40.01	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139410#02	68.04	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139427#05	0.00	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139427#02	0.00	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139451#02	22.14	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139474#05	29.11	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139474#02	49.51	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139483#02	20.04	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139491#04	104.77	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139491#02	0.00	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139491#03	22.35	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139498#02	1.44	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139506#05	0.00	0.00	0.00	0.00	0.00	0.00
	ELECTRIC EQUIPMENT#139506#02	30.89	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	General	0.00	0.00	0.00	0.00	0.00	0.00
Fans	Ventilation (simple)	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	General	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	General	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	General	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	General	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	DHW 137538	0.00	0.00	0.00	0.00	949.90	0.00
	DHW 137586	0.00	0.00	0.00	0.00	1118.85	0.00
	DHW 137618	0.00	0.00	0.00	0.00	1265.84	0.00
	DHW 139218	0.00	0.00	0.00	0.00	67.85	0.00
	DHW 139266	0.00	0.00	0.00	0.00	79.92	0.00
	DHW 139298	0.00	0.00	0.00	0.00	90.42	0.00
	DHW 139403	0.00	0.00	0.00	0.00	67.85	0.00
	DHW 139451	0.00	0.00	0.00	0.00	79.92	0.00
	DHW 139483	0.00	0.00	0.00	0.00	90.42	0.00
Refrigeration	General	0.00	0.00	0.00	0.00	0.00	0.00
Generators	General	0.00	0.00	0.00	0.00	0.00	0.00

Report: **Climatic Data Summary** Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

SizingPeriod:DesignDay

	Maximum Dry Bulb [C]	Daily Temperature Range [deltaC]	Humidity Value	Humidity Type	Wind Speed [m/s]	Wind Direction
SUMMER DESIGN DAY IN DLF (01-01:31-12) MAY	42.20	9.60	22.70	Wetbulb [C]	0.00	0.00
WINTER DESIGN DAY IN DLF (01-01:31-12)	6.20	0.00	6.20	Wetbulb [C]	7.00	0.00

Weather Statistics File

	Value
None	

Report: **Envelope Summary** Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

Opaque Exterior

	Construction	Reflectance	U-Factor with Film [W/m2-K]	U-Factor no Film [W/m2-K]	Gross Area [m2]	Net Area [m2]	Azimuth [deg]	Tilt [deg]	Cardinal Direction
137538_WALL_4_0_0	9	0.85	0.512	0.554	75.49	75.49	225.00	90.00	W
137538_WALL_5_0_0	9	0.85	0.512	0.554	115.61	108.11	315.00	90.00	N
137545_WALL_7_0_0	9	0.85	0.512	0.554	90.28	90.28	225.00	90.00	W
137545_WALL_8_0_0	9	0.85	0.512	0.554	213.24	125.81	315.00	90.00	N
137555_WALL_2_0_0	9	0.85	0.512	0.554	165.91	165.91	45.00	90.00	E
137555_WALL_5_0_0	9	0.85	0.512	0.554	25.71	25.71	315.00	90.00	N
137562_WALL_6_0_0	9	0.85	0.512	0.554	159.95	106.39	225.00	90.00	W
137572_WALL_4_0_0	9	0.85	0.512	0.554	165.09	165.09	45.00	90.00	E
137586_WALL_2_0_0	9	0.85	0.512	0.554	77.27	77.27	45.00	90.00	E

139437_GROUNDFLOOR_0_0_2	15	0.40	2.645	4.629	6.90	6.90	135.00	180.00	
139451_WALL_2_0_0	9	0.85	0.512	0.554	5.52	5.52	45.00	90.00	E
139451_WALL_3_0_0	9	0.85	0.512	0.554	4.42	4.06	135.00	90.00	S
139451_GROUNDFLOOR_0_0_0	15	0.40	2.645	4.629	4.20	4.20	135.05	180.00	
139460_GROUNDFLOOR_0_0_0	15	0.40	2.645	4.629	1.31	1.31	135.00	180.00	
139467_GROUNDFLOOR_0_0_0	15	0.40	2.645	4.629	1.31	1.31	135.00	180.00	
139474_WALL_4_0_0	9	0.85	0.512	0.554	11.30	7.47	225.00	90.00	W
139474_GROUNDFLOOR_0_0_0	15	0.40	2.645	4.629	7.45	7.45	135.00	180.00	
139474_GROUNDFLOOR_0_0_1	15	0.40	2.645	4.629	4.08	4.08	135.00	180.00	
139483_WALL_2_0_0	9	0.85	0.512	0.554	5.40	5.40	45.00	90.00	E
139483_WALL_6_0_0	9	0.85	0.512	0.554	4.42	4.06	315.00	90.00	N
139483_GROUNDFLOOR_0_0_0	15	0.40	2.645	4.629	3.88	3.88	135.00	180.00	
139491_WALL_4_0_0	9	0.85	0.512	0.554	7.35	5.03	225.00	90.00	W
139491_GROUNDFLOOR_0_0_0	15	0.40	2.645	4.629	8.35	8.35	135.00	180.00	
139498_WALL_2_0_0	9	0.85	0.512	0.554	7.35	7.35	45.00	90.00	E
139498_GROUNDFLOOR_0_0_0	15	0.40	2.645	4.629	8.23	8.23	135.00	180.00	
139506_WALL_2_0_0	9	0.85	0.512	0.554	5.44	3.58	45.00	90.00	E
139506_WALL_3_0_0	9	0.85	0.512	0.554	22.58	22.58	135.00	90.00	S
139506_WALL_4_0_0	9	0.85	0.512	0.554	11.84	6.23	225.00	90.00	W
139506_WALL_7_0_0	9	0.85	0.512	0.554	6.40	6.40	45.00	90.00	E
139506_WALL_8_0_0	9	0.85	0.512	0.554	2.75	2.75	135.00	90.00	S
139506_GROUNDFLOOR_0_0_0	15	0.40	2.645	4.629	1.57	1.57	135.00	180.00	
139506_GROUNDFLOOR_0_0_1	15	0.40	2.645	4.629	23.82	23.82	135.00	180.00	

Exterior Fenestration

	Construction	Glass Area [m2]	Frame Area [m2]	Divider Area [m2]	Area of One Opening [m2]	Area of Multiplied Openings [m2]	Glass U-Factor [W/m2-K]	Glass SHGC	Glass Visible Transmittance	Frame Conductance [W/m2-K]	Divider Conductance [W/m2-K]	Shade Control	Parent Surfac
137538_WALL_5_0_0_0_0_WIN	1001	0.39	0.12	0.03	0.54	7.50	3.820	0.299	0.461	9.500	9.500	Yes	137538_WALL_5_0_
137545_WALL_8_0_0_1_0_1_WIN	1002	3.38	0.30	0.07	3.76	52.65	3.820	0.299	0.461	9.500	9.500	Yes	137545_WALL_8_0_
137562_WALL_6_0_0_0_0_WIN	1003	3.44	0.31	0.07	3.83	53.56	3.820	0.299	0.461	9.500	9.500	Yes	137562_WALL_6_0_
137586_WALL_3_0_0_0_0_WIN	1001	0.25	0.09	0.02	0.36	5.07	3.820	0.299	0.461	9.500	9.500	Yes	137586_WALL_3_0_
137609_WALL_4_0_0_0_0_WIN	1002	3.44	0.31	0.07	3.82	53.54	3.820	0.299	0.461	9.500	9.500	Yes	137609_WALL_4_0_
137618_WALL_6_0_0_0_0_WIN	1004	0.25	0.09	0.02	0.36	5.05	3.820	0.299	0.461	9.500	9.500	Yes	137618_WALL_6_0_
137626_WALL_4_0_0_0_0_WIN	1005	2.00	0.25	0.06	2.31	32.39	3.820	0.299	0.461	9.500	9.500	Yes	137626_WALL_4_0_
137641_WALL_4_0_0_0_0_WIN	1006	2.71	0.28	0.07	3.06	42.78	3.820	0.299	0.461	9.500	9.500	Yes	137641_WALL_4_0_
137641_WALL_4_0_0_2_0_2_WIN	1006	0.52	0.13	0.03	0.68	9.50	3.820	0.299	0.461	9.500	9.500	Yes	137641_WALL_4_0_
139218_WALL_5_0_0_0_0_WIN	1001	0.39	0.12	0.03	0.54	0.54	3.820	0.299	0.461	9.500	9.500	Yes	139218_WALL_5_0_
139225_WALL_8_0_0_1_0_1_WIN	1002	3.38	0.30	0.07	3.76	3.76	3.820	0.299	0.461	9.500	9.500	Yes	139225_WALL_8_0_
139242_WALL_6_0_0_0_0_WIN	1003	3.44	0.31	0.07	3.83	3.83	3.820	0.299	0.461	9.500	9.500	Yes	139242_WALL_6_0_
139266_WALL_3_0_0_0_0_WIN	1001	0.25	0.09	0.02	0.36	0.36	3.820	0.299	0.461	9.500	9.500	Yes	139266_WALL_3_0_
139289_WALL_4_0_0_0_0_WIN	1002	3.44	0.31	0.07	3.82	3.82	3.820	0.299	0.461	9.500	9.500	Yes	139289_WALL_4_0_
139298_WALL_6_0_0_0_0_WIN	1004	0.25	0.09	0.02	0.36	0.36	3.820	0.299	0.461	9.500	9.500	Yes	139298_WALL_6_0_
139306_WALL_4_0_0_0_0_WIN	1005	2.00	0.25	0.06	2.31	2.31	3.820	0.299	0.461	9.500	9.500	Yes	139306_WALL_4_0_
139321_WALL_4_0_0_0_0_WIN	1006	2.71	0.28	0.07	3.06	3.06	3.820	0.299	0.461	9.500	9.500	Yes	139321_WALL_4_0_
139321_WALL_4_0_0_2_0_2_WIN	1006	0.52	0.13	0.03	0.68	0.68	3.820	0.299	0.461	9.500	9.500	Yes	139321_WALL_4_0_
139403_WALL_5_0_0_0_0_WIN	1001	0.39	0.12	0.03	0.54	0.54	3.820	0.299	0.461	9.500	9.500	Yes	139403_WALL_5_0_
139410_WALL_8_0_0_1_0_1_WIN	1002	3.38	0.30	0.07	3.76	3.76	3.820	0.299	0.461	9.500	9.500	Yes	139410_WALL_8_0_
139427_WALL_6_0_0_0_0_WIN	1003	3.44	0.31	0.07	3.83	3.83	3.820	0.299	0.461	9.500	9.500	Yes	139427_WALL_6_0_
139451_WALL_3_0_0_0_0_WIN	1001	0.25	0.09	0.02	0.36	0.36	3.820	0.299	0.461	9.500	9.500	Yes	139451_WALL_3_0_
139474_WALL_4_0_0_0_0_WIN	1002	3.44	0.31	0.07	3.82	3.82	3.820	0.299	0.461	9.500	9.500	Yes	139474_WALL_4_0_
139483_WALL_6_0_0_0_0_WIN	1004	0.25	0.09	0.02	0.36	0.36	3.820	0.299	0.461	9.500	9.500	Yes	139483_WALL_6_0_
139491_WALL_4_0_0_0_0_WIN	1005	2.00	0.25	0.06	2.31	2.31	3.820	0.299	0.461	9.500	9.500	Yes	139491_WALL_4_0_
139506_WALL_4_0_0_0_0_WIN	1006	2.71	0.28	0.07	3.06	3.06	3.820	0.299	0.461	9.500	9.500	Yes	139506_WALL_4_0_
139506_WALL_4_0_0_2_0_2_WIN	1006	0.52	0.13	0.03	0.68	0.68	3.820	0.299	0.461	9.500	9.500	Yes	139506_WALL_4_0_
Total or Average						299.46	3.820	0.299	0.461				
North Total or Average						5.77	3.820	0.299	0.461				
Non-North Total or Average						293.69	3.820	0.299	0.461				

Interior Fenestration

	Construction	Area of One Opening [m2]	Area of Openings [m2]	Glass U-Factor [W/m2-K]	Glass SHGC	Glass Visible Transmittance	Parent Surface
Total or Average			0.00	-	-	-	

DX Heating Coils

	DX Heating Coil Type	High Temperature Heating (net) Rating Capacity [W]	Low Temperature Heating (net) Rating Capacity [W]	HSPF [Btu/W-h]	Region Number
None					

Heating Coils

	Type	Design Coil Load [W]	Nominal Total Capacity [W]	Nominal Efficiency [W/W]
None				

Fans

	Type	Total Efficiency [W/W]	Delta Pressure [pa]	Max Air Flow Rate [m3/s]	Rated Electric Power [W]	Rated Power Per Max Air Flow Rate [W-s/m3]	Motor Heat In Air Fraction	End Use
None								

Pumps

	Type	Control	Head [pa]	Water Flow [m3/s]	Electric Power [W]	Power Per Water Flow Rate [W-s/m3]	Motor Efficiency [W/W]
None							

Service Water Heating

	Type	Storage Volume [m3]	Input [W]	Thermal Efficiency [W/W]	Recovery Efficiency [W/W]	Energy Factor
None						

Report: **HVAC Sizing Summary** Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

Zone Sensible Cooling

	Calculated Design Load [W]	User Design Load [W]	User Design Load per Area [W/m2]	Calculated Design Air Flow [m3/s]	User Design Air Flow [m3/s]	Design Day Name	Date/Time Of Peak {TIMESTAMP}	Thermostat Setpoint Temperature at Peak Load [C]	Indoor Temperature at Peak Load [C]	Indoor Humidity Ratio at Peak Load [kgWater/kgAir]	Outdoor Temperature at Peak Load [C]	Outdoor Humidity Ratio at Peak Load [kgWater/kgAir]	Minimum Outdoor Air Flow Rate [m3/s]	H G R fr DO [
137538	0.00	0.00	0.00	0.000	0.129	SUMMER DESIGN DAY IN DLF (01-01:31-12) MAY		30.82	0.00	0.00000	42.20	0.00977	0.129	0
137545	14761.48	16975.71	1247.44	0.842	0.969	SUMMER DESIGN DAY IN DLF (01-01:31-12) MAY	5/15 16:00:00	26.00	26.00	0.00866	41.62	0.00977	0.000	0
137562	11969.52	13764.95	1372.13	0.714	0.821	SUMMER DESIGN DAY IN DLF (01-01:31-12) MAY	5/15 16:00:00	26.00	26.00	0.00822	41.62	0.00977	0.000	0
137586	0.00	0.00	0.00	0.000	0.133	SUMMER DESIGN DAY IN DLF (01-01:31-12) MAY		30.73	0.00	0.00000	42.20	0.00977	0.133	0
137609	12560.71	14444.81	1458.75	0.722	0.830	SUMMER DESIGN DAY IN DLF (01-01:31-12) MAY	5/15 16:00:00	26.00	26.01	0.00869	41.62	0.00977	0.000	0
137618	0.00	0.00	0.00	0.000	0.133	SUMMER DESIGN DAY IN DLF (01-01:31-12) MAY		30.32	0.00	0.00000	42.20	0.00977	0.133	0
137626	0.00	0.00	0.00	0.000	0.344	SUMMER DESIGN DAY IN DLF (01-01:31-12) MAY		31.66	0.00	0.00000	42.20	0.00977	0.344	0
137633	2390.14	2748.66	381.77	0.121	0.139	SUMMER DESIGN DAY IN DLF (01-	5/15 21:00:00	28.00	28.00	0.01036	36.54	0.00977	0.000	0

139451	0.00	0.00	0.00	0.000	0.010	WINTER DESIGN DAY IN DLF (01-01:31-12)		0.00	0.00	0.00000	6.20	0.00603	0.010	0.0
139483	0.00	0.00	0.00	0.000	0.009	WINTER DESIGN DAY IN DLF (01-01:31-12)		0.00	0.00	0.00000	6.20	0.00603	0.009	0.0
139491	0.00	0.00	0.00	0.000	0.025	WINTER DESIGN DAY IN DLF (01-01:31-12)		0.00	0.00	0.00000	6.20	0.00603	0.025	0.0

The Design Load is the zone sensible load only. It does not include any system effects or ventilation loads.

System Design Air Flow Rates

	Calculated cooling [m3/s]	User cooling [m3/s]	Calculated heating [m3/s]	User heating [m3/s]
None				

Plant Loop Coincident Design Fluid Flow Rate Adjustments

	Previous Design Volume Flow Rate [m3/s]	Algorithm Volume Flow Rate [m3/s]	Coincident Design Volume Flow Rate [m3/s]	Coincident Size Adjusted	Peak Sizing Period Name	Peak Day into Period {TIMESTAMP}[day]	Peak Hour Of Day {TIMESTAMP}[hr]	Peak Step Start Minute {TIMESTAMP}[min]
None								

Report: **System Summary** Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

Economizer

	High Limit Shutoff Control	Minimum Outdoor Air [m3/s]	Maximum Outdoor Air [m3/s]	Return Air Temp Limit	Return Air Enthalpy Limit	Outdoor Air Temperature Limit [C]	Outdoor Air Enthalpy Limit [C]
None							

Demand Controlled Ventilation using Controller:MechanicalVentilation

	Controller:MechanicalVentilation Name	Outdoor Air Per Person [m3/s-person]	Outdoor Air Per Area [m3/s-m2]	Air Distribution Effectiveness in Cooling Mode	Air Distribution Effectiveness in Heating Mode	Air Distribution Effectiveness Schedule
None						

Time Not Comfortable Based on Simple ASHRAE 55-2004

	Winter Clothes [hr]	Summer Clothes [hr]	Summer or Winter Clothes [hr]
137538	604.00	653.00	548.00
137545	3167.50	2981.00	2458.50
137562	4094.00	3593.00	2706.00
137586	599.00	666.50	552.00
137609	2959.50	2840.50	2112.50
137618	380.50	431.50	351.00
137626	2396.50	2656.50	2183.50
137633	877.00	984.50	794.50
137641	2463.00	2251.00	1839.00
139218	620.00	648.50	559.50
139225	3258.00	3211.50	2738.50
139242	4241.50	4106.00	3311.00
139266	614.50	658.50	565.00
139289	3073.50	3180.50	2540.00
139298	388.00	431.00	359.50
139306	2449.50	2659.50	2231.50
139313	909.50	974.00	823.00
139321	2517.50	2429.50	2063.00
139403	575.00	682.00	540.00
139410	3051.00	3357.50	2670.00
139427	3880.00	4378.00	3230.00
139451	579.50	695.00	555.50

Report: **Outdoor Air Summary**

Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

Average Outdoor Air During Occupied Hours

	Average Number of Occupants	Nominal Number of Occupants	Zone Volume [m3]	Mechanical Ventilation [ach]	Infiltration [ach]	AFN Infiltration [ach]	Simple Ventilation [ach]
137538	0.58	0.92	8.14	2.591	0.251	0.000	0.026
137545	1.87	1.95	44.23	0.000	0.252	0.000	0.172
137562	1.76	1.96	32.60	0.000	0.252	0.000	0.375
137586	0.59	0.95	9.59	2.261	0.251	0.000	0.006
137609	1.88	1.96	32.18	0.000	0.252	0.000	0.506
137618	0.42	0.95	8.68	3.310	0.251	0.000	0.003
137626	0.71	0.98	22.70	2.079	0.250	0.000	0.352
137633	1.57	3.93	23.40	0.000	0.250	0.000	0.391
137641	3.61	3.85	66.93	0.000	0.249	0.000	0.087
139218	0.58	0.92	8.14	2.594	0.251	0.000	0.044
139225	1.87	1.95	44.23	0.000	0.252	0.000	0.183
139242	1.76	1.96	32.60	0.000	0.252	0.000	0.405
139266	0.59	0.95	9.59	2.265	0.251	0.000	0.021
139289	1.88	1.96	32.18	0.000	0.253	0.000	0.538
139298	0.42	0.95	8.68	3.315	0.252	0.000	0.007
139306	0.71	0.98	22.70	2.082	0.251	0.000	0.356
139313	1.57	3.93	23.40	0.000	0.250	0.000	0.521
139321	3.61	3.85	66.93	0.000	0.249	0.000	0.101
139403	0.58	0.92	8.39	2.501	0.250	0.000	0.000
139410	1.87	1.95	45.59	0.000	0.251	0.000	0.101
139427	1.76	1.96	33.61	0.000	0.251	0.000	0.196
139451	0.59	0.95	9.89	2.183	0.250	0.000	0.000
139474	1.88	1.96	33.17	0.000	0.252	0.000	0.321
139483	0.42	0.95	8.95	3.195	0.250	0.000	0.000
139491	0.71	0.98	23.40	2.008	0.249	0.000	0.103
139498	1.57	3.93	24.12	0.000	0.248	0.000	0.089
139506	3.61	3.85	68.99	0.000	0.248	0.000	0.029

Values shown for a single zone without multipliers

Minimum Outdoor Air During Occupied Hours

	Average Number of Occupants	Nominal Number of Occupants	Zone Volume [m3]	Mechanical Ventilation [ach]	Infiltration [ach]	AFN Infiltration [ach]	Simple Ventilation [ach]
137538	0.58	0.92	8.14	0.981	0.011	0.000	0.000
137545	1.87	1.95	44.23	0.000	0.007	0.000	0.000
137562	1.76	1.96	32.60	0.000	0.007	0.000	0.000
137586	0.59	0.95	9.59	0.856	0.011	0.000	0.000
137609	1.88	1.96	32.18	0.000	0.007	0.000	0.000
137618	0.42	0.95	8.68	0.942	0.011	0.000	0.000
137626	0.71	0.98	22.70	0.000	0.008	0.000	0.000
137633	1.57	3.93	23.40	0.000	0.008	0.000	0.000
137641	3.61	3.85	66.93	0.000	0.008	0.000	0.000
139218	0.58	0.92	8.14	0.980	0.011	0.000	0.000
139225	1.87	1.95	44.23	0.000	0.007	0.000	0.000
139242	1.76	1.96	32.60	0.000	0.007	0.000	0.000
139266	0.59	0.95	9.59	0.855	0.011	0.000	0.000
139289	1.88	1.96	32.18	0.000	0.007	0.000	0.000
139298	0.42	0.95	8.68	0.941	0.011	0.000	0.000
139306	0.71	0.98	22.70	0.000	0.008	0.000	0.000
139313	1.57	3.93	23.40	0.000	0.008	0.000	0.000
139321	3.61	3.85	66.93	0.000	0.008	0.000	0.000
139403	0.58	0.92	8.39	0.953	0.011	0.000	0.000
139410	1.87	1.95	45.59	0.000	0.007	0.000	0.000
139427	1.76	1.96	33.61	0.000	0.007	0.000	0.000
139451	0.59	0.95	9.89	0.832	0.011	0.000	0.000
139474	1.88	1.96	33.17	0.000	0.007	0.000	0.000
139483	0.42	0.95	8.95	0.915	0.011	0.000	0.000
139491	0.71	0.98	23.40	0.000	0.008	0.000	0.000
139498	1.57	3.93	24.12	0.000	0.008	0.000	0.000

139506	3.61	3.85	68.99	0.000	0.008	0.000	0.000

Values shown for a single zone without multipliers

Report: **Object Count Summary** Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

Surfaces by Class

	Total	Outdoors
Wall	180	60
Floor	54	18
Roof	54	18
Internal Mass	0	0
Building Detached Shading	630	630
Fixed Detached Shading	0	0
Window	27	27
Door	51	9
Glass Door	0	0
Shading	0	0
Overhang	0	0
Fin	0	0
Tubular Daylighting Device Dome	0	0
Tubular Daylighting Device Diffuser	0	0

HVAC

	Count
HVAC Air Loops	0
Conditioned Zones	27
Unconditioned Zones	12
Supply Plenums	0
Return Plenums	0

Input Fields

	Count
IDF Objects	6578
Defaulted Fields	392
Fields with Defaults	12301
Autosized Fields	42
Autosizable Fields	108
Autocalculated Fields	210
Autocalculatable Fields	1203

Report: **Sensible Heat Gain Summary** Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

Annual Building Sensible Heat Gain Components

	HVAC Zone Eq & Other Sensible Air Heating [GJ]	HVAC Zone Eq & Other Sensible Air Cooling [GJ]	HVAC Terminal Unit Sensible Air Heating [GJ]	HVAC Terminal Unit Sensible Air Cooling [GJ]	HVAC Input Heated Surface Heating [GJ]	HVAC Input Cooled Surface Cooling [GJ]	People Sensible Heat Addition [GJ]	Lights Sensible Heat Addition [GJ]	Equipment Sensible Heat Addition [GJ]	Window Heat Addition [GJ]	Interzone Air Transfer Heat Addition [GJ]	Infiltration Heat Addition [GJ]	Opaque Surface Conduction and Other Heat Addition [GJ]	Equipment Sensible Heat Removal [GJ]	Window Heat Removal [GJ]	Interzone Air Transfer Heat Removal [GJ]
137538	0.169	-0.651	0.000	0.000	0.000	0.000	1.320	0.144	0.329	2.847	0.000	0.591	0.000	0.000	-1.013	0.000
137545	0.000	-24.910	0.000	0.000	0.000	0.000	22.396	0.670	13.099	25.681	0.000	3.339	0.001	0.000	-7.875	0.000
137562	0.000	-25.824	0.000	0.000	0.000	0.000	27.102	0.867	3.224	33.800	0.000	2.476	0.003	0.000	-8.754	0.000
137586	0.194	-0.628	0.000	0.000	0.000	0.000	1.318	0.516	0.727	1.452	0.000	0.774	0.000	0.000	-0.505	0.000
137609	0.000	-21.843	0.000	0.000	0.000	0.000	22.087	0.487	9.532	33.666	0.000	2.226	0.003	0.000	-9.442	0.000
137618	0.135	-0.515	0.000	0.000	0.000	0.000	0.663	0.070	0.658	1.525	0.000	0.756	0.000	0.000	-0.481	0.000
137626	4.309	-4.522	0.000	0.000	0.000	0.000	6.341	1.446	15.081	18.467	0.000	1.099	0.001	0.000	-5.926	0.000
137633	0.000	-1.092	0.000	0.000	0.000	0.000	5.072	0.662	0.107	0.000	0.000	1.921	0.000	0.000	0.000	0.000
137641	0.000	-36.702	0.000	0.000	0.000	0.000	31.816	1.894	5.714	27.344	0.000	5.259	0.006	0.000	-8.370	0.000
139218	0.009	-0.050	0.000	0.000	0.000	0.000	0.091	0.010	0.024	0.191	0.000	0.036	0.000	0.000	-0.079	0.000
139225	0.000	-2.416	0.000	0.000	0.000	0.000	1.575	0.048	0.936	1.736	0.000	0.211	0.000	0.000	-0.598	0.000

139242	0.000	-2.507	0.000	0.000	0.000	0.000	1.912	0.062	0.230	2.335	0.000	0.161	0.000	0.000	-0.650	0.000
139266	0.009	-0.049	0.000	0.000	0.000	0.000	0.090	0.037	0.052	0.118	0.000	0.045	0.000	0.000	-0.041	0.000
139289	0.000	-2.073	0.000	0.000	0.000	0.000	1.559	0.035	0.681	2.311	0.000	0.140	0.000	0.000	-0.707	0.000
139298	0.005	-0.040	0.000	0.000	0.000	0.000	0.045	0.005	0.047	0.099	0.000	0.044	0.000	0.000	-0.040	0.000
139306	0.251	-0.350	0.000	0.000	0.000	0.000	0.432	0.103	1.077	1.264	0.000	0.063	0.000	0.000	-0.463	0.000
139313	0.000	-0.162	0.000	0.000	0.000	0.000	0.351	0.047	0.008	0.000	0.000	0.112	0.000	0.000	0.000	0.000
139321	0.000	-3.515	0.000	0.000	0.000	0.000	2.238	0.135	0.408	1.871	0.000	0.342	0.000	0.000	-0.650	0.000
139403	0.027	-0.037	0.000	0.000	0.000	0.000	0.105	0.010	0.024	0.255	0.000	0.071	0.000	0.000	-0.057	0.000
139410	0.000	-0.500	0.000	0.000	0.000	0.000	1.684	0.048	0.936	2.179	0.000	0.356	0.000	0.000	-0.460	0.000
139427	0.000	-0.502	0.000	0.000	0.000	0.000	2.017	0.062	0.230	2.741	0.000	0.251	0.000	0.000	-0.513	0.000
139451	0.033	-0.036	0.000	0.000	0.000	0.000	0.105	0.037	0.052	0.142	0.000	0.093	0.000	0.000	-0.029	0.000
139474	0.000	-0.473	0.000	0.000	0.000	0.000	1.663	0.035	0.681	2.779	0.000	0.246	0.000	0.000	-0.546	0.000
139483	0.026	-0.031	0.000	0.000	0.000	0.000	0.053	0.005	0.047	0.149	0.000	0.090	0.000	0.000	-0.028	0.000
139491	0.538	-0.251	0.000	0.000	0.000	0.000	0.522	0.103	1.077	1.548	0.000	0.153	0.000	0.000	-0.323	0.000
139498	0.000	-0.000	0.000	0.000	0.000	0.000	0.399	0.047	0.008	0.000	0.000	0.233	0.000	0.000	0.000	0.000
139506	0.000	-0.826	0.000	0.000	0.000	0.000	2.389	0.135	0.408	2.258	0.000	0.542	0.001	0.000	-0.469	0.000
137555	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.178	0.000	0.000	0.000	0.000
137572	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.154	0.000	0.000	0.000	0.000
137595	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.353	0.000	0.000	0.000	0.000
137602	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.353	0.000	0.000	0.000	0.000
139235	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000
139252	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.179	0.000	0.000	0.000	0.000
139275	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.000
139282	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.000
139420	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.000
139437	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.378	0.000	0.000	0.000	0.000
139460	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.042	0.000	0.000	0.000	0.000
139467	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.042	0.000	0.000	0.000	0.000
Total Facility	5.706	-130.509	0.000	0.000	0.000	0.000	135.344	7.721	55.395	166.759	0.000	26.379	0.016	0.000	-48.019	0.000

Peak Cooling Sensible Heat Gain Components

	Time of Peak {TIMESTAMP}	HVAC Zone Eq & Other Sensible Air Heating [W]	HVAC Zone Eq & Other Sensible Air Cooling [W]	HVAC Terminal Unit Sensible Air Heating [W]	HVAC Terminal Unit Sensible Air Cooling [W]	HVAC Input Heated Surface Heating [W]	HVAC Input Cooled Surface Cooling [W]	People Sensible Heat Addition [W]	Lights Sensible Heat Addition [W]	Equipment Sensible Heat Addition [W]	Window Heat Addition [W]	Interzone Air Transfer Heat Addition [W]	Infiltration Heat Addition [W]	Opaque Surface Conduction and Other Heat Addition [W]	Equipment Sensible Heat Removal [W]	Win Rem
137538	27-DEC-07:06	0.00	-1580.60	0.00	0.00	0.00	0.00	1173.32	87.70	140.32	0.00	0.00	0.00	460.90	0.00	-17
137545	12-JUN-22:02	0.00	-16872.55	0.00	0.00	0.00	0.00	788.91	238.15	1752.76	553.00	0.00	317.29	13222.45	0.00	
137562	09-JUN-15:02	0.00	-13404.86	0.00	0.00	0.00	0.00	1317.33	0.00	1095.47	5226.93	0.00	536.58	5228.56	0.00	
137586	27-DEC-07:06	0.00	-1574.78	0.00	0.00	0.00	0.00	1079.41	103.30	309.91	0.00	0.00	0.00	304.82	0.00	-10
137609	23-MAY-15:02	0.00	-14340.80	0.00	0.00	0.00	0.00	933.16	0.00	1100.73	4406.80	0.00	444.21	7455.91	0.00	
137618	27-DEC-07:06	0.00	-1560.28	0.00	0.00	0.00	0.00	626.63	46.75	280.50	0.00	0.00	0.00	822.71	0.00	-11
137626	09-DEC-07:08	0.00	-3762.18	0.00	0.00	0.00	0.00	1411.18	244.47	312.92	0.00	0.00	0.00	2756.69	0.00	-70
137633	09-JUN-20:02	0.00	-2848.98	0.00	0.00	0.00	0.00	1127.90	251.99	50.40	0.00	0.00	175.63	1243.06	0.00	
137641	12-JUN-13:02	0.00	-20271.07	0.00	0.00	0.00	0.00	1743.18	0.00	864.92	2580.06	0.00	835.30	14247.62	0.00	
139218	27-DEC-07:06	0.00	-111.17	0.00	0.00	0.00	0.00	84.26	6.26	10.02	0.00	0.00	0.00	30.60	0.00	-1
139225	12-JUN-22:02	0.00	-1375.48	0.00	0.00	0.00	0.00	42.70	17.01	125.20	29.08	0.00	19.27	1142.22	0.00	
139242	15-JUN-15:02	0.00	-1130.79	0.00	0.00	0.00	0.00	94.09	0.00	78.25	274.88	0.00	35.12	648.44	0.00	
139266	27-DEC-07:06	0.00	-109.55	0.00	0.00	0.00	0.00	77.10	7.38	22.14	0.00	0.00	0.00	18.61	0.00	
139289	12-JUN-22:02	0.00	-1151.61	0.00	0.00	0.00	0.00	47.26	12.38	91.10	32.47	0.00	15.46	952.95	0.00	
139298	27-DEC-07:06	0.00	-108.39	0.00	0.00	0.00	0.00	45.19	3.34	20.04	0.00	0.00	0.00	55.11	0.00	
139306	09-DEC-07:08	0.00	-268.35	0.00	0.00	0.00	0.00	100.86	17.46	22.35	0.00	0.00	0.00	196.55	0.00	-5
139313	23-MAY-20:03	0.00	-329.16	0.00	0.00	0.00	0.00	67.49	18.00	3.60	0.00	0.00	1.75	238.32	0.00	
139321	12-JUN-13:02	0.00	-1741.96	0.00	0.00	0.00	0.00	100.65	0.00	61.78	171.81	0.00	55.33	1352.40	0.00	
139403	27-DEC-07:06	0.00	-112.17	0.00	0.00	0.00	0.00	84.03	6.26	10.02	0.00	0.00	0.00	31.75	0.00	-1
139410	10-JUN-16:00	0.00	-652.41	0.00	0.00	0.00	0.00	111.79	0.00	108.05	394.56	0.00	62.77	0.00	0.00	
139427	14-APR-15:05	0.00	-531.77	0.00	0.00	0.00	0.00	98.66	0.00	78.25	353.25	0.00	22.10	0.00	0.00	
139451	27-DEC-07:06	0.00	-113.98	0.00	0.00	0.00	0.00	77.10	7.38	22.14	0.00	0.00	0.00	23.60	0.00	
139474	13-JUN-16:00	0.00	-576.10	0.00	0.00	0.00	0.00	111.07	0.00	78.62	375.11	0.00	42.03	0.00	0.00	
139483	27-DEC-07:06	0.00	-112.14	0.00	0.00	0.00	0.00	44.68	3.34	20.04	0.00	0.00	0.00	59.63	0.00	
139491	22-JAN-07:08	0.00	-257.18	0.00	0.00	0.00	0.00	108.66	17.46	22.35	0.00	0.00	0.00	176.27	0.00	-4
139498	18-JUN-20:15	0.00	-21.82	0.00	0.00	0.00	0.00	105.10	18.00	3.60	0.00	0.00	17.79	0.00	0.00	
139506	23-MAY-18:05	0.00	-716.97	0.00	0.00	0.00	0.00	186.11	0.00	61.78	103.01	0.00	51.44	314.64	0.00	

139506 IDEAL LOADS AIR	0.000000	0.043627		833.62		

User-Specified values were used. Design Size values were used if no User-Specified values were provided.

Report: **Adaptive Comfort Summary**

Table of Contents

For: **Entire Facility**

Timestamp: **2018-06-30 00:32:53**

Time Not Meeting the Adaptive Comfort Models during Occupied Hours

	ASHRAE55 90% Acceptability Limits [Hours]	ASHRAE55 80% Acceptability Limits [Hours]	CEN15251 Category I Acceptability Limits [Hours]	CEN15251 Category II Acceptability Limits [Hours]	CEN15251 Category III Acceptability Limits [Hours]
PEOPLE 137538	291.50	147.50			
PEOPLE 137545	1081.00	550.00			
PEOPLE 137555	0.00	0.00			
PEOPLE 137562	802.00	407.00			
PEOPLE 137572	0.00	0.00			
PEOPLE 137586	302.50	205.00			
PEOPLE 137595	0.00	0.00			
PEOPLE 137602	0.00	0.00			
PEOPLE 137609	562.50	192.00			
PEOPLE 137618	188.50	132.00			
PEOPLE 137626	1103.00	570.50			
PEOPLE 137633	327.50	182.50			
PEOPLE 137641	657.50	335.50			
PEOPLE 139218	348.50	198.50			
PEOPLE 139225	1236.50	643.50			
PEOPLE 139235	0.00	0.00			
PEOPLE 139242	1016.50	520.50			
PEOPLE 139252	0.00	0.00			
PEOPLE 139266	363.50	260.50			
PEOPLE 139275	0.00	0.00			
PEOPLE 139282	0.00	0.00			
PEOPLE 139289	785.00	286.50			
PEOPLE 139298	226.50	160.00			
PEOPLE 139306	1513.00	845.00			
PEOPLE 139313	406.00	221.50			
PEOPLE 139321	803.00	427.00			
PEOPLE 139403	291.50	202.00			
PEOPLE 139410	1292.00	830.00			
PEOPLE 139420	0.00	0.00			
PEOPLE 139427	1407.00	694.50			
PEOPLE 139437	0.00	0.00			
PEOPLE 139451	386.00	240.50			
PEOPLE 139460	0.00	0.00			

Baseline Activity Schedule for Children Bedroom Residential Buildings

SN	Description	0 to :	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to	8 to	9 to 1	10 to 1	11 to	12 to	13 to	14 to	15 to	16 to	17 to	18 to	19 to	20 to	21 to	22 to	23 to
Children bed room Weekday																									
1	occupancy	1	1	1	1	1	1	0.5								1	1					0.7	0.7	1	1
2	lighting						0.25	1	0.7										0.5	0.7	1	1	1	0.5	
3	equipment															0.7	0.7				0.5	0.5	0.5	0.5	
4	HVAC cooling	1	1	1	1											1	1				0.7	0.7	0.7	1	1
5	Ceiling Fan	1	1	1	1											1	1				1	1	1	1	1
6	HVAC HEATING	0.5	0.5																			0.5	0.5	0.5	0.5
7	Window opening schedule Everyday						1	1	1												1				
8	Window opening schedule Everyday	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	1	1				0.5	0.5	0.5	0.5	1	1	0.5	0.5	0.5	0.5
9	Task Light							1												0.5	0.5	1	1	0.5	
10	Window Shade Winter																								
	Window Shade Summer	1	1	1	1	1				1	1	1	1	1	1	1	1	1	1	1		1	1	1	1
Children bed room Weekend																									
1	occupancy	1	1	1	1	1	1	1	0.5	0.5	0.5				0.5	0.5	1					1	1	1	1
2	lighting								0.5	0.5									1	1	1	1	1	0.5	
3	equipment										0.7			0.7	0.7	0.7	0.7				0.5	0.5	0.5	0.5	
4	HVAC cooling	1	1	1	1					0.5	0.5				0.5	0.5	1			1	1	1	1	1	1
5	Ceiling Fan	1	1	1	1	1	1	1	1	0.5	0.5				0.5	0.5	1			1	1	1	1	1	1
6	HVAC HEATING																								
7	Window opening schedule Everyday Summer						1	1	1												1				
8	Task Light							1												0.5	0.5	0.5	1	0.5	
9	Window Shade Winter	1	1	1	1	1	1												1	1	1	1	1	1	1
10	Window Shade Summer	1	1	1	1	1				1	1	1	1	1	1	1	1	1	1	1		1	1	1	1

APPENDIX 5

Research Papers Published In Conferences/Journals

Research Journals

1. Initiatives to Achieve Energy Efficiency for Residential Buildings in India: A Review. Review research paper. *Indoor and Built Environment*- SAGE publication. Published 13.9.2018 online eISSN: 14230070 | ISSN: 1420326X

2. A Conceptual Framework for Sustainability Indicators in Retrofitting Existing Housing. *International Journal of Architecture, Engineering and Construction*. Vol. 5, No 3, Sep. 2016, pp 148-160 , ISSN 1911-110X (print) ISSN 1911-1118 (online)

3. Computing Uncertainty in Electrical Energy Consumption in Residential Buildings. under review in *Building and Environment- The International Journal of Building Science and its Applications*- a peer reviewed international journal. ISSN: 0360-1323

4. Energy Management Plan for sustainability - A step towards smart city initiatives. *Journal of Indian Building Congress,* Vol. 23 No: 2, 2016 ISSN 2349-7475, pp 151-158

5. Optimizing Building Performance for Energy Efficiency in Cooling Buildings Sustainably. *International Journal on Emerging Technologies.* 7(1): pp 126-131(2016) ,ISSN No. (Print) : 0975-8364, ISSN No. (Online) : 2249-3255

International Conferences

6. Retrofitting Neighborhoods for Sustainable Urbanism. Research paper and poster presentation in *International conference of Sustainable Built Environment* 2017, IIT Roorkee.

7. Design Parameters for Energy Efficient Building Fabric in Residential Buildings. Conference proceedings of *International Conference on Trends in Architecture and Construction ICTAC 2017*, from 18.9.2017 at University Institute of Architecture, Chandigarh university

8. Sustainable Building Materials for Energy Efficiency in *International Conference on Urban Sustainability, Emerging Trends, Themes, Concepts and Practices* from 16.3.18 to 18.3.18 at MNIT, Jaipur.

APPENDIX 6

Workshops / Conferences / Training Programs attended

1. *Built Environment Sustainability and Quality of Life*. 11.9.2017 to 15.9.2017. Global Initiatives for Academic Networks (GIAN) . DCRUST, Murthal.
2. *Thoughtful Cooling – a workshop for architects to incorporate Sustainable Cooling & Building Energy Modeling* on Design builder Software. 20.1.17 to 22.1.17. Indo Swiss Fair conditioning program The State Of Geneva, Switzerland and The Oak Foundation. New Delhi.
3. Training and capacity building program on *Energy Conservation Building Code* on 7.3.17, HAREDA and Deptt of Architecture, DCRUST, Murthal
4. International Conference on Energy Efficiency in Buildings (ICEEB 2015). 17-18 December 2015 , New Delhi.
5. National Seminar *Towards Building Smart & Sustainable Infrastructure in Urban Development.* 6.10.2016- 7.10.2016. Indian Buildings Congress, Delhi
6. FDP on *Current Trends in Heating, Ventilation, Air conditioning and Refrigeration Engineering* held at DCRUST, Murthal from 8.2.2016-12.2. 2016
7. Workshop on *Computational Field* Dynamics CFD for Airflow Modelling in Buildings on 22.1.2016, organized by Deptt of Architecture, DCRUST, Murthal.
8. FDP *Multi-criteria Decision Making Methods and Analysis*. 9.9.2016 to 13.9.2016 . Department of Mechanical Engg, Murthal, Haryana .
9. STC from *Energy Conservation in Buildings and HVAC Systems*. 6.6.16 to 13.6.16 . IIT, Delhi
10. Workshop *Hands on workshop on Building Energy Simulation Softwares and Integrated building design approach,* trained on e quest, designbuilder and ecotect softwares for energy modelling. 1.5.2017 -5.5.2017 .Murthal
11. Workshop *Hands on workshop on Building Energy Simulation and Modelling*. 14.1.15 to 15.1.15. DCRUST, Murthal
12. *Façade Conference* on 17.2.2016 . GRIHA Council . N.Delhi.
13. International conference of **Sustainable Built Environment 2017**, IIT Roorkee
14. International Conference on *Trends in Architecture and Construction* ICTAC 2017, 18.9.2017. University Institute of Architecture, Chandigarh university.
15. International Conference on *Urban Sustainability, Emerging Trends, Themes, Concepts and Practices*.16.3.18 to 18.3.18. MNIT, Jaipur

APPENDIX 7

RESEARCH PLAN TIME FRAME

Research progress		January – June 2016						July–December 2016						January – June 2017						July – December 2017						January – June 2018					
Week duration		2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Preamble	**Coursework**																														
	Candidacy Examination																														
	State of Art Seminar (Literature review)																														
	Research Plan Defining Problem statement Defining Scope , validity, significance																														
	Hypothesis Formulation																														
	Defining Objectives																														
	Research Methodology																														
Theoretical Framework	Theoretical Sustainability parameters																														
	Rating Systems																														
	Post occupancy Evaluation																														
	Retrofitting tools and techniques																														
Research Design	Defining Study area and Sample Frame																														
	study area parameters Sampling Design Instrumentation																														
	Pilot Sample Study																														

	Formation of Questionnaire
	software for simulation
Data Collection	**Secondary Data Collection**
	Drawings / permissions
	Primary Data Collection
	a)For Energy Audit
	b)For Post occupancy evaluation
	c)Study area building envelope details
	d) Thermal comfort data loggers
	e) Conducting Interviews
	f) Interaction with experts
Data Analysi	POE data
	Data loggers data
	Calibration
	Simulation
	Synthesis and Findings, Results
Paper Publication	
Organization Draft Report	
Pre PhD Seminar	Feedback and revisions
Synopsis	
Final Report	

Bio Data

Ar. Neeti , Research Scholar

Ar**.** Neeti is a research scholar registered in Department of Architecture and Planning, Malaviya National Institute of Technology (MNIT), Jaipur. She has graduated in architecture from Government college of Architecture, Lucknow in 1997. She was awarded Masters in Architecture (Hons.) degree from D C R University in Science and Technology, Murthal, Haryana in 2011. Thereafter she joined PhD program in architecture in July 2015 as a regular candidate under supervision of Dr. Ashwani Kumar and Dr. Satish Pipralia.

She has 21 years of rich experience of professional consultancy dealing with institutional, industrial, commercial and residential projects of varying magnitudes in and around National Capital Region of Delhi. She is empanelled as an architect with Haryana Urban Development Authority (HUDA) and Haryana State Industrial and Infrastructure Development Corporation (HSIIDC). She has to her credit several government projects successfully completed.

She has been actively involved with the world of academia as visiting faculty in Department of Architecture, D C R University in Science and Technology, Murthal since 2002 and delivered several expert lectures in institutions on diverse topics. She is trained as Energy Conservation Building Code ECBC Architect and GRIHA certified professional. Her areas of interest are sustainable green buildings, green building rating systems, architectural education. She has published many research papers in international journals and conference proceedings.