Assessing the Potential of Micro Generation to Achieve Energy Sustainability in the Housing Sector

Thesis submitted by

Siddhartha Koduru

Doctor of Philosophy (Engineering)

Department of Architecture
Faculty Council of Engineering & Technology
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CERTIFICATE FROM THE SUPERVISOR

This is to certify that the thesis entitled **"Assessing the Potential of Micro Generation to Achieve Energy Sustainability in the Housing Sector"** submitted by **Sri. Siddhartha Koduru,** who got his name registered on 25 February 2011 for the award of Ph. D. (Engineering) degree of Jadavpur University is absolutely based upon his own work under the supervision of **Prof. Madhumita Roy** and that neither his thesis nor any part of the thesis has been submitted for any other academic award anywhere before.

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Acknowledgement

I take this nice opportunity to acknowledge the guidance, cooperation and help extended to me in various ways by many during the period of my work.

Words will always be inadequate to express my profound sense of gratitude to Prof. Madhumita Roy, my revered guide for her continuous encouragement, valuable suggestions, guidance and all possible help in my research and preparation of this report.

I would like to thank Ar. S.K. Midha, Former Chief Architect, Haryana; Ms. Gurmeet Kaur, Senior Town Planner, Dept. of Urban Planning, Chandigarh Administration and the local residents of Chandigarh Urban Complex some of whom are my students for the help extended to me in collecting data for my work.

I am also thankful to Prof. S.K. Roy, Advisor to West Bengal Government and Visiting Professor, Jadavpur University and Prof. R.L. Muni Chakraborty, Former Professor and Head, Dept. of Architecture and Regional Planning, IIT Kharagpur along with other members of the doctorate committee for their positive criticism and constructive suggestions at the onset and subsequent stages of my research work.

Thanks are also due to my employers during this period namely Chitkara School of Planning and Architecture, Chitkara University, Punjab and School of Architecture and Design, Manipal University Jaipur for providing a conducive environment to carry on my research.

I express my heartfelt thanks to my wife, Swati Dutta for her unconditional help, support and suggestions in completing this work.

Last but not the least; I am grateful to my *family* for providing me constant encouragement and my daughter Sukanya for being around and relieving my stress with her cheerful mood and playful activities now and then.

Above all, I owe it all to Almighty for giving me the insight, strength, patience and guidance throughout my work.

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INDEX NO. 143/11/E

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   ii. Koduru, S. and Roy, M. (2017) **Decision Tool to Define Choice of Microgeneration Retrofit for Indian Households – A Conceptual Framework**. *SPECIAL ISSUE of International Journal on Emerging Technologies (IJET)*, 8 (1), 433 – 442.

4. List of Patents: Not Applicable

5. List of Presentations in National / International Conferences / Workshops:

   iii. Koduru, S. and Roy, M. (2017) **Decision Tool to Define Choice of Microgeneration Retrofit for Indian Households – A Conceptual Framework** presented at *National Conference on Urban Environmental Management: Problems and Prospects* organized by Department of Architecture and Planning, MNIT Jaipur, 13-14 February 2017.

6. List of Abstracts (under review):

iv. Koduru, S. and Roy, M. (unpublished) **Assessment of Wind Resource in Housing Typologies: Case of Chandigarh**. Abstract sent for forthcoming issue of *Journal of Sustainable Design and Applied Research (SDAR),* Dublin Institute of Technology, Dublin.

v. Koduru, S. and Roy, M. (unpublished) **Role of Built Form in Enhancing Solar Energy Potential – Case of Chandigarh Solar City**. Abstract sent for *2nd International Conference on Energy Research and Social Science 2019*, Arizona State University, Tempe, USA.

Abstract

Urban growth has resulted in increased built up area, primarily catering to the housing sector and rising household incomes have resulted in increased energy demand of buildings. Urban areas are responsible for almost 68% to 74% of global CO_2 emissions from energy use derived by conversion of fossil fuels into electricity. With increasing demand the energy grids are unable to meet the targets leading to deficit and power outages. Decentralized energy generation systems need to be promoted within the scope of existing housing development to immediately meet the increasing energy demand and achieving global carbon emission targets.

Existing studies highlight the gap in relating the performance of Renewable Energy Sources (RES) within the context of the built environment. The present research tries to assess the micro generation potential of solar and wind resources within existing housing typologies. The research hypothesis is formulated accordingly as - *Solar and Wind Energy based Residential Hybrid Energy Mix (RHEM) model can meet 25% of existing household energy demand.*

As part of the work, industry standard computer modelling and simulation tools like ANSYS Fluent for Computational Fluid Dynamics (CFD) analysis and DIVA - a parametric daylighting tool of RHINO 3D are used to assess wind and solar energy output. This is followed by a microgrid simulation software - HOMER (Hybrid Optimization Model for Multiple Energy Resources) that is used to define the performance of a Residential Hybrid Energy Mix (RHEM) Model based on choice of RES for each housing typology.

The case study area comprises of urban areas of Union Territory of Chandigarh, Panchkula from Haryana and Mohali from Punjab collectively known as the Chandigarh Urban Complex (CUC). CUC experiences extreme climatic conditions and has high household affordability and penetration of electrical appliances. Based on comparative analysis of housing typologies of CUC four Representative Residential Units (RRUs) are identified – low rise plotted housing (detached, semi-detached and row), low rise group housing, medium rise group housing and high rise apartments.

The energy performance of each RRU is assessed on basis of household questionnaire survey and compared with simulated assessment using Energy Plus to generalize and define the energy consumption benchmark across each typology. The questionnaire survey is intended to collect information related to existing conditions of household, cooling and heating needs, internal plug load intensity and household occupancy patterns. The simulated assessment of RRUs using EnergyPlus is undertaken considering the parameters defined by IGBC, GRIHA, ASHRAE and TERI for energy efficient buildings. The validity of the model is checked by comparing the simulated energy estimate with monthly electricity bills.

The household energy assessment reveals that occupants spend most of their time in the living room and bedrooms. Also, cooling demand is the major consumer of annual electricity followed by lighting and heating demand. Comparison of different RRUs highlights that high rise residential units need not necessarily be energy intensive due to their scale, it is the case of plotted development that can impact energy performance. The survey highlights that joint families are prevalent across the low rise plotted unit which may be an advantage with respect to social structure, but can act as a deterrent to energy consumption due to behavioural issues. Also, it is understood that dissemination of information for the promotion and easy acceptance of renewable infrastructure by the home owners is necessary as only 12-14% of existing home occupants are aware of similar strategies.

The household energy benchmarking is followed by assessment of existing wind resource in CUC and its feasibility as a potential energy generating resource is measured across the housing typologies. Assessment is undertaken using both statistical and ANSYS Fluent, a Computational Fluid Dynamic (CFD) tool to visualize and understand the pattern of wind in and around buildings. The approach is conservative as the north western dominant winds have only been used as part of the assessment. The statistical process involves deriving the parameters of the Weibull function, a prominent approach to define wind speed probability. Wind flow dynamics are analysed at the scale of each typology and various locations are identified for placement of wind turbines. In addition, numerical assessments are undertaken to calculate the maximum wind energy that can be generated. With reference to observed wind speed of 2.26m/sec, CFD based analyses highlight wind speeds are accelerated to 3.25-4.85m/sec due to the different built-form configurations and commercial micro wind turbine of 1kW is able to generate energy equivalent to 118-340kWh/year based on its location across the varied housing typologies.

Solar energy as a resource restricted to retrofitting has been looked at from a new perspective of inclusion in housing with the use of parametric tools – DIVA and Grasshopper. Its maximum potential and viability considerations are investigated to derive more innovative and dynamic solutions. With an an annual average horizontal irradiance of 5.21kWh/m^2/day and physical development based on a sectoral grid it is possible to integrate solar infrastructure into the households of CUC.

On the basis of technical and simulated assessment, it is observed that out of the four different typologies, medium rise group housing with connected roofs have highest solar generation potential. The vertical high rise apartments have the inherent weakness of low roof area compared to overall built-up area thus reducing the solar output. Plotted development exhibits varied results based on their form and orientation. Some of the units overshadow others thereby influencing their contribution. The low rise group housing performs equivalent to the medium rise typology but the low width of each block results in more overshadowing in comparison to the latter thereby effecting the output.

Built form geometry and building controls have a great role to play in the enhancement of solar energy generation. In simulation models it is observed that the inclusion of 0.9m parapet wall leads to overshadowing thereby reducing effective solar area and energy generation. The study of built form and its contribution towards solar energy generation is undertaken based on the solar envelope concept defined by Prof. Ralph L. Knowles.

Finally, assessment of the availability of solar and wind resource is integrated in the framework of a Residential Hybrid Energy Mix (RHEM) Model that relates the actual energy demand of the RRUs with a mix of renewable energy choices. HOMER simulation software is used to find the optimum renewable energy infrastructure composition based on solar and wind resources along with the diesel generators as backup option. The energy mix meeting the energy demand with low Cost of Energy (COE) is considered as the most viable option.

It is observed that on an average wind and diesel based infrastructure incorporated at the site level rather than the roof consume around 10-12% of the total plot area. In similar context, Solar PV infrastructure can be installed covering 60% of roof area with remaining 40% left for essential services. Under ideal conditions the rooftop based Solar PV layout can meet up to 24-26% of actual energy demand. Various avenues like interconnected roof policy, exploiting spaces in between building blocks at higher level in case of high and medium rise housing need to be devised for enhancing the area for solar PV and wind based energy generation to generate more power.

Future avenues of the research include redefining/reframing existing building controls with the scope of promoting solar and wind based renewable energy. Further, development of a visual decision tool for the aid of home owners and architects in making decisions regarding micro generation can help in making optimum design solutions and achieve energy sustainability. Emphasis should be to relate energy based goals that can be achieved as an outcome of built form development and usage patterns rather than forcing mandatory guidelines for installation of solar infrastructure irrespective of the above considerations.

Realization of a true solar city starts from a household. As architects it is our responsibility to meet the demands of the household by ensuring all possible conservation measures and passive design inputs so that there is minimum energy demand from the households. The demand that arises should be addressed through inclusion of renewable infrastructure right from the design concept stage. For this to be achieved it is necessary to simulate the scenario and find all possible alternative solutions through the use of modern day computational tools along with the integration of our traditional knowledge and wisdom.

The study highlights that there is no clear winner or loser in case of solar and wind based renewable energy generation in the housing sector. Both the resources have their inherent advantages and disadvantages. Integrating them together in form of hybrid energy mix model can compensate each other’s shortcomings. Hybrid energy systems should be promoted in comparison to stand alone systems as they aid in ensuring energy supply in case of failure of any one of the resources.

Here it is also pertinent to mention that RES infrastructure in form of hybrid energy systems need to be implemented at neighbourhood level to maximize the gains out of renewable resources and achieve energy sustainability in the housing sector.

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Chapter 1

Introduction

1.1 Scope of Micro Generation in Housing

Urban areas are responsible for almost 68% to 74% of global CO_2 emissions from global energy use (**Seto, 2015**) derived by conversion of fossil fuels into electricity. Owing to the location of the resource and scale of the power generation the electricity grid networks are designed as vertically integrated networks with large power plants and passive household grid. The energy grids owing to increasing demand are unable to meet the targets leading to deficit and power outages. Increase in energy consumption and rise of dependency on energy imports has emphasized the need localized generation apart from efficient use of energy. If measures are not taken, lack of substantial energy infrastructure will impend the development of about 60% urban population in India by 2030 (**MoUD, 2012**).

Housing is a necessity for human survival in urban areas. It is a measures of an individual's ability, viability and determination for survival in the urban world. Urban growth has resulted in increased built up area, primarily catering to the housing sector and rising household incomes have resulted in increasing energy demand of buildings. To immediately meet the global carbon emission targets decentralized energy generation systems have to be promoted within the scope of existing housing development rather than awaiting creation of new renewable energy integrated setups (**Madlener & Sunak, 2011**).

The interaction between various elements of architectural form and their influence on overall energy behaviour individually is apparent through statistical assessment but when the need is to understand collective interaction between various aspects of built form there is a need for computational tools (**Attia et al., 2012**). Modern day computational tools can be used to simulate and understand the multi-variable interaction of energy and built form across various housing typologies and determine the consumption and generation patterns.

Analysis of the built form and energy interaction taken across various housing typologies - plotted unit, row housing, medium rise unit and high rise unit at building and neighbourhood level shall aid in understanding the potential of each typology and also defining guidelines for energy generation in future housing (**Bahaj & James, 2007**).

1.2 Background Study

Renewable energy planning and management by creating the right energy mix and bi-directional energy chain conditions (**Bandyopadhyay, 2017**) shall be the guiding criteria for a sustainable energy future across housing sector. There is a need to understand the role of small and microgeneration energy systems based on renewable energy resources at the household level and their contribution towards energy targets. The attempt is not to meet the operational energy demand but also integrating the end user into the energy management system so as to reduce energy wastage.

There are concerns associated with existing strategies from the perspective of an architect and the end user that need to be addressed. The first concern with existing strategies is that they are technical in nature but there is a need to understand the actual potential of urban level renewable resources like solar, wind and biomass considering the architectural character and built form configuration of various housing typologies (**Coles et al., 2015**). The second concern that needs investigation is the ideal conditions under which these resources either on standalone or combined hybrid mode become viable energy sources for the housing community. The third concern is related to ways of empowering the home owners in making a conscious decision about choice of renewable energy infrastructure rather than forcing them to follow a set of guidelines.

1.2.1 Urbanization and World Energy Scenario

Urban areas occupy only 2% of the total land area on earth but our cities are going through transformation and by 2050, 70% of world's population is expected to live in urban areas. Urbanization is an outcome of the economic development, leading to population growth, better economic and livelihood opportunities which result in increased resource consumption. Urban areas account for two-thirds of total global energy demand, with electricity being the primary form of energy (**Al-Juaied and Whitmore, 2009**). Better access to electricity in urban areas over traditional fuels has resulted in an increasing ownership of electrical appliances which results in increasing energy demand (**UNEP SBCI, 2009**). To meet this growing demand governments propose creation of non-renewable fuel based energy generation infrastructure, primarily coal which not only add to the financial burden on governments but also add towards global carbon-dioxide emissions (**Salat, 2009**).

Buildings form the major fabric of our urban landscape and are the major consumers of urban energy accounting to 32% of global energy consumption and also contributors towards 25% of global CO_2 emissions (**World Energy Outlook, 2016**). To reduce the energy burden of the built environment energy efficiency and conservancy measures at various levels have been proposed to ensure better energy access, reliability and security (**Jones, 1991**). With the up rise in natural, seasonal and man-made disasters the urban areas are completely shut off from basic services thereby prompting the need to promote onsite energy generation using renewable energy sources like solar, wind, hydro, biomass etc. (**Li, 2005**). A major hurdle in promotion of renewable energy systems is the guarantee in meeting energy demand and uncertainty in quantifying the payback (**WRI, 2014**).

Buildings primarily housing form 80% of total built environment and play a major role in the energy balance of urban areas. Energy security within the housing sector can help improve the quality of life by enhancing comfort and improving indoor and outdoor conditions. Various policy interventions have been made to reduce the demand side along with energy conservation at various levels of housing, but the implementation has not delivered desired results leading to energy insecurity (**Smil, 2003**). Also, user behaviour and varied age groups lead to diverse energy consumption patterns challenging energy demand predictions.

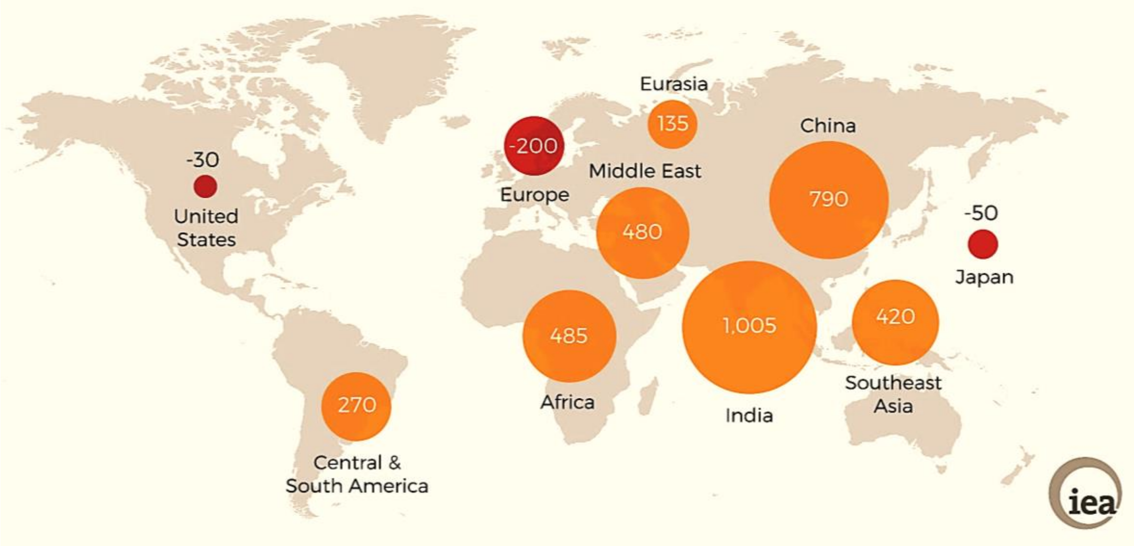


Figure 1.1: Change in Primary Energy Demand (Source: World Energy Outlook 2017)

As per International Energy Agency (**IEA, 2016**) with the aggressive implementation of renewable energy generation, and promoting energy conservancy it is possible for buildings to reduce CO_2 emissions up to a tune of 5.8 billion tonnes (Gt) by 2050 and reducing greenhouse gas emissions by up to 83% as per business-as usual scenario (**Juaied & Whitmore, 2009**). Countries and cities around the globe have committed through master plans to reduce their part of global carbon emissions.

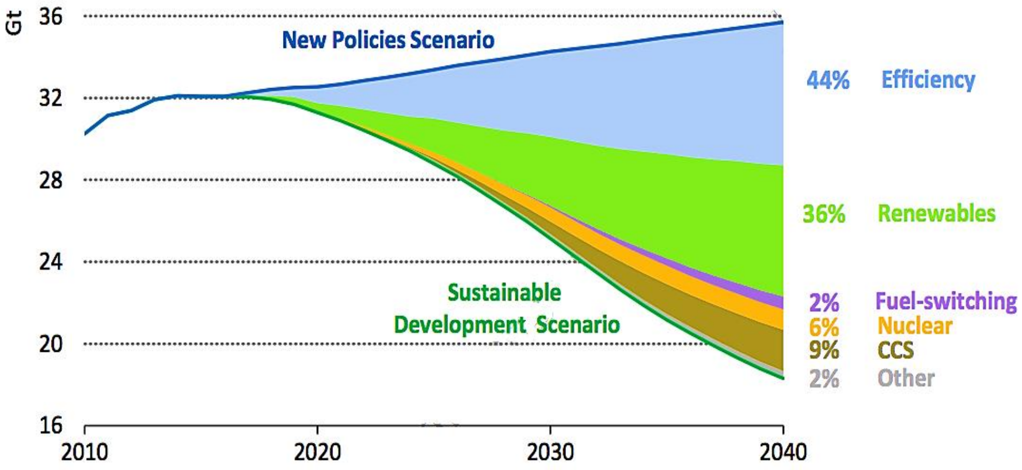


Figure 1.2: **Comparison of CO_2 emissions between Sustainable Development and New Policies Scenario** (Source: World Energy Outlook, 2017)

1.2.2 Urbanization and Energy Scenario of Urban India

India is one of the major growing economies of the world and by 2020 would be the 'World's Youngest Country' with a major portion of its population forming the workforce. India's urban population owing to economic development and better opportunities has increased from 20% in 1971 to 31% in 2011 of total national population (**Census, 2011**). At this rate by 2020 the urban population is expected to form 40% of total national population.

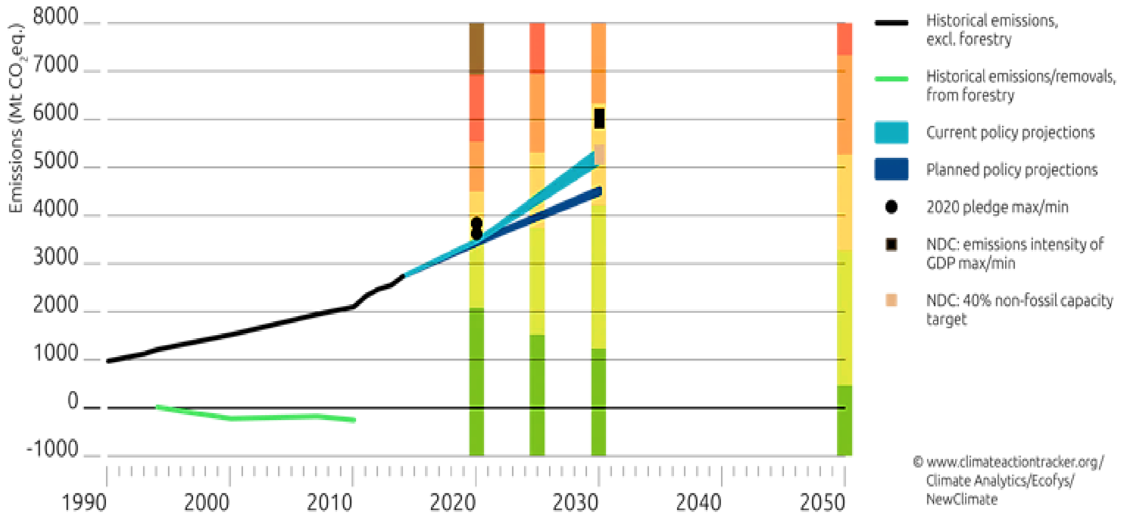


Figure 1.3: **Climatic Action Scenarios of India** (Source: Climate Action Tracker, 2017)

Electricity is the major form of energy consumed in urban areas and its generation contributes to 35.5% Carbon Emissions in India. In 2016-17 as per Central Electricity Authority (**CEA, 2015**), 80.6% of the electricity was produced by burning coal, diesel or gas in thermal power plants, 10.5% from hydro-energy projects, 3.1% from nuclear power plants and 5.8% from renewables.

India on October 02, 2016 has committed through its Nationally Determined Contribution (NDC) under the Paris Agreement to lower its carbon emissions intensity in 2030 by 33-35% of its GDP from 2005 levels and also generate 40% of its energy from non-fossil based fuels. In continuation to these commitments the Government of India has initiated the National Energy Policy which aims to ensure 175 GW renewable energy generation by 2022.

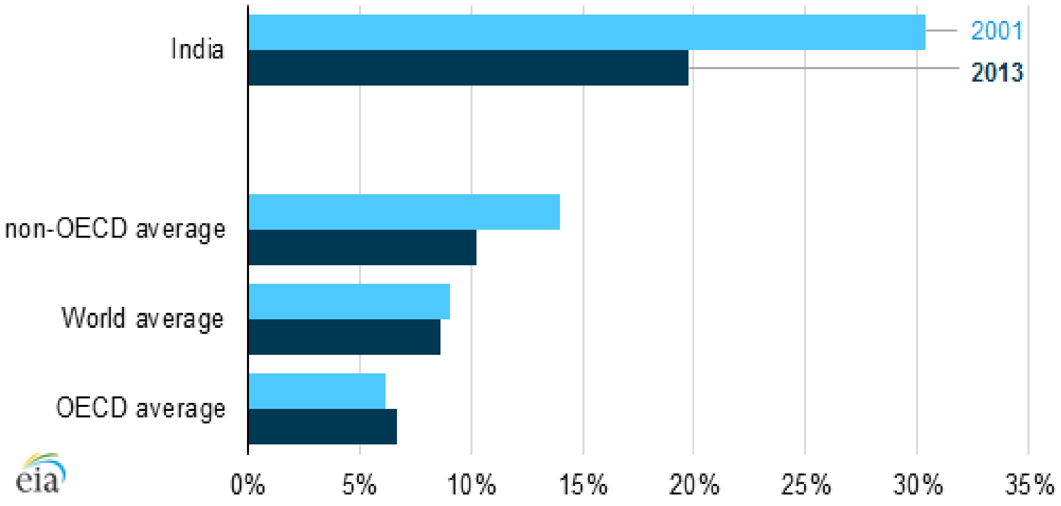


Figure 1.4: **Comparative Transmission and Distribution (T&D) Losses of India to World Economics** (Percentage of total electricity generated) (Source: EIA, 2014)

India also faces the challenge of Transmission and Distribution (T&D) losses amounting to 23% of total electricity produced at national level, which is almost three times of world average and in some Indian states it is up to 50% (**EIA, 2015**). The major reason behind T&D losses is attributed to electricity theft, faulty or tampered electricity meters and need for upgradation of transmission infrastructure. The viable option to reduce T&D losses is by avoiding electricity transmission over longer distance and control over transmission through decentralized power generation based on renewable energy sources across various sectors of the society and economy (**Bhatia & Gulati, 2004**).

If the targets envisioned by the Government of India are to be achieved it requires identifying the right set of tools and strategies across various sectors of Indian economy. One such strategy is the 'National Solar Mission' which aims to develop 'Solar Cities' across India. A total of 60 cities have been identified and Master Plans being prepared with the primary aim of promoting off-grid solar based power generation.

The Government of India has proposed various national plans and programmes as part of the NITI Aayog for overall urban development with specific measures addressing energy demand like Power for All by 2022, Housing for All by 2022, 100 Smart Cities and 175 GW of renewable energy by 2022 (**NITI AAYOG, 2017**). The attempt is to develop strategies that have co-benefits through mandatory or voluntary involvement of stakeholders or agencies and also ensure liability in meeting the desired targets. Defining measurable targets with specified timeframes and introducing a penalty mechanism have also been proposed to check in case desired goals or deadlines are not achieved.

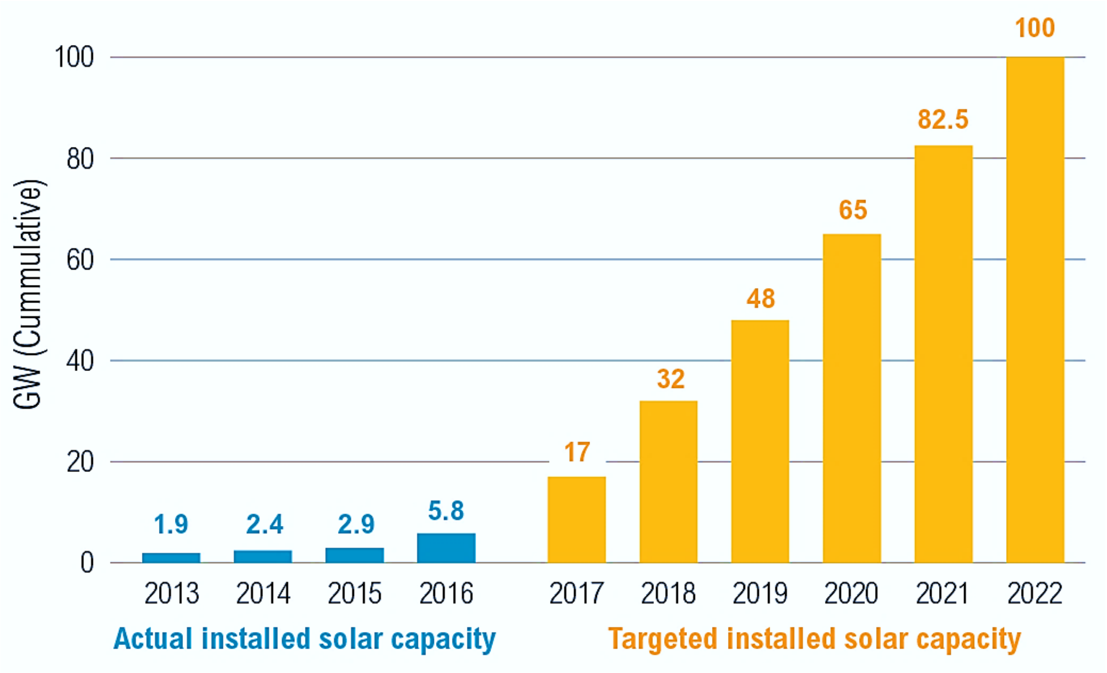


Figure 1.5: **India's Solar Goals as part of National Solar Mission**
(Source: World Resources Institute, 2016)

The National Solar Mission envisions setting of utility scale grid-connected solar parks on sites primarily deemed to be waste lands. The mission also proposes setting up 1 GW of solar power infrastructure on rooftops of government, commercial and residential buildings. This requires investigation of existing built forms and their design characteristics in meeting the requirements of the occupants and also enhancing the potential of rooftop solar infrastructure. No such initiatives have been proposed at urban level for wind based renewable energy generation.

1.2.3 Housing and Energy Demand

On the consumer side, industry and domestic sector are the primary consumers of electricity at 42.10% and 23.53% (**Prayas, 2016**). The rate of growth in electricity consumption by the industry from 2010-2015 is 26.56% whereas for domestic sector it has increased by 34.70% (**CE, 2015**). The revised Energy Conservation Building Code (ECBC) launched in 2017 defined guidelines to ensure 50% reduction of energy demand in buildings by 2030. With a major part of the housing stock yet to be built the domestic sector is going to be a key component in mitigating the goals set by India with respect to energy demand and carbon emissions. The India Energy Security Scenarios (IESS) 2047 Tool (**http://indiaenergy.gov.in/**) by the NITI Aayog envisions that by 2047 with a determined effort scenario based on higher energy efficiency and conservation measures the domestic sector energy demand shall reduce to 12.6% of total energy demand.

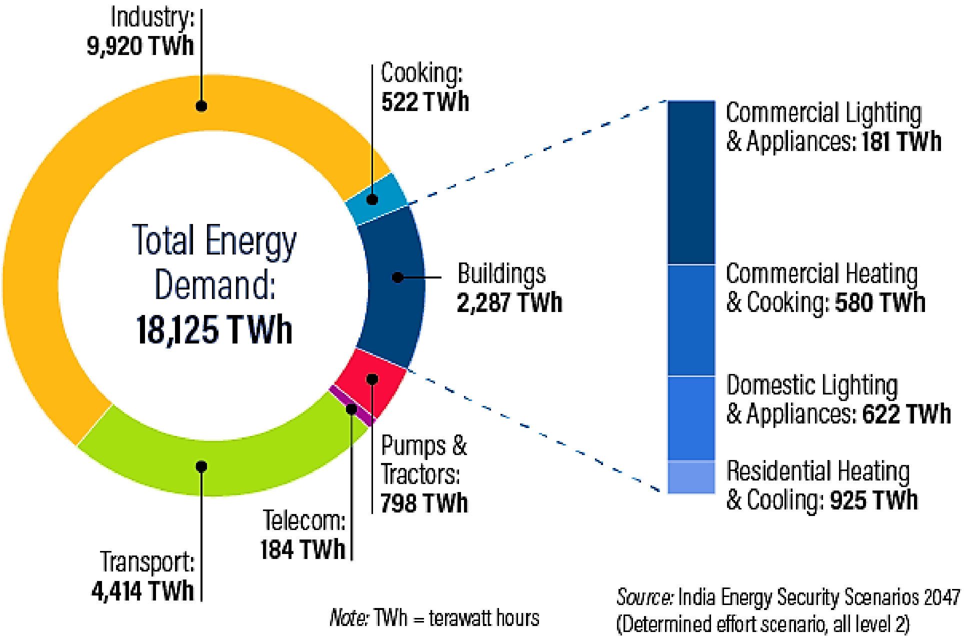


Figure 1.6: **India's Projected Energy Demand 2047**
(Source: World Resources Institute, 2016)

Domestic energy consumption is highly dependent on housing typology, location, energy consuming activities within the household, socio-demographic and economic conditions of the occupants, varying needs of multiple age groups within the house, types of electrical appliances and their efficiency, etc. Indian housing is going through major transformation in the past decade with the most notable feature being the growth in high rise medium density and high rise high density housing.

Urban and peri-urban areas have become major centers of aggressive competition between the private developers to take advantage of the situation leading to development of high rise gated housing projects promoted majorly by private developers termed as 'Integrated Gated Housing Townships'. The varied household configurations within these housing projects have opened up options for people from different economic classes and affordability levels, but without any consideration to the pressure created on both land and resources.

Though the embodied energy of a dwelling in these townships is generally lower than that of an individual household, they are intensive in the operational energy which represents a major component of energy in the total life cycle of a building. With a competitive market and price conscious consumer selling out the dwelling units is a major challenge for most of the developers.

a) Plotted / Row Housing **b) Medium Rise** **c) High Rise**

Figure 1.7: Prevalent Upcoming Housing Typologies in Urban Periphery

To attract the masses and also ensure affordability, the urban gated housing developments comprise of varied housing typologies like plotted, row housing, medium and high rise but predominantly high density in character (as indicated in figure 1.7) and; integrated with energy intensive infrastructure including lifts, fire safety systems, centralized air conditioning systems, electronic surveillance, etc. They are dependent on backup energy networks to compensate for power outages and failure of the power grid. The households are also flooded with energy intensive electrical appliances primarily split air conditioners and geysers rather than understanding the importance of more efficient centralized facilities and their integration into overall design.

To meet the ever increasing energy demand in these townships owing to already deficient power supply from the grid, backup power systems are provided and listed under Unique Selling Point

(USP). The backup systems comprise of generators which run on conventional fossil fuels like diesel. The whole setup involves huge initial investment and recurring maintenance costs, which later on influences the monthly expenditure of households in these townships. Apart from cost they contribute towards global carbon emissions.

1.3 Need of the Study

Energy access to all and energy security are key for the sustainable development of the urban areas. With growing environmental concern it is necessary to promote renewable energy systems with equal access to all. Conflicting interests and lack of a decision tool to guide the process of incorporating renewable energy infrastructure into the housing design process is one of the major cause for not achieving desired energy targets by the domestic sector.

From the perspective of an Architect the nature of existing guidelines need to be end user oriented to give strategic, customisable and situation specific solutions. Energy efficiency guidelines laid down by the Energy Conservation and Building Code (ECBC) need to be linked with ‘Micro Generation Potential’ to ensure implementation of energy generation and efficiency strategies right at the design conceptual stage. Linking energy efficiency with sustainable energy generation can ensure overall reduction in energy demand, promoting energy security, reduction in energy bills, lowering investment required to set up new energy infrastructure and overall environmental development.

Solar access in the modern day context is associated with energy, health, prosperity, quality of life and aesthetics. It also has a greater impact on the overall architectural and urban pattern of our cities. As Ralph Knowles (**Knowles, 2003**) observed that solar access is everybody’s need and right. Ensuring solar access has a direct reflection on the daylighting, heating, cooling and ventilation needs of the built environment (**Ratti et al., 2005**). It also defines the potential and output of solar renewable energy infrastructure.

With increasing density and rising building heights the concept of solar access to every household becomes a challenge. In countries like Hong Kong there are strict guidelines that permit every household a minimum of 2 hours of direct sunlight every day. It is necessary in India’s context that if we need to ensure creation of sustainable urban areas based on ‘Solar City’ concept and energy efficient neighbourhoods, architects need to play a key role in understanding these forgotten concepts and put them to application.

Architects of the new era are also expected to have design, visual and scientific skills as the profession demands an integrated design approach. Today's buildings are supposed to abide by set of development controls without compromising on user comfort, adaptability to climatic challenges and consume the least of energy resources. The impact of buildings on the environment need to be assessed and a synergy established between energy efficiency and energy generation strategies based on renewable and hybrid energy sources.

Architects need to take initiative in defining this new form of integrated design process which not only aims to meet specific design requirements and aesthetics but also integrates energy goals and renewable energy infrastructure as part of the design process. To achieve this a major change in mind set is required wherein buildings should not be considered as energy consumers, rather they should be considered as energy generators and avenues explored to integrate various renewable energy generation systems as part of the built form.

Home owners and architects are facing a lack of general awareness, technical advancements and guiding process for inclusion of alternate renewable energy sources into the built environment, which is effecting the overall investment in renewable energy infrastructure and meeting a major portion of household energy demand. Existing strategy of 'Solar Cities' involves promotion of solar based renewable energy systems with solar PV or solar thermal infrastructure getting due attention (**Mariam et al., 2013**). But, within the existing urban fabric some of the urban forms have higher solar potential over others owing to their built form, development controls and orientation.

It is necessary that alternate microgeneration strategies like wind, combined heat and power (CHP) and biomass need to be looked into as well so as to mitigate their inclusion into the domestic sector both technically and architecturally. This requires understanding the viability conditions of each of these renewable energy source and measures to enhance their microgeneration contribution at household level. Incorporating the research into a visual platform can aid architects and homeowners in decision making.

1.4 Area of Research

Promotion of microgeneration based infrastructure in the housing sector involves two major aspects – first, understanding the relationship between energy, design of buildings and neighbourhoods to define the viability conditions for each of the renewable energy sources (**Hinnells, 2009**). Second, application of microgeneration technologies on a larger scale, thereby making them efficient and economical.

The study area taken as part of the research is Chandigarh Urban Complex comprising of Union Territory of Chandigarh, Panchkula from Haryana and Mohali from Punjab. The significance of the study is also because Chandigarh is selected as a model city for the promotion of 'Solar City' concept with the goal to meet 10% of total energy demand through solar and renewable energy systems.

The research looks into the performance of solar and wind resources in the existing housing typologies and existing site layout or arrangement of units. The performance of the resource is a measure of the necessary upgradation that the typologies need to undergo thereby enhancing the existing potential. The research aims to enhance the potential of the existing solar and wind resource by understanding their performance within the context of existing housing development. Modern day computational tools have been used as part of the study to aid in the analysis of complex scenarios.

To overcome the deficit caused by a particular energy source owing to regional or climatic factors an integrated energy model 'Residential Hybrid Energy Mix (RHEM) Model' is proposed that integrates various renewable energy sources to ensure standard energy generation over the year. Simulated assessment of the performance and contribution of each energy model across various typologies and meeting a major portion of household energy demand shall be a measure of its viability.

1.5 Key Research Questions and Research Hypothesis

Assessing the promotion of microgeneration infrastructure within the context of existing housing stock can aid in meeting the growing energy demand of for the future housing stock. The assessment process would require multi-objective optimization to achieve desired results. This necessitates the use of evolutionary 'Parametric' based computing tools. The research uses 3D simulation models of different housing typologies to quantify the overall energy performance and microgeneration potential. Details about the various computing tools used as part of the research are discussed briefly in Research Methodology, Section 1.9 of Chapter 1.

Wind based microgeneration has the least environmental concerns and needs less maintenance than the solar infrastructure. Wind based energy generation within the urban context especially the housing sector is under neglect and if given the right boost can be more economical than solar based energy generation.

Research Question 1:

How do existing typologies of Chandigarh Urban Complex perform with respect to wind based microgeneration?

Wind energy has been established to be more mature and higher output generating option at global scale. Wind as a renewable energy resource at urban and building level has a great potential if its turbulent character in the urban environment could be exploited. Also, it gives architects a challenge to design buildings that are aesthetic and also take advantage of wind. The question intends to establish the role, design considerations, maximum potential and viability of wind based energy sources within the context of existing housing typologies.

Research Question 2:

How do existing typologies of Chandigarh Urban Complex perform with respect to solar based microgeneration?

Solar based microgeneration is already on the rise with a lot of input from the government and various agencies. But the existing retrofit based process of integrating solar infrastructure is aimed only to meet targets. There is no provision for the home owner to take a stand based on the actual potential of solar energy from their roof. The question seeks to find out if the existing housing typologies are capable to generate the desired energy outcome? Which typologies of Chandigarh Urban Complex are capable to meet their energy needs with basic solar infrastructure? What are the built form considerations under which solar based microgeneration is viable and can achieve maximum potential?

Research Question 3:

What would be the character of the Residential Hybrid Energy Mix (RHEM) Model? How would it aid in choosing between stand-alone and hybrid renewable energy systems for housing?

The question address the conceptual framework of inter mix model of wind and solar resource termed as Residential Hybrid Energy Mix (RHEM) Model and applicable across various housing typologies. The model is intended to ensure maximum contribution towards household energy demand by a mix of solar and wind energy systems. The overall contribution by each solar and wind energy source across various housing typologies is different. The model gives due consideration to the viability conditions under which each of the renewable energy system can contribute their maximum to energy generation. What will be the character of the model so that it can achieve maximum output?

With the Solar City concept defining a 10% energy generation based on renewable energy systems and the vision of the NITI AAYOG to reduce national domestic energy consumption to 12.6% of total energy generated by 2047. The guidelines defined by ECBC in 2017 to ensure 50% reduction in energy demand of buildings by 2030. Based on the targets the research is guided by the hypothesis:

"Solar and Wind Energy based Residential Hybrid Energy Mix (RHEM) model can meet up to 25% of existing household energy demand."

1.6 Aim and Objectives of the Study

The aim of the research is to define the viability conditions for integration of solar and wind based renewable energy systems across different housing typologies and identify measures to enhance their microgeneration potential.

The energy mix is influenced by the inherent weakness of both the solar and wind resources, like in case of solar maximum output is achieved during summers owing to the high intensity of solar radiation and clear skies whereas the contribution shall reduce during monsoons and winters due to rain, fog and cloudy conditions. To understand the performance of each of these energy sources, they are subject to assessment considering various housing typologies – plotted, row, medium rise and high rise. In some cases the assessment is undertaken at neighbourhood level. The criteria for assessment shall be based on the floor area, geometry or form and height of the housing typology. The built form of any housing typology has a direct relationship with heating and cooling needs, but the emphasis of the study is to estimate the area available on roof and wall for solar energy generation. The impact of the housing form and geometry on wind resource potential needs to be investigated. The overall goal of the research can be defined by a series of smaller aims listed below:

1) To define potential of solar and wind resource in microgeneration across various typologies
2) To establish the ideal conditions under which solar and wind based microgeneration systems are viable for each typology at household, building or neighbourhood level
3) To enhance microgeneration potential through identification of ideal energy mix using 'Residential Hybrid Energy Mix (RHEM) Model'

Each of the aims is guided by a set of objectives listed below:

1) *To define potential of solar and wind resource in microgeneration across various typologies*
    - Identification of predominant housing typologies in Chandigarh Urban Complex (CUC)
    - Establishing Household energy consumption patterns across typologies
    - Simulation of microgeneration assessment of different energy source across typologies
    - Comparison between microgeneration potential and actual energy demand
2) *To establish the ideal conditions under which solar and wind based microgeneration systems are viable for each typology at household, building or neighbourhood level*
    - Defining solar based microgeneration viability and promotion conditions across typologies
    - Defining wind based microgeneration viability and promotion conditions across typologies
    - Identifying physical interventions in built form to enhance the microgeneration potential
3) *To enhance microgeneration potential through identification of ideal energy mix using 'Residential Hybrid Energy Mix (RHEM) Model'*
    - Conceptualize the framework of 'Residential Hybrid Energy Mix (RHEM)Model'
    - Comparison of solar and wind energy resource in standalone and hybrid conditions
    - Establishing the ideal renewable energy mix to meet typology specific energy demand

1.7 Scope of Research

The primary focus of the study is to understand the relation between primary energy demand of households and measures to meet a major portion of the demand through hybrid renewable energy systems.

The study discusses scenarios specific to existing housing typologies. 3D models of different housing typologies are subjected to parametric simulation in order to assess their energy performance based on built form characteristics laid down by the National Building Code (**NBC, 2016**), Energy Conservation Building Code (**ECBC, 2017**) for heating and cooling needs.

The scope of research is limited to application of solar and wind based renewable energy system in standalone and hybrid mode within the context of the housing sector. The study focuses on the active role of solar and wind energy infrastructure and not passive utilization. Other forms of microgeneration systems - Biomass and CHP systems have not been considered as part of the study owing to their contribution towards carbon dioxide emissions and particulate matter.

Energy simulation assessment of the housing typologies is undertaken on basis of building envelope guidelines laid down as per ideal case scenario of ECBC and GRIHA. Energy conservation measures are considered to be of highest standards thereby ensuring least amount of wastage.

1.8 Limitations

The first major limitation of the study is that as part of the household energy assessment the impact of user behaviour on energy demand has not been considered as part of research. Secondly, in case of solar and wind based renewable energy assessment the influence of vegetation and trees has not been considered as part of the study. In CFD analysis the limitation on number of faces resulted in not considering trees and vegetation. In solar analysis the impact of vegetation is primarily on vertical surfaces of low rise structures as a result vegetation is not considered as part of rooftop assessment. Thirdly, the role of balconies and other projections has been negated in CFD analysis owing to complexity in geometry.

1.9 Research Methodology

The research methodology (as indicated in figure 1.8) behind the research is from the perspective of an architect and appraisal of the built form. Study of existing housing typologies is undertaken to delineate Representative Residential Units (RRUs) and their energy demand assessed through house hold survey. This was followed by creation of 3D computational models in SketchUp for analysis in EnergyPlus. The energy assessment defines the energy consumption patterns of each typology.

Statistical analysis of wind data from metrological center is undertaken to identify the most probable wind speeds. But the performance of winds in the built environment is dependent on existing built forms, so the 3D computational models are subjected to Computational Fluid Dynamics (CFD) assessment in ANSYS Fluent. Sensors are placed at defined locations to derive data of high velocity winds within the site and also define the locations of placing the wind turbines. The wind velocities derived are used to calculate the wind energy potential by integrating data of micro turbines ranging from 1 kW to 5 kW and assess the energy output. This gives us the potential of wind resources in the different typologies. Solar assessment is done using DIVA a parametric lighting tool to assess the radiation received by a surface based on the angle of inclination and distance between the surfaces. Using test model conditions the assessment of solar energy based on different inclination angles and distance between panels is undertaken. Similar assessment is done for façade based panels to identify the potential of BIPV systems. This resulted in the solar potential across typologies. The combination of both solar and wind resources into a Residential Hybrid Energy Mix (RHEM) model is undertaken in HOMER software and multiple scenarios generated to define the potential and contribution of each resource. Some of the key computational tools used as part of the study and their role are detailed below.

1.9.1 ANSYS Fluent

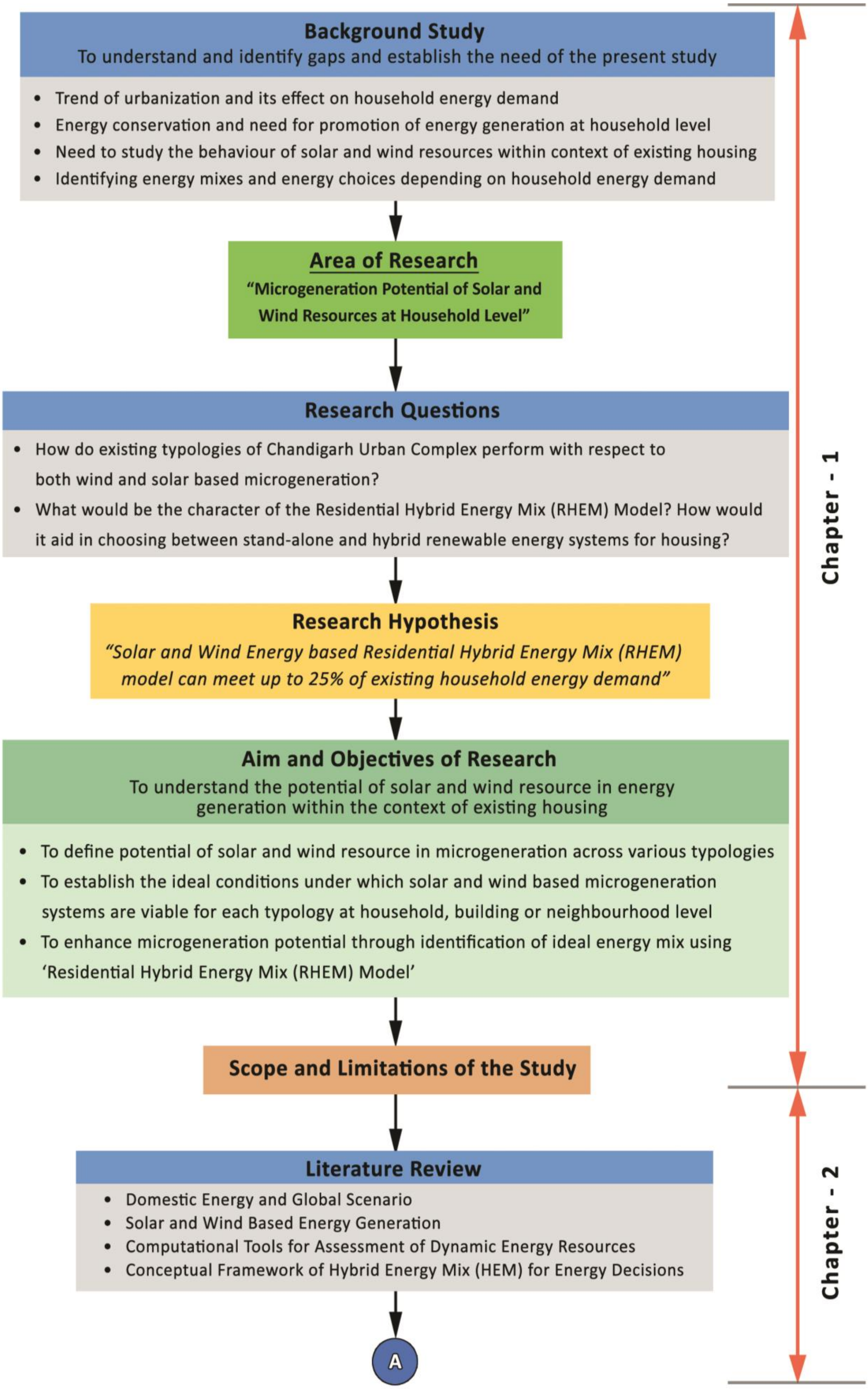
ANSYS Fluent is a CFD tool used to model flow, heat transfer, turbulence and other fluid dynamics related applications as per need ranging from aircraft design to blood flow in the body. In the study ANSYS Fluent is used to model flow of wind and study its behaviour in response to the physical development of existing housing typologies.

1.9.2 DIVA for Rhino

DIVA for Rhino is a parametric daylight and energy modelling plugin to undertake environmental performance evaluation ranging from individual buildings to urban context. In the study the plugin assesses the performance and energy output of rooftop Solar PV panels. It is also used in Grasshopper to study the shadow free area available for solar applications.

1.9.3 Grasshopper for Rhino

Grasshopper is a graphical algorithm editor integrated into the Rhino 3D modelling workspace that allows building scripting in form of visual algorithms. In the study it is used along with DIVA to study the role of Solar Envelope and assessment of rooftop and façade based Solar PV panels.



Background Study

To understand and identify gaps and establish the need of the present study

- Trend of urbanization and its effect on household energy demand
- Energy conservation and need for promotion of energy generation at household level
- Need to study the behaviour of solar and wind resources within context of existing housing
- Identifying energy mixes and energy choices depending on household energy demand

Area of Research

"Microgeneration Potential of Solar and Wind Resources at Household Level"

Research Questions

- How do existing typologies of Chandigarh Urban Complex perform with respect to both wind and solar based microgeneration?
- What would be the character of the Residential Hybrid Energy Mix (RHEM) Model? How would it aid in choosing between stand-alone and hybrid renewable energy systems for housing?

Research Hypothesis

"Solar and Wind Energy based Residential Hybrid Energy Mix (RHEM) model can meet up to 25% of existing household energy demand"

Aim and Objectives of Research

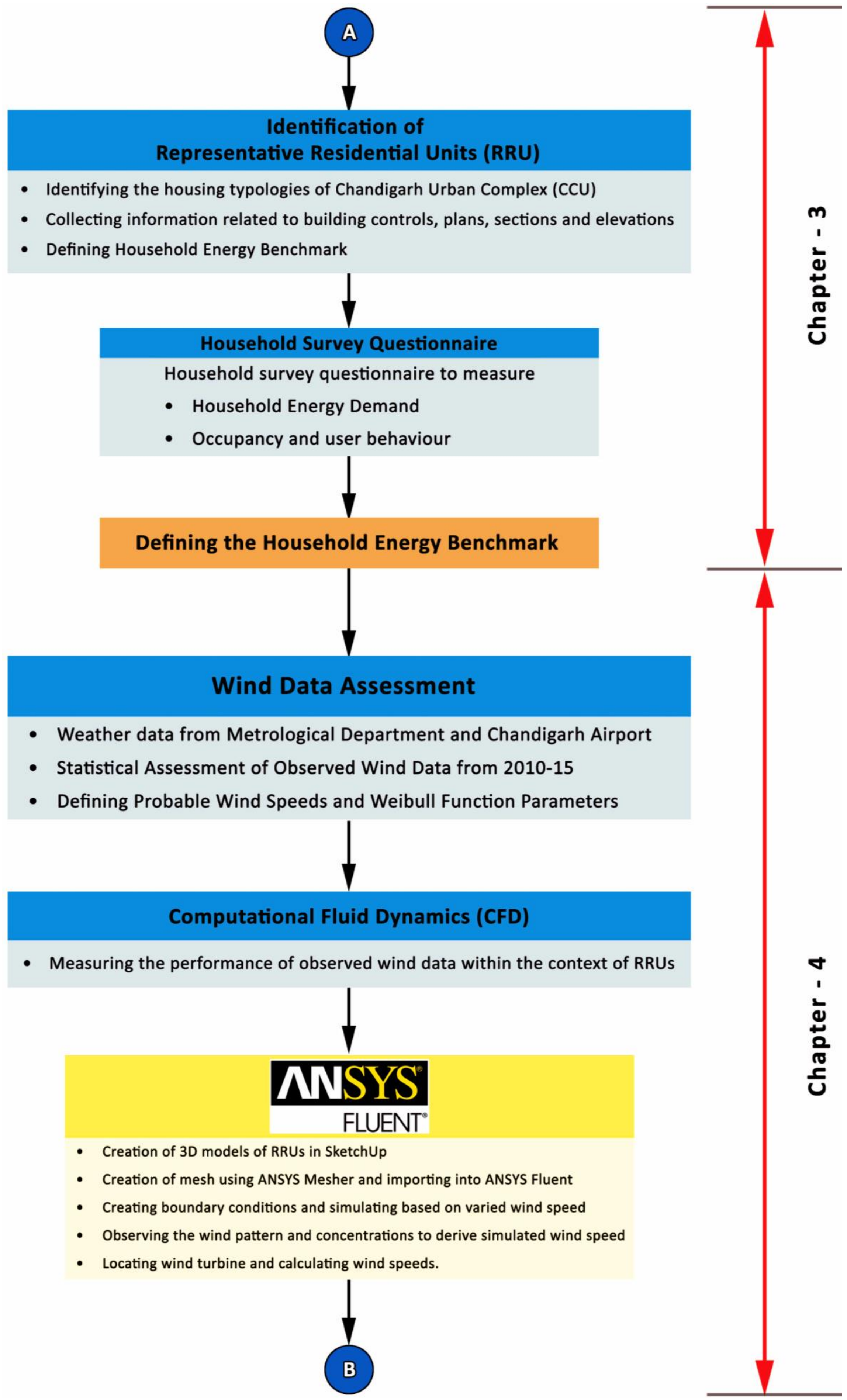
To understand the potential of solar and wind resource in energy generation within the context of existing housing

- To define potential of solar and wind resource in microgeneration across various typologies
- To establish the ideal conditions under which solar and wind based microgeneration systems are viable for each typology at household, building or neighbourhood level
- To enhance microgeneration potential through identification of ideal energy mix using 'Residential Hybrid Energy Mix (RHEM) Model'

Scope and Limitations of the Study

Literature Review

- Domestic Energy and Global Scenario
- Solar and Wind Based Energy Generation
- Computational Tools for Assessment of Dynamic Energy Resources
- Conceptual Framework of Hybrid Energy Mix (HEM) for Energy Decisions



Identification of Representative Residential Units (RRU)

- Identifying the housing typologies of Chandigarh Urban Complex (CCU)
- Collecting information related to building controls, plans, sections and elevations
- Defining Household Energy Benchmark

Household Survey Questionnaire

Household survey questionnaire to measure

- Household Energy Demand
- Occupancy and user behaviour

Defining the Household Energy Benchmark

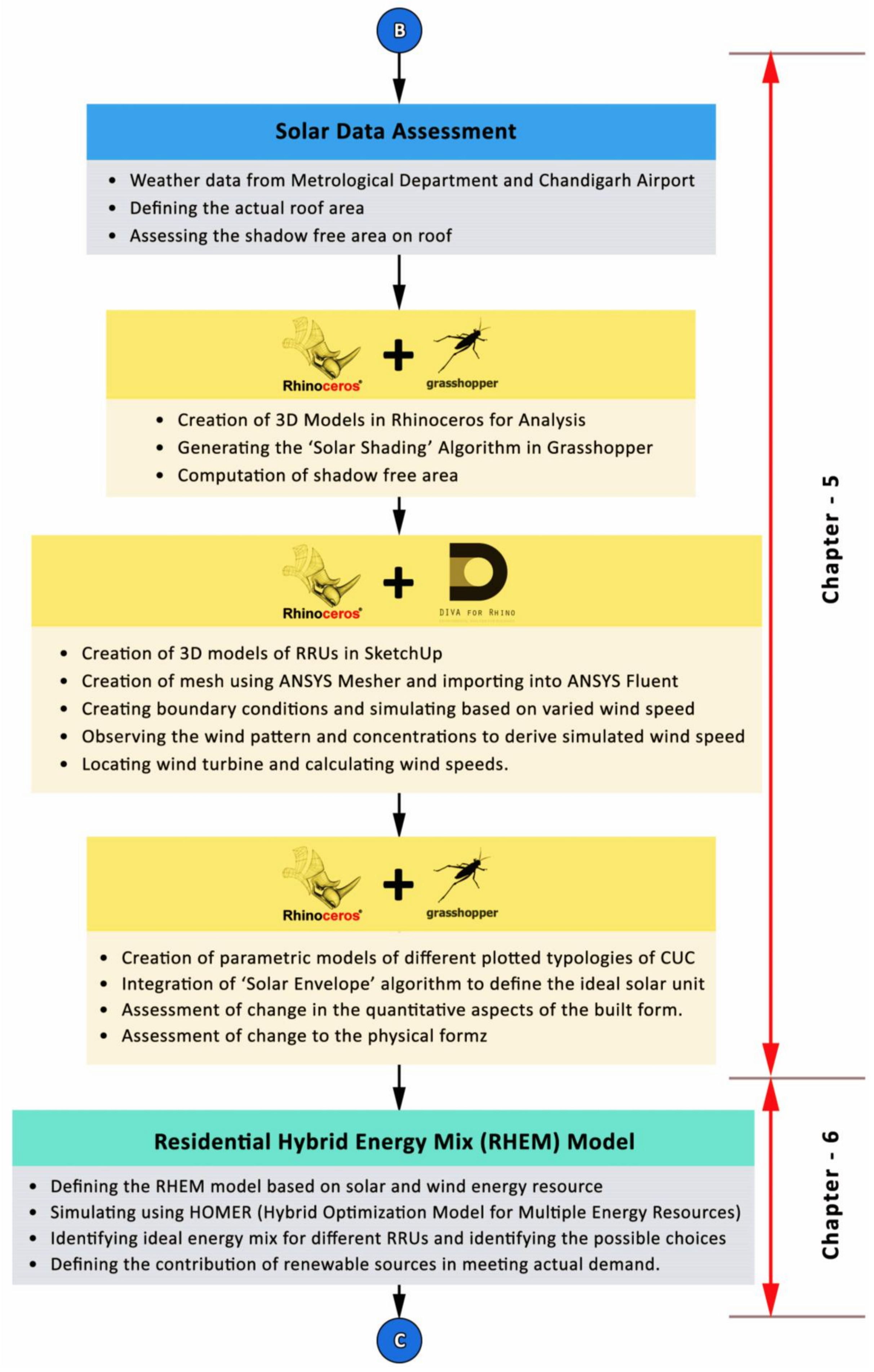
Wind Data Assessment

- Weather data from Metrological Department and Chandigarh Airport
- Statistical Assessment of Observed Wind Data from 2010-15
- Defining Probable Wind Speeds and Weibull Function Parameters

Computational Fluid Dynamics (CFD)

- Measuring the performance of observed wind data within the context of RRUs

- Creation of 3D models of RRUs in SketchUp
- Creation of mesh using ANSYS Mesher and importing into ANSYS Fluent
- Creating boundary conditions and simulating based on varied wind speed
- Observing the wind pattern and concentrations to derive simulated wind speed
- Locating wind turbine and calculating wind speeds.



Solar Data Assessment

- Weather data from Metrological Department and Chandigarh Airport
- Defining the actual roof area
- Assessing the shadow free area on roof

- Creation of 3D Models in Rhinoceros for Analysis
- Generating the 'Solar Shading' Algorithm in Grasshopper
- Computation of shadow free area

- Creation of 3D models of RRUs in SketchUp
- Creation of mesh using ANSYS Mesher and importing into ANSYS Fluent
- Creating boundary conditions and simulating based on varied wind speed
- Observing the wind pattern and concentrations to derive simulated wind speed
- Locating wind turbine and calculating wind speeds.

- Creation of parametric models of different plotted typologies of CUC
- Integration of 'Solar Envelope' algorithm to define the ideal solar unit
- Assessment of change in the quantitative aspects of the built form.
- Assessment of change to the physical formz

Residential Hybrid Energy Mix (RHEM) Model

- Defining the RHEM model based on solar and wind energy resource
- Simulating using HOMER (Hybrid Optimization Model for Multiple Energy Resources)
- Identifying ideal energy mix for different RRUs and identifying the possible choices
- Defining the contribution of renewable sources in meeting actual demand.

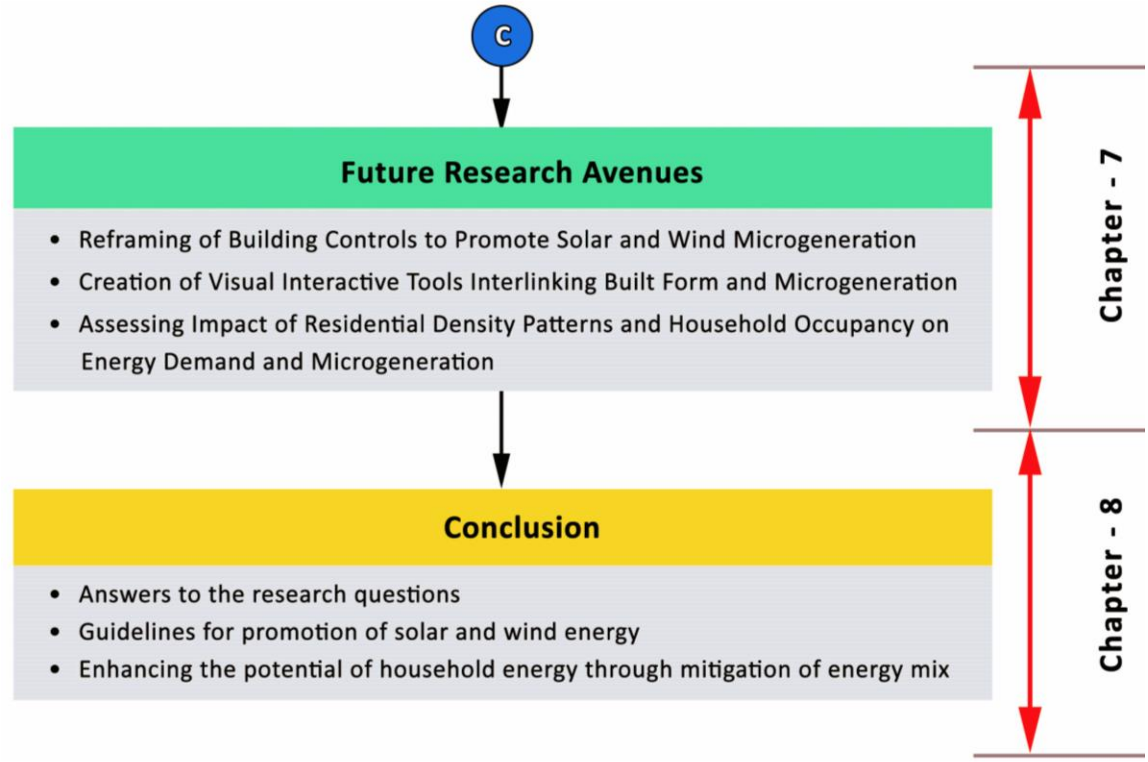


Figure 1.8 : Research Methodology

1.10 Conclusion

The study is a step towards understanding the role of microgeneration within the context of housing. It attempts to assess the behaviour of solar and wind resources within the context of existing housing typologies. The study is undertaken in various stages aimed to understand the energy performance of existing households, assessing the potential of wind resource within the turbulent conditions of the built environment, maximizing the output from solar resources and defining a conceptual energy mix model that aims to maximize renewable energy output and its inclusion depending on multi-dimensional factors. The outcome can guide future researchers in promotion of renewable energy systems at micro level and thereby contribute towards the common goal of ensuring energy security to all and also reduce global carbon emissions.

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Chapter 2

Review of Earlier Works

2.1 Introduction

Electrical energy has become a major source for the sustainability of human life. As the global population is increasing, dependability on electricity has also increased. Statistics estimate that the world population may reach to 8 billion by 2020 and this increase is typically in developing countries. This necessitates the expansion of utility grid to meet this ever-increasing demand (**Jaganmohan et al., 2012**). In the existing energy distribution network, the grid is overloaded and faces problems of fossil fuel depletions, less efficient and ageing machinery at generation; poor efficiencies in transmission and distribution; high installation and operational costs at distribution. To address these issues the power sector is undergoing rapid change. India's grid connected Renewable Energy Sources (RES) capacity has increased seven times to about 35 GW in the last decade. India has also set up an ambitious target of installing 175 GW of RES by 2022, which implies an addition of 3 MW of RES capacity for every 2 MW of conventional capacity added. RES is highly weather dependent making load management an important tool to increase its utility. Load management either includes reducing load (i.e. use of electricity) through conservation and efficiency, or shifting it to time periods when RES generation is high.

Besides, steady evolution of the regulatory and functional changes of electric utilities there is a new theme of local power generation using RES at distribution level to form flexible, modular, and task-oriented systems known as Micro Generation. Micro Generation grids are being formed as an aggregation of various distributed resources and storage systems typically located at the site of use and seamlessly integrated with the utility grid (**Bozchalui MC et al., 2012**). The primary fuel of these micro grids include RES such as solar, biogas, hydel, wind, hydrogen, etc., and at times conventional fuels like diesel and natural gas. Micro Generation based microgrids operate in utility grid as a single and self-controlled entity called island operation or integrated and running in parallel with national grid called grid mode operation (**Nelson et al., 2006**).

The chapter looks into the applicability of two major RES – wind and solar in the development of micro grids in Chandigarh within the context of housing. The study looks into literature and existing studies relevant to understanding household energy demand and methods of estimating the demand. This is followed by looking into the applicability of wind resource as energy generating option and defining its potential at urban level using statistical and Computational

Fluid Dynamics (CFD) based analysis. The solar potential assessment is done using industry standard based DIVA a parametric computational tool for RHINO 3D. The study also looks into the concept of 'Solar Envelope' and its role in enhancing solar potential through mitigation of the built form, but for the purpose of the study the scope is restricted to plotted units. Finally the scale and size of the micro grid based on both wind and solar resource and optimized using HOMER (Hybrid Optimization Model for Multiple Energy Resources) a microgrid simulation software with the operational and economic parameters compared to define the optimal hybrid energy system.

2.2 Household Energy Demand and Estimation

Electrical energy has become a major source for the sustainability of human life. As the global population is increasing, dependability on electricity has also increased. Existing literature indicates that studies in the past have been undertaken to model the electrical demand at the utility level (**Paatero et al., 2006** and **Larsen et al., 2004**). Different assessment methods like short-term load forecasting (**Gross et al., 1987**), neural network (**Hippert et al., 2001** and **Deihimi et al., 2013**), fuzzy logic (**Ukil, 2007**), genetic algorithm and expert systems (**Bennett et al., 2014**) have been used in the past. These methods are applied in absence of details regarding household appliance list and user group details.

Capsso (**1994**), **Swan** (**2009**), **Paatero** (**2006**) and **Larsen** (**2004**) in their works highlighted the reliability of bottom-up approach in estimating and simulating the household energy consumption based on the end user. The approach estimates the energy demand based on the appliance list in the household. This enables to assess the impact of a particular appliance on the overall energy demand and derive a usage pattern. The working process of the bottom-up approach is highlighted in the figure. 2.1.

The bottom up approach is a continuous learning based system. Based on the data sets already created in its system the category of household if given, the list of appliances in the household are listed statistically. Estimation of hourly electricity demand requires extensive data sets about the consumer and the appliances list at household level.

A typical limitation for detailed bottom-up method as detailed by **Capasso** (**1994**) and **Larsen** (**2004**) is the need for extensive detailed information about the house, its occupants and the electrical appliances. To collect such information there is a need for conducting household surveys which are quite exhaustive. In case of household survey of similar typology units like in an apartment complex instead of undertaking survey of each household representative household based data samples and statistical averages are derived.

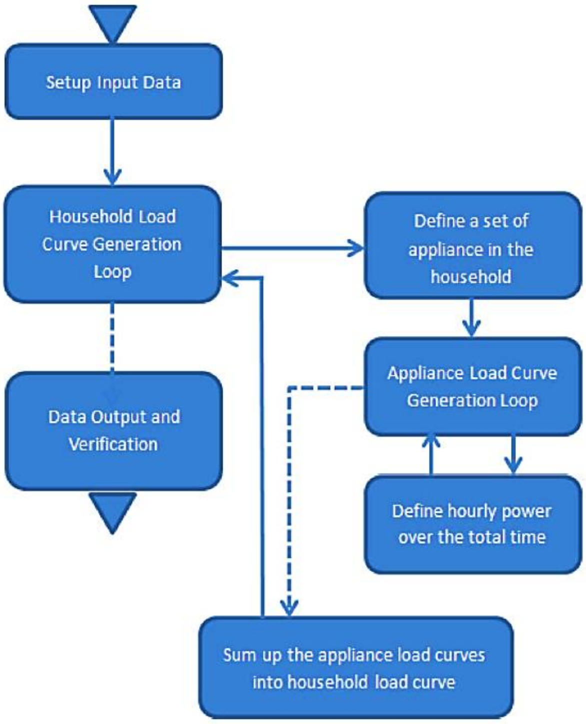


Figure 2.1. Working Process of a Bottom-Up Approach (Luo and Ukil, 2015)

A questionnaire prepared to undertake household surveys as part of the study across four major housing typologies of Chandigarh Urban Complex is listed under **Annexure – 1**. All electrical appliances that are shortlisted and used for energy estimation are considered to be energy rated with highest energy conservation.

2.3 Wind Resource and its Potential in Urban Built Environment

Wind power is rapidly growing as n popularity in recent years along with other major renewable types of energy resources. Efforts in the past have been carried out to conduct power density analyses for micro-wind turbines catering primarily to suburban areas (**Ledo et al., 2011; Matahaba et.al, 2012; Millward-Hopkins et.al, 2013; Dahbi et al., 2013 and Ying et al., 2015**). Wind as an energy resource needs to be further studied in urban areas as it is prone to high turbulence intensity due to buildings as indicated in figure 2.2 and the directional factor also varies with one location to another, making it difficult to pin point the ideal location for placement of wind turbines (**Toja-Silva et.al, 2013; Walker et al., 2013 and Morbiato et al.; 2014**).

Despite the potential of urban wind power, there are many issues in incorporating wind generation into urban situations (**Sunderland et al., 2013**). The seasonal variation of the wind due to the local climate, landscape, building shapes and other obstacles in the complex urban environment can substantially influence wind speed and local turbulence intensity in the process of selecting suitable installation sites of micro-wind turbines to exploit wind energy (**Kalmikov et al., 2010**). The location of micro wind turbines with the consumption sites results in reducing transmission and distribution losses and the saving the cost of extra infrastructure needed over a distributed network thereby enhancing power production and also saving within the context of densely urbanized areas (**Merten et al., 2002**).

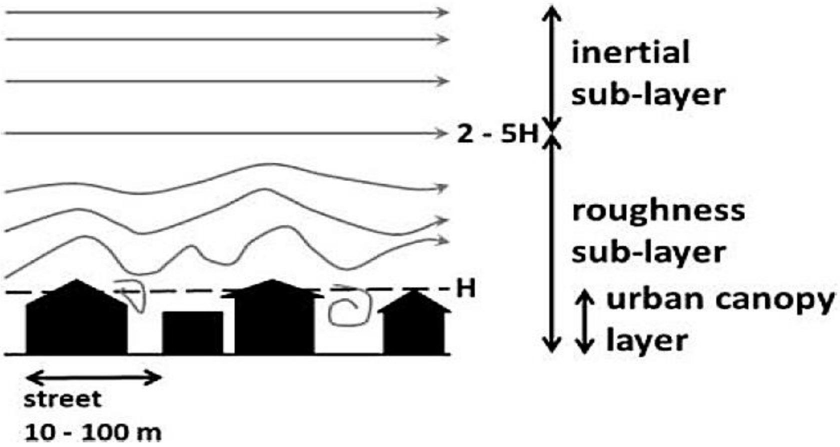


Figure 2.2: **Schematic Diagram of Urban Boundary Layers**
(*Source: Barlow, 2014)*

Li (**2015**) and **Bontempo** (**2014**) highlighted that low wind speed and high turbulence in and around buildings reduce wind power yield and also result in stress on turbine blades effecting their efficiency and causing wear and tear. This results in questioning the deployment of micro-wind turbines in and around urban areas. There is a need to accurately estimate wind speed and possible energy yield that can lead to identifying potential mounting sites of micro-wind turbines.

Earlier studies have employed varied statistical and computational tools such as the Weibull analysis, micrometeorology data, experimental measurements and Computational Fluid Dynamics (CFD) to evaluate the wind power available for energy production (**Cace et al., 2007**; **Mertens et al., 2002** and **Chandel et al., 2014**).The Weibull analysis can in general provide useful information for the macro-siting of wind turbines but lack the precision for micro-siting. Hence, high resolution measurements and more accurate wind field statistics are necessary for micro-siting so as to improve power output from wind turbines in urbanized areas (**Leblebici et al., 2013**). To determine the airflow field, on-site measurements are the most commonly used approach to acquire local wind data; however, they are also costly and time-consuming (**Blocken et al., 2014**). Instead, CFD techniques have been confirmed as an affordable alternative to simulate the wind flow for application and installation of micro-wind turbines on different potential sites in congested urban environments with less time and investment as modern computer systems have a growing computational power to- cost ratio (**van Hooff et al., 2014**).

In effect, the local wind characteristics above the roof of buildings in dense urban areas are indeed highly complex and the adaptability of wind turbines to such real life cases has not been assessed yet (**Balduzzi et al., 2012**). For instance, a number of studies have analyzed wind energy for the airflow across an isolated building (**Ohunakin et al., 2011 and Ledo et al., 2011**) or two identical buildings (**Lu et al., 2009 and Khayrullina et al., 2013**) without taking into consideration the surrounding structures.

The possible installation sites of wind turbine systems obtained from CFD simulations have been further integrated into building designs to realize the implementation of urban wind power (**Padmanabhan, 2013** and **Watson et al., 2007**). In considering the complicated geometry of urban areas, **Kalmikov** (**2010**) used CFD simulations to assess the wind energy potential on the campus of the Massachusetts Institute of Technology (MIT) campus in the USA. No major study has been undertaken to study the wind flow within the context of housing.

As the wind field above the roof of buildings is very different from that over flat terrains or around isolated buildings, it is important that local wind characteristics such as the flow pattern, velocity and turbulence intensity are examined and carefully analyzed before integrating wind turbines into built environments. Previous research has demonstrated that CFD simulations are very useful for capturing small-scale details around urban features owing to the finer scale topography of computational models.

Moreover, field measurements are necessary to validate the CFD predictions in local urban environments as well as compare them against the results from wind tunnel experiments, because only field data can completely indicate the real complexity of the problem under investigation (**Moonen et al., 2012**). However, studies in which field measurements have been used to verify CFD models for evaluating urban wind energy are extremely limited (**Kalmikov et al., 2010** and **Tabrizi et al., 2014**) and even wind tunnel experiments are relatively scarce.

Hence, there is the need to properly validate the predictions of local airflow characteristics specifically wind speed and wind direction to define probable wind speeds and ideal location of wind turbines as part of this study. As mentioned above, various overly simplified methods that use Weibull analysis and local weather data have been carried out in studies to determine the potential installation sites of micro wind turbines and estimate the wind power generation for urban environments.

However, relatively few studies have conducted detailed analyses of the interactions of building configurations with the wind to resolve the airflow field that the turbines may experience during their operation. The influence of the local urban topology on the wind speed and turbulence intensity fields in a given locality is therefore an important determinant of the optimum location of micro-wind turbines.

Statistical tools can resolve data sets spanning over years and give optimum results but to resolve the distributions of wind speed, power density and turbulence intensity within the turbulent context of housing built forms CFD tools like ANSYS Fluent need to be employed.

2.3.1 Statistical Estimation of Wind Speed

The use of reliable meteorological data is of major importance in wind turbines installation planning. However, it is not usually economic or practical to make long term measurements in any potential urban development site for installation and therefore, the use of existing data is imperative.

Consequently, for a methodology to be generalized to a wide range of sites, it is desirable to be able to translate data available from public weather stations to the target location. The data collected from the regional meteorological station contains the hourly wind speed and direction values at a reference point at 15m height, where the flow is considered not to be obstructed by any obstacles. Based on the data collected a series of statistical tests (**Akpinar, 2006**) are conducted to define the probable wind speed that are considered for CFD analysis.

a) Time Series based Distribution of Wind Data

The monthly average wind speed (V_m) and the standard deviation (σ_{ts}) are calculated for the hourly series wind data based on equation 2.1 and 2.2.

$$v_m = \frac{1}{N}\left(\sum_{i=1}^{N} v_i\right)$$ **Equation. 2.1**

and

$$\sigma_{ts} = \left[\frac{1}{N-1}\sum_{i=1}^{N}(v_i - v_m)^2\right]^{1/2}$$ **Equation. 2.2**

Where v_m = Average wind speed (m/sec) σ_{ts} = Standard deviation of data (m/sec)

v_i = Hourly wind speed (m/sec) N = Total wind speed data measured hours

b) Frequency Distribution of Wind Data

The domain of observed wind data are divided into intervals with a difference of 1 m/sec. Wind speed bins are created starting with 0-1 m/sec, mean wind speed (v_i) for each class interval are calculated using equation 2.3 along with frequency of occurrence of each wind speed class (f_i).

$$\overline{V} = \frac{\sum_{i=1}^{N} f_i \cdot v_i}{\sum_{i=1}^{N} f_i} = \frac{1}{N}\left[\sum_{i=1}^{N} f_i \cdot v_i\right]$$ **Equation. 2.3**

The probability of occurrence of measured wind speed $f(v_i)$ is calculated using the equation 2.4.

$$f(v_i) = \frac{f_i}{\sum_{i=1}^{N} f_i} = \frac{f_i}{N}$$ **Equation. 2.4**

The standard deviation (σ_m) of the mean wind speed are calculated using the equation 2.5.

$$\sigma_m = \left[\frac{1}{N-1}\sum_{i=1}^{n} f_i \cdot (v_i - v_m)^2\right]^{1/2}$$ **Equation. 2.5**

c) Comparison of Time Series and Frequency Distribution of Wind Speed Data

A comparison of the average wind speed (V_m and $\overline{V}$) and standard deviation (σ_{ts} and σ_m) from time series and frequency distribution of wind speed data derived from equation 2.1-2.5 is conducted and the relative error (ε_v and ε_σ) of the average wind speed is derived.

d) Calculating the Weibull Parameters

To characterize the wind profile of a site statistical assessment of the wind data is done using the two parameter Weibull and two parameter Raleigh distribution. The Weibull distribution is defined by two parameters, 'k' the dimensionless shape parameter and 'c' the scale parameter measured in m/sec. The 'f(v)' probability density function (PDF) and 'F(v)' cumulative density function (CDF) of the Weibull distribution are defined as per equation 2.6 & 2.7.

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$ **Equation. 2.6**

and

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$$ **Equation. 2.7**

Where $f(v)$ & $F(v)$ = Probability of observing wind speed 'v'

v = Wind Speed (m/sec) c = Weibull scale parameter (m/sec)

k = Weibull dimensionless shape parameter

Estimation of the Weibull parameters 'k' and 'c' is done using two numerical methods listed below:

i) Energy Pattern Factor Method (f_{EPF}) and

ii) Empirical Method (f_{EM})

e) Energy Pattern Factor Method (f_{EPF})

The energy pattern factor method (**Akdag et al., 2009**) is based on the average wind speed calculated from the observed wind data. It is defined by the equation 2.8.

$$F_{ep} = \frac{\left(v^3\right)_m}{\left(v_m\right)^3} = \frac{\left(\frac{1}{n}\sum_{i=1}^{n} v_i^3\right)}{\left(\frac{1}{n}\sum_{i=1}^{n} v_i\right)^3}$$ **Equation. 2.8**

Where F_{ep} = Energy Pattern Factor v = Wind Speed (m/sec)

v_m = Mean Wind Speed (m/sec) n = Count of wind speed data hours

Based on the value of F_{ep}, k and c are defined on basis of the equation 2.9 and 2.10.

$$k = 1 + \left(3.69 / \left(F_{ep}\right)^2\right)$$ **Equation. 2.9**

and

$$c = \frac{v_m}{\Gamma . (1 + 1/k)}$$ **Equation. 2.10**

Where F_{ep} = Energy pattern factor k = Weibull shape parameter

V_m = Mean wind speed (m/sec) c = Weibull scale parameter (m/sec)

Γ = Standard gamma function

The standard gamma function (Γ) is given by the equation 2.11.

$$\Gamma(z) = \int_0^\infty e^{-t} t^{z-1} dt$$ **Equation. 2.11**

f) Empirical Method (fEM)

The empirical method is based on the mean wind speed (V_m) and standard deviation (σ) of observed wind data. The k and c values derived using the equation 2.12 and 2.13.

$$k = (\sigma / v_m)^{-1.089}$$ **Equation. 2.12**

and

$$C = \frac{v_m}{\Gamma(1 + 1/k)}$$ **Equation. 2.13**

Where k = Weibull shape parameter

σ = Standard deviation

V_m = Mean wind speed (m/sec)

c = Weibull scale parameter (m/sec)

Γ = Standard gamma function

g) Rayleigh Distribution (f_R)

The Rayleigh distribution is a special form of the Weibull distribution where the k value is considered as equal to 2. It is a one parameter based entity as a result it has less flexibility and suitable for certain wind conditions.

h) Comparison of Energy Pattern Factor (f_{EPF}), Empirical Method (f_{EM}) and Rayleigh Function (f_R)

The k and c values derived from the Energy Pattern Factor Method (f_{EPF}) and Empirical Method (f_{EM}) are plotted using the Probability Density Function (PDF) of Weibull and Rayleigh distribution along with the observed wind data. To confirm the accuracy in estimating the wind speeds three statistical tests are undertaken.

i) Root Mean Square Error (RMSE)
ii) Coefficient of Determination (R^2)
iii) Chi-square Test (χ^2)

i) Root Mean Square Error (RMSE)

The Root Mean Square Error (RMSE) is a measure of the deviation between the actual and predicted values. The value is expected to be near to zero. Lower value of RMSE indicate successful prediction in comparison to deviation in care of higher values. RMSE is expressed in form of the equation 2.14.

$$\mathrm{RMSE} = \left[\frac{1}{N} \cdot \sum_{i=1}^{N} (y_i - x_i)^2 \right]^{1/2}$$ **Equation. 2.14**

Where y_i = Observed data x_i = Predicted data N = Number of observations

j) Coefficient of Determination (R^2)

The R^2 is a linear relationship between the measured data and predicted data from various distribution functions. The value of R^2 is expected to be higher with the maximum value being equal to 1. The Coefficient of Determination is expressed by the equation 2.15.

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - \bar{y}_i)^2 - \sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y}_i)^2}$$ **Equation. 2.15**

Where y_i = Observed data x_i = Predicted data $\bar{y}_i$ = Mean of y_i
N = Number of observations

k) Chi-square Test (χ^2)

The χ^2 is a measure of the mean square of the deviations between observed wind data and predicted data. It is expressed by the equation 2.16 and is expected to be close to zero.

$$\chi^2 = \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{x_i}$$ **Equation. 2.16**

Where y_i = Observed data x_i = Predicted data N = Number of observations

The values of the three test confirm which function derives the most probable wind speed that are used to quantify the wind speeds specific to site conditions.

l) Wind Speeds Specific to Site Conditions

Wind speeds are subject to site conditions, two type of wind speeds that are of interest and need to be assessed are the most probable wind speed (V_{mp}) and the wind speed carrying the maximum energy (V_{Emax}). Both the wind speeds are based on the Weibull parameters and defined by equation 2.17 and 2.18.

$$v_{\text{Emax}} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}}$$ **Equation. 2.17**

and

$$v_{\text{mp}} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}}$$ **Equation. 2.18**

Where V_{Emax} = Wind speed carrying maximum energy V_{mp} = Most probable wind speed

c = Weibull scale parameter (m/sec) k = Weibull shape parameter

The wind speed calculated are based on the observed wind speed data, but the wind speed varies with height for which the Weibull parameters need to be extrapolated with increasing height to quantify wind speeds in case of high rise structures.

m) Extrapolation of Weibull parameters

Assessing the wind speeds at varying heights statistically is possible through the extrapolation of k and c parameters of Weibull distribution. The function for extrapolation of k and c for a particular height 'z' are highlighted by equation 2.19 and 2.20. The extrapolated k and c values of CUC with varying heights of 10 meter interval are highlighted in table 4.18.

$$\mathbf{C_z} = \mathbf{C_{10}} \times (\mathbf{z}/\mathbf{z_{10}})^{\mathbf{n}}$$ **Equation. 2.19**

and

$$\mathbf{k_z} = \frac{\mathbf{k_{10}}}{1 - 0.00881\ln(z/10)}$$ **Equation 2.20**

Where C_Z = Extrapolated value of *C* for height z C_{10} = Probable value of *C* for height of 10m

k_Z = Extrapolated value of *k* at height z k_{10} = Probable value of *k* at height of 10m

z = Desired height in meter for *C* and *k* values z_{10} = Height of 10m

n = Power law exponent expressed by the equation 2.21

$$\mathbf{n} = [0.37 - 0.088\ln(\mathrm{C_{10}})$$ **Equation 2.21**

n) Wind Power Density (WPD) and Wind Energy Density (WED) with varying heights

Wind Power Density (WPD) is a measure of the wind resource available at a particular site. It is measured in Watt per meter square (W/m2). It is expressed by the equation 2.22.

$$\mathrm{WPD} = p(v) = P(v)/A = \frac{1}{2} . \rho . C^3 . \Gamma\left(1 + \frac{3}{k}\right)$$ **Equation. 2.22**

Where P(v) = Wind power (W) p(v) = Wind power density (W/m^2)

ρ = Air density (kg/m^3) A = Sweep area of wind vane blades (m^2)

C and k = Weibull scale and Shape parameters

The air density is dependent on the elevation of the site from sea level and defined by the equation. 2.23.

$$\rho = \rho_0 - 1.194 \times 10^{-4} \times H_m$$ **Equation. 2.23**

Where ρ_0 = Air density at sea level equal to 1.225 kg/m^3

H_m = Site elevation from sea level

The outcome of the WPD is more relevant in the form of Wind Energy Density (WED), which is a product of WPD and total hours in a year (T) generally taken as 8760 hours. WED is measured in kWh/m^2 and derived by the equation. 2.24.

$$\mathrm{WED} = p(v) . T = \frac{P(v)}{A} . T = \frac{1}{2} . \rho . C^3 . \Gamma\left(1 + \frac{3}{k}\right) . T$$ **Equation 2.24**

Where P(v) = Wind power (W) p(v) = Wind power density (W/m^2)

ρ = Air density (kg/m^3) A = Sweep area of wind vane blades (m^2)

c and k = Weibull scale and Shape parameters

2.3.2 Computational Fluid Dynamics (CFD) based Estimation of Wind Speed

Urban built environment and the shape of its buildings have a great effect on the wind speed and turbulence intensity thereby affecting the overall energy output from wind turbines. The layout of buildings and their built character is of prime importance in defining the location of wind turbines (**Burton et al., 2001** and **Rafailidis, 1997**) so as to ensure optimum cut in velocity to generate energy. Vegetation an integral part of urban environment plays a major role in the surface roughness along with other factors like varying building heights, air temperature and built form configuration thereby influencing simple winds and convert them into gusty, turbulent and varying in speed and direction.

Accurate simulation of wind speed and direction in built environments is necessary to estimate the probable Wind Power Density (WPD) and Wind Energy Density (WED). Numerical based Computational Fluid Dynamics (CFD) simulation can aid in accurate prediction of wind speeds within complex urban settings. Modelling of wind flow in the urban settings and around buildings has already been undertaken using CFD simulation (**Mertens, 2003; Santiago et al., 2007** and **Heath et al., 2007**) and turbulence models of varying degree like the Large Eddy Simulation (LES) (**Uchida et al., 2008** and **Tutar et al., 2004**), Direct Numerical Simulation (DNS) (**Takahashi et al., 2006**) and varied forms of Navier-Stokes equation. The flow conditions required and computing resources dictate the choice of turbulence models.

In spite of very few earlier studies listed in table 2.1 the application of the three dimensional Reynolds averaged Navier Stokes (RANS) equation in urban settings has established it as the ideal model to simulate the wind flow and its behaviour in the complex built form of housing typologies (**Menter, 1994**).

Table 2.1: Recent CFD studies on evaluation of wind power in built environment (Yang et al., 2016)

Publication	2D / 3D Analysis	Configuration	Turbulence Modeling	Validation
Heath et al. (2007)	3D	Urban landscape considered an array of cubes	Steady RANS	Wind Tunnel
Kalmikov et al. (2010)	3D	Simplified model of MIT campus	Steady RANS	On Site
Ledo et al. (2011)	3D	An array of cubic buildings with different types of roofs	Steady RANS	Wind Tunnel
Balduzzi et al. (2012)	2D	Generic urban environment	Steady RANS	Wind Tunnel
Khayrullina et al. (2013)	3D	Two simple parallel rectangular building blocks	Steady RANS	Wind Tunnel
Abohela et al. (2013)	3D	An array of cubic buildings with different types of roof	Steady RANS	Wind Tunnel
Tabrizi et al. (2014)	3D	A rectangular building with a radius of 200m surrounding area	Steady RANS	On Site
Toja-Silva et al. (2015a)	3D	A rectangular building with inclined solar panels	Steady RANS	Wind Tunnel
Toja-Silva et al. (2015b)	3D	A rectangular building	Steady RANS	Wind Tunnel
Wang et al. (2015)	3D	Two perpendicular buildings	Steady RANS	Wind Tunnel
Yang et al. (2016)	3D	Generic urban environment	Steady RANS	On Site

a) Three Dimensional RANS Computational Model

The three dimensional Reynolds Navier Stokes (RANS) equation defined by the equation 2.25 is based on the original incompressible Navier Stokes equation and has been used in various studies to simulate and measure the velocity and pressure parameters of wind. Due to the open nature of the RANS equation different situation specific turbulence models have been associated as extensions like the standard *k*-ε transport model (**Shih et al., 1995** and **Karava et al., 2011**). The standard *k*-ε transport model assumes the flow to be fully turbulent and the effects of viscosity are expected to be negligible.

The standard *k*-ε transport model used in previous studies dealing with turbulent incompressible wind flows that are part of the built form configurations is used to measure the turbulence kinetic energy *k* and its specific dissipation rate ε based on the equation 2.26 and 2.27.

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$\rho\frac{\partial U_i}{\partial t} + \rho\frac{\partial}{\partial x_j}(U_iU_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}(2\mu S_{ij} - \rho\overline{u_i'u_j'})$$

Equation. 2.25

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k$$

Equation. 2.26

and

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon$$

Equation. 2.27

Where *k* = Turbulence kinetic energy ε = Dissipation rate of Kinetic energy

G_k = Generation of turbulence kinetic energy due to mean wind velocities

G_b = Generation of turbulence kinetic energy due to buoyancy

Y_m = Contribution of fluctuating dilatation to overall dissipation rate

σ_k and σ_ε = Turbulent Prandtl numbers for *k* and ε

$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ = Constants

2.3.3 Measuring Wind Parameters and Turbine Energy Output

The energy output of a wind turbine is based on the kinetic energy generated by the wind that is converted into electrical energy on basis of mechanical movement of the turbine blades. The electrical energy generated by a wind turbine at a certain speed is defined by the equation 2.28.

The power density of wind (P_{density}) is defined by the power in the wind divided by the swept are of the wind turbine.

$$P_v = \frac{1}{2}\rho A U^3 \text{x}\, C_p \text{x}\, n_g \text{x}\, n_b$$ **Equation. 2.28**

Where P_v= Power in the wind (kilowatt) ρ = Air density (kg/m^3)

A = Swept area of the wind turbine (m^2) U = Mean wind speed (m/sec)

C_p= Maximum Power Coefficient n_g = Efficiency of Generator

n_b = Efficiency of Gearbox

The maximum power coefficient (Cp) is a measure of the actual power captured by the wind turbine in comparison to theoretically wind power available and expressed by the equation 2.29.

$$C_p = \frac{P_R}{P}$$ **Equation 2.29**

Where C_p= Power Coefficient P_R = Realized wind power by turbine

P = Wind power available

The value of C_p theoretically can reach a value of 0.53 called the Betz limit in thermodynamics but due to aerodynamic and mechanical conversion losses the value is considered between 0.25 and 0.45. In the case of wind turbines C_p is termed as the Tip Speed Ratio (TSR), a point at which the power captured by the turbine is the highest.

The electrical power generated by a wind turbine is less than the actual potential owing to impact of losses in the gear box and generator. Both these are defined by efficiencies n_g and n_b, based on the power output to power input. The gear box efficiency (n_g) is considered to be 90-95% whereas the generator box efficiency (n_b) ranges between 50-80% defined by the quality of the model. For a grid connected wind turbine setup the n_b value is typically 80%.

Wind speeds and turbulence intensity at varying heights estimated through the CFD simulation are used to develop the velocity boundary layer and turbulence intensity layer varying with height based on the power law equation 2.30.

$$u = u_{\text{ref}}\left(\frac{z}{z_{\text{ref}}}\right)^{\alpha}$$ **Equation. 2.30**

Where u = Wind speed estimated at a particular point α = Wind shear

u_{ref} = Wind speed at a reference height

z = Height of the point for wind speed estimation

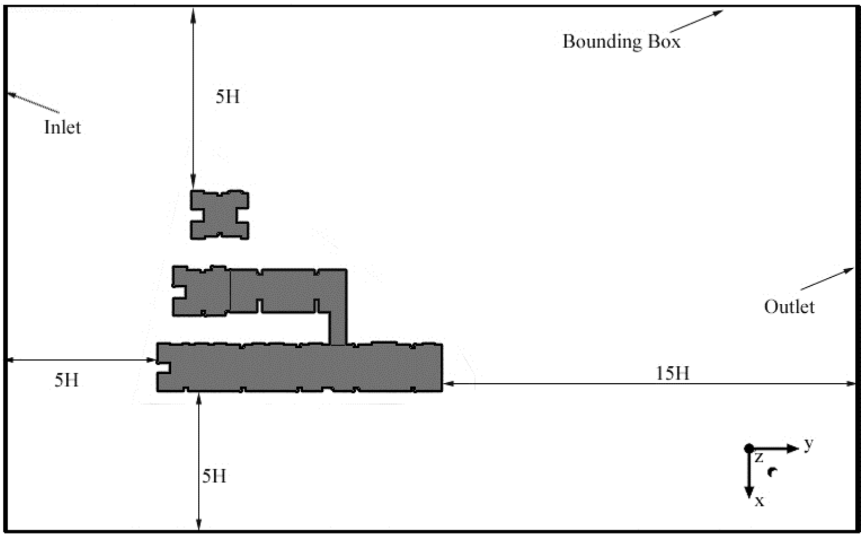
z_{ref} = Height of the reference wind speed

The thickness of the boundary layer is dependent upon the wind shear which is influenced by time of day, height, surface material of buildings, temperature, terrain and turbulence. Higher value α of indicates larger vertical gradient of wind speed. In case of neutral conditions, α is considered equal to 0.143.

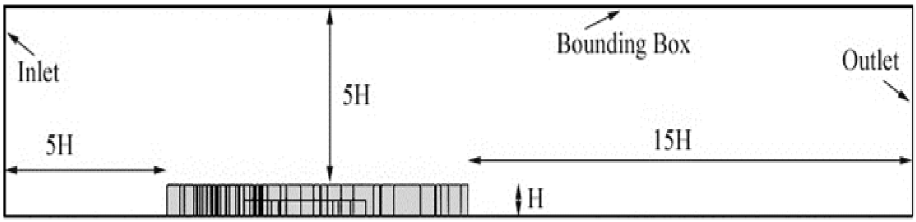
b) Test Models and Mesh Generation

The CFD based simulation is undertaken using academic version of ANSYS Fluent (Release 18.0). The academic/student version of ANSYS Fluent restrict the meshing of models to a maximum of 5,12,000 elements (**ANSYS 15 User Manual, 2013**). The models comprising of the built forms either grouped as a single unit or separate blocks and the ground surface are generated in SketchUp and then imported into ANSYS Fluent. The numerical surface grid based meshed models are generated through ANSYS Meshing tool. To ensure accuracy without effecting the quality of the mesh scaled computational models of existing housing typologies are used. Also to meet the meshing constraints set by the academic version of ANSYS Fluent vegetation is negated as part of the analysis. The mesh is generated using the patch independent tetrahedron meshing method which ensures the refinement of the mesh especially near the faces and edges, but maintains larger elements whenever required to ensure faster computation.

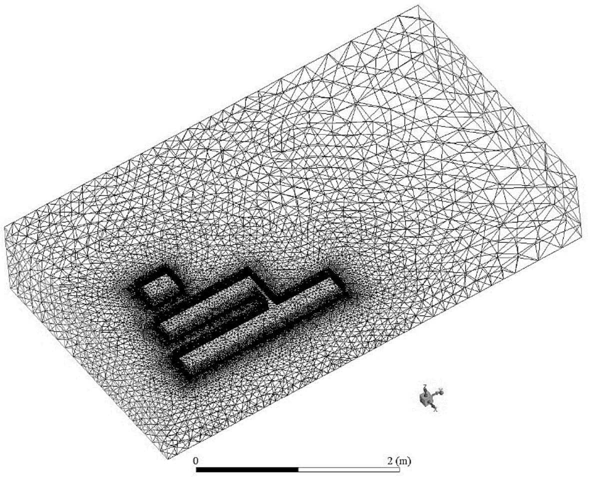
c) CFD Boundary Box Geometry and Conditions

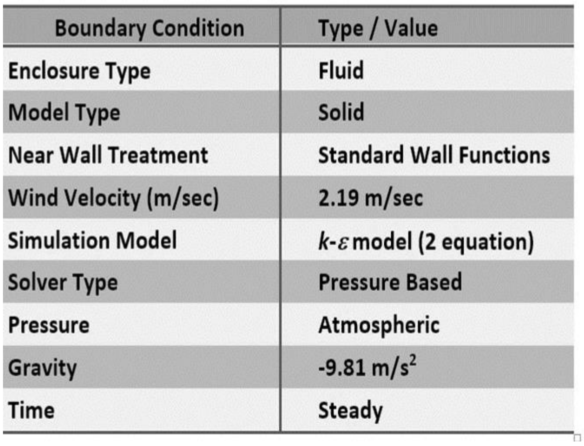


a) Horizontal Dimensions of the CFD Bounding Box



b) Vertical Dimensions of the CFD Bounding Box





Boundary Condition	Type / Value
Enclosure Type	Fluid
Model Type	Solid
Near Wall Treatment	Standard Wall Functions
Wind Velocity (m/sec)	2.19 m/sec
Simulation Model	k-ε model (2 equation)
Solver Type	Pressure Based
Pressure	Atmospheric
Gravity	-9.81 m/s^2
Time	Steady

c) Final Meshing Model

d) Boundary Conditions of CFD Simulation

Figure 2.3. CFD Bounding Box Geometry Conditions and Final Model Generated

The bounding box geometry and boundary conditions for CFD analysis are detailed out in the figure 2.3. The dimensions of the bounding box are defined with reference to the height of the highest object in the mesh. The inlet and side dimensions of the bounding box are 5 times the height and 15 times the height towards the outlet (**Richard et al., 1993**).

2.4 Solar Resource and its Potential in Built Environment

If the 19th century was the age of coal and the 20th of oil, the 21st will be the age of the sun. The use of renewable energy is no more a substitute, but rather a modern complement that is aimed at energy saving. However, the use of renewable energies is currently viewed mainly as a goal within the scope of new buildings.

Solar energy is set to play an ever-increasing role in generating the form, and affecting the appearance and construction, of buildings. The principal reason for this is that photovoltaic (PV) systems which produce electricity directly from solar radiation are becoming more widespread as their advantages become apparent and as costs fall. PVs are an advanced materials technology that will help us design buildings which are environmentally responsible, responsive and exciting.

Within the built environment solar energy can be divided into two applications - passive and active. In a passive system, solar energy is directly used as a source of natural light and radiated heat through the windows and building envelopes. In case of active systems, solar energy is transferred from a photovoltaic module and thermal collectors in the form of electricity and heat respectively.

Solar thermal and photovoltaic facilities can be particularly well integrated if they are planned along with the building as a whole from very early in the design. Solar technologies imply vast opportunities for aesthetics and interesting solutions and solar heating technology is amongst the least expensive in the area of renewable energy (**Hermannsdorfer and Rub, 2005;** and **Kjellerup et al., 2010**).

The importance of planning and design concepts that contribute to an increase in public acceptance of the solar building through convincing visualization and realization has to be emphasized. The installation of a solar facility during the renovation of an existing building produces both synergies and savings. Solar facilities can also be easily integrated into planned extensions in the form of retrofits (**Hermannsdorfer and Rub, 2005**).

Despite of these facts, a large portion of the potential to utilize solar energy still remains unused today (**Devin, 2006**). According to the International Energy Agency (**IEA, 2009**), this is caused by several factors:

- Economic factors;
- lack of technical knowledge;
- reluctance to use ‘new’ technologies; and
- Architectural (aesthetic) factors

Evolutionary parametric and Building Information Management (BIM) computational tools like RHINO, Revit, Grasshopper etc., make it is easy to employ solar energy in its passive form and integrate active form infrastructure right from the design concept stage and pushing renewable energy generation based goals as a major component of every housing project (**Attia et al., 2016**).

2.4.1 Modelling Solar Radiation

It can be argued that the most important factor influencing photovoltaic electricity generation is the amount of incoming solar radiation. Solar radiation, or insolation, is the sun's energy reaching the earth's surface. It is comprised of three components: direct beam, diffuse, and ground-reflected radiation (**Perez et al. 1987**). Figure 2.1 displays the way the three components reach the earth's surface.

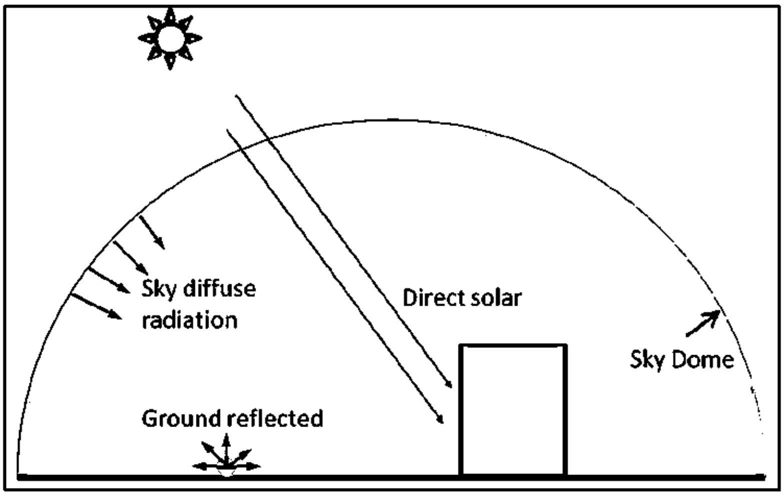


Figure 2.4: Components of Solar Radiation

Direct radiation is the direct beam of solar energy that is intercepted by the surface without any interactions with particles in the atmosphere (**Hetrick et al., 1993**). Diffuse radiation is the intercepted radiation that is scattered in the atmosphere by gases and aerosols (**Hetrick et al., 1993**; **Kumar et al., 1997**). Reflected radiation is reflected from terrain and surrounding surfaces (**Kumar et al. 1997**). Together, direct, diffuse and reflected radiations make up global radiation, or total radiation, reaching the surface.

Solar design of buildings is very much site specific. Architectural building design must respond to both exterior context and interior programming. Using simple graphical tools is one of the ways to develop and evaluate solutions specific to the building being designed. They allow the architect to perform a number of tasks quickly and accurately such as determining shadows' cast, determining spatial relationships between buildings and sun access to public space or to the internal spaces of buildings, etc. In some cases, the important information is not really quantifiable at all, but is qualitative or perceptual. One of the leading concept related to sun and the built environment is the 'Solar Envelope' concept by **Prof. Ralph L. Knowles** (**1980**).

2.4.2 Defining Actual Roof Area for Solar Energy

Determining the actual solar potential for urban renewable applications can be a challenging task. The complex urban environment, with varying building block densities and even more so building elevations, combined with limited available construction data about the existing building stock, are the main reasons for the difficulties emerging in the effort to assess solar potential.

Jakubiec and **Reinhart** (**2012**) explain that two of the most crucial components for calculating PV potential include the amount of solar radiation reaching the surface and the amount of useable rooftop area that can be dedicated to photovoltaic panels. **Jo** and **Otanicar** (**2011**) propose a methodology for quantifying the usable rooftop surface by accounting for existing obstructions like chimneys, air conditioning equipment and skylights that would limit the space available for PV panels.

In practice, different approaches have been applied for estimating the solar energy potential in an urban setting. A state-of-the-art review has been carried out in (**Freitas et al., 2015**) comparing 21 computational solar radiation models ranging from simple 2D visualization and solar constant methods, to more sophisticated 3D representation and web-based solar maps. A common element of the analyzed tools is that they mostly focus on the solar yield only, the demand side and the solar distribution system characteristics are not taken into account. For very precise calculations the most appropriate option is 3Dmodeling and building simulation. A good example to mention is the DIVA tool developed for daylighting and solar energy performance evaluations of individual buildings and urban landscapes (**DIVA, 2015**).

Buildings heterogeneity and the complexity of the urban environment generally require assumptions and input data for the solar energy use computation, which will ensure that only safe propositions and valid information will be produced about PV utilization, thus eliminating possible misleading of researchers and energy policy makers. The key that enhances the significance of the present research was, as supported by **Gadsden et al.** (**2003**) and **Rylatt et al.** (**2001**) the development of an attractive and alternative estimation model, which can extract from digital urban maps the solar energy potential, without the need for time-consuming and expensive site surveys. Therefore, the recognition of the construction constraint variants, which interfere with the solar energy utilization in residential buildings, was set as the primary goal. The second target regarded the formulation of an accepted, validated and comprehensive model for the approximation of the suitable built areas for PVs under both architectural and solar aspects. The latter involve the determination of architecturally available roof areas and thereafter the approximation of suitable unshaded areas.

Several authors have applied GIS techniques, empirical rules and statistical analyses quantifying the solar energy utilization potential in the urban fabric. Some of them took into detailed consideration shading effects and construction restrictions, in order to examine a small-scale sample of representative building typologies and then extrapolate the results on a whole region level (**Theodoridou et al., 2012**). Others, for the same purpose, just applied simplified reducing coefficients on the built urban surfaces studying them as a whole and without in depth calculations. **Wiginton Nguyen** and **Pearce** (**2010**) developed a five-step procedure for estimating the PV potential on rooftop areas, by geographically dividing a certain region, assessing a sample of typical buildings and finally analysing results by applying built areas-population relationships.

For the rooftop PV suitable areas calculation process, they set parameters such as shading effects and roof component unavailable areas, by using relative coefficients found in literature. **Pillai** and **Banerjee** (**2007**) focused on the potential estimation for Solar Water Heating (SWH) systems successfully linking micro and macro-level factors from an individual end-use to a market level, and when it came to detailed accounting for suitable areas, they proposed an arbitrary utilization coefficient.

Similarly, **Lehmann** and **Stefan** (**2003**) presented a mathematical correlation between solar energy usable areas and population density in the EU, while total available roof and facade areas were multiplied by a theoretical exploitation factor of 0.9 and 0.66 respectively. Following the same pattern, **Yue** and **Wang** (**2006**) evaluated wind, solar, and biomass energy sources in rural regions in Taiwan with the aid of GIS analysis, by taking into consideration several local restrictions, whereas for solar potential estimation, a 25% of the total rooftop area of the buildings was supposed to be suitable.

Moreover, **Castro** (**2006**) focused on the forecast of possible future scenarios of grid-connected PV buildings in Spain, without detailed consideration of restrictive installation issues such as shading effects. The International Energy Agency estimated average PV roof areas for certain member states, but the procedure was not described in detail (**IEA, 2002**).

2.4.3 Calculating Solar Energy Potential using DIVA

Assessment of available solar radiation and available shade free roof area are essential to calculate electricity generated from solar PV. Various aspects that are of importance include the efficacy of the photovoltaic panel, maintenance and tilt angle. Conversion of electricity from solar panels involves conversion from Direct Current (DC) to Alternating Current (AC). **Hofierka** and **Kanuk** (**2009**) estimated the photovoltaic potential in urban areas and calculated the total annual electricity output in kWh from a solar panel using the equation 2.31

$$E_{out} = A_e \times E_e \times G \qquad \textbf{Equation. 2.31}$$

Where E_{out} = Annual electricity production in kWh

A_e = Total surface area of solar panel in m^2

E_e = Annual mean power conversion efficiency of solar PV panel

G = Annual total global irradiation (Wh/m^2)

The parametric tool DIVA is an optimized daylight and energy modelling plugin for Rhino 3D. It aids in calculating the energy output from solar radiation incident on a surface as in figure 2.5.

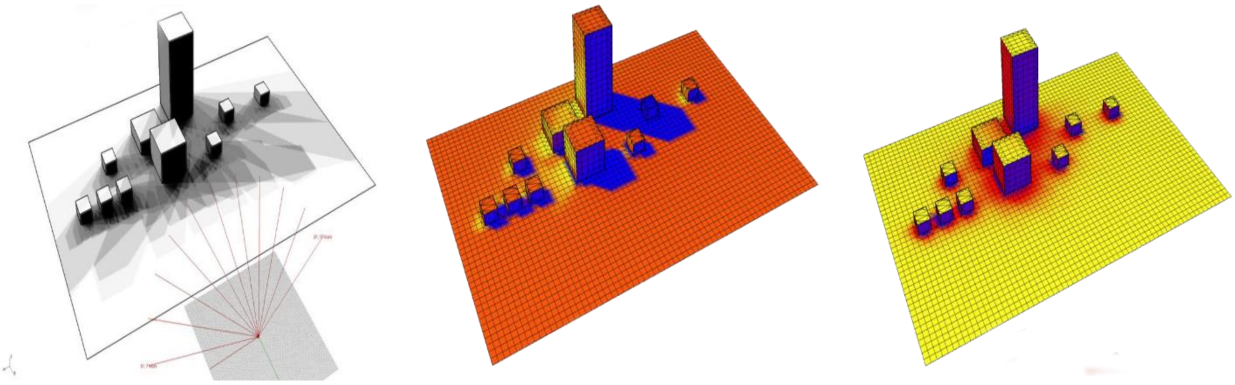


Figure 2.5: Solar Shadow and Radiation Mapping using DIVA for Rhino 3D

Danks et al. (**2014**) compared DIVA with industry standard rendering and geometric tools like RADIANCE, Open Studio and Daysim and found that DIVA and Daysim predicted realistic solar radiation. **Hofer et al.** (**2016**) integrated solar PV panels into shading devices and parametric analysis supported by creating the exact solar 3D solar position over the panels using DIVA. **Jakubiec et al.** (**2011**) used DIVA through grasshopper interface to visualize building performance through parametric design workflow process at the neighbourhood scale. Based on the studies DIVA has been shortlisted to study energy output from rooftop solar PV panels.

2.4.4 Parametric Solar Envelope Algorithm

The solar envelope concept by carries an implied moral obligation to use the sun and to relate to it formally. The designer is encouraged to differentiate building and urban form in graphic response to orientation. One side of a building will not look like another and one side of a street will not look like another. Development will tend to be lower on the south side of a street than on the north where a major southern exposure is thus preserved. Streets take on a directional character where orientation is clearly recognized (**Knowles, 1980**). The solar envelope calls for a design strategy based on natural rhythms. Sunlight is assured within the envelope's boundaries, hence designers can make use of the changing directions and properties of light without fear that a taller building will one day cancel their ideas. The potential exists to conceive of architecture in other than static terms of form and space.

The solar envelope is a construct of space and time: the physical boundaries of surrounding properties and the period of their assured access to sunshine. The way these measures are set decides the envelope's final size and shape. First, the solar envelope avoids unacceptable shadows above designated boundaries along neighbouring property lines; these boundaries have been called shadow fences (**Knowles, 1980**). The height of shadow fences can be set in response to any number of different surrounding elements such as privacy fences, windows, or party walls. Their height may also be set by adjacent land-uses with, for example, housing demanding lower shadow fences than commercial or industrial uses. Different heights of shadow fence will affect the shape and size of the solar envelope as displayed in figure 2.6.

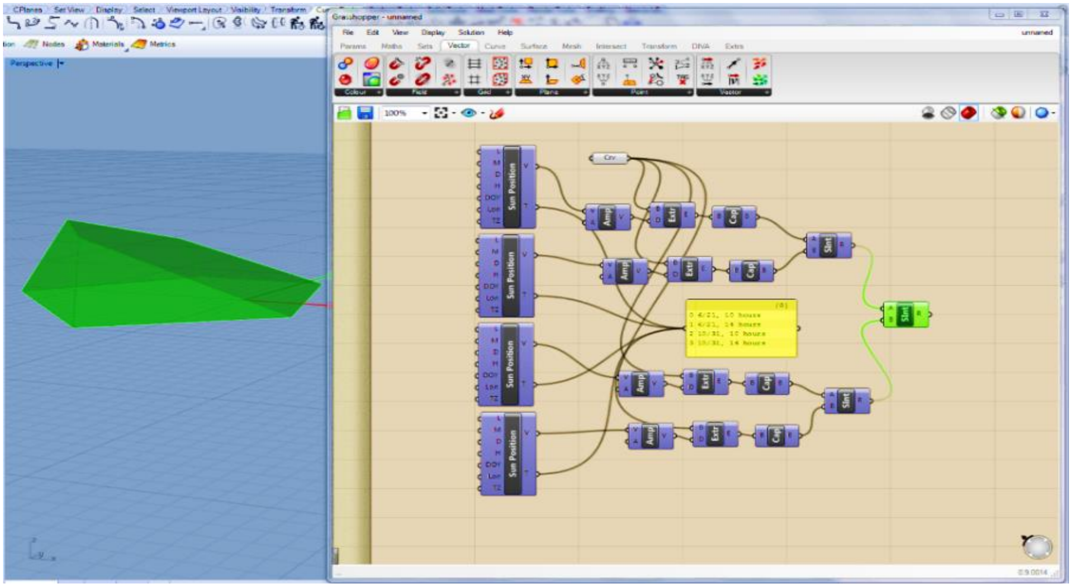


Figure 2.6: Parametric Algorithm to generate Solar Envelope

Second, the envelope provides the largest volume within time constraints, called cut-off times. The envelope accomplishes this by defining the largest theoretical container of space that would not cast shadows off-site between specified times of the day. Greater periods of assured solar access will be more constraining on the solar envelope.

2.5 Basis of Hybrid Energy Mix (HEM) Model

In recent years, renewable power generation has become good choice to meet environmental protection requirements and electricity demands. Because of the complementary between solar and wind energy resources, solar-wind-diesel hybrid systems present an unbeatable option for the supply of small electrical loads for some remote locations where no utility grid power supply exists (**Diaf, 2007**). Sometimes, when there is no sun, there is plenty of wind. Compared with standalone solar or wind systems, the PV-wind hybrid system has two main advantages. First the reliability of the system is enhanced. Secondly, the size of battery storage can be reduced.

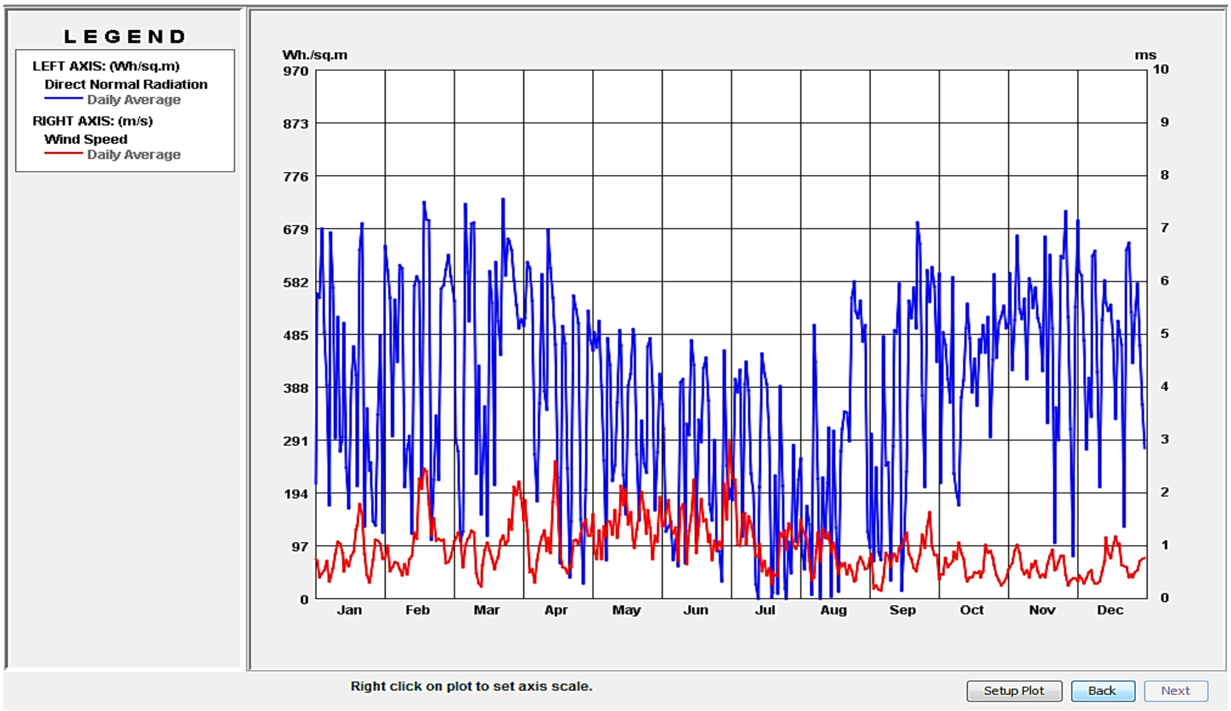


Figure 2.7: Annual Wind Speed and Direct Normal Radiation Graph of Chandigarh

In case of CUC, figure 2.7 highlights that from May to July low Direct Normal Irradiation (DNI) represented by blue line is compensated by high wind speeds represented by red line, whereas from October to December high DNI balance out low wind speeds. It is during the month of July to August that both the resources have their lowest availability and need a third source to compensate for the shortage in power generation.

There are various Hybrid Energy Models proposed in previous studies, but for the purpose of the study and defining a Solar PV, Wind, Diesel Generator based Residential Hybrid Energy Mix (RHEM) model a two-step process is used. The first step involves defining the various components of the energy mix that will be part of the model.

a) Solar PV Array

The output from the Solar PV array is calculated on basis of the equation 2.32

$$E_{\textit{Solar PV}} = Y_{PV}\ F_{PV}\ (G_T / G_{T,STC})\ [1+\alpha\ (T_c - T_{c,STC})]$$ **Equation 2.32**

Where

Y_{PV} = Rated capacity of the PV array (power output under standard test condition (kW)

F_{PV} = PV derating factor

G_T = Solar radiation incident on the PV array in current time step (kW/ m^2)

$G_{T,STC}$ = Incident radiation at standard test condition (1 kW/m2)

α = Temperature co-efficient of power (% °C)

Tc = PV cell temperature in the current time step (°C)

$T_{c,STC}$ = PV cell temperature under standard test condition (25°C)

Temperature effects the overall performance of Solar PV cells but if the assumption is that there is no effect of temperature on the PV array, then the temperature co-efficient of power (α) is considered to be zero and equation 2.33 is modified as:

$$E_{\textit{Solar PV}} = Y_{PV}\ F_{PV}\ (G_T - G_{T,STC})$$ **Equation 2.33**

b) Wind Turbine

The output from the wind turbine is calculated on basis of the equation 2.34

$$E_{\textit{Solar PV}} = 0.5\ A\ \rho\ V_3\ C_p\ (\beta, \lambda)$$ **Equation 2.34**

Where

A = Rotor swept area in m^2

β = Pitch angle

ρ = Air density in kg/m^3

λ = Speed ratio

V = Wind velocity (m/sec)

C_p = Power co-efficient of wind turbine specific to the wind turbine design

c) Diesel Generator

The diesel generator is a standby power option. The output of the diesel generator is based on listed parameters and manufacturer specifications in HOMER software (www.homer.com).

i) Intercept Coefficient (no load fuel consumption of generator / rated capacity) (l/hr/kW)
ii) Slope (marginal fuel consumption of the generator) (l/hr/kW)
iii) Lower Heating Value
iv) Density (kg/m3)
v) Carbon Content (%)
vi) Sulfur Content (%)
vii) Lifetime (Years)

d) Battery

The typical parameters of the battery bank listed below and basis of its performance are defined by manufacturer specifications in HOMER software (www.homer.com).

i) Nominal Capacity (kWh)
ii) Nominal voltage (V)
iii) Nominal capacity (Ah)
iv) Round trip efficiency (%)
v) Max charge current (A)
vi) Max discharge current (A)
vii) Lifetime (Years)
viii) Cell stack lifetime (Years)

e) Converter

The primary role of the converter is to convert AC to DC (rectifier) or DC to AC (inverter). The efficiency of the inverter or rectifier is based on manufacturer specifications defined in the HOMER software (www.homer.com).

2.5.1 Optimization Method – Stage 1

The optimization of the RHEM model is undertaken at two stages. The first step deals with the Power Balance Constraint defined by the equation 2.35.

$$E_{\textit{Solar PV}} + E_{\textit{Wind Turbine}} + E_{\textit{Diesel Generator}} + E_{\textit{Battery}} = E_{\textit{Household Load}} + E_{\textit{Unmet}} + E_{\textit{Loss}} + E_{\textit{Excess Power}}$$ **Equation 2.35**

Where

P_{pv} = PV array output power
P_{load} = Load consumption power
$P_{generator}$ = Generator output power
$P_{battery}$ = Battery output power
P_{wind} = Wind turbine output power
P_{loss} = Loss power
P_{unmet} = Unmet power
P_{exc} = Excess power

The power reliability constraint is given by equation 2.36

$$W_{\textit{Unmet}} / W_{\textit{Consumption}} \leq 0.1\%$$ **Equation 2.36**

Where

$W_{\textit{Unmet}}$ = Unmet work per year
$W_{\textit{Consumption}}$ = Load consumption work per year

2.5.2 Optimization Method – Stage 2

The outcome of stage 1 are ranked based on their qualification with respect to the Net Present Cost (NPC) as defined in equation 2.37.

$$NPC = C_i + C_r \times f_d + C_o \times f_d + C_f \times f_d - S \times f_d$$ **Equation 2.37**

Where

C_i = Capital cost
f_d = Discount factor
C_f = Fuel cost
C_r = Replacement cost
C_o = Operation cost
S = Salvage value

The hybrid energy model defines the optimum energy mix to generate desired energy output with financial options. The model calibrates both the maximum and minimum investment required and corresponding benefits. It depends on the end user to define the investment factor or the output desired to come to a conclusion.

2.6 Chandigarh and its Residential Energy Consumption Pattern

The Union Territory of Chandigarh (latitude 30° 44’ 29.335” N, longitude 76° 46’ 5.0376” E and altitude 308 meters) as shown in figure 2.8 is located in the foothills of the Shivalik hill ranges in the north, which form a part of the fragile Himalayan ecosystem.

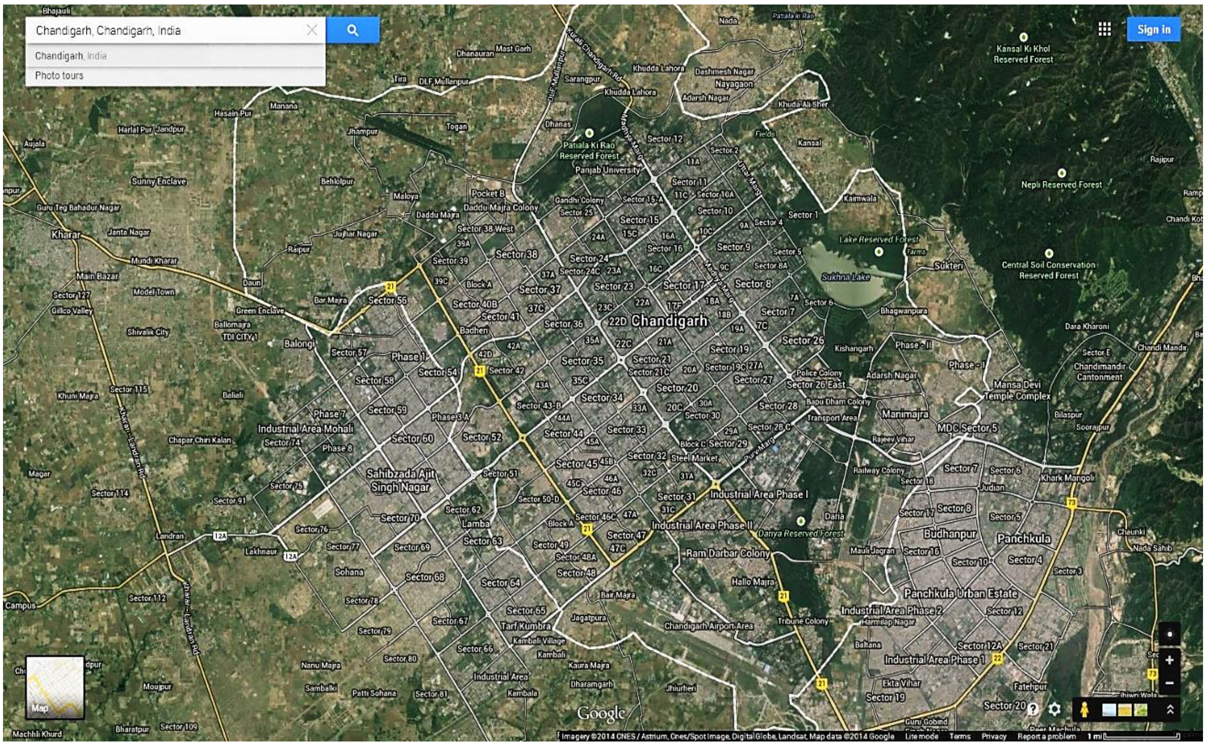
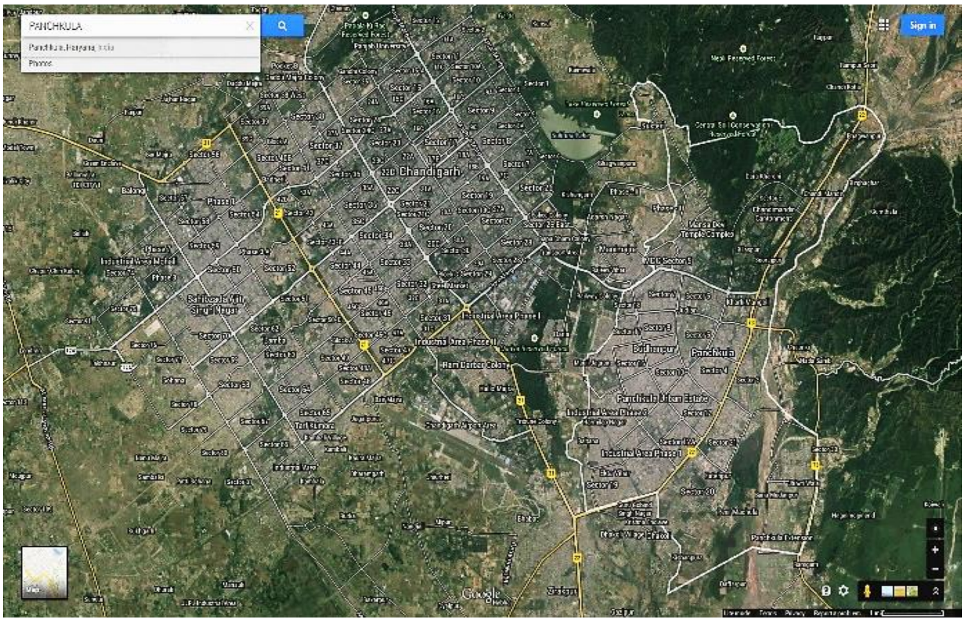


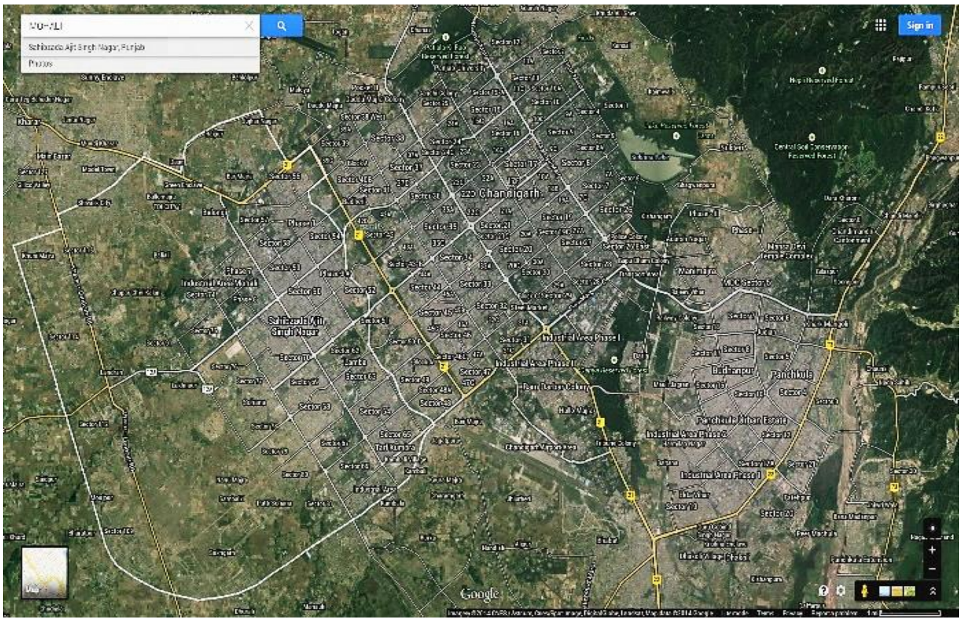
Figure 2.8: Administrative Boundary Map of Chandigarh UT

It covers an area of approximately 114 km² and shares its borders with the states of Haryana in the south and Punjab in the north. The surrounding districts are of Mohali, Patiala and Ropar in Punjab and Panchkula and Ambala in Haryana.

The UT of Chandigarh has only been declared at 'Solar City' in 2011. But with the surrounding counter magnet cities of Panchkula, show in fig 2.9(a) from Haryana and Mohali, shown in fig. 2.9 (b) from Punjab included into a combined area called the Chandigarh Urban Complex (CUC), the study was conducted for the whole of CUC.



a) Panchkula, Haryana



b) Mohali, Punjab

Figure 2.9: Administrative Boundary Map of Panchkula (Haryana) and Mohali (Punjab)

Chandigarh has a sub-tropical continental monsoon climate characterized by a seasonal rhythm: hot summers, cold winters, unreliable rainfall and great variation in temperature (- 1°C to 41.2°C). The 20 year average rainfall for Chandigarh is 1100.7mm. The area experiences primary four seasons:

i) Summer or hot season (March to June)
ii) Monsoon (July to August)
iii) Autumn (September to October)
iv) Winter (November to February)

In order to quantify the Residential Electricity Consumption (REC) in Chandigarh, it is important to understand the profile of existing energy consumption pattern. Residential Electricity consumption (REC) is the total electricity used by households to run appliances like ceiling fans, televisions, and refrigerators. New technology can be energy efficient but also makes usage of more appliances affordable resulting in higher ownership. Rapid electrification, increasing incomes, and technology development is resulting in people buying more appliances in the future and thus using more electricity to run them. As per Census of India, 2011 was estimated to be 10.265 lakh, whereas the population of Panchkula (Urban) was 2.12 lakh and that of Mohali (Urban) was 1.47 lakh.

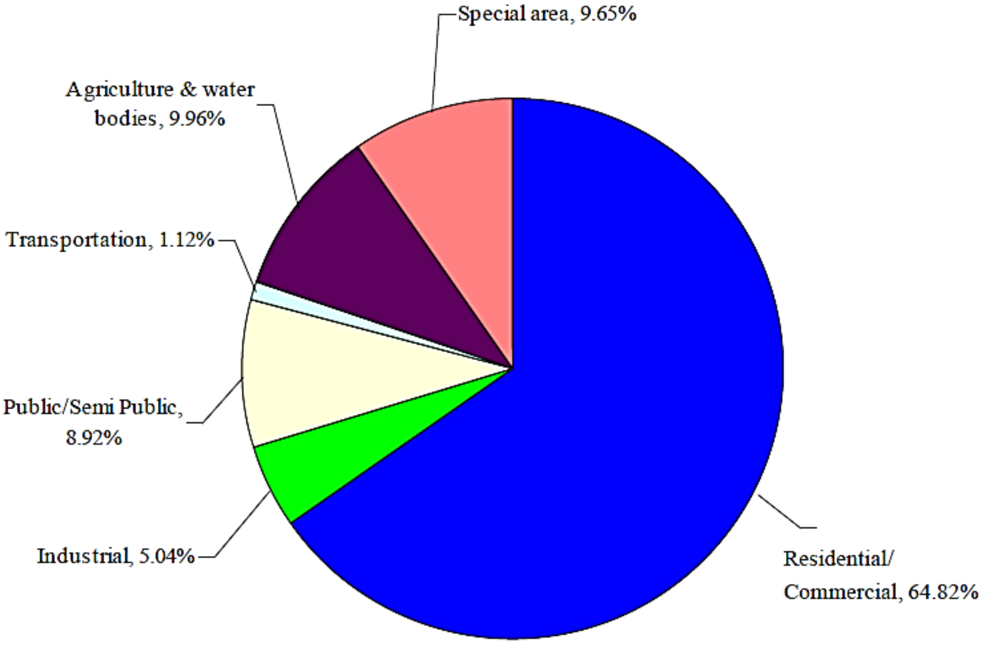


Figure 2.10: **Land Use Pattern of Chandigarh**
(Source: http://chandigarh.gov.in)

Chandigarh city covers an area of approximately 114 km2 (i.e. 28169.9 acres). In addition 25.42 km2 of hilly catchments area is declared as Wildlife Sanctuary. It has been observed that the residential and commercial sectors cover the maximum area of the city. This sector covers an area of 73.9 km2, followed by agriculture & water bodies (11.36 km2), industrial (5.75 km2), public/semi-public (10.71 km2) and transportation (1.28 km2) and around 9.65% (11 km2) is categorized as special area. The land use pattern of Chandigarh is presented in figure 2.10.

2.6.1 Electricity Consumption Scenario

The peak electricity demand of Chandigarh is around 284 MW which is being met from different Central/State Generating stations22. The UT Chandigarh has no generating capacity of its own. At present, the City is receiving 67% of its power through Mohali (PSEB), about 10% through Dhulkote (BBMB) and remaining 23% through Nalagarh. The connected load of the Chandigarh is reported as 901.78 MW; while the maximum demand is approximately 284 MW. The connected load of public lighting has been reported as 3.51 MW.

Chandigarh city ranks first in India in the Human Development Index23, quality of life and e-readiness; hence per capita electricity consumption of the city is much higher than that for India. The per capita consumption of electricity in Chandigarh has increased from 253 kWh in 1967-68 to 1224 kWh in 2007-08. Accordingly the electricity consumption has increased from 0.138 MU per day to 5.5 MU on a particular day. Figure 2.11 presents the pattern of per capita electricity consumption in Chandigarh from the year 2000 to 2006.

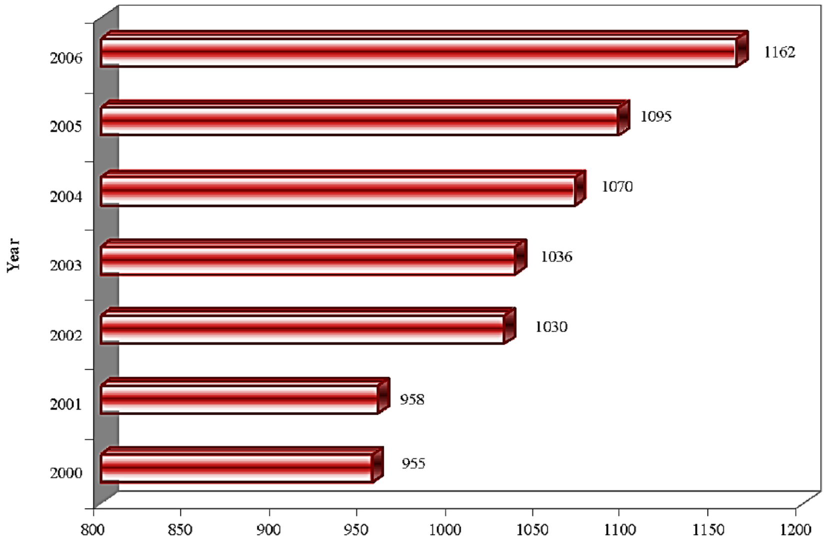


Figure 2.11: **Per Capita Electricity Consumption of Chandigarh**
(Source: www.indiastat.com and www.chandigarh.gov.in)

The major energy consuming categories are residential, commercial/Institutional (offices and shops), municipal services, industrial and transport. Within residential, commercial and municipal services, the major energy sources of energy are electricity, LPG, and kerosene. The Residential sector of Chandigarh is the major electricity consumer and utilizes 36.68 percent of the total electricity consumption of the city as per the Engineering Department (Electricity Wing), Chandigarh Administration. Figure 2.12 presents the sectoral electricity consumption pattern of the city in 2006-07.

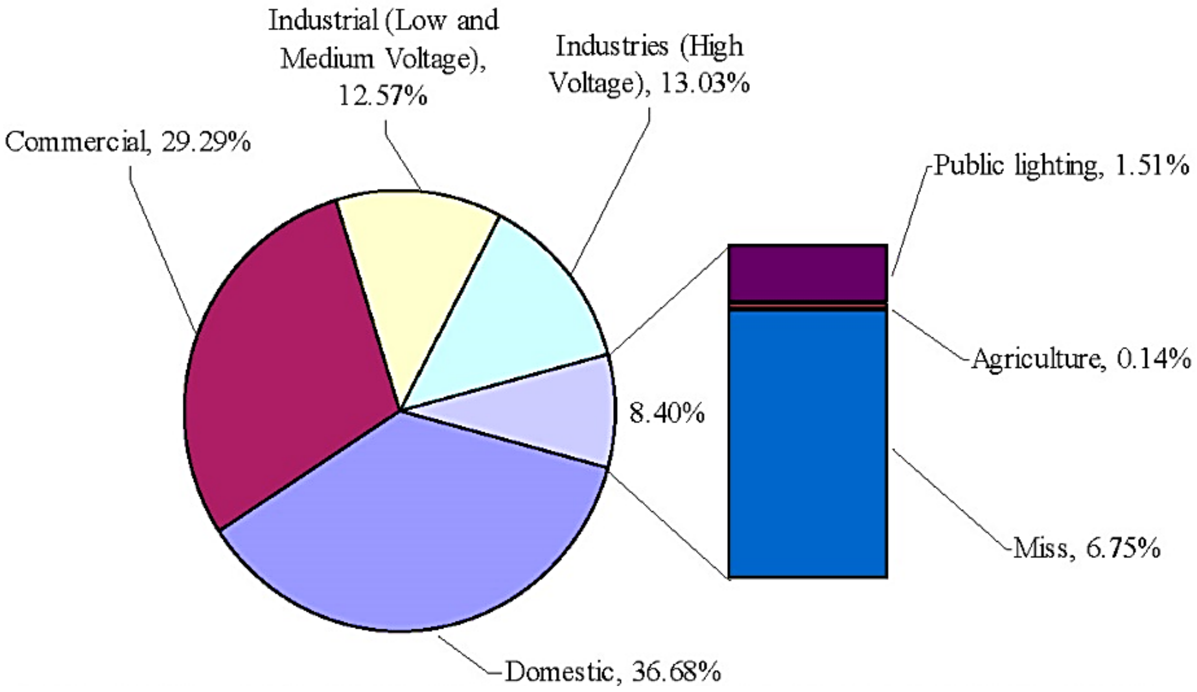


Figure 2.12: **Sector-wise annual electricity consumption (in MU)**
(Source: www.chandigarh.nic.in/statistics)

2.6.2 Residential Sector of Chandigarh

Chandigarh is the first planned city of the country and has highest per capita income (Rs 1, 10,676 in 2008) in India. Hence it might be assumed that maximum of the households are in medium and high income levels. According to Census 2011 there are 244134 houses in Chandigarh; out of which 26428 houses are located in rural area and 217706 houses are in urban area of the city. It has been observed that more than 90 percent houses are permanent type, 7 percent are semi-permanent and around 3 percent are temporary houses in the city. Figure 2.13 presents the use pattern of census houses in the city.

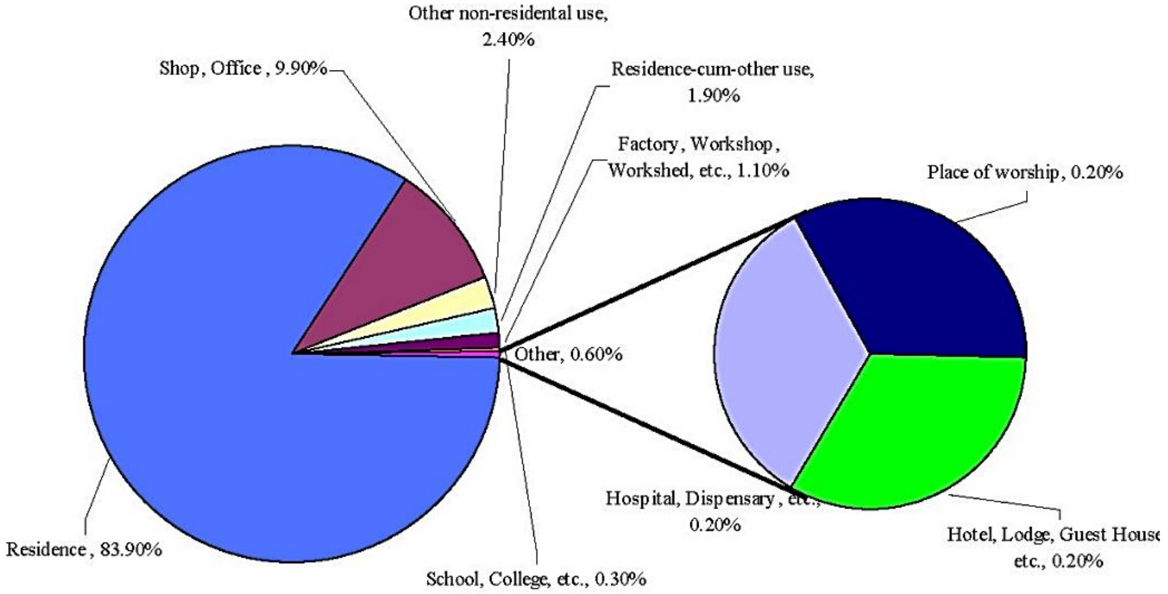


Figure 2.13: **Usage Pattern of Census Houses of Chandigarh**
(Source: Census of India 2011)

The distribution of total households of the city has been made on the basis of number of members and numbers of dwelling room in the house. The city has maximum one dwelling room houses (41.9 %) followed by two rooms (24.8%), three rooms (18.6%) and up to six rooms and above (3.3%). It has been observed that the average family size of the city is 4.4 persons per household and median 2 of the number of rooms. Household statistics of the city has been presented for distribution by size of house and size of family by in figures 2.14 and 2.15 respectively.

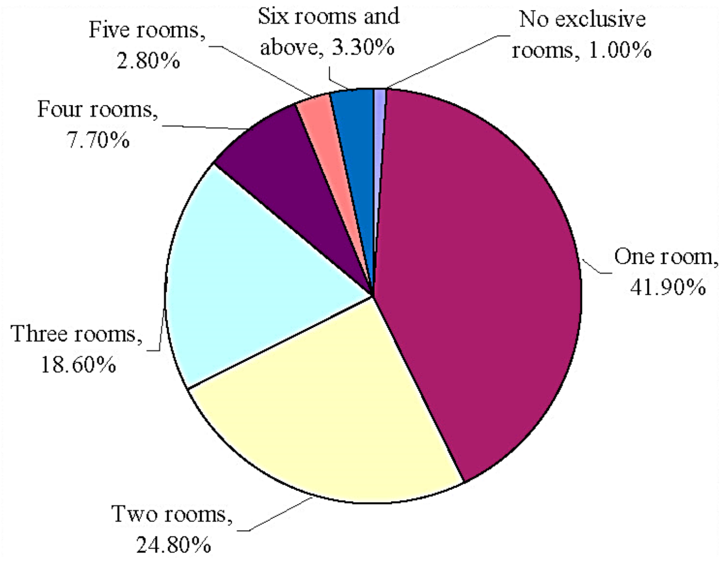


Figure 2.14: **Distribution of Households by number of Dwelling Rooms**
(Source: Census of India 2011)

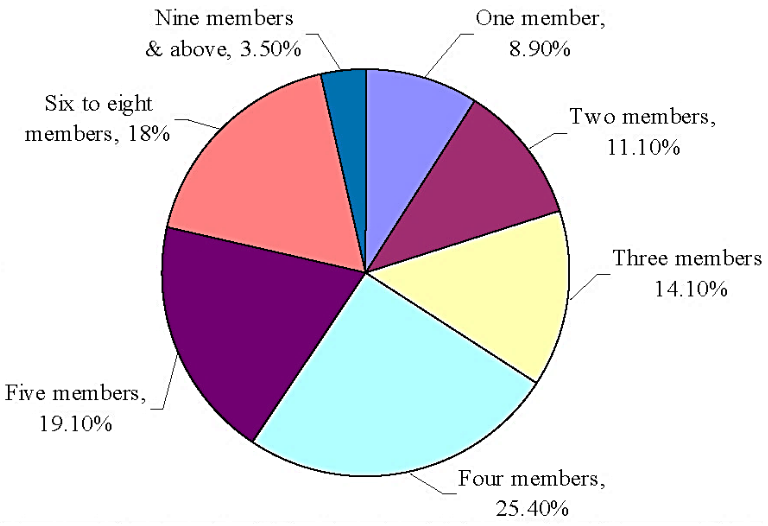


Figure 2.15: **Distribution of Households by Family Size**
(Source: Census of India 2011)

The electricity consumption in residential sector of Chandigarh is rapidly increasing as shown in figure 2.16. The total electricity consumption in residential sector was reported as 435.35 MU in 2007; while it was 357 MU in 2004. With almost all residential houses of the Chandigarh city are fully electrified, it is estimated that out of total households 99.3 percent were electrified in 2011 and using electricity for lighting application.

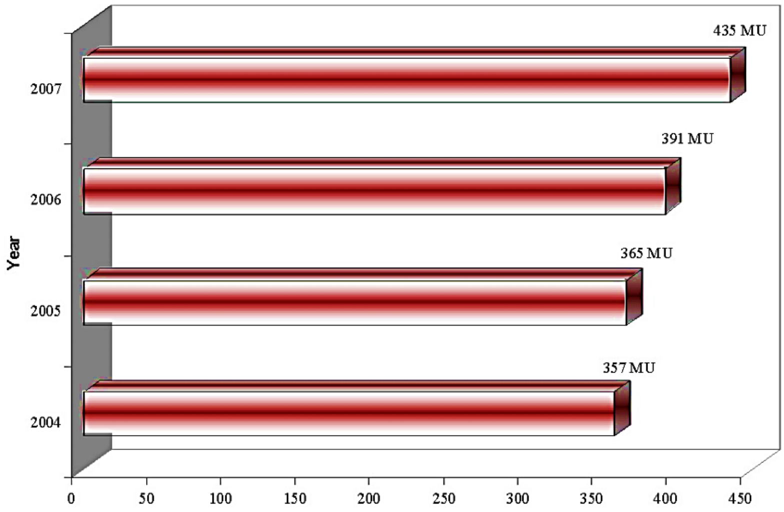


Figure 2.16: **Total Electricity Consumption in the Residential Sector of Chandigarh**
(Source: Environment Information System (ENVIS Centre) Chandigarh)

The load distribution pattern in residential sector of Chandigarh has been assumed similar to a planned city; which shows energy consumption pattern in domestic applications. The distribution of electricity consumption in the residential sector as presented in figure 2.17 shows that cooling and lighting consumes more than 70 percent of the electricity. This is a more generic view and needs to be reconfirmed through house hold surveys.

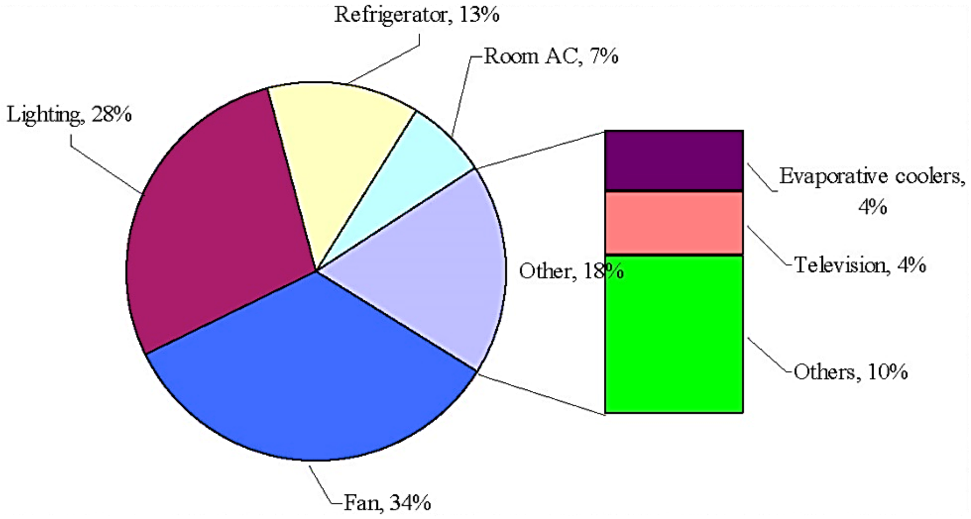


Figure 2.17: **Electricity Consumption Pattern in Residential Sector**
(Source: Steps towards an Energy Efficient Building)

2.6.3 Energy Demand Forecast of Chandigarh

In has been observed that the per capita consumption of electricity in Chandigarh has increased from 253 kWh in 1967- 68 to 1615 kWh in 2010-12. On the basis of time series based data of last seven years it is estimated that the per capita electricity consumption will be increased up to 1827 kWh in 2018 (short term); and up to 2019 (long term) it will be 1975 kWh. Hence the per capita electricity will be increased up to 60 percent. The projection trend of per capita electricity consumption with years is presented in figure 2.18.

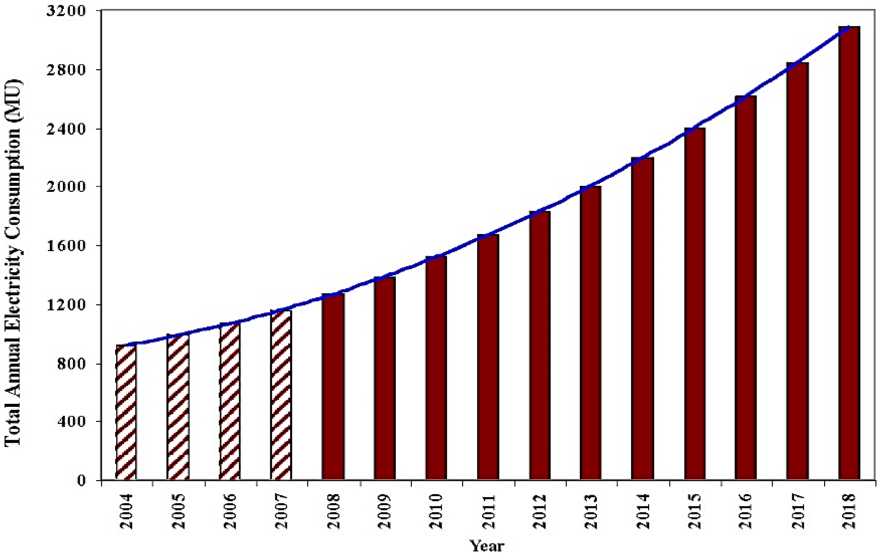


Figure 2.18: **Per capita Electricity Consumption in Chandigarh**
(Source: www.indiastat.com and www.chandigarh.gov.in)

2.6.4 Electricity Consumption in Residential Sector

The time series forecasting has been made on basis of the data of electricity consumption in residential sector from 2008 to 2012. It is estimated that the total electricity consumption in residential sector will increase up to 1246 MU in 2014 and 2103 MU in 2018; while it was reported as 435MU in 2007. Figure 2.19 presents the projection of electricity demand in residential sector up to 2018. The residential sector as per future projections has been found to be the major energy consumer sector in the city followed by commercial and industrial sectors. Figure 2.20 presents the comparative pattern of annual electricity consumption in various sectors with the total electricity consumption up to 2018.

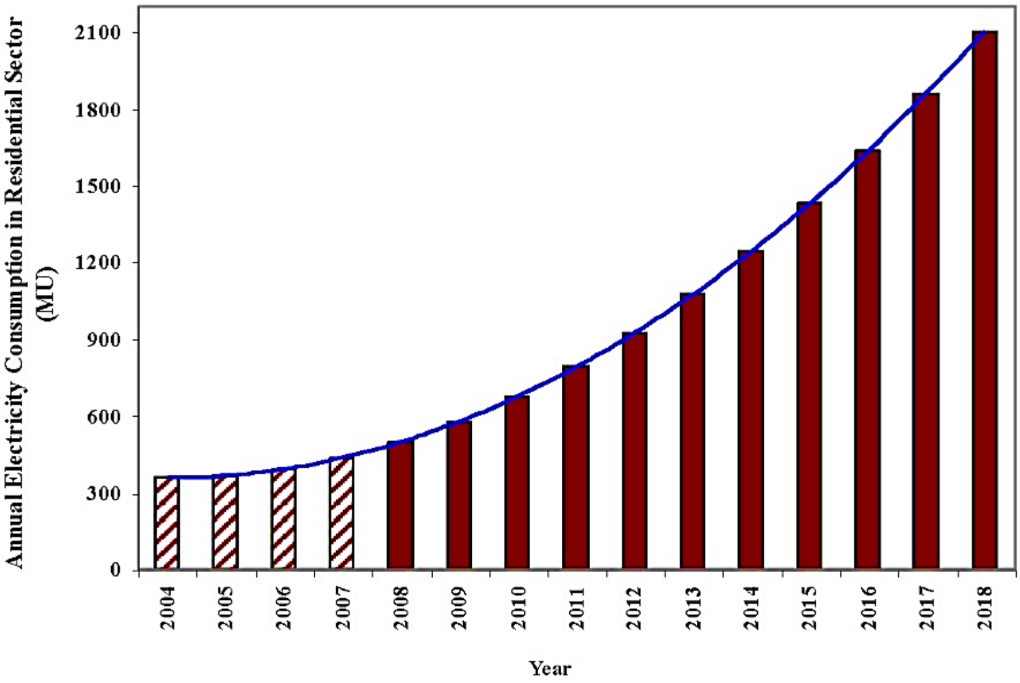


Figure 2.19: **Total electricity Consumption in the Residential Sector**
(Source: Environment Information System (ENVIS Centre) Chandigarh)

Figure 2.21 highlights the contribution of electricity towards Green House Gas Emissions and with the Government of India on October 02, 2016 committing through its Nationally Determined Contribution (NDC) under the Paris Agreement to lower its carbon emissions intensity in 2030 by 33-35% of its GDP from 2005 levels and also generate 40% of its energy from non-fossil based fuels. This was followed by the creation of National Energy Policy which aims to ensure 175 GW renewable energy generation by 2022. An extension of the same is the National Solar Mission under which cities around India have been termed as ‘Solar Cities’ and measures to promote renewable energy systems primarily solar based are in place.

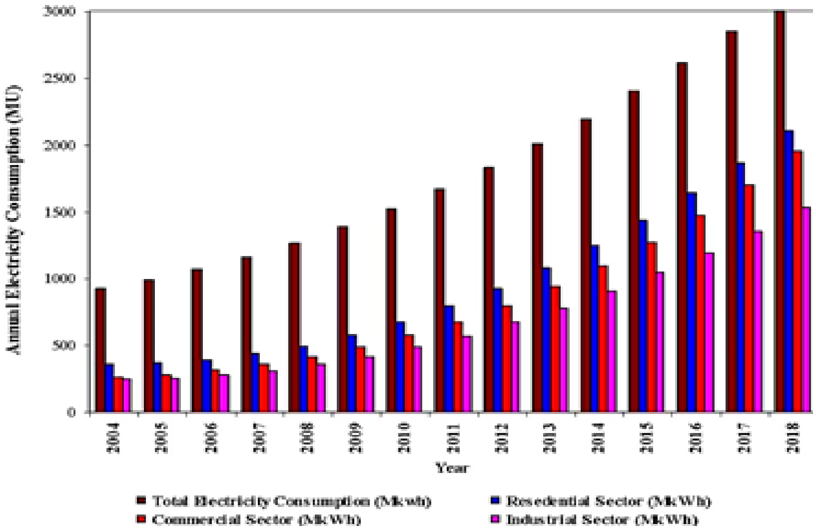


Figure 2.20: **Annual Electricity consumption in various sectors of Chandigarh**
(Source: Environment Information System (ENVIS Centre) Chandigarh)

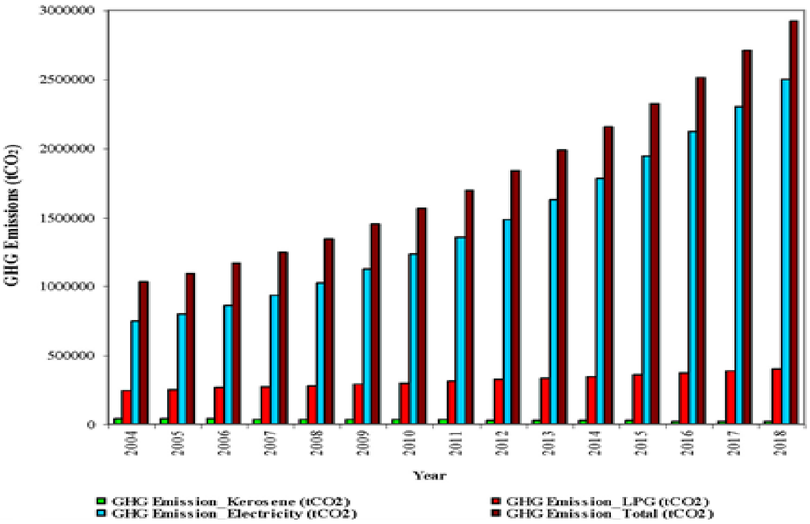


Figure 2.21: **GHG emissions from energy supplied to Chandigarh**
(Source: Environment Information System (ENVIS Centre) Chandigarh)

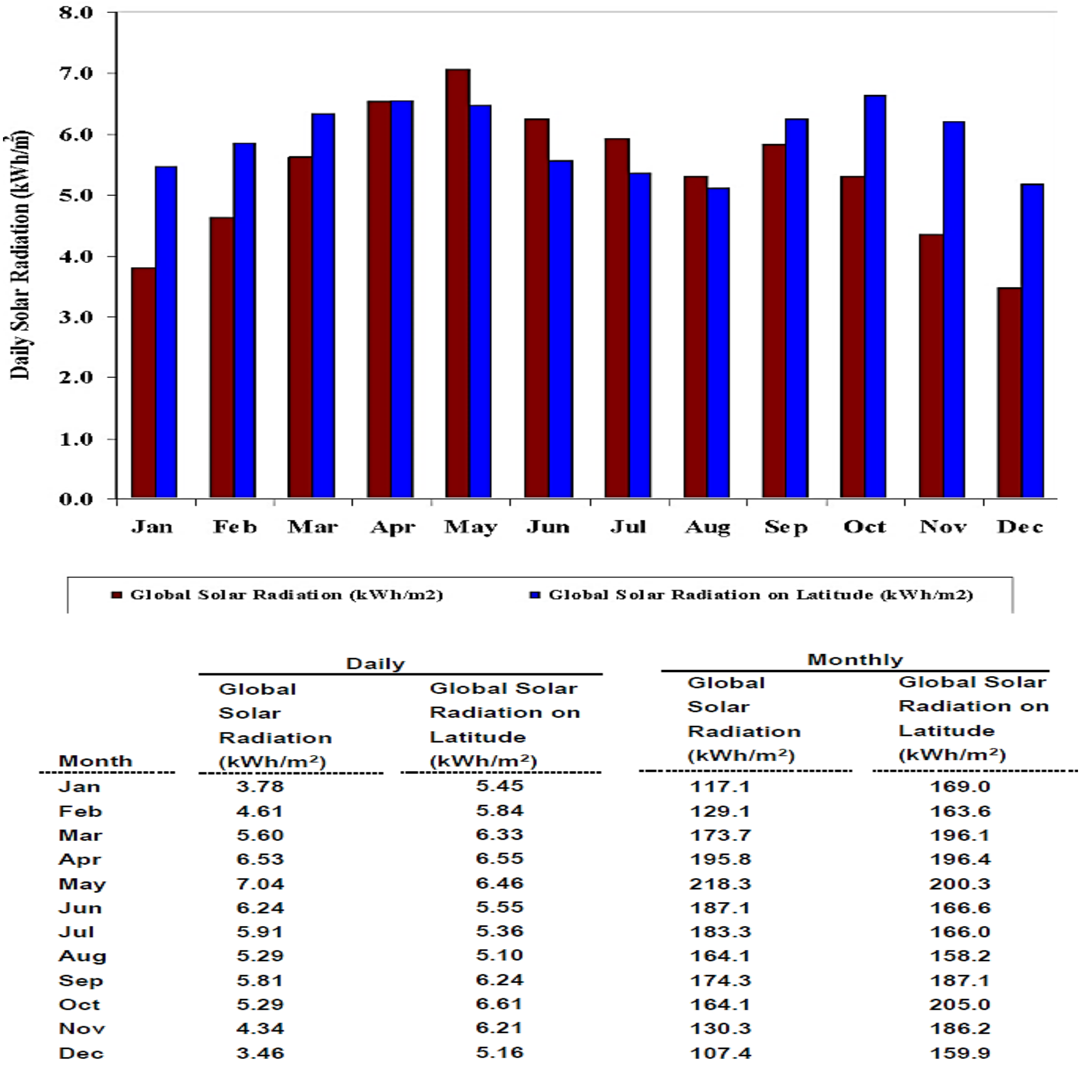
2.7 Renewable Energy Resource Availability in and Around Chandigarh

Chandigarh has a wide forest and agricultural land around it making it quite rich in biomass resources. But a major portion of the forest is protected and reserve, transporting agricultural waste and storing it creates logistic and storage problems. Also, the ban on burning of agricultural waste that leads to pollution doesn't permit agricultural waste as a fuel source. Therefore there is negligible scope for biomass based power generation in Chandigarh. Municipal Solid Waste (MSW) predominantly household or domestic waste collected from all sectors is categorized and being transported to the dumping ground at a landfill site of 46 acres near village

Dadu Majra run by a private company, Sector-38. With no MSW plant of its own Chandigarh cannot generate power from waste.

2.7.1 Solar Energy

Chandigarh receives a good amount of solar radiation over the year. It has been observed that the annual global solar radiation over the city is 1944 kWh/m^2, while the annual diffuse radiation is 846 kWh/m^2. The global solar radiation over the inclined surface (at latitude) is estimated as 2155 kWh/m^2 annually. Figure 2.22 presents the daily values of solar radiation on horizontal and inclined surface in Chandigarh for each month. The data needs to be verified with real time or latest information collected from Chandigarh Meteorological Department.



	Daily		Monthly	
Month	Global Solar Radiation (kWh/m^2)	Global Solar Radiation on Latitude (kWh/m^2)	Global Solar Radiation (kWh/m^2)	Global Solar Radiation on Latitude (kWh/m^2)
Jan	3.78	5.45	117.1	169.0
Feb	4.61	5.84	129.1	163.6
Mar	5.60	6.33	173.7	196.1
Apr	6.53	6.55	195.8	196.4
May	7.04	6.46	218.3	200.3
Jun	6.24	5.55	187.1	166.6
Jul	5.91	5.36	183.3	166.0
Aug	5.29	5.10	164.1	158.2
Sep	5.81	6.24	174.3	187.1
Oct	5.29	6.61	164.1	205.0
Nov	4.34	6.21	130.3	186.2
Dec	3.46	5.16	107.4	159.9

Figure 2.22: **Solar Radiation Information of Chandigarh**
(Source: ENVIS Centre, Chandigarh)

2.8 Conclusion

The literature studies undertaken as part of the chapter give an insight into the field of renewable energy generation based on solar and wind resources. From an architect's perspective the various studies undertaken and tools applied to address multi-dimensional issues and promote micro generation in various housing typologies are discussed. Estimating the household energy demand based on bottom up approach aids in defining the energy targets to be attained by renewable energy infrastructure. The potential of wind energy is understood on basis of statistical tools as well as advanced CFD simulations that result in more precise comprehension of wind behaviour and wind speed estimation in and around buildings. The understanding of solar energy is limited to retrofitting in the housing sector. Certain modern day computational tools are also revisited to revive forgotten concepts like the Solar Envelope and its application in promoting renewable energy generation and reducing energy consumption. Finally, the study of energy models are undertaken to highlight the need for promotion of hybrid energy systems over standalone setup. In this perspective the role of HOMER software in defining the choice and mix of hybrid energy system to be employed as part of the research is reviewed. The chapter concludes with a discussion based on data from secondary sources on the existing energy scenario of the case study area which forms the basis of work in the subsequent chapters.

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Chapter 3

Built Form and Energy Consumption Pattern of Chandigarh Urban Complex

3.1 Choice of Urban Centre

Due to the increase in energy consumption and rise of dependency on energy imports, the efficient use of energy is becoming increasingly important. On a generic scale, out of the total energy produced around 45% is spent to meet the demands of the housing sector. Domestic energy consumption is highly dependent on its housing typologies, location, various energy consuming activities within the household, socio-demographic and economic conditions of the occupants, varied needs of multiple age groups within the house, types of electrical appliances and their efficiency, etc.

To detail out the performance of micro-generation in the housing sector with such variable factors, it is necessary to define the choice of urban centre as part of study. The choice should ideally be uniform in development, have different housing typologies in its urban form, reinforced strict urban controls so that any proposal if implemented would have a uniform degree of implementation and output. The locational factor of the urban centre should be such that it faces extreme conditions of weather with no major energy generation resource. Such an urban centre would be the ideal platform to demonstrate the true potential of renewable micro-generation and its role in meeting demands of the housing sector. The search for such a city point towards one obvious choice – **Chandigarh**.

3.2 Introduction to Chandigarh Urban Complex (CUC)

Why Chandigarh? Chandigarh is the capital of two neighbouring states of India, Haryana and Punjab. It has earned the status of a Union Territory with an independent administrative area of its own. It was the outcome of partition of India after its independence, a vision of then Prime Minister of India, Pandit Jawaharlal Nehru – as a model city of Independent India and hope to house the migrating population without disparity from Pakistan.

Chandigarh also termed as ‘The City Beautiful’ owing to its lush greenery and beautiful surrounding context was envisaged and conceived by renowned international architect, Le Corbusier. It is to date one of the best examples of urban design and architectural excellence world over. It has varied housing typologies to meet the needs of varied socio-economic groups ranging from low rise plotted and row (low, medium and high density) housing to medium rise low density and medium rise high density developments.

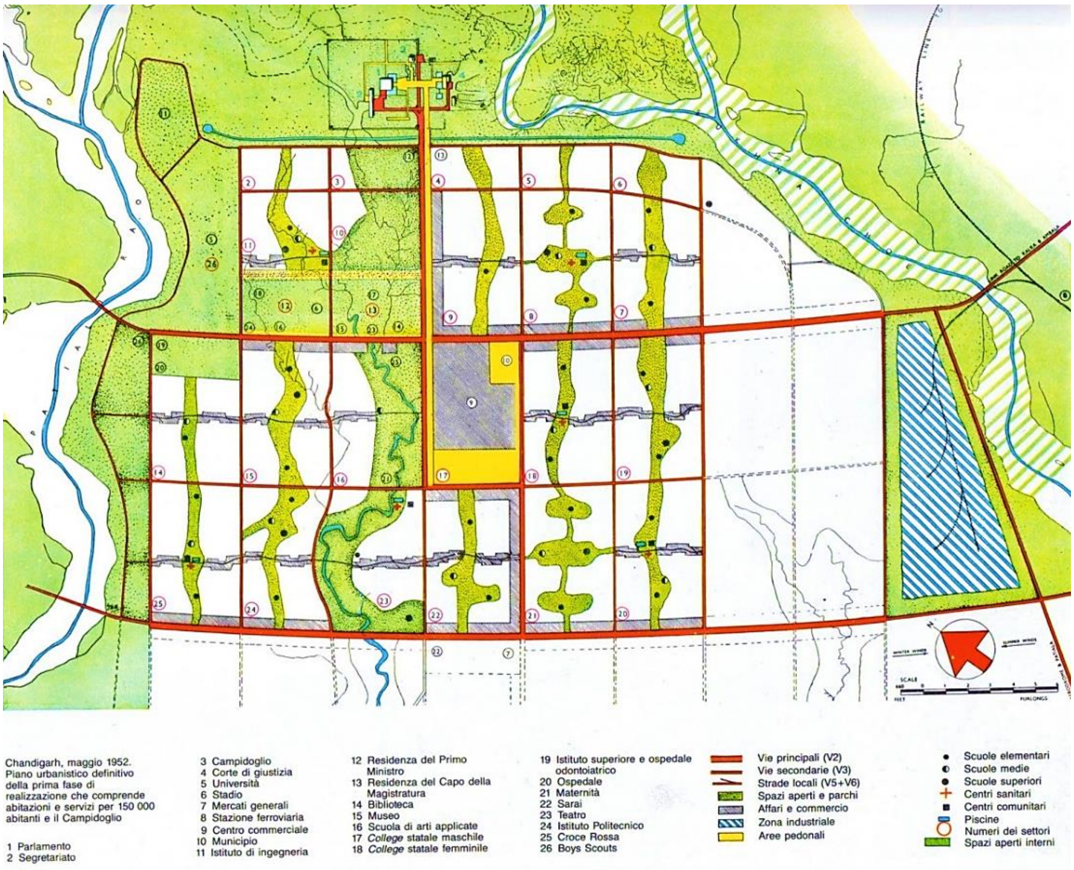


Figure 3.1: **Layout Plan of Chandigarh as proposed by Le Corbusier**
(Source: www.fondationlecorbusier.fr)

Aided with a high rank in the Human Development Index, the lifestyle of the people and their affluence to electrical energy consuming devices has resulted in increasing domestic energy demand. Locational factors and harsh climatic conditions with hot summer and cold winters are also a major cause of high energy consumption. Electricity is imported from neighbouring states with major source of power being the Bhakra-Nangal Hydel Power Project, Himachal Pradesh. With increasing energy demand, new sources of power with decentralized generation need to be exploited and promoted to meet seasonal variations and handle urban disasters.

Chandigarh has been continuously growing. Over the past decade it has been experiencing an average decadal population growth rate of 11.4% that has resulted in the development of counter magnets in the neighbouring states of Punjab and Haryana. The new urban centres – Panchkula in Haryana and Mohali in Punjab have been developing on the sectoral pattern of Chandigarh.

Chandigarh today is trying to balance the rapid urban growth and also maintain the architectural character. With strict built form development controls already in force to preserve the identity of the city, the housing typologies of Chandigarh are not expected to undergo major changes thereby ensuring uniform implementation of strategies at household level. As a result the new development areas in Panchkula and Mohali are experiencing maximum growth with increasing high rise high density housing.

To promote uniform urban development and infrastructure sharing, an administrative boundary termed as the Chandigarh Urban Complex (CUC) as indicated in figure 3.2 was defined as part of a plan prepared by the Chandigarh Union Territory Government comprising of urban areas spanning three administrative regions - Chandigarh Union Territory, Mohali (Punjab) and Panchkula (Haryana) along with peripheral cluster of small villages and towns in 2011 **(TCPO, 2011)**. With 80% portion of land use meant for residential and commercial development, CUC is the ideal site to study the impact of built environment on micro generation of energy in the domestic sector.

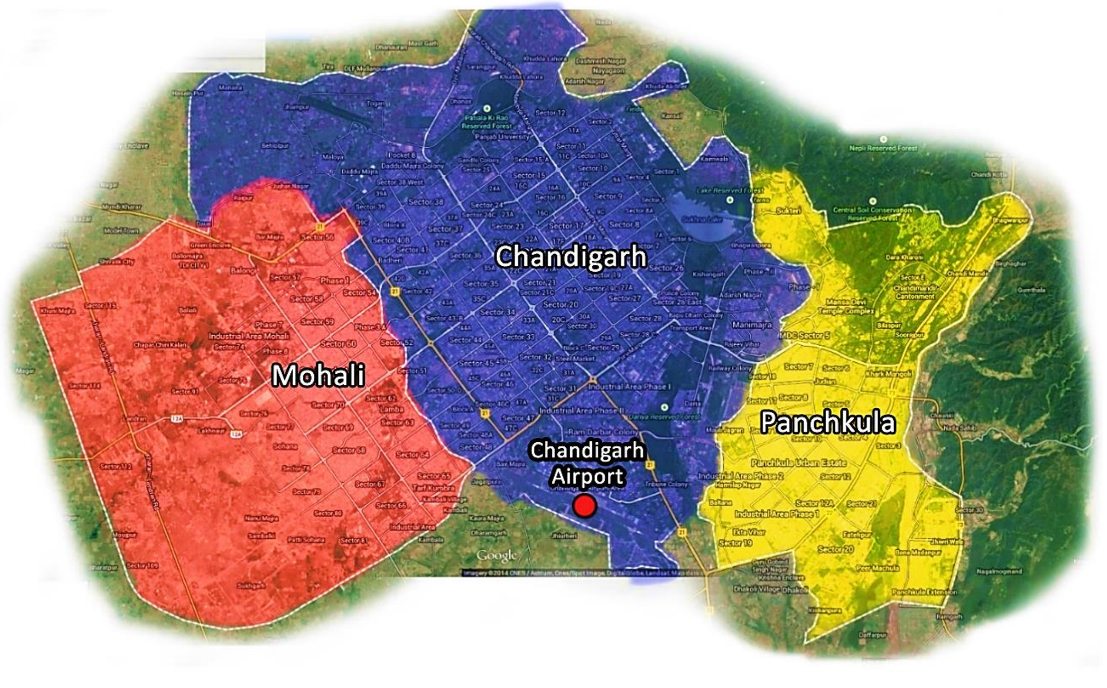


Figure 3.2: **Urban Areas forming Chandigarh Urban Complex (CUC)**
(Source: With reference from www.maps.google.com)

3.2.1 Locational and Climatic Features of CUC

Chandigarh Urban Complex (CUC) is located at 30.73° N latitude, 76.78° E longitude at an altitude of 350 meters above mean sea level. It is situated at the foothills of the Shivalik ranges, forming part of the Himalayan ecosystem. It is listed under the Zone IV (high hazard) zone of earthquake categories. The city is flanked by Haryana on the east, on the west and south by Punjab and on the north by Himachal Pradesh. The primary weather information for Chandigarh Urban Complex (CUC) is collected from the Weather Station at Chandigarh International Airport. The climatic data ranges from January 01, 2010 to December 31, 2015 and is collected from a source 10 meter above the ground level.

CUC experiences extreme climatic conditions with the peak temperature reaching 46°C during hot dry summers and dipping to 1°C in cold winters. The predominant wind direction is from North West to South East with average wind speed of 2.5-3.0m/sec.

3.2.2 Existing Power Scenario of CUC

The UT of Chandigarh has no power generation of its own and the power requirement is met through firm share as well as unallocated quota from the Central Generating Stations. At present the UT of Chandigarh is receiving 51% of electricity from Nalagarh, Himachal Pradesh based Power Grid Corporation of India Limited (PGCIL), 40% power from Mohali based Punjab State Electricity Board (PSEB) and the remaining 9% from Dhulkot, Haryana based Bhakra Beas Management Board (BBMB) **(MECON, 2016)**.

The UT of Chandigarh through a mutual agreement signed with the Government of India in August 2016 has agreed to be part of the program 24x7 power for all. The objective of the program is to connect all unconnected homes to the power grid by the 2018-19 thereby ensuring affordable power, quality of life and energy security all over the year **(MECON, 2016)**.

In 2014-15, UT of Chandigarh had power availability of approximately 1734 MU but with a growth of 35% by 2018-19 the power demand is expected to reach 2328 MU. There was no peak energy storage in the past but from the past two years it is around 6% to 12% even after contribution from the Central Generating Stations. The peak demand is expected to increase by 20% from 395 MW in 2014-15 to 473 MW in 2018-19. Accordingly, to meet the demand, the Electricity Department will have to purchase additional power from open market, banking arrangement or power exchanges. This will be especially required from May to September as from figure 3.3 and 3.4 it can be inferred that Chandigarh experiences maximum energy demand during these months of the year.

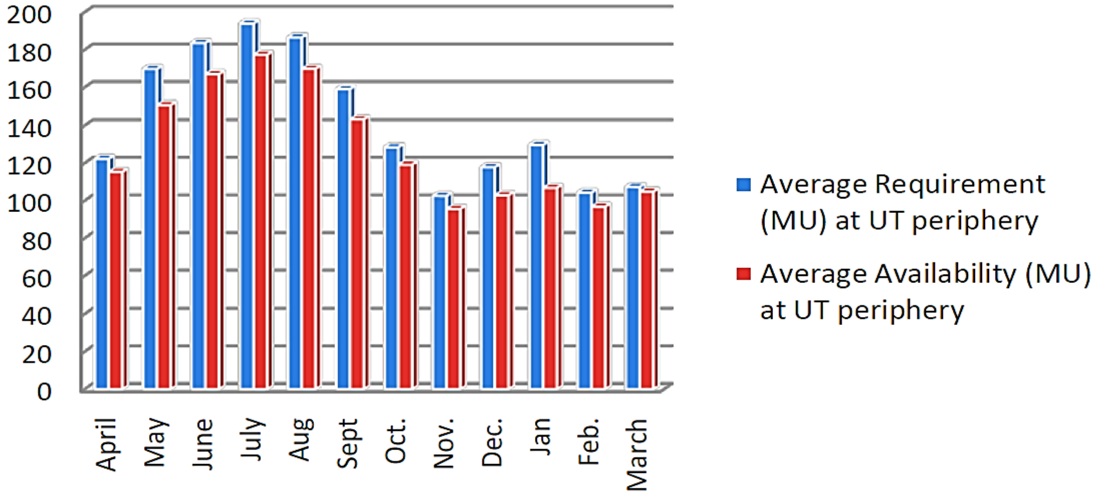


Figure 3.3 : **Monthwise Energy Scenario** (in MU) **(Average of FY 2013-14 to FY 2014-15)**
(Source: Chandigarh Electricity Department, UT Chandigarh)

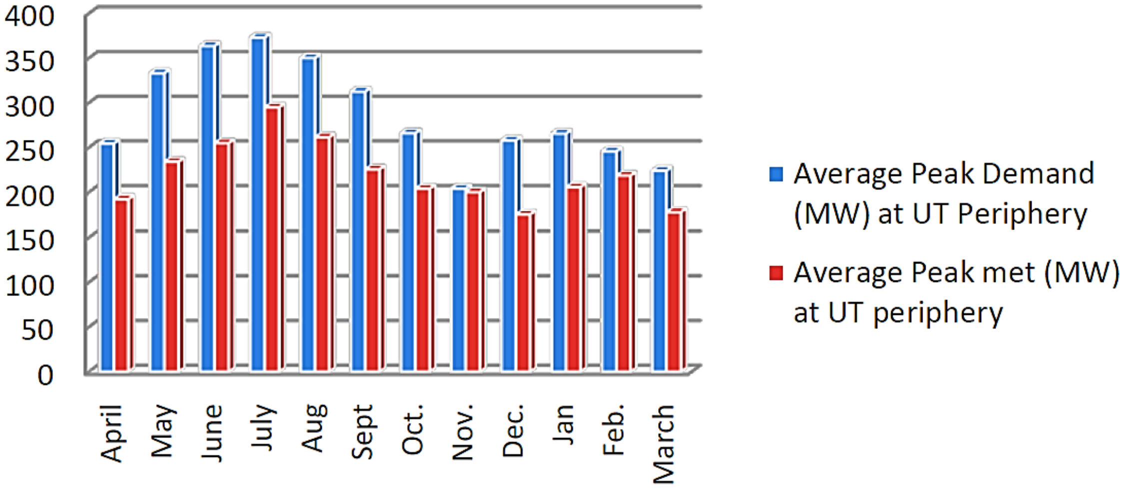


Figure 3.4 : **Monthwise Peak Demand** (in MW) **(Average of FY 2013-14 to FY 2014-15)**
(Source: Chandigarh Electricity Department, UT Chandigarh)

The Chandigarh Electricity Department is meeting the needs of around 2 lakh consumers out of which 86.5% are from the domestic sector. In 2014-15, the domestic sector consumed more than 46% of the total electricity supplied to UT of Chandigarh as indicated in table 3.1 and figure 3.5 with per household daily consumption being 10.50kWh **(MECON, 2016)**. By 2018-19 projections indicate that the domestic demand would reach 56-60%. Here it is significant to mention that the Transmission and Distribution (T&D) losses during the same period are expected to decrease from 12.37% in 2015-16 to 10.82% in 2018-19.

Table 3.1 : Consumer Based Growth in Electricity Consumption

Consumer	Year Wise Demand from 2007-08 to 2014-15							
	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15
Domestic	450	433	471.9	518	525.79	586.54	608.24	719.63
Commercial	313	318	440.5	398	417.36	397.54	446.18	489.4
Large Supply	142	145	141.4	140	128.72	137.5	123.94	115.03
Small Power	16	17	20.7	21	22.02	20.11	104.53	106.3
Medium Supply	91	101	116.5	89	103.71	103.84	20.36	19.57
Agriculture	1	1	1	2	1.27	1.4	1.46	1.67
Public Lighting	15	14	15.1	17	17.45	21.98	21.2	21.88
Bulk Supply	33	39	57.7	73	74.67	87.34	86.56	86.51
Temporary Supply	95	124	10.5	27	10.5	8.79	7.68	6.78
Total	**1156.00**	**1192.00**	**1275.30**	**1285.00**	**1301.49**	**1365.04**	**1420.15**	**1566.77**

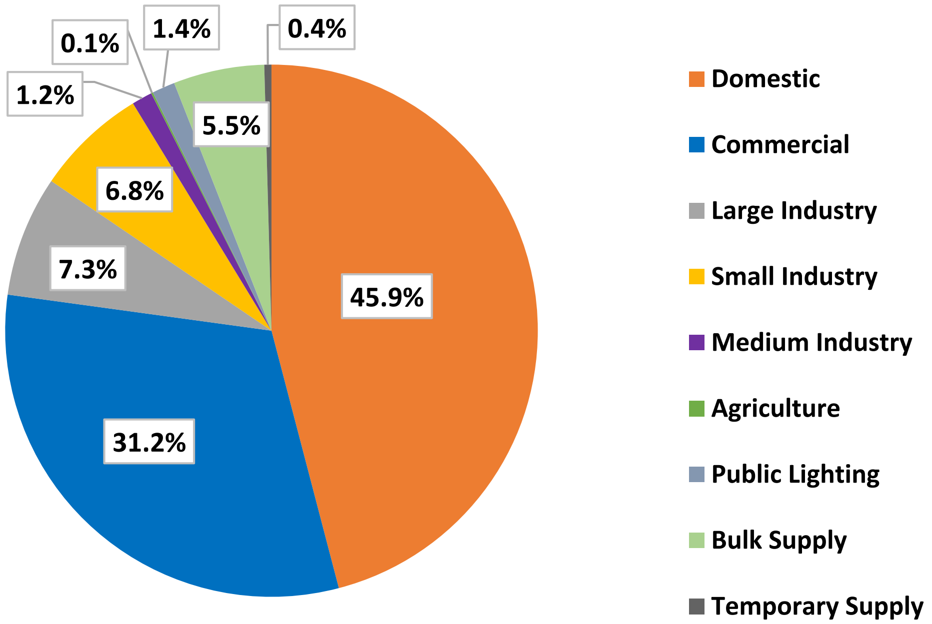


Figure 3.5 : Sector Based Electricity Consumption in 2014-15
(Source: Chandigarh Electricity Department, UT Chandigarh)

3.2.3 Solar City Chandigarh

In an attempt to reduce carbon dioxide emissions from thermal power plants and also meet a portion of the increasing energy demand through non-renewable energy sources, power generation units primarily based on solar, thermal and municipal waste have been initiated across India. A major step in this regard is the 'Solar Cities' initiative by Union Ministry of New and Renewable Energy (MNRE), Government of India in 2010. The mission has identified about 60 cities as part of the 11th Five Year Plan period. Chandigarh has been selected as one of the 'Solar City' with an approved fund of Rupees 20crores by MNRE, the master plan is formulated by Tata Energy Research Institute (TERI) and executed by local Chandigarh Renewal Energy Science and Technology Promotion Society (CREST).

The main objective behind selection of a Solar City is that the city or urban area has the potential to conserve and also utilize renewable energy resources like solar, wind, small hydro or employ alternative technologies like biomass and waste available in the region to achieve 10% reduction in conventional energy demand over a span of 5 years after execution. TERI in its master plan has defined setting up of Solar Photo Voltaic (SPV) panel and solar water heating installations at various locations like public and administrative buildings, land fill sites, residential and commercial areas. The project presently under implementation involves public buildings only. Proposal from individuals and private ownership has been invited which would attract subsidy on the initial cost of the installation.

The UT of Chandigarh has set a target of generating 44.32 MW of power through renewable energy sources primarily solar by 2018-19, with an expected growth of 146% from 2017-18 where the target is 30.30 MW. CUC receives overall annual direct normal solar irradiance ranging between 4.0-4.5kWh/m^2/day, whereas the annual global horizontal irradiance ranges between 5.0-5.5kWh/m^2/day. The duration of direct radiation ranges from 10-13hours/day over the year. With targets set and solar resource assessed it is necessary to assess the siting of solar infrastructure.

With public buildings already considered under the existing program it is the rooftops of residential units that can be exploited. But existing technologies are very definitive in nature and guidelines need to be reframed for alternate integration. It is important to understand that rooftops are used for various purpose, as in case of low rise housing they are an integral part of daily household activities apart from providing space for services like overhead water tanks.

The effective area available for installation of roof top systems in group housing is greatly reduced with provision of lift rooms, plumbing lines for water tanks and ownership issues. In similar circumstance with effective space available for setting up solar technologies being 40-50% of total roof area it is imperative that rooftop based systems alone may not be enough in achieving desired energy output across various typologies. In case of privately developed group housing with penthouses the effective public roof area available is further reduced. The design guidelines for energy efficient multi storey residential buildings by Bureau of Energy Efficiency (BEE), Ministry of Power, Government of India considers 60% of roof area available for solar power and thermal applications (BEE, 2014) in case of composite and hot-dry climate. There is a need to validate the same and define the benchmark of effective roof area available for solar based energy generation across various typologies over the year.

Apart from this, to achieve a target of 10% reduction in residential demand using standard procedures it would require creation of ideal climatic conditions whereas wind and solar resources are dynamic in nature. If solar and wind based onsite microgeneration in existing group housing have to be promoted, development guidelines will need reframing taking due consideration of existing built configuration and retrofitting renewable infrastructure without changing the architectural character.

3.2.4 Building Controls within CUC

With increasing inflow of population into CUC, Mohali and Panchkula have been experiencing major growth in group housing projects with average number of floors ranging from 12-18. Chandigarh architectural controls leave no scope for high rise housing, but with increasing housing demand certain sectors have been demarcated for Chandigarh Housing Board to undertake low rise group housing societies spanning 4 floors.

In CUC, the development of group housing projects within the sectors and peripheral areas comes under the jurisdiction of three different development agencies, resulting in independent and distinct building controls. In case of Chandigarh UT, the building controls are framed keeping in view the architectural character by the Office of the Chief Architect, Chandigarh. In case of Mohali, building controls are framed by the Greater Mohali Area Development Authority (GMADA) and in case of Panchkula, the development of building controls is under the purview of the Haryana Urban Development Authority (HUDA). A comparison of various development controls related to group housing across all the three development agencies are listed in table. 3.2.

Table 3.2: Comparison of Building Controls for Group Housing in CUC

S. No.	Parameter	Chandigarh			Mohali			Panchkula		
1.	Minimum Area of Site	4047sqm			4000sqm			-		
2.	Maximum Ground Coverage (% of Site Area)	40%			40%			33.33%		
3.	Maximum FAR	1:1.2			1:2			1:1.75		
4.	Maximum Height (Inclusive of Parapet)	46’- 9” (14.25 meter)			71’- 6” (21.80 meter)			No Restriction, but above 30m needs approval		
5.	Setback	Minimum 6m			Minimum 6m or 1/3rd height of building			Minimum 6m or 1/3rd height of building		
6.	Distance between blocks	-			2/3rd average height of building			-		
7.	Density of Dwelling Units (Category Wise Units per Acre)	A	B	C	A	B	C	A	B	C
		25	35	45	50	60	75	20	40	60
8.	Category Wise Area of Dwelling (Area in sqm)	A	B	C	A	B	C	A	B	C
		130 to 140	93 to 100	75 to 78	> 280	112 to 280	Up to 112	350	77 to 349	76
9.	Organized Green Area (% of Site Area)	15%			15%			15%		

3.3 Basis of Housing Classification and Defining Representative Residential Units

Residential buildings within the CUC can be categorized based on their built character into four major typologies. The architectural character of the housing units within individual typologies is predominantly similar in character due to the strict implementation of development controls. The varying factor with respect to energy consumption in the typologies is their age and occupant behaviour.

An architectural character based typology classification of the existing residential building stock is done as part of the research. **Aydinalp et al. (2002)**, **Bianco et al. (2009)** and **Attia et al. (2012)** have established that architectural built form character and layout of units across typologies have a significant contribution towards energy consumption and generation. The research focuses on the energy consumption of the households based on their monthly electricity bills. The energy consumptions related with age of household, material of construction and insulation are presently kept out of the scope of study. The built form characteristics and orientation of existing typologies is considered to understand their role in promotion of renewable energy generation primarily solar and wind. For the purpose of research, the architectural form based classification of residential units across CUC results in four major typologies as highlighted in figure 3.6.

The typologies may have units varying in plot size but the built character, setback, height and plot coverage are predominantly common across them. In case of each typology, certain cases are left out due to lack of availability of information and in case of 4 Kanal (2000sqm) to 8 Kanal (4000sqm) plotted units the users were not willing to share information owing to their energy intensive household and societal status.

1. **Low Rise Detached, Semi-detached and Row Housing**
   - G+2 structure consisting of single or joint family unit.
   - Varying plot sizes ranging between 4 Marla to 8 Kanal.
   - Front, rear and one side setback.

2. **Low Rise Group Housing**
   - G+3 structure with multifamily (single/joint) units.
   - Plot areas are predominantly same.
   - Front and rear setback.

3. **Medium Rise Group Housing**
   - Medium height blocks ≥ ground+4 floors or stilt+4 floors.
   - Part of group housing setup with lift.
   - Household units may vary in area.

4. **High Rise Apartments**
   - Forming maximum portion of housing stock.
   - >8 storeyed towers.
   - Provision of lift and fire safety infrastructure.
   - Household units may vary in area.

Figure 3.6: Representative Residential Units of CUC

3.4 Assessing Household Energy Demand and Identifying Representative Residential Units

To assess the energy consumption of various housing typologies identified within CUC, a questionnaire is prepared and household survey is undertaken with a sample size of 20 households across each typology. The questionnaire is also used to shortlist Representative

Residential Units (RRU) based on the extent to which the household follows the building controls as laid down within CUC. Another factor is the information gaps in the questionnaire, with the household having least information gaps getting due credit.

The questionnaire involves an understanding of user behavior, physical form and construction technology of the housing units, neighbourhood development, climatic considerations, external fenestration and issues related to already integrated micro-generation technologies. The questionnaire is divided into two sections – the first section deals with defining the built character of the household and establishing it as a RRU. The RRU's shortlisted as part of the survey accordingly are converted into 3D models and analysed by different simulation tools based on the type of assessment.

The second section deals with assessing the energy consumption pattern across typologies and establishing a trend that can be generalized for similar housing typologies. The primary respondent in case of Section-2 are home owners themselves. Tenants are not considered as part of assessment due to their inability in decision making. The section also aids in detailing out the list of energy intensive appliances that are common to a particular typology, hours of operation and understanding human behaviour based on time of operation of the appliances.

3.4.1 Section – 1: Defining Character of existing household and Identifying RRUs

The Representative Residential Unit (RRU) is a standard existing housing unit that is converted into a 3D model and undertaken for simulation based assessment. The various built form parameters defining the character of existing household and basis of identification of a RRU are listed below:

Table 3.3 Parameters Defining the Character of Existing Household

a) Single Family / Multi Family / Ownership	b) Site Coverage
c) Shape	d) Height
e) Volume	f) Internal Floor Area
g) Open Spaces / Balconies	h) External Wall Area
i) Roof Area	j) Shape of Roof
k) Window Area	l) External Shading Devices
m) Construction Material	n) Age of Construction

Some of the parameters are not directly defined in the building controls but have been incorporated based on dealing with categorization of households to assess their energy performance **(Attia et al. 2012 and Bianco et al. 2009)**.

3.4.2 Section – 2: Defining existing household Energy Demand and Consumption Pattern

This section deals with defining the household energy demand on the basis of list of energy intensive equipment, hours of operation, user-behaviour and consumption pattern across various housing typologies. The various energy parameters that are assessed as part of the questionnaire are listed below:

Table 3.4 Parameters Defining the Existing Household Energy Demand

a) Family Structure and Age Groups	b) Existing Energy Sources
c) Existing Renewable Energy Infrastructure	d) Electrical Equipment in Use
e) Operating Hours of Equipment	f) Awareness towards Energy Rating
g) Heating Needs and Usage	h) Cooling Needs and Usage
i) Lighting Needs and Usage	j) Community Energy Needs and Usage

The questions related to community energy need and usage are primarily for the multi-family dwelling with multiple ownership. This includes energy consumption towards common space lighting, club house or community facility, landscaping, water pumping, etc.

3.5 Shortlisted Representative Residential Unit (RRU)

The Representative Residential Units (RRUs) that are shortlisted on basis of their character and location across CUC with respect to the building controls and geometry are detailed out in this section. With reference to the material of construction as per Census 2011, out of 2,68,758 households surveyed 88.8% households report using burnt brick as wall material followed by 5% having concrete as the construction material. In case of floor 70% use cement as followed by 13% using mosaic and floor tiles and 10% using stone. 83.2% households use reinforced concrete as the roofing material followed by 10% using G.I roofing sheet. Accordingly more than 91% of houses are categorized as permanent, 7% as semi-permanent and 3% as temporary houses.

Also, as per Census 2011, out of 2,28,276 urban households in UT Chandigarh, 27.4% households have household size of 4 followed by 19% having 3 and 17% with a family size of 6-8. In terms of dwelling rooms 38.5% households have only one dwelling room, 25.8% have two rooms and 19%

have three rooms. On basis of the above data the average household size is observed to be 4.4 which is considered for the present study.

3.5.1 Uppals Marble Arch, Manimajra, Chandigarh

a) Site Plan of Uppals Marble Arch **b) Green Spaces between Blocks**

c) Character of Built Form **d) Club House in between the Blocks**

Figure 3.7: Built Form Characteristics and Development of Uppals Marble Arch, Manimajra, Chandigarh

Uppal's Marble Arch is a housing project completed around 2011-12 and spread over 5.4 acres in Manimajra, Chandigarh with a total built up area of 40,000sqm. The FAR is 1.5 with 40% ground coverage and maximum height of 15.25 meters. The development consists of 9 blocks of 5 storey arranged in three rows with green spaces in between the rows. Each floor comprises of 4 apartments thereby providing for 168 units consisting of 3 and 4 bedroom units with penthouses on the top floor. The average area of the households ranges between 205sqm to 262sqm. The blocks are placed with the longer faces towards north and south. The volumetric play is achieved by provision of terraces at different levels. Ancillary facilities like club house, gym, swimming pool, play courts and social interaction spaces are also provided.

3.5.2 Sushma Elite Cross, Gazipur, Punjab

Sushma Elite Cross is located in Gazipur, Punjab and was completed around 2015-16. It is spread over 9 acres comprising of 348 units arranged in three towers resembling the form X and four towers in a rectangular block form. The X form towers comprise of 13 floors each with an overall height of 46 meter while the rectangular box towers are 12 floors each and overall height of 42.5 meter. Both the towers comprise of pent houses at the terrace level. In between the blocks is the club house comprising of all possible facilities like gym, swimming pool, children's play area, etc., within its three levels.

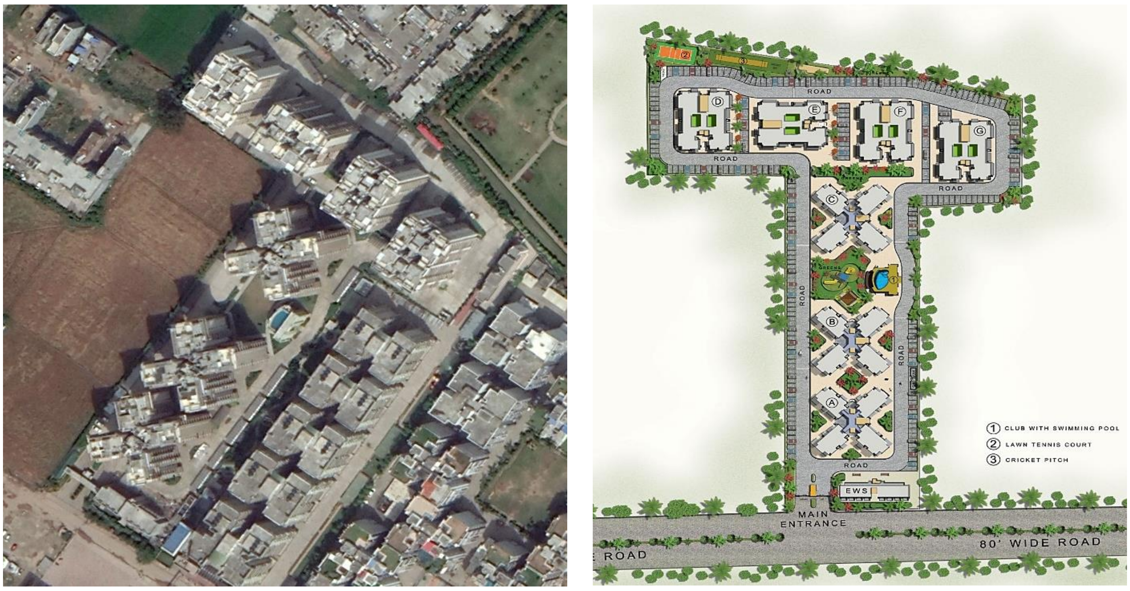


Figure 3.8: Site Plan and Surrounding Context of Sushma Elite Cross, Gazipur, Punjab

Figure 3.9: Vertical Built Form of Sushma Elite Cross, Gazipur, Punjab

There are only two types of residential units with area of 168.5sqm and 182.5sqm. The housing project is taken for the study owing to its vertical character and combination of all possible forms within the same premises that can aid in better understanding of the behaviour of wind and sun.

3.5.3 Sector 51, Chandigarh

The housing typology of Sector 51, Chandigarh is the simplest of all the RRUs comprising of low rise group housing societies with blocks of 14.65 meter height. The site is spread over 2.3 acres comprising of four units per floor in each block. There are 208 households of area ranging from 105sqm to 125sqm. The housing blocks are short linear units and generally separated from each other by road or open space.

a) Plan of a Group Housing Society **b) Typical Built Form Characteristics**

Figure 3.10: Site Plan and Surrounding Details of Group Housing Society in Sector 51, Chandigarh

3.5.4 Sector 19A, Chandigarh

The study considers the predominant plotted housing typologies found in Chandigarh. The plotted development within Chandigarh is categorized on basis of Marla and Kanal. 250sqm is equal to 10 Marla and 20 Marla is equal to 1 Kanal which is equivalent to 500sqm. However, plotted units beyond 2 Kanal are not considered due to their higher social order and lack of information about these energy intensive households. The plotted units considered as part of the household survey include:

i) 10 Marla Housing Unit
ii) 15 Marla Housing Unit
iii) 1 Kanal Housing Unit
iv) 2 Kanal Housing Unit

Figure 3.11: Typical Plotted Housing Typologies of Chandigarh

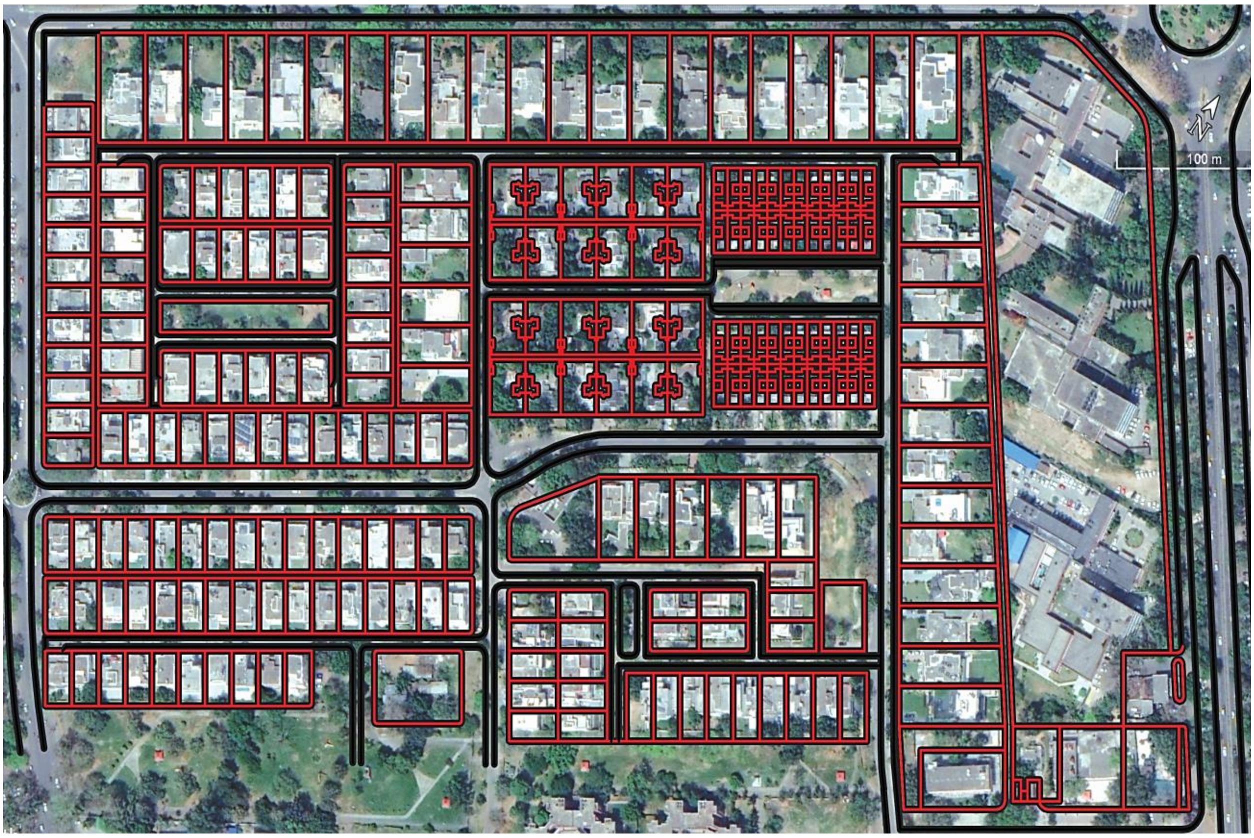


Figure 3.12: Sector Plan showing Plotted Development of Sector 19A, Chandigarh

The housing in Sector 19A, Chandigarh primarily comprises of 1 Kanal, 2 Kanal and 3 Kanal plotted units. The 1 Kanal housing units have a front and rear setback defined as per Chandigarh Administration. In case of 2 Kanal and 3 Kanal, in addition there is a provision for side setback on one side of the plot so as to ensure light and ventilation to both the units and the other side wall is shared with the neighbouring property. The units comprise of maximum 3 floors with a maximum height of 10.65 meter. Table 3.5 summarises the characteristic features of the different RRUs as given on the next page.

Table 3.5 Characteristic Features of Representative Residential Units (RRUs)

Component	Uppals Marble Arch Manimajra	Sushma Elite Cross Gazipur	Sector 51 Chandigarh	Sector 19A Chandigarh
Type of Development	Linear Block	High Rise Apartment	Multifamily Blocks	Plotted Development
Site / Plot Area **(Acres /sqm)**	5.4 Acres (21,850sqm)	9 Acres (43,700sqm)	2.3 Acres (9,300sqm)	Sector 19A = 45 Acres 1 Kanal = 500sqm 2 Kanal = 1,000sqm 3 Kanal = 1,500sqm
Number of Households	168	348	150	194
No. of Floors & Height **(m)**	5 floors & 10.25m	12/13 floors & 42.5m / 46.0m	4 floors & 14.65m	3 floors & 10.65m
Household Density **(Households per acre)**	31	39	65	4-5
Roof Area as % of Site Area	38.8%	12.4%	39.8%	17.5%
Average Floor Area	234sqm	175sqm	115sqm	375sqm
Façade Glazing **(%) approximately**	60%	50%	30%	30%

3.6 Energy Consumption Pattern and Seasonal Variation in Representative Residential Units

As per Census of India, 2011 out of 2,28,276 urban households, 99.7% are electrified and use electricity for lighting hence negating the need to shortlist households with electricity. An energy audit is conducted across 20 households in each of the RRUs to define the energy consumption pattern of the RRUs. The audit is undertaken at two levels - the first audit is based on the assessment of the electricity meter bills collected from each household while the second level is through a questionnaire survey as listed in **Annexure – I** with respondents which includes home owners only. The choice of the household is based on the orientation of the unit so that energy performance of all possible orientations can be assessed and values of similar orientations across different RRUs can be averaged out to create the benchmark models.

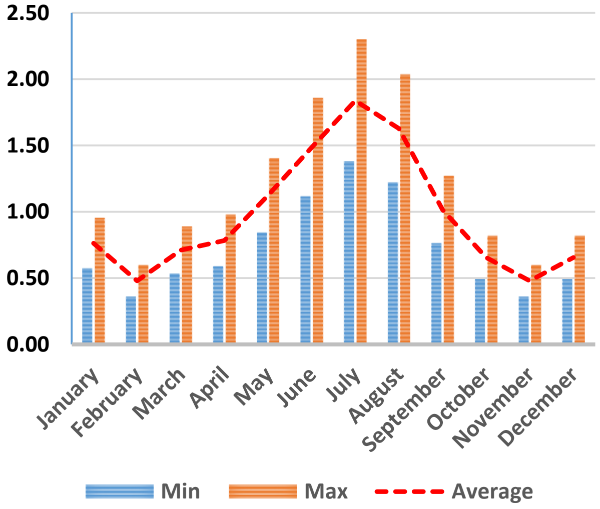
At the time of questionnaire survey, physical examination of the household is also undertaken to identify major electrical equipment (heating, cooling, lighting etc.) and establish the area out of the total built up space that actually needs such infrastructure. The emphasis is on spaces that use air conditioning. The overall data is combined and analysed to define the energy performance model with hourly electricity usage and user behaviour based patterns of utilizing cooling, heating and lighting equipment.

3.6.1 Annual Energy Consumption Pattern

The surveyed monthly electricity consumption per household area (kWh/m^2) of the different RRUs is highlighted in Table 3.6. The consumption patterns indicate that out of the four RRUs, plotted units of Sector 19A are the highest consumers with annual consumption of 17.10kWh/m^2/year in comparison with Uppals Marble Arch based medium rise housing typology having the least annual consumption of 11.61kWh/m^2/year. The electricity consumption of Sushma Elite Cross is near to 11.72kWh/m^2/year and that of Sector 51 is 14.47kWh/m^2/year.

Table 3.6 : Electricity Consumed per Unit Area in RRUs

Uppals Marble Arch	Consumption per area (kWh/m^2)		
Month	**Min**	**Max**	**Average**
January	0.57	0.95	0.76
February	0.36	0.60	0.48
March	0.53	0.89	0.71
April	0.59	0.98	0.78
May	0.84	1.40	1.12
June	1.11	1.86	1.49
July	1.38	2.30	1.84
August	1.22	2.03	1.63
September	0.76	1.27	1.02
October	0.49	0.82	0.66
November	0.36	0.60	0.48
December	0.49	0.82	0.66



Sushma Elite Cross	Consumption per area (kWh/m^2)		
Month	**Min**	**Max**	**Average**
January	0.47	0.81	0.64
February	0.42	0.72	0.57
March	0.45	0.78	0.61
April	0.53	0.91	0.72
May	0.88	1.52	1.20
June	1.26	2.18	1.72
July	1.45	2.49	1.97
August	1.31	2.25	1.78
September	0.54	0.92	0.73
October	0.44	0.76	0.60
November	0.42	0.72	0.57
December	0.44	0.76	0.60

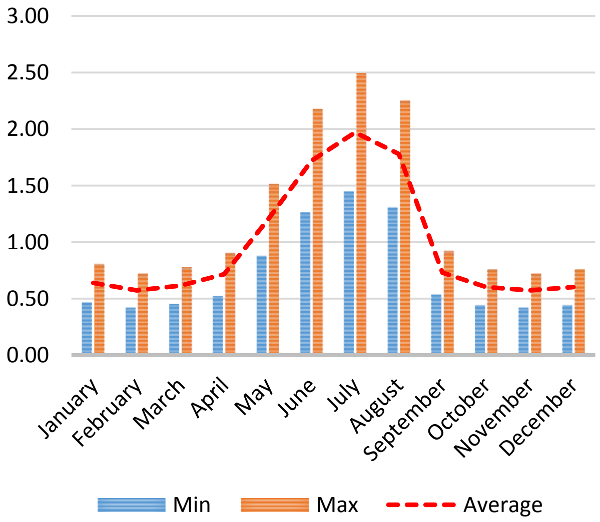
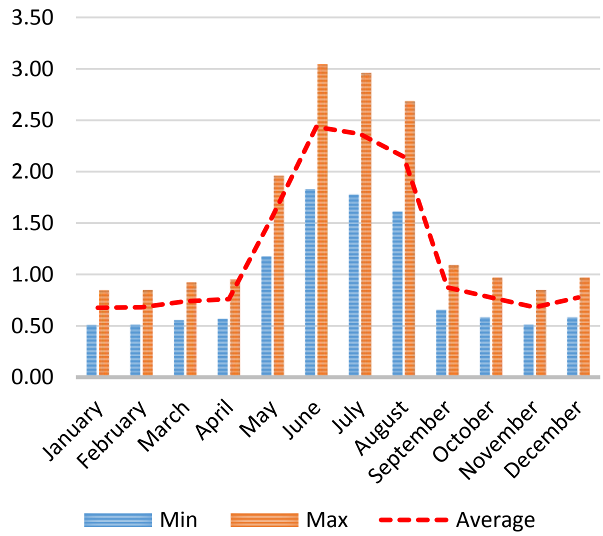
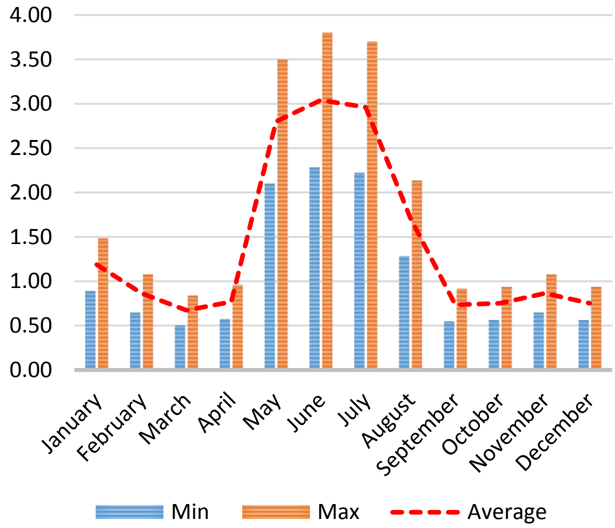


Table 3.6 (contd.) : Electricity Consumed per Unit Area in RRUs

Sector 51 Chandigarh	Consumption per area (kWh/m²)		
Month	Min	Max	Average
January	0.51	0.84	0.68
February	0.51	0.85	0.68
March	0.55	0.92	0.74
April	0.57	0.95	0.76
May	1.18	1.96	1.57
June	1.83	3.04	2.43
July	1.77	2.96	2.37
August	1.61	2.68	2.15
September	0.66	1.09	0.87
October	0.58	0.97	0.78
November	0.51	0.85	0.68
December	0.58	0.97	0.78



Sector 19A Chandigarh	Consumption per area (kWh/m²)		
Month	Min	Max	Average
January	0.89	1.48	1.19
February	0.65	1.08	0.86
March	0.50	0.84	0.67
April	0.58	0.96	0.77
May	2.10	3.50	2.80
June	2.28	3.80	3.04
July	2.22	3.70	2.96
August	1.28	2.14	1.71
September	0.55	0.92	0.73
October	0.56	0.94	0.75
November	0.65	1.08	0.86
December	0.56	0.94	0.75



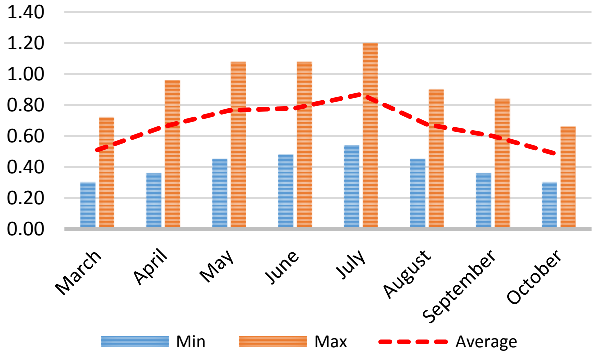
One possible explanation for the high electricity consumption in case of Sector 19A can be the prominence of joint families with varied age groups in a household leading to varied user behaviour. Through physical survey it is observed that the households of Sector 19A have more air-conditioned spaces than the other RRUs.

3.6.2 Space Cooling and Ventilation Demand

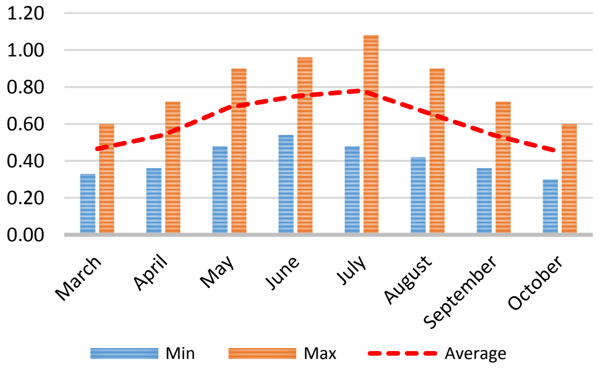
Seasonal variation based energy consumption indicates that cooling during summer months from April to June is the highest consumer of electricity with the daily peak load reaching 28.5kWh. Apart from cooling, ventilation is needed during March to October. Ceiling fans are the primary form of spot ventilation in the households and consume about 1.08-1.20kWh of electricity per day during summers. The monthly variation of ventilation and space cooling are highlighted in table 3.7 and 3.8.

Table 3.7 : Average Daily Electricity Consumed for Ventilation in RRUs

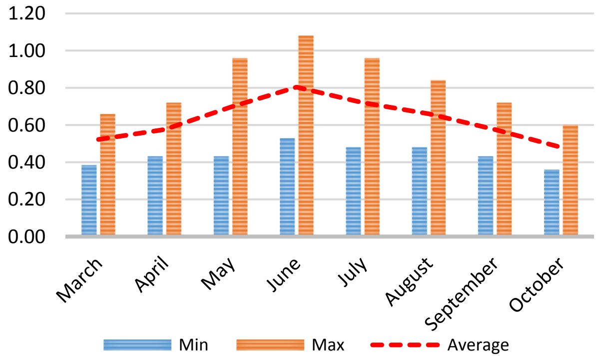
Uppals Marble Arch	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
March	0.53	0.89	0.71
April	0.59	0.98	0.78
May	0.84	1.40	1.12
June	1.11	1.86	1.49
July	1.38	2.30	1.84
August	1.22	2.03	1.63
September	0.76	1.27	1.02
October	0.49	0.82	0.66



Sushma Elite Cross	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
March	0.45	0.78	0.61
April	0.53	0.91	0.72
May	0.88	1.52	1.20
June	1.26	2.18	1.72
July	1.45	2.49	1.97
August	1.31	2.25	1.78
September	0.54	0.92	0.73
October	0.44	0.76	0.60



Sector 51 Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
March	0.55	0.92	0.74
April	0.57	0.95	0.76
May	1.18	1.96	1.57
June	1.83	3.04	2.43
July	1.77	2.96	2.37
August	1.61	2.68	2.15
September	0.66	1.09	0.87
October	0.58	0.97	0.78



Sector 19A Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
March	0.50	0.84	0.67
April	0.58	0.96	0.77
May	2.10	3.50	2.80
June	2.28	3.80	3.04
July	2.22	3.70	2.96
August	1.28	2.14	1.71
September	0.55	0.92	0.73
October	0.56	0.94	0.75

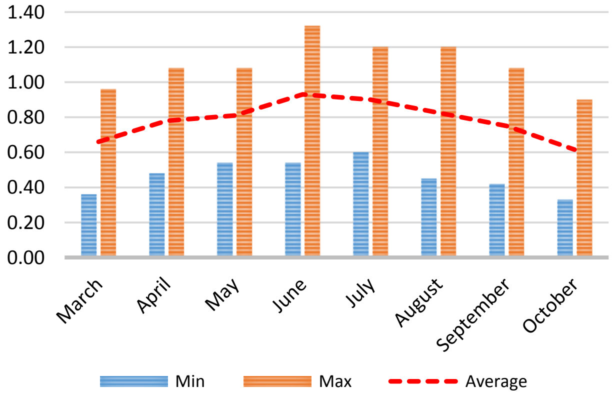
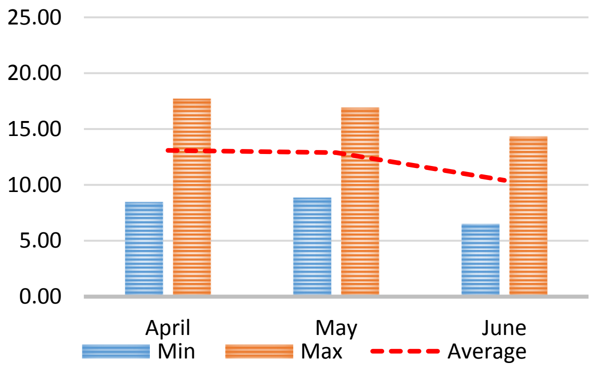
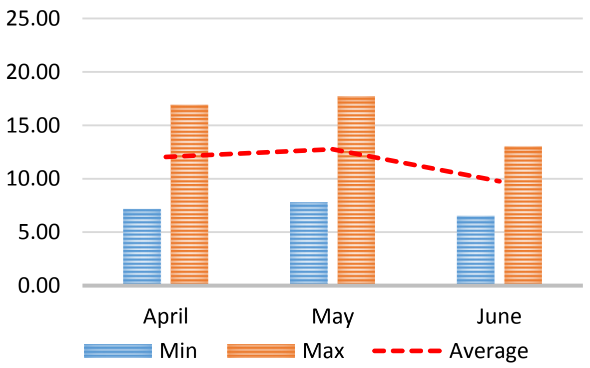


Table 3.8 : Average Daily Electricity Consumed for Space Cooling in RRUs

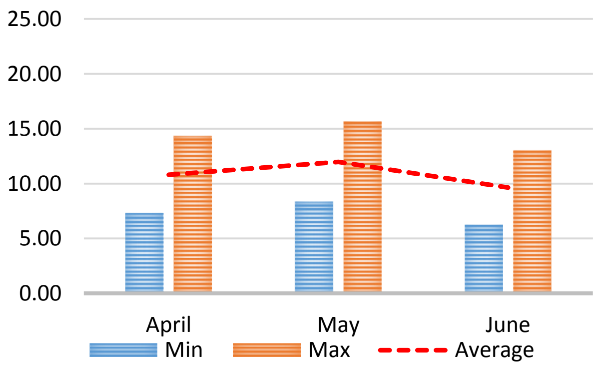
Uppals Marble Arch	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
April	8.46	17.71	13.09
May	8.86	16.93	12.89
June	6.51	14.32	10.42



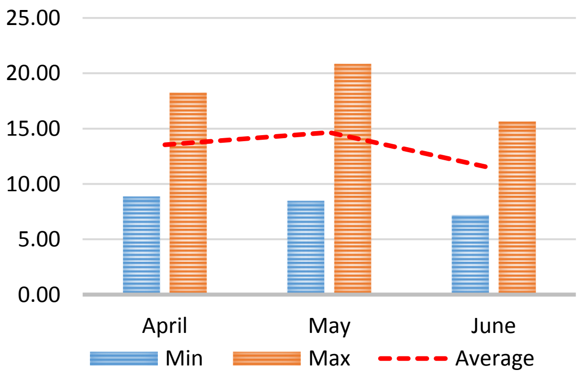
Sushma Elite Cross	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
April	7.16	16.93	12.05
May	7.81	17.71	12.76
June	6.51	13.02	9.77



Sector 51 Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
April	7.29	14.32	10.81
May	8.33	15.63	11.98
June	6.25	13.02	9.64



Sector 19A Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
April	8.86	18.23	13.54
May	8.46	20.84	14.65
June	7.16	15.63	11.39



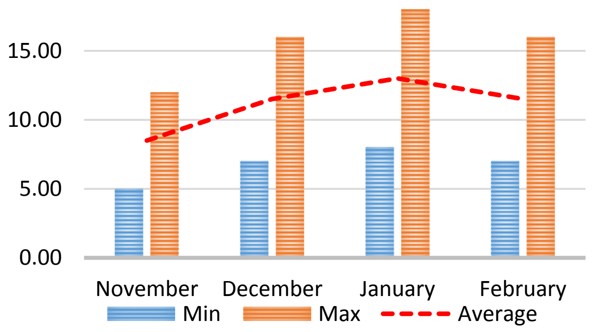
3.6.3 Space Heating and Domestic Hot Water Demand

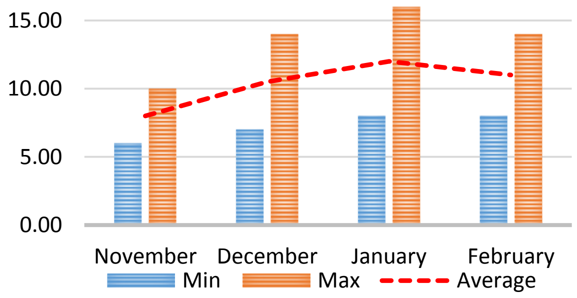
Winters months from November to February require both space and water heating and the energy spent on both is the third most energy consuming activity of households on annual basis. The amount of electricity spent for space heating due to low winter temperatures reaches a peak of 12.4kWh and the demand of hot water of a household increases from 40-65liters per day in summers to 120-135liters per day in winters and electricity consumption increases from 3-4kWh to 8-10kWh. The monthly variations of space heating and hot water demand are highlighted in table 3.9 and 3.10.

Table 3.9: Average Daily Electricity Consumed for Space Heating in RRUs

Uppals Marble Arch	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
November	5.00	12.00	8.50
December	7.00	16.00	11.50
January	8.00	18.00	13.00
February	7.00	16.00	11.50

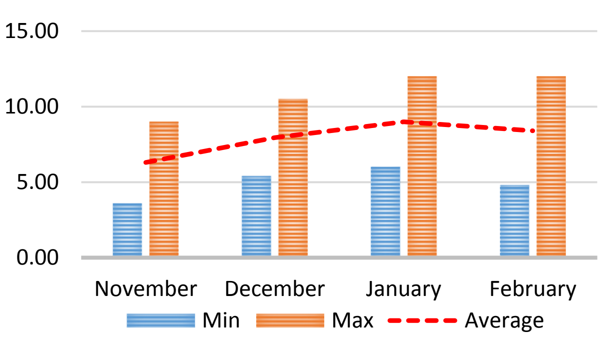
Sushma Elite Cross	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
November	6.00	10.00	8.00
December	7.00	14.00	10.50
January	8.00	16.00	12.00
February	8.00	14.00	11.00





Sector 51 Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
November	3.60	9.00	6.30
December	5.40	10.50	7.95
January	6.00	12.00	9.00
February	4.80	12.00	8.40

Sector 19A Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
November	6.00	12.00	9.00
December	8.00	18.00	13.00
January	9.00	20.00	14.50
February	8.00	16.00	12.00



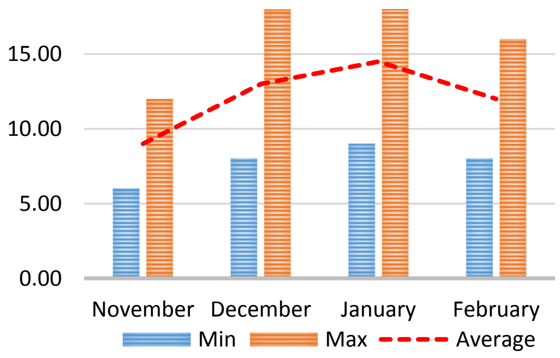
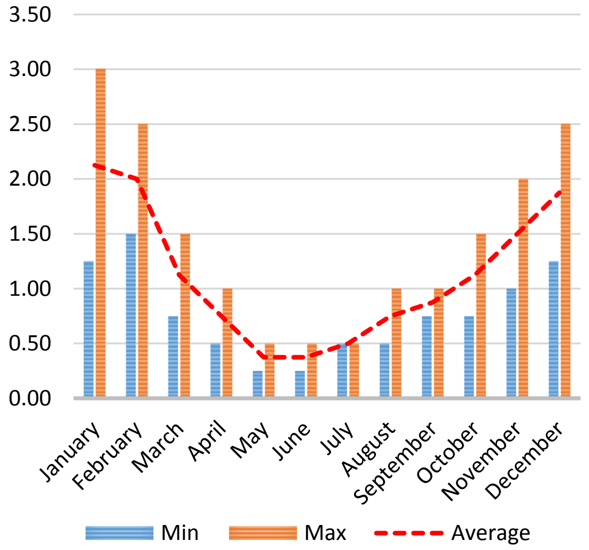
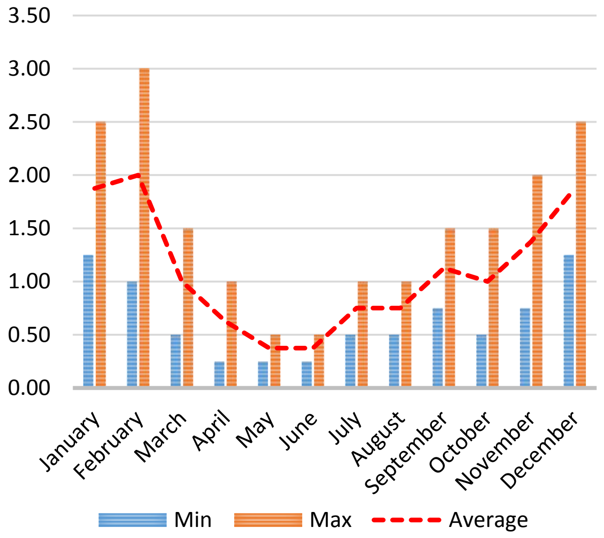


Table 3.10: Average Daily Electricity Consumed for Water Heating in RRUs

Uppals Marble Arch	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
January	1.25	3.00	2.13
February	1.50	2.50	2.00
March	0.75	1.50	1.13
April	0.50	1.00	0.75
May	0.25	0.50	0.38
June	0.25	0.50	0.38
July	0.50	0.50	0.50
August	0.50	1.00	0.75
September	0.75	1.00	0.88
October	0.75	1.50	1.13
November	1.00	2.00	1.50
December	1.25	2.50	1.88



Sushma Elite Cross	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
January	1.25	2.50	1.88
February	1.00	3.00	2.00
March	0.50	1.50	1.00
April	0.25	1.00	0.63
May	0.25	0.50	0.38
June	0.25	0.50	0.38
July	0.50	1.00	0.75
August	0.50	1.00	0.75
September	0.75	1.50	1.13
October	0.50	1.50	1.00
November	0.75	2.00	1.38
December	1.25	2.50	1.88



Sector 51 Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
January	2.00	2.50	2.25
February	1.50	2.00	1.75
March	1.00	1.00	1.00
April	0.50	0.50	0.50
May	0.50	0.50	0.50
June	0.25	0.50	0.38
July	0.25	1.00	0.63
August	0.50	1.00	0.75
September	0.75	1.50	1.13
October	1.00	1.00	1.00
November	1.25	1.50	1.38
December	1.50	2.50	2.00

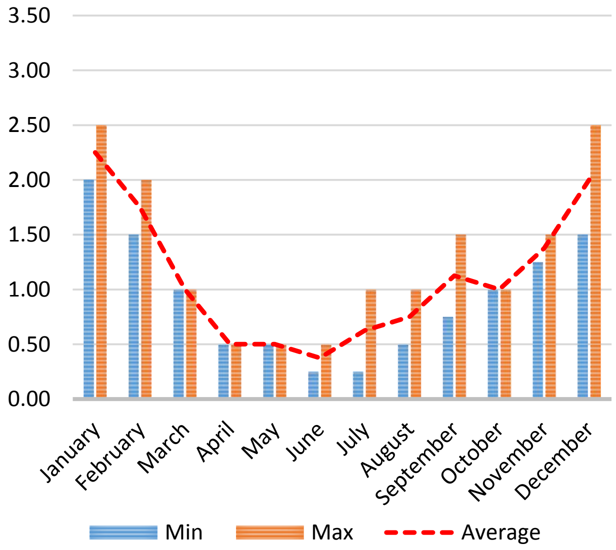
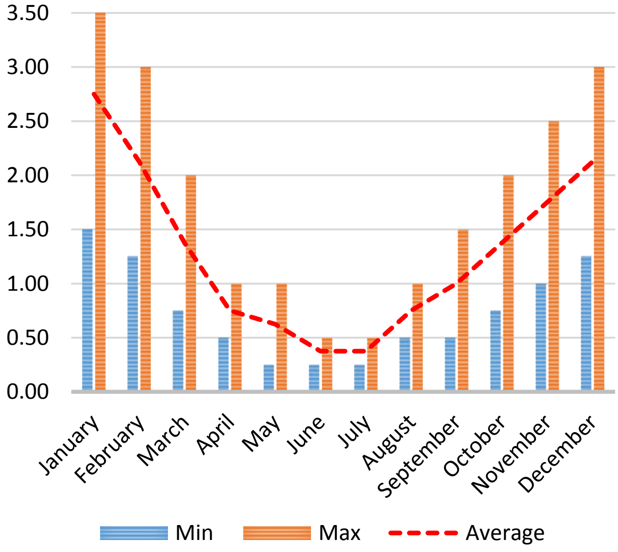


Table 3.10 (contd.): Average Daily Electricity Consumed for Water Heating in RRUs

Sector 19A Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
January	1.50	4.00	2.75
February	1.25	3.00	2.13
March	0.75	2.00	1.38
April	0.50	1.00	0.75
May	0.25	1.00	0.63
June	0.25	0.50	0.38
July	0.25	0.50	0.38
August	0.50	1.00	0.75
September	0.50	1.50	1.00
October	0.75	2.00	1.38
November	1.00	2.50	1.75
December	1.25	3.00	2.13



3.6.4 Lighting Demand and Usage Pattern

With the penetration of Light Emitting Diode (LED) and Compact Fluorescent Light (CFL) in the market and awareness towards energy saving initiatives it is observed that irrespective of the high hours of operation, lighting is the least intensive consumer of electricity in residences. As part of the interview survey it is observed that household members are well aware of the initiatives towards lighting based energy conservancy. The winter months from November to February observe major consumption of electricity for lighting due to the foggy conditions and lack of sun for most part of the day. The details of electricity consumption for lighting are highlighted in table 3.11.

Table 3.11: Average Daily Electricity Consumed for Lighting in RRUs

Uppals Marble Arch	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
January	0.90	2.10	1.50
February	0.75	1.80	1.28
March	0.60	1.35	0.98
April	0.45	1.20	0.83
May	0.45	0.90	0.68
June	0.45	0.90	0.68
July	0.60	1.20	0.90
August	0.68	1.35	1.01
September	0.75	1.20	0.98
October	0.75	1.35	1.05
November	0.90	1.50	1.20
December	0.90	1.80	1.35

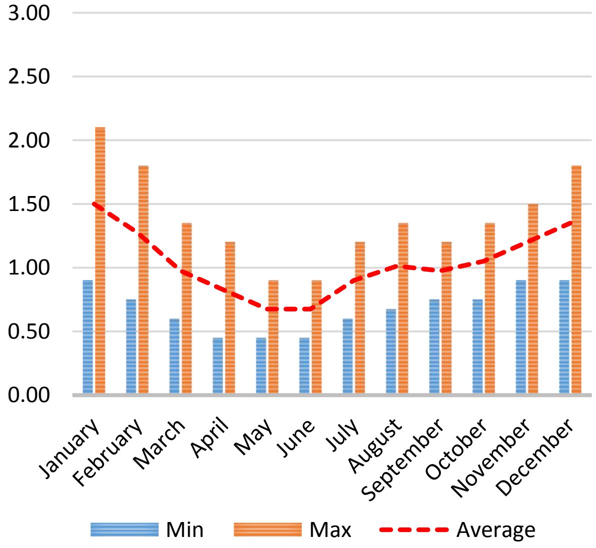
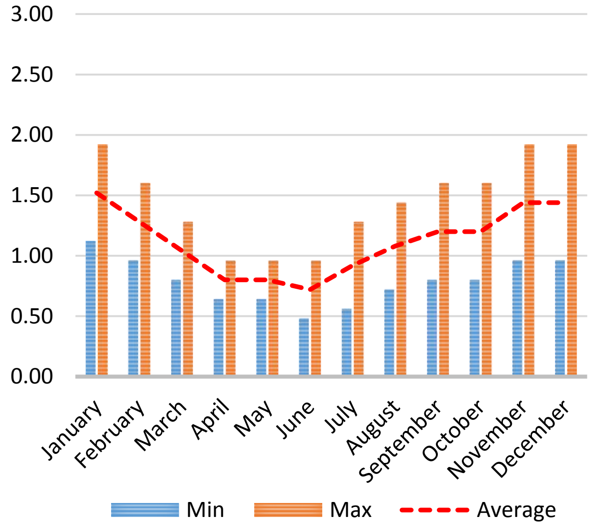
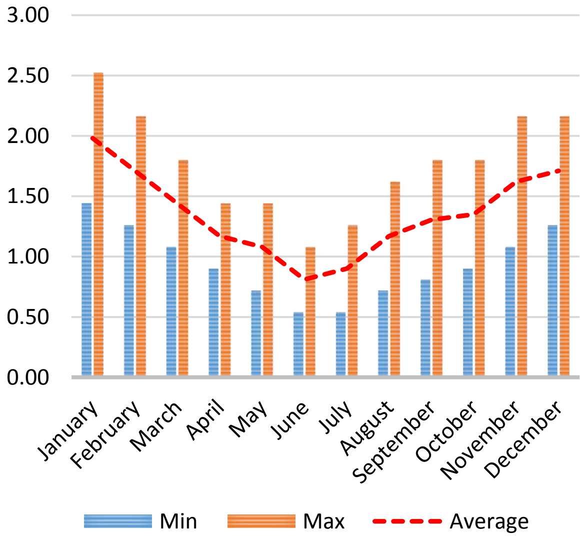


Table 3.11 (contd.): Average Daily Electricity Consumed for Lighting in RRUs

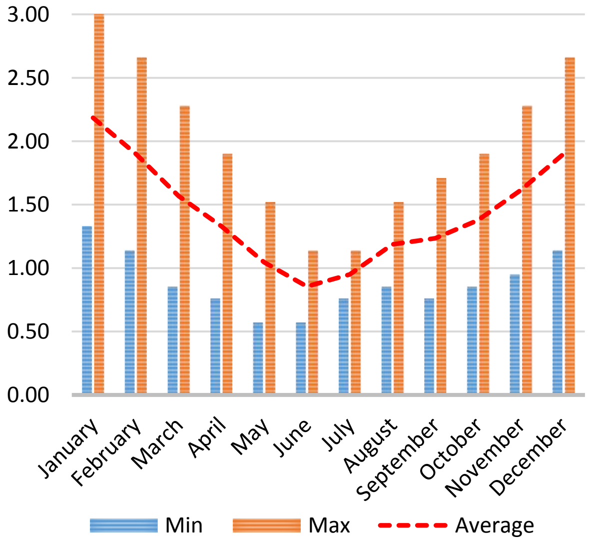
Sushma Elite Cross	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
January	1.25	2.50	1.88
February	1.00	3.00	2.00
March	0.50	1.50	1.00
April	0.25	1.00	0.63
May	0.25	0.50	0.38
June	0.25	0.50	0.38
July	0.50	1.00	0.75
August	0.50	1.00	0.75
September	0.75	1.50	1.13
October	0.50	1.50	1.00
November	0.75	2.00	1.38
December	1.25	2.50	1.88



Sector 51 Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
January	1.44	2.52	1.98
February	1.26	2.16	1.71
March	1.08	1.80	1.44
April	0.90	1.44	1.17
May	0.72	1.44	1.08
June	0.54	1.08	0.81
July	0.54	1.26	0.90
August	0.72	1.62	1.17
September	0.81	1.80	1.31
October	0.90	1.80	1.35
November	1.08	2.16	1.62
December	1.26	2.16	1.71



Sector 19A Chandigarh	Average Daily Electricity Consumption (kWh)		
Month	**Min**	**Max**	**Average**
January	1.33	3.04	2.19
February	1.14	2.66	1.90
March	0.86	2.28	1.57
April	0.76	1.90	1.33
May	0.57	1.52	1.05
June	0.57	1.14	0.86
July	0.76	1.14	0.95
August	0.86	1.52	1.19
September	0.76	1.71	1.24
October	0.86	1.90	1.38
November	0.95	2.28	1.62
December	1.14	2.66	1.90



3.6.5 Energy Intensive Utilities and Scoring System

The different household utilities that require electricity and their consumption profile on monthly basis has already been discussed in Section 3.6.1 to 3.6.4. Based on the monthly electricity consumption pattern across different typologies the maximum and minimum values are taken for each utility are taken and the range in between them divided into 9 equal parts. The scale developed from 1 to 9, with 9 being the most intensive and 1 the least intensive for each of the utilities is listed in table 3.12.

Table 3.12: Energy Intensity Score of Utilities across Typologies

Score	Water Heating	Lighting	Ventilation	Space Cooling	Space Heating
9	2.75 - 2.49	2.19 - 2.02	0.93 - 0.88	14.65 - 14.09	14.50 - 13.59
8	2.48 - 2.23	2.01 - 1.85	0.87 - 0.83	14.08 - 13.53	13.58 - 12.68
7	2.22 - 1.97	1.84 - 1.68	0.82 - 0.78	13.52 - 12.97	12.67 - 11.77
6	1.96 - 1.71	1.67 - 1.51	0.77 - 0.73	12.96 - 12.41	11.76 - 10.86
5	1.70 - 1.44	1.50 - 1.34	0.72 - 0.68	12.40 - 11.85	10.85 - 9.95
4	1.43 - 1.18	1.33 - 1.17	0.67 - 0.63	11.84 - 11.29	9.94 - 9.04
3	1.17 - 0.92	1.16 - 1.00	0.62 - 0.58	11.28 - 10.73	9.03 - 8.13
2	0.91 - 0.65	0.99 - 0.83	0.57 - 0.53	10.72 - 10.17	8.12 - 7.22
1	0.64 - 0.38	0.82 - 0.68	0.52 - 0.45	10.16 - 9.64	7.21 - 6.30

Based on the scale in table 3.12 the scoring pattern of each of the typologies for various utilities are listed in table 3.13.

Table 3.13: Energy Intensity Score achieved by Utilities across Typologies

Utility	Uppals Marble Arch	Sushma Elite Cross	Sector 51 Chandigarh	Sector 19A Chandigarh
Water Heating	3	3	3	4
Lighting	3	3	5	5
Ventilation	4	3	4	7
Space Cooling	5	4	4	6
Space Heating	6	5	4	7
Average Value	**4.2**	**3.6**	**4.0**	**5.8**

The visual form of table 3.13 is displayed as figure 3.13. The red line denotes the observed values for each of the utility and the green line is the average of all the utilities with respect to the typologies. It is observed that space heating and space cooling are the two major energy consuming utilities and the low rise plotted typology (Sector 19A) is the most energy intensive across different typologies.

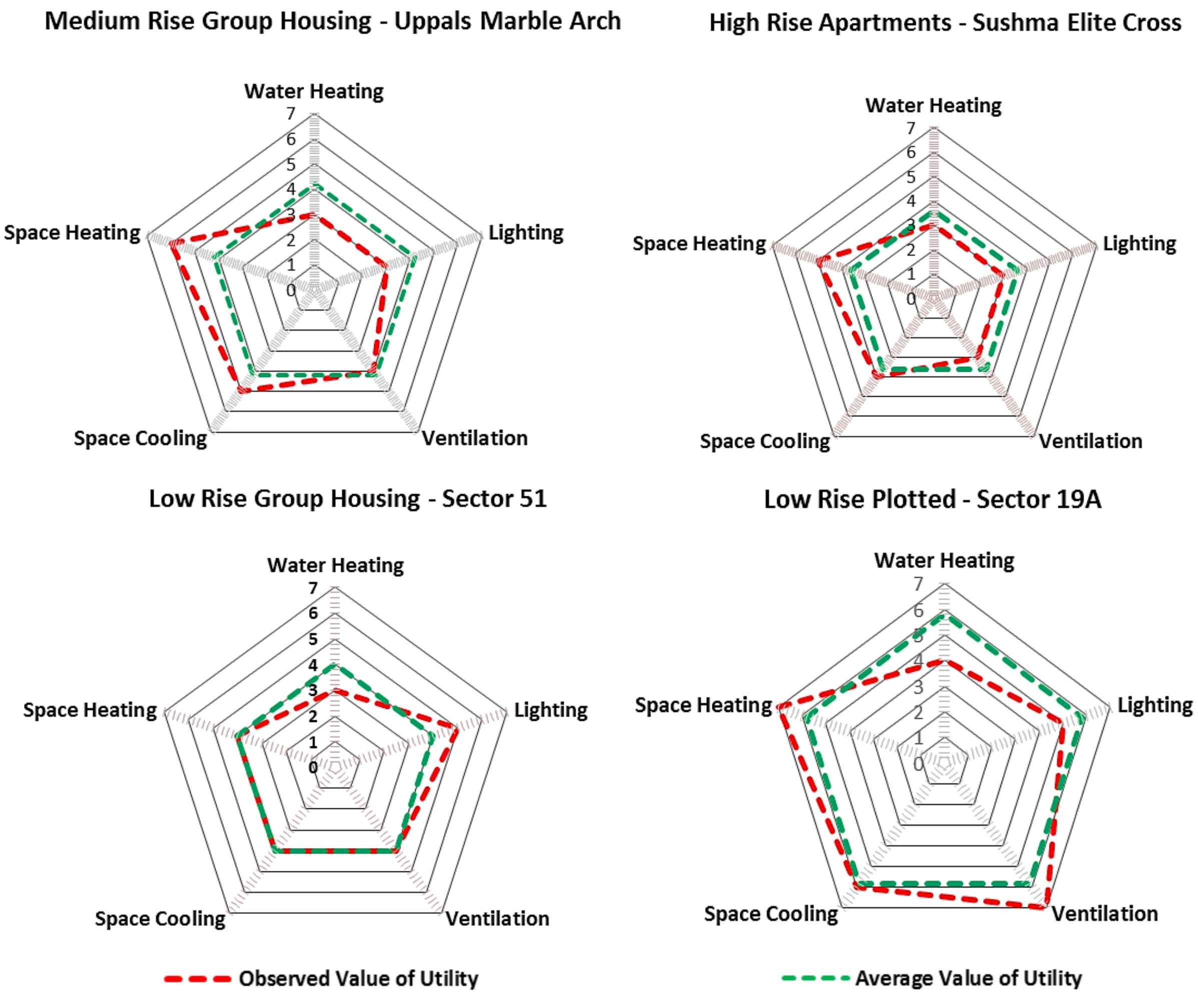


Figure 3.13 Energy Intensive Utilities and their Score across Different Typologies

Based on the scale in table 3.12 the seasonal scoring pattern of all the typologies for various utilities are listed in table 3.14.

Table 3.14: Seasonal Energy Intensity Score achieved by Utilities across all Typologies

Activity	Summer (Mar-Apr-May-Jun)	Monsoon (Jul-Aug)	Autumn (Sept-Oct)	Winter (Nov-Dec-Jan-Feb)
Water Heating	2	2	3	6
Lighting	2	3	4	6
Ventilation	5	6	2	0
Space Cooling	4	0	0	0
Space Heating	0	0	0	5
Average Value	**2.6**	**2.2**	**1.8**	**3.4**

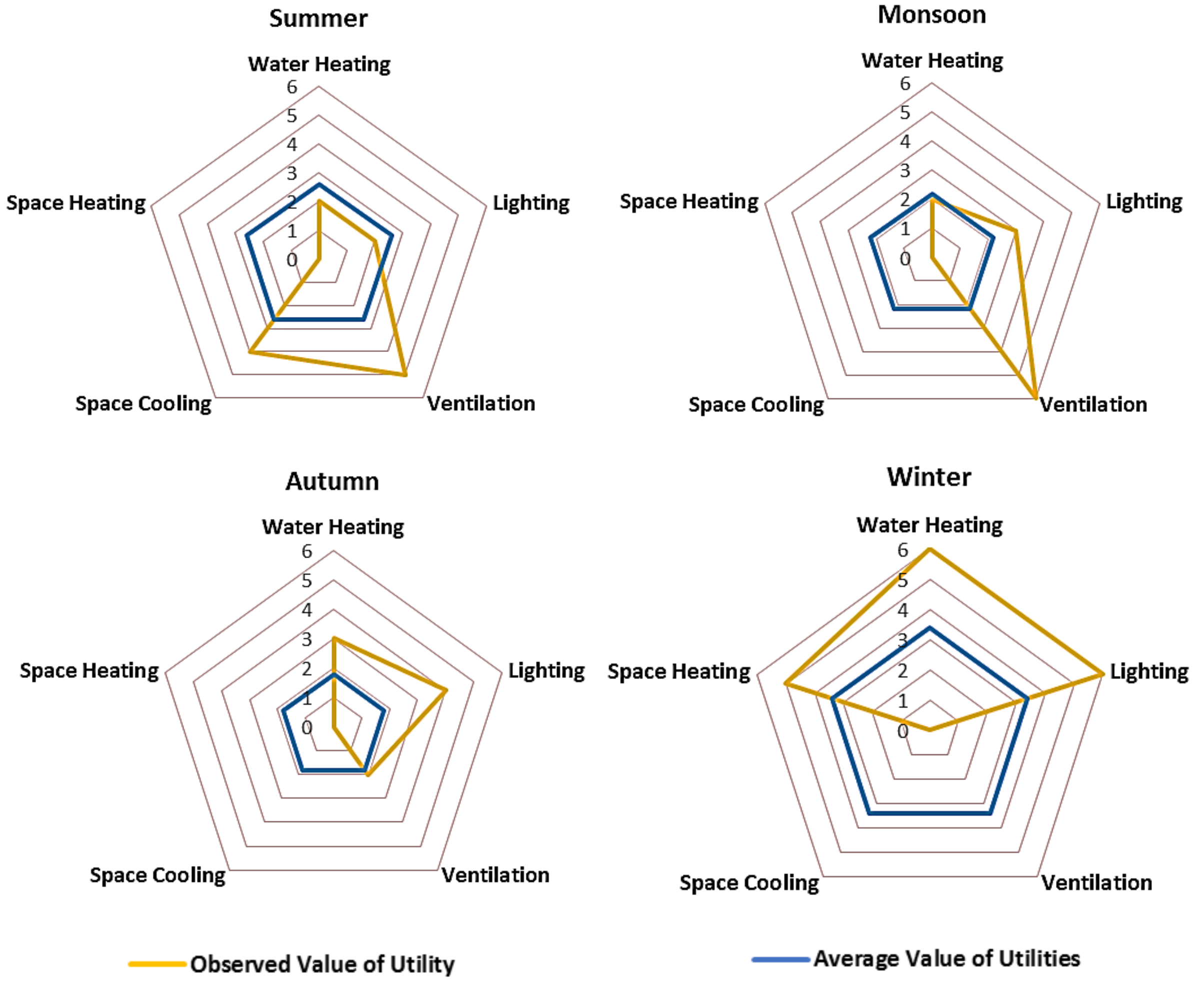


Figure 3.14 Seasonal Energy Intensive Utilities and their Score across all Typologies

In figure 3.14 the seasonal energy intensive activities and their scoring across all typologies is indicated. The yellow line denotes the observed values for each of the utility and the blue line is the average of all the utilities with respect to seasonal variation. In the case of winter major portion of energy is spent on water heating and lighting followed by space heating. Autumn has the lowest energy intensity with sharing of energy between water heating, lighting and ventilation. In case of summers, ventilation is the prime energy consumer than space cooling.

3.6.6 Household Equipment Ownership and Operating Duration

The household survey across typologies is used to estimate and generalize the ownership of electrical appliances across households as it has an overall influence on total energy consumption. Also of significance are the hours of operation of the electrical appliances. An inventory of electrical appliances is prepared after the survey with those appliances that are found to have high penetration and utility value in each of the household. Those appliances which are dependent on plug load and are observed in more than 70% of the households are considered in the final inventory. Considering that the appliances shortlisted are of highest energy efficiency as per **Bureau of Energy Efficiency (BEE)** labelling irrespective of which brand is observed in the households, the average plug load intensity of households in each RRU is calculated. The inventory of electrical appliances with their power consumption parameters as per BEE labelling and average hours of their operation in the household are listed in table 3.15.

Table 3.15: Inventory of Common Electrical Appliances in the RRUs and their Operating Duration

S. No.	Appliance	Star Rating	Watt	Quantity	Daily Operating Hours
1	CFL Bulbs	5 Star	15 W	4	6 hours
2	LED Bulbs	3 Star	11 W	6	8 hours
3	Ceiling Fan	5 Star	50 W	5	8 hours
4	Exhaust Fan	N.A.	100 w	3	4 hours
5	LED Television(32Inch)	5 Star	34 W	2	8 hours
6	Satellite Decoder	N.A.	8 W	2	6 hours
7	Mobile Charger	N.A.	4 W	3	6 hours
8	Two Door Refrigerator (250liters)	4 Star	24 W	1	24 hours
9	Split Air Conditioner (1.5Ton)	3 Star	1495 W	3	8 hours
10	Air Cooler	N.A.	200 W	2	10 hours
11	Washing Machine	5 Star	1000 W	1	0.5 hour
12	Kitchen Mixer	N.A.	500 W	1	0.2 Hour
13	Toaster	N.A.	1000 W	1	0.3 Hour
14	Microwave Oven	N.A.	800 W	1	1 Hour
15	Vacuum Cleaner	N.A.	1000 W	1	0.5 hour
16	Electric Geyser (15litre)	5 Star	2000 W	2	4 hours
17	Electric Iron	N.A.	1200 W	1	0.3 Hour
18	Audio Stereo	N.A.	650 W	1	1 Hour
19	PC or Laptop	N.A.	175 / 60 W	1	4 hours
20	Monobloc Water Pump (1 HP)	5 Star	6000 W	1	0.5 hour

3.6.7 Occupancy Schedule of Users

According to Census of India, 2011 the dominant age group within the households are people in the age group of 20-24 years (11.5%) and 25-29 years (10.4%). Considering the age group from 0-19 years (47%) comprising of users who are most likely school or university students and age group from 60-80+ years (6%) comprising of users who have retired from active employment, almost half the population are not active decision makers at the household level. With the remaining 47% population in the age group of 20-59 years and commercial activity being the major economic base of CUC, a major portion of the ladies are homemakers or involved in home based trades.

Based on the survey it is observed that 22% of household occupants primarily comprising of ladies, non-school going kids and the elderly remain in the home on all days of the week. About 28% occupants comprising of school and college students are away from home between 7.00 am to 3.00 pm. 21% of occupants comprising of students seeking professional education are away from 9.00 am to 6.00 pm. The remaining 29% comprising of occupants going to their workplace generally leave by 9.00 am and are back by around 8.00 pm. Under ideal conditions all the occupants are expected to be in the household after 10.00 pm and on Sundays, all the household occupants are ideally at home.

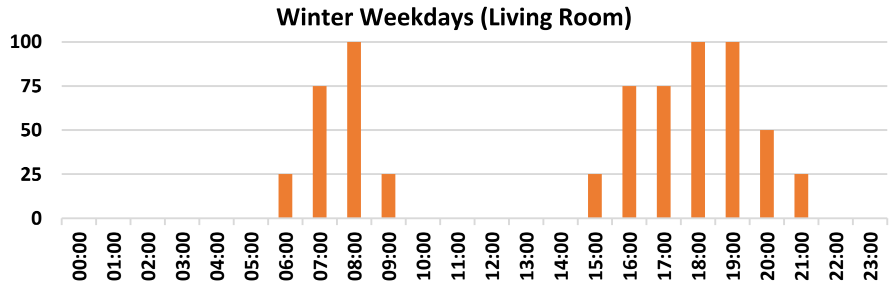
For the purpose of the research based on the prevalent family structure – joint and nuclear family across the RRUs and with reference to household survey two predominant household occupancy schedules are defined. The details regarding the occupancy schedule of the two categories are listed in table 3.16 and 3.17. The **occupancy pattern – 1** is indicative of nuclear families in CUC, with four family members out of which both the wife and husband leave for their workplaces and two children who are still seeking education at various levels. The household on a regular day of week is generally vacant between 9.00 am to 3.00 pm, until one of the child comes back from school. On weekends and holidays the family spends quality time at home together with very few visitors. **Occupancy pattern – 2** is based on the joint family structure visible in CUC, the household composition comprises of elderly wife and husband with husband still working or managing business. Their son and daughter-in-law along with their child complete the household. Both the son and daughter-in-law leave for work with the elderly lady taking care of the household and the grandchild. On weekends and holidays the family spends time together and has visitors frequenting the household.

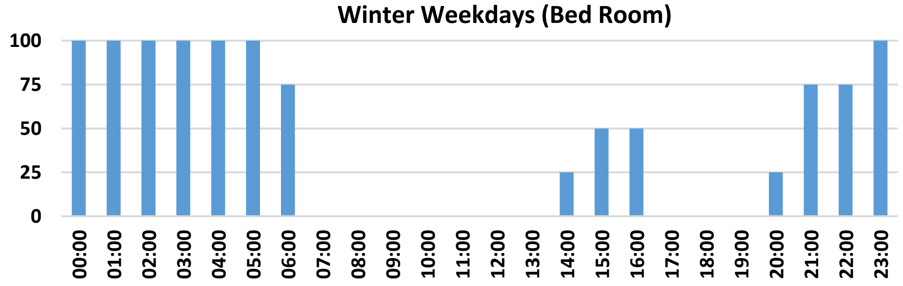
Figure 3.15 is a depiction of time spent by the members of household in the living and bedroom spaces and measured on basis of an hour divided into 4 segments with each segment representing 15 minutes. The occupancy patterns are indicative averaged scenarios and can undergo variations as per user interaction.

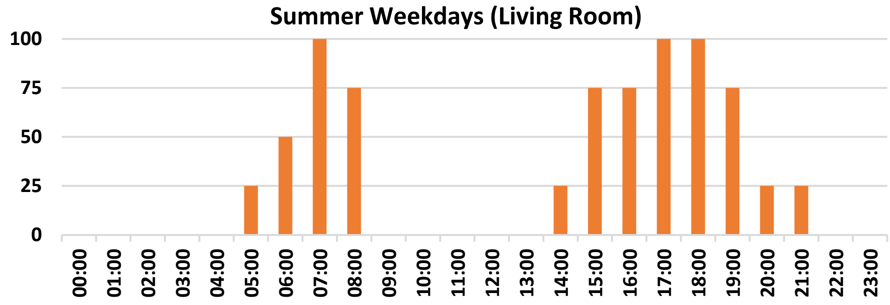
Table 3.16 : Occupancy Pattern Type – 1

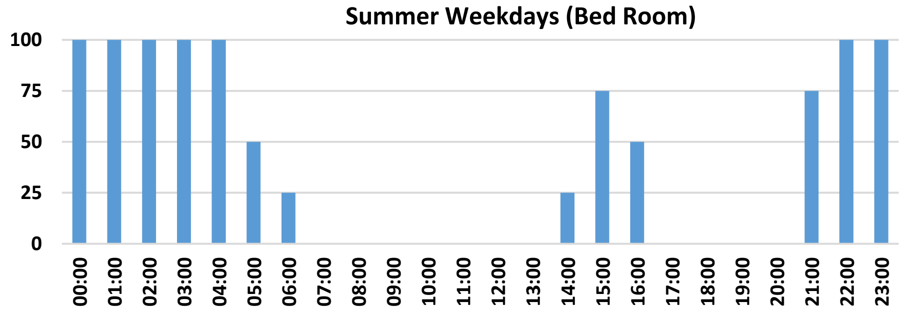
Occupancy Pattern	**1**	Total Members:	**4**	Age Group:	0-19 Years =	**2**	20-59 Years =	**2**	60-80+ Years =	**0**
		Employment:	**2**							

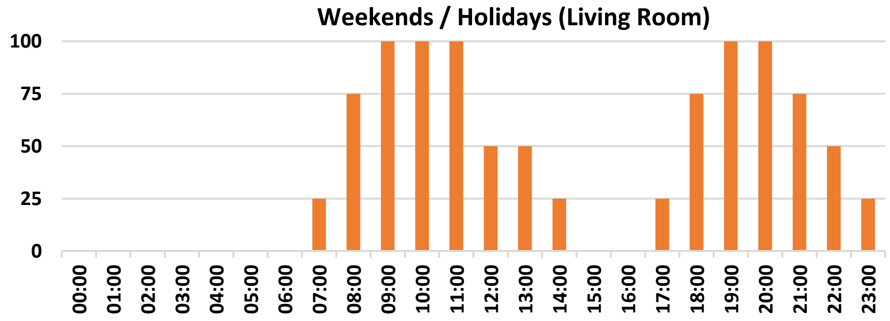
Member 1 **Employed Male**	Member 2 **Employed Female**	Member 3 **University Student**	Member 4 **School Student**


Winter Weekdays (Living Room)


Winter Weekdays (Bed Room)


Summer Weekdays (Living Room)


Summer Weekdays (Bed Room)


Weekends / Holidays (Living Room)

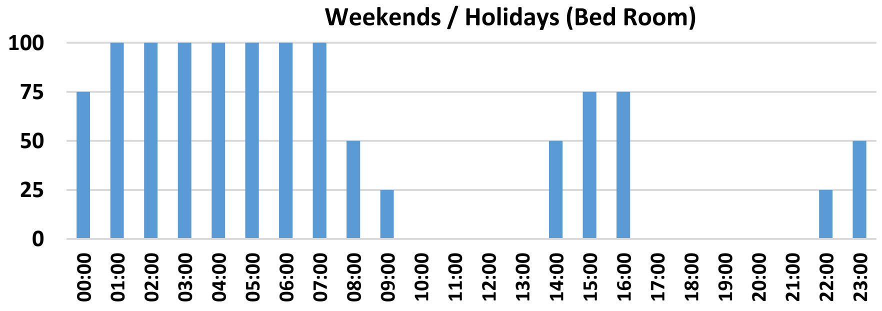
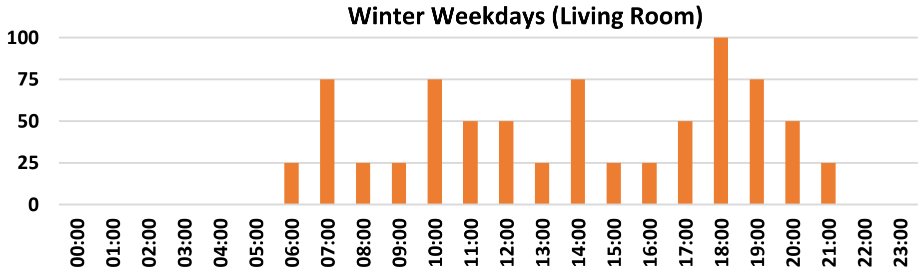
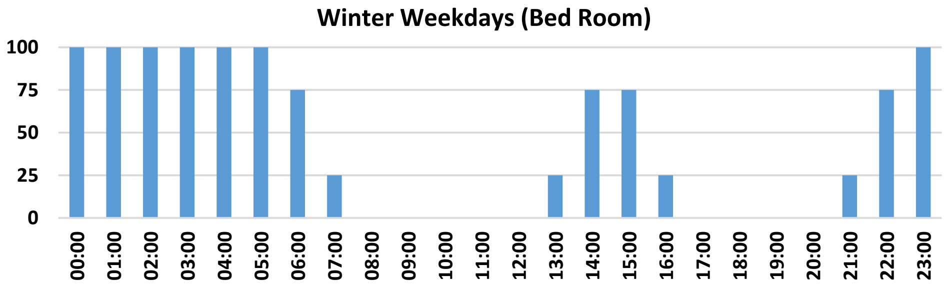

Weekends / Holidays (Bed Room)

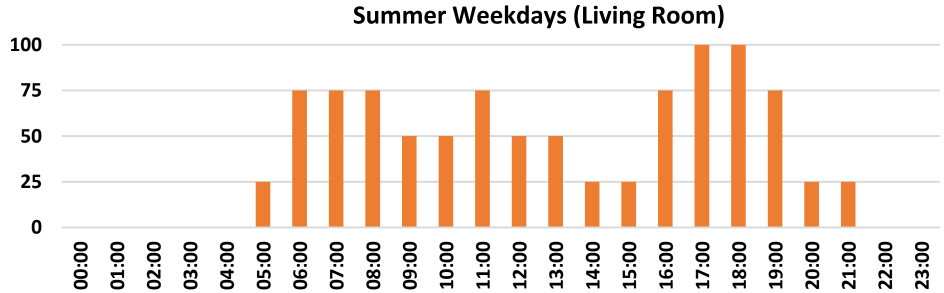
Table 3.17: Occupancy Pattern Type - 2

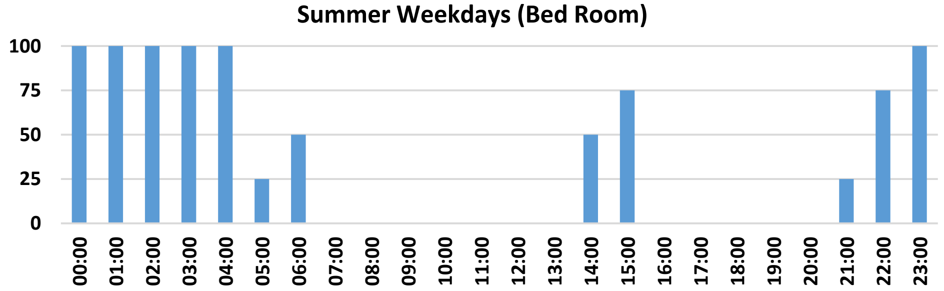
Occupancy Pattern	**2**	Total Members:	**5**	Age Group:	0-19 Years =	**1**	20-59 Years =	**2**	60-80+ Years =	**2**
		Employment:	**3**							

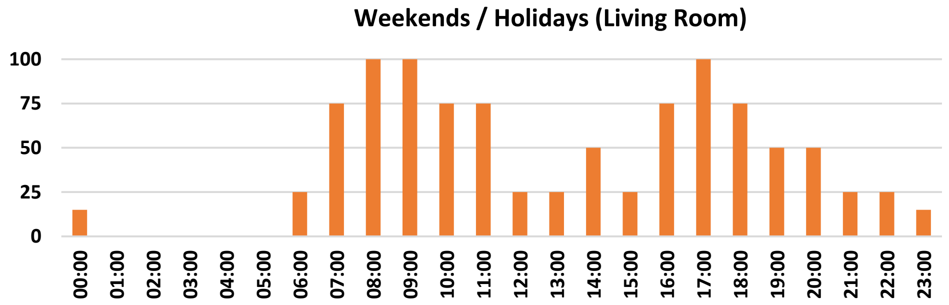
Member 1	Member 2	Member 3	Member 4	Member 4
Employed Male	**Unemployed Female**	**Employed Male**	**Employed Female**	**School Student**

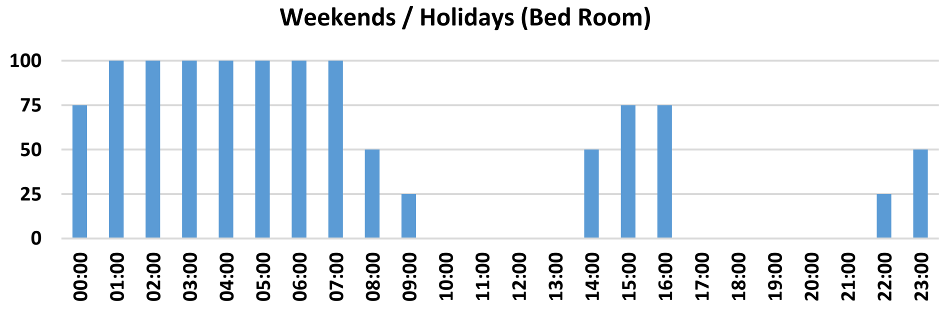

Winter Weekdays (Living Room)


Winter Weekdays (Bed Room)


Summer Weekdays (Living Room)


Summer Weekdays (Bed Room)


Weekends / Holidays (Living Room)


Weekends / Holidays (Bed Room)

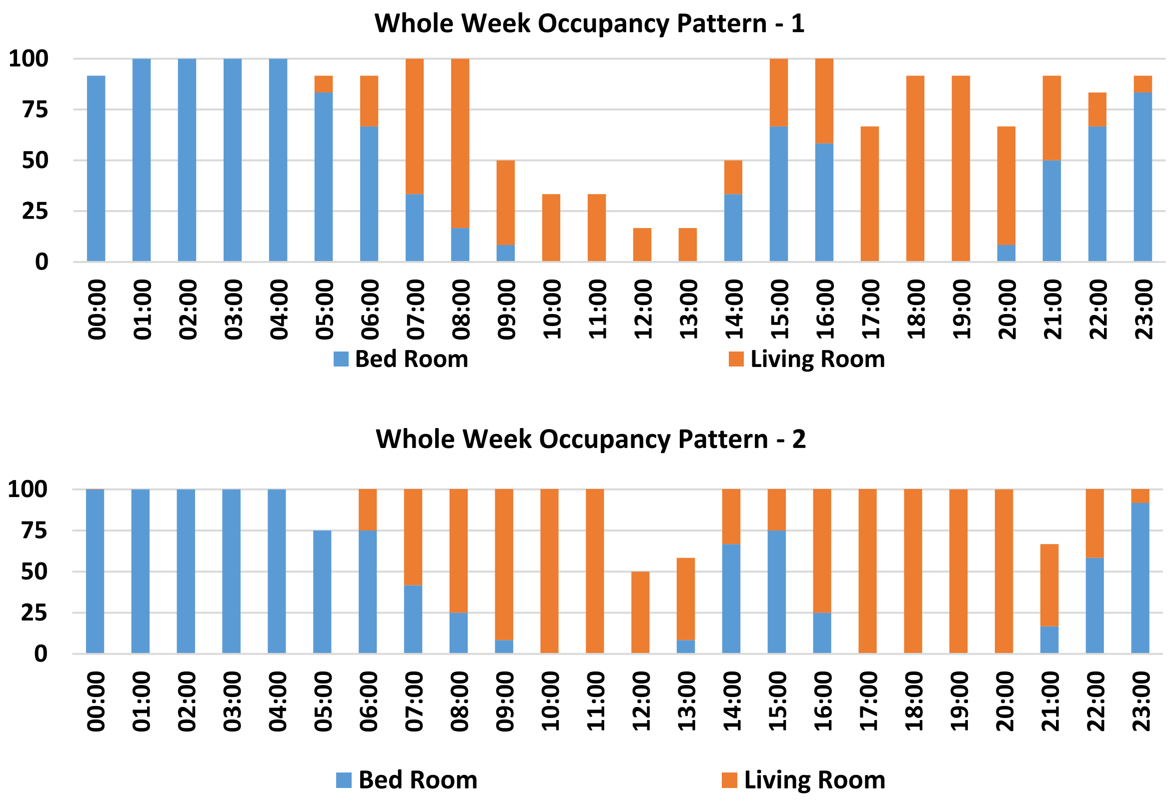


Figure 3.15: Weekly Combined Occupancy Pattern – 1 and 2

3.7 Defining Representative Energy Benchmarks

Existing conditions of household, cooling and heating needs, internal plug load intensity and patterns are defined but to generalize the overall energy demand there is a need to construct the representative energy benchmarks of the RRUs. For this purpose simulated assessment of RRUs using EnergyPlus is undertaken based on parameters defined by IGBC, GRIHA, ASHRAE and TERI for energy efficient green buildings and highlighted in table 3.15. The validity of the model is checked by comparing the margin of error between the simulated energy estimate and the monthly energy bills.

3.7.1 Building Simulation Model

EnergyPlus based shoe box model of the four RRUs are created comprising of external envelope, glazing and roof. The living room and bedrooms in the models are considered to be air conditioned, which constitute 50% of total floor area of the household unit. The basic construction of the units is reinforced concrete column and beam structure with burnt brick infill of 0.23m without any insulation. From the household survey, the glazing area is estimated between 30-60% of wall area without any window protection. The glazing considered is transparent glass of 3.5mm with no solar factor.

Table 3.18: Characteristics of the Simulated RRUs and Average Energy Demand

S. No.	Model Characteristics	Units	Uppals Marble Arch	Sushma Elite Cross	Sector 51, Chandigarh	Sector 19A, Chandigarh
1.	**Building Envelope**					
1.1	**U_{wall}**	**(Watt/m^2 K)**	**2.5**	**2.5**	**2.5**	**2.5**
1.2	**U_{roof}**	**(Watt/m^2 K)**	**1.2**	**1.2**	**1.2**	**1.2**
1.3	**$U_{glazing}$**	**(Watt/m^2 K)**	**2.8**	**2.8**	**2.8**	**2.8**
1.4	**Wall Surface Absorption**	**CCF**	**0.7**	**0.7**	**0.7**	**0.7**
1.5	**Roof Surface Absorption**	**CCF**	**0.6**	**0.6**	**0.6**	**0.6**
1.6	**Window to Wall Ratio**	**%**	**60**	**50**	**30**	**30**
1.7	**Glazing Shading Coefficient**	**SC**	**0.7**	**0.7**	**0.7**	**0.7**
1.8	**Solar Heat Gain Coefficient**	**SHGC**	**0.20**	**0.20**	**0.25**	**0.25**
2.	**Ventilation & Air Conditioning**					
2.1	**COP / SEER**		**2.00 / 6.8**	**2.00 / 6.8**	**2.00 / 6.8**	**2.00 / 6.8**
2.2	**Outside Air**	**m^3/h per person**	**20**	**20**	**20**	**20**
2.3	**Temperature Set Point**	**°C**	**24**	**24**	**24**	**24**
2.4	**Relative Humidity Set Point**	**%**	**60**	**60**	**60**	**60**
3.	**Occupancy Density**	**m^2/person**	**50**	**39**	**25**	**58**
4.	**Lighting**					
4.1	**Living Room Lighting Density**	**W/m^2**	**21**	**21**	**21**	**21**
4.2	**Bed Room Lighting Density**	**W/m^2**	**18**	**18**	**18**	**18**
4.3	**Ancillary Lighting Density**	**W/m^2**	**9**	**9**	**9**	**9**
5.	**Equipment Plug Loads**					
5.1	**Average Plug Load Power Density**	**W/m^2**	**8**	**8**	**8**	**8**
6.	**Domestic Hot Water Load**					
6.1	**November to February**	**l/m^2/day**	**0.42**	**0.42**	**0.42**	**0.42**
6.2	**March to June**	**l/m^2/day**	**0.20**	**0.20**	**0.20**	**0.20**
6.3	**July to October**	**l/m^2/day**	**0.35**	**0.35**	**0.35**	**0.35**

Simulated assessment of the RRUs with the parameters indicate that the total energy demand in case of Uppals Marble Arch is 11.94kWh/m^2. For Sushma Elite Cross the same value is around 12.04kWh/m^2 and Sector 51 Chandigarh has a demand of 14.12kWh/m^2. In case of Sector 19A, Chandigarh, 1 Kanal plotted unit has an energy demand of 15.20kWh/m^2, 2 Kanal plotted unit has a demand of 16.72kWh/m^2 and 3 Kanal plotted unit has a demand of 18.20kWh/m^2.

The margin of error between simulated electricity demands to the actual monthly electricity bills is displayed in table 3.19 for each of the typology.

Table3.19 : Comparison of Simulated Electricity Demand and Actual Electricity Consumption

Electricity Demand	**Uppals Marble Arch**	**Sushma Elite Cross**	**Sector 51 Chandigarh**	**Sector 19A, Chandigarh**
From Meter Bills (kWh/m^2)	11.61	11.72	14.47	1 Kanal = 13.74 2 Kanal = 15.25 3 Kanal = 17.10
Simulated Value (kWh/m^2)	11.94	12.04	14.12	1 Kanal = 12.80 2 Kanal = 14.12 3 Kanal = 15.72
Error %	+2.8%	+2.7%	-2.5%	-6.8% -7.4% -8.1%

From table 3.19, it is evident that in the case of Sector 51 and Sector 19A, Chandigarh simulated values are lower than the actual values an indication that energy is consumed more than required. A deviation of ± 5% still justifies that the annual energy consumption behaviour and the simulated energy demand are in line. It is the case of the plotted development that the simulated energy demand is lower by a margin of 6.8 – 8.1% and is a point of concern that needs reconsideration. One possible reasons can be the need for improving energy efficiency and insulation measures at household level. There is also a need to look into the building controls so as to enhance the passive character and solar access to the plotted units which can aid in reducing energy demand.

The role of renewable energy infrastructure and the demand that needs to be bridged for each of the typologies is clearly defined. With the inherent advantages and disadvantages of each renewable resource, the siting and exploitation of their potential needs to be assessed to define the extent to which renewable infrastructure can meet actual demand and lower the dependency on the grid for balance electricity.

3.8 Conclusion

Energy generation at household level through exploitation of renewable energy resources is the key for ensuring energy security in the housing sector. The objective of this study is to assess the actual energy demand that needs to be met by renewable energy infrastructure in case of each RRU. The simulation model has to match the actual electricity consumption derived from monthly electricity bills so as to validate the future energy demand. Detailed analysis of the households with a wider database and based on the family size and structure, financial decision making status of occupants, independent habitable space of occupants and hours spent by each individual in different spaces can result in wide range of occupancy schedules that can lead to a better understanding of the energy demand.

From the household energy assessment it is evident that occupants spend most of their time in the living room and bedrooms. Also, cooling demand is the major consumer of annual electricity followed by lighting and heating demand. Comparison of different RRUs highlights that high rise residential units need not necessarily be energy intensive due to their scale, it is the case of plotted development that can impact energy performance. Household surveys highlight that joint families are prevalent across the plotted development which may be an advantage with respect to social structure, but can acts as deterrents to energy consumption due to behavioural issues.

Nuclear families though may be less energy intensive but as evident from the household survey tend to spend the weekends at home rather than involving in outdoor activities. This not only has effect on health and hampers social interaction, staying indoors leads to increase in energy demand on a single day in comparison to the weekday’s pattern. Another notable feature is the presence of pets in the households surveyed. One out of every three households has pets from a wide range of species. Pets are also active consumers of electricity especially in case of aquariums which run on power 24x7x365 but have not been considered as part of the assessment.

Promotion of CFL and LED lights to reduce energy demand is the most prevalent energy saving initiative across different types of households. Apart from this, the scope of conservancy, renewable infrastructure, solar and wind resource etc., are in the knowledge of only 12-14% of home occupants across different typologies. It is necessary to disseminate such information for the promotion and easy acceptance of renewable infrastructure by the home owners.

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Chapter 4

Wind Resource Assessment and Potential

4.1 Assessing the Potential of Wind Energy

The chapter investigates in depth the wind resource available in the Chandigarh Urban Complex (CUC) and its energy generating potential through rooftop based wind turbines in different housing typologies. The wind resource assessment of CUC involves investigating hourly based wind data over a span of 6 years using both Statistical **(Kubik et al., 2011)** and Computational Fluid Dynamics (CFD) **(Chaudhry et al., 2011)** approaches. Statistical assessment of wind resource involves estimation and representation of wind data in the form of wind speed histograms and fitting the data into two-parameter Weibull and Rayleigh Probability Distribution Functions (PDF). Assessment of the distribution functions leads to deriving the dimensionless 'k' shape parameter and 'c' scale parameter. To ensure accurate wind energy potential assessment the PDFs are evaluated for goodness of fit using three tests – chi-square test (χ^2), R square (R^2) and the Root Mean Square Error (RMSE). Both the PDFs are accurate and efficient but the Weibull distribution fits the observed data better than the Rayleigh distribution.

Computational Fluid Dynamics (CFD) simulation **(Chung, 2002)** of four housing typologies is undertaken to understand behaviour and effect of wind within the urban built configuration and identify ideal locations for placing the wind turbines. Wind within the built environment is subject to gusts and turbulence. High resolution measurement using CFD reveals ideal locations where it is possible to capture wind energy greater than that derived by statistical methods. The analysis highlights the need to study impact of built form of housing typologies on wind energy potential.

4.2 Weather Data of Chandigarh Urban Complex (CUC)

The primary weather data for Chandigarh Urban Complex (CUC) is collected from the Weather Station at Chandigarh International Airport. The hourly wind speed data from January 01, 2010 to December 31, 2015 is collected from a source 10 meter above the ground level as indicated in table 4.1.

Table 4.1: Geographical Coordinates of Chandigarh Meteorological Station

Location	Parameter	Value
Chandigarh	Latitude	30° 44' 29.335" N
	Longitude	76° 46' 5.0376" E
	Measurement Height of Anemometer	10 meter
	Elevation over Sea Level	308 meter

Assessment of the weather information visually from figure 4.1 reveals that the maximum temperature ranges between 38°-45°C in summers and minimum temperature ranges between 3°-15°C in winters. The annual maximum average temperature from 2010-2015 was 45.3°C in the months of May and June, the minimum average temperature for the same duration was 4.3°C in the month of January. The annual average Direct Normal Irradiance (DNI) is 4.67kWh/m^2/day with the highest DNI of 5.72-6.18kWh/m^2/day in the summer months of March, April and May. The annual average Global Horizontal Irradiance (GHI) is 5.21kWh/m^2/day with the highest GHI of 5.70-7.32kWh/m^2/day in March, April, May and June.

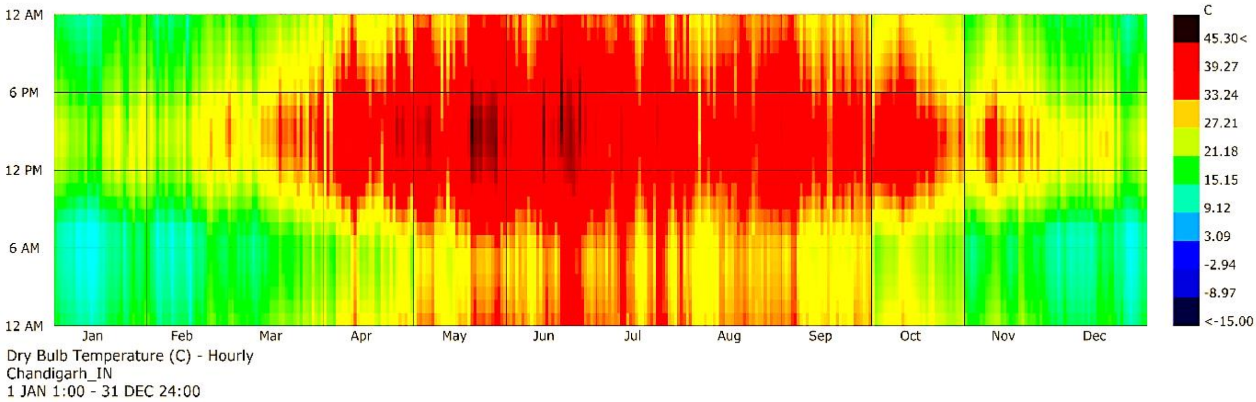


Figure 4.1: Hourly Temperature Gradient Map of Chandigarh Urban Complex (CUC), 2010-15

Visual assessment of wind data for 2010-15 from figure 4.2 reveals that CUC experiences wind of maximum speed in the months of May and June, whereas moderate winds are experienced in the months of February, March and April. The lowest wind speeds are experienced in the months of October, November and December.

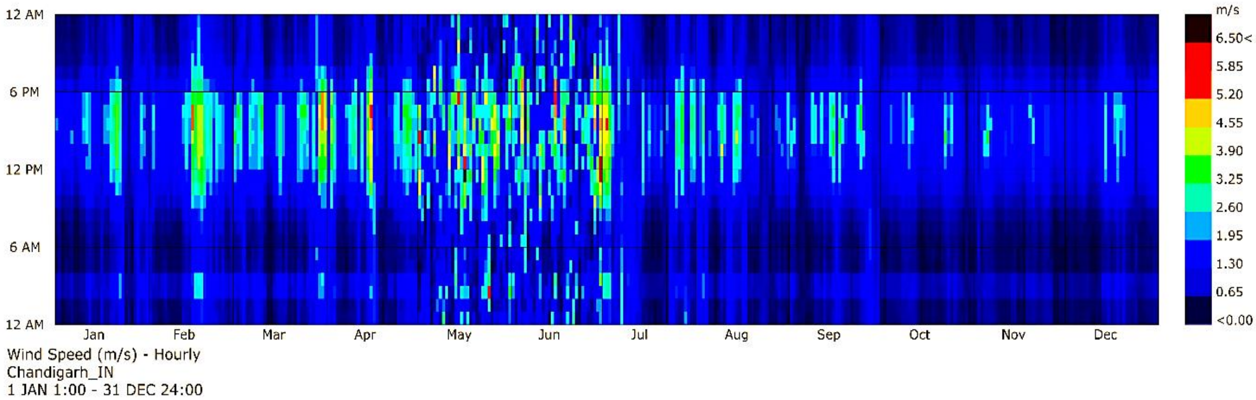


Figure 4.2: Hourly Wind Speed Gradient Map of Chandigarh Urban Complex (CUC), 2010-15

4.3 Wind Speed and Direction in Chandigarh Urban Complex (CUC)

Hourly wind speed data for the period 2010-15 was plotted on a Windrose diagram as indicated in figure 4.3 and the predominant wind directions were plotted. As indicated graphically by

Windrose diagrams CUC experiences maximum velocity wind speeds from South-East to North-West direction and moderate wind speeds from North-West to South-East direction.

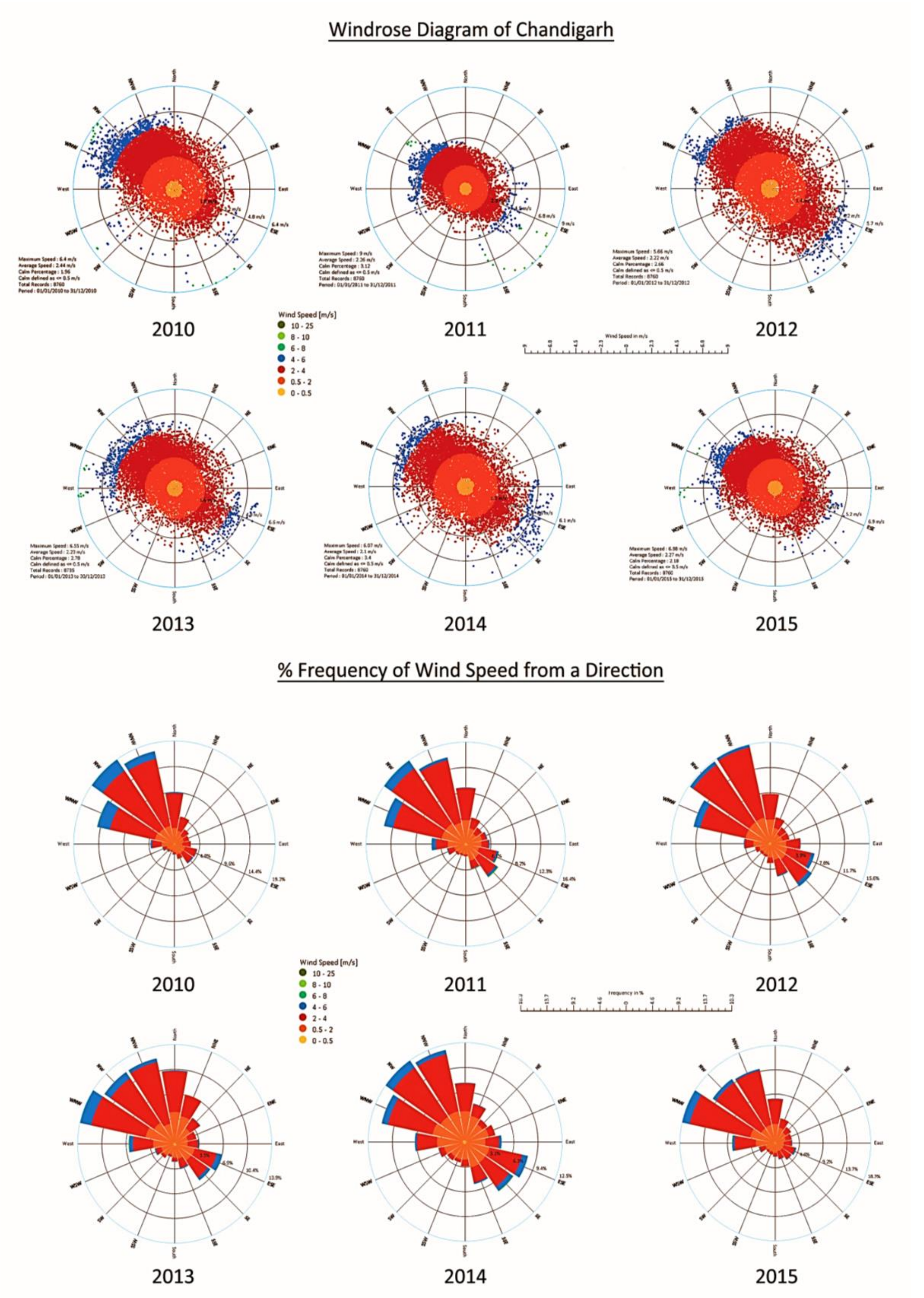


Figure 4.3: Windrose Diagram of CUC based on Wind Speed Data from 2010-15

The monthly average wind speed from 2010-15 are listed in table 4.2 and graphically represented in figure 4.4. The seasonal mean wind speed for summer (March, April, May and June), winter (November, December, January and February) and rest of the year (July, August, September and October) are listed in table 4.3. It can be inferred that the wind speed of highest velocity (2.6-2.9m/sec) occurs during the summer months followed by winters (2.0-2.3m/sec).

Table 4.2: Monthly Average Wind Speed (m/sec) of CUC, 2010-15

Month	2010	2011	2012	2013	2014	2015	Average Wind Speed (m/sec)
January	2.24	2.16	2.47	2.12	2.03	1.92	**2.16**
February	2.64	2.53	2.37	2.43	2.36	2.06	**2.40**
March	2.40	2.42	2.55	2.66	2.42	2.17	**2.44**
April	3.29	2.95	2.28	2.32	2.49	2.65	**2.66**
May	2.64	3.17	2.69	2.86	2.73	2.66	**2.79**
June	3.31	2.87	2.60	3.09	2.59	2.94	**2.90**
July	1.83	2.21	1.94	2.08	1.84	2.30	**2.03**
August	1.73	1.63	1.73	1.56	1.65	1.81	**1.69**
September	1.84	1.52	1.68	1.50	1.43	1.86	**1.64**
October	2.45	1.91	2.05	1.74	1.44	1.99	**1.93**
November	2.41	1.87	2.21	1.90	2.12	2.58	**2.18**
December	2.57	1.94	2.03	2.50	2.09	2.33	**2.24**
Yearly	**2.45**	**2.27**	**2.22**	**2.23**	**2.10**	**2.27**	**2.26**

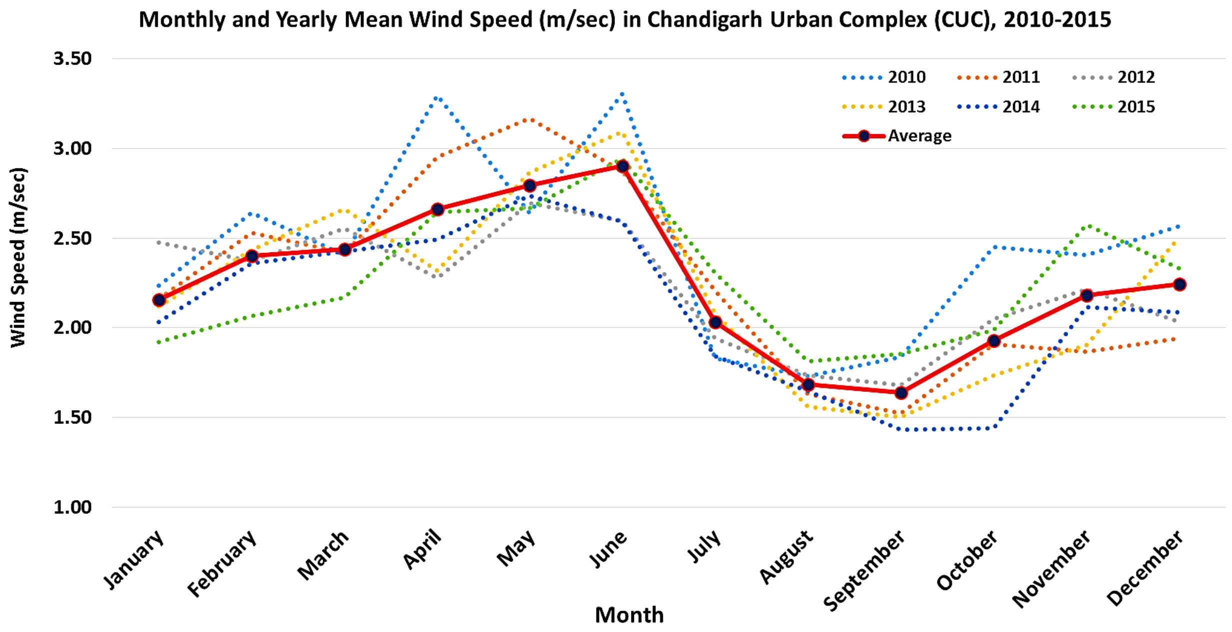


Figure 4.4: Graphical Representation of Monthly Average Wind Speed (m/sec) in CUC, 2010-15

Table 4.3: Seasonal Mean Wind Speed (m/sec) Variation of CUC, 2010-15

Season	2010	2011	2012	2013	2014	2015	Average Wind Speed (m/sec)
Summer	2.91	2.85	2.53	2.73	2.56	2.61	**2.70**
Monsoon	1.78	1.92	1.84	1.82	1.75	2.06	**1.86**
Autumn	2.14	1.72	1.86	1.62	1.44	1.92	**1.78**
Winter	2.46	2.13	2.27	2.24	2.15	2.22	**2.25**

4.4 Time Series based Distribution of Wind Data

The monthly mean wind speed (V_m) and the standard deviation (σ_{ts}) of the time series data are calculated using the equation 2.1 and 2.2 (Chapter 2) as indicated in table 4.4.

Table 4.4: Monthly Mean Wind Speed (m/sec) and Standard Deviations in CUC, 2010-15

Year	2010		2011		2012		2013		2014		2015	
Parameter	V_m	σ_{ts}	V_m	σ_{ts}	V_m	σ_{ts}	V_m	σ_{ts}	V_m	σ_{ts}	V_m	σ_{ts}
January	2.24	0.94	2.16	0.93	2.47	1.04	2.12	0.96	2.03	0.99	1.92	0.72
February	2.64	0.96	2.53	0.98	2.37	0.99	2.43	0.95	2.36	1.24	2.06	1.00
March	2.40	0.90	2.42	0.84	2.55	0.92	2.66	0.98	2.42	1.00	2.17	0.88
April	3.29	1.11	2.95	0.91	2.28	0.89	2.32	0.85	2.49	1.02	2.65	0.81
May	2.64	1.03	3.17	1.25	2.69	1.06	2.86	0.96	2.73	0.95	2.66	0.92
June	3.31	1.09	2.87	1.13	2.60	1.08	3.09	1.15	2.59	1.10	2.94	1.20
July	1.83	0.89	2.21	1.03	1.94	0.91	2.08	1.00	1.84	0.67	2.30	1.03
August	1.73	0.74	1.63	0.78	1.73	0.88	1.56	0.78	1.65	0.75	1.81	0.84
September	1.84	0.77	1.52	0.88	1.68	0.75	1.50	0.73	1.43	0.64	1.86	0.83
October	2.45	1.01	1.91	0.94	2.05	0.73	1.74	0.58	1.44	0.68	1.99	0.70
November	2.41	0.98	1.87	0.96	2.21	0.96	1.90	0.76	2.12	0.86	2.58	0.75
December	2.57	0.87	1.94	1.04	2.03	0.90	2.50	1.18	2.09	1.04	2.33	1.02
Annual Average	**2.44**	**1.06**	**2.26**	**1.10**	**2.22**	**0.99**	**2.23**	**1.04**	**2.10**	**1.02**	**2.27**	**0.97**

The average wind velocity ranging between 2.19 –2.64m/sec is insignificant for power generation as most micro-wind turbines require a start-up/cut-in wind speed of 2.5-4.0m/sec. With high resolution Computational Fluid Dynamics (CFD) analysis the potential of such low velocity winds need to be investigated in relation with the built form so that specific locations can be identified where the wind flow is enhanced and ensures optimum cut-in speed for installation of wind turbines that can promote electricity generation. Also, the study of variation in wind speeds with respect to housing typology and height needs to be investigated to promote rooftop wind turbines in case of high rise buildings.

4.5 Frequency Distribution of Wind Data

The domain of observed wind data for CUC are divided into intervals with a difference of 1m/sec. The transformed time series data into frequency distribution format are listed below in table 4.5.

Table 4.5: Frequency Distribution of Observed Wind Data of CUC, 2010-15

Bins	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
January	0.117	0.401	0.418	0.065	0.000	0.000	0.000	0.000
February	0.140	0.379	0.302	0.135	0.043	0.000	0.000	0.000
March	0.091	0.337	0.422	0.128	0.015	0.007	0.000	0.000
April	0.039	0.157	0.468	0.299	0.038	0.000	0.000	0.000
May	0.055	0.183	0.351	0.356	0.052	0.003	0.000	0.000
June	0.063	0.153	0.297	0.307	0.140	0.031	0.010	0.000
July	0.095	0.340	0.288	0.220	0.047	0.009	0.000	0.000
August	0.175	0.422	0.308	0.095	0.000	0.000	0.000	0.000
September	0.156	0.432	0.315	0.097	0.000	0.000	0.000	0.000
October	0.083	0.403	0.434	0.079	0.000	0.000	0.000	0.000
November	0.024	0.204	0.469	0.293	0.010	0.000	0.000	0.000
December	0.110	0.280	0.329	0.242	0.039	0.000	0.000	0.000
Annual Average	**0.089**	**0.270**	**0.343**	**0.224**	**0.063**	**0.009**	**0.002**	**0.000**

Wind speed bins are created starting with 0-1m/sec, mean wind speed (v_i) for each class interval is calculated using equation 2.3 (Chapter 2) along with frequency of occurrence of each wind speed class (f_i). The probability of occurrence of the measured wind speed $f(v_i)$ is calculated using the equation 2.4 (Chapter 2). The standard deviation (σ_m) of the mean wind speed is calculated using the equation 2.5 (Chapter 2). The monthly mean wind speed (v_i) on basis of the bins or class intervals are highlighted in table 4.6. The 52,584 hours of wind speed data arranged into frequency and cumulative distribution format of 1m/sec interval results in table 4.7.

Table 4.6: Mean Wind Speeds (v_i) Calculated for each Speed Class Interval

Bins	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
January	0.699	1.546	2.430	3.210	0.000	0.000	0.000	0.000
February	0.651	1.512	2.487	3.412	4.331	0.000	0.000	0.000
March	0.765	1.569	2.472	3.373	4.470	5.555	0.000	0.000
April	0.687	1.625	2.554	3.390	4.176	0.000	0.000	0.000
May	0.673	1.600	2.546	3.372	4.327	5.102	0.000	0.000
June	0.693	1.517	2.532	3.483	4.416	5.364	6.461	0.000
July	0.684	1.548	2.468	3.415	4.288	5.139	0.000	0.000
August	0.651	1.486	2.452	3.328	0.000	0.000	0.000	0.000
September	0.707	1.471	2.478	3.357	0.000	0.000	0.000	0.000
October	0.697	1.558	2.400	3.286	0.000	0.000	0.000	0.000
November	0.759	1.591	2.568	3.371	4.055	0.000	0.000	0.000
December	0.639	1.511	2.529	3.473	4.194	0.000	0.000	0.000
Annual Average	**0.692**	**1.545**	**2.493**	**3.373**	**2.855**	**1.763**	**0.538**	**0.000**

Table 4.7: Frequency and Cumulative Distribution of Wind Speed with 1m/sec Width

i	**v**	**v_i**	**f_i**	**$f(v_i)$**	**$f(v)$**
1	0-1	0.684	4656	0.089	0.089
2	1-2	1.538	14202	0.270	0.359
3	2-3	2.502	18006	0.342	0.701
4	3-4	3.435	11812	0.225	0.926
5	4-5	4.356	3336	0.063	0.989
6	5-6	5.418	464	0.009	0.998
7	6-7	6.194	108	0.002	1.000
8	7-8	0.000	0	0.000	1.000
			$\sum_{i=1}^{N} f_i = N = 52584$	$\sum_{i=1}^{N} f(v_i) = 1.000$	

4.6 Comparison of Time Series and Frequency Distribution of Wind Speed Data

A comparison of the average wind speed (V_m and $\overline{V}$) and standard deviation (σ_{ts} and σ_m) from time series and frequency distribution of wind speed data of CUC is presented in table 4.8. The relative error of the average wind speed (ε_v) is 0.000% indicating no change in the mean wind speed in both the distributions. The relative error of standard deviation (ε_s) of the time series distribution is higher than the frequency distribution with a difference of 1.098% to 5.137%.

Table 4.8: Monthly Mean Wind Speed (m/sec) and Standard Deviations of Time Series and Frequency Format

Period	**Time Series Format**		**Frequency Format**		**Relative Error**	
	V_m	**σ_{ts}**	**$\overline{V}$**	**σ_m**	**ε_v**	**ε_s**
January	2.157	0.946	2.157	0.912	0.000	1.832
February	2.390	1.035	2.400	0.982	0.000	3.779
March	2.438	0.934	2.438	0.906	0.000	1.641
April	2.663	0.993	2.663	0.920	0.000	1.098
May	2.793	1.045	2.793	1.015	0.000	1.457
June	2.900	1.155	2.900	1.086	0.000	3.477
July	2.033	0.939	2.033	0.878	0.000	4.730
August	1.687	0.800	1.687	0.756	0.000	4.906
September	1.639	0.784	1.639	0.726	0.000	5.137
October	1.929	0.827	1.929	0.758	0.000	1.758
November	2.180	0.917	2.180	0.848	0.000	3.589
December	2.240	1.037	2.244	0.984	0.000	2.371
Annual Average	**2.190**	**1.016**	**2.250**	**1.008**	**0.000**	**2.152**

The mean wind speeds are only indicative of the wind speed range prevalent in the region, but cannot define the actual scenario as wind speeds vary with height owing to turbulence and physical factors. There is a need for an appropriate probability density function (PDF) that can calculate and fit all the observed wind data at different heights. The Weibull PDF has been extensively used in literature and wind power applications for fitting the measured wind speed data into probability distribution for a given location over a period of time. The two parameter Weibull PDF even with its inherent shortcomings is considered to be accurate for most wind patterns and is easy to use in comparison to other forms such as the 2 parameter gamma, 2 parameter lognormal and 2 parameter inverse Gaussian probability distribution functions **(Chaudhry et al., 2014)**. The Rayleigh PDF is an extended or special version of the Weibull distribution where the shape parameter is taken as 'k' equal to 2. The Rayleigh function is applicable in areas where there are information gaps and quick calculations are preferred owing to its one parameter based evaluation.

4.7 Calculation of the Weibull Parameters

To characterize the wind profile of CUC, the statistical assessment of the wind data is done using the two parameter Weibull and two parameter Rayleigh distribution. The Weibull distribution is defined by two parameters, 'k' the dimensionless shape parameter and 'c' the scale parameter measured in m/sec. The 'f(v)' probability density function (PDF) and 'F(v)' cumulative density function (CDF) of the Weibull distribution are defined as per equation 2.6 and 2.7 (Chapter 2). Estimation of the Weibull parameters 'k' and 'c' is done using two numerical methods listed below:

i) Energy Pattern Factor Method ($\mathbf{f_{EPF}}$)
ii) Empirical Method ($\mathbf{f_{EM}}$)

4.7.1 Energy Pattern Factor Method ($\mathbf{f_{EPF}}$)

The energy pattern factor method is based on the average wind speed calculated from the observed wind data. It is defined by the equation 2.8 (Chapter 2). Based on the value of $f_{EPF,}$ k and c are defined on basis of the equation 2.9 and 2.10 (Chapter 2). The standard gamma function (Γ) is derived from the equation 2.11 (Chapter 2). The monthly and average annual k and c values are derived and listed in table 4.9. The monthly average k value as per the energy pattern factor method ranges between 2.75 and 3.97, average c value ranges between 1.73 and 3.66. The annual average k value ranges between 3.16 and 3.67, average c value ranges between 1.83 and 3.22.

4.7.2 Empirical Method (f_{EM})

The empirical method is based on the mean wind speed (V_m) and standard deviation (σ) of observed wind data. The k and c values derived using the equation 2.12 and 2.13 (Chapter 2) are listed in table 4.10.

Table 4.9: Monthly Shape Parameter (k) and Scale Parameter (c) derived by Energy Pattern Factor Method (f_{EPF})

Years	2010		2011		2012		2013		2014		2015		Average	
Parameter	*c*	*k*	*c*	*k*	*c*	*k*	*c*	*k*	*c*	*k*	*c*	*k*	*c*	*k*
January	2.31	1.08	2.22	1.07	2.52	1.04	2.17	1.07	2.08	1.07	2.01	1.14	**2.22**	**1.08**
February	2.68	1.04	2.57	1.04	2.42	1.05	2.48	1.05	2.39	1.03	2.12	1.07	**2.44**	**1.05**
March	2.45	1.05	2.47	1.06	2.60	1.05	2.70	1.04	2.47	1.05	2.23	1.07	**2.49**	**1.05**
April	3.38	1.07	2.99	1.03	2.33	1.06	2.38	1.07	2.53	1.04	2.70	1.05	**2.72**	**1.05**
May	2.68	1.03	3.19	1.02	2.73	1.03	2.90	1.03	2.77	1.04	2.71	1.04	**2.83**	**1.03**
June	3.38	1.06	2.90	1.03	2.63	1.03	3.12	1.02	2.63	1.03	2.97	1.02	**2.94**	**1.03**
July	1.93	1.16	2.25	1.05	2.01	1.09	2.13	1.07	1.94	1.17	2.35	1.05	**2.10**	**1.10**
August	1.84	1.20	1.72	1.17	1.81	1.12	1.66	1.19	1.75	1.19	1.89	1.12	**1.78**	**1.17**
September	2.04	1.56	1.60	1.15	1.78	1.18	1.61	1.24	1.56	1.34	1.93	1.12	**1.75**	**1.26**
October	2.76	1.87	1.97	1.09	2.13	1.11	1.86	1.23	1.56	1.30	2.08	1.13	**2.06**	**1.29**
November	2.50	1.10	1.93	1.09	2.27	1.06	1.99	1.13	2.18	1.08	2.63	1.05	**2.25**	**1.09**
December	2.65	1.09	1.99	1.07	2.10	1.09	2.54	1.03	2.13	1.06	2.38	1.05	**2.30**	**1.06**
Annual Average	**2.52**	**1.08**	**2.31**	**1.04**	**2.27**	**1.06**	**2.28**	**1.05**	**2.15**	**1.06**	**2.32**	**1.06**	**2.31**	**1.06**

The monthly average k value as per the empirical method ranges between 0.42 and 3.35, average c value ranges between 0.51 and 3.68. The annual average k value ranges between 2.23 and 2.93, average c value ranges between 1.85 and 3.26.

Table 4.10: Monthly Shape Parameter (k) and Scale Parameter (c) derived by Empirical Method (f_{EM})

Years	2010		2011		2012		2013		2014		2015		Average	
Parameters	*c*	*k*	*c*	*k*	*c*	*k*	*c*	*k*	*c*	*k*	*c*	*k*	*c*	*k*
January	2.52	2.57	2.43	2.50	2.79	2.56	2.39	2.37	2.29	2.18	2.15	2.91	**2.43**	**2.51**
February	2.96	3.01	2.84	2.79	2.67	2.58	2.73	2.76	2.66	2.01	2.33	2.20	**2.70**	**2.56**
March	2.70	2.90	2.70	3.14	2.86	3.01	2.98	2.95	2.73	2.63	2.44	2.66	**2.73**	**2.88**
April	3.67	3.26	3.28	3.60	2.56	2.77	2.60	2.98	2.80	2.63	2.94	3.64	**2.97**	**3.15**
May	2.97	2.77	3.56	2.74	3.03	2.74	3.19	3.27	3.06	3.14	2.98	3.18	**3.13**	**2.97**
June	3.68	3.34	3.23	2.76	2.92	2.60	3.47	2.92	2.92	2.54	3.31	2.64	**3.26**	**2.80**
July	2.07	2.19	2.49	2.28	2.19	2.29	2.35	2.21	2.06	3.02	2.60	2.39	**2.29**	**2.40**
August	1.95	2.50	1.84	2.24	1.96	2.09	1.76	2.12	1.86	2.35	2.05	2.31	**1.90**	**2.27**
September	2.07	2.58	1.71	1.82	1.90	2.39	1.70	0.19	1.61	2.42	2.09	2.41	**1.85**	**1.97**
October	2.76	2.63	2.16	2.17	2.29	3.09	1.94	3.28	1.63	2.27	2.22	3.10	**2.17**	**2.76**
November	2.71	2.65	2.11	2.06	2.49	2.48	2.14	2.69	2.38	2.65	2.85	3.82	**2.45**	**2.73**
December	2.86	3.24	2.19	1.97	2.29	2.43	2.83	2.27	2.35	2.13	2.63	2.44	**2.53**	**2.41**
Annual Average	**2.75**	**2.46**	**2.55**	**2.18**	**2.50**	**2.41**	**2.52**	**2.28**	**2.37**	**2.19**	**2.56**	**2.53**	**2.54**	**2.34**

4.7.3 Rayleigh Distribution (f_R)

The Rayleigh distribution is a special form of the Weibull distribution where the k value is taken as equal to 2. The c values derived using the Rayleigh distribution equation are listed in table 4.11. It has only one parameter to be evaluated as a result it has less flexibility and is suitable for only few wind conditions.

Table 4.11: Monthly Scale Parameter (c) derived by Rayleigh Distribution (f_R)

Years	2010		2011		2012		2013		2014		2015		Average	
Parameters	***c***	***k***	***c***	***k***	***c***	***k***	***c***	***k***	***c***	***k***	***c***	***k***	***c***	***k***
January	2.52	2.00	2.44	2.00	2.79	2.00	2.39	2.00	2.29	2.00	2.17	2.00	**2.43**	**2.00**
February	2.98	2.00	1.99	2.00	1.93	2.00	2.09	2.00	2.26	2.00	1.79	2.00	**2.25**	**2.00**
March	2.71	2.00	1.99	2.00	1.93	2.00	2.10	2.00	2.25	2.00	1.79	2.00	**2.22**	**2.00**
April	3.72	2.00	1.98	2.00	1.93	2.00	2.09	2.00	2.25	2.00	1.77	2.00	**2.39**	**2.00**
May	2.98	2.00	2.00	2.00	1.93	2.00	2.09	2.00	2.23	2.00	1.78	2.00	**2.31**	**2.00**
June	3.73	2.00	2.00	2.00	1.93	2.00	2.10	2.00	2.25	2.00	1.78	2.00	**2.44**	**2.00**
July	2.07	2.00	2.01	2.00	1.94	2.00	2.11	2.00	2.23	2.00	1.79	2.00	**2.06**	**2.00**
August	1.95	2.00	2.01	2.00	1.94	2.00	2.11	2.00	2.26	2.00	1.79	2.00	**1.99**	**2.00**
September	2.07	2.00	2.00	2.00	1.94	2.00	2.11	2.00	2.25	2.00	1.79	2.00	**2.00**	**2.00**
October	2.76	2.00	2.01	2.00	1.93	2.00	2.09	2.00	2.26	2.00	1.78	2.00	**2.14**	**2.00**
November	2.72	2.00	2.01	2.00	1.94	2.00	2.10	2.00	2.25	2.00	1.77	2.00	**2.18**	**2.00**
December	2.90	2.00	2.00	2.00	1.94	2.00	2.11	2.00	2.26	2.00	1.79	2.00	**2.22**	**2.00**
Annual Average	**2.76**	**2.00**	**2.04**	**2.00**	**2.01**	**2.00**	**2.12**	**2.00**	**2.25**	**2.00**	**1.82**	**2.00**	**2.53**	**2.00**

4.8 Comparison of Energy Pattern Factor, Empirical Method and Rayleigh Distribution

The k and c values derived from the Energy Pattern Factor Method (f_{EPF}) and Empirical Method (f_{EM}) were plotted using the probability density function (PDF) of Weibull and Rayleigh distribution along with the observed wind data. The PDF values are listed in table 4.12 and represented graphically in figure 4.5. The graph illustrates that both the Weibull Empirical Method (f_{EM}) and the Weibull Energy Pattern Factor Method (f_{EPF}) are better fit with the observed data than the Rayleigh probability functions. To confirm the accuracy in estimating the wind speeds three statistical tests are undertaken.

Table 4.13 shows the statistical comparison of the Weibull Empirical Method (f_{EM}), Weibull Energy Pattern Factor Method (f_{EPF}) and Rayleigh (f_R) Probability function for monthly observed wind speed data from 2010-15 based on equation 2.14, 2.15, 2.16 (Chapter 2) and highlights the Weibull Empirical Method to be more accurate than the other two density functions. Considering the k and c values from the Weibull Empirical Method (f_{EM}), the monthly Probability Density Function (PDF) are highlighted in table 4.14 and graphically represented in figure 4.6. The Cumulative Density Function (CDF) values are displayed in table 4.15 and graphically represented in figure 4.7.

Table 4.12: Probability Density Function (PDF) of Empirical and Energy Pattern Factor based on Weibull and Rayleigh Distribution

Observed Wind Data					Weibull		Rayleigh
Bin	***Vj***	***Vm,j***	**Frequency**	**Actual**	f_{EM}	f_{EPF}	f_R
1	0-0.5	0.25	349	0.007	0.037	0.007	0.084
2	0.5-1.0	0.75	3239	0.062	0.173	0.090	0.231
3	1.0-1.5	1.25	6667	0.127	0.316	0.271	0.325
4	1.5-2.0	1.75	8784	0.167	0.400	0.469	0.353
5	2.0-2.5	2.25	9513	0.181	0.394	0.533	0.323
6	2.5-3.0	2.75	8730	0.166	0.311	0.395	0.259
7	3.0-3.5	3.25	7010	0.133	0.200	0.181	0.184
8	3.5-4.0	3.75	4493	0.085	0.105	0.047	0.117
9	4.0-4.5	4.25	2384	0.045	0.044	0.006	0.068
10	4.5-5.0	4.75	954	0.018	0.015	0.000	0.035
11	5.0-5.5	5.25	288	0.005	0.004	0.000	0.017
12	5.5-6.0	5.75	121	0.002	0.001	0.000	0.007
13	6.0-6.5	6.25	32	0.001	0.000	0.000	0.003
14	6.5-7.0	6.75	8	0.000	0.000	0.000	0.001
15	7.0-7.5	7.25	3	0.000	0.000	0.000	0.000
16	7.5-8.0	7.75	1	0.000	0.000	0.000	0.000
17	8.0-8.5	8.25	1	0.000	0.000	0.000	0.000
18	8.5-9.0	8.75	3	0.000	0.000	0.000	0.000
19	9.0-9.5	9.25	4	0.000	0.000	0.000	0.000
20	9.5-10.0	9.75	0	0.000	0.000	0.000	0.000

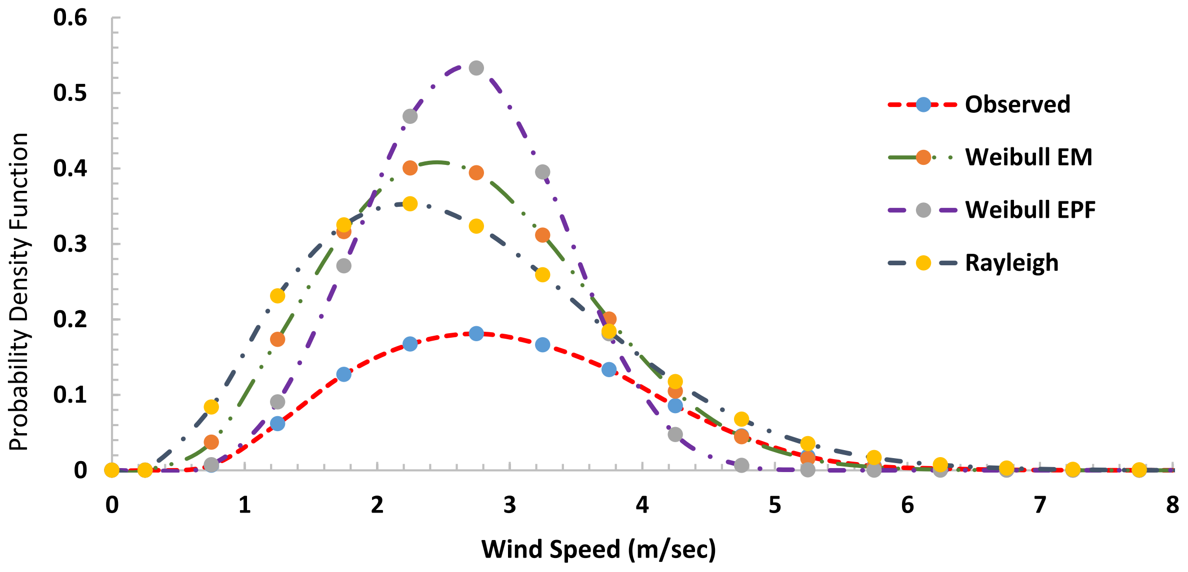


Figure 4.5: Wind Speed Probability Distribution based on Observed Wind Data, Empirical and Energy Pattern Factor based Weibull and Rayleigh Distribution

Table 4.13: Statistical Comparison of Empirical, Energy Pattern Factor and Rayleigh Distributions for Observed Wind Data of CUC, 2010-15

January	Weibull Parameter		Statistical Tests			**February**	Weibull Parameter		Statistical Tests-		
Probability Function	c	k	RMSE	R^2	$\chi2$	Probability Function	c	k	RMSE	R^2	$\chi2$
Empirical (f_{EP})	2.43	2.45	0.054	0.721	0.221	Empirical (f_{EP})	2.69	2.49	0.047	0.754	0.137
Energy Pattern Factor (f_{EPF})	2.40	3.33	0.061	0.785	0.248	Energy Pattern Factor (f_{EPF})	2.66	3.46	0.049	0.773	0.145
Rayleigh (f_R)	2.43	2.00	0.085	0.841	0.478	Rayleigh (f_R)	2.70	2.00	0.068	0.852	0.324
March	Weibull Parameter		Statistical Tests			**April**	Weibull Parameter		Statistical Tests		
Probability Function	c	k	RMSE	R^2	$\chi2$	Probability Function	c	k	RMSE	R^2	$\chi2$
Empirical (f_{EP})	2.74	2.84	0.051	0.669	0.260	Empirical (f_{EP})	2.99	2.93	0.046	0.741	0.145
Energy Pattern Factor (f_{EPF})	2.71	3.57	0.062	0.684	0.289	Energy Pattern Factor (f_{EPF})	2.95	3.67	0.052	0.788	0.168
Rayleigh (f_R)	2.75	2.00	0.084	0.112	0.560	Rayleigh (f_R)	3.01	2.00	0.068	0.824	0.218
May	Weibull Parameter		Statistical Tests			**June**	Weibull Parameter		Statistical Tests		
Probability Function	c	k	RMSE	R^2	$\chi2$	Probability Function	c	k	RMSE	R^2	$\chi2$
Empirical (f_{EP})	3.13	2.92	0.072	0.495	0.312	Empirical (f_{EP})	3.26	2.73	0.042	0.751	0.168
Energy Pattern Factor (f_{EPF})	3.10	3.59	0.084	0.542	0.267	Energy Pattern Factor (f_{EPF})	3.22	3.52	0.065	0.802	0.189
Rayleigh (f_R)	3.15	2.00	0.102	0.762	0.521	Rayleigh (f_R)	3.27	2.00	0.078	0.914	0.326
July	Weibull Parameter		Statistical Tests			**August**	Weibull Parameter		Statistical Tests		
Probability Function	c	k	RMSE	R^2	$\chi2$	Probability Function	c	k	RMSE	R^2	$\chi2$
Empirical (f_{EP})	2.29	2.32	0.091	0.412	0.214	Empirical (f_{EP})	1.90	2.25	0.069	0.691	0.195
Energy Pattern Factor (f_{EPF})	2.27	3.22	0.098	0.502	0.326	Energy Pattern Factor (f_{EPF})	1.88	3.16	0.072	0.706	0.210
Rayleigh (f_R)	2.29	2.00	0.112	0.625	0.442	Rayleigh (f_R)	1.90	2.00	0.084	0.768	0.345
September	Weibull Parameter		Statistical Tests			**October**	Weibull Parameter		Statistical Tests		
Probability Function	c	k	RMSE	R^2	$\chi2$	Probability Function	c	k	RMSE	R^2	$\chi2$
Empirical (f_{EP})	1.85	2.23	0.082	0.468	0.302	Empirical (f_{EP})	2.17	2.52	0.067	0.606	0.182
Energy Pattern Factor (f_{EPF})	1.83	3.17	0.095	0.621	0.341	Energy Pattern Factor (f_{EPF})	2.15	3.43	0.075	0.684	0.210
Rayleigh (f_R)	1.85	2.00	0.104	0.668	0.436	Rayleigh (f_R)	2.18	2.00	0.081	0.790	0.284
November	Weibull Parameter		Statistical Tests			**December**	Weibull Parameter		Statistical Tests		
Probability Function	c	k	RMSE	R^2	$\chi2$	Probability Function	c	k	RMSE	R^2	$\chi2$
Empirical (f_{EP})	2.46	2.57	0.092	0.412	0.281	Empirical (f_{EP})	2.53	2.31	0.080	0.582	0.215
Energy Pattern Factor (f_{EPF})	2.43	3.44	0.097	0.468	0.309	Energy Pattern Factor (f_{EPF})	2.50	3.24	0.091	0.615	0.274
Rayleigh (f_R)	2.46	2.00	0.114	0.522	0.385	Rayleigh (f_R)	2.53	2.00	0.102	0.781	0.385

Table 4.14: Probability Density Function (PDF) of Observed Wind Data, 2010-15

$v_{m,j}$	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.25	0.036	0.020	0.014	0.006	0.005	0.005	0.051	0.113	0.120	0.047	0.028	0.033
0.75	0.163	0.126	0.090	0.055	0.055	0.059	0.198	0.273	0.274	0.161	0.132	0.167
1.25	0.297	0.270	0.202	0.143	0.156	0.175	0.329	0.355	0.347	0.260	0.249	0.318
1.75	0.381	0.386	0.310	0.249	0.282	0.324	0.391	0.360	0.349	0.318	0.336	0.412
2.25	0.385	0.418	0.371	0.336	0.384	0.435	0.371	0.311	0.302	0.326	0.364	0.408
2.75	0.317	0.354	0.362	0.370	0.408	0.435	0.290	0.236	0.233	0.290	0.328	0.318
3.25	0.215	0.236	0.291	0.335	0.339	0.321	0.190	0.160	0.162	0.229	0.249	0.197
3.75	0.121	0.122	0.192	0.248	0.217	0.169	0.105	0.098	0.103	0.161	0.161	0.097
4.25	0.056	0.049	0.103	0.149	0.105	0.061	0.049	0.055	0.060	0.102	0.089	0.037
4.75	0.022	0.015	0.045	0.072	0.037	0.014	0.019	0.028	0.032	0.058	0.041	0.011
5.25	0.007	0.003	0.016	0.027	0.009	0.002	0.006	0.013	0.016	0.029	0.016	0.003
5.75	0.002	0.001	0.004	0.008	0.002	0.000	0.002	0.006	0.008	0.014	0.005	0.000

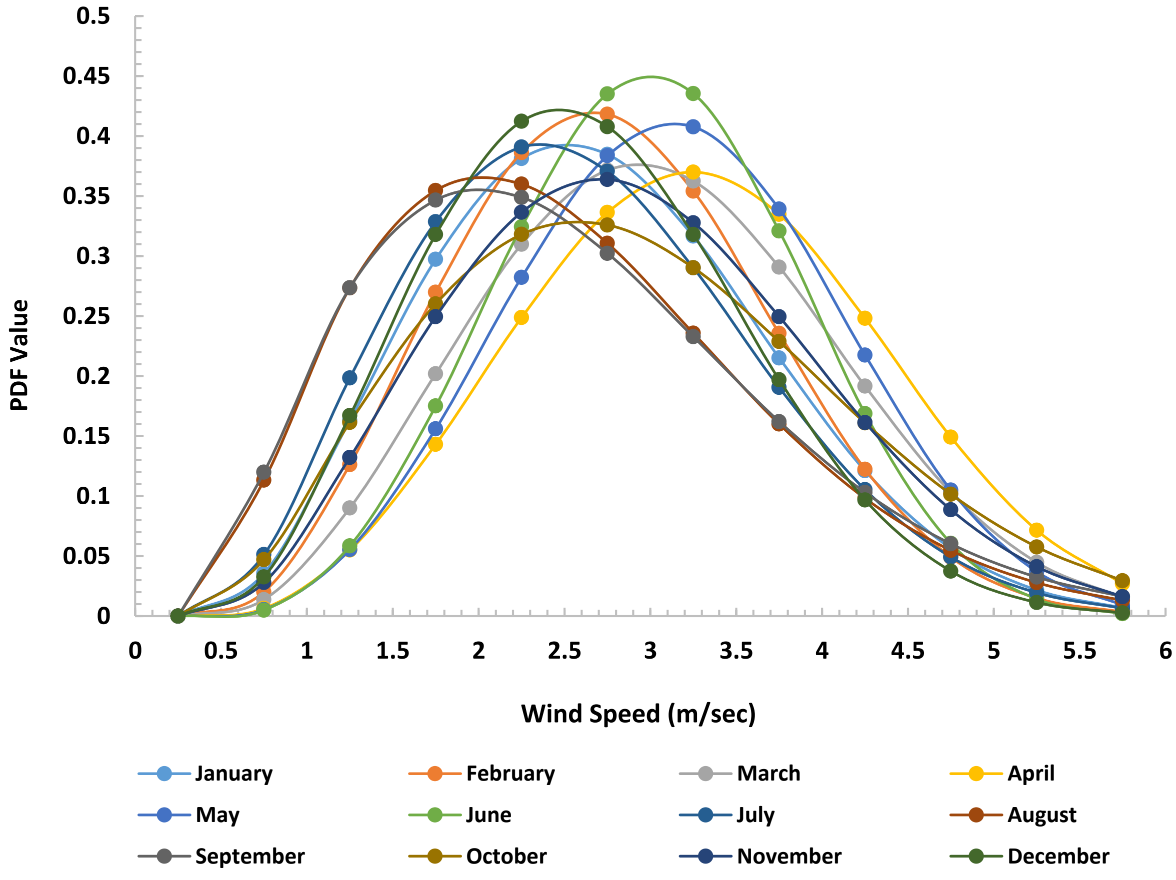


Figure 4.6: Probability Distribution Function (PDF) Plot of Observed Wind Data, 2010-15

Table 4.15: Cumulative Distribution Function (CDF) of Observed Wind Data, 2010-15

$v_{m,j}$	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.25	0.004	0.002	0.001	0.001	0.000	0.000	0.006	0.015	0.016	0.005	0.003	0.003
0.75	0.052	0.036	0.025	0.014	0.013	0.014	0.067	0.115	0.118	0.057	0.041	0.051
1.25	0.168	0.134	0.097	0.062	0.064	0.070	0.201	0.275	0.277	0.164	0.137	0.173
1.75	0.340	0.301	0.226	0.160	0.174	0.194	0.384	0.457	0.453	0.311	0.286	0.359
2.25	0.535	0.506	0.399	0.308	0.343	0.388	0.578	0.626	0.617	0.474	0.463	0.568
2.75	0.713	0.703	0.586	0.487	0.544	0.611	0.745	0.763	0.751	0.629	0.639	0.753
3.25	0.846	0.851	0.751	0.666	0.734	0.803	0.865	0.862	0.850	0.760	0.784	0.881
3.75	0.930	0.939	0.872	0.813	0.874	0.925	0.938	0.925	0.915	0.857	0.887	0.953
4.25	0.973	0.980	0.945	0.912	0.954	0.980	0.975	0.963	0.956	0.922	0.948	0.985
4.75	0.991	0.995	0.980	0.966	0.987	0.996	0.992	0.983	0.978	0.961	0.979	0.996
5.25	0.998	0.999	0.994	0.990	0.997	1.000	0.998	0.993	0.990	0.982	0.993	0.999
5.75	0.999	1.000	0.999	0.997	1.000	1.000	0.999	0.997	0.996	0.993	0.998	1.000

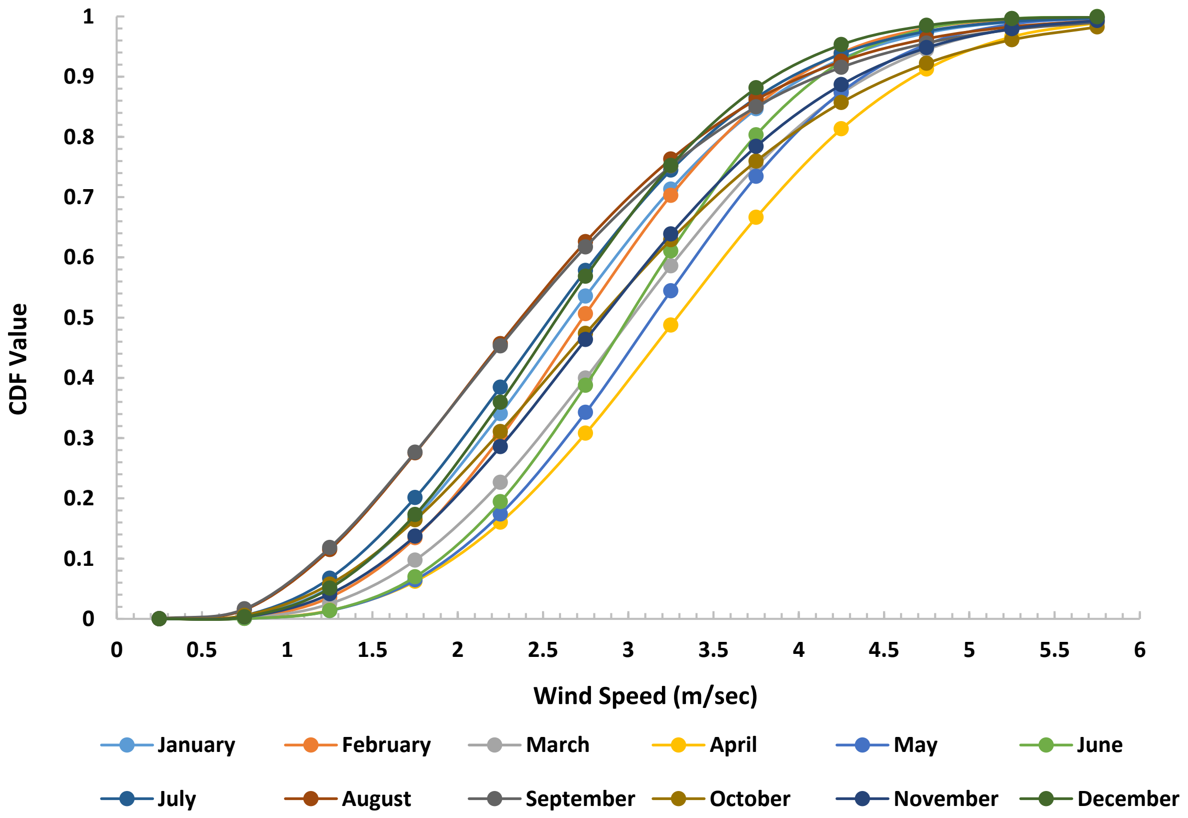


Figure 4.7: Cumulative Distribution Function (CDF) Plot of Observed Wind Data, 2010-15

The final adjusted Weibull PDF and CDF for the whole year wind speed data are detailed out in table 4.16 and graphically presented in figure 4.8.

Table 4.16: PDF and CDF Assessment of Observed Wind Speed and Weibull Distribution, 2010-15

v_j	$v_{m,j}$	PDF		CDF	
		Actual Data	Weibull Distribution	Actual Data	Weibull Distribution
0.00-0.50	0.25	0.040	0.034	0.005	0.003
0.50-1.00	0.75	0.146	0.177	0.050	0.054
1.00-1.50	1.25	0.258	0.336	0.152	0.183
1.50-2.00	1.75	0.342	0.430	0.304	0.379
2.00-2.50	2.25	0.367	0.413	0.484	0.594
2.50-3.00	2.75	0.328	0.309	0.660	0.777
3.00-3.50	3.25	0.244	0.181	0.804	0.899
3.50-4.00	3.75	0.150	0.082	0.902	0.963
4.00-4.50	4.25	0.076	0.029	0.958	0.989
4.50-5.00	4.75	0.033	0.008	0.984	0.998
5.00-5.50	5.25	0.012	0.002	0.994	1.000
5.50-6.00	5.75	0.004	0.000	0.998	1.000

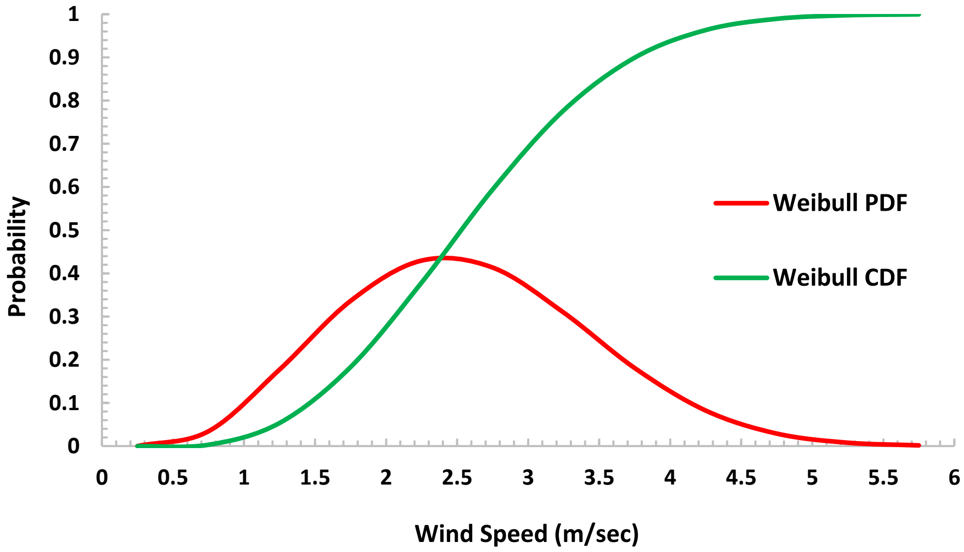


Figure 4.8: Probability and Cumulative Density Function (CDF) Plot of Observed Wind Data

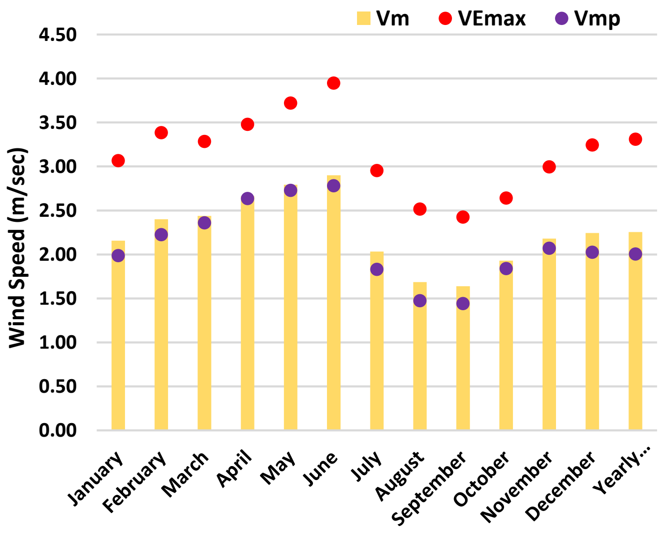
4.9 Wind Speeds Specific to Site Conditions

Wind speeds are subject to site conditions, two type of wind speeds that are of interest and need to be assessed are the most probable wind speed (V_{mp}) and the wind speed carrying the maximum energy (V_{Emax}). Both the wind speeds are based on the Weibull parameters and defined by equation 2.17 and 2.18 (Chapter 2).

Table 4.17: Monthly and Annual Maximum Energy (V_{Emax}) and Most Probable (V_{mp}) Wind Speed

Year	2010			2011			2012		
Parameters	V_m	V_{Emax}	V_{mp}	V_m	V_{Emax}	V_{mp}	V_m	V_{Emax}	V_{mp}
January	2.24	3.15	2.08	2.16	3.08	1.98	2.47	3.49	2.30
February	2.64	3.51	2.59	2.53	3.45	2.42	2.37	3.33	2.21
March	2.40	3.23	2.33	2.42	3.16	2.39	2.55	3.38	2.50
April	3.29	4.25	3.28	2.95	3.70	2.99	2.28	3.11	2.18
May	2.64	3.61	2.52	3.17	4.34	3.02	2.69	3.70	2.57
June	3.31	4.24	3.31	2.87	3.93	2.74	2.60	3.64	2.42
July	1.83	2.78	1.56	2.21	3.28	1.93	1.94	2.88	1.70
August	1.73	2.47	1.59	1.63	2.45	1.41	1.73	2.70	1.43
September	1.84	2.58	1.71	1.52	2.58	1.10	1.68	2.45	1.51
October	2.45	3.42	2.30	1.91	2.92	1.62	2.05	2.69	2.02
November	2.41	3.35	2.26	1.87	2.93	1.53	2.21	3.17	2.03
December	2.57	3.32	2.56	1.94	3.13	1.53	2.03	2.93	1.84
Annual Average	**2.45**	**3.50**	**2.23**	**2.27**	**3.44**	**1.93**	**2.22**	**3.21**	**2.00**
Year	**2013**			**2014**			**2015**		
Parameters	V_m	V_{Emax}	V_{mp}	V_m	V_{Emax}	V_{mp}	V_m	V_{Emax}	V_{mp}
January	2.12	3.10	1.90	2.03	3.09	1.73	1.92	2.58	1.86
February	2.43	3.33	2.32	2.36	3.75	1.89	2.06	3.12	1.77
March	2.66	3.56	2.59	2.42	3.38	2.27	2.17	3.01	2.04
April	2.32	3.09	2.27	2.49	3.48	2.34	2.65	3.31	2.69
May	2.86	3.69	2.86	2.73	3.58	2.70	2.66	3.47	2.64
June	3.09	4.15	3.00	2.59	3.67	2.40	2.94	4.10	2.76
July	2.08	3.14	1.79	1.84	2.44	1.80	2.30	3.35	2.07
August	1.56	2.41	1.31	1.65	2.42	1.47	1.81	2.68	1.60
September	1.50	2.29	1.28	1.43	2.07	1.29	1.86	2.69	1.67
October	1.74	2.24	1.73	1.44	2.15	1.26	1.99	2.61	1.96
November	1.90	2.63	1.80	2.12	2.95	1.99	2.58	3.18	2.63
December	2.50	3.73	2.19	2.09	3.21	1.75	2.33	3.36	2.12
Annual Average	**2.23**	**3.32**	**1.96**	**2.10**	**3.18**	**1.79**	**2.27**	**3.22**	**2.10**

Year	2010-15		
Parameters	V_m	V_{Emax}	V_{mp}
January	2.16	3.50	2.23
February	2.39	3.44	1.92
March	2.44	3.21	2.01
April	2.66	3.31	1.96
May	2.79	3.18	1.80
June	2.90	3.22	2.10
July	2.03	3.50	2.23
August	1.69	3.44	1.92
September	1.64	3.21	2.01
October	1.93	3.31	1.96
November	2.18	3.18	1.80
December	2.24	3.22	2.10
Annual Average	**2.19**	**3.24**	**1.93**



From table 4.17 it is evident that the mean wind speed (V_m) of CUC is around 1.64 - 2.90m/sec, whereas maximum energy (V_{Emax}) is achieved by wind speeds of 3.18 – 3.50m/sec and the most probable wind (V_{mp}) speeds range between 1.80 – 2.23m/sec. The wind speed calculated are based on the observed wind speed data, but the wind speed vary with height for which the Weibull parameters need to be extrapolated with increasing height to quantify wind speeds in case of high rise structures.

4.10 Extrapolation of Weibull Parameters

Assessing the wind speeds at varying heights statistically is possible through the extrapolation of k and c parameters of Weibull distribution. The function for extrapolation of k and c for a particular height ‘z’ are highlighted by equation 2.19 and 2.20 (Chapter 2). The extrapolated k and c values of CUC with varying heights of 10 meter interval are highlighted in table 4.18.

Table 4.18: Extrapolation of Weibull Parameters *k* and *c* with varying Heights

Height	10 meter		20 meter		30 meter		40 meter		50 meter		60 meter	
Parameter	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**
January	2.43	2.45	2.97	2.47	3.35	2.47	3.64	2.48	3.89	2.49	4.10	2.49
February	2.69	2.49	3.27	2.51	3.67	2.51	3.98	2.52	4.24	2.53	4.47	2.53
March	2.74	2.84	3.33	2.86	3.73	2.87	4.05	2.88	4.31	2.88	4.54	2.89
April	2.99	2.93	3.61	2.95	4.04	2.96	4.37	2.97	4.64	2.97	4.88	2.98
May	3.13	2.92	3.77	2.94	4.21	2.95	4.55	2.96	4.83	2.96	5.07	2.97
June	3.26	2.73	3.92	2.75	4.37	2.76	4.71	2.76	5.00	2.77	5.25	2.77
July	2.29	2.32	2.81	2.33	3.17	2.34	3.46	2.35	3.69	2.35	3.90	2.36
August	1.90	2.25	2.36	2.26	2.68	2.27	2.93	2.28	3.15	2.28	3.33	2.29
September	1.85	2.23	2.30	2.24	2.62	2.25	2.87	2.26	3.08	2.26	3.26	2.27
October	2.17	2.52	2.67	2.54	3.02	2.54	3.30	2.55	3.53	2.56	3.73	2.56
November	2.46	2.57	3.01	2.59	3.39	2.60	3.68	2.60	3.93	2.61	4.14	2.61
December	2.53	2.31	3.09	2.32	3.47	2.33	3.77	2.34	4.02	2.34	4.24	2.35
Annual Average	**2.47**	**2.31**	**3.02**	**2.32**	**3.40**	**2.33**	**3.69**	**2.34**	**3.94**	**2.34**	**4.16**	**2.35**

4.11 Wind Power Density (WPD) and Wind Energy Density (WED) with varying Heights

The WPD, monthly and annual WED, V_{mp}, V_{Emax} and V_m are calculated on the basis of equation 2.22, 2.23 and 2.24 (Chapter 2) for CUC at a height of 10 meter based on the extrapolated k and c values from Weibull Empirical distribution and are detailed out in table 4.19. The wind power parameters at varying height of 20m, 30m, 40m, 50m and 60m are highlighted in table. 4.20, 4.21, 4.22, 4.23 and 4.24.

Table 4.19: Wind Power Parameters at 10 meter Height

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Whole Year
V_{emax} (m/sec)	3.10	3.41	3.31	3.57	3.74	3.99	2.99	2.52	2.47	2.74	3.08	3.31	3.24
V_{mp} (m/sec)	1.96	2.19	2.35	2.59	2.71	2.76	1.80	1.46	1.42	1.78	2.03	1.98	1.93
V_m (m/sec)	2.16	2.39	2.44	2.66	2.79	2.90	2.03	1.69	1.64	1.93	2.18	2.24	2.19
σ (m/sec)	0.95	1.04	0.93	0.99	1.05	1.16	0.94	0.80	0.78	0.83	0.92	1.04	1.02
c (m/sec)	2.43	2.69	2.74	2.99	3.13	3.26	2.29	1.9	1.85	2.17	2.46	2.53	2.47
k	2.45	2.49	2.84	2.93	2.92	2.73	2.32	2.25	2.23	2.52	2.57	2.31	2.31
WPD (W/m^2)	9.48	12.72	12.47	15.97	18.35	21.43	8.25	4.83	4.49	6.63	9.53	11.17	10.39
Daily WED (kWh/m^2/day)	0.23	0.31	0.30	0.38	0.44	0.51	0.20	0.12	0.11	0.16	0.23	0.27	0.25
Monthly WED (kWh/m^2/m)	7.05	8.55	9.28	11.50	13.66	15.43	6.14	3.59	3.23	4.93	6.86	8.31	7.48
Annual WED (kWh/m^2/y)	84.6	102.6	111.4	138.0	163.9	185.2	73.7	43.1	38.8	59.2	82.4	99.7	89.8

Table 4.20: Wind Power Parameters at 20 meter Height

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Whole Year
V_{emax} (m/sec)	3.79	4.14	4.01	4.31	4.50	4.78	3.67	3.12	3.06	3.36	3.76	4.04	3.95
V_{mp} (m/sec)	2.41	2.67	2.86	3.14	3.27	3.32	2.21	1.83	1.77	2.19	2.49	2.43	2.37
V_m (m/sec)	2.16	2.39	2.44	2.66	2.79	2.90	2.03	1.69	1.64	1.93	2.18	2.24	2.19
σ (m/sec)	0.95	1.04	0.93	0.99	1.05	1.16	0.94	0.80	0.78	0.83	0.92	1.04	1.02
c (m/sec)	2.97	3.27	3.33	3.61	3.77	3.92	2.81	2.36	2.30	2.67	3.01	3.09	3.02
k	2.47	2.51	2.86	2.95	2.94	2.75	2.33	2.26	2.24	2.54	2.59	2.32	2.32
WPD (W/m^2)	17.32	22.81	22.32	28.14	32.06	37.15	15.24	9.22	8.62	12.36	17.39	20.24	18.92
Daily WED (kWh/m^2/day)	0.42	0.55	0.54	0.68	0.77	0.89	0.37	0.22	0.21	0.30	0.42	0.49	0.45
Monthly WED (kWh/m^2/m)	12.89	15.33	16.61	20.26	23.85	26.75	11.34	6.86	6.21	9.20	12.52	15.06	13.62
Annual WED (kWh/m^2/y)	154.6	184.0	199.3	243.1	286.3	321.0	136.0	82.4	74.5	110.4	150.2	180.7	163.5

Table 4.21: Wind Power Parameters at 30 meter Height

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Whole Year
V_{emax} (m/sec)	4.25	4.63	4.49	4.81	5.02	5.32	4.13	3.54	3.47	3.80	4.22	4.53	4.43
V_{mp} (m/sec)	2.72	3.00	3.21	3.51	3.66	3.71	2.50	2.08	2.02	2.48	2.81	2.73	2.67
V_m (m/sec)	2.16	2.39	2.44	2.66	2.79	2.90	2.03	1.69	1.64	1.93	2.18	2.24	2.19
σ (m/sec)	0.95	1.04	0.93	0.99	1.05	1.16	0.94	0.80	0.78	0.83	0.92	1.04	1.02
c (m/sec)	3.35	3.67	3.73	4.04	4.21	4.37	3.17	2.68	2.62	3.02	3.39	3.47	3.40
k	2.47	2.51	2.87	2.96	2.95	2.76	2.34	2.27	2.25	2.54	2.60	2.33	2.33
WPD (W/m^2)	24.64	32.11	31.38	39.19	44.43	51.24	21.81	13.47	12.62	17.80	24.71	28.67	26.86
Daily WED (kWh/m^2/day)	0.59	0.77	0.75	0.94	1.07	1.23	0.52	0.32	0.30	0.43	0.59	0.69	0.64
Monthly WED (kWh/m^2/m)	18.33	23.89	23.34	29.16	33.06	38.13	16.23	10.02	9.39	13.25	18.39	21.33	19.98
Annual WED (kWh/m^2/y)	220.0	286.7	280.1	349.9	396.7	457.5	194.7	120.2	112.7	159.0	220.6	255.9	239.8

Table 4.22: Wind Power Parameters at 40 meter Height

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Whole Year
V_{emax} (m/sec)	4.62	5.02	4.86	5.20	5.42	5.74	4.49	3.87	3.80	4.14	4.58	4.91	4.81
V_{mp} (m/sec)	2.96	3.26	3.49	3.80	3.96	4.01	2.73	2.28	2.21	2.71	3.06	2.97	2.91
V_m (m/sec)	2.16	2.39	2.44	2.66	2.79	2.90	2.03	1.69	1.64	1.93	2.18	2.24	2.19
σ (m/sec)	0.95	1.04	0.93	0.99	1.05	1.16	0.94	0.80	0.78	0.83	0.92	1.04	1.02
c (m/sec)	3.64	3.98	4.05	4.37	4.55	4.71	3.46	2.93	2.87	3.30	3.68	3.77	3.69
k	2.48	2.52	2.88	2.97	2.96	2.76	2.35	2.28	2.26	2.55	2.60	2.34	2.34
WPD (W/m^2)	31.64	40.93	39.95	49.58	56.01	64.38	28.13	17.62	16.54	23.07	31.71	36.69	34.45
Daily WED (kWh/m^2/day)	0.76	0.98	0.96	1.19	1.34	1.55	0.68	0.42	0.40	0.55	0.76	0.88	0.83
Monthly WED (kWh/m^2/m)	23.54	30.45	29.72	36.88	41.67	47.90	20.93	13.11	12.31	17.16	23.60	27.30	25.63
Annual WED (kWh/m^2/y)	282.5	365.4	356.7	442.6	500.1	574.8	251.1	157.3	147.7	205.9	283.2	327.6	307.5

Table 4.23: Wind Power Parameters at 50 meter Height

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Whole Year
V_{emax} (m/sec)	4.93	5.34	5.17	5.52	5.75	6.09	4.80	4.15	4.07	4.42	4.89	5.24	5.13
V_{mp} (m/sec)	3.16	3.47	3.72	4.05	4.20	4.25	2.92	2.44	2.38	2.90	3.26	3.17	3.11
V_m (m/sec)	2.16	2.39	2.44	2.66	2.79	2.90	2.03	1.69	1.64	1.93	2.18	2.24	2.19
σ (m/sec)	0.95	1.04	0.93	0.99	1.05	1.16	0.94	0.80	0.78	0.83	0.92	1.04	1.02
c (m/sec)	3.89	4.24	4.31	4.64	4.83	5.00	3.69	3.15	3.08	3.53	3.93	4.02	3.94
k	2.49	2.53	2.88	2.97	2.96	2.77	2.35	2.28	2.26	2.56	2.61	2.34	2.34
WPD (W/m^2)	38.42	49.40	48.18	59.49	67.03	76.85	34.27	21.70	20.40	28.20	38.48	44.44	41.78
Daily WED (kWh/m^2/day)	0.92	1.19	1.16	1.43	1.61	1.84	0.82	0.52	0.49	0.68	0.92	1.07	1.00
Monthly WED (kWh/m^2/m)	28.59	33.19	35.85	42.83	49.87	55.33	25.50	16.14	14.69	20.98	27.71	33.06	30.08
Annual WED (kWh/m^2/y)	343.0	398.3	430.2	514.0	598.5	664.0	306.0	193.7	176.3	251.7	332.5	396.8	360.9

Table 4.24: Wind Power Parameters at 60 meter Height

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Whole Year
V_{emax} (m/sec)	5.20	5.62	5.44	5.80	6.04	6.39	5.06	4.39	4.31	4.67	5.15	5.51	5.40
V_{mp} (m/sec)	3.34	3.66	3.91	4.25	4.42	4.47	3.09	2.59	2.52	3.07	3.44	3.35	3.28
V_m (m/sec)	2.16	2.39	2.44	2.66	2.79	2.90	2.03	1.69	1.64	1.93	2.18	2.24	2.19
σ (m/sec)	0.95	1.04	0.93	0.99	1.05	1.16	0.94	0.80	0.78	0.83	0.92	1.04	1.02
c (m/sec)	4.10	4.47	4.54	4.88	5.07	5.25	3.90	3.33	3.26	3.73	4.14	4.24	4.16
k	2.49	2.53	2.89	2.98	2.97	2.77	2.36	2.29	2.27	2.56	2.61	2.35	2.35
WPD (W/m^2)	45.02	57.60	56.16	69.05	77.62	88.81	40.27	25.72	24.22	33.22	45.08	51.97	48.91
Daily WED (kWh/m^2/day)	1.08	1.38	1.35	1.66	1.86	2.13	0.97	0.62	0.58	0.80	1.08	1.25	1.17
Monthly WED (kWh/m^2/m)	33.50	38.71	41.78	49.71	57.75	63.95	29.96	19.14	17.44	24.72	32.45	38.66	35.21
Annual WED (kWh/m^2/y)	402.0	464.5	501.4	596.6	693.0	767.4	359.5	229.6	209.2	296.6	389.5	464.0	422.6

Assessment of various wind energy parameters in table 4.25 highlights that the most probable wind speed (V_{mp}) in CUC lies within a range of 1.93-3.28m/sec with varying height. The annual energy generated with wind speeds in the above range varies from 89.78 – 422.56kWh/m^2, the energy output increasing with height thereby making high rise housing the ideal choice for wind energy generation.

Table 4.25: Comparison of various Wind Energy Parameters with varying Heights

Parameter	10 meter	20 meter	30 meter	40 meter	50 meter	60 meter
V_{emax} (m/sec)	3.24	3.95	4.43	4.81	5.13	5.40
V_{mp} (m/sec)	1.93	2.37	2.67	2.91	3.11	3.28
V_m (m/sec)	2.19	2.19	2.19	2.19	2.19	2.19
σ (m/sec)	1.02	1.02	1.02	1.02	1.02	1.02
c (m/sec)	2.47	3.02	3.40	3.69	3.94	4.16
k	2.31	2.32	2.33	2.34	2.34	2.35
WPD (W/m^2)	10.39	18.92	26.86	34.45	41.78	48.91
Daily WED (kWh/m^2/day)	0.25	0.45	0.64	0.83	1.00	1.17
Monthly WED (kWh/m^2/m)	7.48	13.62	19.98	25.63	30.08	35.21
Annual WED (kWh/m^2/y)	89.78	163.46	239.82	307.53	360.94	422.56

To validate the wind speeds with varying height and energy generated, Computational Fluid Dynamics (CFD) based analysis of the housing typologies is undertaken. This is assumed to aid in understanding the impact of built form on overall wind speeds and identify ideal locations for placement of wind turbines.

4.12 Computational Assessment of Velocity, Pressure and Turbulence using CFD

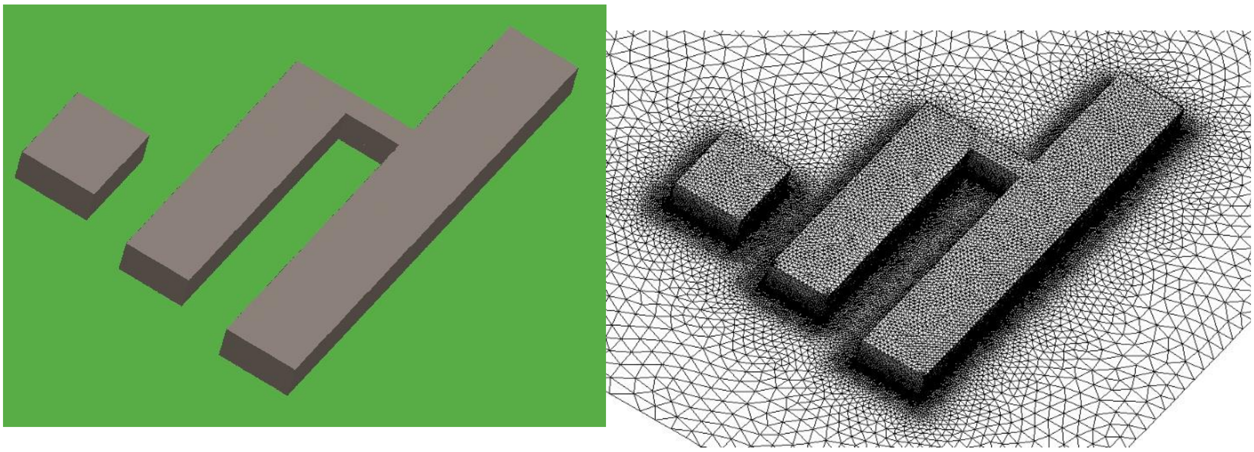
Accurate simulation of wind speed and its direction in built environments can result in estimation of probable Wind Power Density (WPD) and Wind Energy Density (WED). Numerical based Computational Fluid Dynamics (CFD) simulation can aid in accurate prediction of wind speeds within complex urban settings. For the purpose of CFD based analysis, the built form configuration of existing housing typologies in CUC are considered.

Different housing typologies of CUC are put to test based on existing wind pattern and direction. Various parameters like wind speeds, wind pressure and kinetic energy resulting out of turbulence are computationally investigated with increasing height **(Smith et al., 2007)**. The parameters derived are used to estimate the wind energy generation potential for each of the existing housing typologies and identify the ideal locations for installation of micro wind turbines.

Physical design measures that could aid in enhancing the existing energy output are investigated and findings highlighted. The details of each typologies are detailed out in the following sections.

4.12.1 Uppals Marble Arch, Manimajra, Chandigarh

a) Site Image and Surrounding Context **b) Elevation**



c) 3D Model **d) CFD based Mesh Model**

Figure 4.9. CFD Simulation Setup of Uppals Marble Arch, Manimajra, Chandigarh

The typical 3D model of Uppals Marble Arch is converted into a mesh model in Ansys Fluent as shown in figure 4.9 and put for CFD simulation. The blocks are oriented parallel to the prevailing north-west winds and the club house in between the blocks is perpendicular to the wind flow.

Initial visual assessment of the CFD simulation from figure 4.10 and figure 4.11 reveal that major concentration of winds is at the lower level in between the blocks with the wind speed reaching between 3.44 - 4.38m/sec at a height of 10m and similar wind speeds prevailing at a height of 17.5m near the rooftop level. This indicates that the space between the blocks can be potential sites for installation of wind turbines at a height ranging from 7.5-17.5m.

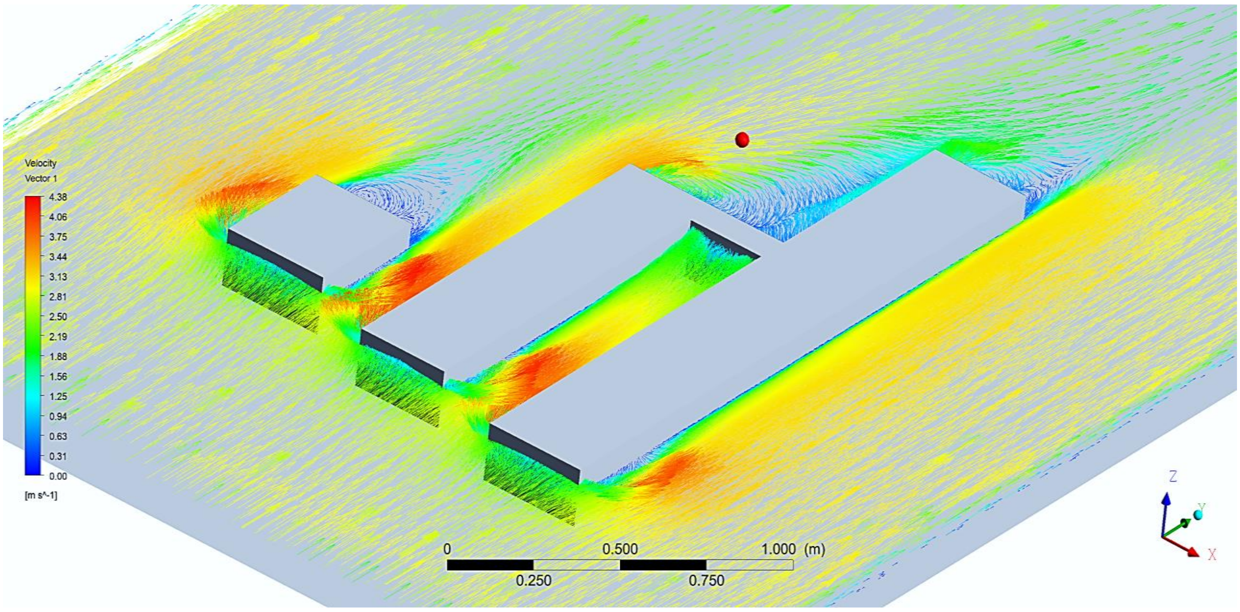
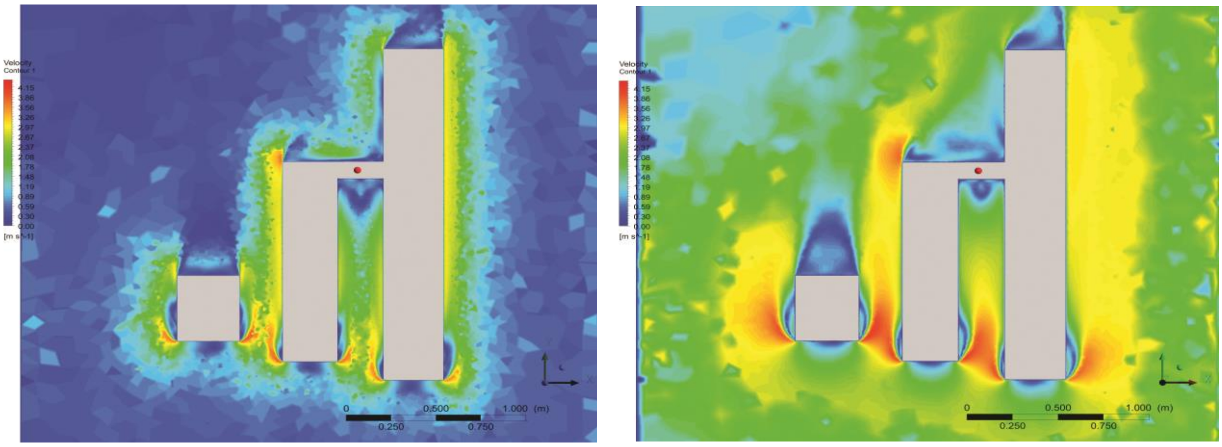
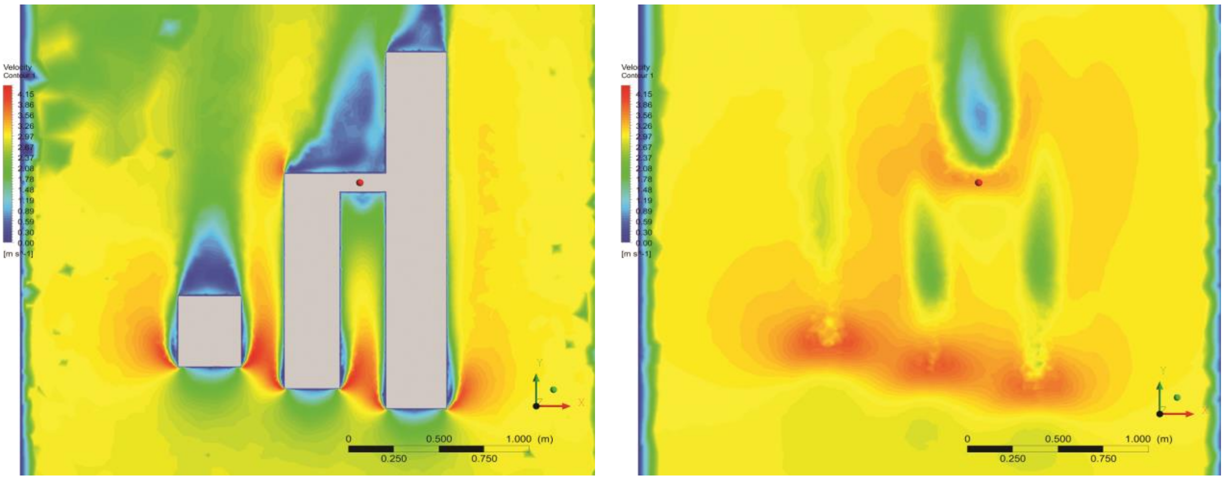


Figure 4.10. Wind Flow Pattern and Turbulence at Uppals Marble Arch, Manimajra, Chandigarh



a) Ground Level

b) Height of 10 meter



c) Height of 17.5 meter (near rooftop level)

d) Height of 30 meter

Figure 4.11. Wind Speed and Turbulence observed at different Heights in Uppals Marble Arch, Manimajra, Chandigarh

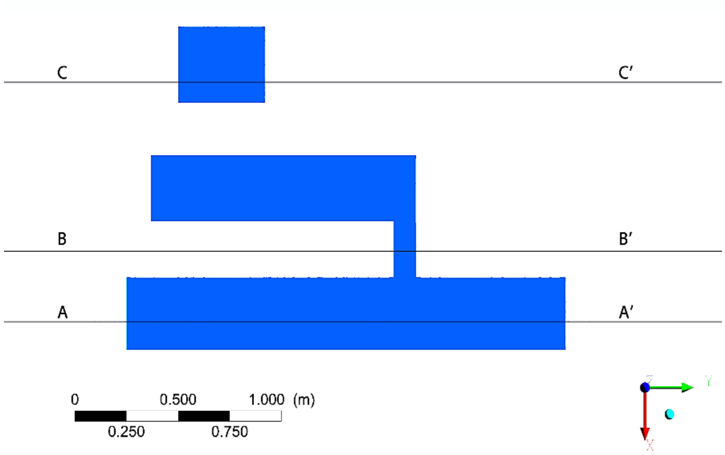
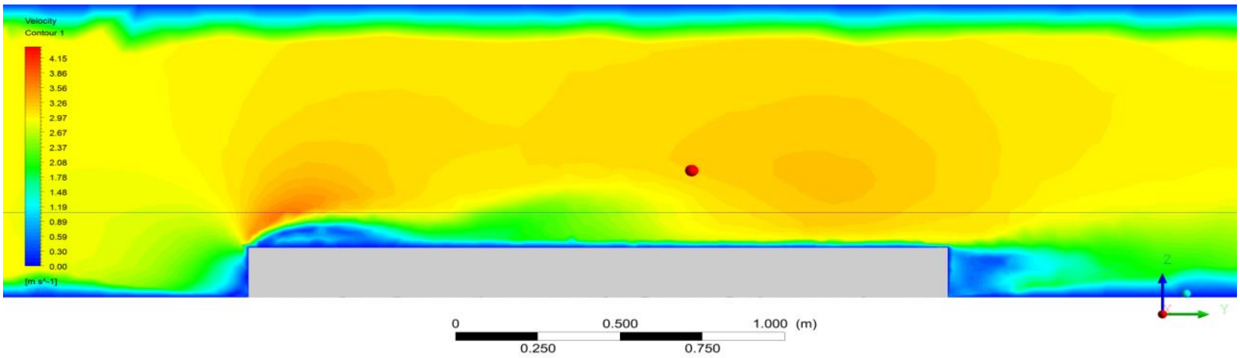
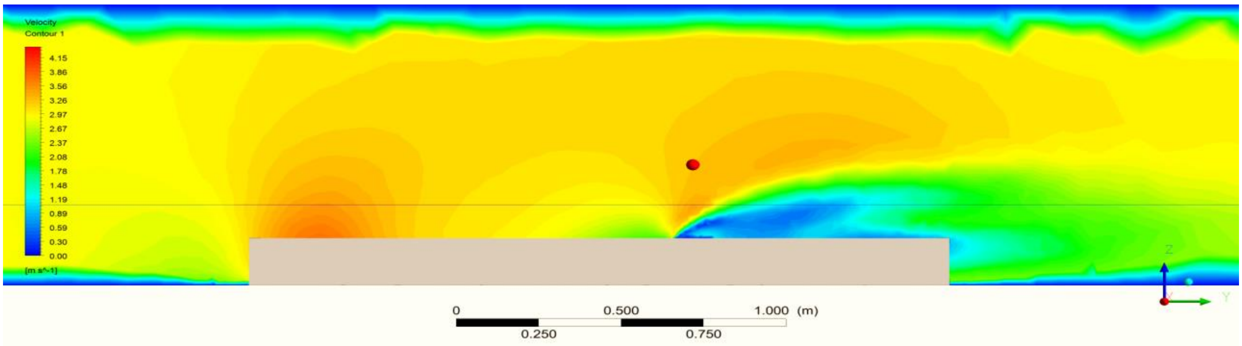


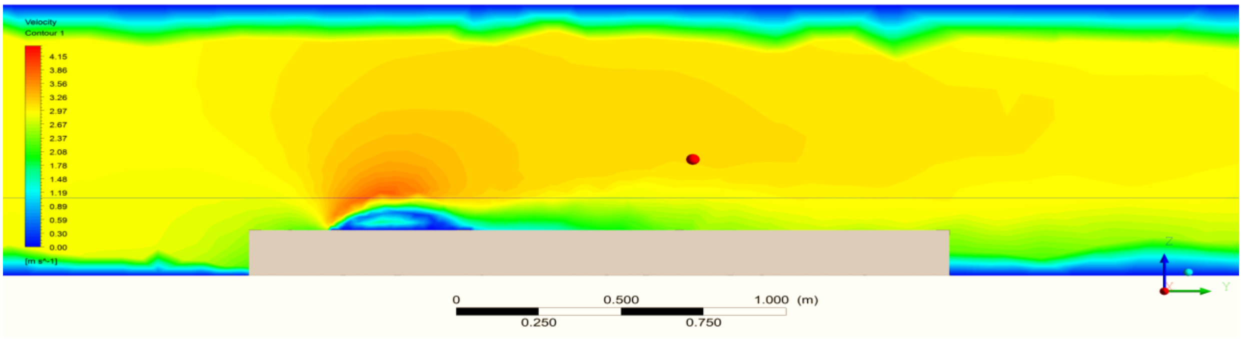
Figure 4.12. Section Planes of Vertical Wind Flow Simulation in Uppals Marble Arch, Manimajra, Chandigarh



a) Section AA'

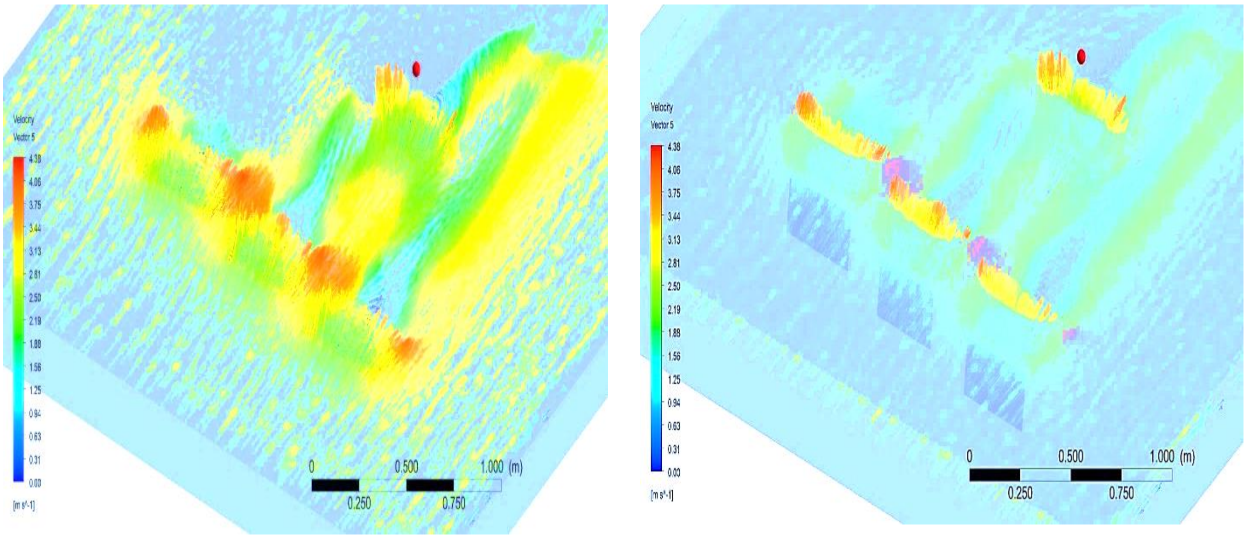


b) Section BB'



c) Section CC'

Figure 4.13. Wind Flow Pattern and Turbulence along the Section Planes in Uppals Marble Arch, Manimajra, Chandigarh



a) At 2.5 meter above roof level **b) At 12.5 meter above roof level**

Figure 4.14. Density of Wind at different Heights to identify Potential Locations for Wind Turbines in Uppals Marble Arch, Manimajra, Chandigarh

As per section planes shown in figure 4.12 and corresponding sections in figure 4.13, at height of 20m, about 2.5m above the roof top, wind speeds of 3.75-4.50m/sec are observed which show a greater potential of power generation through micro turbines. Also wind speeds of 2.81-3.44m/sec are observed at height of 12.5m above the roof top as in figure 4.14. Therefore, for consistent wind speeds of 3.25-3.50m/sec micro turbines can be installed in between the building edges near the rooftop or 2.5–10m above the roof level.

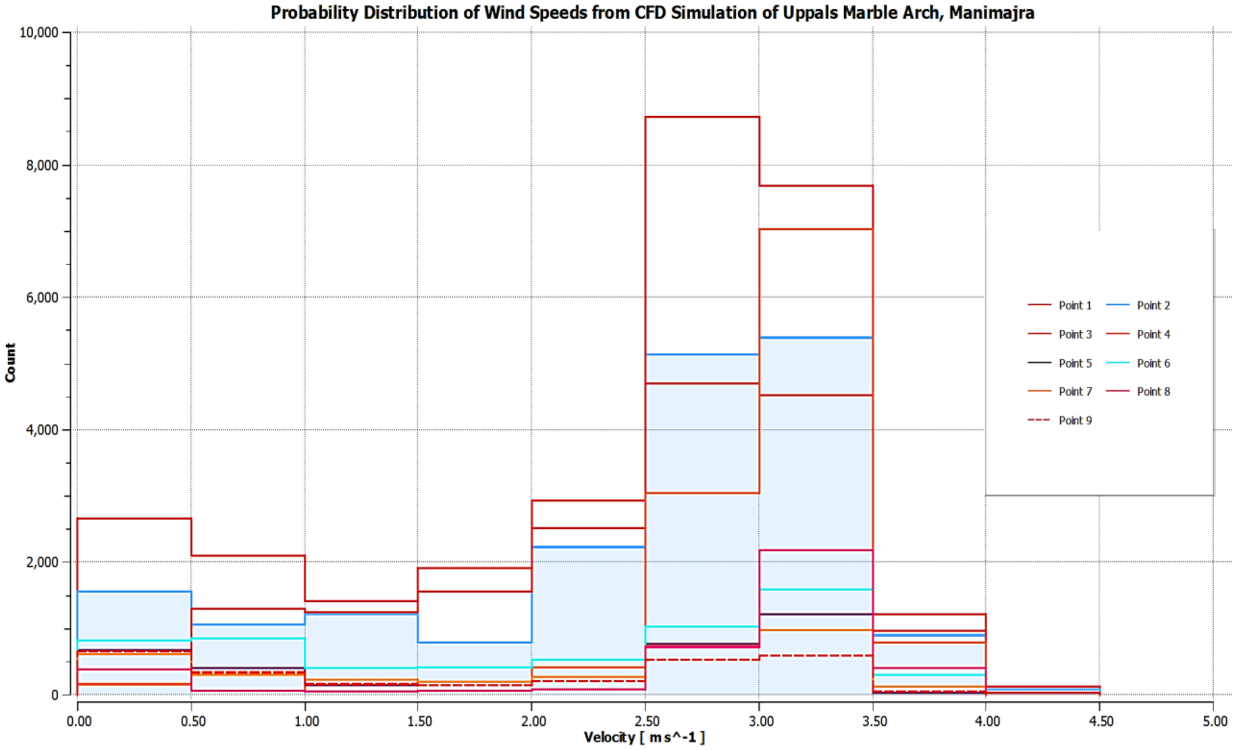


Figure 4.15. Wind Speeds observed in Uppals Marble Arch, Manimajra, Chandigarh

The impact of the built form on the actual wind speed is undertaken through analysis of the probability of observed wind speeds from 9 different points highlighted in figure 4.15 and it is observed that the most prevalent wind speeds range between 2.72–3.26m/sec. The wind speeds are within the range of most probable wind speed quantified by the Weibull distribution.

Wind speeds at varying height of 10m, 17.5m, 20m and 30m are also analysed and as per figure 4.16 the most probable wind speeds common to varying heights is found to lie between 2.50 – 4.00m/sec, but the highest probability is of wind speeds ranging between 3.00-3.50m/sec.

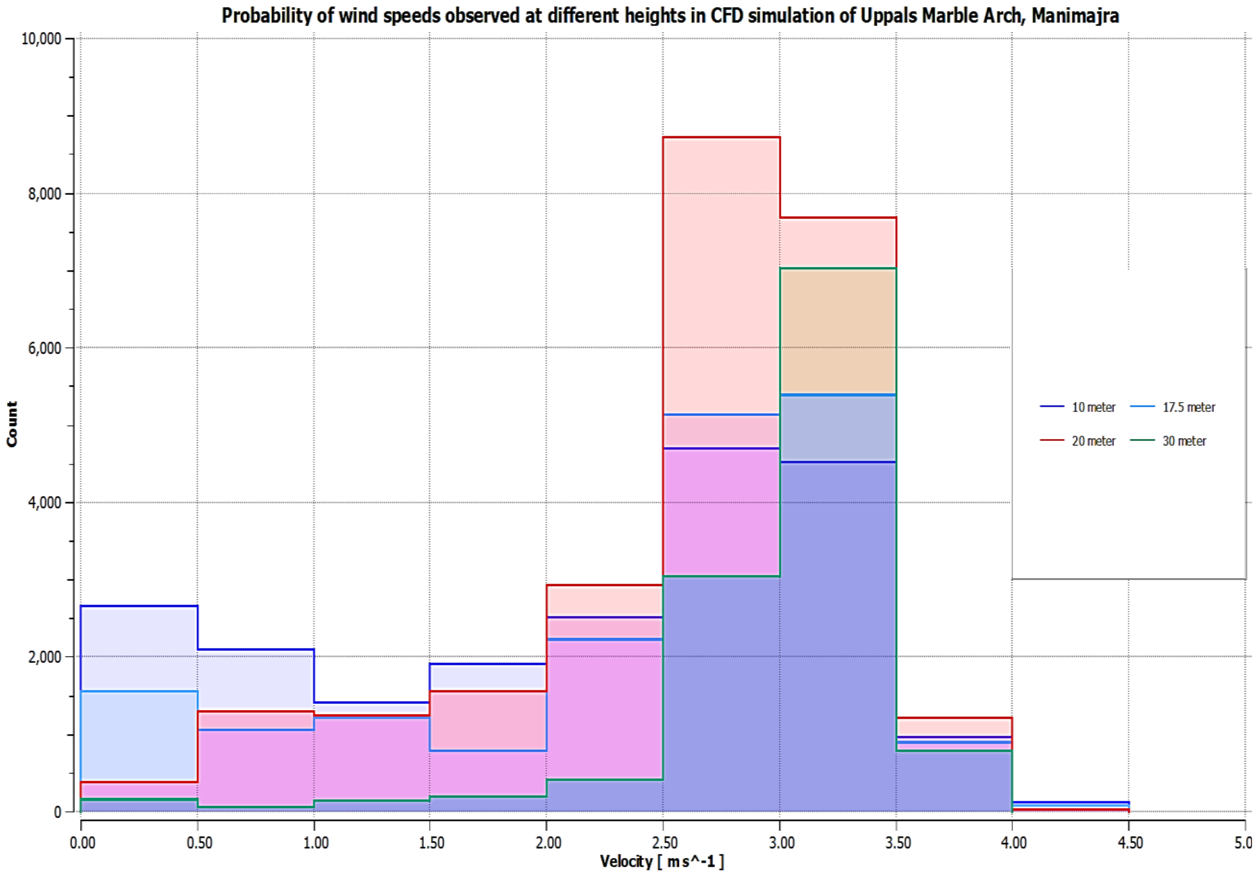


Figure 4.16. Probability of Wind Speeds observed at different Heights in Uppals Marble Arch, Manimajra, Chandigarh

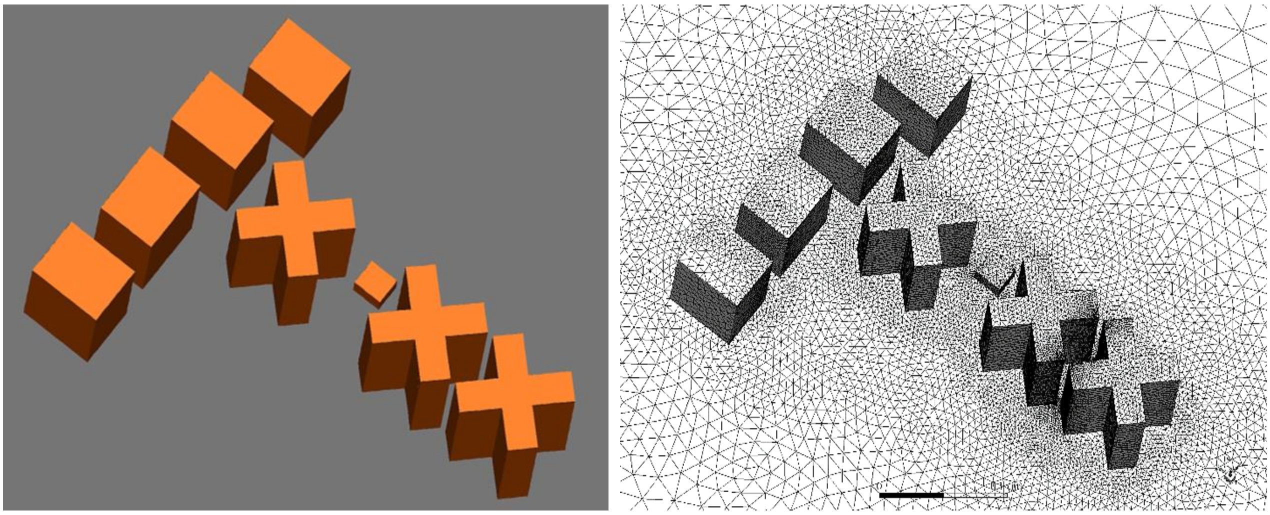
As per equation 2.28 and 2.29 (Chapter 2), considering a grid connected 1kW Luminous Whisper 200 micro turbine with a sweep area of 5.73m^2, average wind speed of 2.50-4.00m/sec, air density of 1.183kg/m^3, maximum power coefficient of 0.593, gear box efficiency (n_g) of 90% and generator efficiency (n_b) of 80%, the electrical power generated is 32.87-52W. The wind power density (WPD) calculated is 22.61 – 62.05W/m^2 and the annual Wind Energy Density (WED) calculated is 80.96 – 222.16kWh/m^2. Therefore, attempt should be to enhance the measures to capture wind with highest wind speed within the built environment to make wind resource viable.

Statistical data based WPD and WED results from table 4.25 for the height of 10m and 30m are higher by 10% and 7% to the values of CFD simulation. The actual values may be less than the predicted values in CFD simulation due to the presence of vegetation. However, in case of CFD simulation the highest wind speed achieved is 4.45m/sec in which a 4.5kW wind turbine having a sweep area of 16.61m^2 can achieve a WPD of 369W and WEP of 52.1W/m^2 resulting in annual WED of 457kWh/m^2.

4.12.2 Sushma Elite Cross, Gazipur, Punjab

The typical 3D model of the high-rise RRU as displayed in figure 4.17 is converted into a mesh model in Ansys Fluent and put for CFD simulation. The blocks are oriented both parallel and diagonally to the prevalent north-west wind direction. The club house building 6m in height is in between the blocks and sits perpendicular to the prevailing wind flow.

a) Site Image and Surrounding Context **b) Elevation**



c) 3D Block **d) CFD based Mesh Model**

Figure 4.17. CFD Simulation Setup of Sushma Elite Cross, Gazipur, Punjab

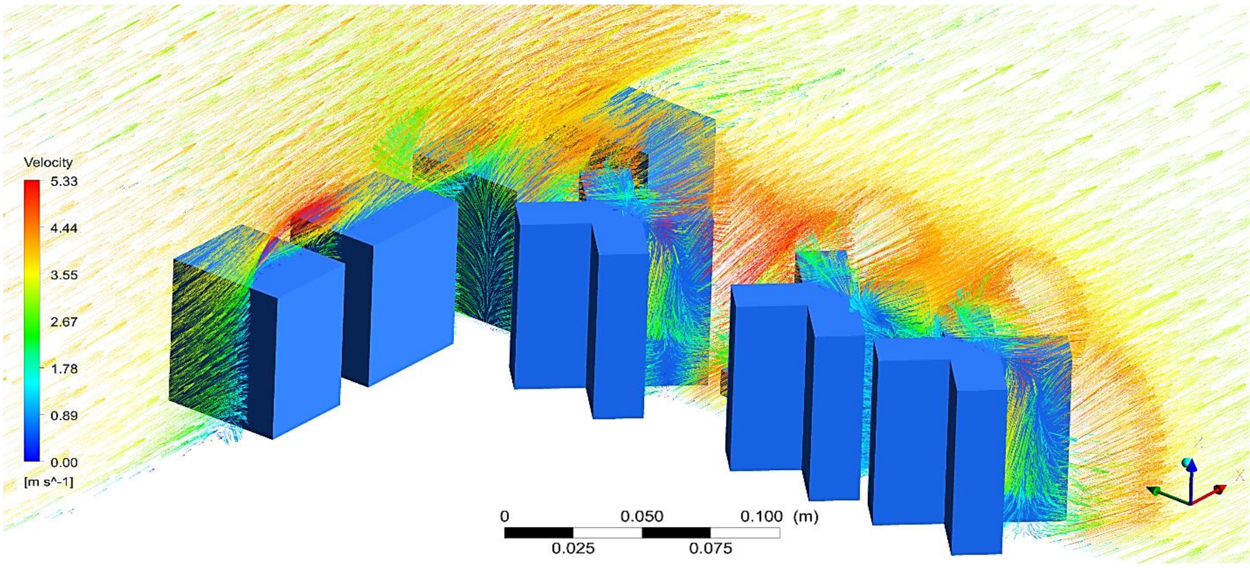
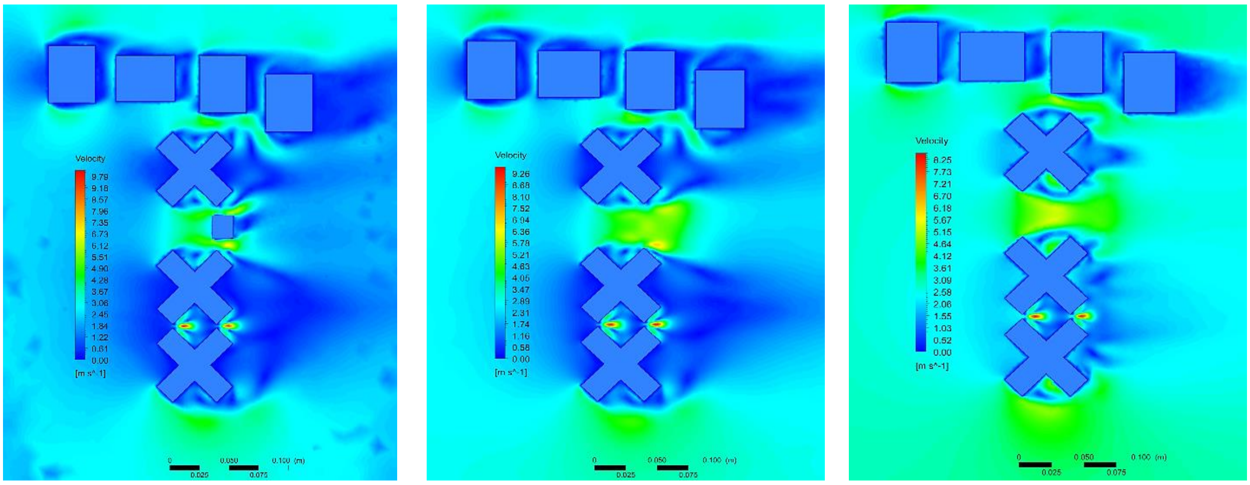
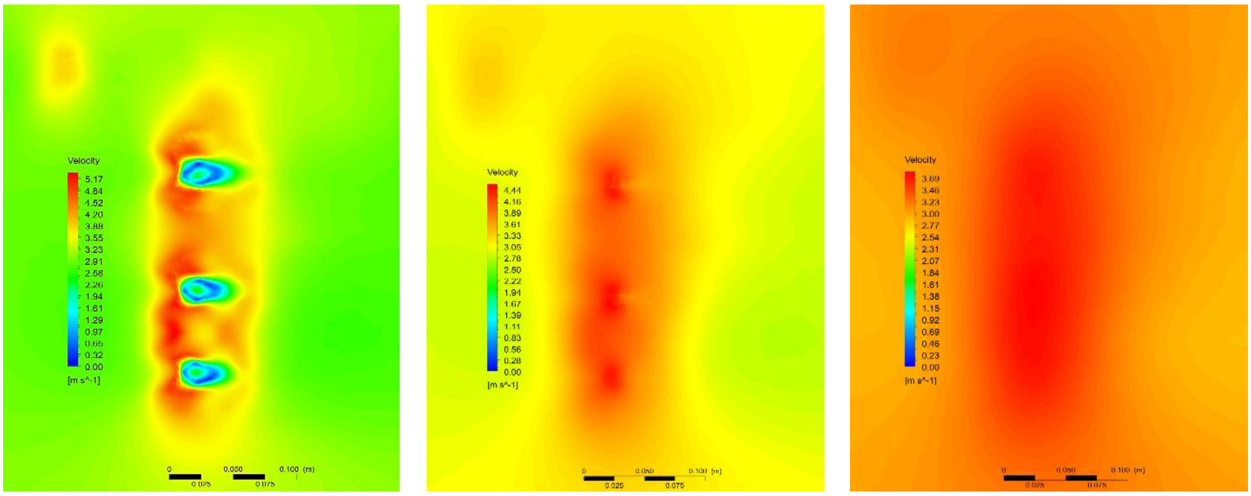


Figure 4.18. **Wind Flow Pattern and Turbulence at Sushma Elite Cross, Gazipur, Punjab**



a) 5 meter above Ground **b) 20 meter** **c) 30 meter**



d) 40 meter **e) 50 meter** **f) 60 meter**

Figure 4.19. **Wind Speeds observed at different Heights in Sushma Elite Cross, Gazipur, Punjab**

Initial visual assessment of the CFD simulation from figure 4.18, 4.19, 4.20 and 4.21 reveal that major concentration of winds is at the roof level and in between the blocks over the club house. Wind speeds of 3.55–5.17m/sec are observed at a height of 30-40m over the club house in between the blocks, similarly wind speeds of 3.59–4.79m/sec are observed at a height of 10m above the roof for taller units, whereas wind speeds of 3.18–4.45m/sec are observed at a height of 8m above the roof for smaller units. The highest wind speeds are observed in the narrow space between the adjacent tall units with the wind speeds ranging from 7.13–10.37m/sec.

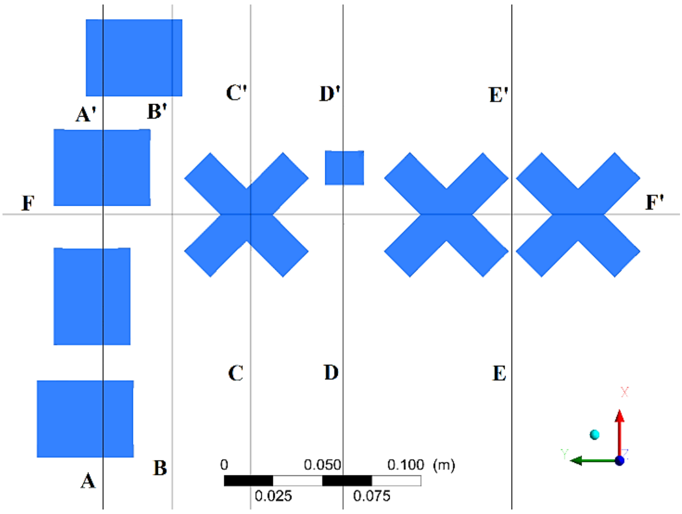
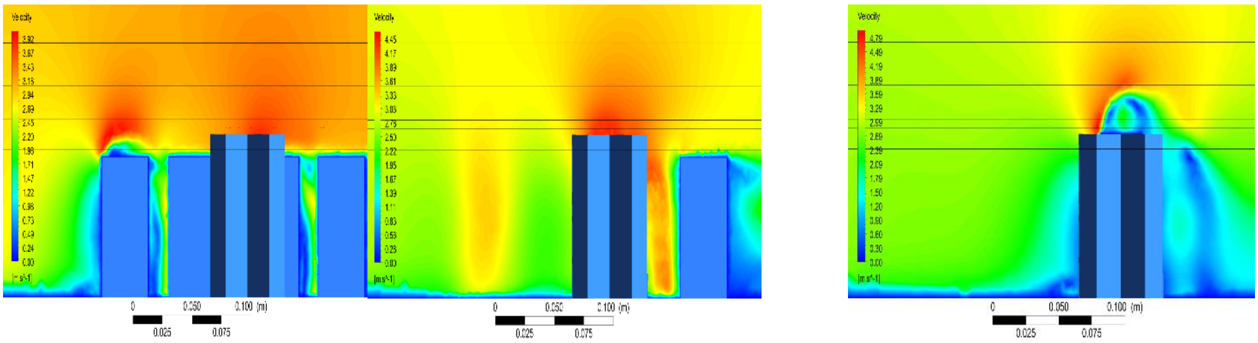
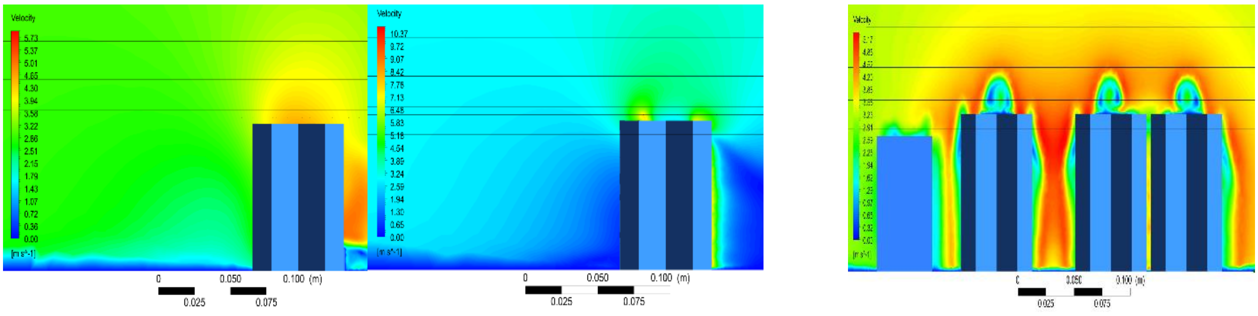


Figure 4.20. **Section Planes of Vertical Wind Flow Simulation in Sushma Elite Cross, Gazipur, Punjab**



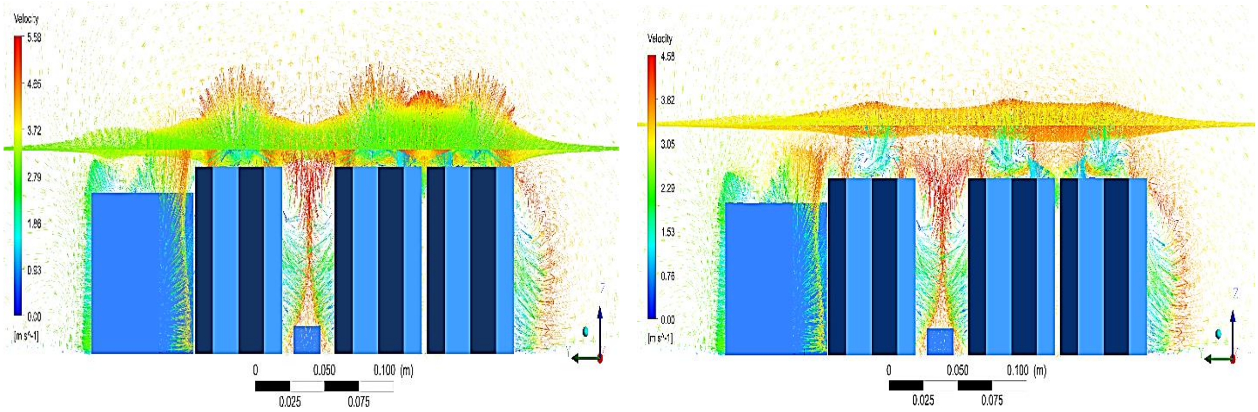
a) Section AA' **b) Section BB'** **c) Section CC'**



d) Section DD' **e) Section EE'** **f) Section FF'**

Figure 4.21. **Wind Speeds observed along Section Planes in Sushma Elite Cross, Gazipur, Punjab**

Figure 4.22 indicates that the space between the blocks can be potential sites for installation of wind turbines at a height ranging from 24-40m. In case of smaller units the ideal location would be 8-10m above the roof and for the taller units wind turbines installed at a height of 10-12m above the roof can generate maximum electricity.



a) At height of 5 meter above roof **b) At height of 10 meter above roof**

Figure 4.22. Wind Flow Concentration in between Building Blocks and above the Roof in Sushma Elite Cross, Gazipur, Punjab

To verify actual range of simulated wind speed a histogram is created with wind speed observed at 12 points. The histogram (figure 4.23) reveals that the high speed winds observed in visual assessment are instantaneous in nature and actual range of wind speed with the highest probability in the built form is within 2.67-4.01m/sec. In figure 4.24 the most probable wind speeds with reference to different heights are found to lie within the range of 2.4 – 4.2m/sec.

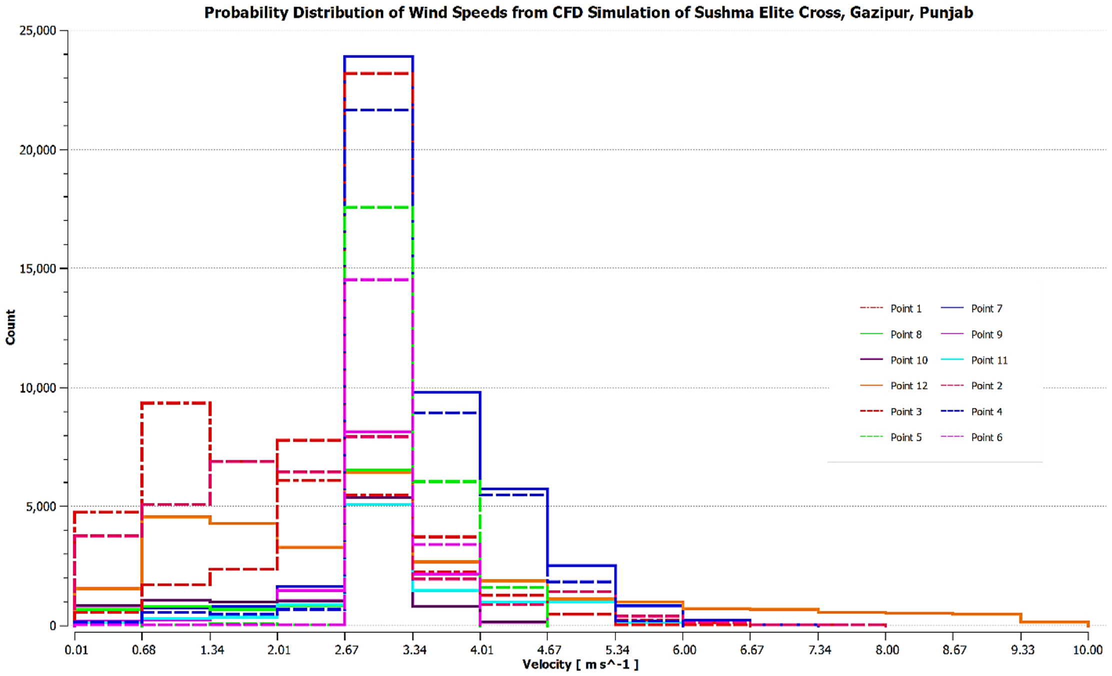


Figure 4.23. Wind Speeds observed in Sushma Elite Cross, Gazipur, Punjab

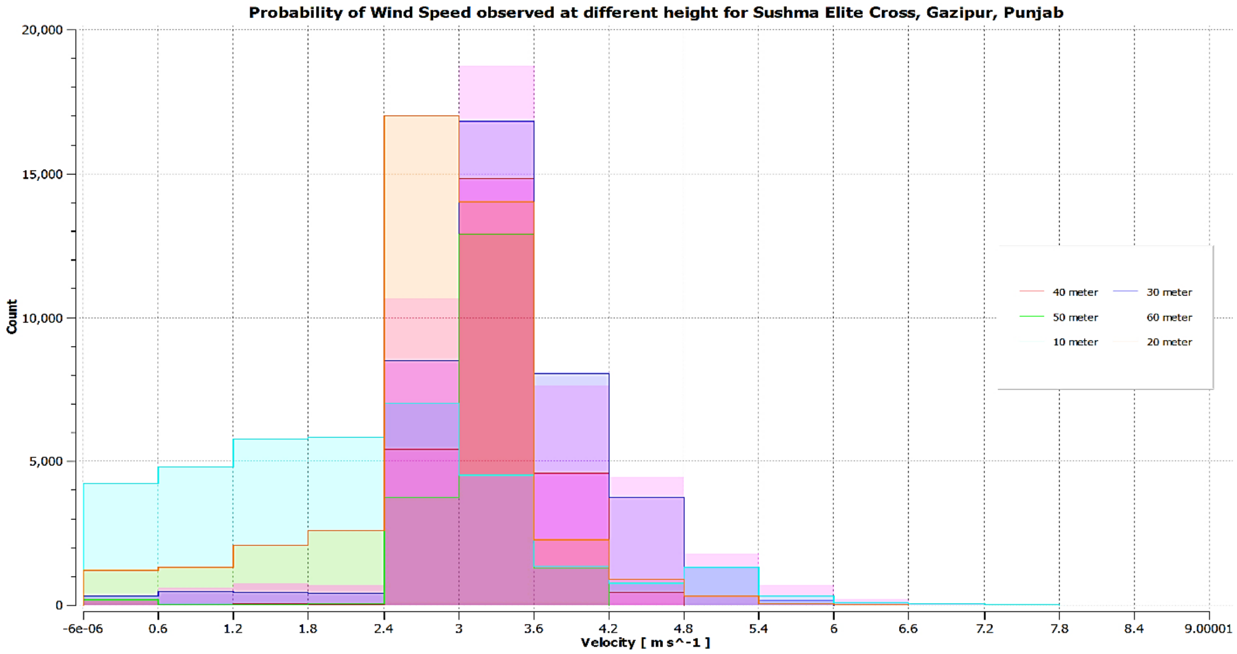
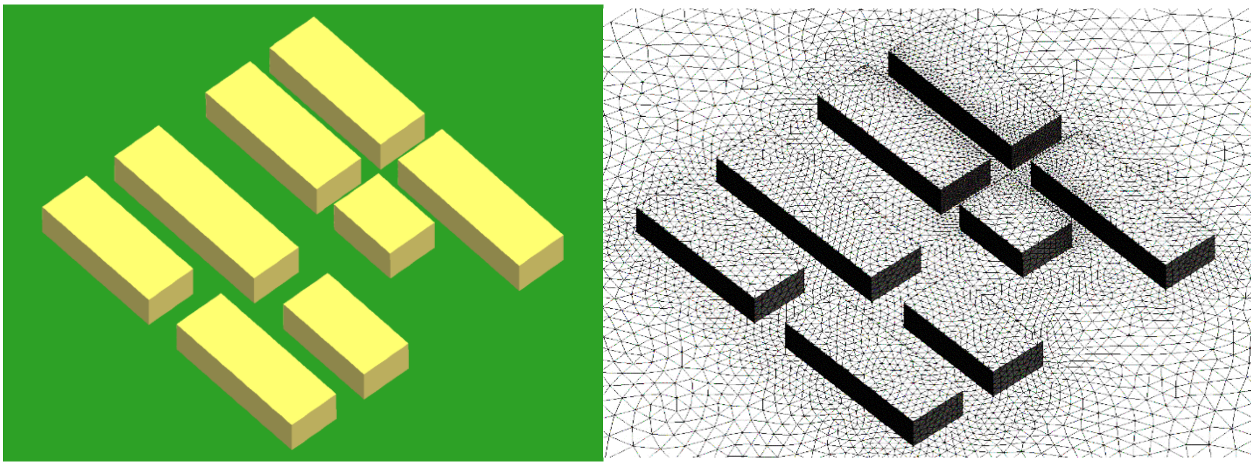


Figure 4.24. Probability of Wind Speeds observed at different Heights in Sushma Elite Cross, Gazipur, Punjab

As per equation 2.28 and 2.29 (Chapter 2), considering a grid connected 1kW Luminous Whisper 200 micro turbine with a sweep area of 5.73m^2, average wind speed of 2.4–4.2m/sec, air density of 1.183kg/m^3, maximum power coefficient of 0.593, gear box efficiency (n_g) of 90% and generator efficiency (n_b) of 80%, the electrical power generated is 20-107W. The wind power density (WPD) calculated is 8.18–43.82W/m^2 and the annual Wind Energy Density (WED) calculated is 71.66–383.89kWh/m^2.

4.12.3 Sector 51, Chandigarh

a) Site Image and Surrounding Context **b) Elevation**



c) 3D Block **d) CFD based Mesh Model**

Figure 4.25. CFD Simulation Setup of Sector 51, Chandigarh

The typical 3D model of an existing low-rise is converted into a mesh model as in figure 4.25 using Ansys Fluent and put for CFD simulation. The blocks are oriented perpendicular to the prevalent north-west wind direction.

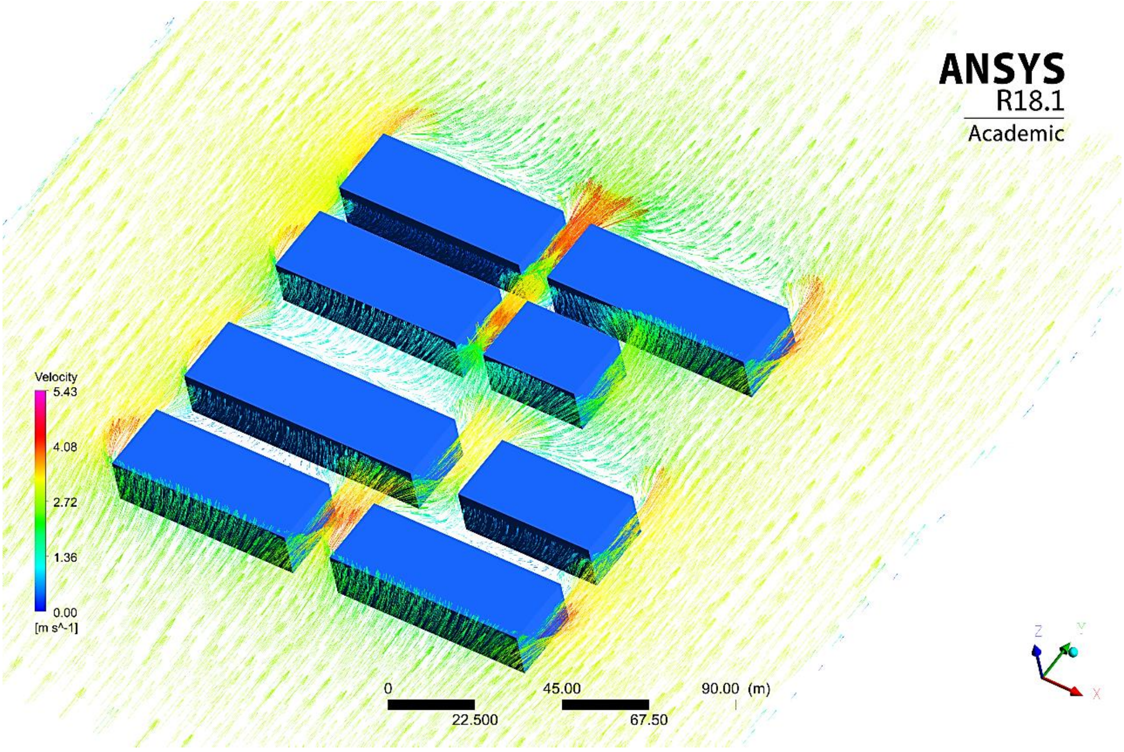
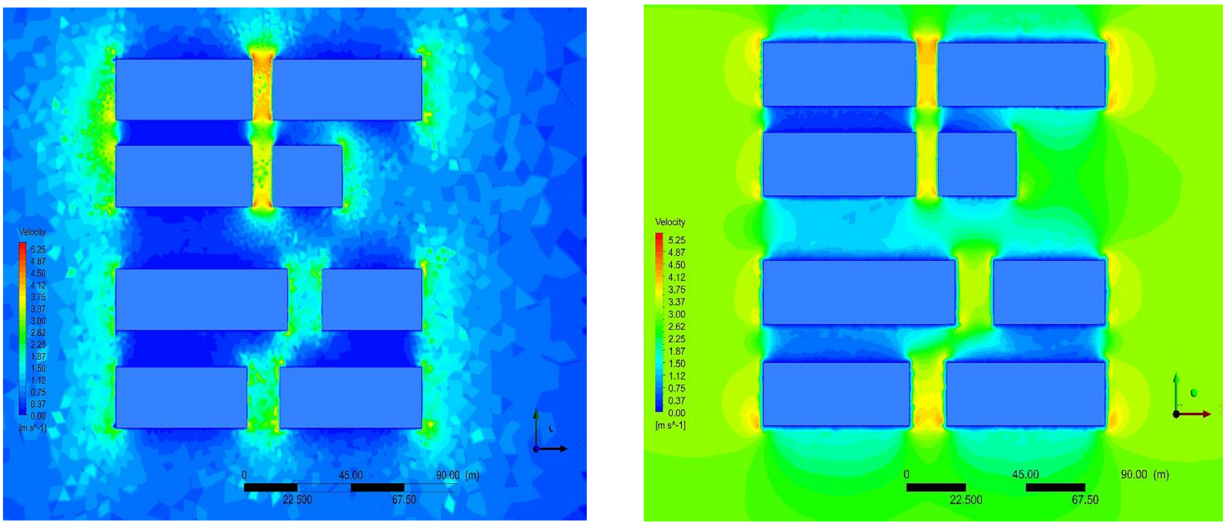


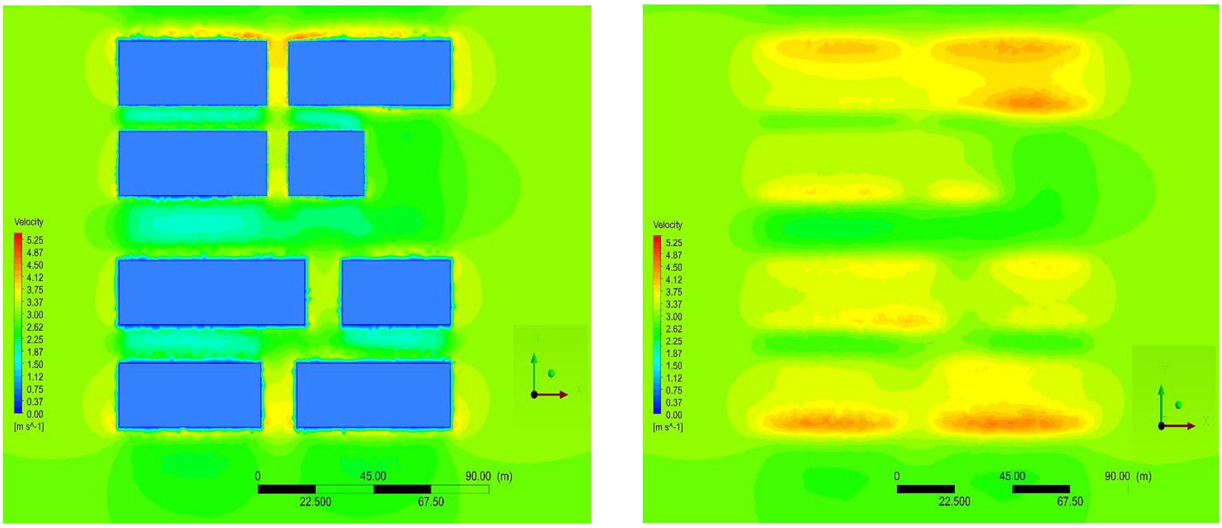
Figure 4.26. Wind Flow Pattern and Turbulence at Sector 51, Chandigarh

Initial visual assessment of the CFD simulation from figure 4.26 and 4.27 reveal that there is increase in wind speed in the narrow street between the blocks with the wind speed ranging between 3.37-4.12m/sec at a height of 10m, but decreasing to 3.00–3.75m/sec at a height of 14.5m near the rooftop level.



a) Ground Level

b) Height of 10 meter

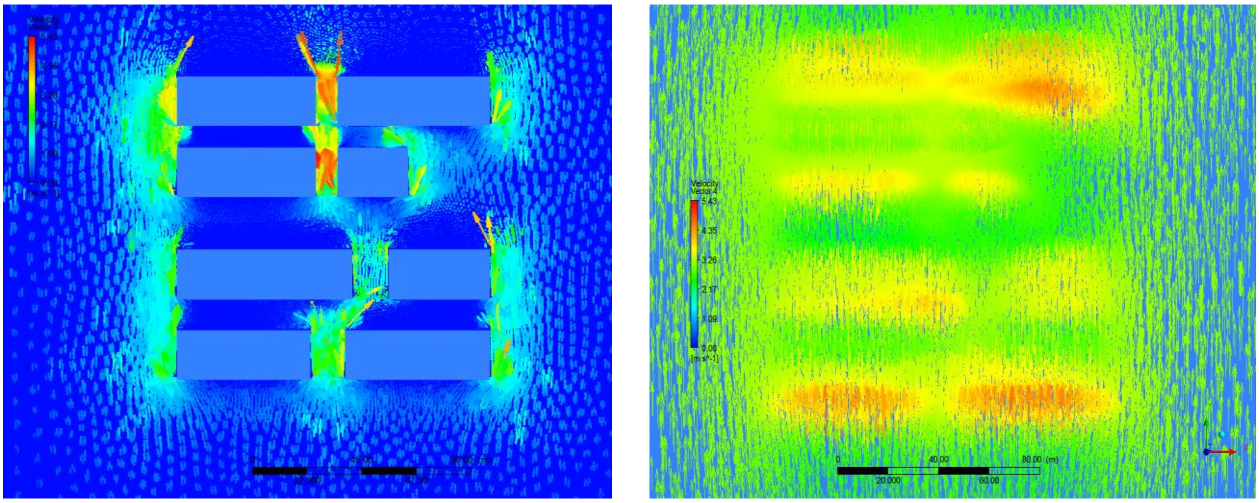


c) Height of 14.5 meter (near roof level)

d) Height of 18 meter

Figure 4.27. Wind Speed and Turbulence observed at different Heights in Sector 51, Chandigarh

Assessment of figure 4.28, 4.29 and 4.30 indicate that the narrow streets along the wind direction can be potential sites for installation of wind turbines at a height ranging from 10-14.5m. At a height of 16-18m, about 2-4m above the rooftop wind speeds of 4.08-4.45m/sec are observed, which indicate a greater potential in power generation through micro turbines. Therefore, the most consistent wind speeds observed at the above locations range between 3.25-3.80m/sec. The impact of the built form on the actual wind speed is considered through analysis of the probability of observed wind speeds from 9 different points highlighted in figure 4.31. It is observed that the most prevalent wind speeds range between 2.72–3.26m/sec. The wind speeds are within the range of most probable wind speed as quantified by the Weibull distribution.



a) **In between the building blocks**

b) **Above the roof level**

Figure 4.28. Potential Locations for Installation of Wind Turbines in Sector 51, Chandigarh

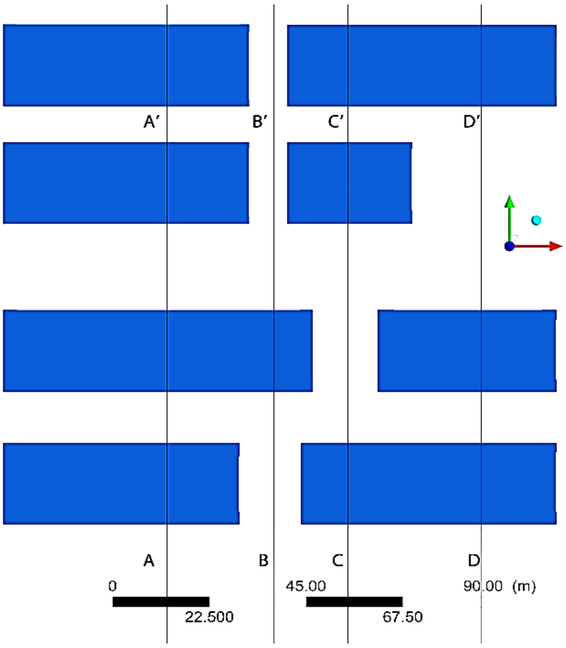
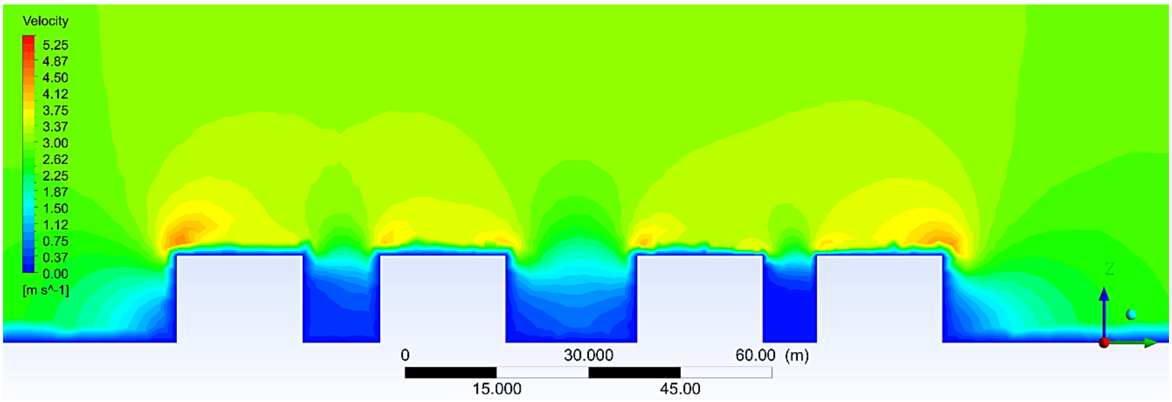
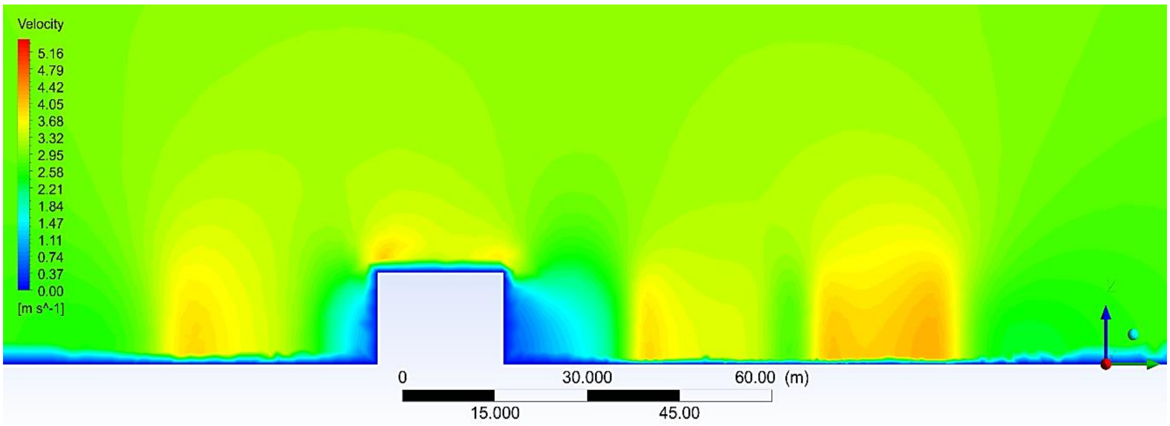


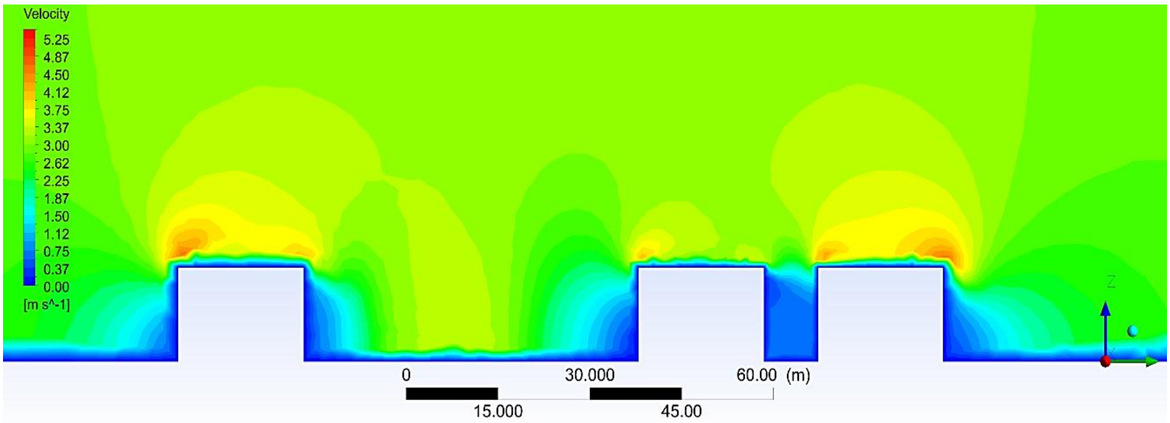
Figure 4.29. Section Planes of Vertical Wind Flow Simulation in Sector 51, Chandigarh



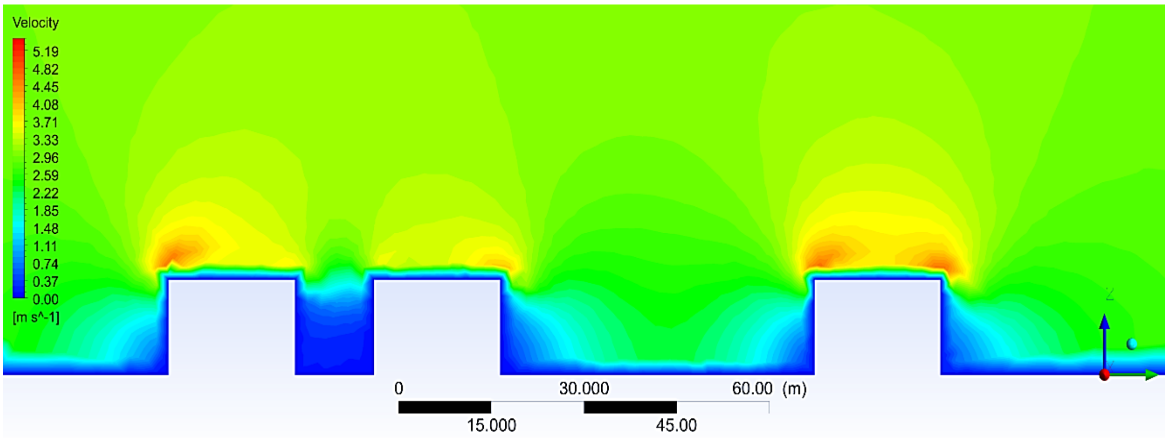
a) Section AA’



b) Section BB’



c) Section CC’



d) Section DD’

Figure 4.30. Potential Locations and Height Requirement for Installation of Wind Turbines in Sector 51, Chandigarh

Wind speeds at varying heights of 10m, 14.5m and 18m are also analysed and as per figure 4.31 and 4.32 the most probable wind speeds common to varying heights lie between 2.36–4.24m/sec, but the highest probability is of wind speeds ranging between 2.83-3.30m/sec.

As per equation 2.28 and 2.29 (Chapter 2), considering a grid connected 1kW Luminous Whisper 200 micro turbine with a sweep area of 5.73m^2, average wind speed of 2.83-3.30m/sec, air density of 1.183kg/m^3, maximum power coefficient of 0.593, gear box efficiency (n_g) of 90% and generator efficiency (n_b) of 80%, the electrical power generated is 32.87-52W. The wind power density (WPD) calculated is 13.41–21.26W/m^2 while the annual Wind Energy Density (WED) calculated is 117.47–186.24kWh/m^2.

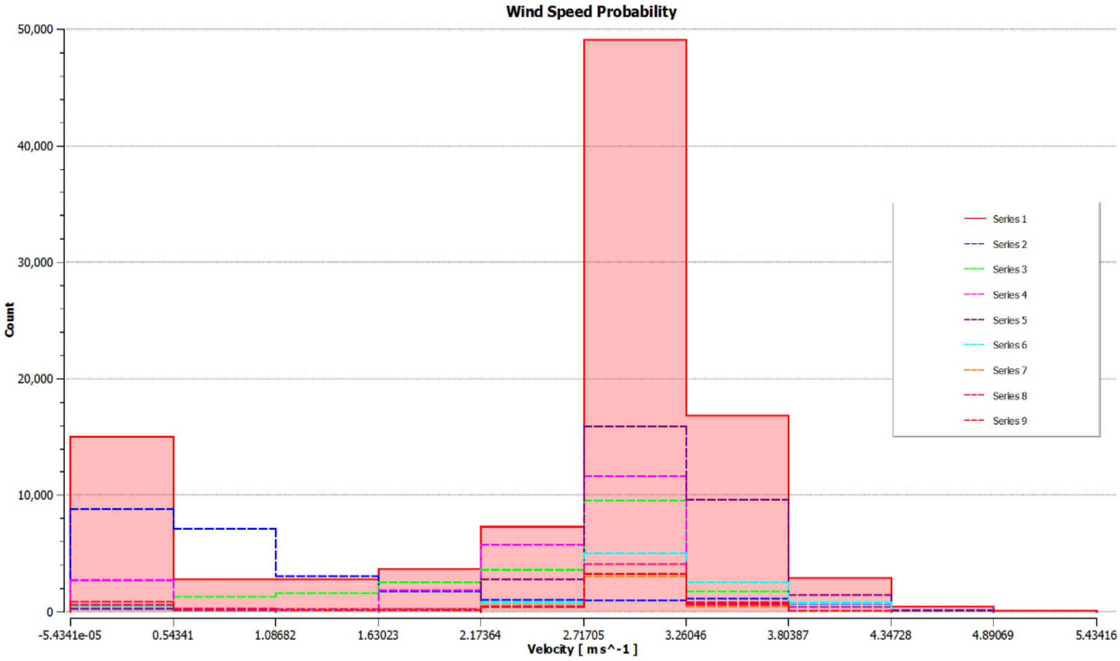


Figure 4.31. Wind Speeds observed in Sector 51, Chandigarh

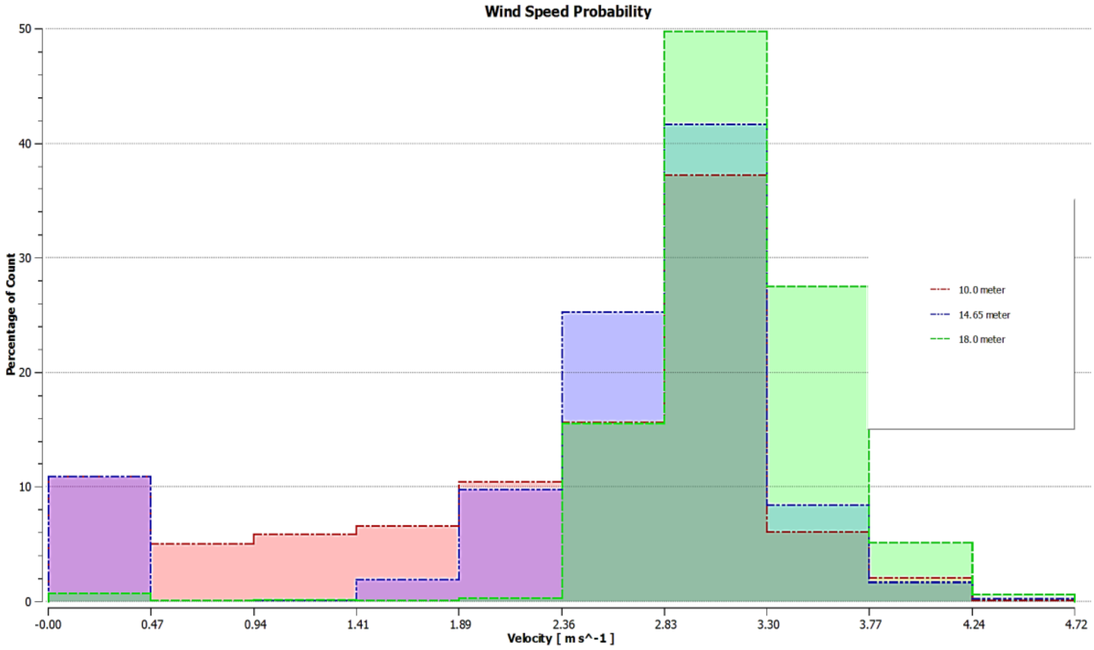
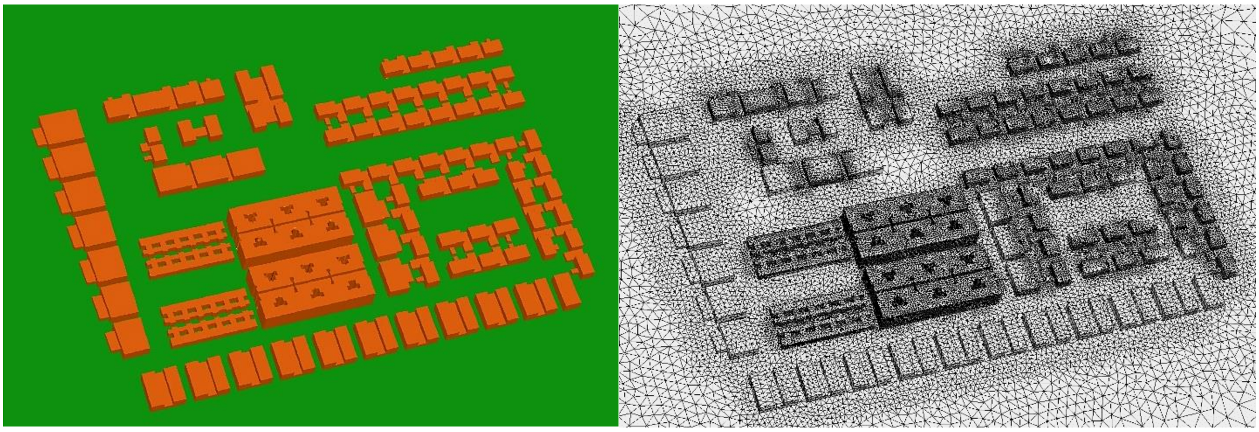


Figure 4.32. Probability of Wind Speeds observed at different Heights in Sector 51, Chandigarh

Statistical data based WPD and WED results from table 4.25 for the height of 10m and 20m are higher by 31% and 14% to the values of CFD simulation. The actual values may be less than the predicted values in CFD simulation due to presence of vegetation. With increasing height the margin of difference between the statistical and CFD simulation based values are going to be equal. However, installation of micro wind turbines at height of 30m and above need lot of considerations that can make wind energy uneconomical. In case of CFD simulation the highest wind speed achieved is 5.43m/sec. Under such circumstances, a 4.5kW wind turbine can achieve a WPD of 671W and WEP of 94.7W/m^2 resulting in annual WED of 830kWh/m^2.

4.12.4 Sector 19A, Chandigarh

Figure 4.33. Site Image and Surrounding Context of Sector 19A, Chandigarh



a) 3D Block b) CFD based Mesh Model

Figure 4.34. CFD Simulation Setup of Sector 19A, Chandigarh

The housing in Sector 19A, Chandigarh comprises of 1 Kanal, 2 Kanal and 3 Kanal plotted units as indicated in figure 4.35. The units comprise of 3 floors with a maximum height of 10.6m. Figure 4.34 displays the typical 3D model of the sector and its mesh model for CFD simulation. The external units are oriented parallel to the prevalent north-west wind direction.

a) Government Quarters **b) Three Kanal House**

c) Two Kanal House **d) One Kanal House**

Figure 4.35. Built form Typologies of Sector 19A, Chandigarh

Initial visual assessment of the CFD simulation from figure 4.36 and 4.37 reveal that major concentration of winds is at the roof level and in between the blocks from where the wind enters the neighbourhood. Wind speeds of 2.64-3.70m/sec are observed at a height of 2-5m grazing past and over the housing units, while wind speeds of 1.59–2.38m/sec are observed over the roofs of the row housing forming the neighbourhood. Major concentration of winds are observed at a height of 3–8m above the roof with a speed of 3.50–3.96m/sec. The ideal placement of the wind turbines can be at the end of the parapet in the units at the start of the wind stream and in the middle of the roofs for remaining units of the neighbourhood.

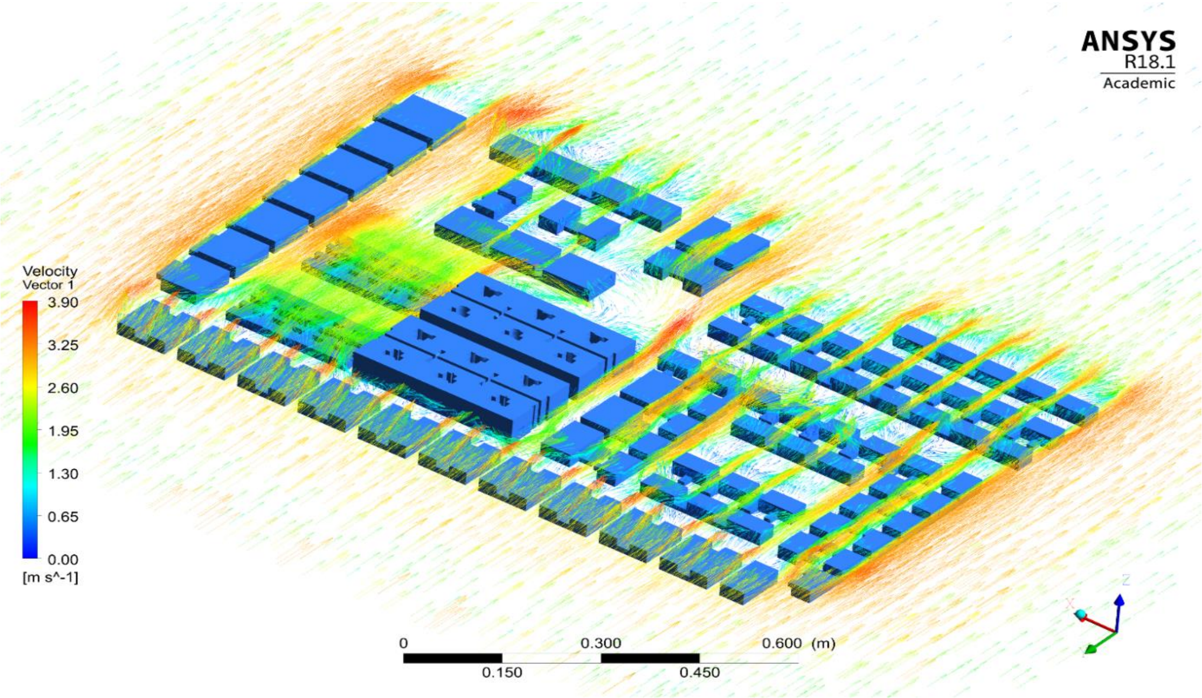
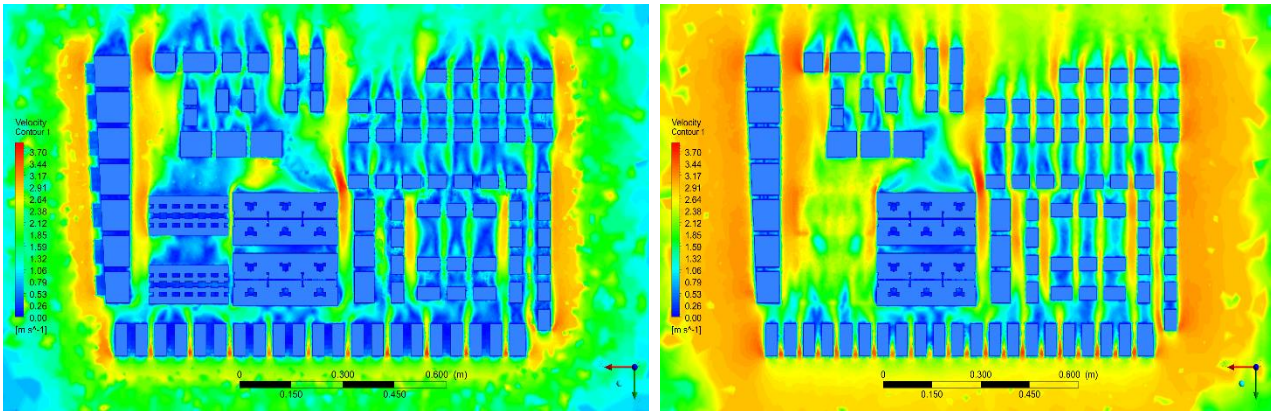
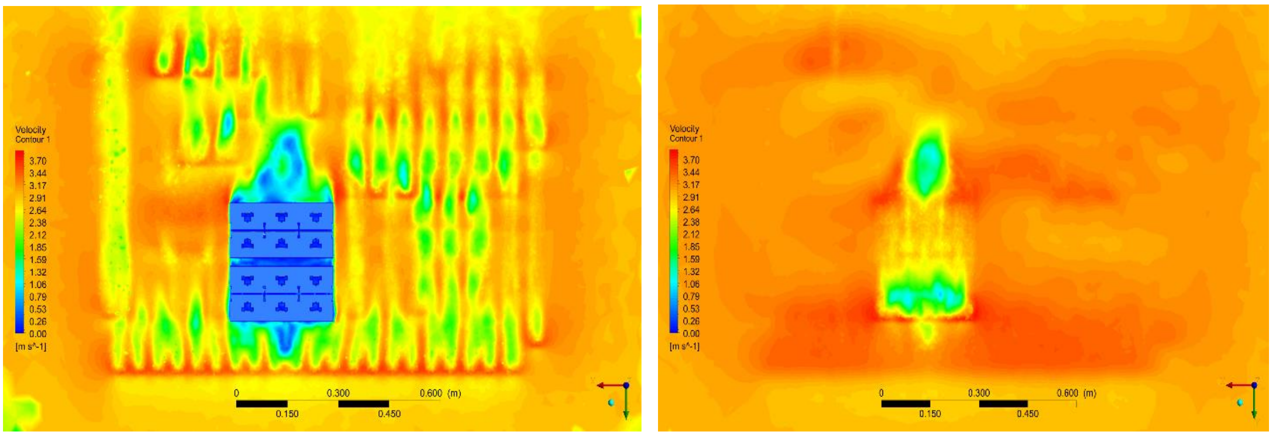


Figure 4.36. Wind Flow Pattern and Turbulence at Sector 19A, Chandigarh



a) 5 meter above Ground

b) 10 meter



c) 12 meter

d) 15 meter

Figure 4.37. Wind Speeds observed at different Heights in Sector 19A, Chandigarh

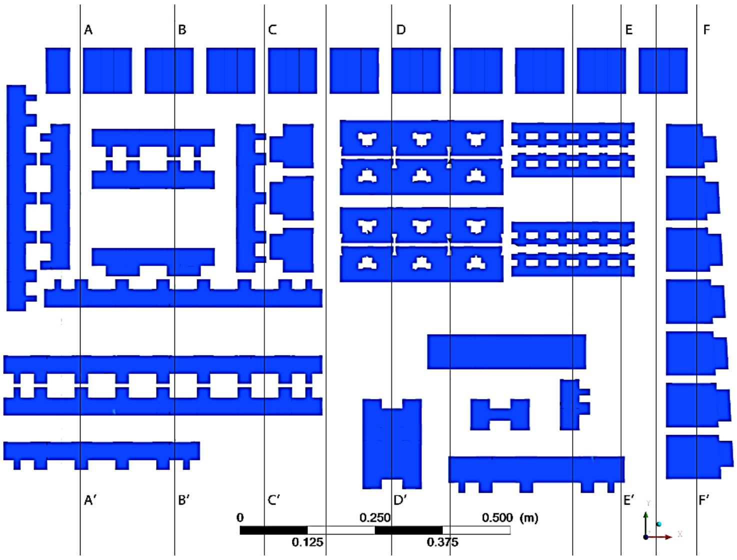
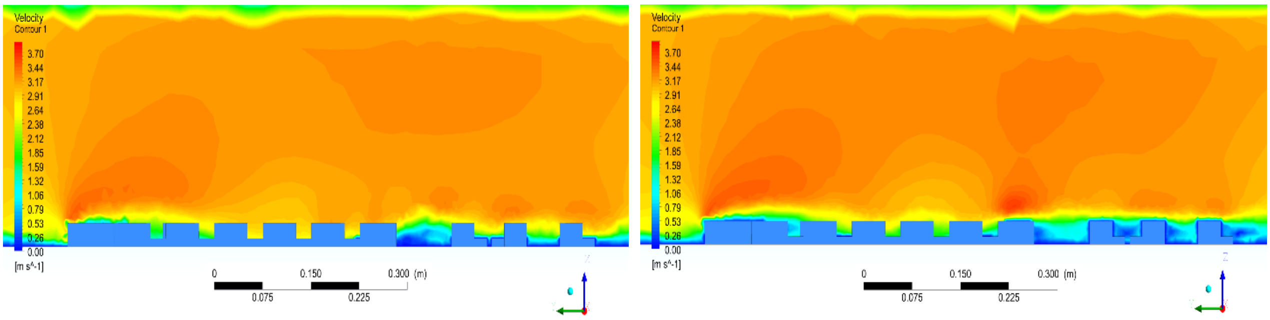
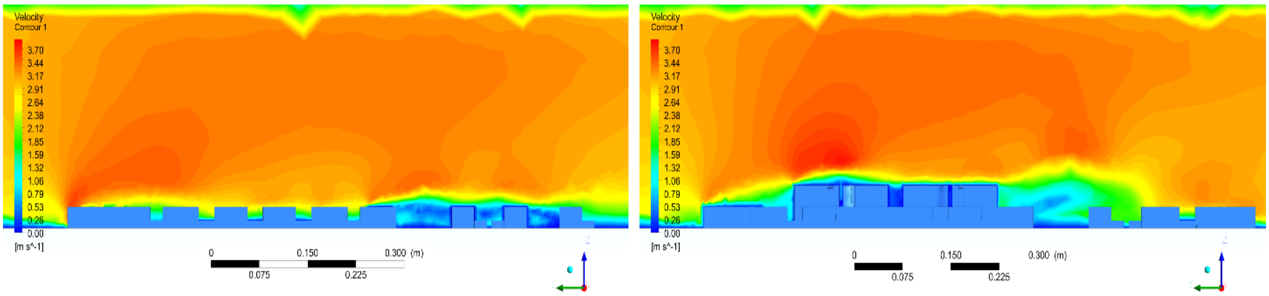


Figure 4.38. Section Planes of Vertical Wind Flow Simulation in Sector 19A, Chandigarh



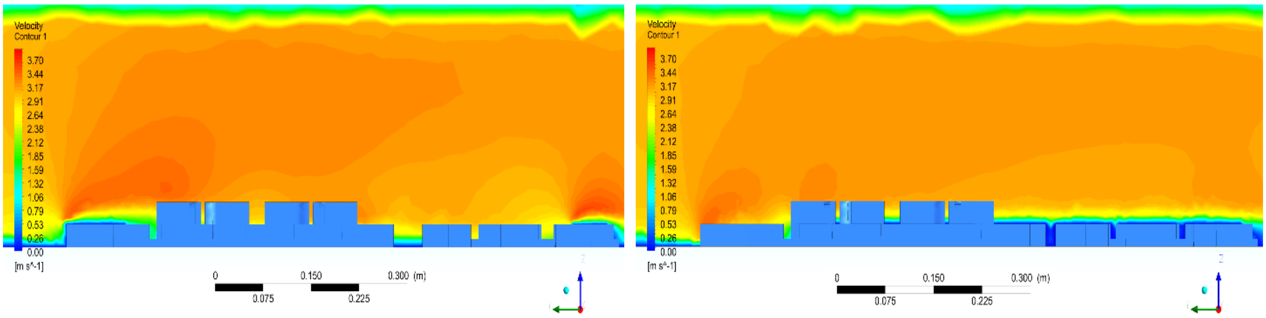
a) Section AA'

b) Section BB'



c) Section CC'

d) Section DD'



e) Section EE'

f) Section FF'

Figure 4.39. Wind Speeds observed along Section Planes in Sector 19A, Chandigarh

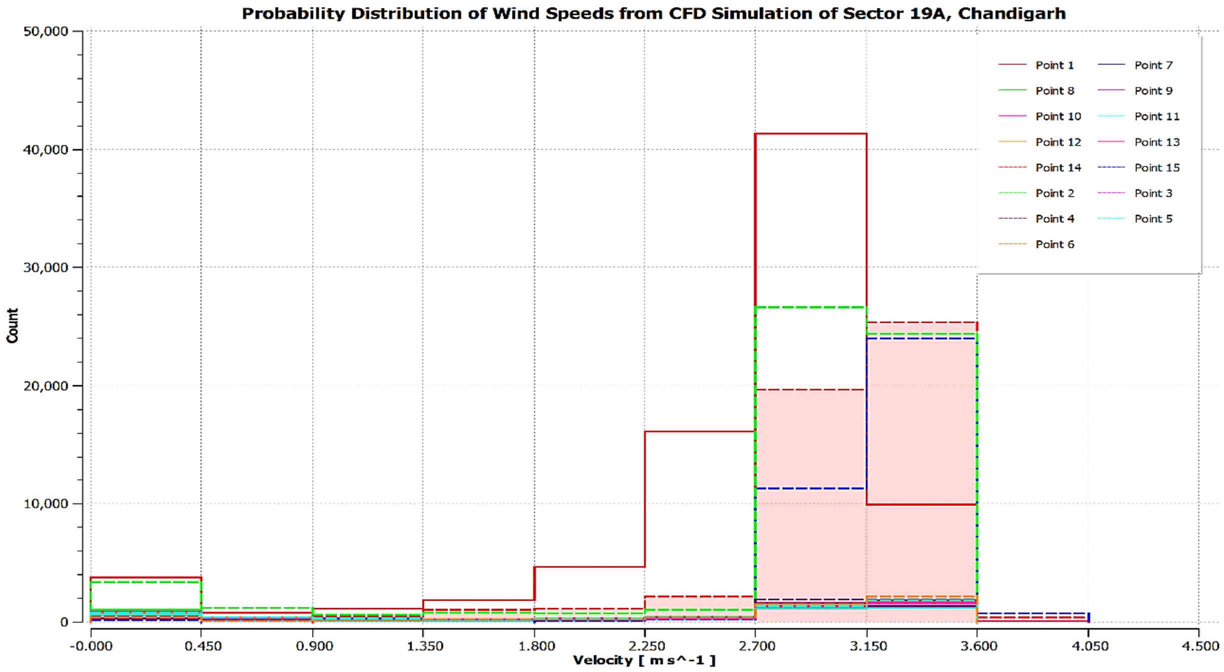


Figure 4.40. Wind Speeds observed in Sector 19A, Chandigarh

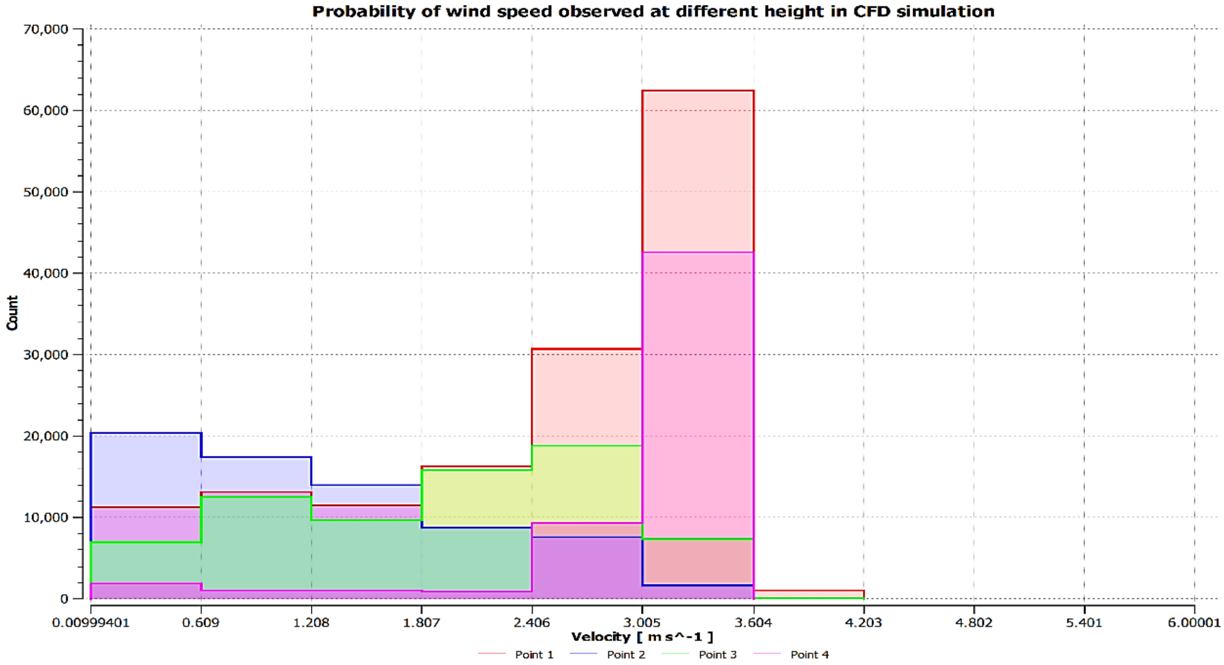


Figure 4.41. Probability of Wind Speeds observed at different Heights in Sector 19A, Chandigarh

As per equation 2.28 and 2.29 (Chapter 2), considering a grid connected 1kW Luminous Whisper 200 micro turbine with a sweep area of 5.73m^2, average wind speed of 2.4–3.6m/sec as indicated in figure 4.41, air density of 1.183kg/m^3, maximum power coefficient of 0.593, gear box efficiency (n_g) of 90% and generator efficiency (n_b) of 80%, the electrical power generated is 20-68 W. The wind power density (WPD) calculated is 8.18–27.60W/m^2 and the annual Wind Energy Density (WED) calculated is 71.66–241.78kWh/m^2.

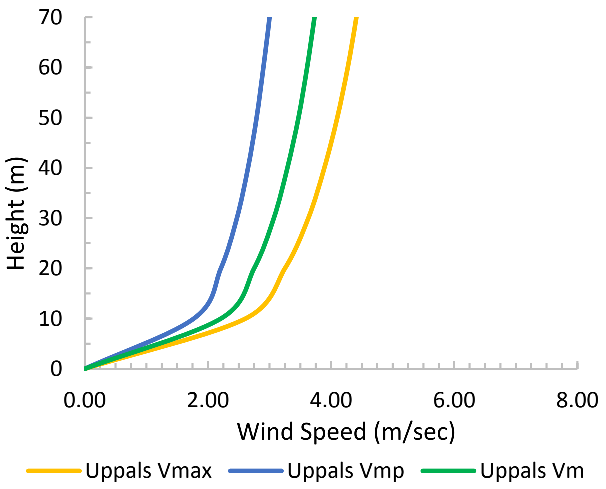
4.13 Wind Profile Comparison of Statistical Data and CFD Simulation Models

Wind Profile study of each scenario is undertaken to assess the performance of wind as a resource within the context of the built environment **(Lu et al., 2014)**. Wind Profiles are constructed for wind data based on Weibull Distribution and CFD simulation models across four typologies – medium rise, high rise, low rise and plotted developments.

The wind profile of the different scenarios and observed wind speeds are used to compute the most probable wind speed (V_{mp}), wind speed carrying the maximum energy (V_{Emax}) and mean wind speed (V_m). The wind speed is used to define the vertical wind shear based on equation 2.30 (Chapter 2) and observe the change in wind speed with height.

Table 4.26: Vertical Wind Profile of Statistical and Simulated Scenarios for Uppals Marble Arch, Manimajra and Sushma Elite Cross, Gazipur Punjab

Height (meter)	Wind Speed (m/sec)					
	Uppals Marble Arch V_{Emax}	Uppals Marble Arch V_{mp}	Uppals Marble Arch V_m	Sushma Elite Cross V_{Emax}	Sushma Elite Cross V_{mp}	Sushma Elite Cross V_m
70	4.41	3.00	3.73	5.29	3.66	4.48
60	4.27	2.90	3.61	5.12	3.55	4.33
50	4.10	2.79	3.47	4.92	3.41	4.16
40	3.89	2.65	3.29	4.67	3.23	3.95
30	3.63	2.47	3.07	4.62	3.01	3.68
20	3.25	2.21	2.75	3.90	2.70	3.30
10	2.61	1.77	2.21	3.13	2.17	2.65



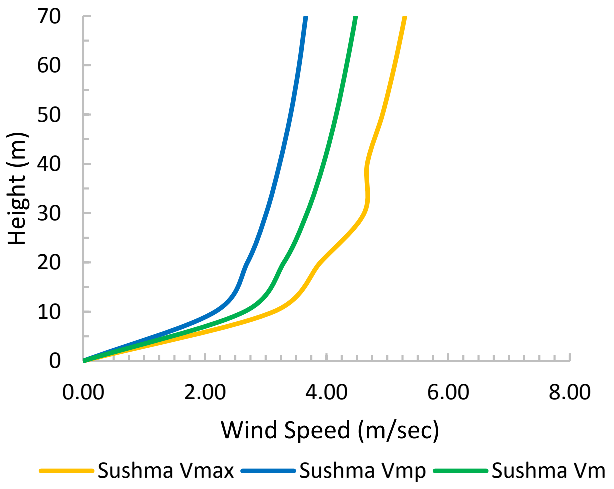
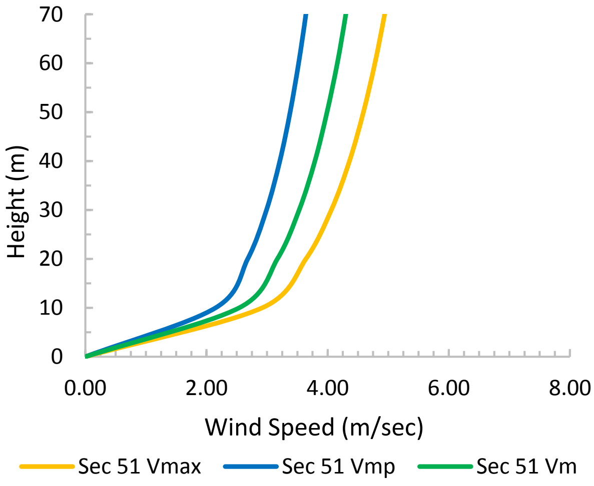
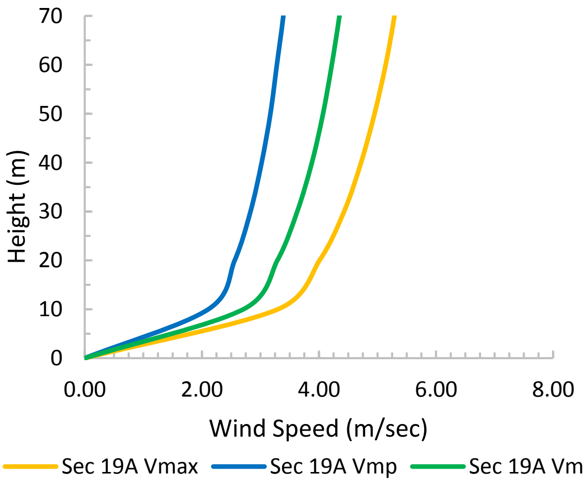


Table 4.27: Vertical Wind Profile of Statistical and Simulated Scenarios for Sector 51 and Sector 19A, Chandigarh

Height (meter)	Wind Speed (m/sec)					
	Sector 51 Chandigarh V_{Emax}	Sector 51 Chandigarh V_{mp}	Sector 51 Chandigarh V_m	Sector 19A Chandigarh V_{Emax}	Sector 19A Chandigarh V_{mp}	Sector 19A Chandigarh V_m
70	4.94	3.64	4.30	5.29	3.39	4.35
60	4.78	3.52	4.16	5.14	3.28	4.22
50	4.59	3.38	3.99	4.95	3.17	4.07
40	4.36	3.21	3.79	4.72	3.02	3.88
30	4.06	2.99	3.53	4.43	2.83	3.63
20	3.64	2.68	3.17	4.01	2.56	3.29
10	2.92	2.15	2.54	3.30	2.11	2.71





The visual form of the vertical wind profiles from table 4.26 and 4.27 indicate that Sushma Elite Cross due to its high rise built form has a major influence on turbulence as is evident by the shape of the V_{max}. The highest velocity are projected in case of Sector 19A followed by Sushma Elite Cross, Sector 51 and Uppals Marble Arch. This indicates that built form placed perpendicular to wind flow and channelizing of wind currents through narrow passages can lead to higher wind speed and have ideal locations for placement of wind turbines. In case of Sector 19A the high velocity can be attributed to lack of vegetation. However, with buildings of 10.65m maximum height and dense vegetation in major part of sectors of Chandigarh, the actual wind velocity shall be less than the simulated version. In case of the other representative units the built forms are higher than 15m so the influence of vegetation is less.

In figure 4.42 the vertical profile of the simulated representative units is compared with the statistical data from table 4.25. The mean wind speed at a height of 10m as per observed hourly wind speed data from 2010-15 data is 2.26m/sec.

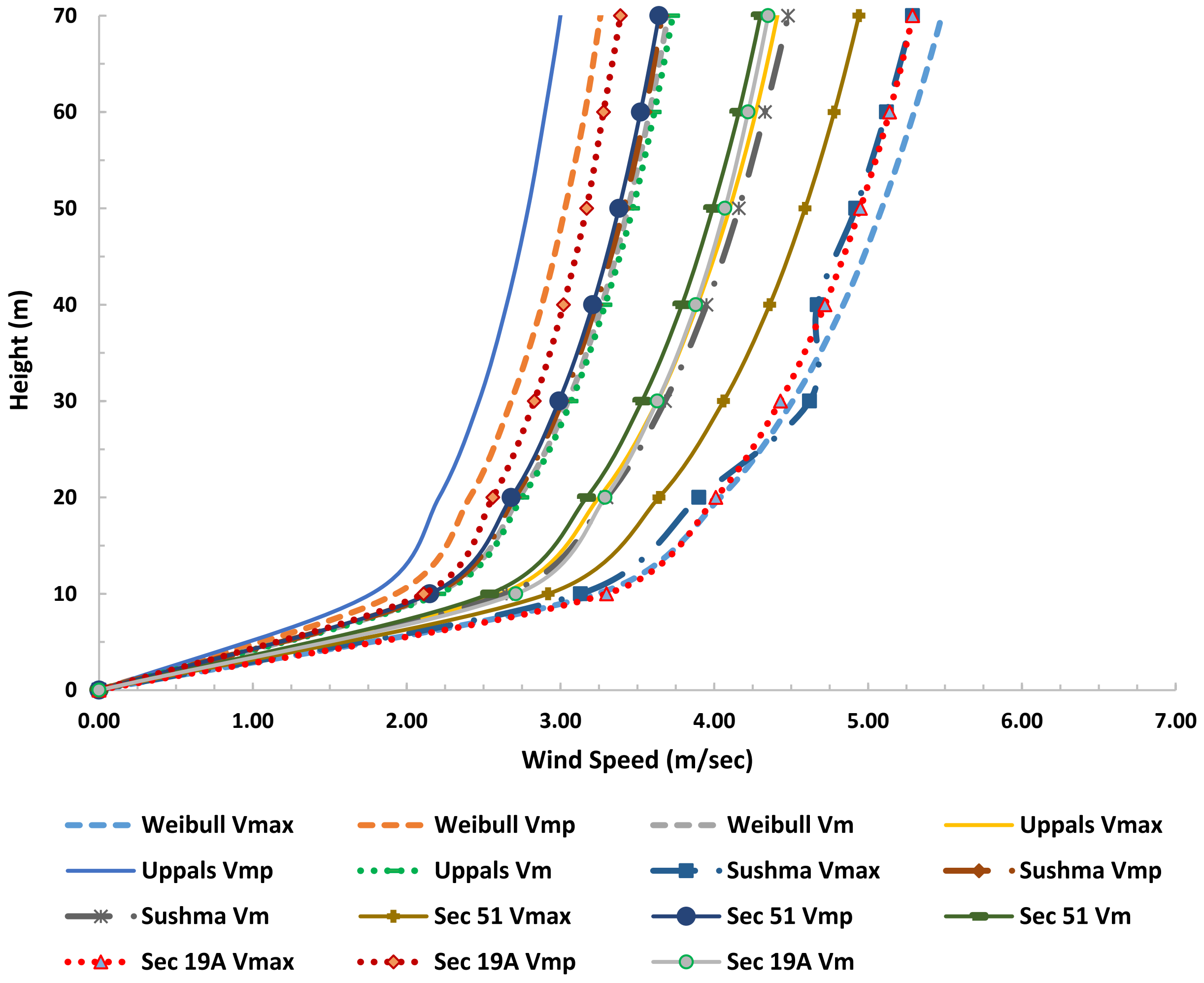


Figure 4.42. Vertical Profile of Statistical Data and Simulated Representative Units Data

With respect to the statistical and CFD based simulated wind speed calculation, the wind speed at a height of 10m in different scenario ranges between 1.75–3.30m/sec. This indicates an increase of 46% in wind speed on the higher side and reduction of 22.6% on the lower side. Thus, with 68% probability of wind speed higher than the mean value exploiting wind resource in the housing typologies can be a very high energy generating resource.

4.14 Validation of Wind Speeds

To confirm the validity of the wind speed calculated through statistical and CFD based simulation, on site measurement of wind speed is undertaken at different heights. A digital thermo anemometer (Model: Beetech AM4208) is tied to a vertical pole and measurements are taken at varying heights in each representative residential unit (RRU).

Figure 4.43. Beetech AM4208 Anemometer used to Validate Simulated Wind Speeds

The wind speed data is collected six times over the year spread over different seasons for 10 minutes at different heights in each of the typology and the mean wind speed values observed are listed down in table 4.28.

Table 4.28: Validation of Wind Speeds and Variation at different Heights in RRUs

Height (meter)	Wind Speed (m/sec)							
	Uppals Marble Arch	Uppals Marble Arch	Sushma Elite Cross	Sushma Elite Cross	Sector 51 Chandigarh	Sector 51 Chandigarh	Sector 19A Chandigarh	Sector 19A Chandigarh
	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed
10	2.25	1.86 (-17%)	2.65	2.27 (-14%)	2.54	2.42 (-4%)	2.71	1.84 (-32%)
15	2.54	2.29 (-10%)	2.92	2.78 (-5%)	2.93	2.98 (+1%)	3.06	2.46 (-20%)
20	2.75	2.64 (-4%)	3.30	3.12 (-6%)	-	-	-	-
25	-	-	3.49	3.53 (+1%)	-	-	-	-
30	-	-	3.68	3.84 (+4%)	-	-	-	-
35	-	-	3.84	4.06 (+6%)	-	-	-	-
40	-	-	3.95	4.19 (+6%)	-	-	-	-
45	-	-	4.18	4.35 (+4%)	-	-	-	-

The lack of vegetation and its roughness as part of CFD simulation is clearly evident in case of Sector 19A Chandigarh as measured values are significantly less than the simulated values. The observed value of wind speed in plotted development questions the viability of wind as an energy resource. In case of Uppals Marble Arch the presence of surrounding context results in low wind speeds near the ground in comparison to the simulated version but with increasing height the difference reduces thereby reoffering the scope of wind energy resource. In case of Sector 51 Chandigarh and Sushma Elite Cross, the actual values are less than simulated version at low levels due to roughness attributed by presence of vegetation and other obstacles, but with increasing height the wind speeds are enhanced and nearly equal to the simulated values especially in case of Sushma Elite Cross.

4.15 Conclusion

The chapter assesses the feasibility of wind as a potential energy generating resource within complex urban built form setting of housing. Assessment is undertaken using both statistical and computational tools. The Weibull statistical distribution determines the energy output based on observed wind data from 2010-15. The three dimensional assessment of wind to understand its behaviour and turbulence within the context of housing is done using the academic version of Ansys Fluent.

Four representative residential units based on their built form and typological variation are used as part of computational assessment. The approach is conservative as the north western dominant winds have been used as part of assessment. Wind flow dynamics are analysed at the scale of each typology and various locations identified for placement of wind turbines. In addition, numerical assessments are undertaken to calculate the maximum wind energy that can be generated.

Using the reference wind speed of 2.26m/sec, it is observed that there is an increase of 46% in wind speed observed from 68% of simulated wind speed data. Based on commercially available micro wind turbine of 1kW the output energy generated is equal to 118-340kWh. It is also observed that the variation in energy output is due to the variation in design parameters of the representative units that enable the prevailing winds to be accelerated and enhance the potential.

Plotted housing units are unable to generate wind power due to high surface roughness resulting out of dense vegetation. Hence, wind may not be a feasible energy resource in this context. In case of low rise development with significant built up around, the ideal location for the wind turbines can be 8 to 10 meter above the roof or at a height of 25 meter from ground level. In case of medium rise development with medium roughness conditions or surrounding built up, wind turbine can be installed 3 to 5 meter above the roof and in case of high rise development with low roughness conditions around, wind turbine can be installed at the terrace level. Thus, it is possible to achieve even higher output and ensure efficiency by considering existing building controls and reframing them to promote wind energy within the context of housing.

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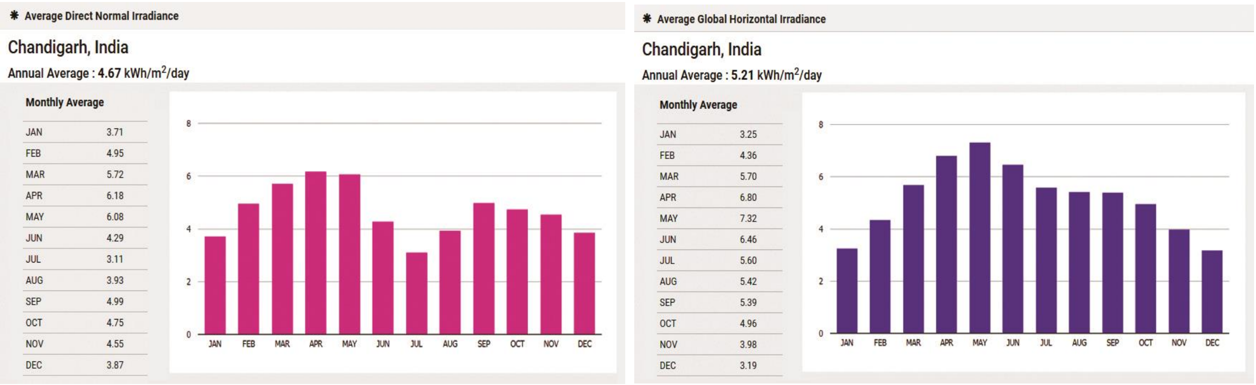
Chapter 5
Solar Resource Assessment and Potential

5.1 Assessing the Potential of Solar Energy

Solar energy is utilized mainly in two ways: actively and passively. Active solar energy systems are solar collectors, photovoltaic panels, power towers, solar ponds, hydrogen generating solar centrals and ocean thermal conversion centrals. Last two of the above mentioned systems are theoretical methods of energy generation but others are known for many years and applied where available. The study conceptualizes and assesses the solar electrical and thermal potential of the rooftop of households. Solar access is the precondition for both active and passive solar design strategies. Passive utilization of solar energy requires improving the energy performance of buildings in three areas; heating, lighting and cooling. The concept of equal sharing of solar resource requires three-dimensional approach to zoning. Each piece of property could be assured equal access under the Solar Envelope concept. The result would be an envelope of developable volume that would derive its size and shape from the size, shape, slope, and orientation of the property.

5.2 Solar Irradiation Data of Chandigarh Urban Complex (CUC)

Chandigarh is located in the north western part of India at the foothills of the Shivalik range and receives good amount of solar radiation over the year. It can be observed from figure 5.1 that the annual Direct Normal Irradiance (DNI) over the city is 1705kWh/m^2, while the annual Global Horizontal Irradiance (GHI) is 1900kWh/m^2 **(NREL, 2016)**.



✹ Average Direct Normal Irradiance

Chandigarh, India

Annual Average : **4.67** kWh/m^2/day

Monthly Average	
JAN	3.71
FEB	4.95
MAR	5.72
APR	6.18
MAY	6.08
JUN	4.29
JUL	3.11
AUG	3.93
SEP	4.99
OCT	4.75
NOV	4.55
DEC	3.87

✹ Average Global Horizontal Irradiance

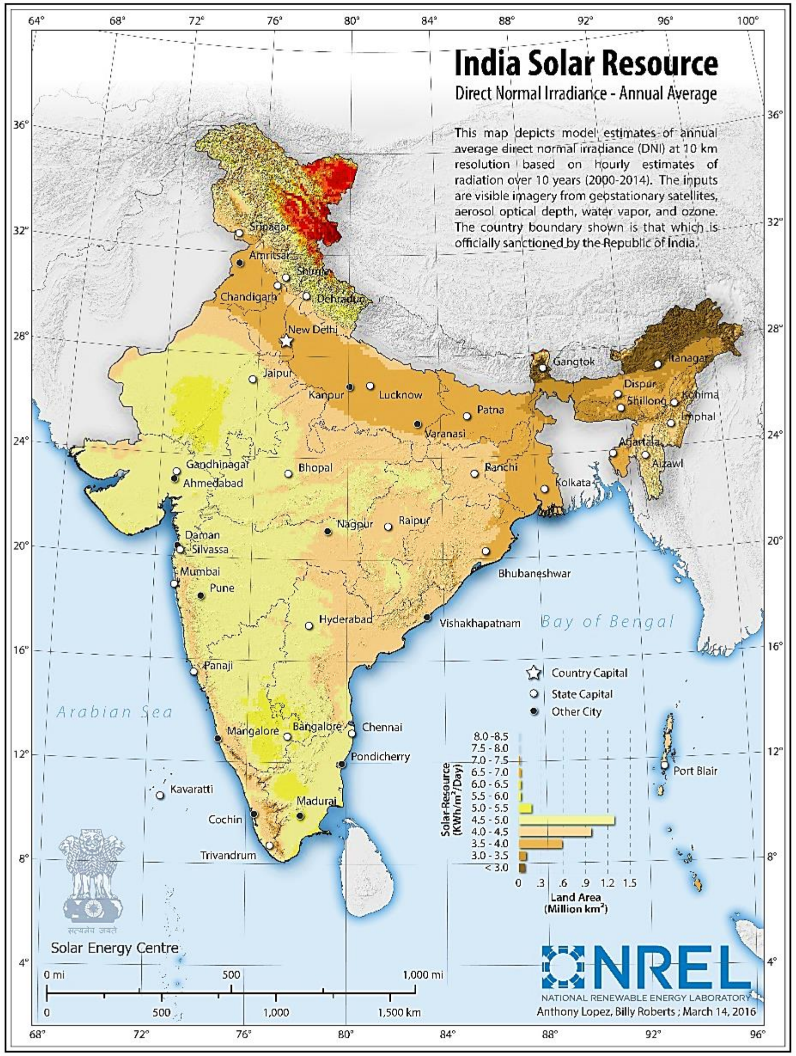
Chandigarh, India

Annual Average : **5.21** kWh/m^2/day

Monthly Average	
JAN	3.25
FEB	4.36
MAR	5.70
APR	6.80
MAY	7.32
JUN	6.46
JUL	5.60
AUG	5.42
SEP	5.39
OCT	4.96
NOV	3.98
DEC	3.19

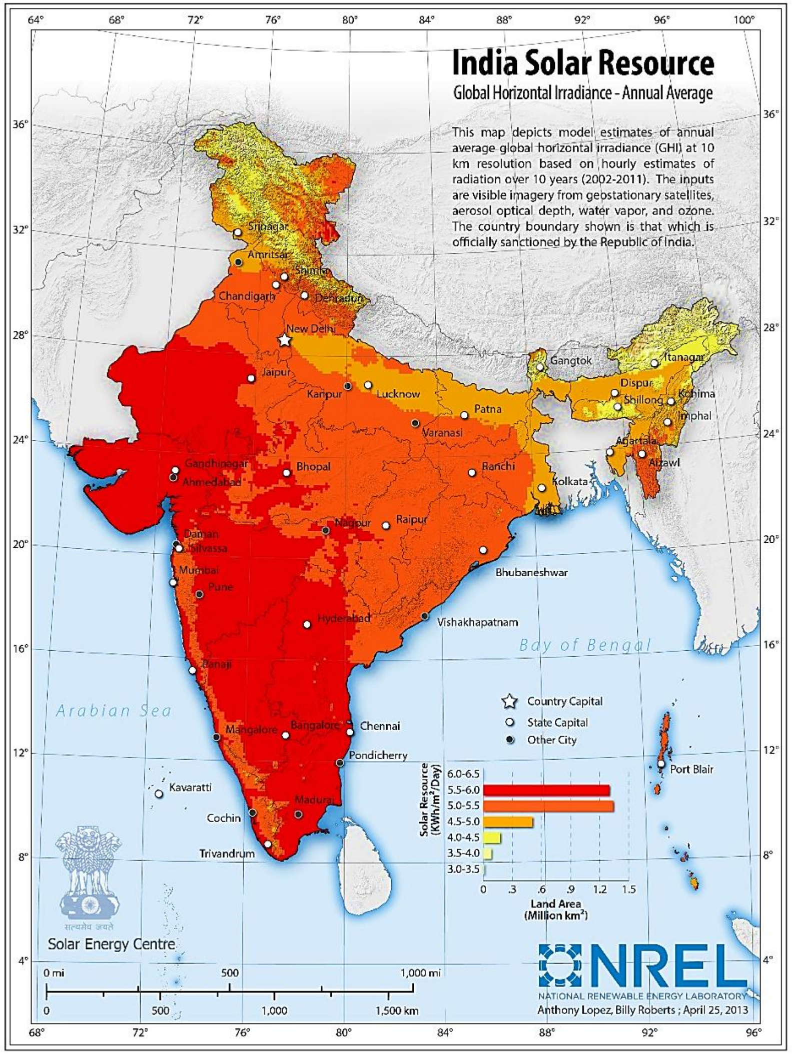
Figure 5.1: Average Direct Normal Irradiance and Global Horizontal Irradiance of Chandigarh
(Source: NREL, 2016)

The Chandigarh Solar City concept is based on the implementation of energy efficiency and conservation measures supported with integration of roof top solar PV and solar water heaters in the residential sector.



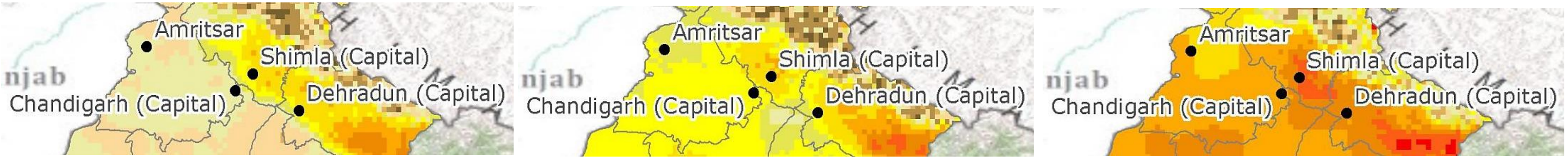
This map depicts model estimates of annual average direct normal irradiance (DNI) at 10 km resolution based on hourly estimates of radiation over 10 years (2000-2014). The inputs are visible imagery from geostationary satellites, aerosol optical depth, water vapor, and ozone. The country boundary shown is that which is officially sanctioned by the Republic of India.

Figure 5.2 : Direct Normal Irradiance (Annual Average) Map of India
(Source: www.mnre.gov.in)

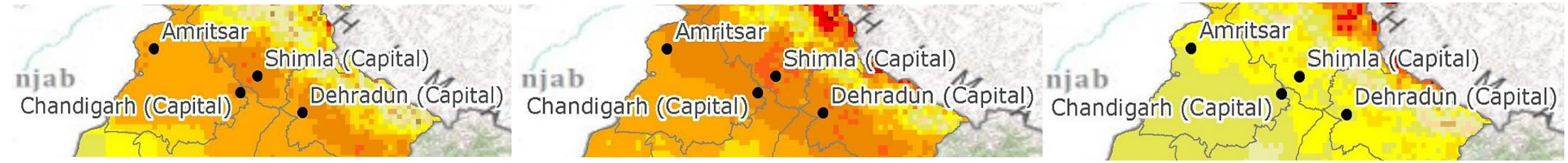


This map depicts model estimates of annual average global horizontal irradiance (GHI) at 10 km resolution based on hourly estimates of radiation over 10 years (2002-2011). The inputs are visible imagery from geostationary satellites, aerosol optical depth, water vapor, and ozone. The country boundary shown is that which is officially sanctioned by the Republic of India.

Figure 5.3 : Global Horizontal Irradiance (Annual Average) Map of India
(Source: www.mnre.gov.in)

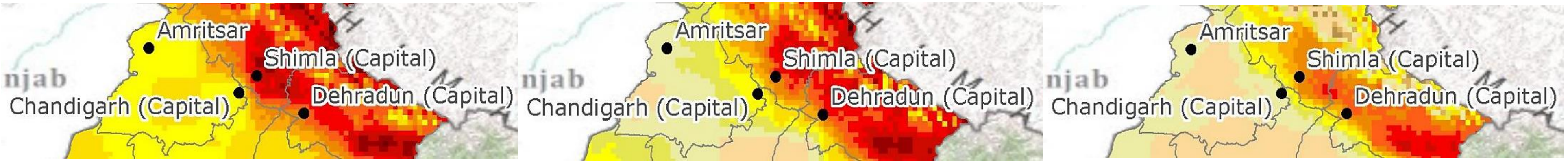


January **February** **March**



April **May** **June**

July **August** **September**



October **November** **December**

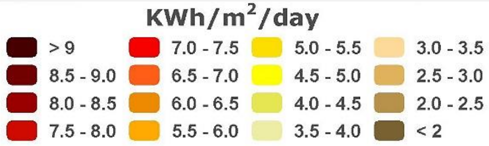


Figure 5.4 : Monthly Direct Normal Irradiance Map of Chandigarh and its Surroundings
(Source: www.mnre.gov.in)

The renewable electricity generation is done through roof top solar PV with the rooftop solar water heaters, and other energy efficiency measures contributing towards electricity/energy saving in the union territory. Figure 5.2 and 5.3 are visual interpretations of the DNI and GHI data of India. Figure 5.4 is the monthly representation of DNI available in CUC and its surrounding region.

5.3 Defining Roof Area for Solar Applications in Housing Typologies of CUC

Estimation of the true potential of solar based infrastructure for an urban household is a complex process, the primary reason being the varying nature of housing typologies, building heights and urban densities which need to be crosschecked at periodic intervals (**White, 1976**). The methodology behind assessing the true potential of rooftop based solar panels for electricity and thermal output in CUC starts with calculating the actual shadow free roof area of households. This is significant as in most cases assessment is based on roof area which is determined from the building floor area. The actual area available on the roof varies based on different aspects – primary being physical construction like mumty of staircase, temporary or permanent sheds, storage areas, etc. Second being physical infrastructure like water tanks, satellite dish, plumbing lines etc. In such scenarios the actual roof area available is reduced.

For the purpose of research, area lost due to physical construction is only considered as for the second case a thorough survey of households at local level needs to be undertaken for generalisation. Due to lack of access to the terrace of many households it is not possible to assess other infrastructure and their extent on the roof. Also, roofs are the least accessed spaces as a result illegal extension or construction go unnoticed, this ascertains the need to integrate remote sensing data for a non-intrusive process of assessing the actual roof area.

There are methodologies and theories based on remote sensing and GIS that can be developed into future avenues of research aiding in isolation of roofs acting as constraint in the promotion of Solar City due to overshadowing by surrounding buildings **(Ratti et al., 2004)**. As part of the study the actual shadow free roof area available over a household all over the year needs to be assessed for solar based electricity and thermal systems. The study also tries to assess the potential of rooftop solar energy in meeting the technical electrical demand of varied housing typologies within the climatic context of CUC. For the purpose of the study only flat roofs have been considered as a major portion of households in CUC have flat roofs due to strict building controls and weather considerations.

To estimate the solar potential, a rule of thumb ratio relationship is developed relating the total built-up area to the roof area. A multiplication factor in the relationship differentiates the solar output across various housing typologies and their performance **(Kaplanis, 2006)**. Table 5.1 is an indication of the total roof area available in each of the RRU's considering no modifications done to initial plans. Out of the total roof area available only 60% of rooftop area has been considered viable as per previous studies by TERI during preparation of Solar City Model for Chandigarh and GRIHA during framing of Green Building Guidelines for high rise community housing. The study tries to define Utilization Factor (UF) a percentage of roof space actually available in comparison to overall roof area based on orientation of the plot and definitive rooftop physical constructions across different typologies.

Table 5.1 : Estimation of Rooftop Area and Total Built-up Area

Parameter	Uppals Marble Arch	Sushma Elite Cross		Sector 51, Chandigarh	Sector 19A, Chandigarh	
Number of Repetitive Blocks / Units	9	X type	03	14	1 Kanal	102
		Box type	04		2 Kanal	26
Number of Floors	5	X / Box	13 / 12	4	3	
Built-up Area of each Floor (sqm)	970	X type	730	260	1 Kanal	250
		Box type	600		2 Kanal	420
Total Built-up Area (sqm)	43650	X type	28470	14560	1 Kanal	76500
		Box type	28800		2 Kanal	32760
Estimated Roof Area (sqm)	970	X type	730	260	1 Kanal	250
		Box type	600		2 Kanal	420
Roof Area as percentage of Total Built-up Area	20%	X type	7.69%	25%	1 Kanal	33.33%
		Box type	8.33%		2 Kanal	33.33%

5.3.1 Theoretical Assessment of Solar Energy Potential Based on Test Model Simulation

The study tries to define the Utilization Factor (UF) as a measure of actual roof area available for solar applications. A study model of 1Kanal (18m x 27.75m) plot with household unit covering 40% of site and FAR of 1.5 has been used with the shorter side of the plot aligned at +38° and -38° to south direction so as to match the layout of plots within the sectors of CUC. The effective roof area available is 250sqm and the only physical construction considered is the staircase and its enclosure as per building control norms. The staircase is shifted to all four corners and in the middle of the service zone (defined by building controls -3.0m from front, rear and side walls and

1.2m from common party walls) leading to 36 options. The black line on the roof in figure 5.5 indicates the service area of the roof where staircase and solar PV infrastructure can be installed.

With the position of the sun changing due to seasonal factors and clouds in the sky also impacting solar behaviour, the shading study of the different scenarios is undertaken using the parametric lighting tool – DIVA **(DIVA4RHINO, 2015)** an extension of 3D modelling software Rhino3D. Whole year climatic data is used to cast the shadows and effective locations are identified with maximum exposure over the year.

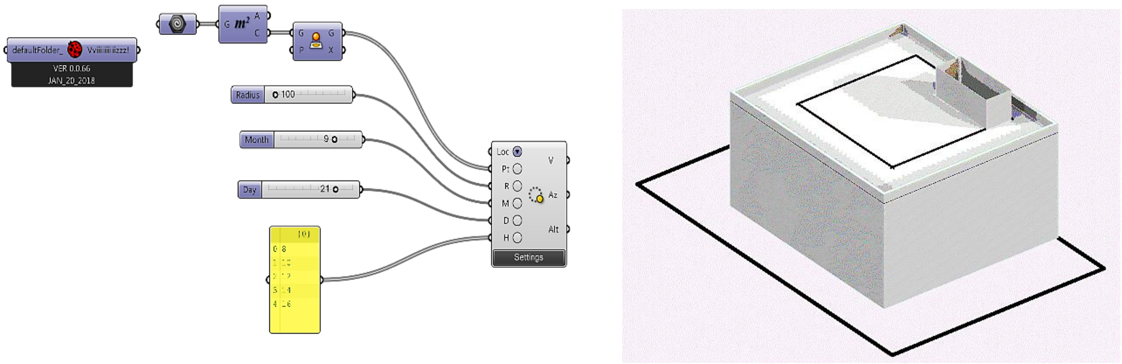


Figure 5.5 : **Parametric Algorithm for Study of Solar Shading and Measurement of Shadow Free Roof Area**

5.3.2 Actual Roof Area Available for Solar Energy

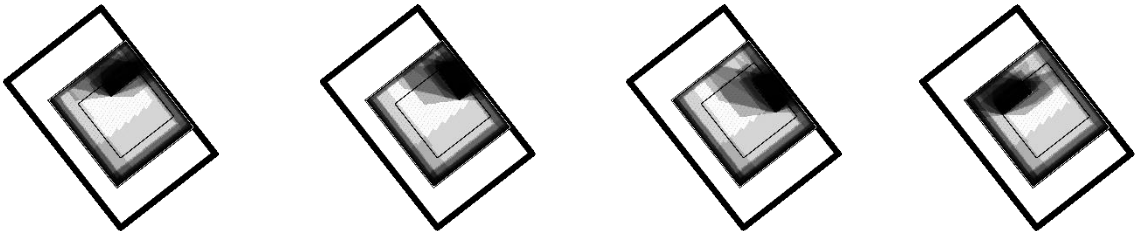
The assessment of 1 Kanal plot with three orientations is undertaken with shadow analysis done for 4 days of the year – 21 June and 21 December (Solstice) and 21 March and 21 September (Equinox). The shadows from 8.00am – 4.00pm are observed and super imposed on each other to find the roof area without any shading within the service area boundary defined in building controls. The parapet for the study is considered to be 0.9m whereas the building control defines it to be 1.2m.

From the visual assessment of figure 5.6, it can be concluded that plots with shorter face oriented towards south have a shadow free area ranging between 28-48% whereas plots facing south-west with an inclination of +38° have the least area in the range of 14-18%. The other layout of plots with their shorter face towards south-east at an inclination of -38° have a shadow free area of 16-26% of the service area. The other variations as part of the assessment are listed in figure 5.7.

Plot with shorter face towards South (0°)

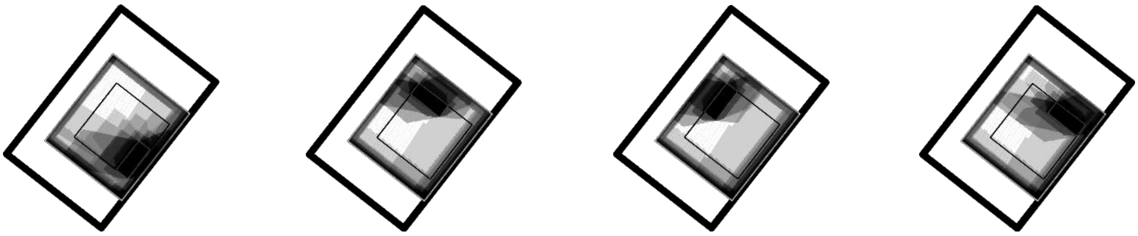
48% **45%** **32%** **28%**

Plot with shorter face towards South East (-38°)



26% **21%** **18%** **16%**

Plot with shorter face towards South West (+38°)



18% **17%** **15%** **14%**

Figure 5.6: **Percentage Roof Area available for Installation of Solar Infrastructure**
(White area within the black box on roof)

In the case of 1 Kanal plot the total roof area is equal to 250sqm with the service area of 114sqm forming 45% of total roof area. From figure 5.7 it can also be inferred that the shadow from the 0.9m high parapet wall reduces the shadow free space if the panels are installed at a low height to the floor. The parapet height defined as per the building controls is 1.2m which would result in further reduction of shadow free area. Interventions need to be devised and modifications in building controls undertaken to increase the effective area for solar panels by 15%-20%.

On March 21 and June 21 the sunlight hours from 10am to 2pm have the shortest shadow length and the shaded area is minimum and consistent. In case of September 21 the hours of sunlight from 11am to 1pm are consistent in shadow area with shortest shadow length. On December 21 there is no significant range observed with consistent shadow area but from 12pm to 1pm the shadow length is the shortest. A visual description of the same is shown in figure 5.8 for south-east facing plot on March 21.

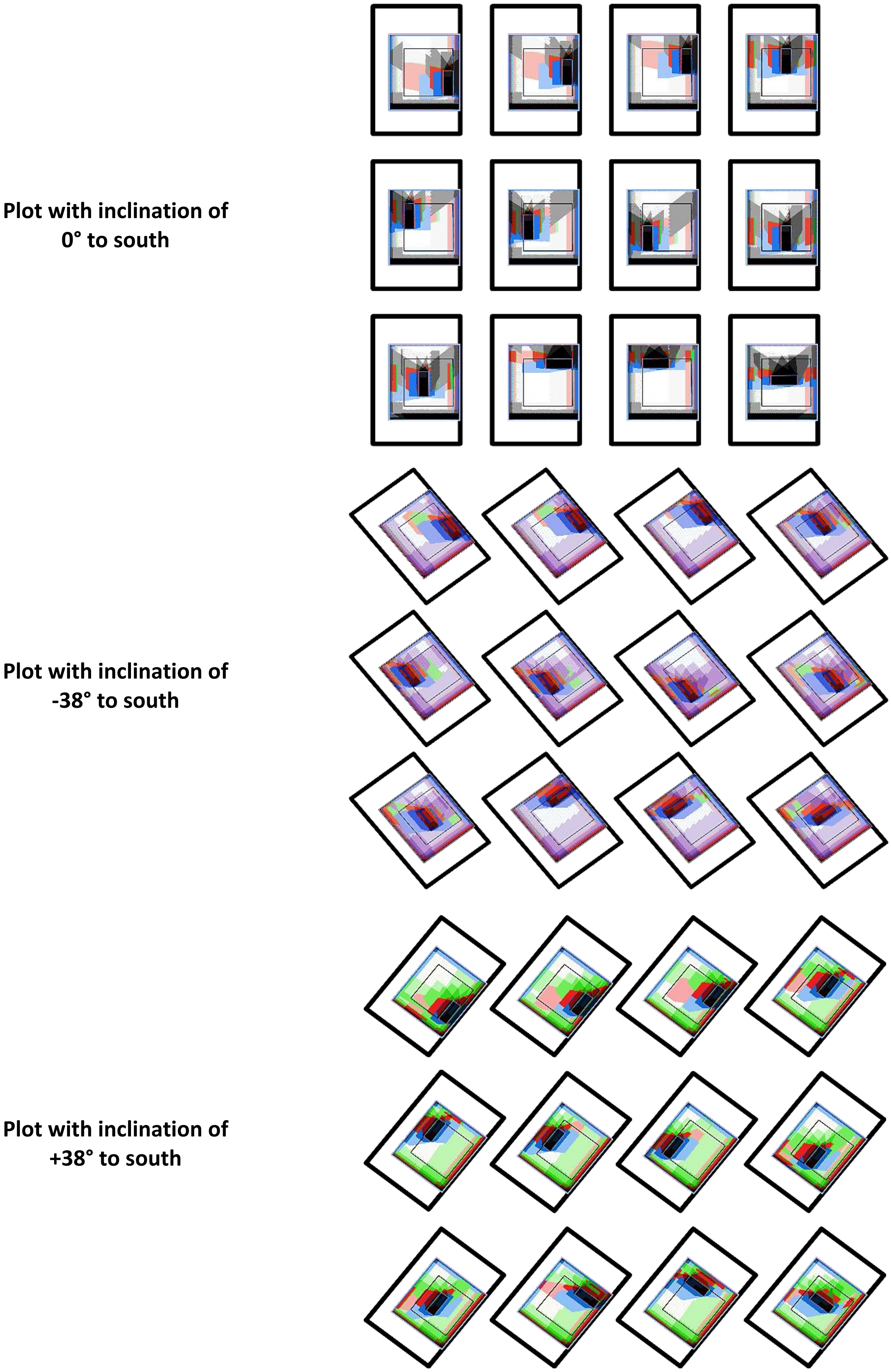


Figure 5.7: Shadow Study of 1 Kanal plot with respect to Orientation to South

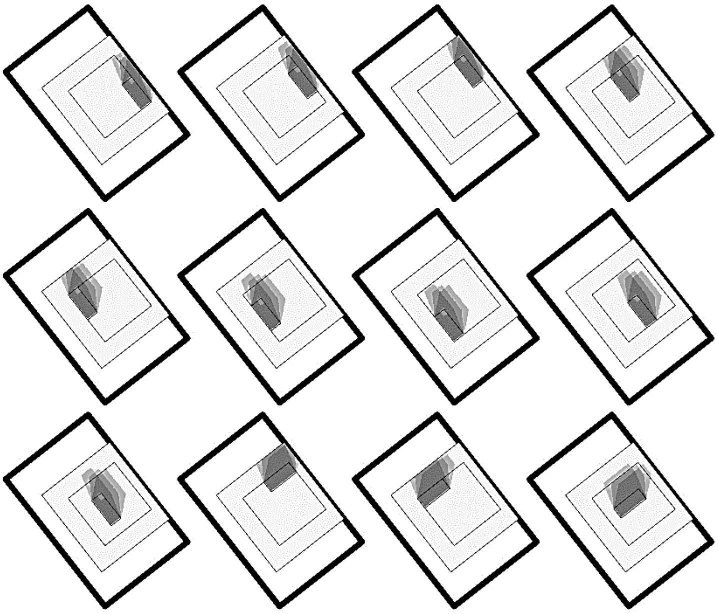


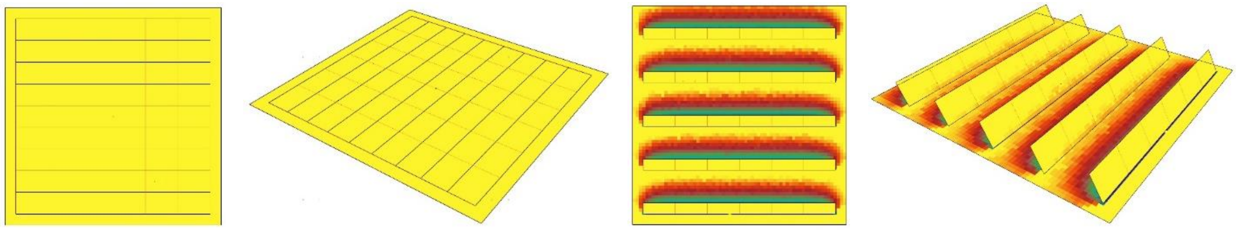
Figure 5.8: Solar Shading of 1 Kanal roof on March 21 between 10am to 2pm

By considering the hourly timings with maximum shade free area it is possible to get a more accurate estimate of solar output as the hours in discussion are also the hours with peak solar irradiance. It could be concluded that in a single day the maximum solar output would be within these hours except in the case of March 21. With increasing temperature the Solar PV output reduces and March experiencing high temperature during middle of the day, output from the Solar PV panels shall be influenced accordingly. The compensation due to temperature needs to be subtracted from the theoretical estimates.

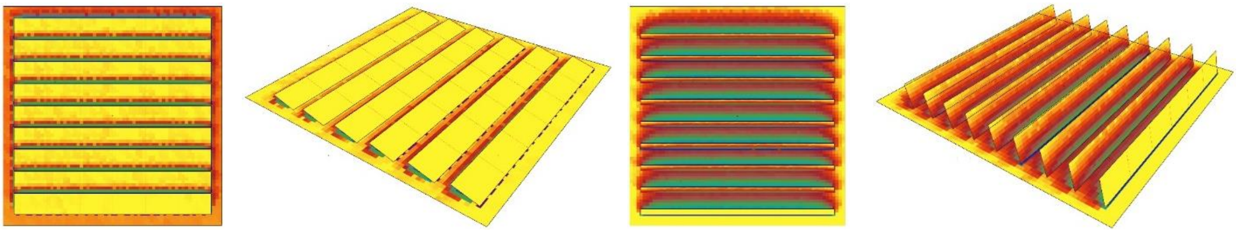
With the plot size increasing the self-shading distance shall increase as a result bigger plots will have more shade free roof area. In comparison to this in case of smaller plots primarily comprising of row housing, if solar infrastructure has to be exploited all the roofs of connected units should be treated as one. With the advantage of having no staircase provision needed in such plotted units except a cat ladder with a hatch door in the roof it becomes easy to integrate the solar infrastructure in comparison to the bigger plotted units. The smaller plots ranging in between 4 Marla to 15 Marla also hold more potential because of their larger numbers that can be major contributors towards solar electricity and solar thermal generation.

5.4 Solar PV Panel Distance and Angle of Inclination

The study is aimed to enhance the realisation of power from each solar panel by ensuring that a tilted PV panel does not lead to lower power output from another panel behind it. This will also ensure generating high quality electricity with minimum number of solar PV panels. For the study a 10m by 10m roof model without any physical structures is integrated with solar panel array of 1.5m by 1m and an allowance of 0.5m provided all around the perimeter for access and maintenance. The effect of inclination and distance on other panels is expressed through examples in figure 5.9.



Distance between Panels = 0m and 0° Inclination **Distance between Panels = 1.0m and 60° Inclination**



Distance between Panels = 0.5m and 15° Inclination **Distance between Panels = 0m and 75° Inclination**

Figure 5.9 : Shading of Solar PV panels with change in Distance between Panels and Inclination

To ensure optimum performance from all panels in an array at any given point of sunlight hours through mitigation of inclination and spacing between the panels requires a dynamic simulation tool. To assess the performance of each panel and row individually a parametric lighting based simulation model shown in figure 5.10 is designed in DIVA - a parametric daylight assessment tool of Rhino 3D. The two variable parameters of the model are the horizontal spacing between the panels expressed in meters and the inclination of the panel to the roof surface expressed in degrees.

Both Solar PV and Solar Thermal systems are independent systems with energy transfer in different forms. The inclination and distance between the panels have similar consideration and both are effectively competing for roof area. For the purpose of study Solar PV panels have been considered for parametric assessment.

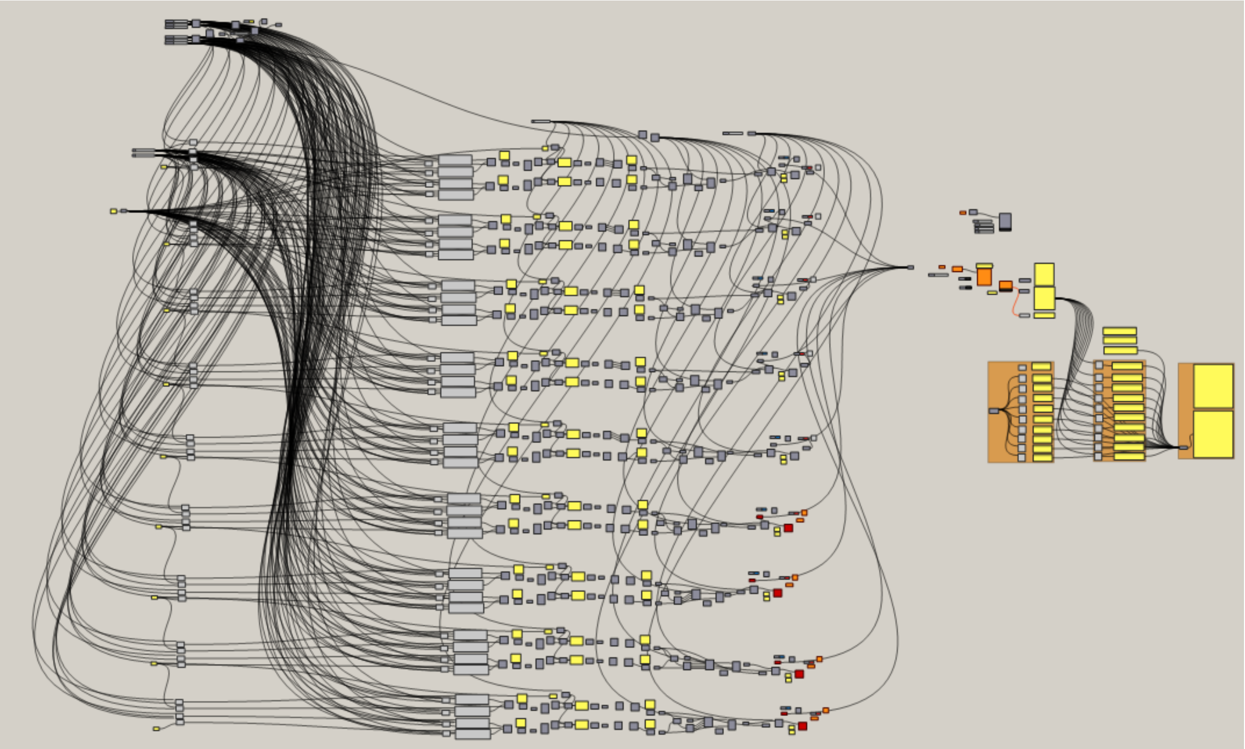


Figure 5.10: Algorithm to Assess Energy Output from Spacing and Inclination of Solar PV panels

On basis of detailed analysis undertaken (**Annexure – II, III and IV**) table 5.2 lists down the expected average peak energy output per month (kWh/month) from each Solar PV. The test conditions include solar radiation (kWh/m^2/day) and temperature (°C) data of Chandigarh, efficiency of solar panels assumed at 20% (higher side), inverter efficiency for conversion from DC to AC power assumed to be 95%.

The south facing plot with an inclination of 30° tend to have the highest solar energy output that increases with an increase in spacing of panels. In case of south east facing plots the trend is same with panels inclined at 30° and 1.5m spacing having the highest energy output. For the south west facing plots the maximum energy output is in case of 15° inclination with 1.5m spacing.

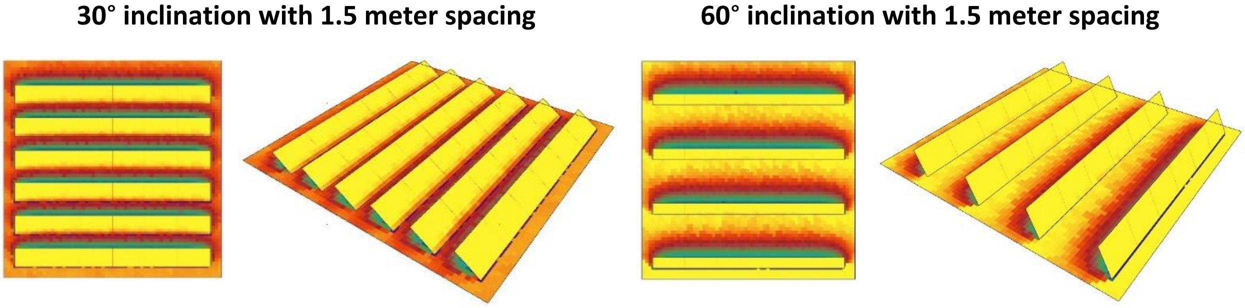


Figure 5.11: Maximum and Minimum Solar Output based on shading behaviour of Solar Panels

Table 5.2: Average Solar Power Output (kWh/month) from Solar Panels on Rooftop based on Orientation and Inclination

Plot Type	Distance Between Panels	Inclination of PV Panels to Roof (degrees)						
		0°	15°	30°	45°	60°	75°	90°
South Facing	0 m	**1808.6**	1773.3	1699.0	1568.9	1451.5	1270.5	1045.6
	0.5 m	1807.9	1957.4	**1966.3**	1874.5	1874.5	1487.8	1216.8
	1 m	1807.2	1970.7	**2017.8**	1958.4	1802.9	1301.5	1301.5
	1.5 m	1808.0	1976.2	**2034.2**	1988.9	1843.6	1618.0	1356.4
South East Facing	0 m	**1810.7**	1728.9	1616.5	1494.1	1342.6	1171.7	974.1
	0.5 m	1807.8	**1905.6**	1866.3	1750.6	1574.4	1369.0	1120.4
	1 m	1805.4	1925.7	**1936.8**	1929.7	1689.3	1476.0	1392.4
	1.5 m	1806.7	1929.6	**1945.0**	1876.1	1721.4	1512.1	1302.0
South West Facing	0 m	1809.0	1699.7	1560.1	**1837.8**	1250.4	1074.0	1074.0
	0.5 m	1811.3	**1872.3**	1792.3	1655.6	1473.1	1275.2	1066.2
	1 m	1808.8	1873.2	**1885.8**	1746.7	1575.9	1372.9	1189.3
	1.5 m	1808.3	**1893.9**	1880.2	1787.2	1628.2	1426.6	1255.2

Table 5.3: Average Solar Power Output (kWh/month) from Solar Panels on Vertical Façade based on Orientation and Inclination

Plot Type	Distance Between Panels	Inclination of PV Panels to Roof (degrees)						
		0°	15°	30°	45°	60°	75°	90°
South Facing	0 m	1336.43	1434.62	1487.09	**1503.92**	1481.25	1404.51	1258.83
	0.25 m	1339.11	1583.67	1692.09	**1736.22**	1715.69	1713.38	1453.92
	0.5 m	1335.60	1608.48	1750.30	**1803.64**	1776.90	1675.84	1499.68
	0.65 m	1337.29	1616.61	1768.86	**1830.56**	1801.47	1699.74	1520.77
	1 m	1337.79	1625.72	1795.07	**1867.85**	1848.10	1750.68	1564.55

In the case of 30° inclination and 1.5m spacing 36 solar panels each with an area of $1.5m^2$ can be installed on the roof and generate energy equivalent to 2034kWh/month which translates to 67.8kWh/day and each panel contributing towards 1.88kWh/day. The panels cover an area of 46.8sqm equivalent to 46.8% of total roof area. The setup can generate annual energy output of 24,408kWh/year. The energy to per unit area of roof utilized quantification results in $522kWh/m^2/year$. The effective annual energy output to the area of roof results in $244kWh/m^2/year$.

In the case of CUC with respect to sector layout, south-east and south-west are significant orientations. The highest output amongst both the orientations is in case of south-east with 30° inclination and spacing of 1.5m between the panels. The monthly energy output is 1945kWh/month which indicates a daily output of 64.8kWh/day from 36 panels. Per day contribution of each panel is 1.80kwh/day. The solar panel setup can generate annual energy of $23,304kWh/m^2/year$ with the panels covering an area equivalent to 46.8% of total roof area. The energy generated to per unit area of roof utilized results in $498kWh/m^2/year$. The annual energy generated to the area of roof is equal to $233kWh/m^2/year$.

The layout with highest solar panel concentration but producing lowest energy output faces south-west at 15° inclination and 0.5m spacing. Scenarios with even less energy output have not been considered due to lack of both the inclination (0°) and distance factor (0m). A total of 54 PV panels are considered covering an area of 61.6% of total roof area in the south-west scenario. The total monthly energy generated equates to 1872.3kWh/month or 62.41kWh/day. Each of the 54 panel contributes about 1.16kWh/day. The setup can generate power equivalent to 22,860kWh/year. The area covered by the panels is equal to 67.6% of total roof area leading to the energy generated per unit area of roof area utilized equal to $338kWh/m^2/year$. The annual energy output to total roof area results in $229kWh/m^2/year$. The mean of both the south–east and south-west orientations annual energy to the roof area is equal to $231kWh/m^2/year$.

Table 5.3 attempts to check the viability of vertical façade based solar power generation. The visual setup and parametric algorithm for the test are displayed in figure 5.12. In terms of output, 45° inclination across all spacing between solar panels is the highest energy generating option as highlighted in **Annexure - V**. The role of Building Integrated Photo Voltaic (BIPV) is yet to be explored within Indian context. The attempt is not to just integrate solar panels into various built form components but ensuring that the overall architectural aesthetics are not compromised. It also needs to be ensured that there is maximum solar exposure on the solar panels thereby enhancing renewable energy potential of households. Avenues of installing solar PV and thermal systems especially as vertical panels need to be explored within the domain of the housing sector as they can act as sun breakers thereby reducing thermal gain by the built mass as a result reducing the cooling demand of spaces and reducing overall energy consumption.

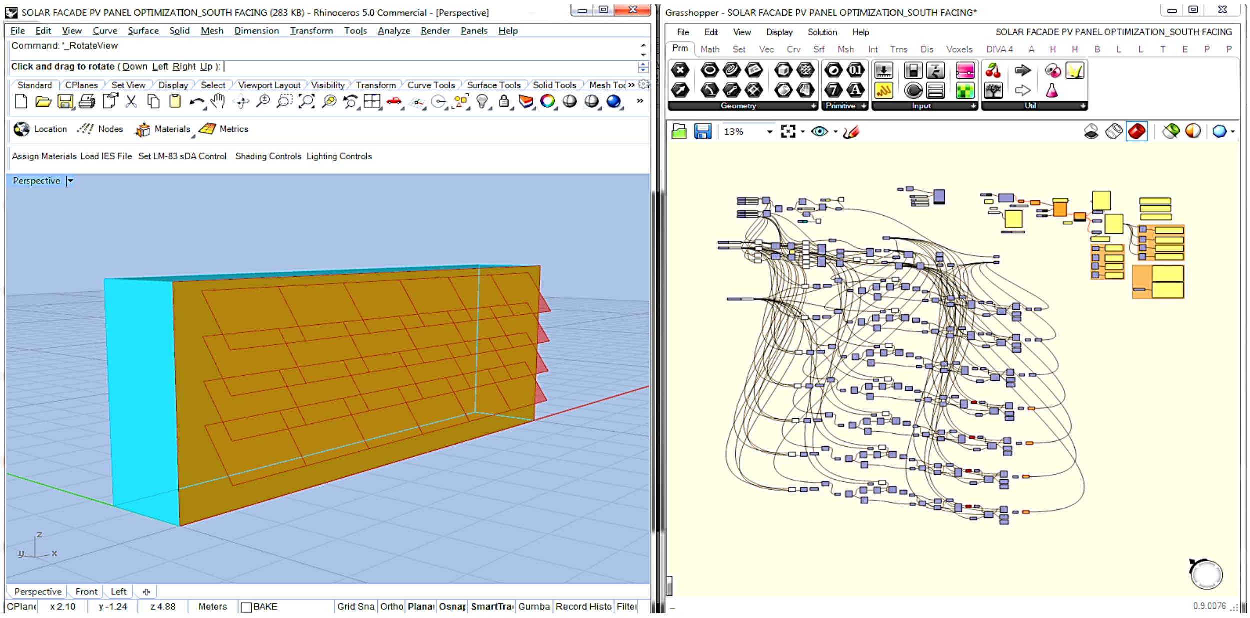


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Figure 5.12: Parametric Assessment of Vertical Façade based Solar PV Systems

5.5 Measuring Solar Energy and Thermal Potential of Representative Units

The theoretical estimation of solar energy potential in case of CUC indicates that the ideal angle of inclination of solar panels for maximizing output is between 30° and 45°. Shading factor is a major challenge in enhancing solar output of plotted units due to building controls. Solar power generation is enhanced in case of plots with the shorter side facing south-east. To measure the solar potential in case of the RRUs, each of the typology is subjected to parametric assessment based on an algorithm displayed in figure 5.13. The common simulation conditions applicable to all the RRUs are highlighted in table 5.4 and the variables assessed are highlighted in table 5.5.

Table 5.4 : Common Simulation Conditions for Solar PV and Thermal Assessment in RRUs

Percentage of Roof for Solar Infrastructure (PV / PV + Thermal)	50%
Solar Array Type	Fixed
PV Module Settings	
a) Module Material	Mono Crystalline Silicone
b) Module Mount Type	Open Rack on Roof
c) Module Active Area (% area generating energy on panel)	80%
d) Module Efficiency	18%
e) Temperature Coefficient (/°C)	-0.5
Overall DC to AC Derate Factor	0.850

Table 5.5 : Variables assessed through Simulation of Solar PV and Thermal System in RRUs

i) Optimal Tilt of Panel (°)	ii) Optimal Azimuth of Panel (°)	iii) Area of Roof (m^2)
iv) Area for Solar PV (m^2)	v) Annual Solar Thermal (m^2)	vi) DC System Size (kW)
vii) Thermal System Size (litre)	viii) AC Power Output / Day (kwh/day)	ix) Annual AC power (kWh)

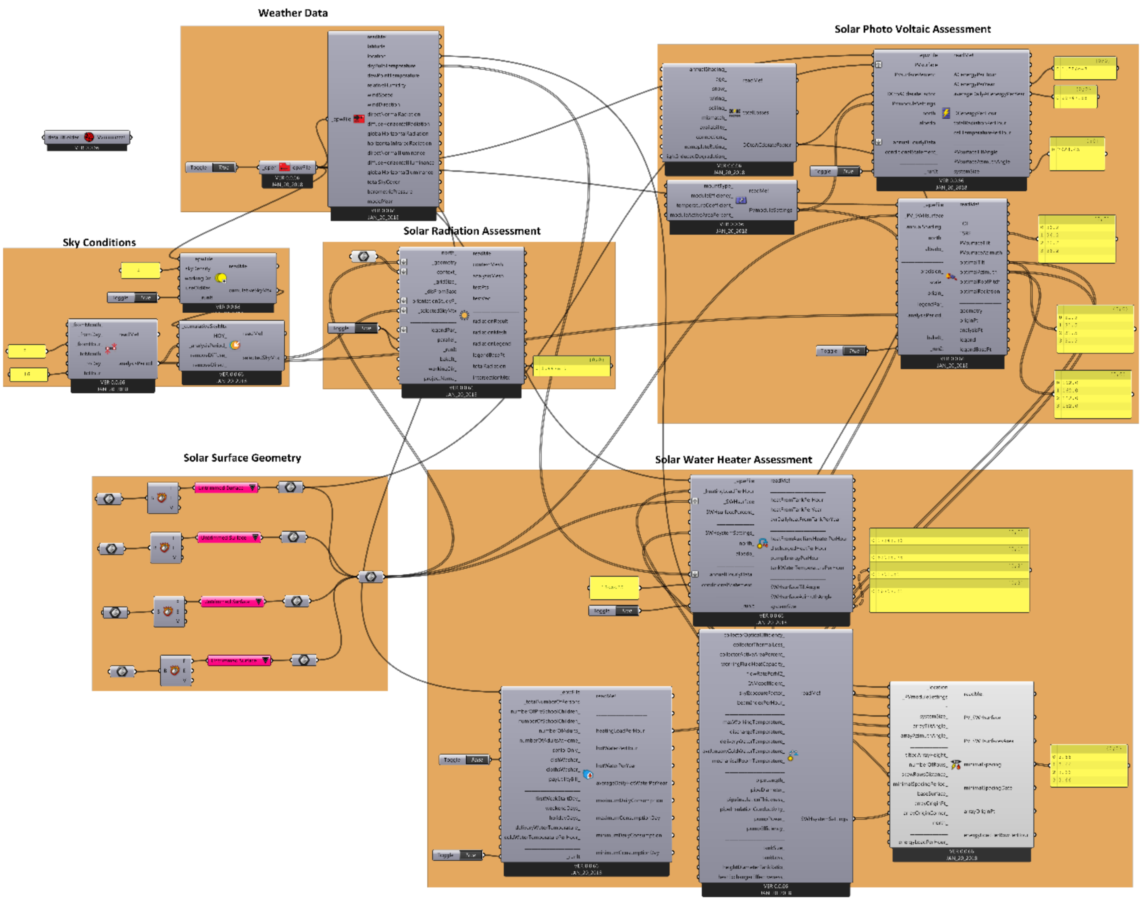

Figure 5.13: Parametric Model to Assess Solar PV and Solar Water Heating Potential of RRUs

5.5.1 Uppals Marble Arch, Manimajra, Chandigarh

The visual interpretation of the total sunlight hours on the roof of Uppals Marble Arch over the year is displayed in figure 5.14. It is observed that 70% of the roof receives around 10 hours of sunlight throughout the year with very less shadow area.

Placement of service blocks in the centre of the block allows for shadow free outward area that also enables ease of access and maintenance. The lack of parapet wall also enhances the shadow free area thereby questioning their existing design and finish. The parametric model of Uppals Marble Arch results in the output detailed in table 5.6.

The primary assumption in all the cases is that 50% of the roof area is only available for solar infrastructure with 75% of the available area utilized for Solar PV system and the remaining 25%

for Solar Thermal systems. The 300kW Solar PV system covers an area of 3,100 sqm whereas the 33,300 litre Solar Thermal system is spread over remaining 1,000 sqm. Effectively per kW of Solar PV system requires 10.33sqm of roof area which is equivalent to the industry standard of 6-10sqm.

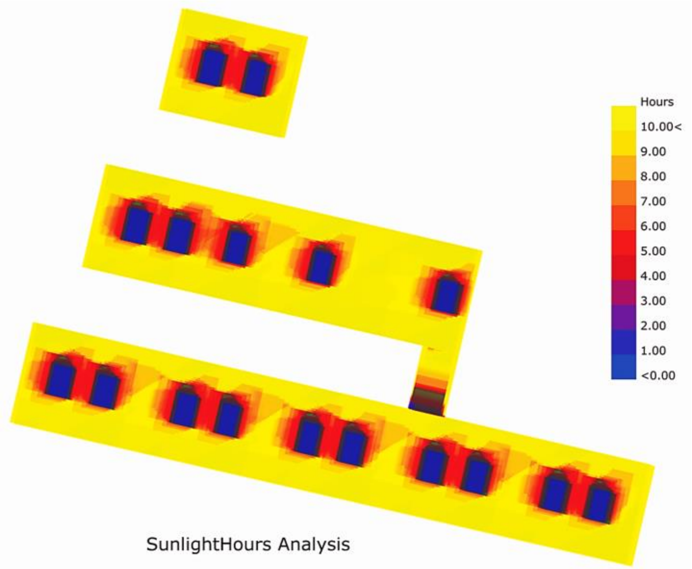

Figure 5.14 : Sunlight Hours on roof of Uppals Marble Arch, Manimajra, Chandigarh

Table 5.6: Simulated Solar Potential Parameters of Uppals Marble Arch, Manimajra, Chandigarh

i)	Optimal Tilt of Panel (°)	31.5°	ii)	Optimal Azimuth of Panel (°)	162°
iii)	Area of Roof (sqm)	8,300	iv)	Area for Solar PV (sqm)	3,100
v)	Area for Solar Thermal (sqm)	1,000	vi)	DC System Size (kW)	300
vii)	Thermal System Size (litre)	33,300	viii)	AC Power Output / Day (kwh/day)	1,110
ix)	Annual AC Power (kWh)	4,05,150	x)	Percentage of Actual Demand (mean / peak)	**60% / 46%**

Depending on the quality of silicone panels and temperature variations 1kW of Solar PV is expected to generate 1100-1600kWh of power annually, which results in 905-1315kWh per day - the average of which is 1110kWh per day. Under ideal conditions the Solar PV system can generate a power of 33,300kWh per month which equates to 230kWh of power or 230 units per household. The monthly electricity demand of 144 households in Uppals Marble Arch, Manimajra is around 380 units with the peak in summer reaching a value of 500 units. The solar thermal system can provide 230litres of hot water to the 144 households whereas the peak demand is 280litres per household in winters.

5.5.2 Sushma Elite Cross, Gazipur, Punjab

In case of Sushma Elite Cross, Gazipur the X shaped towers are more promising with almost 60% of area having sunlight exposure near to 10hours. It can also be observed from figure 5.15 that essential services are placed in the centre of the block leading to lowest shadow area. The C shaped towers due to the placement of service units at the corners have only 35-40% area available with maximum sun exposure. The only C shaped tower with north-south orientation has a marginally higher 40-45% roof area with maximum sun exposure. Another major constraint is the implementation of Solar Thermal systems as the top 12th and 13th floors in the towers are penthouses. In similar scenario Solar PV can still be opted for 50% of the potential areas in form of raise platforms but Solar Thermal systems owing to their weight cannot be implemented on such platforms. The only place for such systems is on top of the service core but accessibility and aesthetics may not permit such solutions.

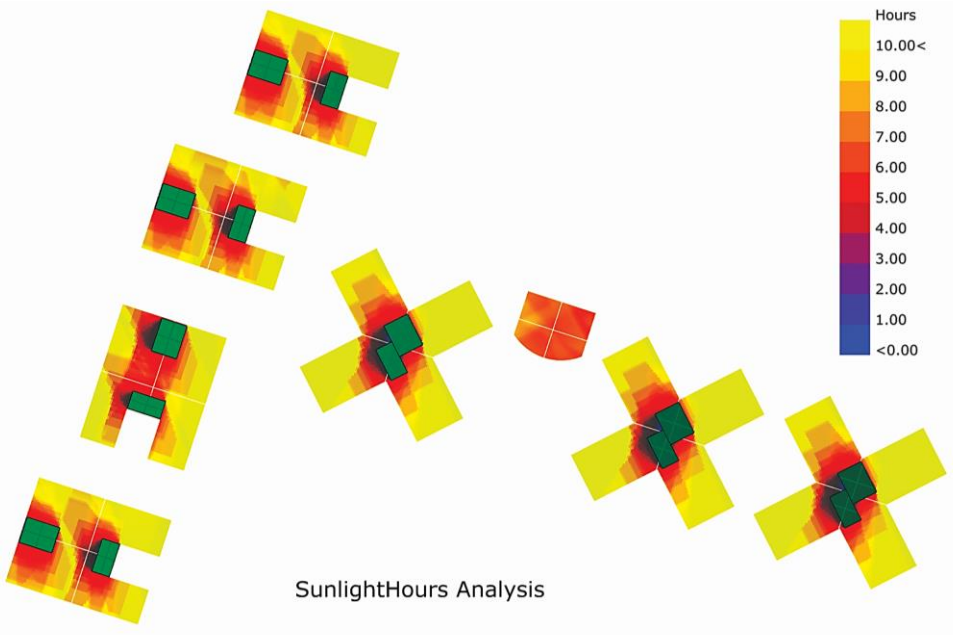

Figure 5.15: Sunlight Hours on roof of Sushma Elite Cross, Gazipur, Punjab

In case of Sushma Elite Cross only Solar PV systems have been considered as part of the study due to technical feasibility issues with Solar Thermal systems. The available area for solar installation here is half of that in Uppals Marble Arch, with the open rack system size reducing from 200kW to 35kW due to high shade factor. This effect can be reduced by installing Solar PV systems at a higher platform thereby reducing the shading. By lifting the panels by 1.8m the DC system size can increase to 120kWh.

Table 5.7 : Simulated Solar Potential Parameters of Sushma Elite Cross, Gazipur, Punjab

i)	Optimal Tilt of Panel (°)	31.5°	ii)	Optimal Azimuth of Panel (°)	162°
iii)	Area of Roof (sqm)	4,950	iv)	Area for Solar PV (sqm)	2,475
v)	Area for Solar Thermal (sqm)	NA	vi)	DC System Size (kW)	120
vii)	Thermal System Size (litre)	NA	viii)	AC Power Output / Day (kwh/day)	365
ix)	Annual AC Power (kWh)	1,33,225	x)	Percentage of Actual Demand (mean / peak)	**10% / 8%**

As per table 5.7, the 320 households with monthly average household energy consumption of 328kWh based on the enhanced setup can have a share of 34kWh on monthly basis. The peak demand is about 412kWh and Solar PV can meet only 21% of monthly household energy demand. If BIPV is promoted then a surface area of 8300sqm facing south can lead to creation of 380-415kW DC system that can generate 418000–456500kWh of AC power. The share of each household annually can be 1305-1425kWh, which is around 33-36% of monthly energy demand.

5.5.3 Sector 51, Chandigarh

The influence of service core and their effect on the solar energy potential of a housing typology can be understood by the case of group housing unit in Sector 51, Chandigarh. From figure 5.16 units with service cores towards the northern side have 60-70% of roof area receiving more than 9 hours of sunlight over the year. Within the same context those units with service core on the southern side have less than 40% of roof area receiving significant sunlight exposure. Also, the available area is along the perimeter of the roof which renders it useless as the same space is used for accessibility and maintenance of the solar panels. An overall review of all the blocks results in less than 40% of roof area available for solar infrastructure.

From table 5.8 considering 40% of available solar area out of which 75% is utilized for Solar PV and remaining 25% for Solar Thermal, the 120kW Solar PV system covers an area of 1,250sqm whereas the 13,300litre Solar Thermal system is spread over remaining 400sqm.

Table 5.8: Simulated Solar Potential Parameters of Sector 51, Chandigarh

i)	Optimal Tilt of Panel (°)	31.5°	ii)	Optimal Azimuth of Panel (°)	162°
iii)	Area of Roof (sqm)	4,200	iv)	Area for Solar PV (sqm)	1,250
v)	Area for Solar Thermal (sqm)	400	vi)	PV System Size (kW)	120
vii)	Thermal System Size (litre)	13,300	viii)	AC Power Output / Day (kwh/day)	360
ix)	Annual AC Power (kWh)	1,32,000	x)	Percentage of Actual Demand (mean / peak)	**23% / 19%**

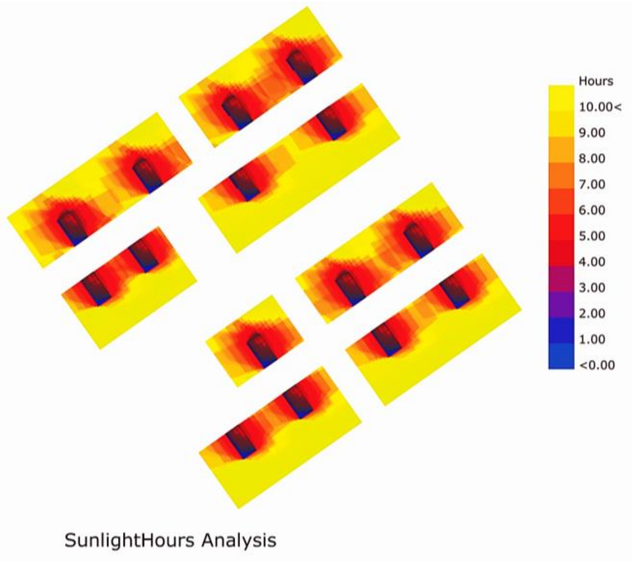

Figure 5.16: Sunlight Hours on roof of Sector 51, Chandigarh

The Solar PV systems generates a power of 360kWh/day which when distributed among the 168 households results in a share of 2.15kWh per day/household. The monthly average household consumption in the housing society is 286kWh which equates to 9.53kWh/day. Effectively with standard setup the Solar PV system is able to meet 23% of the household energy demand in the regular season. During peak season the monthly household electricity consumption increases to 342kWh per month and the Solar PV is capable of handling 19% of the monthly energy demand. The hot water demand of the household during the peak season is around 180litres per day. The Solar Thermal system with a capacity of 13,300litres can supply a maximum of 80litres per day, the rest compensated by alternate means like geyser, gas, etc.

5.5.4 Sector 19A, Chandigarh

Plotted development is the most challenging typology in implementation of renewable infrastructure. The solar analysis for Sector 19A is not feasible at neighbourhood level due to the complexity of household geometry and lack of computing skills to handle such data. To ensure optimum results, a pocket from the sector is taken comprising of three housing typologies based on their area and built form. Emphasis is also given to ensure change in character of associated spaces like streets and open spaces between building blocks. The amount of shade free space on terrace varies accordingly with the plot size and building controls. Visual assessment of figure 5.17 indicates that the larger 3 Kanal plots have the highest solar space followed by the 2 Kanal and the lowest by 1 Kanal.

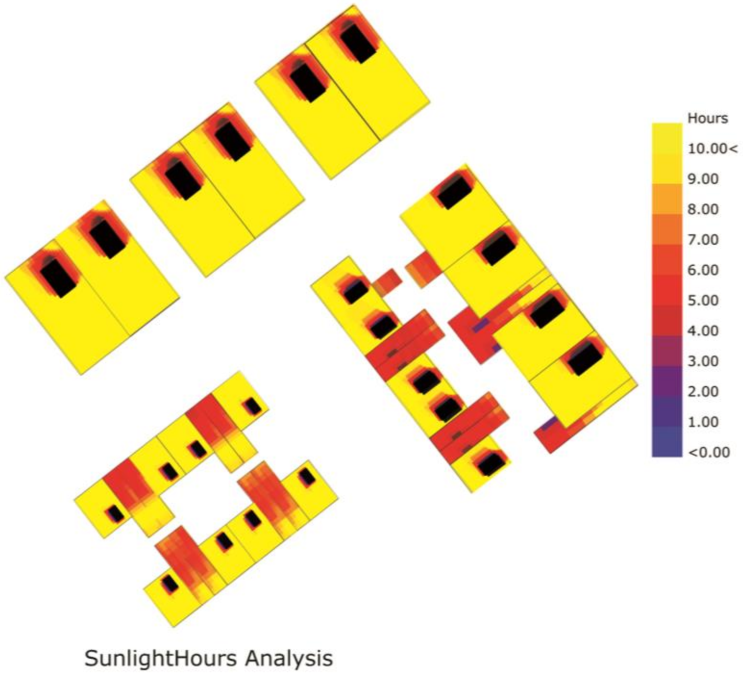

Figure 5.17: Sunlight Hours on roof of Sector 19A, Chandigarh

Orientation of the plot with respect to the sun plays a major role in the solar potential of a plot. In case of 1 Kanal plots those oriented with their shorter side towards south-west have lower sun hours and high shading area in comparison to those with south-east and north-west orientation. The factor of vegetation not considered as part of the study also influences the shading factor as the maximum height permitted is 10.65m which can be achieved by major tree species thereby effecting total sun hours. For the purpose of the study only the roofs at 10.65m level have been considered for assessment and roof of garage, servant quarter, single floor structures, etc. have not been considered.

Table 5.9: Simulated Solar Potential Parameters of 1 Kanal Plot, Sector 19A, Chandigarh

i)	Optimal Tilt of Panel (°)	31.5°	ii)	Optimal Azimuth of Panel (°)	162°
iii)	Area of Roof (sqm)	110	iv)	Area for Solar PV (sqm)	40
v)	Area for Solar Thermal (sqm)	15	vi)	PV System Size (kW)	4 kW
vii)	Thermal System Size (litre)	500	viii)	AC Power Output / Day (kwh/day)	12 kW
ix)	Annual AC Power (kWh)	4,350	x)	Percentage of Actual Demand (mean / peak)	**19% / 14%**

Table 5.10: Simulated Solar Potential Parameters of 2 Kanal Plot, Sector 19A, Chandigarh

i)	Optimal Tilt of Panel (°)	31.5°	ii)	Optimal Azimuth of Panel (°)	162°
iii)	Area of Roof (sqm)	250	iv)	Area for Solar PV (sqm)	90
v)	Area for Solar Thermal (sqm)	35	vi)	PV System Size (kW)	9 kW
vii)	Thermal System Size (litre)	1,150	viii)	AC Power Output / Day (kwh/day)	27 kW
ix)	Annual AC Power (kWh)	9,800	x)	Percentage of Actual Demand (mean / peak)	**36% / 32%**

From table 5.9 and 5.10, the high output values across the different plotted units stimulates and inspires to invest in solar infrastructure. But the reality being a major portion of this energy is never created due to vegetation and shading factors. The plotted houses are created in levels with architectural character as a result they are not as effective as row housing with linear and straight development. Another major reason being the lifestyle of the occupants in these households which is quite evident by the prevalence of fully air-conditioned homes, number of cars and energy intensive infrastructure running these homes. Based on the household analysis all the categories are capable of meeting their monthly average electricity and hot water demand through solar based renewable energy systems.

Considering renewable energy infrastructure at neighbourhood level through connected grid network and net metering can ensure high solar energy generation potential. Under ideal conditions a 1 Kanal plot with effective solar area of 40sqm generates 4,350kWh per year. Considering different plotted orientations and the effective contribution per household reducing to 50%, a single household can generate 2,175kWh of solar energy and 250litres of hot water per day. This equates to 180kWh of solar electricity per month. The household per month average electricity consumption is equal to 960kWh and the average hot water demand is 285litres per day. The hot water demand is still achievable but the electricity demand needs input from the grid. Solar power can meet only 15% of peak demand equal to 1214kWh. In case of 2 Kanal plots with area of 90sqm, the solar output is around 9,780kWh per year. Considering 50% of successful generation due to varied plot orientations the solar energy output is around 4,890kWh per year. This is equal to 13kWh/day whereas the monthly mean electricity consumption is 1120kWh and the peak demand is 1270kWh.

With reference to table 5.6 to 5.10 it is observed that with 50% of roof area dedicated for solar infrastructure, power generation ranges between 8-46% of peak demand across various typologies. Orientation of units and location of physical structures on the roof have a great role in the promotion of solar infrastructure. With the maximum roof area utilized for solar PV and solar thermal systems it is possible to meet 25% of household energy requirement. Solar power can meet the hot water demand in case of the plotted units. But to meet the energy requirements during monsoons and winters for all other utilities, energy conservation measures need to be promoted. However, insulation based retrofitting of households more than 20 years old needs to be undertaken to reduce their energy demand and make solar power a viable option.

5.6 Solar Envelope Concept and its Application in CUC

The concept of Solar Envelope was theorised and tested by Prof. Ralph L. Knowles, Professor Emeritus of Architecture at University of Southern California, USA around 1979 **(Knowles, 1980)**. The aim of the study is to design buildings that shall not overshadow the surroundings for a stipulated duration of time in a day. The modern day significance of the theory is its application in promotion of solar based energy generation wherein every household receives sunlight and contributes towards electricity and thermal energy generation **(Schiler et al., 1993)**. If applied in the initial stages it can aid in defining zoning, building controls, aesthetically designed solar renewable infrastructure that can be integrated into architecture and urban design solutions.

5.6.1 Solar Envelope Parameters of CUC

The study of solar envelope has no direct relationship to the outcome of the research, but is attempted to enhance the solar roof area available for solar electricity and thermal requirements. It also has great potential for further study and application in future housing development. The study is limited to the plotted development of CUC comprising of 4 Marla, 6 Marla, 10 Marla, 15 Marla, 1 Kanal and 2 Kanal plots.

The solar envelope model for the plotted units of CUC is based on the parameters listed in table 5.11. The existing building controls defined by Chandigarh Administration as part of the different plotted development are listed in table 5.12.

Table 5.11: Parameters for creating the Solar Envelope Model

i)	Plot width (m)	ii)	Plot depth (m)	iii)	Plot area (sqm)
iv)	Ground floor area (sqm)	v)	First floor area (sqm)	vi)	Second floor area (sqm)
vii)	Total built-up area (sqm)	viii)	Floor Area Ratio (FAR)	ix)	Available Roof area (sqm)
x)	Angle to South (degrees)	xi)	Ground coverage (%)		

Parameters assessed by the Solar Envelope Model

i)	Modified Ground floor area (sqm)	ii)	Modified First floor area (sqm)
iii)	Modified Second floor area (sqm)	iv)	Modified Total built-up area (sqm)
v)	Modified Available Roof area (sqm)	vi)	New Floor Area Ratio (FAR)

Table 5.12: Building Controls of Different Plotted Units of Chandigarh

Type of Plotted Development	Width of Plot	Depth of Plot	Maximum Height Permissible	Setback				Plot Coverage	FAR	Floor Area			Total Built-up Area	Total Roof Area for Solar Applications
				Front	Rear	Side	Side			Ground Floor	First Floor	Second Floor		
	(m)	(m)	(m)	(m)	(m)	(m)	(m)	%	Ratio	(sqm)	(sqm)	(sqm)	(sqm)	(sqm)
4 Marla	6.00	17.00	10.06	3.00	3.00	0.00	0.00	65	2.00	66.00	66.00	72.00	204.00	**72.00**
6 Marla	7.50	20.00	10.06	3.00	4.00	0.00	0.00	65	2.00	97.50	97.50	105.00	300.00	**105.00**
10 Marla	11.25	22.25	10.06	3.00	4.80	0.00	0.00	65	2.00	162.56	162.56	175.50	500.63	**175.50**
15 Marla	15.00	24.00	10.06	3.50	5.00	0.00	0.00	65	2.00	232.50	232.50	255.00	720.00	**255.00**
1 Kanal	18.00	27.75	10.67	5.00	6.00	3.20	0.00	50	1.50	247.90	247.90	253.45	749.25	**253.45**
2 Kanal	24.00	41.75	10.67	6.00	9.00	3.65	3.65	45	1.25	446.73	359.10	446.73	1252.56	**446.73**

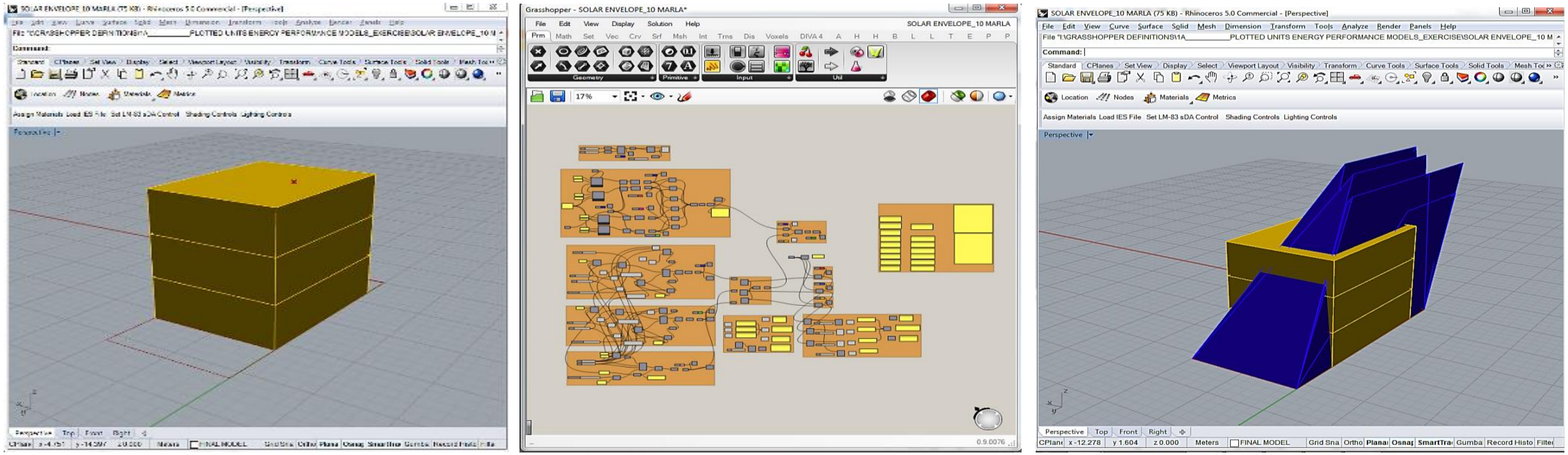

Figure 5.18 : Stages of Developing the Solar Envelope Model for CUC

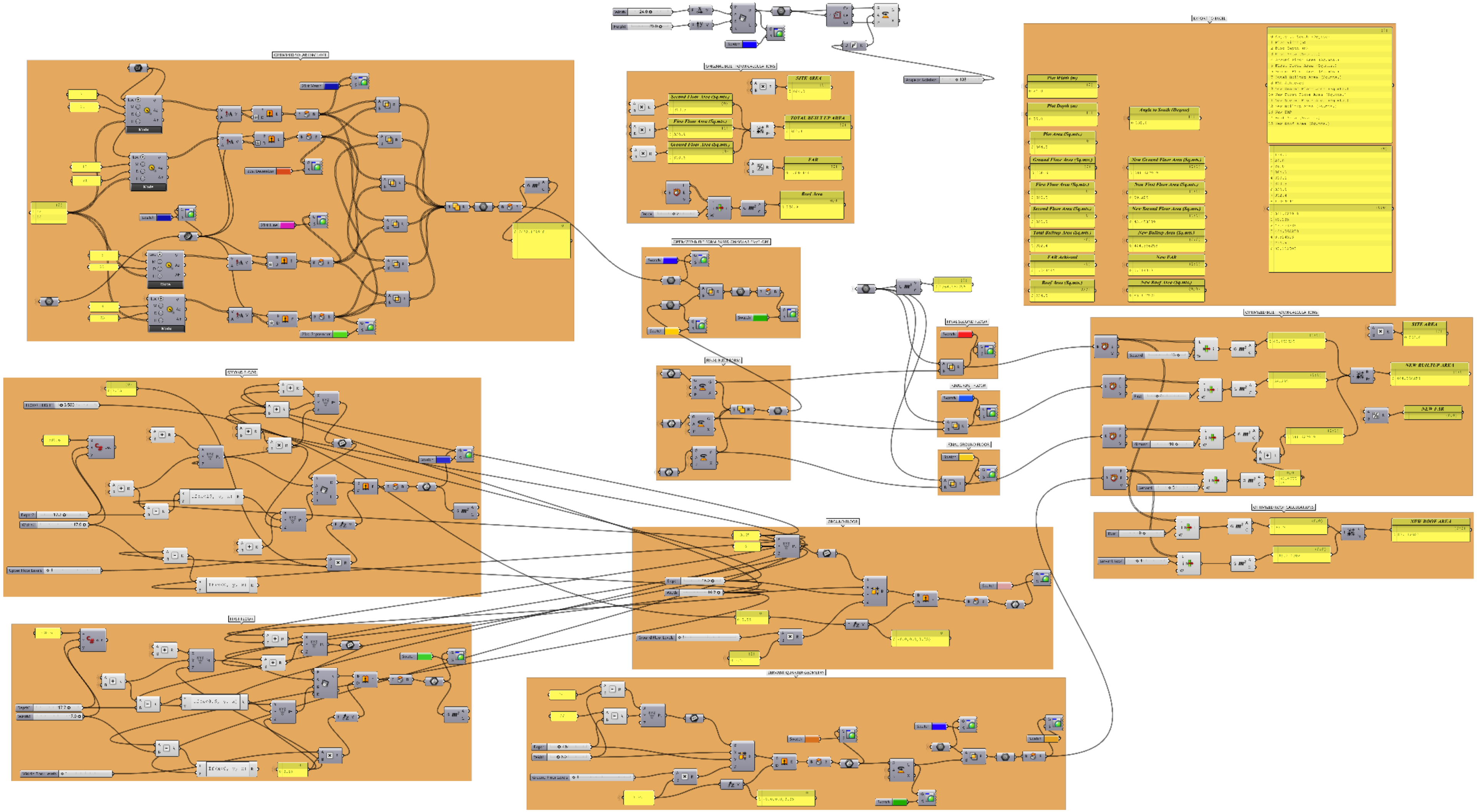

Figure 5.19 : Parametric Algorithm for Solar Envelope of Plotted Units in CUC

5.6.2 Developing the Parametric Solar Envelope Algorithm for CUC

The parametric model as indicated in figure 5.18 is developed to assess the performance of the plotted units so as to minimize self-shading and ensure every part of the unit receives sunlight. The model attempts to enhance overall roof area as a provision for enhancing rooftop solar infrastructure. The assessment also looks into the impact of plot rotation with reference to the sun on overall roof availability. For the present assessment built forms with flat roofs are only considered.

There are two ways of generating the solar envelope - computational and non-computational methods. Both of them are the visualization of solar angles that are based on sun’s relative position with respect to movement of the earth. Considering the speed and visualization opportunities, computer software is the most efficient way of generating the solar envelope. A parametric solar envelope algorithm displayed in figure 5.19 is developed using grasshopper - an extension of Rhino (a 3D modelling software).

5.7 Impact of Solar Envelope Concept on Existing Typologies and Building Controls

Given the context of providing solar access to each individual plot, the solar envelope has a definite impact on the existing building controls i.e. either on the height, FAR, setbacks, and total built up area **(Kensek et al., 1997)**. The parametric optimization looks into the impact on the built form character for different plot sizes prevalent in the CUC. The visual assessment of the optimization displayed in figure 5.20 and 5.21 comprises of the base household unit as per existing building controls, solar envelope as per the household plot and the optimized built form and individual floor levels. The analytical assessment of the optimization and the results detailed out in **Annexure – VI** are discussed in the subsequent sections.

5.7.1 4 Marla Household

The solar behaviour and performance of the 4 Marla plot with respect to change in area and FAR are highlighted in table 5.13. The effective roof area available is highest in case of shorter face of plot oriented towards north-west (128°) whereas maximum area of unit is achieved with the shorter face towards south–east (308°). The area of the inclined wall surface towards south-west in case of 128° orientation is 99sqm which is additional to the 58.20sqm. The overall surface area for solar infrastructure is enhanced to 156sqm. With the change in orientation angle of the plot, the architectural character of each household and its building controls can vary thereby giving due respect to those households which in the past were unable to be part of the solar city project but can now contribute in harnessing solar energy.

Table 5.13: 4 Marla - Orientation based Solar Envelope performance and Output Parameters

Angle to South (Degree)	308	300	128	45	38
New Built-up Area (sqm)	154.93	145.73	147.73	138.45	135.99
New FAR	1.48	1.39	1.41	1.32	1.30
New Roof Area (sqm)	18.60	13.08	58.20	20.29	17.19
Average Area (sqm)	86.76	79.41	102.96	79.37	76.59

5.7.2 6 Marla Household

The solar behaviour and performance of the 6 Marla plot with respect to change in area and FAR are highlighted in table 5.14. The effective roof area available and the new built-up area is highest in case of shorter face of plot oriented towards south-east (308° and 315°). The area of the inclined wall surface towards south-west in case of 128° orientation is 128sqm which is additional to 56.45sqm. The overall surface area for solar infrastructure is enhanced to 184sqm.

Table 5.14: 6 Marla - Orientation based Solar Envelope performance and Output Parameters

Angle to South (Degree)	315	308	330	135	300
New Built-up Area (sqm)	239.24	238.38	232.99	230.78	225.99
New FAR	1.48	1.48	1.44	1.43	1.40
New Roof Area (sqm)	56.04	56.45	37.61	38.63	47.45
Average Area (sqm)	147.64	147.42	135.30	134.71	136.72

5.7.3 10 Marla Household

The solar behaviour and performance of the 10 Marla plot with respect to change in area and FAR are highlighted in table 5.15. The effective roof area available and the new built-up area is highest in case of shorter face of plot oriented towards south-east (308° and 315°). The area of the inclined wall surface towards south-west in case of 308° orientation is 136.06sqm which is additional to 88.61sqm. The overall surface area for solar infrastructure is enhanced to 224.67sqm.

Table 5.15: 10 Marla - Orientation based Solar Envelope performance and Output Parameters

Angle to South (Degree)	315	308	135	128	300
New Built-up Area (sqm)	370.52	370.13	363.09	362.93	357.16
New FAR	1.76	1.76	1.73	1.73	1.70
New Roof Area (sqm)	87.79	88.61	75.11	75.62	80.45
Average Area (sqm)	229.15	229.37	219.10	219.27	218.80

5.7.4 15 Marla Household

The solar behaviour and performance of the 15 Marla plot with respect to change in area and FAR are highlighted in table 5.16. The effective roof area available and the new built-up area is highest in case of shorter face of plot oriented towards south-east (315° and 308°). The area of the inclined wall surface towards south-west in case of 308° orientation is 122.63sqm which is additional to 130.20sqm. The overall surface area for solar infrastructure is 252.83sqm which is less than existing value of 263.25sqm. Here the margin of difference is nominal.

Table 5.16 15 Marla - Orientation based Solar Envelope performance and Output Parameters

Angle to South (Degree)	315	308	135	128	300
New Built-up Area (sqm)	476.05	475.00	469.65	467.59	467.31
New FAR	1.69	1.68	1.67	1.66	1.66
New Roof Area (sqm)	129.70	130.20	112.24	112.07	112.00
Average Area (sqm)	540.90	540.10	525.77	523.63	523.31

5.7.5 1 Kanal Household

The solar behaviour and performance of the 15 Marla plot with respect to change in area and FAR are highlighted in table 5.17. The effective roof area available and the new built-up area is highest in case of shorter face of plot oriented towards south-east (300° and 308°). The area of new terrace formed at the roof level in case of 300° orientation is 12.35sqm which is additional to 216.38sqm. The overall surface area for solar infrastructure is enhanced to 278.95sqm.

Table 5.17: 1 Kanal - Orientation based Solar Envelope performance and Output Parameters

Angle to South (Degree)	300	308	315	225	255
New Built-up Area (sqm)	672.60	672.60	672.60	672.60	672.60
New FAR	1.49	1.49	1.49	1.49	1.49
New Roof Area (sqm)	216.38	214.06	212.85	211.73	211.73
Average Area (sqm)	780.79	779.63	779.03	778.46	778.46

5.7.6 2 Kanal Household

The solar behaviour and performance of the 15 Marla plot with respect to change in area and FAR are highlighted in table 5.18. The effective roof area available and the new built-up area is highest in case of shorter face of plot oriented towards north-east (225°). The overall roof area for solar infrastructure is almost equivalent to existing value of 446.73sqm.

Table 5.18: 2 Kanal - Orientation based Solar Envelope performance and Output Parameters

Angle to South (Degree)	225	150	165	218	135
New Built-up Area (sqm)	1226.80	1226.80	1226.80	1226.80	1226.80
New FAR	1.22	1.22	1.22	1.22	1.22
New Roof Area (sqm)	436.18	408.11	399.88	379.65	357.70
Average Area (sqm)	1410.08	1409.88	1409.79	1409.62	140.35

The final optimized visual models for each of the plotted typologies are displayed in figure 5.20 and figure 5.21.

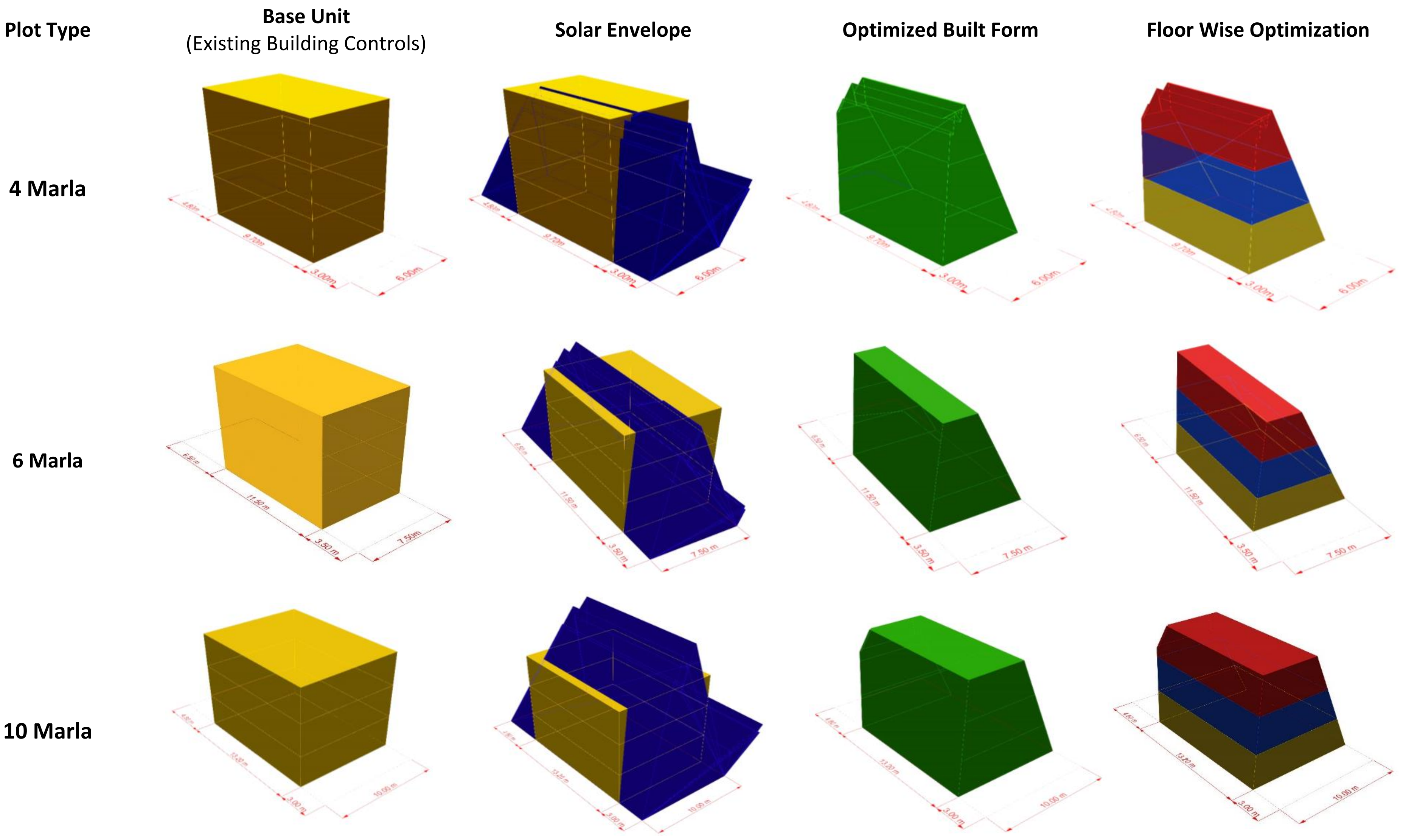

Figure 5.20 : **Optimization of Existing Housing Units (4 Marla, 6 Marla and 10 Marla) on the basis of Solar Envelope Concept**

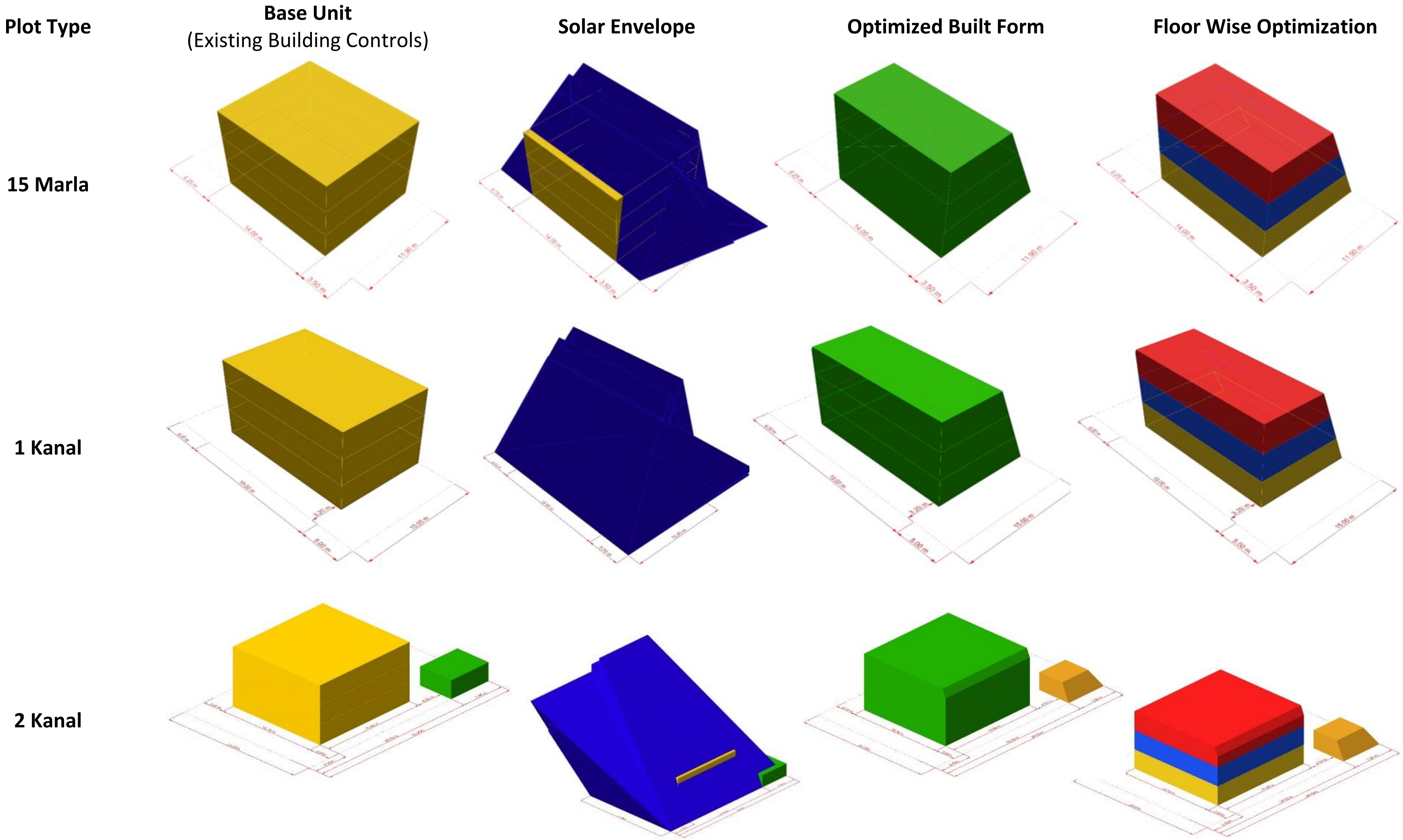

Figure 5.21 : **Optimization of Existing Housing Units (15 Marla, 1 Kanal and 2 Kanal) on the basis of Solar Envelope Concept**

The foremost observation after the analysis is to applaud the architectural skills of Le Corbusier in the design of Chandigarh. The sector layout of Chandigarh is aligned at 38° to north and all the plots are oriented to 38°, 128°, 218° and 308°. The Solar Envelope concept finds 308°, 315° and 128° layouts more beneficial in solar promotion. Smaller plots with shorter face towards north-west are the most solar potential plots. The analysis also indicates that with increasing plot size the concept of solar envelope has no significant effect on the built form. With varying degree of change in the area of built configuration, a mix of architectural solutions can be derived that are aesthetical and also meet the primary goal of solar energy promotion. Further investigation is required to affirm the findings and also study the role of solar envelope in other housing typologies especially the high rise.

5.8 Conclusion

The solar potential assessment of various housing typologies of CUC has shown great potential of solar energy in meeting the energy demands of households. The solar radiation over the year on annual basis can generate significant solar electricity and solar thermal output. The challenge is to understand that there is no one solution that fits all. With an annual average horizontal irradiance near to 5.21kWh/m^2/day and the physical development based on a sectoral grid it is easy to integrate the solar infrastructure into the households. The sectors of Chandigarh due to the visionary architect Le Corbusier were laid out with orientation towards the north-west winds and the grid layout at an angle of 38° ensuring maximum exposure to south-east, south and south-west. The inherent weakness of this layout is that some plots can be major contributors towards solar energy generation whereas others lack the requisite sunlight hours and shadow free area to generate solar energy. The first outcome of the study is that integrating renewable energy infrastructure depending upon volatile energy resources like sun and wind needs to be implemented at neighbourhood level and not as promoted till now at individual household level.

Out of the different typologies on basis of technical and simulated assessment, the row housing typology with connected roofs has highest solar generation potential. The vertical high rise typology has the inherent weakness of less roof area compared to overall built-up area. Plotted development exhibits varied results based on form and orientation. Some of the units overshadow others thereby influencing their contribution. The medium rise unit performs equivalent to the row housing typology but the low width of each block results in more overshadowing in comparison to row housing.

Theoretically it is possible to meet the household energy demand of plotted, low and medium rise through integration of solar based energy generation systems. It is in the case of high rise that rooftop solutions are unable to meet the overall demand. The role of vertical surfaces through BIPV (Building Integrated Photo Voltaic) needs to be researched. The preliminary assessment using parametric environment has indicated the potential of BIPV. Further research is required to understand the architectural integration of solar infrastructure on the vertical skin of high rise buildings.

Built form geometry and building controls have a great role to play in the enhancement of solar energy generation. In simulation models it is observed that the inclusion of 0.9m parapet wall leads to overshadowing thereby leading to loss of effective solar area and reduced energy generation. In the same scenario the building controls define the parapet to be 1.2m which shall further diminish the solar potential. One possible solution in such scenario is to raise the solar platform above the parapet level which has cost and aesthetic implications. Locating the mumty of the staircase is another aspect as it is the only physical structure on the terrace of households that can cast shadows. In the study the placement of mumty in north-west and north reduces the solar shading and its orientation varies with the orientation of the plot. However, solar promotion is not restricted to installing solar based energy systems but due attention needs to be given to the design of building components like parapet, railing, balconies and shading devices as they can indirectly influence the solar goals.

Another major outcome of the study is that physical form of a built unit has a lot of contribution towards solar energy generation. This is evident by the solar envelope study based on the principles laid down by Prof. Ralph L. Knowles. The study indicates that promotion of solar cities like Chandigarh should not be focussed on retrofit measures of installing solar panels and meeting targets. It takes more to ensure that every household has equivalent contribution towards solar energy generation. To achieve the same the built form needs to go through physical transformation varying with orientation with respect to the sun. The analysis of the existing typologies using a parametric tool highlights the reduction in Floor Area Ratio (FAR), thereby promoting low density development. Similar study needs to be undertaken for high rise high density housing as the trend is towards high rise development.

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Chapter 6

Energy Mix Model

6.1 Optimized Hybrid Energy Model

Hybrid energy systems are a combination of multiple renewable resources such that each of the resource tries to cover the inadequacies of the other primarily caused due to seasonal factors. The proposed energy mix model tries to maximize the contribution of multiple RES in standalone and hybrid mode to meet total household energy demand. Simulation based optimization to minimize the investment and per unit cost of electricity generation of the different energy choices is undertaken to define a stable and economical hybrid energy system. The average value of RES resources derived in Chapter 4 and 5 have been considered as part of the analysis.

The study assesses the performance of a solar, wind, diesel generator and battery based hybrid energy system using HOMER (Hybrid Optimization Model for Multiple Energy Resources) a microgrid simulation software with the operational and economic parameters compared to define the optimal hybrid energy system. The attempt is also to investigate the different scheduling scenarios and the effect on Overall Levelized Cost and Net Present Cost of Energy (COE).

The outcome shall be a guiding factor for home owners in making decisions regarding choice of renewable energy system to meet household energy demand, its financial implication and future maintenance factor.

6.2 Conceptual Residential Hybrid Energy Mix (RHEM) Model

The conceptual Residential Hybrid Energy Mix (RHEM) model is a modelling and simulation environment comprising of agents, which are interlinked but autonomous in nature and can make decision based on defined behaviour and goals. The model evolves based on the level of flexibility in interaction between the agents and the environment interacting and influencing each other (**Bonabeua, 2002**). Similar computational models have been proposed in the past to study power and energy network systems based on addressing complex agent behaviour and their interactions (**Rezzouk and Mellit, 2015**) (**Macal and North 2010**).

The proposed RHEM model aims to meet the energy demand of a household using two primary RES – solar and wind. Both the resources are influenced by climatic and regional factors, as a result the availability of wind and solar resource has a great impact on the system. The conceptual

RHEM Model is based upon four agents: household load (**E**$_{HL}$), wind turbine (**E**$_{WT}$), solar photovoltaic (**E**$_{PV}$) and battery (**E**$_{BAT}$). To maintain the balance in the system a third energy source – diesel generator (**E**$_{DG}$) that is already part of backup energy system in urban areas is introduced to balance the equation. 6.1.

$$E_{HL} = E_{PV} + E_{WT} + E_{DG} – E_{BAT} \qquad \text{Equation 6.1}$$

Where,

E_{HL} = Electricity demand of household
E_{PV} = Electricity generated by Solar PV
E_{WT} = Electricity generated by wind turbine
E_{DG} = Electricity supplied by diesel generator
E_{BAT} = Electricity discharged from batteries

Solar thermal has not been considered as part of the energy equation as it has a direct bearing with usage and occupant behaviour as a result quantifying it as part of the model with the limited data was not possible. Diesel generator has been considered as a backup resource though a source of pollution because its contribution towards carbon di oxide emissions is less in comparison to the electricity grid. Also, generators are localised and come to aid in the case of emergencies and urban disasters like floods, terrorism, etc. wherein the whole grid may be offline. This would also ensure a complete self-reliant energy network generating energy from decentralized facilities.

The operating condition of the model is that renewable resources are considered as primary source of energy. In case the electricity demand is not met by the renewable resource, diesel generators would be used to balance out the demand. Excess energy generated from renewable resources beyond demand shall be stored until the battery pack is full. If the battery pack is fully charged then the excess energy is forwarded to the grid. The hybrid energy mix model tries to define the contribution of each resource in varying energy scenarios and assess them on basis of their reliability and economic viability.

6.3 Mathematical Model for Household Load Agent (E$_{HL}$)

The agent defines the household energy load varying on basis of time of operation and seasonal variations. The household energy load is calculated on basis of the equation 6.2.

$$\boldsymbol{E_{HL} = P_r \times P_q \times P_u} \qquad \text{Equation 6.2}$$

Where,

E_{HL} = Electricity consumed by appliances

P_r = Power rating of appliance

P_q= Number of electrical appliance

P_u = Usage of appliance during the week

The list of electrical appliances common across households of study typologies are already listed in Chapter 3, table 3.15. The average daily household electricity demand during different seasons are listed below in table 6.1, 6.2, 6.3 and 6.4.

Table 6.1 : Average Daily Household Electricity Consumption in Summer (March - June)

Appliance	Energy Usage (kWh/hour)	Number of Appliances	Usage Duration (hour)	Power Consumption (kWh)
Lighting	0.04	6	6	1.44
Refrigerator	0.07	1	24	1.68
Television	0.03	2	8	0.48
Air Conditioner	1.50	3	6	27.00
Washing Machine	1.00	1	0.5	0.50
Kitchen Equipment	4.60	1	0.5	2.30
Plug Loads	3.20	1	2	6.40
Laptop	0.06	1	4	0.24
Ceiling Fan	0.05	4	10	2.00
Air Cooler	0.30	2	8	4.80
Water Heater	1.00	2	1	2.00
Public Utilities	4.00	1	2	8.00
Average Daily Electricity Consumption in Summer (kWh)				**56.84**

Table 6.2 : Average Daily Household Electricity Consumption in Monsoon (July - September)

Appliance	Energy Usage (kWh/hour)	Number of Appliances	Usage Duration (hour)	Power Consumption (kWh)
Lighting	0.04	6	6	1.44
Refrigerator	0.07	1	24	1.68
Television	0.03	2	4	0.24
Air Conditioner	1.00	1	1	1.00
Washing Machine	1.00	1	1.5	1.50
Kitchen Equipment	4.60	1	0.5	2.30
Plug Loads	1.80	1	2	3.60
Laptop	0.06	1	4	0.24
Ceiling Fan	0.05	4	8	1.60
Water Heater	1.00	2	1.5	3.00
Public Utilities	5.00	2	0.5	5.00
Maintenance	0.50	1	2	1.00
Average Daily Electricity Consumption in Monsoon (kWh)				**22.60**

Table 6.3 : Average Daily Household Electricity Consumption in Autumn (October – November)

Appliance	Energy Usage (kWh/hour)	Number of Appliances	Usage Duration (hour)	Power Consumption (kWh)
Lighting	0.04	6	8	1.92
Refrigerator	0.07	1	24	1.68
Television	0.03	2	6	0.36
Room Heater	1.00	1	1	1.00
Washing Machine	1.00	1	0.5	0.50
Kitchen Equipment	4.60	1	0.5	2.30
Plug Loads	2.10	1	2	4.20
Laptop	0.06	1	3	1.80
Ceiling Fan	0.05	3	5	0.75
Water Heater	1.00	2	1.5	3.00
Public Utilities	5.00	2	0.5	5.00
Maintenance	0.50	1	3	1.50
Total Average Daily Electricity Consumption in Autumn (kW)				**24.01**

Table 6.4 : Average Daily Household Electricity Consumption in Winter (December - February)

Appliance	Energy Usage (kWh/hour)	Number of Appliances	Usage Duration (hour)	Power Consumption (kWh)
Lighting	0.04	8	8	2.56
Refrigerator	0.07	1	24	1.68
Television	0.03	2	7	0.42
Room Heater	1.00	2	7	14.00
Washing Machine	1.00	1	0.5	0.50
Kitchen Equipment	4.60	1	0.5	2.30
Plug Loads	2.10	1	2	4.20
Laptop	0.06	1	4	0. 24
Water Heater	1.00	2	2.5	5.00
Public Utilities	5.00	1	1.5	7.50
Maintenance	0.50	4	0.20	0.40
Average Daily Electricity Consumption in Winter (kWh)				**38.80**

The average daily electricity consumption in summer is 56.84kWh, winter it is 38.80kWh, in autumn it is 29.51kWh and for monsoon it is 28.60kWh. The annual electricity demand is around 38.30kWh/day or equivalent to 16,750kWh/year.

6.4 Mathematical Model for Solar Photovoltaic Agent (E_{PV})

The average monthly observed Global Horizontal Irradiance (GHI) in case of Chandigarh is indicated in table 6.5 and figure 6.1. The annual average value of GHI is equal to 5.21kWh/m^2/day.

Table 6.5 : Monthly Solar Radiation and Clearness Index of Chandigarh

Month	GHI (kWh/m^2/day)	Clearness Index	Month	GHI (kWh/m^2/day)	Clearness Index
January	3.25	0.50	July	5.60	0.69
February	4.36	0.55	August	5.42	0.68
March	5.70	0.63	September	5.39	0.66
April	6.80	0.69	October	4.96	0.62
May	7.32	0.69	November	3.98	0.54
June	6.46	0.70	December	3.19	0.50

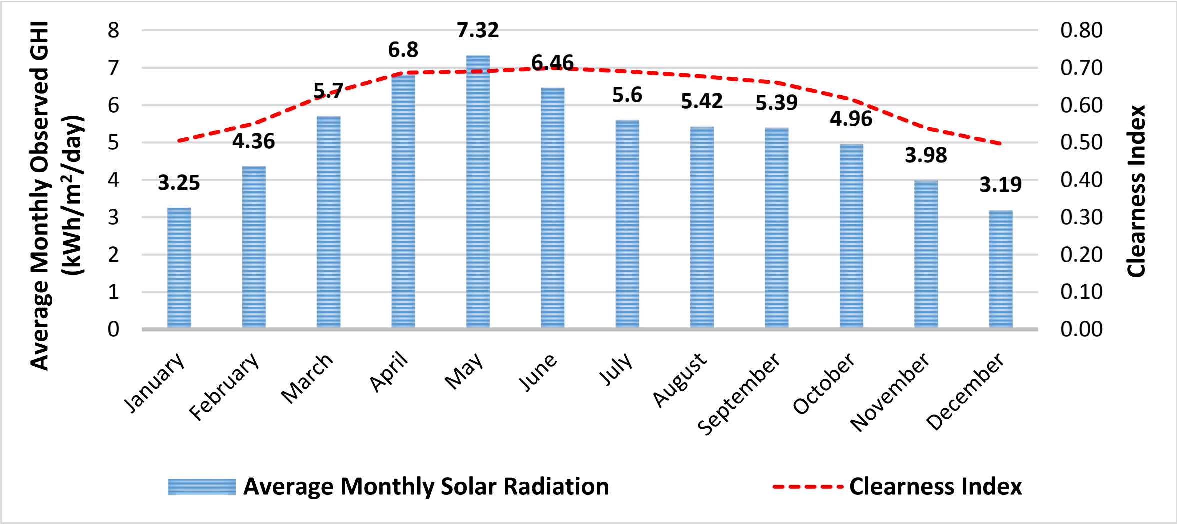

Figure 6.1: Average Monthly Observed GHI and Clearness Index of Chandigarh

The Solar PV power output from a PV array is calculated based on the equation 6.3.

$$E_{PV} = Y_{PV} \times F_{PV} \left(G_T / G_{T,STC}\right) \times \left[1+\alpha \left(T_C - T_{C,STC}\right)\right] \qquad \textbf{Equation 6.3}$$

Where,

E_{PV} = Solar energy generated by PV array

Y_{PV} = Rated capacity of the PV array (power output under standard test condition (kW)

G_T = Solar radiation incident on the PV array in current time step (kW/m^2)

$G_{T,STC}$ = Incident radiation at standard test condition (1 kW/m^2) F_{PV} = PV derating factor

α = Temperature co-efficient of power (% °C) T_C = PV cell temperature in current time (°C)

$T_{C,STC}$ = PV cell temperature under standard test condition (25°C)

Temperature effects the overall performance of Solar PV cells but if assumed that there is no effect of temperature on the PV array, then the temperature co-efficient of power (α) is considered to be zero and equation 6.4 is modified as:

$$E_{PV} = Y_{PV} \times F_{PV} \left(G_T - G_{T,STC}\right) \qquad \textbf{Equation 6.4}$$

6.5 Mathematical Model for Wind Turbine Agent (E_{WT})

The average monthly wind speeds of different RRUs based on CFD simulation described in Section 4.12 and 4.13 of Chapter 4 are listed in table 6.5 and displayed graphically in the figure 6.2.

Table 6.6 : CFD Simulation Based Monthly Average Wind Speed of RRUs

Month	Uppals Marble Arch, Manimajra	Sushma Elite Cross, Gazipur, Punjab	Sector 51, Chandigarh	Sector 19A, Chandigarh	Average Wind Speed (m/sec)
January	2.82	3.56	2.66	2.21	**2.81**
February	3.19	3.80	2.99	2.25	**3.06**
March	3.21	3.83	2.98	2.37	**3.10**
April	3.72	4.74	3.26	2.53	**3.56**
May	3.60	4.56	3.36	2.88	**3.60**
June	3.89	4.77	3.62	2.82	**3.77**
July	2.62	3.18	2.39	1.99	**2.55**
August	2.18	2.61	2.03	1.70	**2.13**
September	2.12	2.68	1.87	1.56	**2.06**
October	2.58	3.53	2.35	1.57	**2.51**
November	3.04	3.72	2.72	2.07	**2.89**
December	2.94	3.70	2.50	2.11	**2.81**

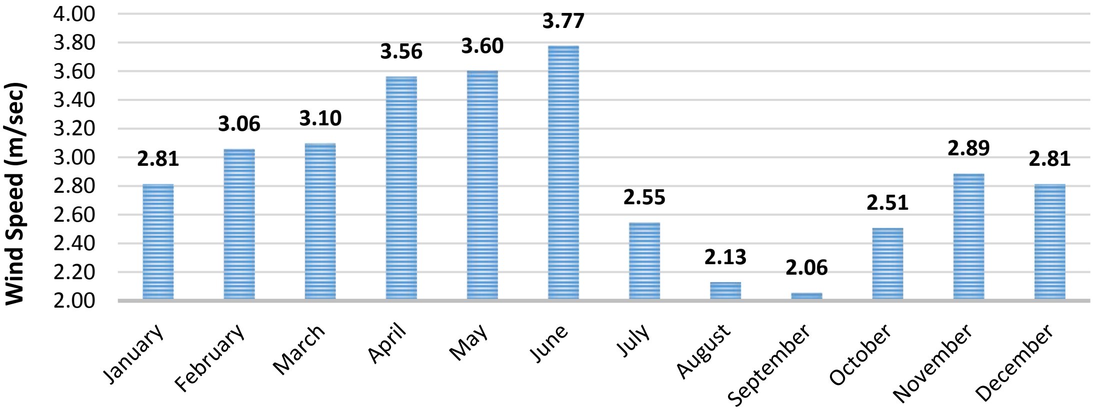

Figure 6.2: CFD Simulation Based Monthly Average Wind Speed of RRUs

The power output from a wind turbine can be computed on basis of the equation. 6.5.

$$E_{WT} = 0.5\, A\, \rho\, v^3\, C_p\, (\beta, \lambda) \qquad \textbf{Equation 6.5}$$

Where,

A = Rotor swept area in m^2

ρ = Air density in kg/m^3

V = Wind velocity (m/s)

C_P = Power coefficient of wind turbine

β = Pitch angle

λ = Speed ratio

6.6 Mathematical Model for Diesel Generator Agent (E_{DG})

The diesel generator is for standby power in case of any emergencies. The primary fuel consumed is diesel, but recent innovations have resulted in operating them with bio fuels. Replacing diesel with biofuels shall reduce the carbon emissions and make diesel generator a more viable energy option. Conversion of diesel generators based on biofuels into Combined Heat and Power (CHP) systems can aid in the process of heat generation as well as power.

The hourly fuel consumed by the diesel generator is given by the equation 6.6.

$$D_f(t) = \alpha_D P_{Dg}(t) + \beta_D P_{Dgr} \qquad \textbf{Equation 6.6}$$

Where,

$D_f(t)$ = Hourly fuel consumption of DG (l/h)

$P_{Dg}(t)$ = Average per hour of the DG

P_{Dgr} = DG rated power (kW)

C_P = Power coefficient of wind turbine

α_D and β_D = Coefficients of consumption curve (l/kWh)

For the purpose of the research α_D is considered equal to 0.246 l/kWh and β_D is considered equal to 0.08145 l/kWh.

6.7 Network and Configuration of the RHEM Model

The RHEM Model setup as displayed in figure 6.3 is designed to meet the electricity requirement of households. The primary sources of electricity in the model are solar PV, wind turbines and diesel generators.

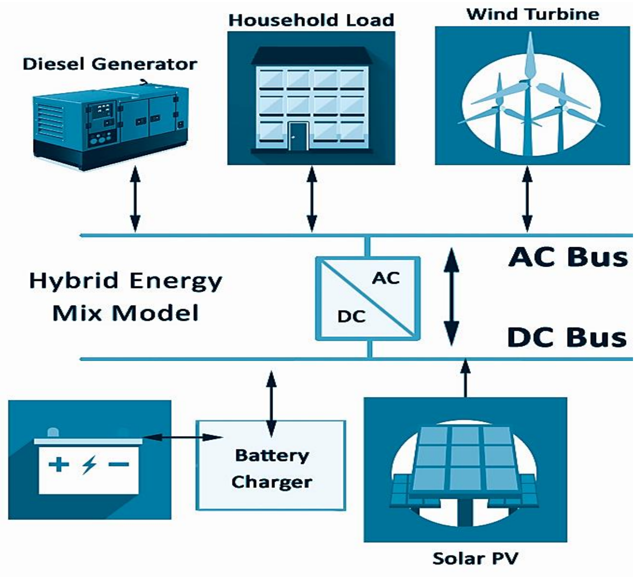

Figure 6.3 : Network Diagram of the Residential Hybrid Energy Mix (RHEM) Model

Excess power in the system is stored in the battery bank. In case of energy generated is less than actual demand the deficit is provided by the diesel generator. The batteries have to be charged and discharged periodically to prevent damage caused by overcharging or over discharge. Solar thermal based energy systems are not considered as part of the model.

In the whole process Solar PV, produces DC power whereas wind turbines and diesel generator generate AC power. Conversion of power from AC to DC or vice versa and regulating the supply of optimum voltage to charge the battery bank is done through a converter whereas DC to AC conversion is done by an inverter. An inverter is required when the excess power generated is to be transferred to the grid network, but the sizing of the RHEM configurations listed below is based on the assumption that total energy generated is consumed within the households.

6.7.1 Solar – Wind – Diesel – Battery Hybrid Network

The system comprises of Solar PV array and battery bank on DC supply and wind turbines with diesel generator on AC supply. Control of flow between both AC and DC is handled by a converter. In normal mode, solar array and wind turbine charge the battery which in turn meets household demand. Diesel generator is used to charge batteries if both the RES are unable to charge the batteries or need to be shut down for maintenance.

In case of DC voltage exceeding the maximum battery voltage and demand less than the generation from solar and wind turbines the system is disconnected from the battery bank and connected to the grid. After the DC voltage reaches the optimal battery bank voltage it will restart charging the batteries.

To prevent excessive discharge that can lead to lowering of battery lifecycle and efficiency in case of DC voltage decreasing below the battery voltage the battery bank stops recharging and supply is cut-off. Compensation for the loss of power is done by provision of emergency power from the diesel generator. On achieving the desired recharging voltage from Solar PV and wind the supply is again transferred to the battery pack.

6.7.2 Solar – Diesel – Battery Hybrid Network

The system similar to a standalone system comprises of solar PV array, battery bank and diesel generator for charging. To meet the load based on only solar resource the size of PV array and the battery bank is increased. The utility of diesel generator also increases to compensate for electricity shortage especially at night.

6.7.3 Wind – Diesel – Battery Hybrid Network

The basic system comprises of wind turbines, battery bank and diesel generator. As wind is a day and night time resource there are chances that the battery bank may get overcharged. The excess power may be diverted to the grid through introduction of an AC inverter.

6.7.4 Solar – Wind – Battery Hybrid Network

This system has no backup power option due to lack of diesel generator. To compensate the same the battery bank size needs up scaling as per demand and matching with the power output from wind turbines and solar PV array.

6.8 Specification and Constraints of the RHEM Model Components

The components and their specifications as part of the RHEM Model setup are listed in table 6.7. The pricing of the components in Indian Rupees are based on their actual market price or with reference to cost of components with similar specifications in existing literature.

Table 6.7 : Specifications of Various Components of RHEM Model

Solar PV Module		**Wind Turbine**	
Component	**Specification**	**Component**	**Specification**
Rated Power	1 KW	Rated Power	1 KW
Lifetime	20 years	Lifetime	15 years
Derating factor	90%	Start up speed	3 m/s
Capital cost	INR 80,000/KW	Capital cost	INR 55,000/KW
Replacement cost	INR 80,000/KW	Replacement cost	INR 55,000/KW
O & M cost	INR 2,000/year	O & M cost	INR 5,000/year
		Rotor Diameter	3 m
Diesel Generator (Generac 50kW Protector)		**Battery Bank**	
Component	**Specification**	**Component**	**Specification**
Intercept coefficient	1.65 l/hour/kW	Nominal voltage	4 V
Lifetime	15 years	Nominal capacity	1,900 Ah(7.6 KWh)
Slope	0.273 l/ hour/kW	Lifetime throughout	10,569kWh
Power capacity	50kW	Capital cost	INR 50,500
Density	820kg/m^3	Replacement cost	INR 32,500
Capital cost	INR 5,00,000	O & M cost	INR 1,100 /year

Table 6.8 : Constraints of various components in the RHEM Model

Solar PV Array (kW)	Wind Turbine (Number)	Diesel Generator (kW)	Battery (Number)	AC/DC Converter (kW)
0	0	0	0	50
10	1	25	5	60
25	2	50	10	70
50	5	60	15	80
75	8	70	20	90
100	10	80	25	100
125	12	90	30	110
Max. 150	Max. 15	Max. 100	Max. 35	Max. 120

The optimization of the RHEM model is undertaken at two stages, as detailed out in Chapter 2, Section 2.5.1. The first step deals with Power Balance Constraint defined by the equation 6.7.

$$E_{\textit{Solar PV}} + E_{\textit{Wind Turbine}} + E_{\textit{Diesel Generator}} + E_{\textit{Battery}} = E_{\textit{Household Load}} + E_{\textit{Unmet}} + E_{\textit{Loss}} + E_{\textit{Excess Power}} \quad \textbf{Equation 6.7}$$

The second step is to rank the options on basis of Net Present Cost (NPC) and levelized Cost of Energy (COE), as detailed out in Chapter 2, Section 2.5.2 and define the most economical solution of all the options.

6.9 Sizing and Optimization of the Residential Hybrid Energy Mix (RHEM) Model

System sizing and optimization of the hybrid energy networks is undertaken using HOMER (Hybrid Optimization Model for Multiple Energy Resources) software. Each of the hybrid energy networks highlighted in section 6.7 along with two standalone networks comprising of solar PV array or wind turbine with battery bank are subject to optimization based on variation in system size constraints indicated in table 6.7. The hybrid energy networks are:

i) Solar – Wind – Diesel – Battery Hybrid Network (T_{SWDB})
ii) Solar – Diesel – Battery Hybrid Network (T_{SDB})
iii) Wind – Diesel – Battery Hybrid Network (T_{WDB})
iv) Solar – Wind – Battery Hybrid Network (T_{SWB})
v) Solar – Battery Hybrid Network (T_{SB})
vi) Wind– Battery Hybrid Network (T_{WB})

The sizing of a hybrid energy network capable to produce 100kW/day as listed in table 6.9 indicates, solar-wind-battery (T_{SWB}) and solar-battery (T_{SB}) based hybrid energy networks are the most economical with lowest NPC and COE values. It also indicates that wind-diesel-battery (T_{WDB}) and standalone wind--battery (T_{WB}) based energy networks using micro wind turbines are not economically viable in urban settings with low wind speeds.

Table 6.9 : Sizing of a 100kW/day Hybrid Energy Network

Hybrid Energy Network	Solar Power (kW)	Wind Turbine (Number)	Diesel Generator (kW)	Battery (Number)	AC/DC Converter (kW)	Total NPC (Rs)	COE (Rs / kWh)
T_{SWDB}	36.7	1	5	45	18.6	1,10,00,000	23.35
T_{SDB}	39.0	-	5	50	20.4	1,10,00,000	23.61
T_{WDB}	-	0	0	0	0	0	0
T_{SWB}	34.0	1	-	72	21.8	1,04,00,000	22.05
T_{SB}	36.7	-	-	78	20.7	1,05,00,000	22.19
T_{WB}	-	0	-	0	0	0	0

6.10 RHEM Infrastructure Specific to Typology

Based on the scenario in table 6.8 the area required for setting up a 100kW/day hybrid energy unit based on each of the energy networks is highlighted in table 6.10. As a thumb rule for every 1kW of solar PV installation area requirement is considered as 10sqm, and for 11kW wind turbine as per standard manufacturer specifications the area is considered to be 135sqm. In case of diesel generator as per standard manufacturer specifications the area for a 50kW diesel generator is considered to be 40 sqm. Area required for the battery pack and AC/DC inverter are not considered as the room containing them requires negligible area in comparison to the RES infrastructure.

Table 6.10 : Area required on roof and ground for setting up of 100kWh Hybrid Energy System

Hybrid Energy Network	Solar PV Output (kW)	Area required for Solar PV (sqm)	Wind Turbine (number)	Area required for Wind Turbine (sqm)	Area required for DG (sqm)	Area required on Roof (sqm)	Area required on Ground (sqm)
T_{SWDB}	36.7	367	1	135	40	367	175
T_{SDB}	39.0	390	-	-	40	390	40
T_{SWB}	34.0	340	1	135	-	340	135
T_{SB}	36.7	367	-	-	-	367	-

6.10.1 Uppals Marble Arch, Manimajra, Chandigarh

In case of Uppals Marble Arch the plot area is 21,850sqm and with a ground coverage of 40%, the ground and roof area are equal to 8740sqm. With 144 households and an average household energy demand of 38.30kWh/day the overall daily energy demand of Uppals Marble Arch is 5,515kWh/day or 230kW/day. The energy mix to meet the average household energy demand is highlighted in table 6.11.

Table 6.11 : Sizing of a Hybrid Energy Network to meet Average Household Energy Demand

Hybrid Energy Network	Solar Power	Wind Turbine	Diesel Generator	Battery	AC/DC Converter	Total NPC	COE
	kW	number	kw	number	kw	Rs	Rs/kWh
T_{SWDB}	12.3	1	5	17	9.24	57,20,000	31.46
T_{SDB}	14.0	-	5	20	9.07	55,40,000	30.49
T_{SWB}	11.7	1		26	9.37	41,50,000	22.86
T_{SB}	15.4	-	-	27	8.87	40,00,000	22.06

The energy mix and the area requirement to meet energy demand of 144 households of Uppals Marble Arch are listed in table 6.12.

Table 6.12 : Energy mix and area requirements for Hybrid Energy Systems at Uppals Marble Arch, Manimajra, Chandigarh

Hybrid Energy Network	Solar PV Output	Area for Solar PV (sqm)	Wind Turbine	Area for Wind Turbine (sqm)	Diesel Generator Output	Area for Diesel Generator (sqm)	Installation area required on Roof (sqm)	Installation area required on Plot (sqm)
	kW	A_{SP}	number	A_{WT}	kW	A_{DG}	A_{Roof}	A_{Plot}
T_{SWDB}	1,771	17,710	13	1,755	720	560	17,710	2,315
T_{SDB}	2,016	20,160	-	-	720	560	20,160	560
T_{SWB}	1,685	16,850	13	1,755	-	-	16,850	1,755
T_{SB}	2,218	22,180	-	-	-	-	22,180	-

Based on table 6.12, it can be observed that the installation area required on roof (A_{Roof}) for Solar PV panels is higher than the actual roof area of 8740 sqm in Uppals Marble Arch. Considering that only 60% of the total roof area is available as discussed in Chapter 5, Section 5.5 for the purpose of Solar PV generation the actual potential of the roof is reduced to 524kW.

In the case of wind and diesel generators the total area required for setting up wind turbines and diesel generators is around 2,315sqm. Expecting that the installation of the wind and diesel infrastructure shall be done on the ground due to their physical criteria the area that they will occupy is about 10.2% of site area.

6.10.2 Sushma Elite Cross, Gazipur, Punjab

Sushma Elite Cross is built on a plot of area 43,700sqm and with a ground coverage of 40%, the ground and roof area are equal to 17,480sqm. With 320 households and an average household energy demand of 38.30kWh/day the overall daily energy demand of Sushma Elite Cross is 12,256kWh/day or 511kW/day.

The energy mix and the area requirement to meet energy demand of 320 households of based on table 6.11 are listed in table 6.13.

Table 6.13 : Energy mix and area requirements for Hybrid Energy Systems at Sushma Elite Cross, Gazipur, Punjab

Hybrid Energy Network	Solar PV Output	Area for Solar PV (sqm)	Wind Turbine	Area for Wind Turbine (sqm)	Diesel Generator Output	Area for Diesel Generator (sqm)	Installation area required on Roof (sqm)	Installation area required on Plot (sqm)
	kW	A_{SP}	number	A_{WT}	kW	A_{DG}	A_{Roof}	A_{Plot}
T_{SWDB}	3,936	39,360	30	4,050	1,600	1,280	39,360	5,330
T_{SDB}	4,480	44,800	-	-	1,600	1,280	44,800	1,280
T_{SWB}	3,744	37,440	30	4,050	0	0	37,440	4,050
T_{SB}	4,928	49,280	-	-	-	-	49,280	-

Based on table 6.13, it can be observed that the installation area required on roof (A_{Roof}) for Solar PV panels is higher than the actual roof area of 17,480 sqm in Sushma Elite Cross. Considering that only 60% of the total roof area is available as discussed in Chapter 5, Section 5.5 for the purpose of Solar PV generation the actual potential of the roof is reduced to 1,050kW. In the case of wind and diesel generators the total area required for installing wind turbines and diesel generators is 12.2% of site area.

6.10.3 Housing Society in Sector 51, Chandigarh

The housing society in Sector 51, Chandigarh is built on a plot of area 9,300sqm and with a ground coverage of 40%, this results in ground and roof area of 3,720sqm. With 168 households and an average household energy demand of 38.30kWh/day the overall daily energy demand of the housing society is 6,435kWh/day or 268kW/day. The energy mix and the area requirement to meet energy demand of 168 households of based on table 6.11 are listed in table 6.14.

Based on table 6.14, it can be observed that the installation area required on roof (A_{Roof}) for Solar PV panels is higher than the actual roof area of 3,720 sqm in Sushma Elite Cross. Considering that only 60% of the total roof area is available as discussed in Chapter 5, Section 5.5 for the purpose of Solar PV generation the actual potential of the roof is reduced to 2,230kW. In the case of wind and diesel generators the total area required for installing wind turbines and diesel generators is 17.5% of site area.

Table 6.14 : **Energy mix and area requirements for Hybrid Energy Systems at Housing Society in Sector 51, Chandigarh**

Hybrid Energy Network	Solar PV Output	Area for Solar PV (sqm)	Wind Turbine	Area for Wind Turbine (sqm)	Diesel Generator Output	Area for Diesel Generator (sqm)	Installation area required on Roof (sqm)	Installation area required on Plot (sqm)
	kW	A_{SP}	number	A_{WT}	kW	A_{DG}	A_{Roof}	A_{Plot}
T_{SWDB}	2,066	20,664	7	945	840	680	20,664	1,625
T_{SDB}	2,352	23,520	-	-	840	680	23,520	680
T_{SWB}	1,966	19,656	7	945	-	-	19,656	945
T_{SB}	2,587	25,872	-	-	-	-	25,872	-

6.10.4 1 Kanal Plotted House in Sector 19A, Chandigarh

The plotted house in Sector 19A, Chandigarh is built on a plot of area 500sqm and with a ground coverage of 50%, this results in ground and roof area of 250sqm. The average daily household energy demand is equal to 38.30kWh/day. The energy mix and the area requirement to meet the energy demand of the household are based on table 6.11 are listed in table 6.15.

Table 6.15 : **Energy mix and area requirements for Hybrid Energy Systems of 1 Kanal House, Sector 19A, Chandigarh**

Hybrid Energy Network	Solar PV Output	Area for Solar PV (sqm)	Wind Turbine	Area for Wind Turbine (sqm)	Diesel Generator Output	Area for Diesel Generator (sqm)	Installation area required on Roof (sqm)	Installation area required on Plot (sqm)
	kW	A_{SP}	number	A_{WT}	kW	A_{DG}	A_{Roof}	A_{Plot}
T_{SWDB}	12.3	123	1	135	5	40	123	175
T_{SDB}	14.0	140	-	-	5	40	140	40
T_{SWB}	11.7	117	1	135	-	-	117	135
T_{SB}	15.4	154	-	-	-	-	154	-

Based on table 6.15, it can be observed that the installation area required on roof (A_{Roof}) for Solar PV panels is less than the actual roof area of 250 sqm. Considering that only 60% of the total roof area is available as discussed in Chapter 5, Section 5.5 for the purpose of Solar PV generation the actual potential of the roof is higher. But, orientation has a major impact in the case of plotted units and certain roofs have negligible potential than others as a result when looked at from a neighbourhood scale the effective roof area is almost half of the actual. Also, vegetation has a greater impact on the wind potential as a result only solar and diesel generator option is viable for plotted development.

From the tables 6.11 to 6.15 it is evident that Solar PV based standalone system are the most economical option than any other hybrid model. This is because of the efforts put by various agencies in the development and setting up of Solar PV infrastructure facilities and promotion of Solar Cities across India. It also raises queries that wind based urban level microgeneration is still under neglect which is quite visible by the cost of micro wind turbines. Comparison of per kW capital cost of wind turbines is almost double to that of Solar PV, whereas the production of solar panels is a high energy and cost intensive process in comparison to wind turbines.

6.11 Area Requirements for Installation of Hybrid Energy Systems

The installation of the RHEM infrastructure in each of the housing typologies requires a portion of area to be devoted either on the roof or on the plot. With reference to table 6.11 to 6.15 it is observed that in the high rise and medium rise category after 60% area is assigned for Solar PV infrastructure the area left can accommodate only 24-26% of the proposed Solar PV infrastructure.

Table 6.16 : Roof Area requirement for Solar Infrastructure as part of Hybrid Energy Model across Typologies

Hybrid Energy Network	**Uppal Marble Arch**		**Sushma Elite Cross**		**Sector 51 Chandigarh**		**Sector 19A Chandigarh**	
	Area required for Solar PV	**% of Roof Area**	**Area required for Solar PV**	**% of Roof Area**	**Area required for Solar PV**	**% of Roof Area**	**Area required for Solar PV**	**% of Roof Area**
T_{SWDB}	17,710	203	39,360	225	20,664	555	123	49
T_{SDB}	20,160	231	44,800	256	23,520	632	140	56
T_{SWB}	16,850	193	37,440	214	19,656	528	117	47
T_{SB}	22,180	254	49,280	282	25,872	695	154	62

Table 6.16 indicates that the area required for installation of Solar PV hybrid infrastructure on the roof of housing units is less than the available roof area. There is a need to search for opportunities to enhance the area required for Solar PV installation. This can be achieved by the following measures:

i) Spaces in between buildings especially the case of high and medium rise units at roof level.
ii) Open landscape areas can be exploited for the same.
iii) Building Integrated Photo Voltaic (BIPV) can be another avenue to be explored.
iv) Balconies and shading devices can be integrated with Solar PV panels.
v) Atriums and cutouts can be covered with Photo Voltaic integrated glass panels.

Table 6.17 : Site Area requirement for Wind and Diesel Generator based Infrastructure as part of Hybrid Energy Model across Typologies

Hybrid Energy Network	Uppal Marble Arch		Sushma Elite Cross		Sector 51 Chandigarh		Sector 19A Chandigarh	
	Area for Wind / DG Infra.	% of Site Area	Area for Wind / DG Infra.	% of Site Area	Area for Wind / DG Infra.	% of Site Area	Area for Wind / DG Infra.	% of Site Area
T_{SWDB}	2,315	10.6	5,330	12.2	1,625	17.5	-	-
T_{SDB}	560	2.6	1,280	2.9	680	7.3	-	-
T_{SWB}	1,755	8.1	4,050	9.3	945	10.2	-	-

The Sector 19A, Chandigarh plotted typologies have not been considered for wind and diesel based infrastructure assessment due to the inherent weaknesses of the housing typology in promotion of both the energy systems. Wind energy is impacted due to the presence of vegetation and the plotted sectors of CUC have the maximum density of trees and diesel generators at individual household level are smaller in output and are not efficient in comparison to units with higher output. Also, both wind and diesel systems if incorporated shall consume 35% of site area which is not feasible.

With reference to table 6.17 it is observed that on an average wind and diesel based infrastructure incorporated at the site level rather than the roof consume around 10-12% of the plot area. In case of future housing development if it can be ensured that at least 10-12% site area will be considered as non-buildable and used for inclusion and promotion of RES through mandatory measures.

Apart from the area required for the installation of the infrastructure, wind energy on ground can be considered only in case of bigger housing development with collective open space all around the wind turbine spanning a distance equivalent to the height of wind turbine hub. This could be attributed to the installation and maintenance of the wind turbine and also as a safety factor in case of damage to the structural form of the wind turbine. This would also ensure good flow of winds in the swept area of the turbine.

Similarly in case of diesel generator ancillary space would be required for stocking and storage of the fuel. Liquid fuels like diesel can be stored in underground storage tanks, whereas biomass and solid fuels based CHP generators require storage containers or rooms which are not considered as part of the study.

6.12 Energy Balancing of the RHEM Model

The energy balancing of the various RHEM models is undertaken based on Chapter 2, equation 2.24 and displayed in table 6.18. This is to ensure that each of the hybrid energy network models is complete and the equation is balanced. This also gives an idea about the contribution of individual RES and the overall energy that is actually in use by the end user to balance the household load.

Table 6.18 : **Energy Balancing Parameters of the different Hybrid Energy Network Models**

Hybrid Energy Network	Production (kWh/Year)				Consumption (kWh/Year)	Unused Energy (kWh/Year)		
	E Solar PV	E Wind Turbine	E Diesel Generator	E Battery	E Household Load	E Excess Power	E Unmet	E Loss
T_{SWDB}	17,710	3,902	93	3,736	14,052	10,930	292	163
T_{SDB}	20,160	0	117	4,172	14,052	8,592	952	844
T_{SWB}	16,850	3,902	0	5,262	14,040	10,178	879	910
T_{SB}	22,180	0	0	5,106	14,040	11,621	769	853

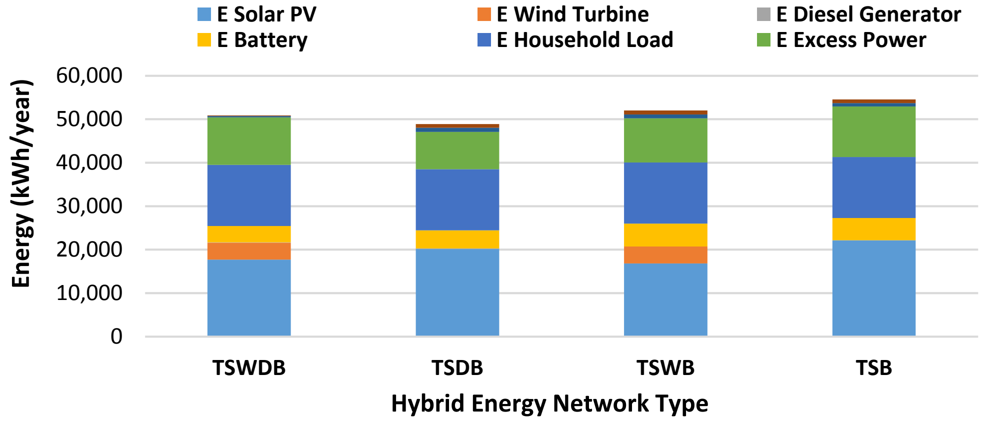

Figure 6.4 : **Energy Contribution by each of the Energy Balancing Parameter as part of the Hybrid Energy Network**

6.13 Conclusion

The RHEM Model is an attempt to make end user understand the benefits of renewable energy primarily solar and wind. To reduce the cost of the infrastructure and sharing of resources especially at neighbourhood and group housing level proper scheduling and time based utilization of the resources needs to be undertaken. The research undertaken has investigated different fuel choices and their operation cycles as a result defining the economic implications, system configurations and emissions.

It is observed that a portion of the site ranging between 10-12% needs to be set aside as part of development controls for the promotion and installation of wind and diesel based energy infrastructure. With the available roof space split into 60% for installation of Solar PV infrastructure and remaining 40% left for essential services, the Solar PV layout possible is only 24-26% of actual installation potential. Various avenues like interconnected roof policy in case of high and medium rise housing need to be devised for enhancing the area for solar PV integration on the roofs. Solar and wind based energy systems are costly in terms of energy production. The overall system cost could be reduced by understanding the ideal time of year when each of this resource performs well and accordingly scheduling may be done. To reduce the extra burden of diesel generator, urban scale biomass setup could be connected to the public waste from toilets of housing units provided there is enough storage space to generate local level fuel and through Combine Heat and Power (CHP) Systems generate both heat and power at times when both solar and wind cannot perform at their maximum levels.

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Chapter 7

Future Research Avenues

7.1 Future Architecture

The research undertaken as part of the present thesis within the perspective of architecture is a humble beginning to explore the vast potential of microgeneration within the setup of existing housing. The research is a step towards understanding the role of renewable energy based microgeneration in meeting the energy requirement of the built environment. The architect centric viewpoint of the research is of significance as designers or creators of the built environment they generally have the least say in energy decisions.

There is a greater need to disseminate information through a visual platform to homeowners and architects who are otherwise bound by framed guidelines for strengthening the decision making process. The research also raises questions regarding our ancient wisdom such as the 'Solar Envelope' concept, which seems to have been forgotten or not made use of in building design in real sense. With changing times and needs, it is necessary that such concepts are reincorporated into modern day computational tools to once again enrich the field of architecture. The tools can aid in making human centric decisions that lead to economically, socially and environmentally sustainable designs.

The research paves way for fellow architects, designers, programmers to work on various avenues highlighted below that range from defining the new built form of the future world that ensures sunlight to every household to creating visual toolkits for the home owners. Housing and infrastructure planners can relook at the house and its occupants as the basis for defining energy based solutions rather than the other way round. With increasing trend towards high rise high density housing, redefining energy demand with respect to density can aid in defining new energy sources and their performance at the household and community level.

7.2 Reframing of Building Controls to Promote Solar and Wind Microgeneration

With due consideration to the international law of 'Right to Sun' there is a need for relooking at our present building controls or byelaws and with the aid of modern day computational tools frame new rules that ensure that every individual household gets a definitive amount of sun and wind . This can ensure each household to be part of the microgeneration initiative. The attempt is not to generate energy only but also to address energy performance of household based on climate and user behaviour (Laurentis & Hunt, 2012). A single initiative empowering the end user in various stages of energy management setup can thereby automatically address issues dealing with energy wastage and conservation. Wind and Solar energy and their potential have already been looked into as part of existing housing in the research but future researchers should define guidelines for future housing wherein wind and sun can be exploited as an energy resource through modification of built forms.

7.3 Creation of Visual Interactive Tools Interlinking Built Form and Microgeneration

A major reason behind microgeneration infrastructure not meeting desired targets is lack of information dissemination among the architects and end user primarily home owners. There is a need to develop a visual platform that acts as a ready reckoner in decision making process and addresses concerns regarding incorporation of microgeneration infrastructure. Home owners can choose from a varied list of retrofit options each supported by details about the energy generation potential of the option, financial model, technical information, carbon savings and return on investment (Gupta et al., 2017). For the architects, the decision tool can be a guide in making decisions about upgradation of existing housing stock through retrofit and integration of renewable energy infrastructure into new design proposals right from the conceptual stage. The development of evolutionary computational tools specifically dealing with multi criteria analysis and optimization can aid in optimum design solutions.

7.4 Impact of Residential Density Patterns and Household Occupancy on Microgeneration

The successful implementation of renewable infrastructure is dependent on the timely utilization of energy generated as a major portion of the energy generation is based on real-time solar and wind resource. In the absence of the end user the generated energy has to be stored in batteries which have inherent short comings. As a result creation of vast banks of storage batteries is not a viable option as it also incurs high investment and maintenance cost (Adam et al., 2016). It is therefore necessary to link residential density patterns and household occupancy rate with energy demand which shall guide the renewable generation and storage requirement. This shall ensure reduction in wastage of investment on unutilized renewable infrastructure, also with time technology becomes redundant as a result the investment saved could be utilized at a later date for infrastructure upgradation.

7.5 Conclusion

The growing awareness towards energy conservation amongst home owners and architects is now expanding towards a new domain – energy generation. Within the built environment the chapter tries to identify future potential avenues of research that shall aid in the development of new guidelines, creation of new tools and interaction platforms. Emphasis should be to relate energy based goals that can be achieved as an outcome of built form development and usage patterns rather than forcing mandatory guidelines for installation of RES infrastructure irrespective of the above considerations.

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Chapter 8

Summary, Findings and Recommendations

8.1 Micro Generation Potential in Housing Typologies

Solar and wind based energy sources are the key to meet the increasing energy demand in the future without emitting carbon di oxide emissions. With the domestic sector being the second major consumer of electricity and increasing urbanisation leading to increase in high rise built spaces the energy demand is going to increase. The research undertaken in the previous chapters gives an insight into the challenges of tapping both the renewable resources and enhancing their potential in the context of the built environment specifically the housing sector. The novelty of the research is based on the fact that there are hardly any or no major existing studies with an architect's perspective that relate the performance of wind resource within the context of housing sector across different typologies. The study reflects the behaviour of wind in the various housing typologies and defines measures for setting up of wind based infrastructure.

The second part of the study highlights the role of solar resource in not only generating energy but also giving shape to the built environment. The study looks into the technical possibilities of generating solar energy within the existing character of the housing typologies through rooftop solar PV systems with the aim is to generate 10% of household energy demand daily through solar energy as envisioned by the 'Solar City' concept. The concept of 'Solar Envelope' is relooked at with respect to the plotted typologies of Chandigarh Urban Complex (CUC) so as to ensure that each household receives sunlight for a certain duration of the day.

The study also felt the need that architects need to upgrade themselves with modern tools addressing multi-dimensional parameters so that the design decisions can answer multi-level issues. The use of computational tools to simulate scenarios can lead to more realistic solutions. The Residential Hybrid Energy Mix (RHEM) model proposed though in its nascent stage can be a major decision making tool for both architects and home owners to define the potential of solar and wind resources in meeting household energy demand.

8.2 Summary of the Studies

Renewable energy planning and management by creating the right energy mix and bi-directional energy chain conditions shall be the guiding criteria for a sustainable energy future across housing sector. There is a need to understand the role of small and microgeneration energy systems based on renewable energy resources at the household level and their contribution towards energy targets. The attempt is not to meet the operational energy demand but also integrating the end user into the energy management system so as to reduce energy wastage.

There are concerns associated with existing strategies from the perspective of an end user and the architect that need to be addressed. The first concern with existing strategies is that they are technical in nature but there is a need to understand the actual potential of urban level renewable resources like solar, wind and biomass considering the architectural character and built form configuration of various housing typologies. The second concern that needs investigation is the ideal conditions under which these resources either on standalone or combined hybrid mode become viable energy sources for the housing community. The third concern is related to ways of empowering the home owners in making a conscious decision about choice of renewable energy infrastructure rather than forcing them to follow a set of guidelines.

8.2.1 Answers to the Research Questions

The study undertook various technical studies and through application of computational skills addressed the concerns raised during different stages of the research. Some of the pertinent questions that directly link the potential and application of solar and wind resource in housing typologies are addressed below:

Research Question 1:

How do existing typologies of Chandigarh Urban Complex perform with respect to wind based microgeneration?

Chandigarh experiences major portion of annual wind flow from North-West to South-East but the highest velocity winds are observed in the months from April to June from South-East to North-West. The average wind speed derived from observed wind data of 2010-15 is 2.26m/sec. Based on the observed wind data and statistical analysis undertaken the mean wind speed derived is 2.19m/sec. The four Representative Residential Units (RRUs) studied as part of the research displayed the following results:

1. **Low Rise Detached, Semi-detached and Row Housing:** Low height housing units with narrow setbacks in between them cause for vertical rise of the winds resulting in the hub height of wind turbine to be installed at 15-18 meters from the ground. The average wind velocity lies in between 1.8 – 2.4m/sec resulting in average wind energy of 135kWh/m^2.

2. **Low Rise Group Housing:** The linear blocks perpendicular to the wind flow cause for the air rising upwards and shadowing other blocks. But the staggered street canyons resulted in concentration of wind near the roof. The hub height in this case can be 18-20 meter from ground. The average wind velocity ranging between 2.8 – 3.3m/sec result in average wind energy of 185kWh/m^2.
3. **Medium Rise Group Housing:** The units are placed parallel to the wind flow as a result there is no turbulence and wind speed remained static. The width to height ratio of the street canyon between the blocks is almost equal to one as a result wind concentration happens in between the blocks at the entrance to the canyon above the ground level. The wind velocity at this point reach up to 3.86-4.15m/sec. Wind turbines with hub height of 10-18 meter from ground can capture more consistent winds. Alternatively, wind turbines placed about 2.5 meter above the roof receive winds with velocity ranging between 2.5-4.0m/sec results in average wind energy of 220kWh/m^2.
4. **High Rise Apartments:** With increasing height wind velocity also increases. In the high rise apartments the hub height can be 40-42 meter above the ground but such infrastructure cannot be installed within a housing society so smaller units of similar capacity can be installed 4-6 meter above the roof. The width to height ratio between the blocks is less than one as a result wind concentrations in between the blocks happen near the roof level. Measures to install wind turbines near the roof level in between the blocks need to be explored as the concentration of winds reach speeds up to 4.8-5.7m/sec. The average wind velocity ranges between 2.4-4.2m/sec resulting in average wind energy of 380kWh/m^2.

Medium rise groups housing and high rise apartments exhibit great potential in the promotion of wind based microgeneration. The only limitation of the assessment is the absence of vegetation based roughness layer due to limitations in the Computational Fluid Dynamics (CFD) simulation. The average wind speeds and corresponding energy output can go through change.

Research Question 2:

How do existing typologies of Chandigarh Urban Complex perform with respect to solar based microgeneration?

Major sectors of CUC are laid out on a grid aligned at an angle of 38° ensuring maximum exposure to South-East, South and South-West and also permitting ideal orientation for the prevalent North-West to South-East winds. The inherent weakness of this layout is that some plots can be major contributors towards solar energy generation whereas others lack the requisite sunlight hours and shadow free area to generate solar energy. The ideal orientation of units to maximize solar potential is 38° towards South-East and major physical construction on roof in North-West direction. The solar potential of the housing typologies is dependent on the shadow free roof area. The study highlights that under regular circumstances the effective shadow free area is less than 30% of total roof area.

The four type of RRUs that were studied as part of the research displayed the following results:

1. **Low Rise Detached, Semi-detached and Row Housing:** The plotted development exhibits varied results depending upon the form and orientation of the unit. Some of the units overshadow others thereby influencing their contribution. On an average solar based microgeneration can generate 14% of peak energy demand.
2. **Low Rise Group Housing:** The low rise group housing unit though consistent in output suffers because of low width of each block resulting in shadowing by building elements like parapet and mumty. Solar based microgeneration can generate 14% of peak energy demand.
3. **Medium Rise Group Housing:** On basis of technical and simulated assessment the medium rise housing typology with connected roofs has highest solar generation potential. This typology can generate 46% of its peak energy demand through solar microgeneration.
4. **High Rise Apartments:** The vertical high rise typology has the inherent weakness of less roof area compared to overall builtup area. The low roof area can be compensated with raised platforms above the mumty level and used for solar panel integration. The roofs in their natural order can generate only 8% of their peak energy demand but use of elevated platform results in 36% of peak energy demand.

Apart from individual cases, certain common observations for all the typologies are:

1. Angle of inclination of solar panels to roof plane facing south is estimated as 36°.
2. Parapet height on terrace shall be less than 0.45 m or in case of accessible terrace parapets should have transparent extensions to maximize shadow free area and ensure safety.
3. Physical construction on North-East side of roof maximizes shadow free area for solar panels.
4. Building Integrated Photovoltaic (BIPV) integration needs exploration.
5. Exploration of balconies, shading devices and spaces in between blocks in high and medium rise typologies as potential solar PV sites needs to be undertaken.
6. Solar power system can generate 25% of average household demand under ideal conditions.

Research Question 3:

What would be the character of the Residential Hybrid Energy Mix (RHEM) Model? How would it aid in choosing between stand-alone and hybrid renewable energy systems for housing?

Based on the study, existing concept of solar city is wrongly interpreted as a process based on retrofit measures by installing solar panels and meeting quantitative targets. It takes more to ensure that every household has equivalent contribution towards solar energy generation. The RHEM model tries to relate total household energy demand to total power generated from solar and wind based renewable sources. The RHEM model proposed in the study also adds diesel generator with the renewable energy sources to act as a backup option in case of emergency.

The RHEM runs on the principle that solar and wind systems will recharge a battery bank through an AC-DC converter. The battery bank shall run the necessary loads thereby getting discharged. In case the battery is going to be completely discharged the supply from battery is disconnected to protect the banks from damage and the power is supplied from diesel generator. Solar and wind will keep charging the battery. In case the charging rate is higher than actual load that can lead to overcharging and damage to battery bank, the charging connection is shut down and connected to the main supply. If the household loads are absent the additional load produced is transferred to an inverter and sold to the grid.

The RHEM model is customizable as it works with more than one energy choice. Depending on the availability of the resource the microgeneration potential can be varied on the same network. If seasonal variations are good for wind based generation but effect the performance of solar system then only the wind based energy generation is permitted, but if the situation improves solar based systems shall also be part of energy generation. At night solar resource is absent so from a hybrid energy system till the sun hours the system transforms into a stand-alone system based on wind energy.

8.3 Recommendations for Promotion of Solar and Wind based Energy Systems in Housing

The findings from the research are defined into a set of recommendations that can guide the integration of solar and wind based renewable infrastructure in the housing built form.

1. High power rated wind turbines with low cut in velocity of 3-4m/sec are preferred as urban areas have wind velocities ranging between 2.5 - 4m/sec due to high surface roughness.

2. Siting of renewable infrastructure primarily wind on ground requires 10-12% of plot area. Similarly roof based solar and wind infrastructure require at least 60% of roof area.
3. Solar and wind based hybrid energy model under ideal circumstances and availability of resource can generate up to 25% of household energy demand.
4. Spaces in between buildings at higher level in case of medium and high rise typologies need to be explored as potential locations for inclusion of solar and wind infrastructure so as to compensate for low terrace area in solar and less open site area in wind applications.
5. Exploration of balconies and shading devices as potential location for solar PV and solar thermal application needs to be further studied.
6. Integration of Building Integrated Photovoltaic (BIPV) especially in case of high rise and medium rise housing units and their potential needs further study.
7. Street canyons with a width to height ratio more than one result in creation of concentration points and gusts near the ground level that can harm pedestrians and vegetation.
8. The ideal points for locating the wind turbine in housing units are at the center of the terrace and along the corners, but irrespective of which ever site is identified for installation of wind turbines safety measures will need to be duly undertaken.
9. All physical construction if done on the North-East or North-West side of the terrace can maximize shadow free area thereby resulting in more area for solar panels.
10. Parapet at roof level should be low with transparent extensions so that it does not cast shadow area on the roof but also meets minimum safety norms.

8.4 Conclusion

After going through the study it can be concluded that there is no clear winner or loser in case of solar and wind based renewable energy generation in the housing sector. Some of the key aspects if addressed can lead to energy sustainability in the housing sector. The significant points are listed below:

1. Integration of renewable infrastructure should be incorporated right from the concept stage and not as a retrofit option. Modern approaches like BIPV integration needs to be further explored (Aguacil et al., 2016).
2. Hybrid Energy Mix (HEM) Models based on different fuel mixes depending upon the availability of fuel resource if properly implemented can meet the growing needs of housing sector and also ensure energy security (Bektas et al, 2011).

3. Promotion of wind based infrastructure needs to be done as it has more potential than solar panels as wind resource is available irrespective of day and night. It also requires infrastructure that needs maintenance but does not become inefficient with time.
4. Hybrid energy systems should be promoted in comparison to stand alone systems as they aid in ensuring energy supply in case of failure of any one of the resources. Also RES infrastructure needs to be implemented at neighbourhood level and not promoted at individual household level.
5. Building controls for different housing units across various typologies need to be reframed with the aim to promote solar and wind based infrastructure.
6. Medium rise group houisng typology is observed to have the highest solar potential but on the other hand due to its orientation is found to perform ordinarily in wind based microgeneration. So, it is necessary to understand the potential of each typology with respect to the resources and exploit them.
7. The low rise group housing has a balanced growth potential in both solar and wind energy assessment (Burton et al., 2003). Due to its low density and less energy intensive infrastructure like lack of lifts, etc. can achieve energy sustainability to the highest degree.
8. Housing typology classification should not be based on the area of a unit but on the orientation and energy generation potential of the unit. In case of CUC, for effective solar based energy generation a total of 12 sqm area is required on the roof for generation of 1 kW of power.
9. If financial planning is properly done along with incentives from central authorities it is possible to say that 100% of housing energy demand can be met through renewable energy sources (Tsanas and Xifara 2012).Built form geometry and building controls have a great role to play in the enhancement of solar energy generation (Strømann-Andersen and Sattrup, 2011).
10. In case of plotted units the high surface roughness due to vegetation and uneven surface structure along with undesirable orientation in some cases results in low wind based performance. Also, due to small roof area in comparison to community or multi floor multifamily setup the energy output is not as desired. For effective utilization of roofs in the plotted typology the roofs of multiple units need to be integrated as one.
11. High rise housing lacks in roof area but gains in wind based assessment. Similarly with the increase in high rise developments the surface of the housing units and the spaces between

the units at terrace level and intermediate levels need to be exploited for promoting solar and wind energy.

12. Vertical Axis Wind Turbine (VAWT) is more functional in buildings than Horizontal Axis Wind Turbines (HAWT) as the ideal location for installing wind turbines is the roof. If HAWTs are not properly anchored and secured to the terrace, they can be a safety concern. VAWT adds to the building's aesthetics.
13. For integration of renewable infrastructure within housing society around 10-12% plot area and around 60% of roof area needs to be dedicated for RES.
14. Solar and Wind based hybrid energy systems under ideal conditions and availability of resources can meet up to 25% of household energy demand.

Realization of a true solar city starts from a household. As architects it is our responsibility to meet the demands of the household by ensuring all possible conservancy measures and passive design inputs so that there is minimum energy demand from the households. The demand that arises should be addressed through inclusion of renewable infrastructure from the concept stage of the household. For this to be achieved it is necessary to simulate the same and find all possible alternative scenarios through the use of modern day computational tools (Attia et al., 2012) along with the integration of our traditional knowledge and wisdom.

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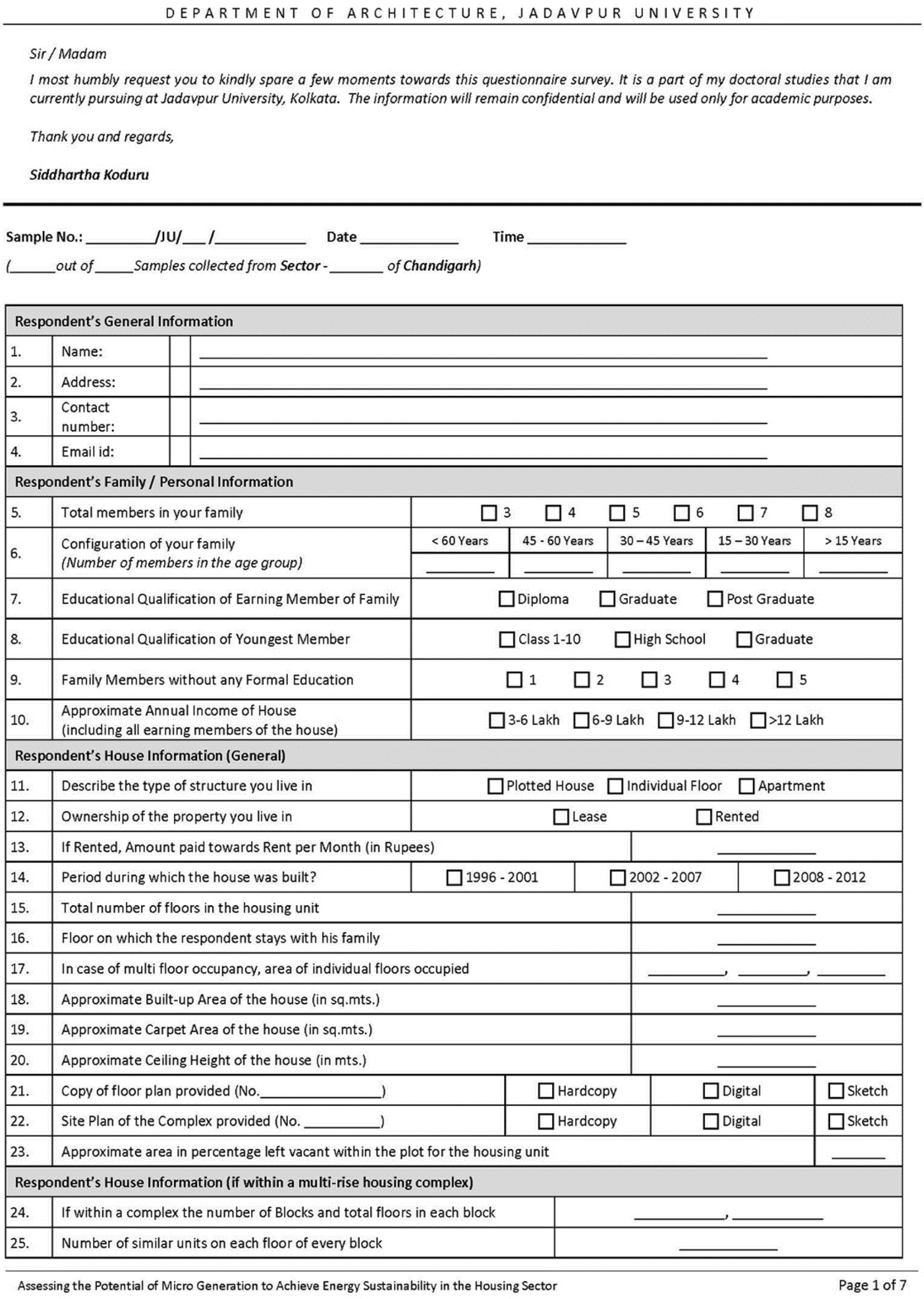
Annexure - I

Household Survey Questionnaire prepared as part of 'Bottom Up Approach' assessment of household energy demand.



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Sir / Madam

I most humbly request you to kindly spare a few moments towards this questionnaire survey. It is a part of my doctoral studies that I am currently pursuing at Jadavpur University, Kolkata. The information will remain confidential and will be used only for academic purposes.

Thank you and regards,

Siddhartha Koduru

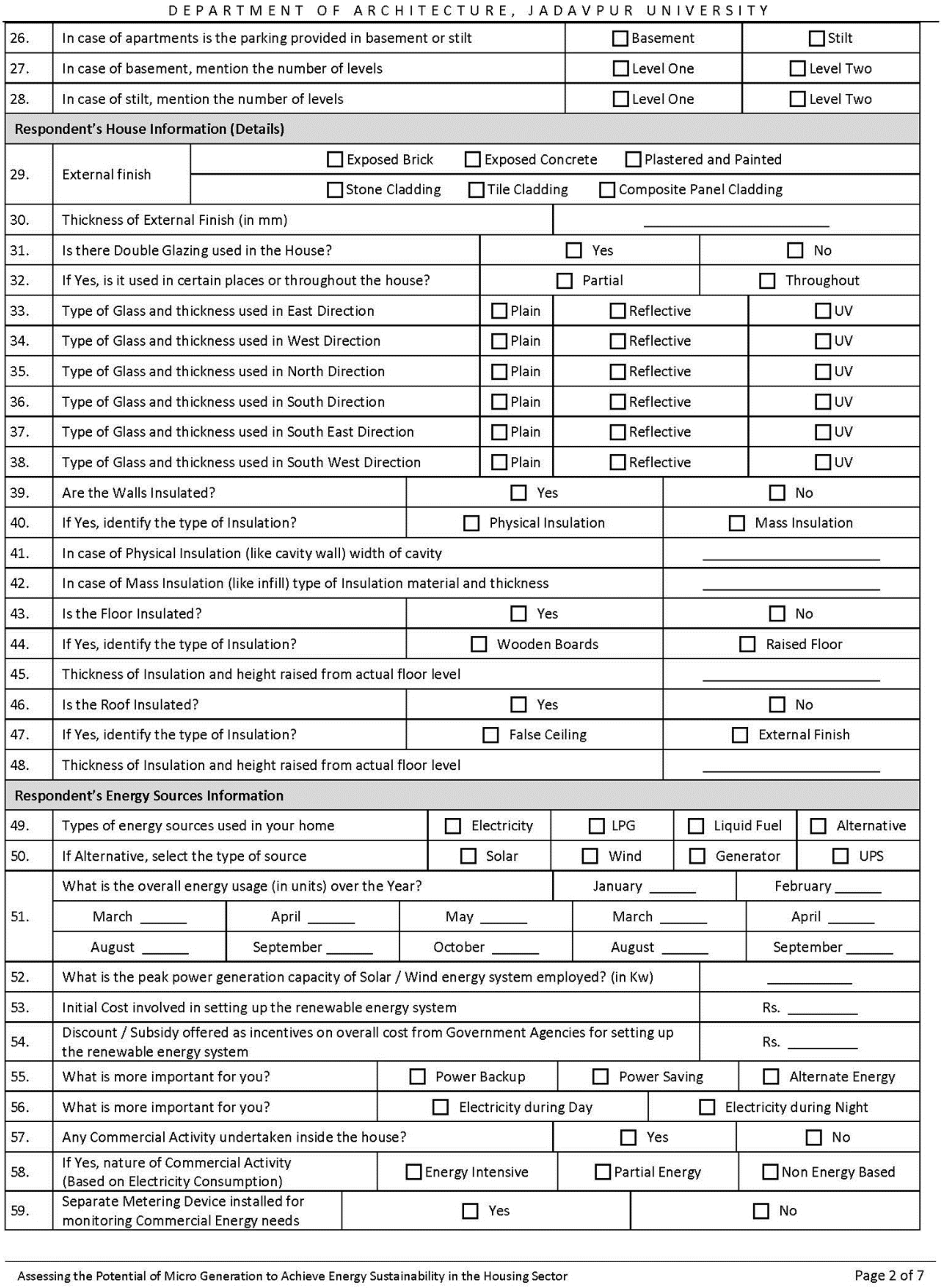
Sample No.: ________/JU/___/__________ **Date** ___________ **Time** ___________

*(______out of _____Samples collected from **Sector** - _______ of **Chandigarh**)*

Respondent's General Information		
1.	Name:	________________________________
2.	Address:	________________________________
3.	Contact number:	________________________________
4.	Email id:	________________________________
Respondent's Family / Personal Information		
5.	Total members in your family	☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8
6.	Configuration of your family *(Number of members in the age group)*	< 60 Years ________ 45 - 60 Years ________ 30 – 45 Years ________ 15 – 30 Years ________ > 15 Years ________
7.	Educational Qualification of Earning Member of Family	☐ Diploma ☐ Graduate ☐ Post Graduate
8.	Educational Qualification of Youngest Member	☐ Class 1-10 ☐ High School ☐ Graduate
9.	Family Members without any Formal Education	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
10.	Approximate Annual Income of House (including all earning members of the house)	☐ 3-6 Lakh ☐ 6-9 Lakh ☐ 9-12 Lakh ☐ >12 Lakh
Respondent's House Information (General)		
11.	Describe the type of structure you live in	☐ Plotted House ☐ Individual Floor ☐ Apartment
12.	Ownership of the property you live in	☐ Lease ☐ Rented
13.	If Rented, Amount paid towards Rent per Month (in Rupees)	__________
14.	Period during which the house was built?	☐ 1996 - 2001 ☐ 2002 - 2007 ☐ 2008 - 2012
15.	Total number of floors in the housing unit	__________
16.	Floor on which the respondent stays with his family	__________
17.	In case of multi floor occupancy, area of individual floors occupied	________, ________, ________
18.	Approximate Built-up Area of the house (in sq.mts.)	__________
19.	Approximate Carpet Area of the house (in sq.mts.)	__________
20.	Approximate Ceiling Height of the house (in mts.)	__________
21.	Copy of floor plan provided (No.______________)	☐ Hardcopy ☐ Digital ☐ Sketch
22.	Site Plan of the Complex provided (No. _________)	☐ Hardcopy ☐ Digital ☐ Sketch
23.	Approximate area in percentage left vacant within the plot for the housing unit	______
Respondent's House Information (if within a multi-rise housing complex)		
24.	If within a complex the number of Blocks and total floors in each block	__________, __________
25.	Number of similar units on each floor of every block	__________

Assessing the Potential of Micro Generation to Achieve Energy Sustainability in the Housing Sector Page 1 of 7

Annexure - I



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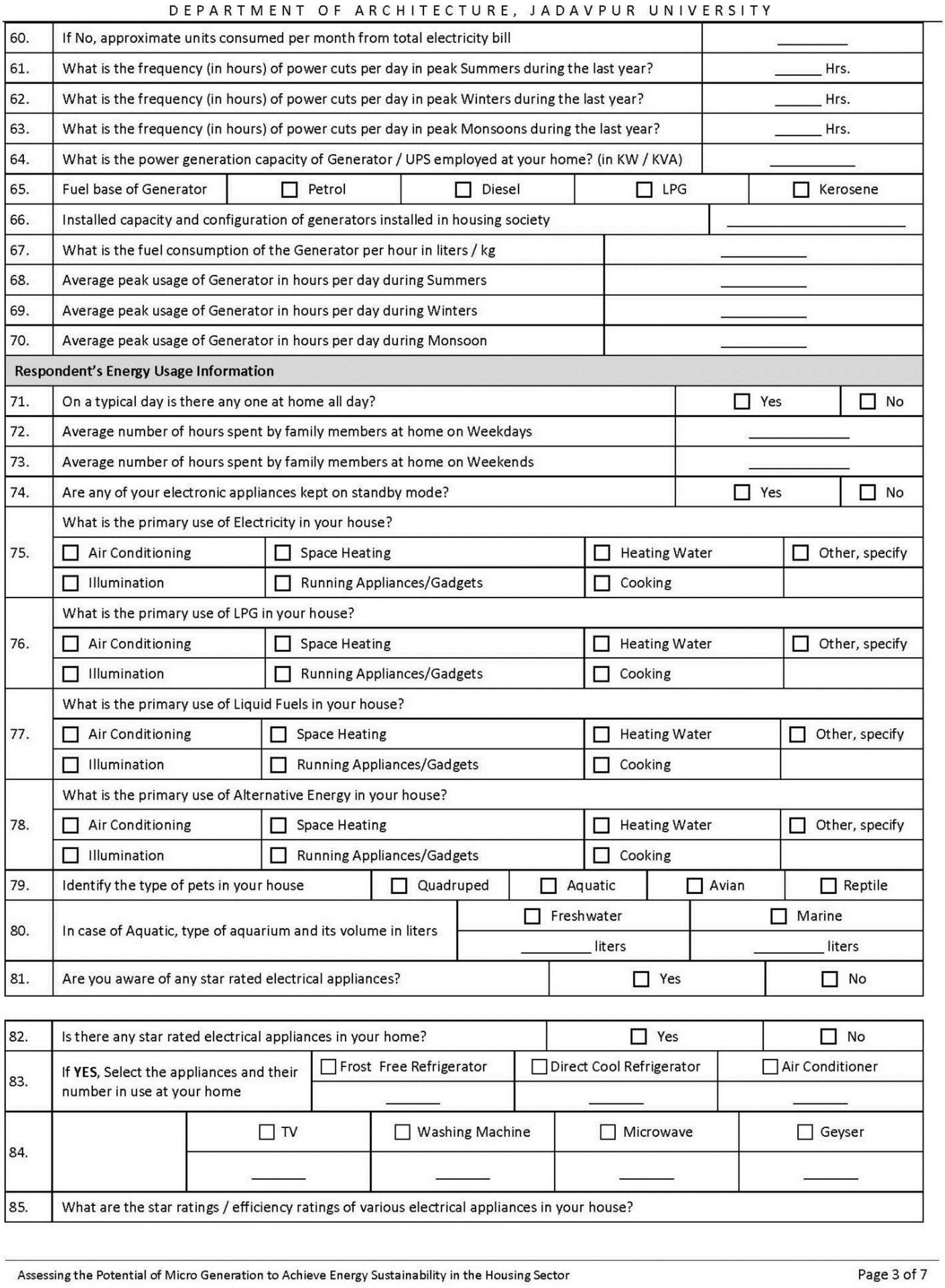
26.	In case of apartments is the parking provided in basement or stilt	☐ Basement	☐ Stilt		
27.	In case of basement, mention the number of levels	☐ Level One	☐ Level Two		
28.	In case of stilt, mention the number of levels	☐ Level One	☐ Level Two		
Respondent's House Information (Details)					
29.	External finish	☐ Exposed Brick	☐ Exposed Concrete	☐ Plastered and Painted	
		☐ Stone Cladding	☐ Tile Cladding	☐ Composite Panel Cladding	
30.	Thickness of External Finish (in mm)	___________________			
31.	Is there Double Glazing used in the House?	☐ Yes	☐ No		
32.	If Yes, is it used in certain places or throughout the house?	☐ Partial	☐ Throughout		
33.	Type of Glass and thickness used in East Direction	☐ Plain	☐ Reflective	☐ UV	
34.	Type of Glass and thickness used in West Direction	☐ Plain	☐ Reflective	☐ UV	
35.	Type of Glass and thickness used in North Direction	☐ Plain	☐ Reflective	☐ UV	
36.	Type of Glass and thickness used in South Direction	☐ Plain	☐ Reflective	☐ UV	
37.	Type of Glass and thickness used in South East Direction	☐ Plain	☐ Reflective	☐ UV	
38.	Type of Glass and thickness used in South West Direction	☐ Plain	☐ Reflective	☐ UV	
39.	Are the Walls Insulated?	☐ Yes	☐ No		
40.	If Yes, identify the type of Insulation?	☐ Physical Insulation	☐ Mass Insulation		
41.	In case of Physical Insulation (like cavity wall) width of cavity	___________________			
42.	In case of Mass Insulation (like infill) type of Insulation material and thickness	___________________			
43.	Is the Floor Insulated?	☐ Yes	☐ No		
44.	If Yes, identify the type of Insulation?	☐ Wooden Boards	☐ Raised Floor		
45.	Thickness of Insulation and height raised from actual floor level	___________________			
46.	Is the Roof Insulated?	☐ Yes	☐ No		
47.	If Yes, identify the type of Insulation?	☐ False Ceiling	☐ External Finish		
48.	Thickness of Insulation and height raised from actual floor level	___________________			
Respondent's Energy Sources Information					
49.	Types of energy sources used in your home	☐ Electricity	☐ LPG	☐ Liquid Fuel	☐ Alternative
50.	If Alternative, select the type of source	☐ Solar	☐ Wind	☐ Generator	☐ UPS
51.	What is the overall energy usage (in units) over the Year?	January ______	February ______		
	March ______	April ______	May ______	March ______	April ______
	August ______	September ______	October ______	August ______	September ______
52.	What is the peak power generation capacity of Solar / Wind energy system employed? (in Kw)	__________			
53.	Initial Cost involved in setting up the renewable energy system	Rs. _________			
54.	Discount / Subsidy offered as incentives on overall cost from Government Agencies for setting up the renewable energy system	Rs. _________			
55.	What is more important for you?	☐ Power Backup	☐ Power Saving	☐ Alternate Energy	
56.	What is more important for you?	☐ Electricity during Day	☐ Electricity during Night		
57.	Any Commercial Activity undertaken inside the house?	☐ Yes	☐ No		
58.	If Yes, nature of Commercial Activity (Based on Electricity Consumption)	☐ Energy Intensive	☐ Partial Energy	☐ Non Energy Based	
59.	Separate Metering Device installed for monitoring Commercial Energy needs	☐ Yes	☐ No		

Assessing the Potential of Micro Generation to Achieve Energy Sustainability in the Housing Sector Page 2 of 7

Annexure – I



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60.	If No, approximate units consumed per month from total electricity bill	_________
61.	What is the frequency (in hours) of power cuts per day in peak Summers during the last year?	______ Hrs.
62.	What is the frequency (in hours) of power cuts per day in peak Winters during the last year?	______ Hrs.
63.	What is the frequency (in hours) of power cuts per day in peak Monsoons during the last year?	______ Hrs.
64.	What is the power generation capacity of Generator / UPS employed at your home? (in KW / KVA)	___________

65.	Fuel base of Generator	☐ Petrol	☐ Diesel	☐ LPG	☐ Kerosene

66.	Installed capacity and configuration of generators installed in housing society	______________________
67.	What is the fuel consumption of the Generator per hour in liters / kg	___________
68.	Average peak usage of Generator in hours per day during Summers	___________
69.	Average peak usage of Generator in hours per day during Winters	___________
70.	Average peak usage of Generator in hours per day during Monsoon	___________

Respondent's Energy Usage Information

71.	On a typical day is there any one at home all day?	☐ Yes	☐ No
72.	Average number of hours spent by family members at home on Weekdays	____________	
73.	Average number of hours spent by family members at home on Weekends	____________	
74.	Are any of your electronic appliances kept on standby mode?	☐ Yes	☐ No

75.	What is the primary use of Electricity in your house?			
	☐ Air Conditioning	☐ Space Heating	☐ Heating Water	☐ Other, specify
	☐ Illumination	☐ Running Appliances/Gadgets	☐ Cooking	
76.	What is the primary use of LPG in your house?			
	☐ Air Conditioning	☐ Space Heating	☐ Heating Water	☐ Other, specify
	☐ Illumination	☐ Running Appliances/Gadgets	☐ Cooking	
77.	What is the primary use of Liquid Fuels in your house?			
	☐ Air Conditioning	☐ Space Heating	☐ Heating Water	☐ Other, specify
	☐ Illumination	☐ Running Appliances/Gadgets	☐ Cooking	
78.	What is the primary use of Alternative Energy in your house?			
	☐ Air Conditioning	☐ Space Heating	☐ Heating Water	☐ Other, specify
	☐ Illumination	☐ Running Appliances/Gadgets	☐ Cooking	

79.	Identify the type of pets in your house	☐ Quadruped	☐ Aquatic	☐ Avian	☐ Reptile

80.	In case of Aquatic, type of aquarium and its volume in liters	☐ Freshwater	☐ Marine
		_________ liters	_________ liters
81.	Are you aware of any star rated electrical appliances?	☐ Yes	☐ No

82.	Is there any star rated electrical appliances in your home?	☐ Yes	☐ No

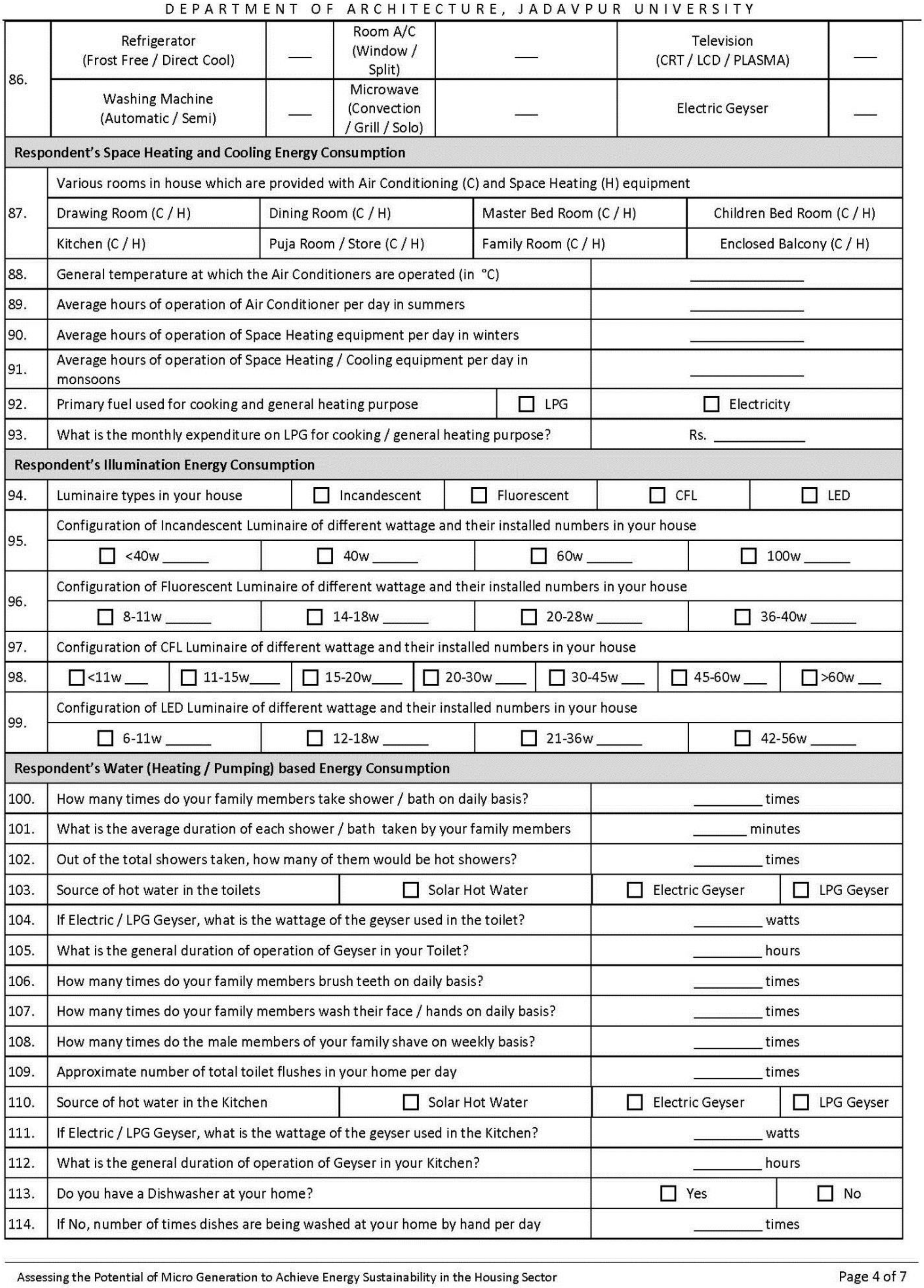
83.	If **YES**, Select the appliances and their number in use at your home	☐ Frost Free Refrigerator	☐ Direct Cool Refrigerator	☐ Air Conditioner
		_______	_______	_______

84.		☐ TV	☐ Washing Machine	☐ Microwave	☐ Geyser
		_______	_______	_______	_______

85.	What are the star ratings / efficiency ratings of various electrical appliances in your house?

Assessing the Potential of Micro Generation to Achieve Energy Sustainability in the Housing Sector Page 3 of 7

Annexure – I



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86.	Refrigerator (Frost Free / Direct Cool)	___	Room A/C (Window / Split)	___	Television (CRT / LCD / PLASMA)	___
	Washing Machine (Automatic / Semi)	___	Microwave (Convection / Grill / Solo)	___	Electric Geyser	___

Respondent's Space Heating and Cooling Energy Consumption

87.	Various rooms in house which are provided with Air Conditioning (C) and Space Heating (H) equipment			
	Drawing Room (C / H)	Dining Room (C / H)	Master Bed Room (C / H)	Children Bed Room (C / H)
	Kitchen (C / H)	Puja Room / Store (C / H)	Family Room (C / H)	Enclosed Balcony (C / H)

88.	General temperature at which the Air Conditioners are operated (in °C)		______________
89.	Average hours of operation of Air Conditioner per day in summers		______________
90.	Average hours of operation of Space Heating equipment per day in winters		______________
91.	Average hours of operation of Space Heating / Cooling equipment per day in monsoons		______________
92.	Primary fuel used for cooking and general heating purpose	☐ LPG	☐ Electricity
93.	What is the monthly expenditure on LPG for cooking / general heating purpose?		Rs. ___________

Respondent's Illumination Energy Consumption

94.	Luminaire types in your house	☐ Incandescent		☐ Fluorescent	☐ CFL		☐ LED
95.	Configuration of Incandescent Luminaire of different wattage and their installed numbers in your house						
	☐ <40w ______	☐ 40w ______		☐ 60w ______	☐ 100w ______		
96.	Configuration of Fluorescent Luminaire of different wattage and their installed numbers in your house						
	☐ 8-11w ______	☐ 14-18w ______		☐ 20-28w ______	☐ 36-40w ______		
97.	Configuration of CFL Luminaire of different wattage and their installed numbers in your house						
98.	☐ <11w ___	☐ 11-15w ____	☐ 15-20w ____	☐ 20-30w ____	☐ 30-45w ___	☐ 45-60w ___	☐ >60w ___
99.	Configuration of LED Luminaire of different wattage and their installed numbers in your house						
	☐ 6-11w ______	☐ 12-18w ______		☐ 21-36w ______	☐ 42-56w ______		

Respondent's Water (Heating / Pumping) based Energy Consumption

100.	How many times do your family members take shower / bath on daily basis?		________ times	
101.	What is the average duration of each shower / bath taken by your family members		______ minutes	
102.	Out of the total showers taken, how many of them would be hot showers?		________ times	
103.	Source of hot water in the toilets	☐ Solar Hot Water	☐ Electric Geyser	☐ LPG Geyser
104.	If Electric / LPG Geyser, what is the wattage of the geyser used in the toilet?		________ watts	
105.	What is the general duration of operation of Geyser in your Toilet?		________ hours	
106.	How many times do your family members brush teeth on daily basis?		________ times	
107.	How many times do your family members wash their face / hands on daily basis?		________ times	
108.	How many times do the male members of your family shave on weekly basis?		________ times	
109.	Approximate number of total toilet flushes in your home per day		________ times	
110.	Source of hot water in the Kitchen	☐ Solar Hot Water	☐ Electric Geyser	☐ LPG Geyser
111.	If Electric / LPG Geyser, what is the wattage of the geyser used in the Kitchen?		________ watts	
112.	What is the general duration of operation of Geyser in your Kitchen?		________ hours	
113.	Do you have a Dishwasher at your home?		☐ Yes	☐ No
114.	If No, number of times dishes are being washed at your home by hand per day		________ times	

Assessing the Potential of Micro Generation to Achieve Energy Sustainability in the Housing Sector

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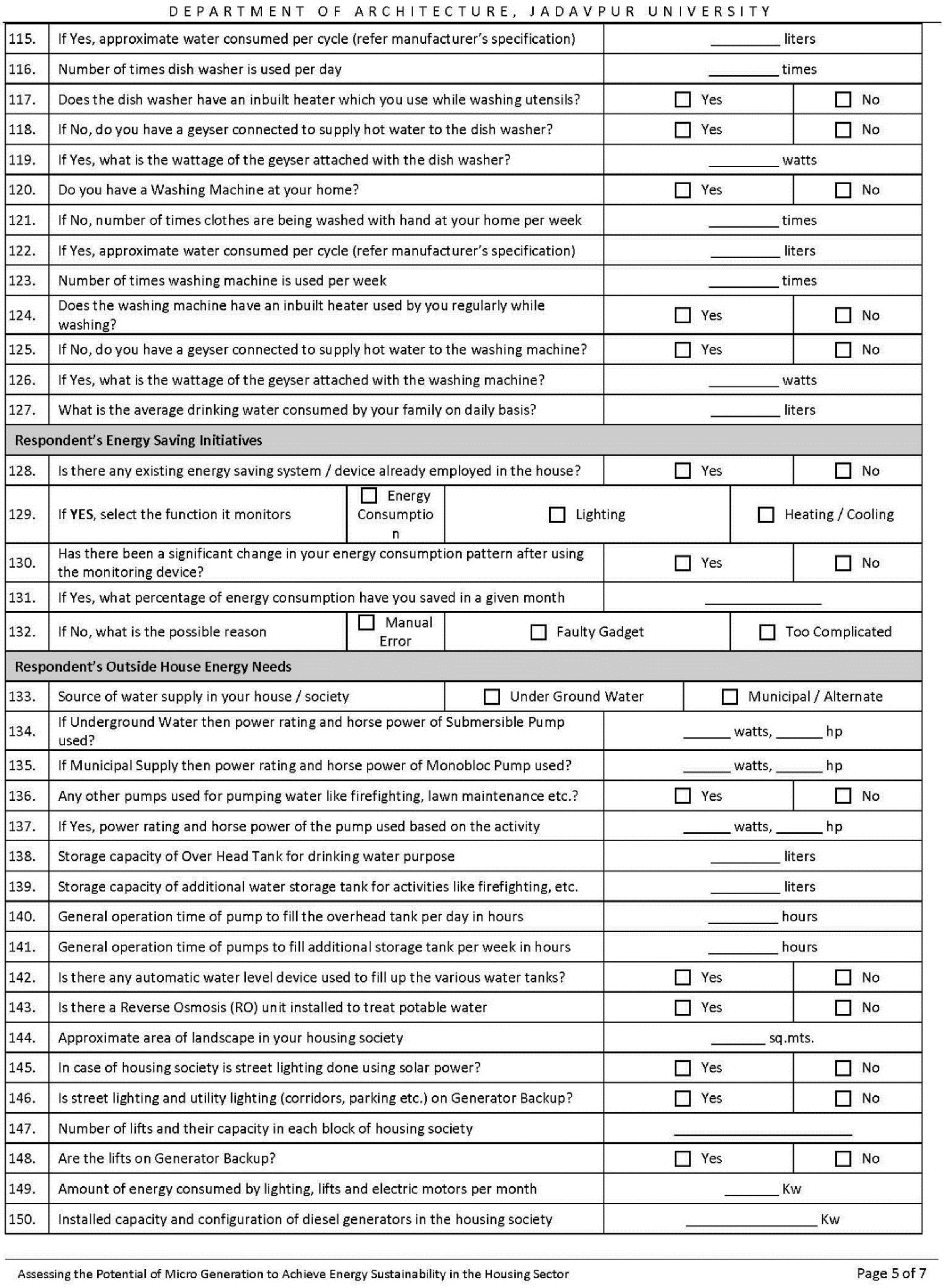
Annexure – I



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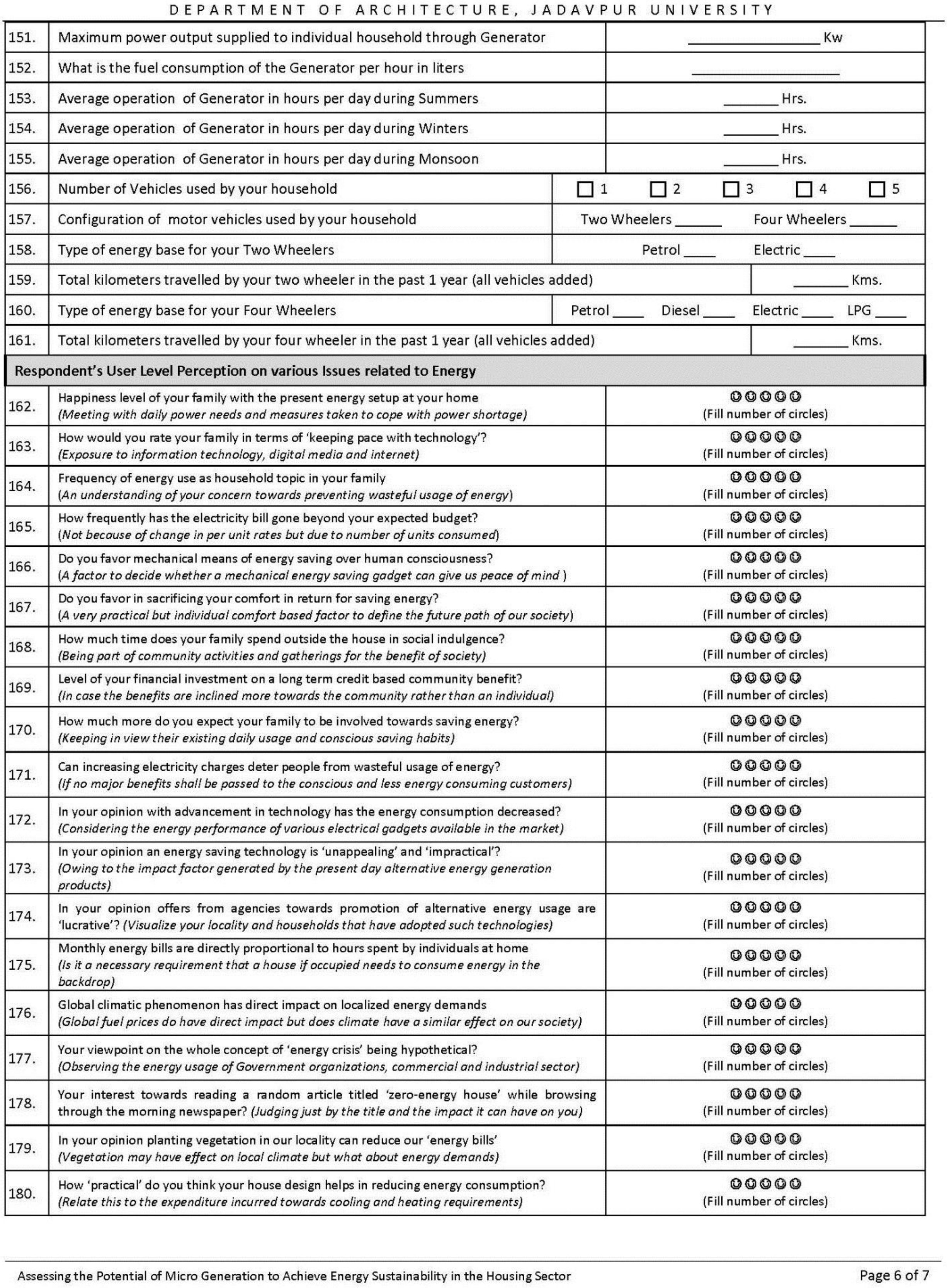
115.	If Yes, approximate water consumed per cycle (refer manufacturer's specification)	_________ liters		
116.	Number of times dish washer is used per day	_________ times		
117.	Does the dish washer have an inbuilt heater which you use while washing utensils?	☐ Yes	☐ No	
118.	If No, do you have a geyser connected to supply hot water to the dish washer?	☐ Yes	☐ No	
119.	If Yes, what is the wattage of the geyser attached with the dish washer?	_________ watts		
120.	Do you have a Washing Machine at your home?	☐ Yes	☐ No	
121.	If No, number of times clothes are being washed with hand at your home per week	_________ times		
122.	If Yes, approximate water consumed per cycle (refer manufacturer's specification)	_________ liters		
123.	Number of times washing machine is used per week	_________ times		
124.	Does the washing machine have an inbuilt heater used by you regularly while washing?	☐ Yes	☐ No	
125.	If No, do you have a geyser connected to supply hot water to the washing machine?	☐ Yes	☐ No	
126.	If Yes, what is the wattage of the geyser attached with the washing machine?	_________ watts		
127.	What is the average drinking water consumed by your family on daily basis?	_________ liters		
Respondent's Energy Saving Initiatives				
128.	Is there any existing energy saving system / device already employed in the house?	☐ Yes	☐ No	
129.	If **YES**, select the function it monitors	☐ Energy Consumption	☐ Lighting	☐ Heating / Cooling
130.	Has there been a significant change in your energy consumption pattern after using the monitoring device?	☐ Yes	☐ No	
131.	If Yes, what percentage of energy consumption have you saved in a given month	_______________		
132.	If No, what is the possible reason	☐ Manual Error	☐ Faulty Gadget	☐ Too Complicated
Respondent's Outside House Energy Needs				
133.	Source of water supply in your house / society	☐ Under Ground Water	☐ Municipal / Alternate	
134.	If Underground Water then power rating and horse power of Submersible Pump used?	______ watts, ______ hp		
135.	If Municipal Supply then power rating and horse power of Monobloc Pump used?	______ watts, ______ hp		
136.	Any other pumps used for pumping water like firefighting, lawn maintenance etc.?	☐ Yes	☐ No	
137.	If Yes, power rating and horse power of the pump used based on the activity	______ watts, ______ hp		
138.	Storage capacity of Over Head Tank for drinking water purpose	_________ liters		
139.	Storage capacity of additional water storage tank for activities like firefighting, etc.	_________ liters		
140.	General operation time of pump to fill the overhead tank per day in hours	_________ hours		
141.	General operation time of pumps to fill additional storage tank per week in hours	_________ hours		
142.	Is there any automatic water level device used to fill up the various water tanks?	☐ Yes	☐ No	
143.	Is there a Reverse Osmosis (RO) unit installed to treat potable water	☐ Yes	☐ No	
144.	Approximate area of landscape in your housing society	_______ sq.mts.		
145.	In case of housing society is street lighting done using solar power?	☐ Yes	☐ No	
146.	Is street lighting and utility lighting (corridors, parking etc.) on Generator Backup?	☐ Yes	☐ No	
147.	Number of lifts and their capacity in each block of housing society	______________________		
148.	Are the lifts on Generator Backup?	☐ Yes	☐ No	
149.	Amount of energy consumed by lighting, lifts and electric motors per month	_______ Kw		
150.	Installed capacity and configuration of diesel generators in the housing society	________________ Kw		

Assessing the Potential of Micro Generation to Achieve Energy Sustainability in the Housing Sector Page 5 of 7

Annexure – I



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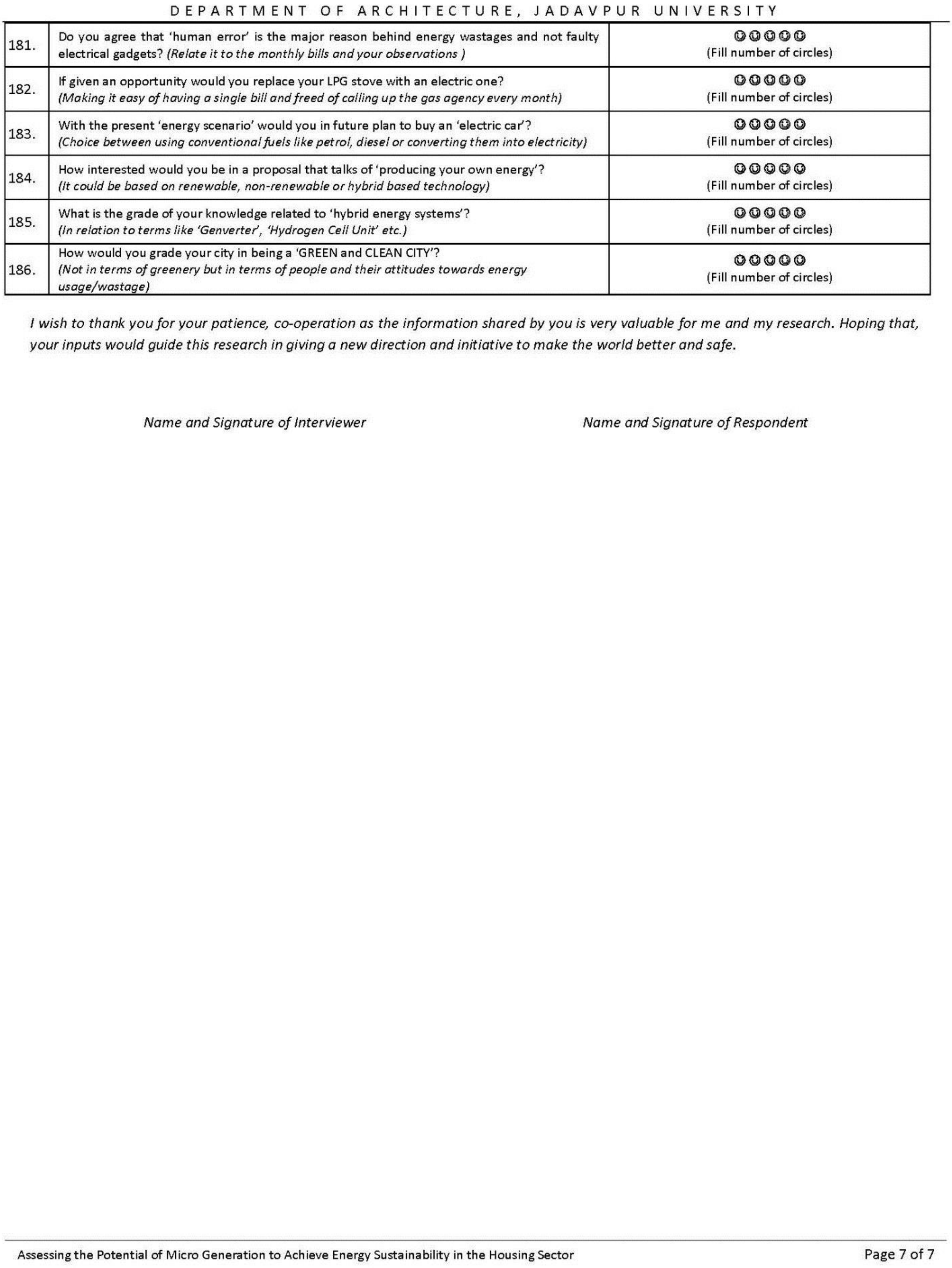
151.	Maximum power output supplied to individual household through Generator	__________ Kw
152.	What is the fuel consumption of the Generator per hour in liters	__________
153.	Average operation of Generator in hours per day during Summers	_______ Hrs.
154.	Average operation of Generator in hours per day during Winters	_______ Hrs.
155.	Average operation of Generator in hours per day during Monsoon	_______ Hrs.
156.	Number of Vehicles used by your household	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
157.	Configuration of motor vehicles used by your household	Two Wheelers ______ Four Wheelers ______
158.	Type of energy base for your Two Wheelers	Petrol ____ Electric ____
159.	Total kilometers travelled by your two wheeler in the past 1 year (all vehicles added)	_______ Kms.
160.	Type of energy base for your Four Wheelers	Petrol ____ Diesel ____ Electric ____ LPG ____
161.	Total kilometers travelled by your four wheeler in the past 1 year (all vehicles added)	_______ Kms.
Respondent's User Level Perception on various Issues related to Energy		
162.	Happiness level of your family with the present energy setup at your home *(Meeting with daily power needs and measures taken to cope with power shortage)*	☺☺☺☺☺ (Fill number of circles)
163.	How would you rate your family in terms of 'keeping pace with technology'? *(Exposure to information technology, digital media and internet)*	☺☺☺☺☺ (Fill number of circles)
164.	Frequency of energy use as household topic in your family *(An understanding of your concern towards preventing wasteful usage of energy)*	☺☺☺☺☺ (Fill number of circles)
165.	How frequently has the electricity bill gone beyond your expected budget? *(Not because of change in per unit rates but due to number of units consumed)*	☺☺☺☺☺ (Fill number of circles)
166.	Do you favor mechanical means of energy saving over human consciousness? *(A factor to decide whether a mechanical energy saving gadget can give us peace of mind)*	☺☺☺☺☺ (Fill number of circles)
167.	Do you favor in sacrificing your comfort in return for saving energy? *(A very practical but individual comfort based factor to define the future path of our society)*	☺☺☺☺☺ (Fill number of circles)
168.	How much time does your family spend outside the house in social indulgence? *(Being part of community activities and gatherings for the benefit of society)*	☺☺☺☺☺ (Fill number of circles)
169.	Level of your financial investment on a long term credit based community benefit? *(In case the benefits are inclined more towards the community rather than an individual)*	☺☺☺☺☺ (Fill number of circles)
170.	How much more do you expect your family to be involved towards saving energy? *(Keeping in view their existing daily usage and conscious saving habits)*	☺☺☺☺☺ (Fill number of circles)
171.	Can increasing electricity charges deter people from wasteful usage of energy? *(If no major benefits shall be passed to the conscious and less energy consuming customers)*	☺☺☺☺☺ (Fill number of circles)
172.	In your opinion with advancement in technology has the energy consumption decreased? *(Considering the energy performance of various electrical gadgets available in the market)*	☺☺☺☺☺ (Fill number of circles)
173.	In your opinion an energy saving technology is 'unappealing' and 'impractical'? *(Owing to the impact factor generated by the present day alternative energy generation products)*	☺☺☺☺☺ (Fill number of circles)
174.	In your opinion offers from agencies towards promotion of alternative energy usage are 'lucrative'? *(Visualize your locality and households that have adopted such technologies)*	☺☺☺☺☺ (Fill number of circles)
175.	Monthly energy bills are directly proportional to hours spent by individuals at home *(Is it a necessary requirement that a house if occupied needs to consume energy in the backdrop)*	☺☺☺☺☺ (Fill number of circles)
176.	Global climatic phenomenon has direct impact on localized energy demands *(Global fuel prices do have direct impact but does climate have a similar effect on our society)*	☺☺☺☺☺ (Fill number of circles)
177.	Your viewpoint on the whole concept of 'energy crisis' being hypothetical? *(Observing the energy usage of Government organizations, commercial and industrial sector)*	☺☺☺☺☺ (Fill number of circles)
178.	Your interest towards reading a random article titled 'zero-energy house' while browsing through the morning newspaper? *(Judging just by the title and the impact it can have on you)*	☺☺☺☺☺ (Fill number of circles)
179.	In your opinion planting vegetation in our locality can reduce our 'energy bills' *(Vegetation may have effect on local climate but what about energy demands)*	☺☺☺☺☺ (Fill number of circles)
180.	How 'practical' do you think your house design helps in reducing energy consumption? *(Relate this to the expenditure incurred towards cooling and heating requirements)*	☺☺☺☺☺ (Fill number of circles)

Assessing the Potential of Micro Generation to Achieve Energy Sustainability in the Housing Sector Page 6 of 7

Annexure – I



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181.	Do you agree that 'human error' is the major reason behind energy wastages and not faulty electrical gadgets? *(Relate it to the monthly bills and your observations)*	○○○○○ (Fill number of circles)
182.	If given an opportunity would you replace your LPG stove with an electric one? *(Making it easy of having a single bill and freed of calling up the gas agency every month)*	○○○○○ (Fill number of circles)
183.	With the present 'energy scenario' would you in future plan to buy an 'electric car'? *(Choice between using conventional fuels like petrol, diesel or converting them into electricity)*	○○○○○ (Fill number of circles)
184.	How interested would you be in a proposal that talks of 'producing your own energy'? *(It could be based on renewable, non-renewable or hybrid based technology)*	○○○○○ (Fill number of circles)
185.	What is the grade of your knowledge related to 'hybrid energy systems'? *(In relation to terms like 'Genverter', 'Hydrogen Cell Unit' etc.)*	○○○○○ (Fill number of circles)
186.	How would you grade your city in being a 'GREEN and CLEAN CITY'? *(Not in terms of greenery but in terms of people and their attitudes towards energy usage/wastage)*	○○○○○ (Fill number of circles)

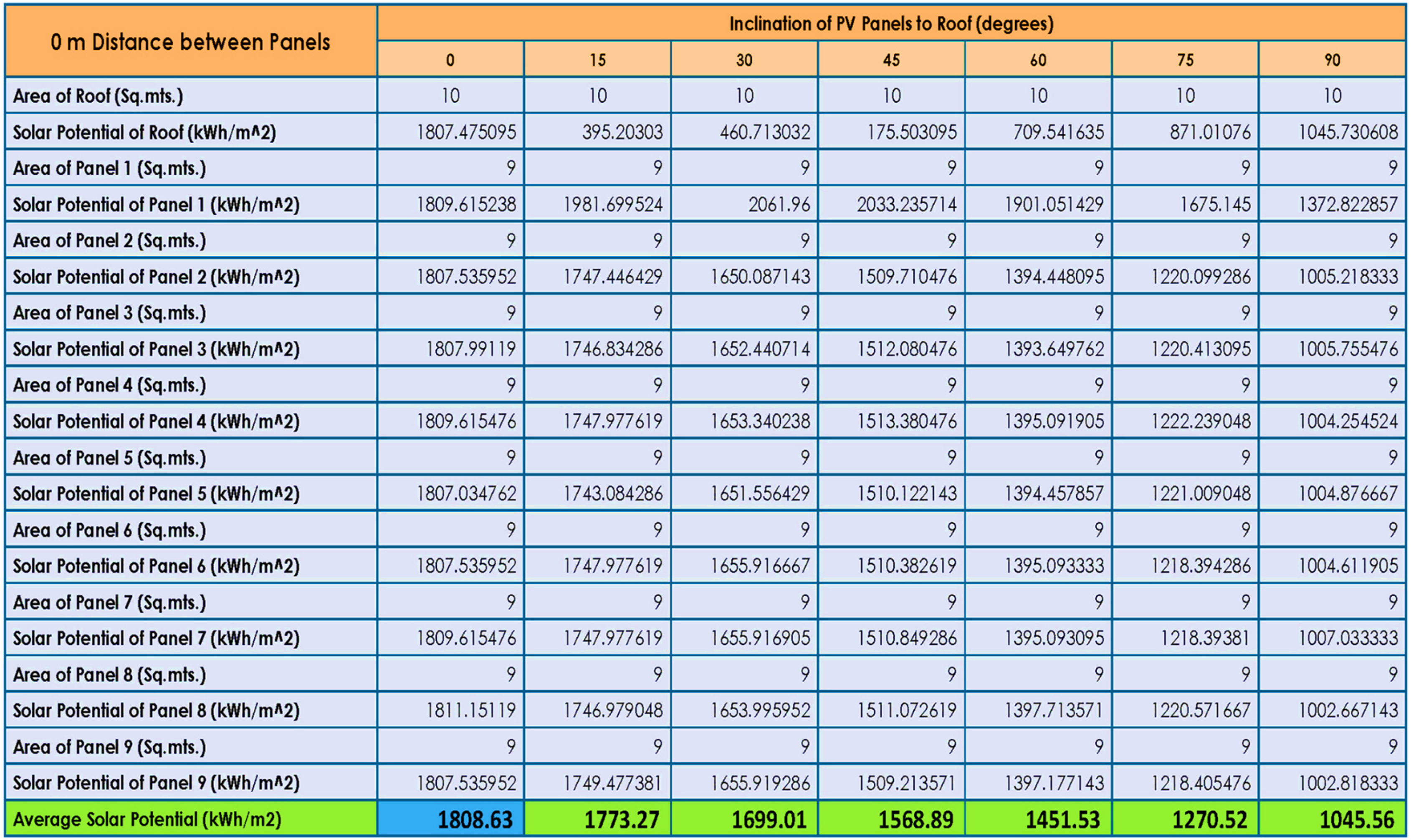
I wish to thank you for your patience, co-operation as the information shared by you is very valuable for me and my research. Hoping that, your inputs would guide this research in giving a new direction and initiative to make the world better and safe.

Name and Signature of Interviewer

Name and Signature of Respondent

Annexure – II (a)

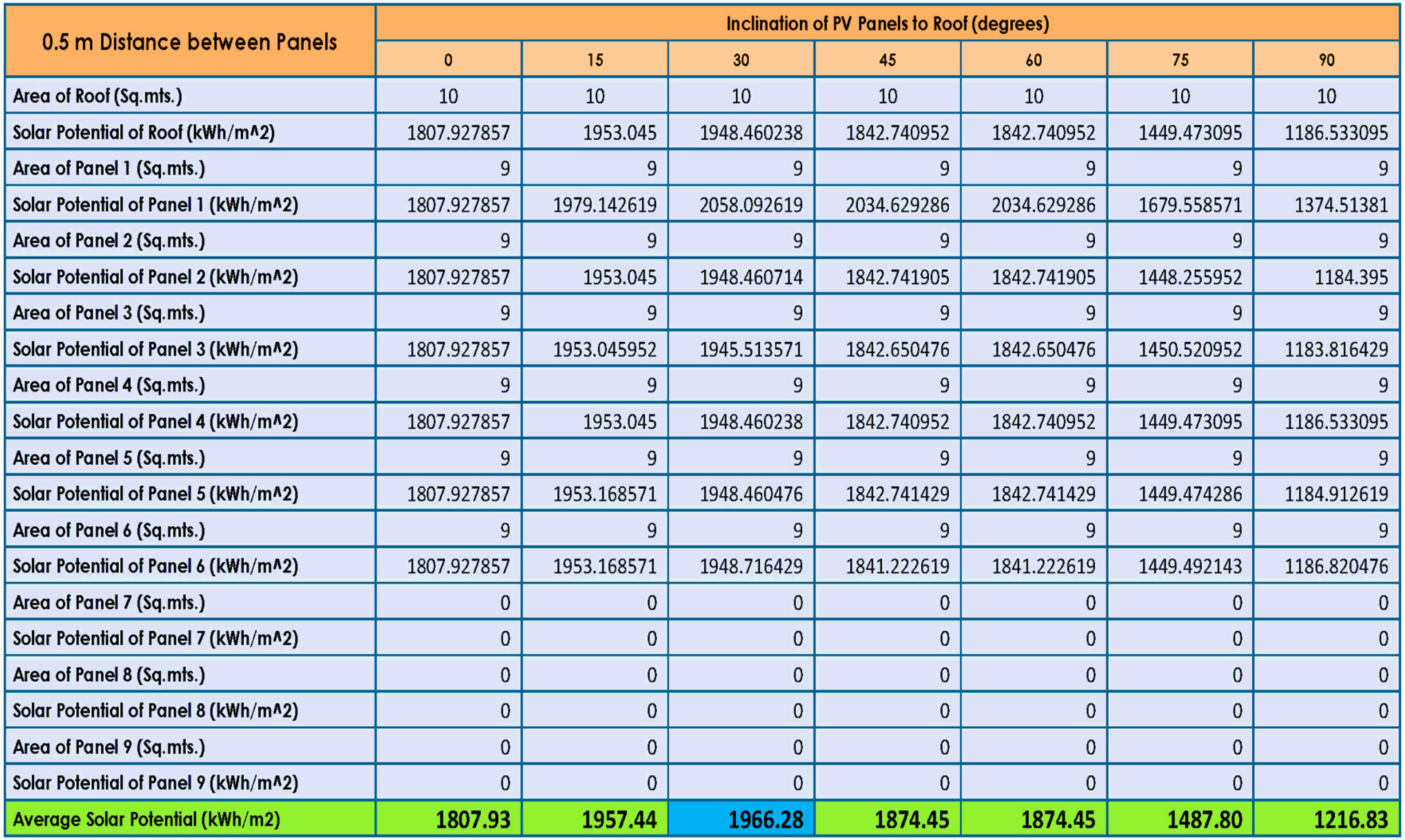
Energy Output of South facing Plot based on Inclination of PV Panels to Roof Surface and 0m distance between panels



0 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	10	10	10	10	10	10	10
Solar Potential of Roof (kWh/m^2)	1807.475095	395.20303	460.713032	175.503095	709.541635	871.01076	1045.730608
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1809.615238	1981.699524	2061.96	2033.235714	1901.051429	1675.145	1372.822857
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1807.535952	1747.446429	1650.087143	1509.710476	1394.448095	1220.099286	1005.218333
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1807.99119	1746.834286	1652.440714	1512.080476	1393.649762	1220.413095	1005.755476
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1809.615476	1747.977619	1653.340238	1513.380476	1395.091905	1222.239048	1004.254524
Area of Panel 5 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 5 (kWh/m^2)	1807.034762	1743.084286	1651.556429	1510.122143	1394.457857	1221.009048	1004.876667
Area of Panel 6 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 6 (kWh/m^2)	1807.535952	1747.977619	1655.916667	1510.382619	1395.093333	1218.394286	1004.611905
Area of Panel 7 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 7 (kWh/m^2)	1809.615476	1747.977619	1655.916905	1510.849286	1395.093095	1218.39381	1007.033333
Area of Panel 8 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 8 (kWh/m^2)	1811.15119	1746.979048	1653.995952	1511.072619	1397.713571	1220.571667	1002.667143
Area of Panel 9 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 9 (kWh/m^2)	1807.535952	1749.477381	1655.919286	1509.213571	1397.177143	1218.405476	1002.818333
Average Solar Potential (kWh/m2)	**1808.63**	**1773.27**	**1699.01**	**1568.89**	**1451.53**	**1270.52**	**1045.56**

Annexure – II (b)

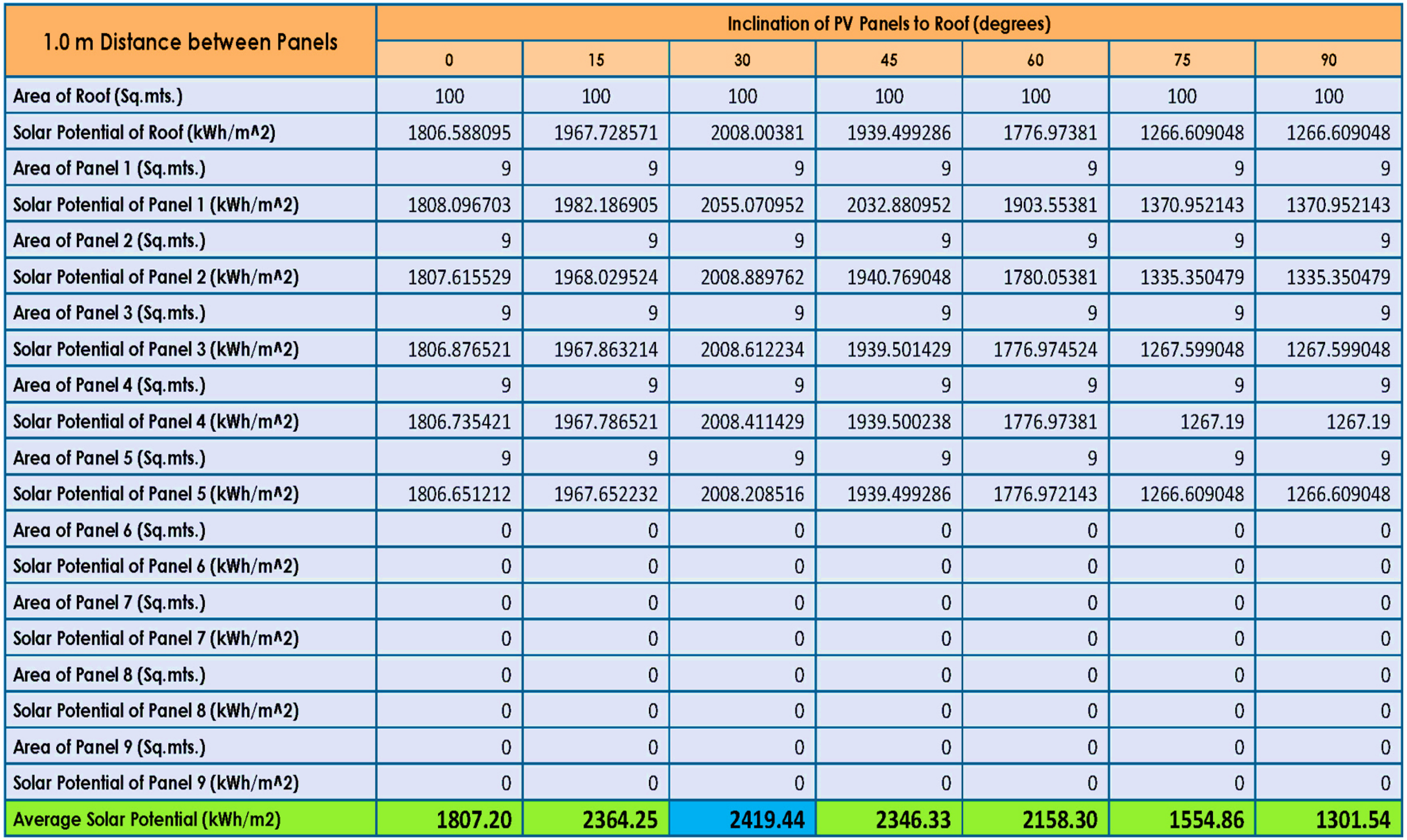
Energy Output of South facing Plot based on Inclination of PV Panels to Roof Surface and 0.5m distance between panels



0.5 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	10	10	10	10	10	10	10
Solar Potential of Roof (kWh/m^2)	1807.927857	1953.045	1948.460238	1842.740952	1842.740952	1449.473095	1186.533095
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1807.927857	1979.142619	2058.092619	2034.629286	2034.629286	1679.558571	1374.51381
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1807.927857	1953.045	1948.460714	1842.741905	1842.741905	1448.255952	1184.395
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1807.927857	1953.045952	1945.513571	1842.650476	1842.650476	1450.520952	1183.816429
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1807.927857	1953.045	1948.460238	1842.740952	1842.740952	1449.473095	1186.533095
Area of Panel 5 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 5 (kWh/m^2)	1807.927857	1953.168571	1948.460476	1842.741429	1842.741429	1449.474286	1184.912619
Area of Panel 6 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 6 (kWh/m^2)	1807.927857	1953.168571	1948.716429	1841.222619	1841.222619	1449.492143	1186.820476
Area of Panel 7 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 7 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 8 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 8 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 9 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 9 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1807.93**	**1957.44**	**1966.28**	**1874.45**	**1874.45**	**1487.80**	**1216.83**

Annexure – II (c)

Energy Output of South facing Plot based on Inclination of PV Panels to Roof Surface and 1.0m distance between panels



1.0 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1806.588095	1967.728571	2008.00381	1939.499286	1776.97381	1266.609048	1266.609048
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1808.096703	1982.186905	2055.070952	2032.880952	1903.55381	1370.952143	1370.952143
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1807.615529	1968.029524	2008.889762	1940.769048	1780.05381	1335.350479	1335.350479
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1806.876521	1967.863214	2008.612234	1939.501429	1776.974524	1267.599048	1267.599048
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1806.735421	1967.786521	2008.411429	1939.500238	1776.97381	1267.19	1267.19
Area of Panel 5 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 5 (kWh/m^2)	1806.651212	1967.652232	2008.208516	1939.499286	1776.972143	1266.609048	1266.609048
Area of Panel 6 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 6 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 7 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 7 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 8 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 8 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 9 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 9 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1807.20**	**2364.25**	**2419.44**	**2346.33**	**2158.30**	**1554.86**	**1301.54**

Annexure – II (d)

Energy Output of South facing Plot based on Inclination of PV Panels to Roof Surface and 1.5m distance between panels

1.5 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1807.726909	1154.157296	1111.04941	1145.360793	1219.904589	1318.772956	1422.21947
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1808.122143	1977.789524	2058.863571	2036.247619	1903.97619	1675.88881	1422.21947
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1808.122143	1975.725476	2025.147857	1973.28619	1824.238571	1600.019762	1374.462143
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1808.122143	1975.725476	2026.339762	1973.017381	1823.577619	1598.126429	1314.793333
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1807.578993	1975.725238	2026.339286	1973.049762	1822.733095	1598.119762	1314.309048
Area of Panel 5 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 5 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 6 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 6 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 7 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 7 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 8 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 8 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 9 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 9 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1807.99**	**1976.24**	**2034.17**	**1988.90**	**1843.63**	**1618.04**	**1356.45**

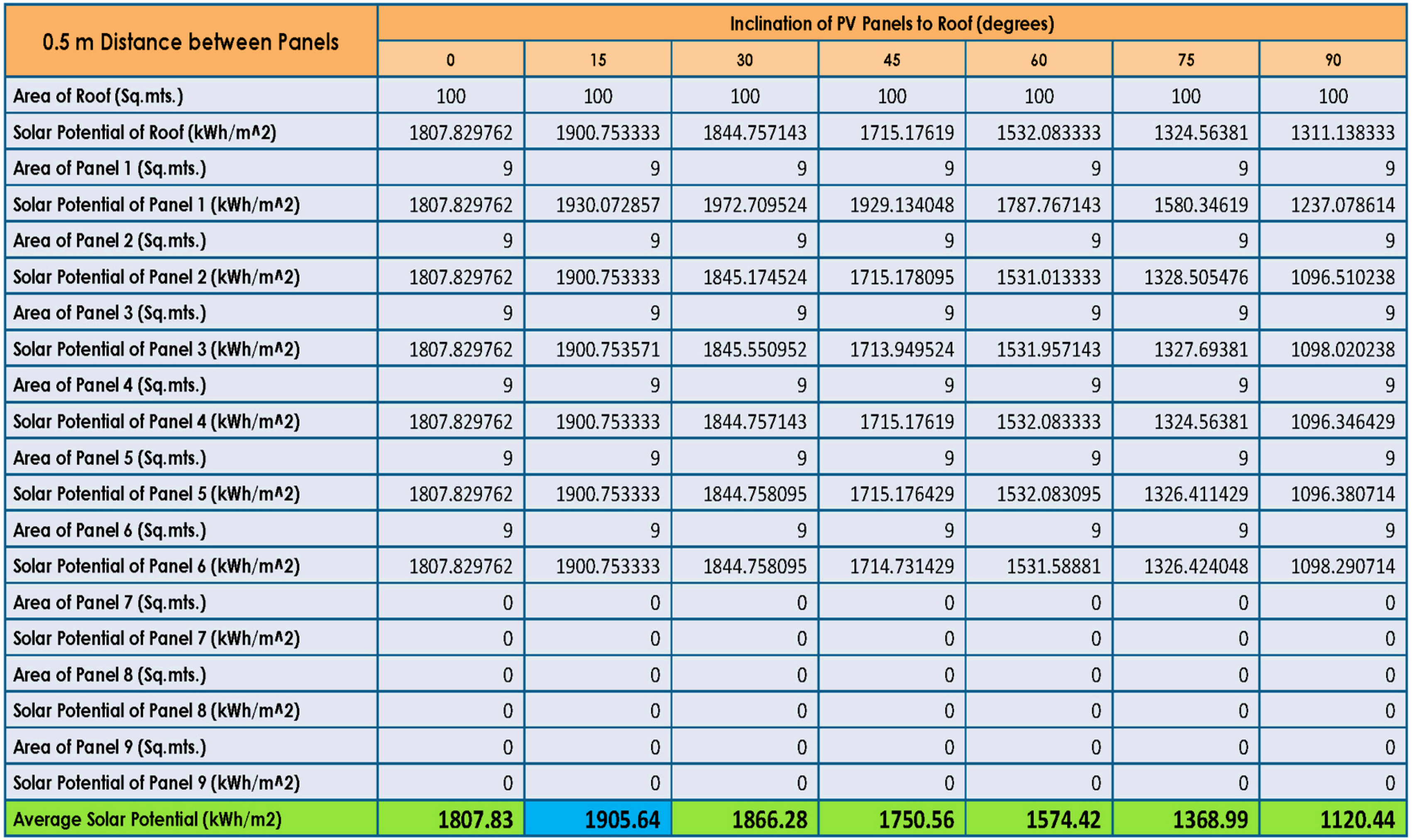
Annexure – III (a)

Energy Output of South-East facing Plot based on Inclination of PV Panels to Roof Surface and 0m distance between panels

0 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1807.394743	426.902005	522.291758	636.705636	766.350457	901.213032	1029.180575
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1811.888095	1706.90119	1572.601905	1437.319762	1289.181667	1122.09381	930.149286
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1808.936667	1705.233095	1573.882143	1443.462619	1285.085952	1120.091667	931.010238
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1811.888095	1701.500952	1572.602143	1440.177143	1285.724524	1119.352857	933.349048
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1811.888095	1699.714762	1572.602143	1441.347143	1289.182143	1122.094048	930.151429
Area of Panel 5 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 5 (kWh/m^2)	1807.27881	1701.090714	1571.919048	1441.435476	1285.259762	1122.042381	931.525952
Area of Panel 6 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 6 (kWh/m^2)	1811.888095	1703.97119	1573.167143	1437.588333	1284.767619	1122.120238	930.532857
Area of Panel 7 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 7 (kWh/m^2)	1808.936667	1702.630714	1572.299762	1440.37	1288.077619	1118.663571	934.663333
Area of Panel 8 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 8 (kWh/m^2)	1811.888095	1705.048095	1569.251905	1438.162381	1289.064048	1120.615	934.02881
Area of Panel 9 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 9 (kWh/m^2)	1811.888095	1934.260714	1970.24119	1927.427619	1787.251667	1578.625476	1311.668571
Average Solar Potential (kWh/m2)	**1810.72**	**1728.93**	**1616.51**	**1494.14**	**1342.62**	**1171.74**	**974.12**

Annexure – III (b)

Energy Output of South-East facing Plot based on Inclination of PV Panels to Roof Surface and 0.5m distance between panels



0.5 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1807.829762	1900.753333	1844.757143	1715.17619	1532.083333	1324.56381	1311.138333
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1807.829762	1930.072857	1972.709524	1929.134048	1787.767143	1580.34619	1237.078614
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1807.829762	1900.753333	1845.174524	1715.178095	1531.013333	1328.505476	1096.510238
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1807.829762	1900.753571	1845.550952	1713.949524	1531.957143	1327.69381	1098.020238
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1807.829762	1900.753333	1844.757143	1715.17619	1532.083333	1324.56381	1096.346429
Area of Panel 5 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 5 (kWh/m^2)	1807.829762	1900.753333	1844.758095	1715.176429	1532.083095	1326.411429	1096.380714
Area of Panel 6 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 6 (kWh/m^2)	1807.829762	1900.753333	1844.758095	1714.731429	1531.58881	1326.424048	1098.290714
Area of Panel 7 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 7 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 8 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 8 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 9 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 9 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1807.83**	**1905.64**	**1866.28**	**1750.56**	**1574.42**	**1368.99**	**1120.44**

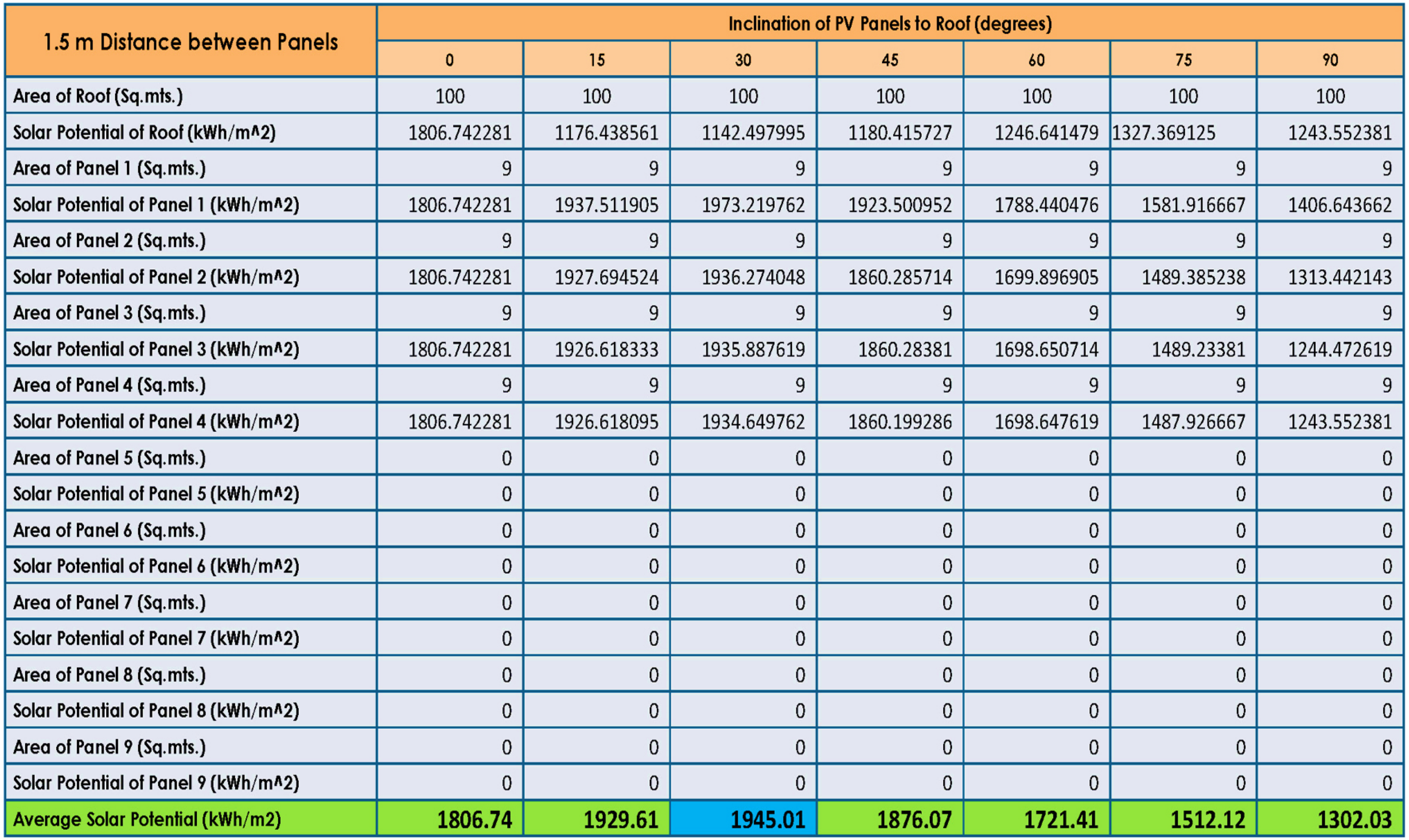
Annexure – III (c)

Energy Output of South-East facing Plot based on Inclination of PV Panels to Roof Surface and 1.0m distance between panels

1.0 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1804.828333	1918.250952	1926.233333	1918.777778	1662.433333	1447.544444	1288.422619
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1804.828333	1936.150714	1978.944444	1973.622222	1789.066667	1578.877778	1808.19481
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1804.828333	1919.86881	1926.233333	1918.777778	1667.444444	1454.155556	1288.422619
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1807.467498	1918.250952	1926.233333	1918.777778	1665.044444	1447.555556	1288.422619
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1804.828571	1936.150714	1926.233333	1918.777778	1662.444444	1454.155556	1288.422619
Area of Panel 5 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 5 (kWh/m^2)	1804.828571	1918.250952	1926.233333	1918.777778	1662.444444	1445.39	1288.422619
Area of Panel 6 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 6 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 7 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 7 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 8 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 8 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 9 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 9 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1805.36**	**1925.73**	**1936.78**	**1929.75**	**1689.29**	**1476.03**	**1392.38**

Annexure – III (d)

Energy Output of South-East facing Plot based on Inclination of PV Panels to Roof Surface and 1.5m distance between panels



1.5 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1806.742281	1176.438561	1142.497995	1180.415727	1246.641479	1327.369125	1243.552381
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1806.742281	1937.511905	1973.219762	1923.500952	1788.440476	1581.916667	1406.643662
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1806.742281	1927.694524	1936.274048	1860.285714	1699.896905	1489.385238	1313.442143
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1806.742281	1926.618333	1935.887619	1860.28381	1698.650714	1489.23381	1244.472619
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1806.742281	1926.618095	1934.649762	1860.199286	1698.647619	1487.926667	1243.552381
Area of Panel 5 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 5 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 6 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 6 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 7 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 7 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 8 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 8 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 9 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 9 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1806.74**	**1929.61**	**1945.01**	**1876.07**	**1721.41**	**1512.12**	**1302.03**

Annexure – IV (a)

Energy Output of South-West facing Plot based on Inclination of PV Panels to Roof Surface and 0m distance between panels

0 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1808.667988	447.402562	567.595032	1808.129472	829.815193	1029.006429	1029.006429
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1809.542619	1672.076429	1516.876667	1837.486429	1191.137143	1027.506667	1027.506667
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1807.827857	1672.023333	1518.261905	1838.36381	1194.778333	1030.955952	1030.955952
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1809.542619	1673.67881	1516.877381	1837.486429	1191.077143	1030.093571	1030.093571
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1809.542619	1676.727143	1516.877381	1838.346667	1191.137619	1028.938095	1028.938095
Area of Panel 5 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 5 (kWh/m^2)	1808.332619	1677.581905	1513.88119	1837.248571	1193.036667	1028.458571	1028.458571
Area of Panel 6 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 6 (kWh/m^2)	1809.542619	1677.311905	1516.879762	1838.346667	1191.204762	950.985275	950.985275
Area of Panel 7 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 7 (kWh/m^2)	1807.492619	1674.41381	1516.416667	1838.36381	1196.281667	1511.231429	1511.231429
Area of Panel 8 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 8 (kWh/m^2)	1809.542619	1672.944286	1516.22881	1837.486429	1195.995952	1029.500714	1029.500714
Area of Panel 9 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 9 (kWh/m^2)	1809.542619	1900.72119	1908.824286	1837.486429	1709.360714	1028.677619	1028.677619
Average Solar Potential (kWh/m2)	**1808.99**	**1699.72**	**1560.12**	**1837.85**	**1250.45**	**1074.04**	**1074.04**

Annexure – IV (b)

Energy Output of South-West facing Plot based on Inclination of PV Panels to Roof Surface and 0.5m distance between panels

0.5 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1811.307143	1867.049524	1767.551905	1616.930714	1424.949286	1230.197143	1024.679286
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1811.307143	1903.449048	1913.465238	1853.49619	1707.777381	1511.913095	1264.744286
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1811.307143	1867.049762	1771.341429	1616.930714	1429.227619	1230.197143	1028.330476
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1811.307143	1867.049524	1768.569762	1616.93	1426.935476	1228.660952	1026.90881
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1811.307143	1867.049524	1767.551905	1616.132857	1424.95881	1227.187381	1026.685952
Area of Panel 5 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 5 (kWh/m^2)	1811.307143	1867.049524	1766.602857	1615.078571	1424.95881	1226.87381	1026.087143
Area of Panel 6 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 6 (kWh/m^2)	1811.306905	1862.441667	1766.017857	1614.941429	1424.949286	1226.415714	1024.679286
Area of Panel 7 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 7 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 8 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 8 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 9 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 9 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1811.31**	**1872.35**	**1792.26**	**1655.58**	**1473.13**	**1275.21**	**1066.24**

Annexure – IV (c)

Energy Output of South-West facing Plot based on Inclination of PV Panels to Roof Surface and 1.0m distance between panels

1.0 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1809.497857	1902.27619	1902.27619	1718.992143	1543.094048	1339.085476	1119.136429
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1809.497857	1902.27619	1902.27619	1854.342857	1707.313333	1510.459048	1326.008978
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1809.497857	1881.812143	1881.812143	1720.654762	1543.590476	1340.42	1265.560714
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1809.497619	1881.811905	1881.811905	1720.654048	1543.097381	1339.085476	1119.136429
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1808.624816	1881.32881	1881.811905	1718.992143	1543.094048	1337.336667	1118.20881
Area of Panel 5 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 5 (kWh/m^2)	1806.940952	1818.578659	1881.32881	1718.796667	1542.496429	1337.331667	1117.411429
Area of Panel 6 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 6 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 7 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 7 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 8 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 8 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 9 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 9 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1808.81**	**1873.16**	**1885.81**	**1746.69**	**1575.92**	**1372.93**	**1189.27**

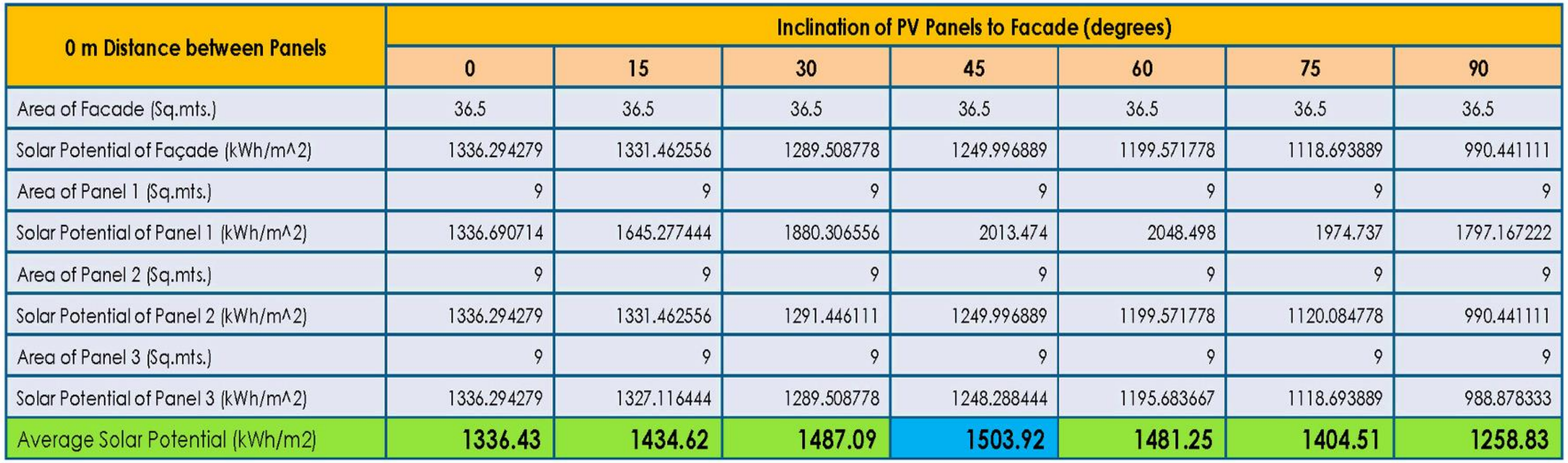
Annexure – IV (d)

Energy Output of South-West facing Plot based on Inclination of PV Panels to Roof Surface and 1.5m distance between panels

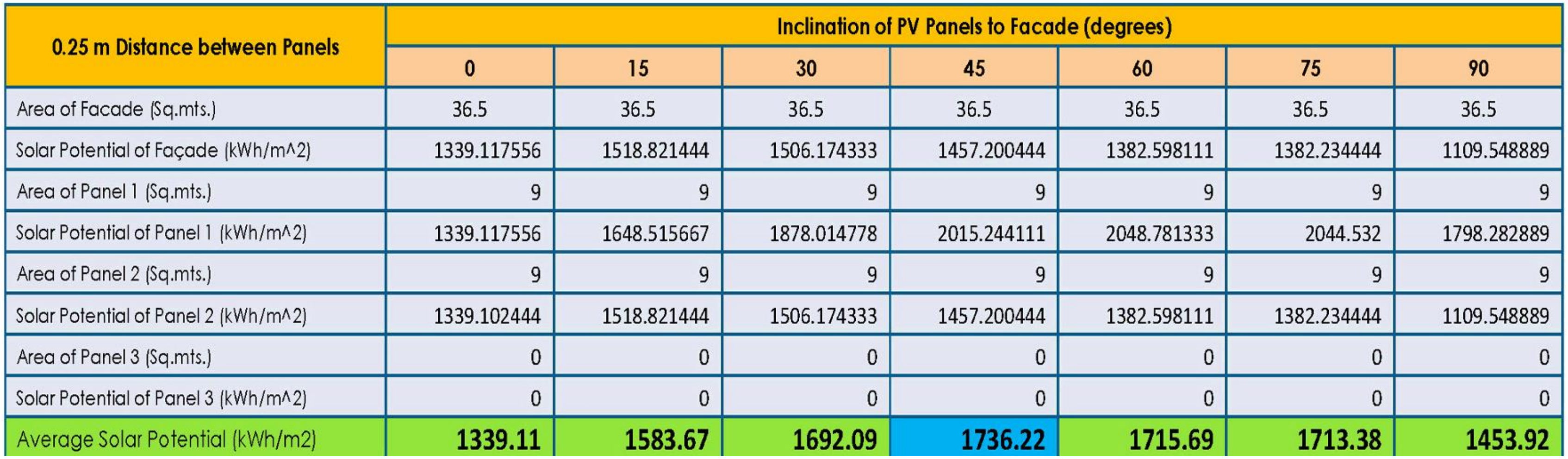
1.5 m Distance between Panels	Inclination of PV Panels to Roof (degrees)						
	0	15	30	45	60	75	90
Area of Roof (Sq.mts.)	100	100	100	100	100	100	100
Solar Potential of Roof (kWh/m^2)	1809.084629	1182.130898	1168.088372	1211.657897	1277.818957	1352.078726	1412.14667
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1808.09119	1904.42119	1912.21	1851.442619	1712.196905	1512.324048	1412.14667
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1808.09119	1889.734286	1869.539048	1769.494524	1601.720476	1398.564762	1262.438571
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1808.09119	1889.734048	1869.506905	1764.187619	1601.24	1398.00619	1171.862857
Area of Panel 4 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 4 (kWh/m^2)	1809.084629	1891.554048	1869.481429	1763.789048	1597.774286	1397.608333	1174.480952
Area of Panel 5 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 5 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 6 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 6 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 7 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 7 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 8 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 8 (kWh/m^2)	0	0	0	0	0	0	0
Area of Panel 9 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 9 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1808.34**	**1893.86**	**1880.18**	**1787.23**	**1628.23**	**1426.63**	**1255.23**

Annexure – V (a)

Energy Output of South Façade based PV Panels with 0m and 0.25m distance between panels



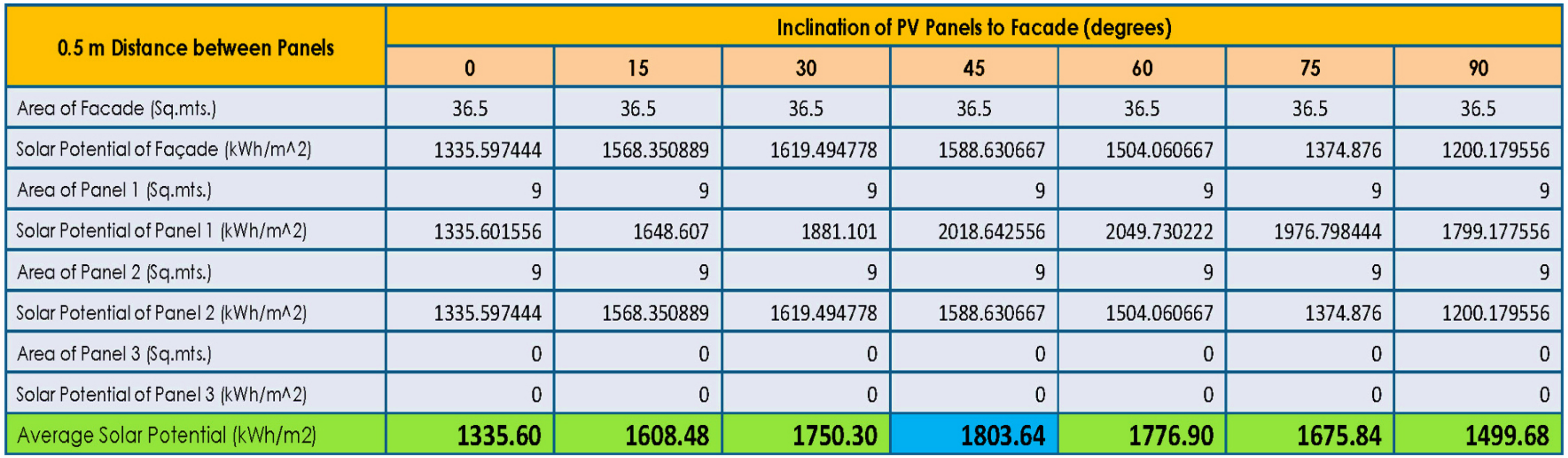
0 m Distance between Panels	Inclination of PV Panels to Facade (degrees)						
	0	15	30	45	60	75	90
Area of Facade (Sq.mts.)	36.5	36.5	36.5	36.5	36.5	36.5	36.5
Solar Potential of Façade (kWh/m^2)	1336.294279	1331.462556	1289.508778	1249.996889	1199.571778	1118.693889	990.441111
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1336.690714	1645.277444	1880.306556	2013.474	2048.498	1974.737	1797.167222
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1336.294279	1331.462556	1291.446111	1249.996889	1199.571778	1120.084778	990.441111
Area of Panel 3 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 3 (kWh/m^2)	1336.294279	1327.116444	1289.508778	1248.288444	1195.683667	1118.693889	988.878333
Average Solar Potential (kWh/m2)	**1336.43**	**1434.62**	**1487.09**	**1503.92**	**1481.25**	**1404.51**	**1258.83**



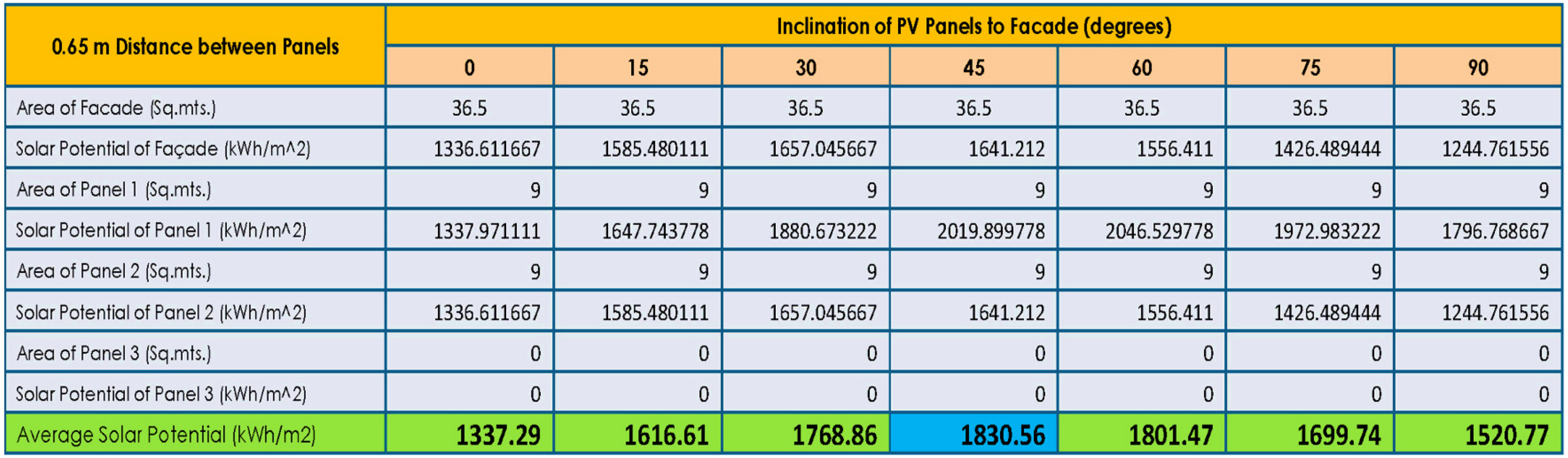
0.25 m Distance between Panels	Inclination of PV Panels to Facade (degrees)						
	0	15	30	45	60	75	90
Area of Facade (Sq.mts.)	36.5	36.5	36.5	36.5	36.5	36.5	36.5
Solar Potential of Façade (kWh/m^2)	1339.117556	1518.821444	1506.174333	1457.200444	1382.598111	1382.234444	1109.548889
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1339.117556	1648.515667	1878.014778	2015.244111	2048.781333	2044.532	1798.282889
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1339.102444	1518.821444	1506.174333	1457.200444	1382.598111	1382.234444	1109.548889
Area of Panel 3 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 3 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1339.11**	**1583.67**	**1692.09**	**1736.22**	**1715.69**	**1713.38**	**1453.92**

Annexure – V (b)

Energy Output of South Façade based PV Panels with 0.5m and 0.65m distance between panels



0.5 m Distance between Panels	Inclination of PV Panels to Facade (degrees)						
	0	15	30	45	60	75	90
Area of Facade (Sq.mts.)	36.5	36.5	36.5	36.5	36.5	36.5	36.5
Solar Potential of Façade (kWh/m^2)	1335.597444	1568.350889	1619.494778	1588.630667	1504.060667	1374.876	1200.179556
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1335.601556	1648.607	1881.101	2018.642556	2049.730222	1976.798444	1799.177556
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1335.597444	1568.350889	1619.494778	1588.630667	1504.060667	1374.876	1200.179556
Area of Panel 3 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 3 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1335.60**	**1608.48**	**1750.30**	**1803.64**	**1776.90**	**1675.84**	**1499.68**



0.65 m Distance between Panels	Inclination of PV Panels to Facade (degrees)						
	0	15	30	45	60	75	90
Area of Facade (Sq.mts.)	36.5	36.5	36.5	36.5	36.5	36.5	36.5
Solar Potential of Façade (kWh/m^2)	1336.611667	1585.480111	1657.045667	1641.212	1556.411	1426.489444	1244.761556
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1337.971111	1647.743778	1880.673222	2019.899778	2046.529778	1972.983222	1796.768667
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1336.611667	1585.480111	1657.045667	1641.212	1556.411	1426.489444	1244.761556
Area of Panel 3 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 3 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1337.29**	**1616.61**	**1768.86**	**1830.56**	**1801.47**	**1699.74**	**1520.77**

Annexure – V (c)

Energy Output of South Façade based PV Panels with 1.0m distance between panels and Comparison of Different Scenarios

1.0 m Distance between Panels	**Inclination of PV Panels to Facade (degrees)**						
	0	**15**	**30**	**45**	**60**	**75**	**90**
Area of Facade (Sq.mts.)	36.5	36.5	36.5	36.5	36.5	36.5	36.5
Solar Potential of Façade (kWh/m^2)	1337.414639	610.228611	553.210444	577.65275	633.762583	721.774667	828.079361
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	1337.788667	1605.391333	1873.39	2014.211111	2047.219111	1981.028444	1798.315333
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	1337.788667	1646.051222	1716.751556	1721.487444	1648.983667	1520.328333	1330.791444
Area of Panel 3 (Sq.mts.)	0	0	0	0	0	0	0
Solar Potential of Panel 3 (kWh/m^2)	0	0	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1337.79**	**1625.72**	**1795.07**	**1867.85**	**1848.10**	**1750.68**	**1564.55**

Comparison	**Inclination of PV Panels to Facade (degrees)**						
	70	**45**	**45**	**45**	**45**	**45**	**78**
Distance between Panels	**-0.25**	**0**	**0.25**	**0.5**	**0.65**	**1.00**	**1.25**
Solar Potential of Façade (kWh/m^2)	411.994139	1249.996889	1457.200444	1588.630667	1641.212	577.65275	765.739083
Area of Panel 1 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 1 (kWh/m^2)	2010.552222	2013.474	2015.244111	2018.642556	2019.899778	2014.211111	1948.439556
Area of Panel 2 (Sq.mts.)	9	9	9	9	9	9	9
Solar Potential of Panel 2 (kWh/m^2)	930.488556	1249.996889	1457.200444	1588.630667	1641.212	1721.487444	1532.484111
Area of Panel 3 (Sq.mts.)	9	9	0	0	0	0	0
Solar Potential of Panel 3 (kWh/m^2)	929.607556	1248.288444	0	0	0	0	0
Average Solar Potential (kWh/m2)	**1200.05**	**1503.92**	**1736.22**	**1803.64**	**1830.56**	**1867.85**	**1740.46**

Annexure – VI (a)

Change in Built-up Area and FAR of 4 Marla Plotted Unit due to Solar Envelope

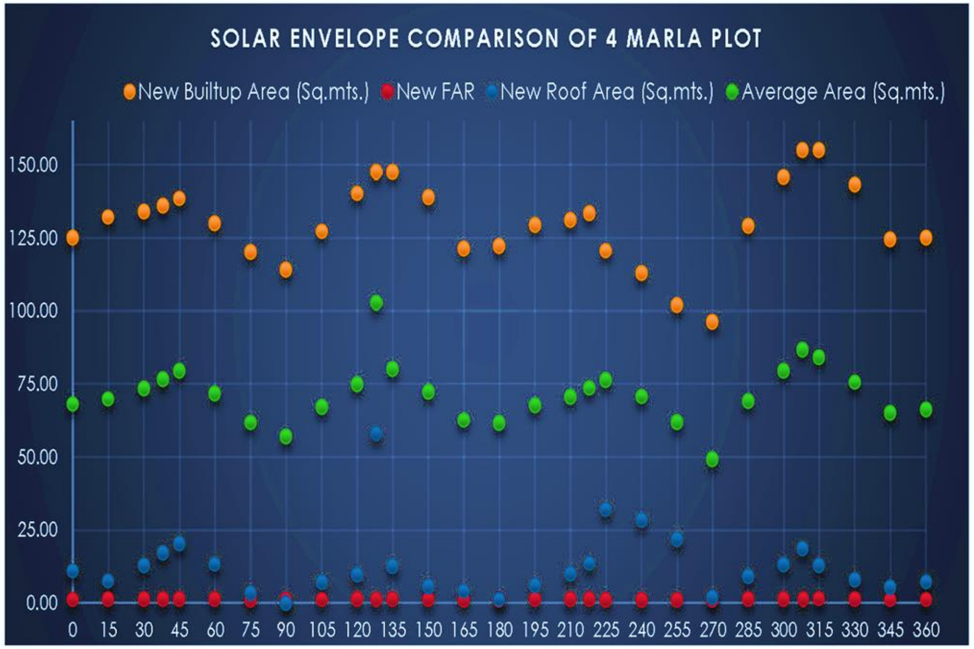
Angle to South (Degree)	0	15	30	38	45	60	75	90	105	120	128	135	150	165	180	195	210	218	225	240	255	270	285	300	308	315	330	345	360
New Built-up Area (Sq.mts.)	125.1	132.1	133.9	136.0	138.5	130.0	120.1	114.1	127.2	140.1	147.7	147.6	138.9	121.2	122.1	129.5	131.1	133.5	120.5	113.0	101.9	96.2	128.9	145.7	154.9	155.1	143.2	124.5	125.1
New FAR	1.2	1.3	1.3	1.3	1.3	1.2	1.1	1.1	1.2	1.3	1.4	1.4	1.3	1.2	1.2	1.2	1.2	1.3	1.1	1.1	1.0	0.9	1.2	1.4	1.5	1.5	1.4	1.2	1.2
New Roof Area (Sq.mts.)	11.0	7.5	12.8	17.2	20.3	13.3	3.4	0.0	7.1	9.7	58.2	12.5	5.8	4.1	1.2	5.8	10.0	13.6	32.0	28.4	21.9	2.0	9.2	13.1	18.6	12.9	7.9	5.4	7.3
Average Area (Sq.mts.)	68.1	69.8	73.4	76.6	79.4	71.6	61.7	57.0	67.1	74.9	103.0	80.1	72.3	62.6	61.7	67.6	70.6	73.5	76.3	70.7	61.9	49.1	69.1	79.4	86.8	84.0	75.6	65.0	66.2

Angle to South (Degree)	308	128	300	45	38
New Built-up Area (Sq.mts.)	154.93	147.73	145.73	138.45	135.99
New FAR	1.48	1.41	1.39	1.32	1.30
New Roof Area (Sq.mts.)	18.60	58.20	13.08	20.29	17.19
	86.76	102.96	79.41	79.37	76.59

Angle to South (Degree)	308	128	300	45	38
New Builtup Area (Sq.mts.)	154.93	147.73	145.73	138.45	135.99
New FAR	1.48	1.41	1.39	1.32	1.30
New Roof Area (Sq.mts.)	18.60	58.20	13.08	20.29	17.19
	86.76	102.96	79.41	79.37	76.59

Angle to South (Degree)	128	45	308	38	300
New Builtup Area (Sq.mts.)	147.73	138.45	154.93	135.99	145.73
New FAR	1.41	1.32	1.48	1.30	1.39
New Roof Area (Sq.mts.)	58.20	20.29	18.60	17.19	13.08
	102.96	79.37	86.76	76.59	79.41

Angle to South (Degree)	128	308	300	45	38
New Builtup Area (Sq.mts.)	147.73	154.93	145.73	138.45	135.99
New FAR	1.41	1.48	1.39	1.32	1.30
New Roof Area (Sq.mts.)	58.20	18.60	13.08	20.29	17.19
Average Area of Roof & Floors (Sq.mts.)	102.96	86.76	79.41	79.37	76.59

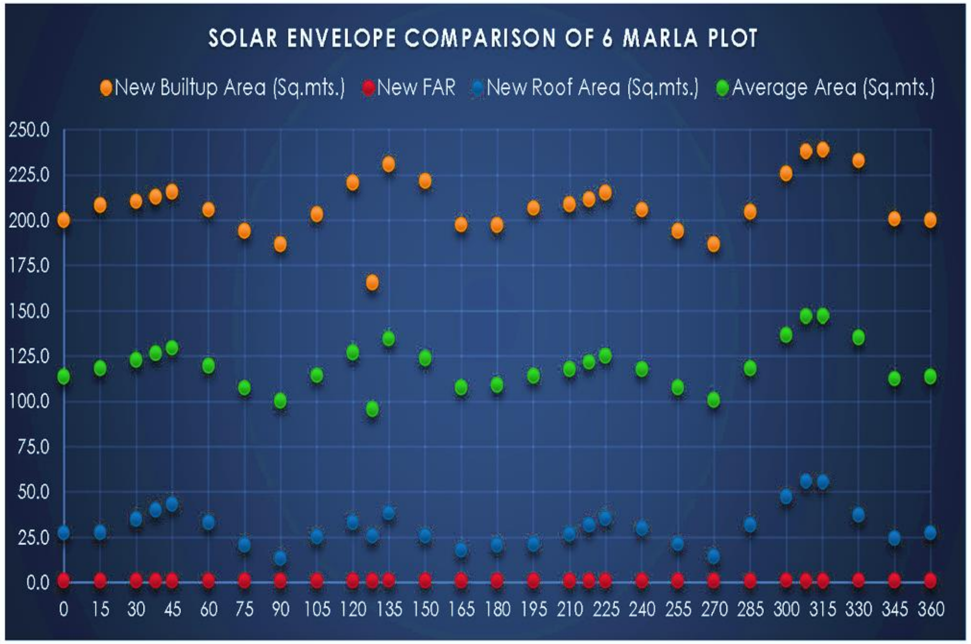


Annexure – VI (b)

Change in Built-up Area and FAR of 6 Marla Plotted Unit due to Solar Envelope

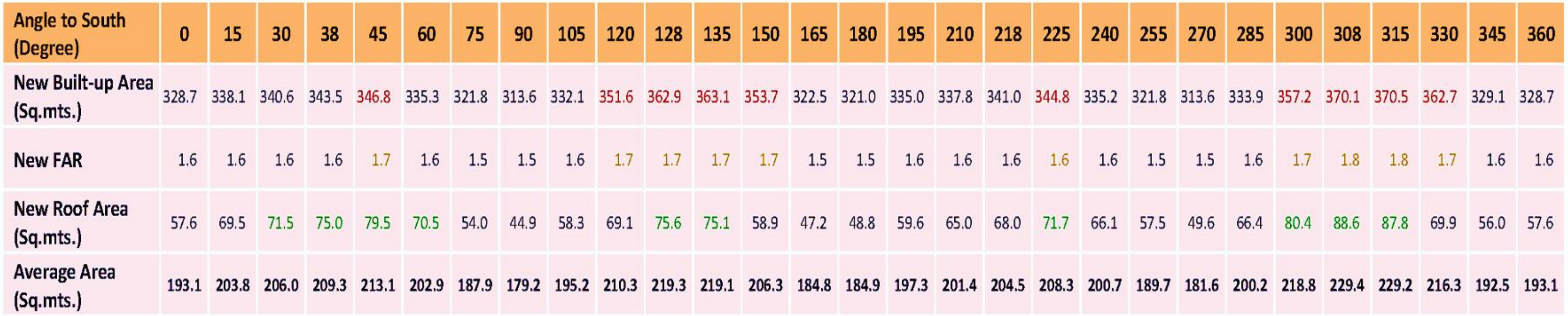
Angle to South (Degree)	**0**	**15**	**30**	**38**	**45**	**60**	**75**	**90**	**105**	**120**	**128**	**135**	**150**	**165**	**180**	**195**	**210**	**218**	**225**	**240**	**255**	**270**	**285**	**300**	**308**	**315**	**330**	**345**	**360**
New Built-up Area (Sq.mts.)	200.1	208.3	210.5	213.0	215.9	205.9	194.1	187.0	203.5	220.7	165.6	230.8	221.9	197.6	197.4	206.8	208.9	211.8	215.3	205.9	194.1	187.0	204.7	226.0	238.4	239.2	233.0	200.8	200.3
New FAR	1.2	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.3	1.4	1.0	1.4	1.4	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.3	1.4	1.5	1.5	1.4	1.2	1.2
New Roof Area (Sq.mts.)	27.6	28.0	35.1	40.3	43.4	33.4	21.0	13.5	25.4	33.5	26.1	38.6	26.2	18.1	21.0	21.3	26.8	31.8	35.6	30.3	21.6	14.5	31.9	47.5	56.4	56.0	37.6	24.5	27.6
Average Area (Sq.mts.)	**113.9**	**118.2**	**122.8**	**126.6**	**129.6**	**119.6**	**107.5**	**100.3**	**114.5**	**127.1**	**95.9**	**134.7**	**124.0**	**107.9**	**109.2**	**114.1**	**117.8**	**121.8**	**125.4**	**118.1**	**107.9**	**100.8**	**118.3**	**136.7**	**147.4**	**147.6**	**135.3**	**112.6**	**113.9**

Angle to South (Degree)	**315**	**308**	**330**	**135**	**300**
New Built-up Area (Sq.mts.)	239.24	238.38	232.99	230.78	225.99
New FAR	1.48	1.48	1.44	1.43	1.40
New Roof Area (Sq.mts.)	56.04	56.45	37.61	38.63	47.45
	147.64	**147.42**	**135.30**	**134.71**	**136.72**
Angle to South (Degree)	**308**	**315**	**330**	**135**	**300**
New Builtup Area (Sq.mts.)	238.38	239.24	232.99	230.78	225.99
New FAR	1.48	1.48	1.44	1.43	1.40
New Roof Area (Sq.mts.)	56.45	56.04	37.61	38.63	47.45
	147.42	**147.64**	**135.30**	**134.71**	**136.72**
Angle to South (Degree)	**308**	**315**	**45**	**38**	**135**
New Builtup Area (Sq.mts.)	238.38	239.24	215.89	212.97	230.78
New FAR	1.48	1.48	1.34	1.32	1.43
New Roof Area (Sq.mts.)	56.45	56.04	43.39	40.32	38.63
	147.42	**147.64**	**129.64**	**126.65**	**134.71**
Angle to South (Degree)	**315**	**308**	**300**	**330**	**135**
New Builtup Area (Sq.mts.)	239.24	238.38	225.99	232.99	230.78
New FAR	1.48	1.48	1.40	1.44	1.43
New Roof Area (Sq.mts.)	56.04	56.45	47.45	37.61	38.63
Average Area of Roof & Floors (Sq.mts.)	**147.64**	**147.42**	**136.72**	**135.30**	**134.71**

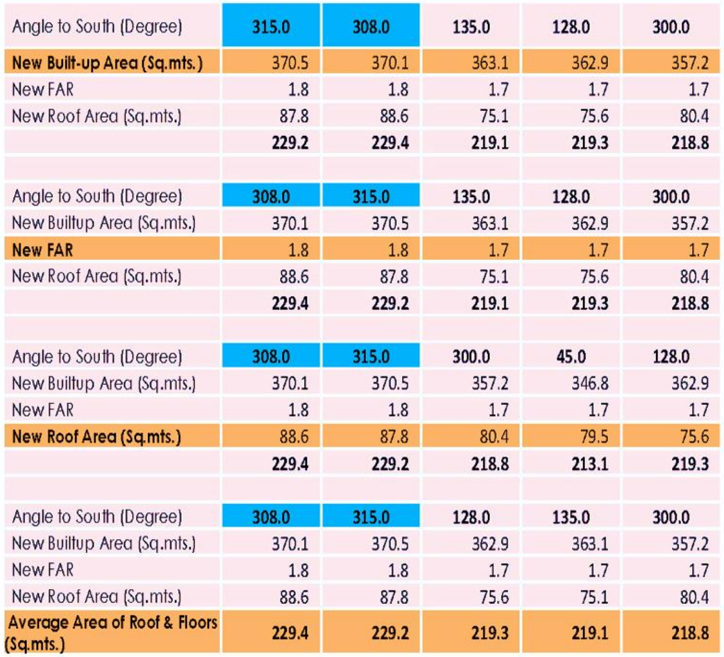


Annexure – VI (c)

Change in Built-up Area and FAR of 10 Marla Plotted Unit due to Solar Envelope



Angle to South (Degree)	0	15	30	38	45	60	75	90	105	120	128	135	150	165	180	195	210	218	225	240	255	270	285	300	308	315	330	345	360
New Built-up Area (Sq.mts.)	328.7	338.1	340.6	343.5	346.8	335.3	321.8	313.6	332.1	351.6	362.9	363.1	353.7	322.5	321.0	335.0	337.8	341.0	344.8	335.2	321.8	313.6	333.9	357.2	370.1	370.5	362.7	329.1	328.7
New FAR	1.6	1.6	1.6	1.6	1.7	1.6	1.5	1.5	1.6	1.7	1.7	1.7	1.7	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.6	1.7	1.8	1.8	1.7	1.6	1.6
New Roof Area (Sq.mts.)	57.6	69.5	71.5	75.0	79.5	70.5	54.0	44.9	58.3	69.1	75.6	75.1	58.9	47.2	48.8	59.6	65.0	68.0	71.7	66.1	57.5	49.6	66.4	80.4	88.6	87.8	69.9	56.0	57.6
Average Area (Sq.mts.)	**193.1**	**203.8**	**206.0**	**209.3**	**213.1**	**202.9**	**187.9**	**179.2**	**195.2**	**210.3**	**219.3**	**219.1**	**206.3**	**184.8**	**184.9**	**197.3**	**201.4**	**204.5**	**208.3**	**200.7**	**189.7**	**181.6**	**200.2**	**218.8**	**229.4**	**229.2**	**216.3**	**192.5**	**193.1**

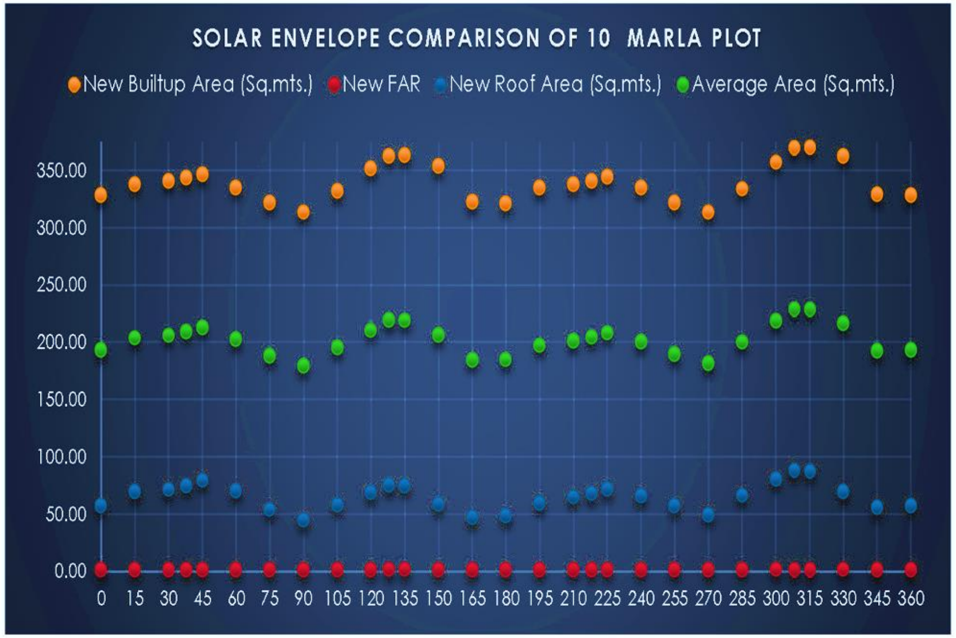


Angle to South (Degree)	315.0	308.0	135.0	128.0	300.0
New Built-up Area (Sq.mts.)	370.5	370.1	363.1	362.9	357.2
New FAR	1.8	1.8	1.7	1.7	1.7
New Roof Area (Sq.mts)	87.8	88.6	75.1	75.6	80.4
	229.2	**229.4**	**219.1**	**219.3**	**218.8**

Angle to South (Degree)	308.0	315.0	135.0	128.0	300.0
New Builtup Area (Sq.mts.)	370.1	370.5	363.1	362.9	357.2
New FAR	1.8	1.8	1.7	1.7	1.7
New Roof Area (Sq.mts.)	88.6	87.8	75.1	75.6	80.4
	229.4	**229.2**	**219.1**	**219.3**	**218.8**

Angle to South (Degree)	308.0	315.0	300.0	45.0	128.0
New Builtup Area (Sq.mts.)	370.1	370.5	357.2	346.8	362.9
New FAR	1.8	1.8	1.7	1.7	1.7
New Roof Area (Sq.mts.)	88.6	87.8	80.4	79.5	75.6
	229.4	**229.2**	**218.8**	**213.1**	**219.3**

Angle to South (Degree)	308.0	315.0	128.0	135.0	300.0
New Builtup Area (Sq.mts.)	370.1	370.5	362.9	363.1	357.2
New FAR	1.8	1.8	1.7	1.7	1.7
New Roof Area (Sq.mts.)	88.6	87.8	75.6	75.1	80.4
Average Area of Roof & Floors (Sq.mts.)	**229.4**	**229.2**	**219.3**	**219.1**	**218.8**



Annexure – VI (d)

Change in Built-up Area and FAR of 15 Marla Plotted Unit due to Solar Envelope

Angle to South (Degree)	0	15	30	38	45	60	75	90	105	120	128	135	150	165	180	195
New Built-up Area (Sq.mts.)	428.4	438.4	441.0	425.5	430.2	413.9	421.1	412.5	432.8	454.6	467.3	467.6	459.0	425.2	422.8	436.9
New FAR	1.5	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.7	1.7	1.6	1.5	1.5	1.5
New Roof Area (Sq.mts.)	94.9	104.5	107.7	129.4	131.8	123.7	85.6	74.9	90.1	103.6	112.0	112.1	91.7	76.0	76.5	91.2
Average Area (Sq.mts.)	475.9	490.7	494.9	490.2	496.1	475.8	464.0	449.9	477.8	506.5	523.3	523.6	504.8	463.2	461.1	482.5

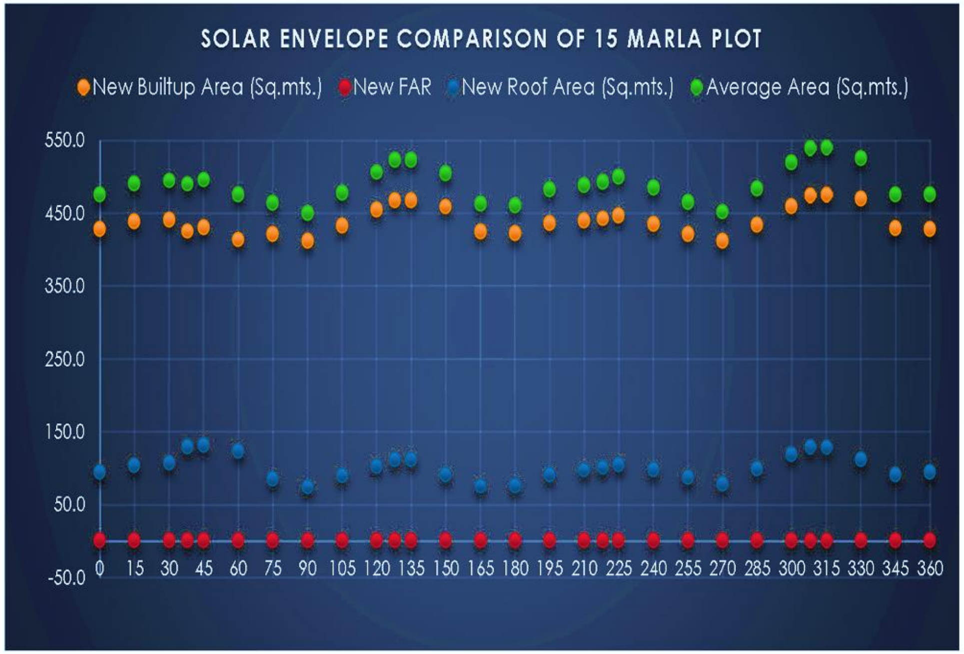
Angle to South (Degree)	210	218	225	240	255	270	285	300	308	315	330	345	360
New Built-up Area (Sq.mts.)	439.5	442.9	447.0	435.4	421.1	412.5	433.9	459.9	475.0	476.1	469.6	429.4	428.4
New FAR	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.6	1.7	1.7	1.7	1.5	1.5
New Roof Area (Sq.mts.)	98.1	101.4	105.5	98.7	87.9	79.3	99.9	119.3	130.2	129.7	112.2	92.0	94.9
Average Area (Sq.mts.)	488.5	493.6	499.8	484.8	465.1	452.1	483.9	519.6	540.1	540.9	525.8	475.4	475.9

Angle to South (Degree)	315	308	330	135	128
New Built-up Area (Sq.mts.)	476.1	475.0	469.6	467.6	467.3
New FAR	1.7	1.7	1.7	1.7	1.7
New Roof Area (Sq.mts.)	129.7	130.2	112.2	112.1	112.0
	540.9	540.1	525.8	523.6	523.3

Angle to South (Degree)	315.0	308.0	330.0	135.0	128.0
New Builtup Area (Sq.mts.)	476.1	475.0	469.6	467.6	467.3
New FAR	1.7	1.7	1.7	1.7	1.7
New Roof Area (Sq.mts.)	129.7	130.2	112.2	112.1	112.0
	540.9	540.1	525.8	523.6	523.3

Angle to South (Degree)	308.0	315.0	300.0	330.0	135.0
New Builtup Area (Sq.mts.)	475.0	476.1	459.9	469.6	467.6
New FAR	1.7	1.7	1.6	1.7	1.7
New Roof Area (Sq.mts.)	130.2	129.7	119.3	112.2	112.1
	540.1	540.9	519.6	525.8	523.6

Angle to South (Degree)	315.0	308.0	330.0	135.0	128.0
New Builtup Area (Sq.mts.)	476.1	475.0	469.6	467.6	467.3
New FAR	1.7	1.7	1.7	1.7	1.7
New Roof Area (Sq.mts.)	129.7	130.2	112.2	112.1	112.0
Average Area of Roof & Floors (Sq.mts.)	540.9	540.1	525.8	523.6	523.3



Annexure – VI (e)

Change in Built-up Area and FAR of 1 Kanal Plotted Unit due to Solar Envelope

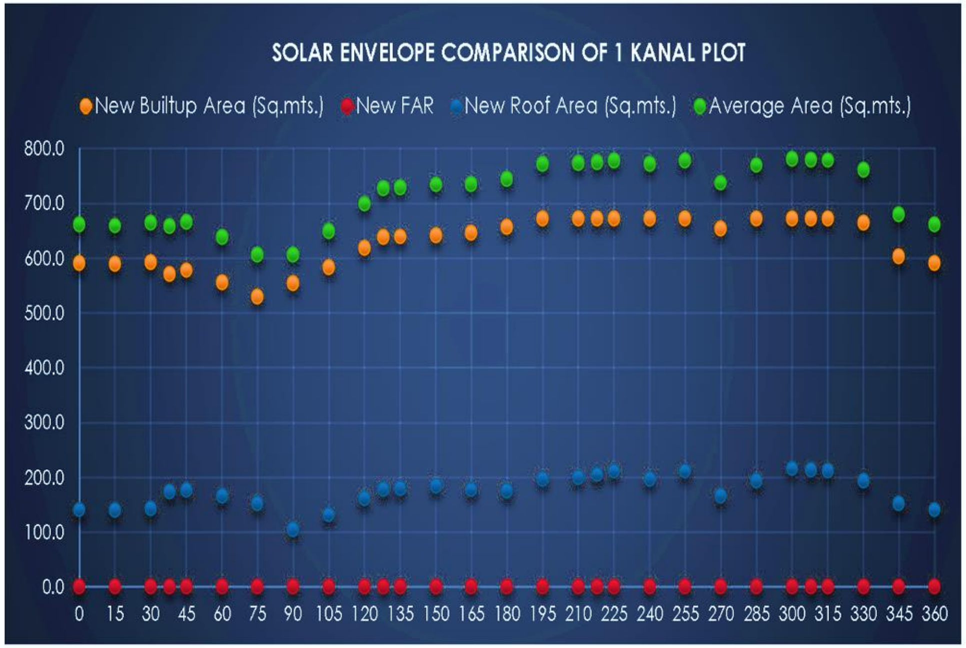
Angle to South (Degree)	0	15	30	38	45	60	75	90	105	120	128	135	150	165	180	195	210	218	225	240	255	270	285	300	308	315	330	345	360
New Built-up Area (Sq.mts.)	591.4	589.3	592.8	571.8	578.2	556.1	530.3	554.1	583.2	618.4	638.3	639.5	641.8	646.5	656.9	672.6	672.6	672.6	672.6	672.6	672.6	654.4	672.6	672.6	672.6	672.6	664.4	603.5	591.4
New FAR	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.3	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.3	1.3
New Roof Area (Sq.mts.)	141.2	139.9	143.7	173.8	177.0	165.9	153.0	105.7	132.1	161.5	178.6	180.2	185.3	178.2	175.8	197.6	200.9	205.7	211.7	197.6	211.7	166.5	194.4	216.4	214.1	212.9	194.0	152.9	141.2
Average Area (Sq.mts.)	**662.1**	**659.2**	**664.7**	**658.6**	**666.7**	**639.0**	**606.8**	**606.9**	**649.3**	**699.1**	**727.6**	**729.6**	**734.5**	**735.6**	**744.8**	**771.4**	**773.0**	**775.5**	**778.5**	**771.4**	**778.5**	**737.6**	**769.8**	**780.8**	**779.6**	**779.0**	**761.4**	**679.9**	**662.1**

Angle to South (Degree)	300	308	315	225	255
New Built-up Area (Sq.mts.)	672.6	672.6	672.6	672.6	672.6
New FAR	1.5	1.5	1.5	1.5	1.5
New Roof Area (Sq.mts.)	216.4	214.1	212.9	211.7	211.7
	780.8	**779.6**	**779.0**	**778.5**	**778.5**

Angle to South (Degree)	300	308	315	225	255
New Builtup Area (Sq.mts.)	672.6	672.6	672.6	672.6	672.6
New FAR	1.5	1.5	1.5	1.5	1.5
New Roof Area (Sq.mts.)	216.4	214.1	212.9	211.7	211.7
	780.8	**779.6**	**779.0**	**778.5**	**778.5**

Angle to South (Degree)	300	308	315	225	255
New Builtup Area (Sq.mts.)	672.6	672.6	672.6	672.6	672.6
New FAR	1.5	1.5	1.5	1.5	1.5
New Roof Area (Sq.mts.)	216.4	214.1	212.9	211.7	211.7
	780.8	**779.6**	**779.0**	**778.5**	**778.5**

Angle to South (Degree)	300	308	315	225	255
New Builtup Area (Sq.mts.)	672.6	672.6	672.6	672.6	672.6
New FAR	1.5	1.5	1.5	1.5	1.5
New Roof Area (Sq.mts.)	216.4	214.1	212.9	211.7	211.7
Average Area of Roof & Floors (Sq.mts.)	**780.8**	**779.6**	**779.0**	**778.5**	**778.5**



1. List of Journal Publications:

- i. Koduru, S. and Roy, M. (2014) **Indian Domestic Sector and the Need for Promoting Community Based Microgeneration over Stand-Alone Systems**. *International Journal of Research in Engineering and Technology (IJRET)*, 3 (11), 12 – 19.
- ii. Koduru, S. and Roy, M. (2017) **Decision Tool to Define Choice of Microgeneration Retrofit for Indian Households – A Conceptual Framework**. *SPECIAL ISSUE of International Journal on Emerging Technologies (IJET)*, 8 (1), 433 – 442.

2. List of Presentations in National / International Conferences / Workshops:

- i. Koduru, S. and Roy, M. (2017) **Decision Tool to Define Choice of Microgeneration Retrofit for Indian Households – A Conceptual Framework** presented at *National Conference on Urban Environmental Management: Problems and Prospects* organized by Department of Architecture and Planning, MNIT Jaipur, 13-14 February 2017.

INDIAN DOMESTIC SECTOR AND THE NEED FOR PROMOTING COMMUNITY BASED MICROGENERATION OVER STAND-ALONE SYSTEMS

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Abstract

Urban growth has resulted in increasing demand for energy primarily in form of electricity. With depleting energy resources, growing concern for promotion of alternative energy sources urban housing is going through a transition phase. There is a greater need for promotion of on-site microgeneration systems at community level to ensure a near zero sustainable domestic sector. The paper tries to define three major concerns that need to be addressed in ensuring near zero housing communities – the first being understanding the character of existing renewable energy strategies and promoting them in the context of changing housing typologies, second, identifying the need for development of hybrid energy generation systems in conjunction with renewable energy systems to balance energy demand at times of climatic inconsistencies, the third concern being the integration of on-site microgeneration infrastructure within the context of the built environment without altering the existing character and aesthetics.

Keywords: *Micro generation, Near Zero Housing Communities, Hybrid Energy Systems, Housing Typologies, Integrated Development*

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1. INTRODUCTION

Housing has become a necessity for human survival in urban areas. It is an individual’s ability, viability and determination for survival in this urban world. India as other major developing countries has been experiencing an increase in urban growth, corresponding to this the urban population to total population of India ratio has increased from 20% in 1971 to 28% in 2001 and 31% in 2011 [1]. Till 1980-90 migration in search for a better quality of life had accelerated the growth in urban population, with time the dimensions of the urban areas have expanded through inclusion of periphery rural areas. In the past decade upgradation of small and medium towns has brought down the rate of migration but the urban population numbers are still on the rise. Population increase has put excessive pressure on urban infrastructure like transportation, housing, potable water, electricity and sanitation. If measures are not taken, lack of sufficient funds will impend provision of basic infrastructure required to meet the needs of about 60% India’s population living in urban areas by 2030 [2].

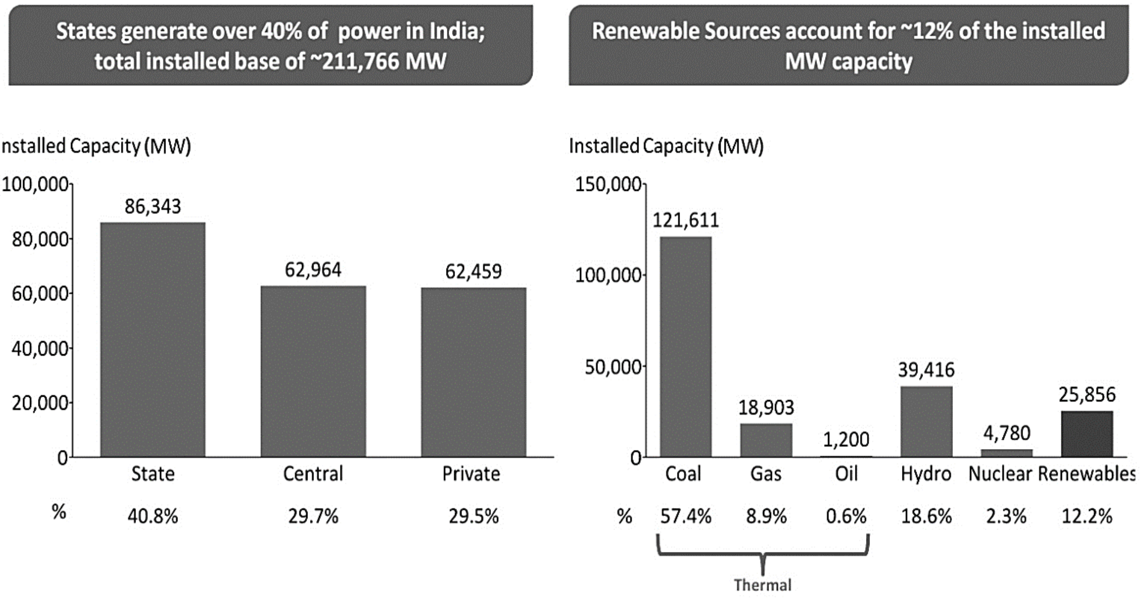
Increasing housing demand in urban areas on the other hand has prompted private developers to take advantage of the situation by indiscriminately developing high rise high density housing projects both within the urban areas and their periphery. The varied household configurations within these housing projects have opened up options for people from varied economic classes and affordability levels, but without any consideration to the pressure created on both land and resources.

To attract the masses and also ensure affordability, these urban housing society developments are predominantly high rise in character and integrated with heavy energy intensive infrastructure setups which include lifts, fire safety systems, centralized air conditioning systems, electronic surveillance, etc., which are dependent on backup energy networks to compensate for power outages and failure of the power grid. The backup systems primarily comprise of generators which run on conventional fossil fuels like diesel or natural gas. The whole setup involves huge initial investment and recurring maintenance costs, which later on influences the monthly expenditure of households in these townships.

In the present age of growing energy crisis attempts are being made to reduce the demand side along with energy conservation at various levels, but the scale of implementation has not delivered desired results in domestic sector leading to energy insecurity. Also, user behaviour and varied age groups lead to diverse energy consumption patterns thereby challenging energy demand predictions. To meet the global carbon emission regulations along with the domestic sector energy demand India has to develop and promote decentralized energy generation systems within the scope of existing housing development so as to meet their operational energy demand along with user interaction based energy management to reduce energy wastage.

2. ENERGY SCENARIO OF INDIA

India is the third largest energy consumer of the world after China and United States, followed by Russia and Japan with a significant growth in domestic energy demand after China in between 2010-2012. A major portion of electricity produced in India is by burning coal, diesel or gas in thermal power plants (66.9%) or from hydro-energy projects (18.6). Nuclear power plants (2.3%) contribute a very small portion along with non-renewable and biomass based sources (12.2%) (Fig.1) [3]. With non-renewable fuels as the primary source of power generation there has been an increase in import of coal and oil, also in the recent past accelerated development of hydro projects has resulted in major environmental disasters, causing extensive damage to life and property, as in case of June 2013 floods in Uttarakhand.


States generate over 40% of power in India; total installed base of ~211,766 MW

Renewable Sources account for ~12% of the installed MW capacity

Fig 1 Power generation configuration of India
(Source: Ministry of New and Renewable Energy, Ministry of Energy; India and Rev Partners Analysis)

Nuclear power generation has observed a major boost in the past decade, but low uranium supplies and import restrictions due to pressure from global nuclear treaties are threatening the future maintenance and sustainability of these high infrastructure setups. The development of power projects based on alternative energy sources primarily solar and wind based technologies is still in its initial stage, and the present level of implementation has been possible through government subsidy, international pressure and sponsorship from other countries. Such alternate energy sources also lack easy acceptability by the community, owing to their efficiency rate primarily defined by the geological location and under developed technological inputs.

Indian power generation has significantly grown from around 1,362 Mega Watts (MW) to over 160,000 MW in between 1947 and mid of 2010, rating India as the third largest producer of power in Asia. Despite the growth in electricity over the years, there has also been an increase in energy deficit. Transmission and distribution losses based on choice of fuel source and location of various power generation sources contribute majorly to the energy deficit, making India rank as no. 1 in the world for transmission and distribution losses of total electricity produced (Fig.2). As a result of this between 2003, and 2010 the energy deficit reached a value of 9.1 percent, and the average-peak power deficit reached 12.8 percent.

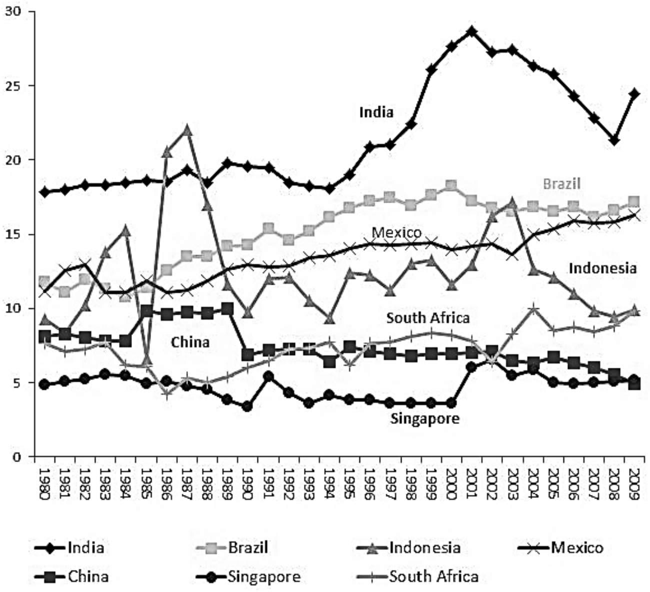


Fig 2 Global comparison of transmission and distribution losses as percent of power output
(Source: World Bank, World Development Indicators)

It would be significant to consider the locational vulnerability of the existing energy infrastructures due to climate change and both natural and manmade disasters (Fig.3). As depicted in the map major portion of India is prone to disasters, and with time and human development interventions even the areas which are least expected area showing signs of vulnerability. Major hydro power projects have become cause for flooding of lower areas during monsoons, the vast expanse of coast line prone to cyclones pose a threat to both off shore and on shore wind energy systems, being a major seismic zone certain parts of India are periodically cut off from the rest of the country, adding to this climatic vulnerability and global influences add to all these problems.

Energy deficit and rising energy consumption have resulted in an increase in power outage frequency, duration and impact range affecting various sectors of the economy and overall GDP growth rate. The revenue loss due to this wastage has effected investment for development of new power generation projects and capacity additions in existing power projects [4]. As a result, present day power demand problems and failing infrastructure are threatening future energy demand projections, forcing the need to search for alternative energy sources which are ideally renewable in nature, decentralized to minimize transmission losses, localized so that they can be planned accordingly to locational vulnerability and community based to ensure participatory approach in setting up, upkeep and maintenance of such infrastructure.

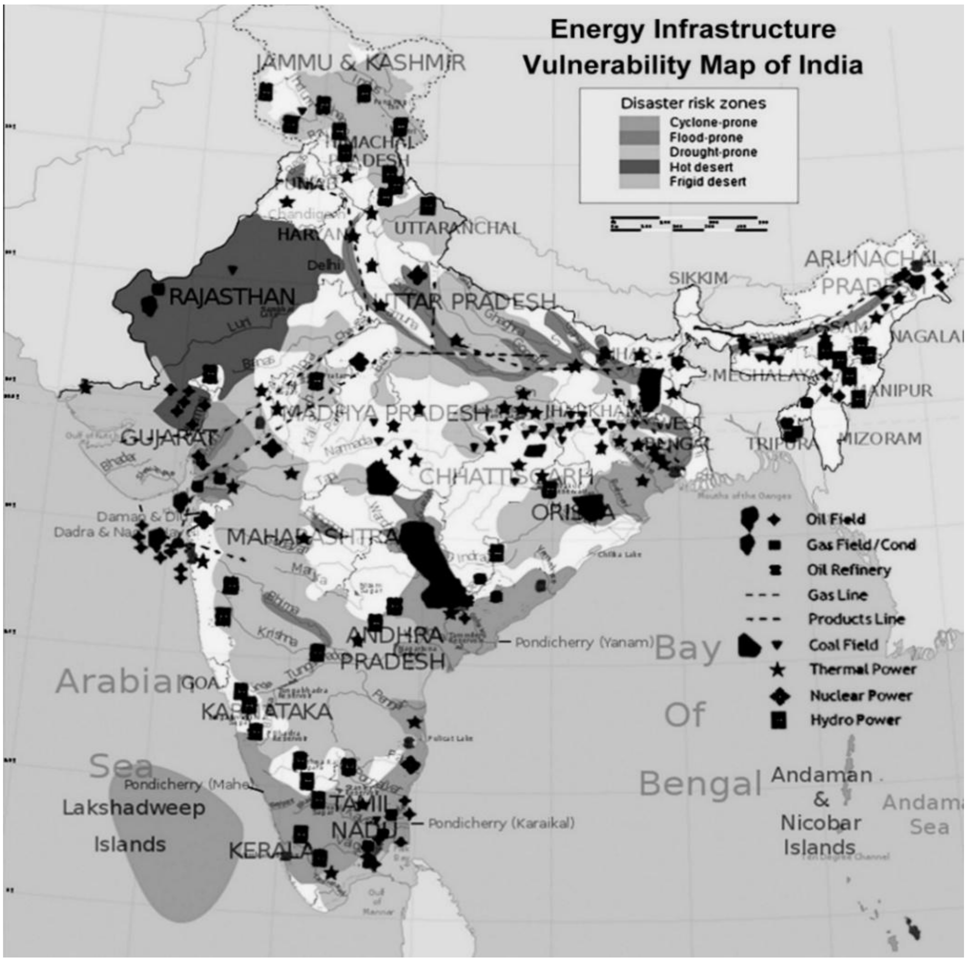


Fig 3 Energy infrastructure vulnerability map of India
(Source: Wikipedia and Live Journal)

3. SCOPE OF RENEWABLE ENERGY IN URBAN CONTEXT

Considering the scope of renewable energy available across diverse geographical configuration of India, the principle types available are – biomass, solar, hydro, wind, municipal waste, industrial waste, geothermal heat, tidal and wave energy. Within the context of urban housing the potential contributors are solar, wind and biomass based energy systems. Solar based heating and energy generation systems are already the most established in the form of solar water heating or solar photovoltaic (SPV) systems. Wind based energy systems are yet to find their place within the urban context due to the varied factors that include rising height of buildings, local factors impacting wind patterns, technical and financial feasibility. Though a lot of research is underway in enhancing the efficiency of both these technologies they are yet to find their full potential in implementation and integrated development within the context of urban housing to meet the growing energy demand. Biomass and municipal waste based energy systems have been limited primarily to pilot projects and in most cases they are non-operational owing to technical and financial issues.

If the solar potential is assessed the average solar energy incident of India is around 4 to 7 kWh/m^2 and with around 1,200-1,800 sunshine hours per year varying on basis of location, the total energy generated could surpass the actual energy demand. Theoretically, the total solar energy output of India for a duration of about 300 clear sunny days in a year could reach up to 60,00,000 GW. The problems in meeting this production target range from availability of land for setting up solar array based power facilities, which demand around 250 acres of land for 20 – 60 MW output.

Second, in the urban context where there is scarcity of land rooftops are the only available space for setting up solar based infrastructure, which again depends on the architectural character and disaster vulnerability of the place. The economics of setting up such infrastructure on an individual household basis when equated to total duration after which returns are derived are not quite promising for the end user as a result leading to demand in reducing the investment cost by provision of subsidies.

Though wind energy accounts for 67% of total grid interactive renewable energy in India in comparison to only 7% from solar based systems, most of the power generated is through off shore wind farms along the coast and inland areas of Gujarat and Rajasthan. The topography of India also offers least scope for setting up wind farms in the inland areas (Fig.4) with a major portion of northern regions falling under wind power density of 0-100 W/Sq.mts., thereby rendering it of least scope for microgeneration based strategies within urban areas.

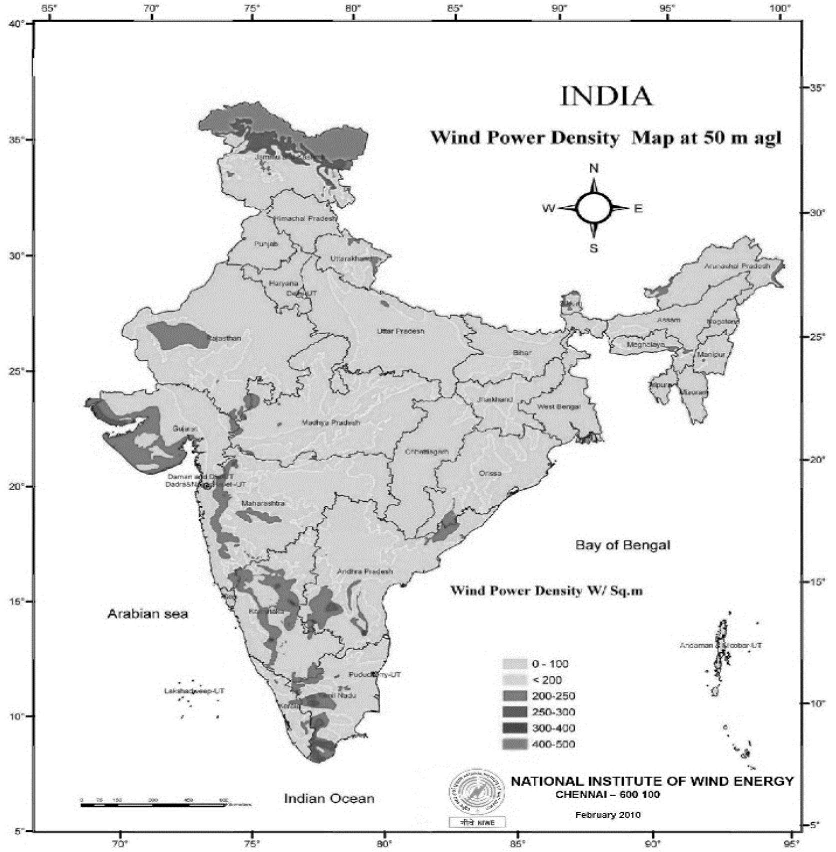


Fig 4 Wind power density map of India
(Source: Center for Wind Energy Technology, www.cwet.tn.nic.in)

Biomass and municipal waste based energy systems are viable due to the agrarian character of suburban areas around major urban centers which ensure availability of agricultural waste in addition to urban waste that could be converted into energy. Such energy systems have been a success in rural areas owing to the vast expanse of agricultural land and animal husbandry. But within the context of urban areas they have failed due to logistic reasons of delivery and storage of waste which otherwise have become centers of environmental degradation and health factors. The still immature and lower efficiency of the technology result in not generating optimum output in comparison to other renewable technologies, as a result most units have either been shut down or have become financial burdens for municipal authorities. In view of all these observations, solar based energy generation offers greater potential than other sources in housing sector, but integrating them into the physical built and ensuring social acceptance and financial viability need to be addressed.

4. DOMESTIC ENERGY DEMAND AND FUTURE TRENDS

In the past three decades, Indian domestic sector has become the third major consumer of total energy produced through consumption of various fuels after industry and transport. In the year 2010-2011, industries consumed about 45% of total energy produced followed by the domestic sector with 22% consumption (Fig.5) with an increase of 8% annually. Trend analysis indicates that domestic sector has seen an increase of 9.67% electricity consumption in comparison to 5.57% by the industry from 1970-1971 to 2010-2011 [3].

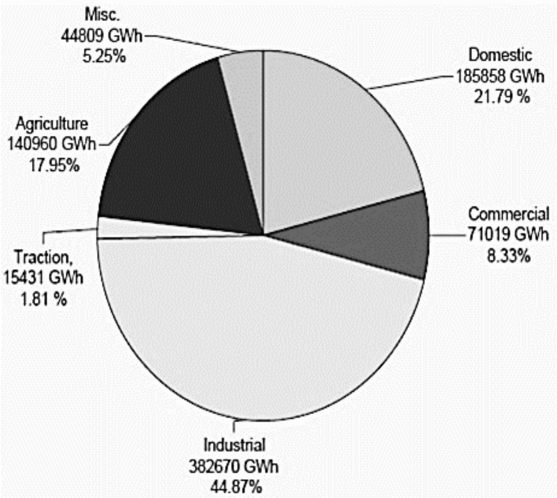


Fig 5 Sector wise electricity consumption pattern of India (Source: Central Electricity Authority, www.cea.nic.in)

Increasing global consciousness towards greenhouse gas emissions has pushed the need for promotion of alternative renewable energy sources in various sectors including the domestic sector, as it is the highest consumer of utility electricity and fossil fuels for heating, thereby contributing majorly towards increase in global carbon-di-oxide levels [5, 6].

The primary factors that contribute to the increase in domestic energy demand include sedentary lifestyle demanding continuous information exchange across various media and climatic change which influence the ownership of electrical appliances and their operating hours. Even though efforts are underway to increase their efficiency through development of energy labelling and smart networks the demand for power has been increasing. Power theft is another major deterrent in the upgradation of existing energy infrastructure leading to huge financial losses for power generation companies and in some states it has reached up to 30% of total power generated.

Gauging the future energy demand of urban households and defining a common threshold in housing energy demand and efficiency is quite challenge owing to varied user groups differing on basis of their age, financial status, occupation and lifestyle [14, 15]. The dynamic user behaviour and occasional surge in power demand during festivals, cricket matches and regional climatic disturbances result in volatile nature of energy demand within urban areas in comparison to more static energy demand of rural areas.

Promotion of centralized solar power plants to meet domestic energy demand involves high initial investment costs and dependence on geographical location and weather conditions. The cost of transmission and distribution losses result in increase of pre unit cost of power consumed. Also, the quantum of energy generated through such systems can operate low energy demanding appliances like general lighting, fans but high energy rated appliances like air conditioners or space heating equipment which are seasonal based need a different energy source. Such solar power projects also require vast land area in setting the infrastructure and viable in meeting energy demand of low energy users like a cluster of rural areas, and future increase in energy demand met through up-scaling of existing infrastructure.

5. ISSUES WITH EXISTING SOLAR ENERGY BASED STRATEGIES IN VIEW OF CHANGING HOUSING TYPOLOGIES

In the year 2005 residential spaces formed 16,300 Million sq.ft, which is about 78% of the total 20,882 Million sq.ft floor space area available, and it is projected that the residential area would increase to 69,823 Million sq.ft by 2030. In such a scenario, high rise high density gated housing development is the viable option in meeting future housing demand, which apart from ensuring affordable housing with increasing land price also promote a sense of security for the community living within these townships. With increasing affordability levels, varying lifestyles and job character housing typologies have undergone major transformation. Today’s housing typologies could be classified into three categories – low rise – low density plotted development, low rise – high density row housing, high rise – high density townships.

Table 1 gives a broad overview of the issues concerning renewable energy infrastructure integration in these housing typologies based on their physical development, ownership pattern and present state of renewable infrastructure integration.

Table 1 Issues concerning Renewable Energy Infrastructure integration in various Housing Typologies

Housing Typology	**Issues concerning Renewable Energy Infrastructure integration with respect to Physical Development, Ownership and Existing Renewable Technologies**	
Low Rise Low Density Plotted Development	Physical Development Character	• Individual households with front and rear setback or on all sides. • Maximum three floors • Varying architectural character
	Ownership	• Single owner with multifamily occupancy • Owner with single or multiple tenant occupancy
	Existing character of Renewable Technologies	• Ample space per household for renewable energy strategies • Individual user based solar water heating systems on roof
Low Rise High Density Row Housing with Floor Wise Ownership	Physical Development Character	• Low density gated community comprising of row housing • Primarily front and rear setback with common walls • Maximum three floors • Uniform architectural character within community
	Ownership	• Floor wise ownership • Owner or tenant based occupancy • Ownership of terrace varies – treated as common area or rights given to the owner with the terrace as roof
	Existing character of Renewable Technologies	• Varies on basis of terrace ownership • Individual or multi user solar water heating systems on roof
High Rise High Density Townships	Physical Development Character	• High density gated community comprising of high rise towers • Clear distance between each block as per developmental controls • Minimum 4 floors and maximum 16 floors • Uniform architectural character within community
	Ownership	• Flat wise ownership • Owner or tenant based occupancy • Ownership of terrace varies – treated as common area or terrace right with owner in case of penthouse
	Existing character of Renewable Technologies	• Varies on basis of terrace ownership • Less open terrace space per household due to provision of service areas for water tanks, lifts, staircase and ducts • Difficult to meet demand of all households even after installation of multi user solar water heating systems

Provision of roof based solar water heating systems accounts for the most common renewable energy strategy being employed in the above housing typologies. Scope of SPV or BIPV systems in domestic sector has to be explored and their implementation strategies detailed out. Existing energy conservation and domestic level renewable energy generation initiatives that are being employed in the above typologies are only definitive with the solutions being generalized and loaded with incentives, in such a complex domestic setup a generalized solution may have low rate of success owing to variable character of factors affecting energy demand of households [7].

Energy metering slabs have been undergoing revision across various states of India and at present the slabs for calculating monthly domestic electricity charges range from up to 100 units, 101-300 units, 301-500 units and above 501 units. The average per unit rate across various states range from 4.25-5.00 rupees per unit for up to 300 units and increases to 6.25-9.50 rupees per unit for above 400 units

Considering the average energy consumption of a 106 sq.mts, 4 member individual household with a connected load of 4.8 kW being around 320 - 500 kWh per month. The annual energy consumption of the household ranges from 3,840 – 6000 kWh and the monthly electricity costs could range between 1, 450 – 4,000 rupees across various states. Considering the floor area equal to roof area of 106 sq.mts, a solar roof energy system of 4 kW with multiple PVs of 16% efficiency covering 25 sq.mts each under ideal conditions can generate a power of 1,500 – 2,200 kWh per month (as per calculations by NREL web tool). This is more than enough to meet the requirements of a three storied (G+2) housing unit, but beyond this there would be a need for energy input from the grid.

Also present approach towards solar based strategies are driven by incentives. Incentives in the form of subsidies do not reach every level of the housing structure owing to location, administrative and information transfer issues, this invariably gives scope for middle men to take advantage if there is lack of transparency in the whole system [8, 9]. Any incentive should be based on the household energy saving output rather than on the input for energy generating infrastructure. This would ensure incentives administered by government to those potential households which have achieved desired targets, leading to better awareness and information transfer at the household level [10, 11, 12].

6. DEFINING THE NEED AND SCOPE OF COMMUNITY LEVEL MICROGENERATION BASED MICRO GRIDS IN HOUSING

The attempt of any alternative approach should be to reduce the burden of monthly energy expenditure on a household, for which a decisive approach needs to be worked out searching for alternative implementation strategies that would promote energy generation as well as conservation without compromising on the true energy needs of a household. Such power generation initiatives shall define the future pathways for promotion of sustainable energy generation, and also lead to significant job creation than centralized projects. Household based microgeneration at community level can be a viable option for it allows housing society or communities to generate their own power and any excess production could be transferred to the grid in return for incentives or credit [7, 8]. At times of need or in case of low production rate the supply from grid could compensate for the deficit and paid back through credits or bills. This results in a dual channel approach that is very dynamic and ensure a near zero housing development.

Solar based systems can meet the demand for plotted and low rise low density row housing development if the true potential of the roofs is exploited. But in case of high rise high density townships the energy demand surpasses the production through roof based solar based energy systems. To enhance energy production and ensure a near zero housing development the potential of Building Integrated Photovoltaic Systems (BIPV) need to be investigated along with development of hybrid energy systems. Hybrid energy systems are energy networks that offer greater flexibility and potential to cover up deficit in energy production primarily due to climatic factors.

Similar to stand alone systems the hybrid systems can sell out additional generated power thereby reducing or completely eliminating central grid dependency, but also reduce transmission losses resulting in grid stability and less power outages. The operation of such units shall aid in meeting energy demand at times of grid failure due to disasters, as has been demonstrated in numerous international scenarios like the successful case of Sendai micro grid being operational during the March 2011 earthquake and subsequent tsunami in Japan.

Hybrid energy generation systems within housing development could either function as stand-alone facilities or integrated into a single network with solar based infrastructure forming the major component. The other components of such multiple energy generation systems within the context of urban housing could be ground and air source heat pumps or Combined Heat and Power (CHP) systems based on biomass, natural gas or traditional fuels [16].

Further research is required to understand the integration of various hybrid infrastructure into the physical structure of existing housing with respect to their siting and provision of access for their maintenance. Studies would also be required to understand the impact of hybrid infrastructure integration on built form aesthetics, as it has been observed that most renewable energy technologies are installed after the overall planning and construction of any built form is undertaken, resulting in their functional reasons based integration without any consideration on aesthetics [17].

The research shall aid in defining guidelines and provision in byelaws for the promotion of renewable energy infrastructure through built form integrated development for under construction and future housing. Decentralized energy generation networks in form of building integrated micro-generation and hybrid technologies could be an effective way of ensuring energy efficiency and meeting the near zero energy target in housing.

7. CONCLUSION

There is a greater need for promotion of household and community based microgeneration in meeting the increasing energy demand with reduced carbon emissions. The financial model for output based incentives that can aid in better promotion and involvement of the community towards renewable energy systems needs to be investigated. There is a highlighted need to search for hybrid energy systems rather than pure renewable energy based systems to meet energy demand at times of climatic and local inconsistencies. Further research has to be undertaken for promotion of built environment integrated microgeneration so as to meet energy demand targets without compromising on aesthetics and character of the built forms.

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International Journal on Emerging Technologies **8**(1): 433-442(2017)

ISSN No. (Print) : 0975-8364
ISSN No. (Online) : 2249-3255

Decision Tool to Define Choice of Microgeneration Retrofit for Indian Households: A Conceptual Framework

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(Received 25 December, 2016 accepted 22 January, 2017)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: In India, housing sector is the second major consumer of electricity with the rate of demand increasing by 11.08% from 1984-85 to 2014-2015 in comparison to -16.92% by industries. around 97% of the electricity is generated using non-renewable energy sources. in contrast to this the government of India has promised to reduce the greenhouse gas emissions upto 33-35% by 2030 from 2005 levels. In 2010 the government of India also proposed the 'Jawaharlal Nehru national solar mission' to promote solar-based energy generation. in these 'solar cities' households and group housing societies are expected to install solar-based energy systems to satisfy the numbers without understanding their true potential and association with the built form parameters and user behavior. the consumer is not exposed to alternate renewable energy systems like wind based, heat pump, combined heat and power (chp). The paper defines the conceptual framework of a decision tool for homeowners to choose from different microgeneration retrofits. assessment includes analyzing existing consumption pattern of the household and its true energy demand to identify possible alternate measures. The output shall guide homeowner to make a decision based on the financial commitment and retrofitting required for the housing unit.

I. INTRODUCTION

India through its Intended Nationally Determined Contributions (INDCs) proposal in 2015 pledged at the United Nations Climate Secretariat that it would reduce carbon emissions by upto 33-35% relative of its GDP from 2005 levels by 2030. It also affirmed that out of the total electricity generated by 2030, 40% electricity shall be from non-renewable energy sources like solar and wind power (Neha, 2014).In 2014-15, industry sector was the highest consumer of electricity at 42.10% followed by the domestic sector at 23.53%. But if the historical values are compared from 1984-85 to 2014-15 the industrial sector has seen a decline of 16.92% in electricity consumption from 59.02% to 42.10%, whereas within the same duration the domestic sector has seen a growth of 11.08% in electricity consumption from 12.45% to 23.53%. In addition to the changing electricity scenario, India has the highest transmission and distribution losses in the world at 23.65% in 2012 (Central Statistics Office, 2016). Also, the per capita consumption of electricity in 2012 was 884 whereas the world average was 2,972 and countries like Brazil achieved a value of 2509.

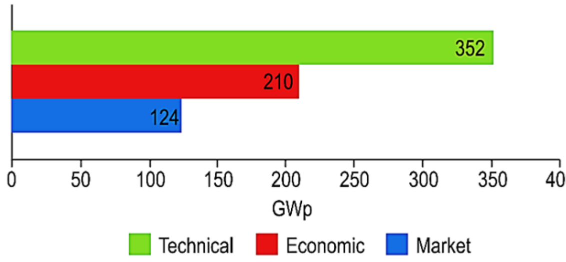

Fig. 1. India's Potential for Rooftop Solar Photo Voltaic Capacity. (Source: TERI, Reaching the Sun with Rooftop Solar Report, 2014).

The residential electricity use in India in expected to four-fold in 2030 and an average household shall consume upto five times electricity by 2020 in comparison to 2000 (Agency, 2007) (Ghosh, 2002).To meet this growing electricity demand there is a major momentum towards creation of energy infrastructure in different parts of India.

The present power generation configuration in India is mainly attributed to Coal (75.61%), Hydro (11.69%), Renewable Energy Sources (5.59%), Gas based sources (3.72%), Nuclear (3.27%) and Diesel (0.13%) based sources (Central Statistics Office, 2016). To increase the present renewableenergy based power generation from 5.59% to 40% within a span of 15 years it would require measures to enhance generation, control consumption and promote conservation. This would also require contribution from all the major consumer of electricity primarily the housing sector.

A major initiative towards promotion of renewable energy systems especially solar power based was the Jawaharlal Nehru National Solar Mission initiated in January 2010. The first stage goals of the mission is to deploy grid connected solar power of 20,000 MW by 2020 (Shrimali, 2012). Another simultaneous outcome of this mission was to create 'Solar Cities' across India. The main goal for these solar cities is to reduce their projected electricity demand met through conventional energy by 10% over a span of 5 years (TERI, 2014). The choice of renewable energy systems to be developed based on the availability of resources included solar, biomass, wind, waste to energy, small hydroetc. On the global scenario heat pump, combined heat and power (CHP) systems are also promoted as part of renewable energy systems.

The electricity sector is the major contributor of CO_2 and CO emission in India. In 2012, it contributed towards 35.5% of total emissions. Out of the total emission coal based power plants contributed towards 50.1% emission (Shrimali, 2012).With rapid urbanization and increasing ownership of electric appliances the contribution towards carbon emissions is expected to increase.

As per the World Bank Report 2014, out of the total electricity used in urban areas, 69% was utilized for heating and cooling, kitchen appliance and entertainment whereas 31% was used for lighting. With increasing power demand the frequency of outages owing to power shortage have increased, primarily during the summer season when the power consumption is the highest. Another major challenge is the vulnerability of our energy infrastructure as India is prone to various natural calamities like floods, drought, earthquake, tsunami and cyclones. As a result the whole electric grid fails resulting in loss ofemergency power to places affected by natural calamities or disasters at both urban and rural level, like the recent floods in Chennai and Uttarakhand. This calls in for decentralized and localized power generation initiatives that are primarily based on renewable energy systems, which have low distribution and transmission losses, easy maintenance and recovery, need less skilled manpower in comparison to conventional energy systems and understands the availability of local resources and their potential in energy generation.

To ensure that the goals set by the Government of India are met it is necessary to implement a range of initiatives, some of which are already underway like measures to conserve energy. Apart from these concrete measures towards developing a network of decentralized renewable energy based Microgeneration power systems are required. Another approach should aim to reduce wasteful consumption of energy through retrofit measures to the existing setup. In case of the housing sector the present rate of urban development demands for high rise high density development, resulting in such initiatives be initiated at the neighborhood level.

To accommodate the growing urban population various mega housing projects are being proposed all over the country thatare supported by high energy intensive service networks. To ensure effective implementation of any initiative and promote equal contribution from every household all proposal should be planned at the community level. Existing strategies adopted by various agencies are dictatorial in nature and aimed to meet the numbers rather than involve the community; as a result they are unable to meet the desired results. Heavy subsidies upto a tune of 40% (Bijli, 2016) on investment being offered on different renewable energy systems is the only reason behind their installation and there is no cross check mechanism to ensure their working condition or maintenance once there are installed.Instead of promoting these systems and awarding the subsidies on individual basis they should be awarded to communities based on their involvement and scale of implementing the Micro generation systems. The extent of subsidy offered to the community could be based on how the strategy adopted by them has ensured energy security, reduced carbon emissions and improved the living standards of all the community members.

To ensure a greater understanding towards various Micro generation systems there is a need to develop a decision making tool that would guide the community to make a decision regarding the choice, implementation and financial constraints of different systems. The other part of the tool would define the payback period and assured returns both financially and environmentally. The tool would predict potential interventions to achieve energy efficiency and possible renewable energy systems by taking into account the existing consumption patterns, climatic conditions ofthe place, possible energy saving through retrofit of housing unit, user behavior and actual energy demand.

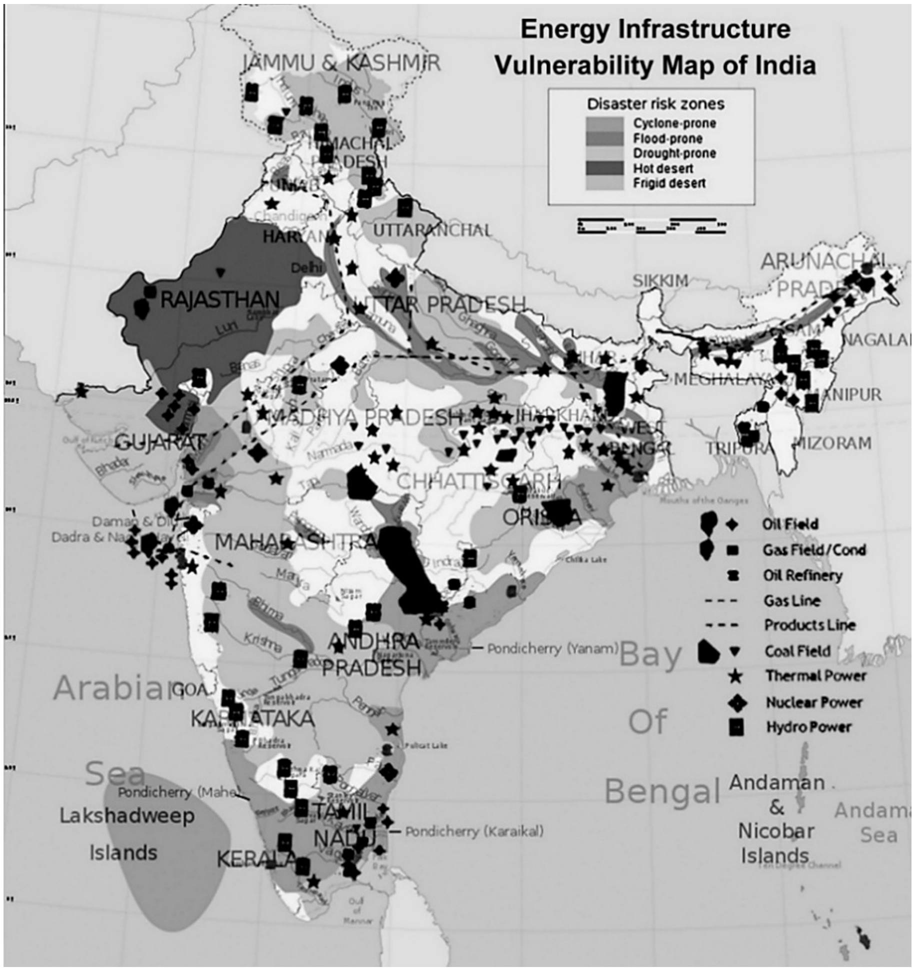

Fig. 2. Energy infrastructure vulnerability map of India.

It would guide the end users to make an evaluation based on financial and environmental benefits at household, building and neighborhood levels.

II. TOP DOWN AND BOTTOM UP VARIABLES

Energy modelling to define the energy consumption patterns at community level within the housing sector are guided by two approaches – ‘Top-Down’ and ‘Bottom-Up’ (Tuladhar et al. 2009). The Top-Down approach tries establish a relation between total energy supplied and actual energy demand in order to define measures of achieving balance. It includes collection of data for a series of variables that are based on a user, particular time period and the geographical location (Hourcade et al. 2006).

The top-down analysis relies on establishing the link between factors affecting energy consumption and total energy consumed by an individual household (Swan and Ugursal 2009). The advantage of top-down approach is that it can be analyzed using data collected through collected information like reports and processed information sets. It fails in modelling energy consumption at a larger scale and cannot model irregular changes in energy strategies or technologies (Swan and Ugursal 2009). The approach also tries to establish a relationship on basis of past data, but while modeling for scenarios related to environment, social and economic conditions and climate change it has been pointed out that the experience factor may not be the same or need not follow a trend (Kavgic et al. 2010). These limitations clearly indicate that the top-down approach cannot be the only option to identify key areas of trends in energy consumption and improving the demand side of energy at neighbourhood level (Swan and Ugursal 2009).

The Bottom-Up approach relies on data collected at household level andneighbourhood level. Based on the information collected, the energy consumption patterns identified are generalized for regional, city or national level.

The data can be analyzed at two levels – first processing involves the statistical methods and the second involving building assessment through physics based energy models.

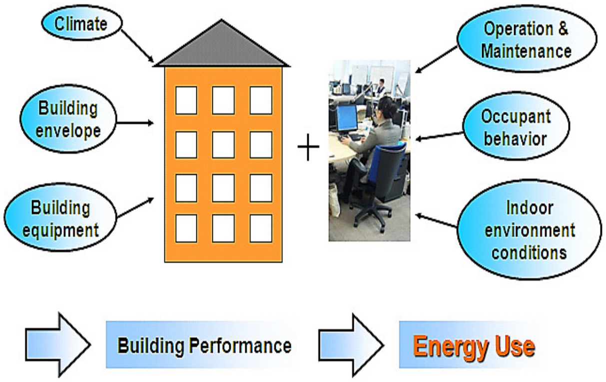

Fig. 3. Factors Influencing Total Energy Use in Buildings.

The statistical modelling process involves collection of large data sets primarily involving the monthly electricity bills, economic base, fuel types used, hours of operation, etc. The reliability and information sharing of such data is always a challenge. The final coefficient of the input values derived through regression analysis is an indicator of energy consumption of households (Fung 2003). The end result is only an indicator of energy consumption within the household or neighborhood but cannot define the possible impact of measures taken up to reduce energy consumption through different scenarios (Fung 2003).

The short comings of the statistical methods could be answered by the building physics model which calculates the energy performance of a building or its components. This involves identifying the various physically measurable variables of a housing unit, its occupants and energy consuming infrastructure that would be required for quantitative assessment. The first and most predominant set of variables are linked to the area and dimensions of the housing unit and its various elements like floor, roof, walls, door and windows. The second set of variables includes the materials, components used in the construction of the unit and their corresponding thermal performance in form of U-values. The third set of variables are related to the occupants and their behaviour pattern listed in form of total number of occupants, heating and cooling needs, indoor and outdoor temperatures. The fourth set of variables are related to the configuration of energy consuming appliances in the household, their efficiency levels, period and duration of operation etc. (Johnston 2003).

The data sets for building physics modelling could be collected from surveys conducted both at household and neighborhood level, national, state or regional level information sets. The analysis will result in defining the existing energy consumption patterns and also estimate the future energy consumption of the households and neighbourhood (Larsen and Nesbakken 2004). In depth analysis would also aid in understanding the user behavior at household and neighborhood levels thereby making effective strategies aimed at reducing wasteful energy consumption and promoting energy conservation. Another major outcome would be the performance of electrical appliances and measures to enhance their efficiency.

The level and detail of information in the data sets defines the accuracy of the building physics model. The algorithm in the models being modular in nature, they could be modified to suit the needs and define the desired output (Kavgic *et al.* 2010). To check the accuracy and performance of the models, calibration could be done using historical data. Due to their diverse applicability and possible iterations building physics models have evolved to be the ideal method to estimate sector based energy consumption taking into view all possible impacts of any new technology, at the same not dependent on historical data for reference or identifying trends (Swan and Ugursal 2009).

III. MICROGENERATION CHOICES AND NEED FOR THE TOOL

The materials that are used in the construction of a housing unit account to 50% of total carbon footprint generated by the energy consumed by the unit in its lifetime. If the insulation of a unit is not taken care of then it becomes 25%. Interventions to minimize the carbon footprint of a housing unit through mitigation of its insulation and possible retrofitting should be promoted to reduce the overall energy demand.

Microgeneration infrastructure can be another set of measures to reduce dependence on fossil fuels as a result impacting the carbon footprint of the unit. Depending on the overall energy demand the type and configuration of the Microgeneration infrastructure can be defined. They could be standalone systems or a combination of two or more systems which are collectively called ‘co-generation’ or ‘tri-generation’ systems. These systems due to the close proximity between source and the point of use are more efficient than conventional grid based networks.

Fig. 4. Types of Microgeneration Infrastructure relevant to Housing Sector.

The various types of Microgeneration infrastructure (Fig. 4) that could be part of individual household and neighborhood are – solar water heating, photovoltaic, wind power, biomass, combined heat and power (CHP), heat pumps and hybrid technologies.

*A. Solar Water Heating and Solar Photo Voltaic (SPV)*Solar water heating systems are the simplest way to utilize sun's energy in heating water or air. The system is easy to adapt to various built form typologies. But the major challenge is its applicability in places that experience extreme cold conditions. The second major choice in Microgeneration infrastructure is the solar photovoltaic cells, which convert sun's energy into electrical energy and store it in batteries. Due to lack of moving parts they are the most easy to operate and maintain. The two major varieties that are commercially available are 'Mono Crystalline' and 'Poly Crystalline' modules.

The mono crystalline photovoltaic (PV) cells are costly due to highly refined circular solar cells but have higher efficiency of upto 45%, on the other hand poly crystalline PV cells have impurities as a result are less efficient and cheaper than mono crystalline cells. Apart from these a third generation of solar cells called Photo Electro Chemical (PEC) cells are being developed that can achieve an efficiency of 65%.

B. Wind Power: After solar, wind power is the next major renewable energy infrastructure being deployed at various part of the country. These wind farms are primarily located along the cost and open areas to take full advantage of the local resources.In the urban context, due to space constraints they are preferred to be installed on rooftops so that they are clear of any obstruction. To run the blades of the utility turbines, continuous air flow ranging over a speed of 6 m/s would be required.

With a lot of obstructions, tree coverage and built mass it would be very difficult to achieve wind speeds that could run the turbines. To ensure better operation of the wind mill the turbine and blades should be at least 10 m above the highest obstruction. This possess a challenge for neighborhoods near airports due to height restrictions. The overall efficiency of wind mills range from 25% - 40% thereby the return period is longer than solar based systems.

C. Biomass: Biomass is a major source of energy in the rural parts of India. The most common form of biomass is agricultural waste, apart from that municipal waste converted into combustible pellets are also being considered as a form of biomass. Biomass is burnt in kilns to generate hot air or hot water that drive turbines to generate electricity.

The whole setup requires creation of large scale infrastructure that demands space and equipment to convert waste into combustible form and then burn the same to generate energy.

Storage of biomass as per the demand also requires a lot of space and most existing facilities have failed owing to problems related to storage and logistics of transporting municipal waste or agricultural waste to the biomass energy plants. The overall efficiency of biomass plant is about 22%-35% which is comparatively less than coal based power plants. Environmental concerns have also been raised towards disposal of ash generated by the biomass plants.

*D. Combined Heat and Power (CHP):*Combustion of any fuel to generate both heat and power thereby getting combined benefits is the working principle behind a Combined Heat and Power (CHP) energy systems. These systems also termed as 'Co-generation' and their variations like 'Tri-generation' or 'Quad-generation' are best suited for community level integration. The heat generated due to combustion of fuels can be used directly for heating needs of the communityand generation of power, alternatively generating steam using water canincrease the energy generation.

The primary fuel used for these CHP systems include all hydrocarbon based fuels like biomass, biogas, natural gas. Alternatively, petroleum based fuels like diesel and bio fuels like rapeseed oil could also be used. If such systems are integrated at neighborhood levels then there would be no more need for Diesel Generators for power backup and the diesel used in these DG sets could power the whole community. Gas based CHP units that could be powered by LPG or natural gas would enable more economical and environmental friendly option and with most community housing setups have piped LGP gas supply and storage facilities thereby facilitating easy integration of these systems in the housing sector.

CHP systems have a general efficiency of 80% - 85% varying on basis of choice of fuel used. In comparison conventional power generation systems using similar fuels have an efficiency of 49% - 56%. The CHP systems ideally have low investment costs, high rate of return and proven reliability, but the cost factor depends on the heat exchangers which are key to extract maximum energy out of fuel combustion. In case of excess heat is generated it could be stored either in specially designed thermal stores or converted into electrical energy and stored in batteries for future use.

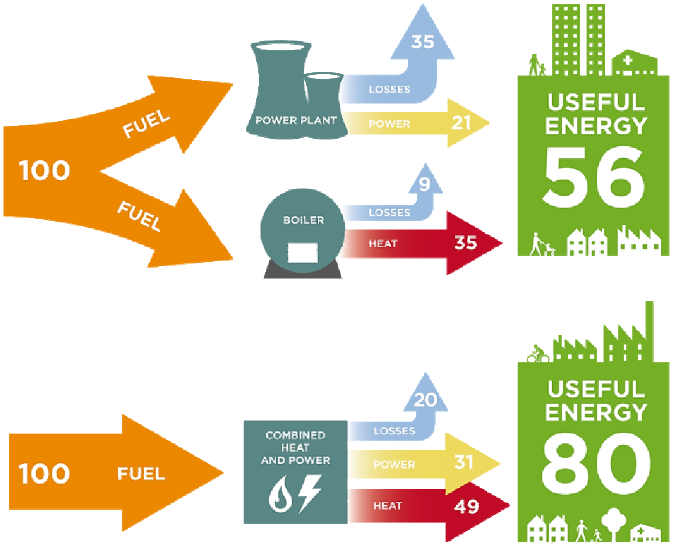

Fig. 5. Efficiency comparison of Conventional Power Generation and CHP Systems.

E. Heat Pumps: They are electrical energy driven systems that are ideal for space heating applications, but the added advantage of these systems is that their operation cycles are reversible. The heat pump transfers heat from one location to another. In winters, the heat pump captures heat from surroundings and concentrates it before delivering it to the occupants inside the building, alternatively in summers it could do the reverse by extracting heat from inside and dissipating it outside or storing it for other applications like water heating.

They are efficient for space heating rather than cooling, but if well planned during winters they could extract heat from the southern side of housing unit which are warm and deliver it to the cooler northern side spaces.

The integration of heat pumps and being completely dependent on them to achieve balance between heating and cooling needs is a great challenge. To meet both heating and cooling needs simultaneously independent heat pump need to be installed as the sizing of a single unit becomes difficult owing to their full efficient in heating but while dealing with cooling needs their efficiency is reduced to half. In view of all these observations, heat pumps ideally have a major role to play in winters like water and space heating as solar based systems fail during similar conditions and integrating the heat pump with a thermal store where heat energy could be collected all over the year and used during winters will enhance their viability and efficiency.

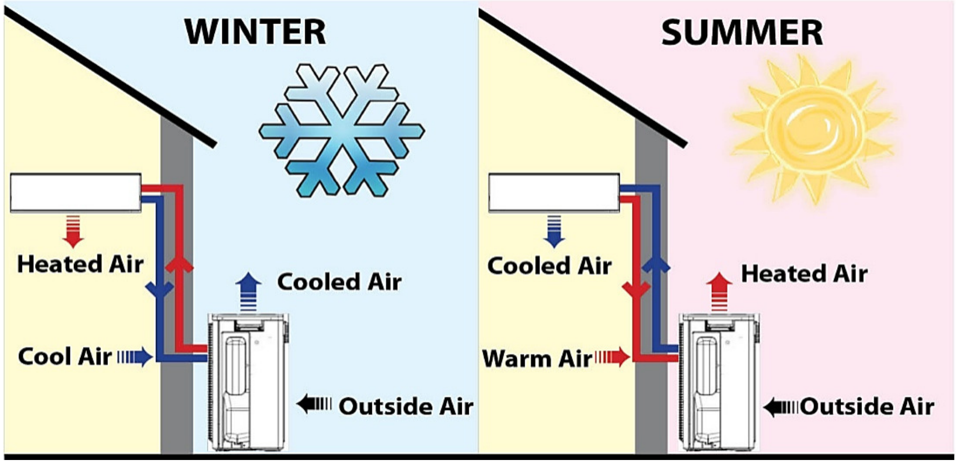

Fig. 6. Working Cycle of Heat Pump in Winter and Summer.

In view of varied options in Micro generation based infrastructure, it becomes a major challenge for the end user to understand and identify the ideal solution. The decision tool is expected to ease the challenges faced by the user by understanding their existing built-form characteristics, household power consumption, user behavior, expected demand versus actual consumption analysis, financial constraints and integration within the built environment and define possible interventions at household, built-form and neighborhood level.

All the systems listed above have their own inherent benefits and challenges, but no consumer would prefer to be part of a housing community that relies only on Microgeneration energy based infrastructure. Grid connected communities would have the added advantage of being dependent on the grid as and when the demand arises, primarily due to shortage of fuel, shutting down of the facility for maintenance and repairs, occasional increase in energy demand due to festivals or extreme seasonal variations etc. This demands for installation of net meters that monitor inflow of grid power as per need and excess power generated by the community that could be shared with the grid in return. Based on such scenarios the decision tool should not only limit itself to plan and choose the type of infrastructure but also indicate the expected expenditure gained or incurred by the community in case of power exchange with the grid.

IV. DECISIONTOOL METHODOLOGY AND ITS ASSEMBLY

There have been various building energy modelling engines developed specifically for the domestic sector, most of them are based on the BREDEM (Building Research Establishment Domestic Energy Model). On basis of the BREDEM model other models have been developed like The Community Domestic Energy Model (CDEM) (Firth *et al.* 2010). The Domestic Energy Carbon Counting and Carbon Reduction Model (DECoRuM) (Gupta 2009). The DECarb Model (Natarajan and Levermore 2007). The Energy and Environmental Prediction (EEP) Tool (Jones et al. 2007). Each of these models has been modified to varying degree based on their data structure and expected future deployment of the model. The major problem with most of these models was in the implementation of their policy or interventions as they lacked the ability to be developed as a user or stakeholder level interface (Mhalas *et al.* 2013).

The key aspect in the development of a decision tool based on building energy modelling engine is identifying the various architectural types or archetypes possible and integrating them into the model. This also highlights that the initial application of such a model would be restricted to those neighborhoods where the archetypes are limited and continue to the same without any major modifications to the built form. The challenge would arise in those neighborhoods where there is no defined or uniformity in development of households or there have been major changes to the architectural character of built form. To encounter these challenges alternative visualization techniques and database generation tools need to be employed which are not within the scope of this study.

The decision tool is expected to take into consideration the various stakeholders at household level or at community level in case of multistoried housing units and define various scenarios along with their possible impact on the existing energy consumption pattern, retrofitting required within the housing unit to further reduce energy consumption, renewable energy infrastructure and their configuration to promote energy generation and finally the financial component to guide the household in terms of investment required, quantifying possible benefits into financial variables and payback duration. The tool should employ multi-criteria analysis and decision technique to define the possible benefits divided into social, environmental, technical and economic criteria (Mhalas *et al.* 2013). A key aspect of the decision tool would be understand the complexity in estimating energy savings from combined initiatives like in case of a well-insulated house the payback returns from a heat pump would require more time as the energy required for the operation of the heat pump would be reduced. So, special consideration should be given when calculating the payback period in case of households that involve combined interventions (Mhalas *et al.* 2013).

In Table 1, the various segments of the decision tool and their data inputs are detailed out – the first segment of information details out the physical geometry of the housing unit, the second segment defines the impact of climate, wind and sun on the overall energy performance of the unit as a result the role of artificial light and ventilation is being analyzed, the third segment defines the performance and utility of all household electrical equipment, their usage pattern and user behavior.

Table 1: List of Data Sets and their corresponding Variables.

Physical Geometry of Housing Unit	
• Site Area	• Floor Area and Perimeter of Unit
• Height of Roof	• Total Number of Storeys
• Area of Roof	• Area of Doors and Windows
Heating Cooling and Ventilation of Housing Unit	
• Geographical Location of Unit	• Solar Irradiation Value for the Location
• Wind Speed and Direction	• Architectural Typology of Housing Unit
• Material for Walls and Windows (U-Value)	• Material for Floor and Roof (U-Value)
• Types of Doors and Windows	• Orientation of Doors and Windows
• Overhangs / Chhajas	• Balconies / Verandahs
• Types of Mechanical Ventilation	• Efficiency of Mechanical Ventilation
• Type of Cooling System	• Efficiency of Cooling Systems
• Type of Heating System	• Efficiency of Heating Systems
Energy Consumption of Housing Unit	
• Number of Occupants	• Operating Hours of Electrical Equipment
• Type of Household Appliances	• Efficiency of Household Appliances
• Type of Cooling System	• Efficiency of Cooling Systems
• Type of Heating System	• Efficiency of Heating Systems
• Type of Lighting System	• Efficiency of Lighting Systems

The information sets collected under Physical Geometry of Housing Unit shall aid in developing a physical dwelling model of different housing typologies varying on basis of their shape, material of construction and height. Incorporation of Heating Cooling and Ventilation data sets with the physical model shall define the actual energy demand in maintaining habitable living conditions. Comparison of the actual energy demand in relation with existing energy consumption based on data sets under Energy Consumption of Housing Unit shall assess the performance of the housing unit under three categories – High, Moderate and Balanced.

The high categories indicates that the actual energy demand is less than existing consumption. This demands that interventions related to building retrofitting and energy conservancy need to be initiated before integration of Microgeneration infrastructure. In case of moderate scenario the energy demand is marginally higher than the energy consumption, this shall require initiation of interventions related to energy conservancy only. In case of balanced scenario, energy demand and energy consumption are nearly equal and act as the perfect platform to meet the energy demand through incorporation of Microgeneration infrastructure.

The choice of infrastructure and its incorporation within the housing unit or neighborhood shall be based on the building form, peak energy demand, installation feasibility, initial cost, maintenance cost, expected savings and payback period.

V. CONCLUSION

There is a greater need for the housing sector to reduce its dependence on grid power and search for alternative Microgeneration options. Avenues to strengthen the end user through development of a decision support tool shall aid in promotion of logical and informed decision making leading to development of sustainable neighborhoods. The implementation of the tool right at the early stage of designing housing units could further ensure development of near zero energy based housing. The conceptual framework is only an insight into the actual tool, but with further research and findings it is expected that the tool would undergo changes to enhance its accuracy. With inflow of more efficient and varied Microgeneration infrastructure options, the database and choices of energy saving interventions shall increase. The tool in its existing form is limited to regular archetypes and further research is needed to identify and incorporate the diverse housing typologies in the Indian housing sector. The financial component of the tool needs working as energy pricing and subsidy on Microgeneration infrastructure vary from state to state.

If developed fully with an interactive interface that enables user groups and decision makers to make key decisions right at the start of any housing project or define the possible interventions required in existing housing stock, the tool can ensure sustainable energy generation and total energy security at neighborhood level.

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DEPARTMENT OF ARCHITECTURE AND PLANNING
MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY, JAIPUR
J.L.N. Marg, Jaipur - 302017

First Impression: 2017

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Department of Architecture and Planning
Malaviya National Institute of Technology,
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ISBN: 978-93-86238-12-2

Published by
EXCELLENT PUBLISHING HOUSE
Kishangarh, Vasant Kunj, New Delhi-110 070
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Decision Tool to Define Choice of MicroGeneration Retrofit for Indian Households: A Conceptual Framework

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ABSTRACT

In India, housing sector is the second major consumer of electricity with the rate of demand increasing by 11.08% from 1984-85 to 2014-2015 in comparison to -16.92% by industries. Around 97% of the electricity is generated using non-renewable energy sources. In contrast to this the Government of India has promised to reduce the Greenhouse Gas Emissions upto 33-35% by 2030 from 2005 levels. In 2010 the government of India also proposed the 'Jawaharlal Nehru National Solar Mission' to promote solar-based energy generation. in these 'Solar Cities' households and group housing societies are expected to install solar-based energy systems to satisfy the numbers without understanding their true potential and association with the built form parameters and user behavior. The consumer is not exposed to alternate renewable energy systems like wind based, heat pump, combined heat and power (CHP). The paper defines the conceptual framework of a decision tool for homeowners to choose from different Microgeneration retrofits. Assessment includes analyzing existing consumption pattern of the household and its true energy demand to identify possible alternate measures. The output shall guide homeowner to make a decision based on the financial commitment and retrofitting required for the housing unit.