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Alliance for an Energy Efficient Economy

Guidelines for Climate-Responsive and Low Carbon Building Design in the Cold Climate of Uttarakhand

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Project

Towards climate responsive and low carbon development: addressing the critical urban issues in residential and transport sector in Uttrakhand

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Disclaimer

The guidelines have been prepared to address issues in the current construction practices in Uttarakhand, and it aims to reduce the building's operational carbon in the residential sector. This guidelines report is based on the best available information in the public domain and the Government of Uttarakhand websites. Every attempt has been made to ensure the correctness of the data. However, AEEE does not guarantee the accuracy of any data nor accept any responsibility for the consequences of using such data.

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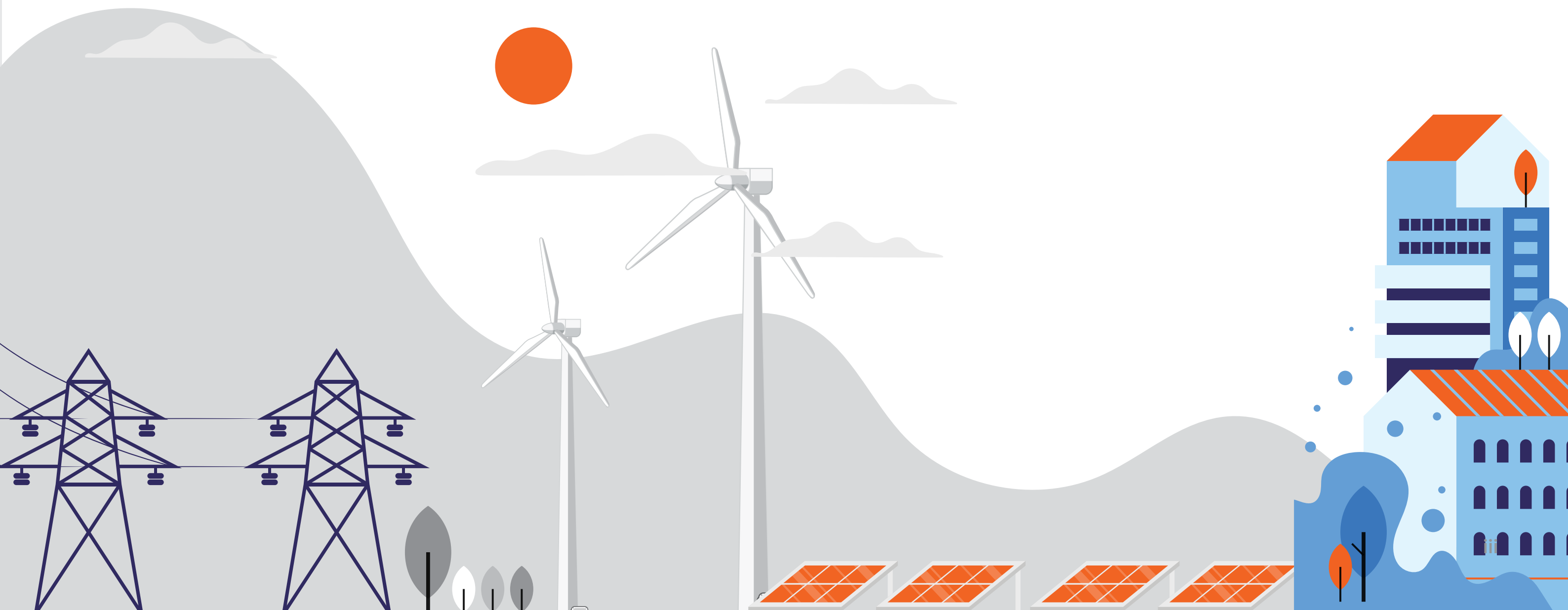

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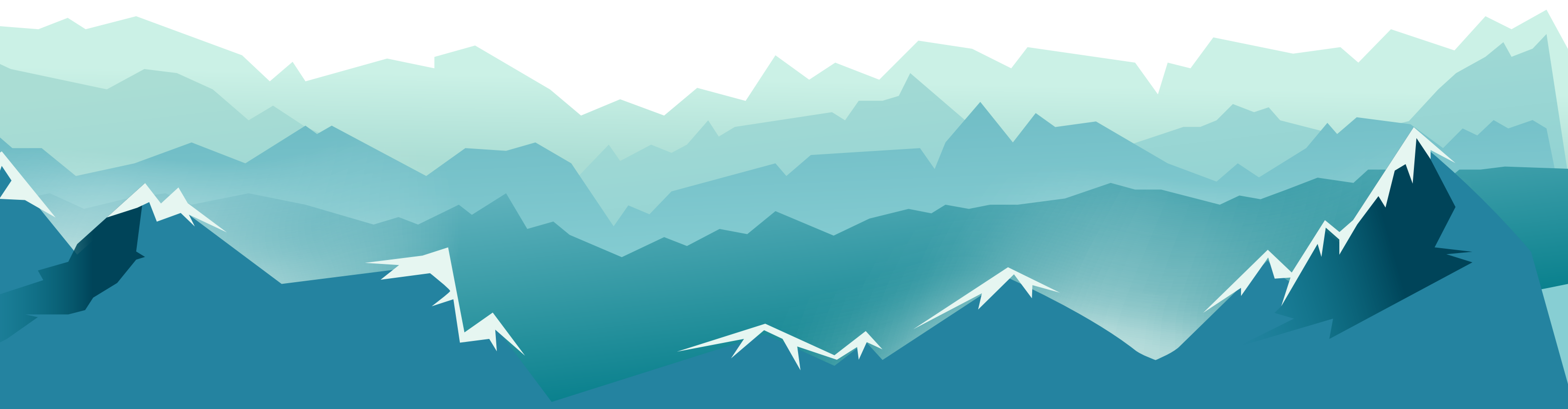
Abbreviations

AAC	Autoclaved Aerated Concrete
AC	Air Conditioner
AMRUT	Atal Mission for Rejuvenation and Urban Transformation
AQI	Air Quality Index
BEE	Bureau of Energy Efficiency
BHK	Bedroom Hall Kitchen
CED	Cooling Energy Demand
CO_2	Carbon dioxide
Co_2 eq.	Carbon Dioxide Equivalent
CPWD	Central Public Works Department
CSEB	Compressed stabilized earth block
DBT	Dry Bulb Temperature
DGU	Double glazed system
DHW	Domestic Hot Water
ECM	Energy conservation measure
E-W	East West
EN ISO	European International Standard
ENS	Eco Niwas Samhita
EPS	Expanded polystyrene
ESCO	Energy Service Company
GDP	Gross Domestic Product
GHAR	Green Habitat Accomplished Rating
GHG	Greenhouse Gas Emissions
GI	Galvanised Iron
HED	Heating Energy Demand
HDD	Heating Degree Day
IAQ	Indoor Air Quality
ICS	Indian Cookstove
IHR	Indian Himalayan Regions
INDC	India's Nationally determined contributions
ISHRAE	Indian Society of Heating, Refrigerating and Air Conditioning Engineers
LED	Light Emitting Diode
LIG	Low Income Group
LPG	Liquid Petroleum
Max	Maximum
MDDA	Mussoorie Dehradun Development Authority
MIG	Middle Income Group

Min	Minimum
MoUD	Ministry of Urban Development
MRP	Maximum Retail Price
MSME	Micro, Small & Medium Enterprises
N-W	North West
NE-SW	North East and South West
NMHS	National Mission on Himalayan Studies
NSM	National Solar Mission
NVP	Natural Ventilation Potential
NW-SE	North West and South East
PMAY-U	Pradhan Mantri Awas Yojana - Urban
PTCUL	Power Transmission Corporation of Uttarakhand Limited
PV	Photovoltaics
PWD	Public Works Department
RCC	Reinforced Cement Concrete
RE	Renewable Energy
S-E	South East
SDG	Sustainable development Goal
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar heat gain coefficient
SoR	Schedule of Rates
TCPO	Town and Country Planning Office
TV	Television
UAPCC	Uttarakhand Action Plan for Climate Change
UDD	Urban Development Directorate
ULB	Urban Local Body
UP	Uttar Pradesh
UPCL	Uttarakhand Power Corporation Limited
UPVC	Unplasticized polyvinyl chloride
UREDA	Uttarakhand Renewable Energy Development Agency
WWR	Window to wall ratio
XPS	Extruded Polystyrene

Units

ACH	Air Change per Hour
cm	Centimetre
GW	Gigawatt
kW	Kilowatt
kWh	Kilowatt hour
kWh/m²	Kilowatt hour per metre square
m	Metre
mm	Millimetre
MW	Megawatt
Pa	Pascal
Sq.m	Square Metre
W	Watt
W/m²·K	Watts-per- meter-square-kelvin
°C	Degree Celsius



Energy consumption profile assessment in the Himalayan region shows that annual energy consumption depends not only on housing architecture and construction materials but also on income category and type of settlements, such as rural and urban. Fuel consumption profile assessment shows that there is a fuel mix use type in the Himalayan regions

Executive Summary

The rampant urbanization of Uttarakhand, noted by the World Bank at 32.4% in 2018, poses challenges for housing, infrastructure, environment, economy, and society and also exposes Uttarakhand to disaster vulnerability. Increased population concentration has resulted in higher demand for housing infrastructure, with 23.5% of urban households in Uttarakhand lives in rental housing in urban areas, indicating a significant demand for housing infrastructure.

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of urban households in Uttarakhand lives in rental housing in urban areas, indicating a significant demand for housing infrastructure.

The growing demand for housing infrastructure led to a shift in the construction practices from traditional to contemporary, which resulted in shifting to modern high embodied carbon construction materials, improper building design, and inefficient construction practices.

To address the critical issue of the urban residential sector in Uttarakhand, AEEE and IIT Roorkee undertook the project titled "**Towards Climate Responsive and Low Carbon Development: Addressing the Critical Urban Issues in Residential and Transport sector in Uttarakhand**". The objectives of the project were as follows:

- Development of residential building guidelines that will be applicable to buildings being built in Indian Himalayan Region (IHR) States (e.g., UK, HP, J&K, and NE states)
- Support demonstration projects by integrating guidelines' recommendations
- Facilitating for capacity building of relevant stakeholders

To develop guidelines for climate-responsive and low-carbon building construction practices in urban residential areas, a multi-pronged approach was taken. This involved reviewing international best practices and policies for sustainable building design practices, assessing national policies and interventions needed to promote climate-responsive residential sector development in Uttarakhand, conducting surveys on building typologies, construction materials, thermal performance, energy consumption patterns, and socio-economic conditions in different regions of Uttarakhand, identifying key interventions for building envelopes using whole building energy simulations, analyzing the advantages of using energy-efficient water and space heating appliances, and exploring the potential of utilizing solar energy.

The survey-based study conducted at three locations, viz., Chakrata, Mussoorie, and New Tehri, shows that heating degree days ranged from 2872 to 3158, indicating prevalent heating energy demand (HED). Housing profile assessment indicates that there is a dominance of traditional architecture in rural settlements like Chakrata and contemporary architecture in urban settlements like Mussoorie and New Tehri. Construction materials' profiling shows that stone, wood, and slate are the primary construction materials used in traditional architecture, whereas brick, wood, RCC, and GI sheets are more prevalent in contemporary architecture. Energy consumption profile assessment shows that annual energy consumption depends not only on housing architecture and construction materials but also on income category and type of settlements, such as rural or urban. Fuel consumption profile assessment shows that there is a fuel mix use type. There is a dominance of wood for cooking and water and space heating in rural settlements due to its abundance, whereas liquefied petroleum gas (LPG) and electricity are the primary fuel for cooking and water and space heating, respectively, in urban settlements.

Thermal performance of different typologies of houses and seasonal as well as diurnal electricity consumption patterns are analysed through year-round measurements. Houses constructed with high thermal transmittance value materials are observed to perform poorly during peak summer and winter conditions. It is also inferred that houses with longer façade with windows facing south keep the indoor environment thermally comfortable compared to the houses with longer façade with windows facing north. The daily electricity consumption profile shows that electricity demand peaks during morning and night time.

After assessing the type of settlements, housing typologies, architectural design, construction materials and thermal performance, and energy consumption pattern, in the Uttarakhand region, the key energy conservation measures (ECMs) have been identified for building envelopes through whole building simulation models. Key findings indicate that

- Having south-facing façades helps reduce HED by 13-21% over the base case, i.e., north-facing façades and annual monetary and carbon saving potential in the range of Rs. 2244-3186 and 300-400 kg CO_2 eq., respectively.
- South-facing windows with a 30% window-to-wall ratio (WWR) reduce annual HED by 3-6% compared to a 10% WWR and create annual monetary and carbon saving potential in the range of Rs. 300-583 and 75-78 kg CO_2 eq., respectively.
- Out of the building envelope categories roof has significant role in reducing HED, monetary saving and CO_2 reduction. A roof assembly with low thermal transmittance value helps in reducing HED by 14-17% over base case
- A wall assembly with a low thermal transmittance value (e.g., autoclaved aerated concrete (AAC) with insulation) reduces the annual HED by 5-6% over a brick wall and creates annual monetary and carbon saving potential in the range of Rs. 807-1119 and

Out of the building envelope categories roof has significant role in reducing HED, monetary saving and CO2 reduction. A roof assembly with low thermal transmittance value helps in reducing HED by

14-17%

over base case

108-150 kg CO_2 eq., respectively.

- A roof assembly with a low thermal transmittance value (e.g., RCC with insulation) reduces the annual HED by 14-17% over an RCC roof building and creates annual monetary and carbon saving potential in the range of Rs. 1349-1932 and 181-259 kg CO_2 eq., respectively.
- Minimising infiltration can reduce annual HED by 11-14% and lead to annual monetary and carbon saving potential in the range of Rs. 1473-1832 and 197-245 kg CO_2 eq., respectively.

The potential of solar energy in Uttarakhand was also analysed. It was observed that during the winter season, which is the season for peak electricity demand, the solar PV power output of a typical 200 W PV panel installed on the roof of a household was in the range of 227-279 kWh against the energy consumption, which was in the range of 40-310 kWh.

Finally, the buildings' operational energy demand in Uttarakhand was analysed by assessing water and space heating appliances' energy consumption. For space heating appliances, shifting to 5-star rated appliances over the base case, i.e., 3-star rated appliances, resulted in a 12-23% reduction in annual HED. Additionally, shifting from 3-star to 5-star appliances creates annual monetary and carbon saving potential in the range of Rs. 2500-3800 and 416-510 kg CO_2 eq., respectively. For water heating, it is recommended to use solar water heaters.

The study concludes by describing energy efficiency as the first pillar of the transition in the building sector in Uttarakhand. The lifetime of the building stock is typically very long, and the stock is rapidly expanding in the Uttarakhand region. To decarbonise the building sector, mandatory zero carbon-ready building energy codes should be used, at least for government buildings in Uttarakhand. Moreover, there is a need to introduce a mechanism for thermal-specific retrofitting of existing buildings.

To deliver short-term impact focusing on modifying current building construction practices in Uttarakhand, there is a need to explore and promote the potential of low-carbon and energy-efficient building materials and techniques such as locally sourced low-carbon building materials like adobe, mud blocks, and compressed stabilized earth blocks (CSEB). Further, there is a need to research the cost-benefit of retrofitting existing buildings with measures such as insulation of walls and roofs and replacing single-glazed windows with double-glazed ones. Additionally, awareness and training programs and financial incentives mechanism needs to be devised for adopting low-carbon building construction practices

For long-term impact, emphasizing the importance of climate-sensitive sustainable building design, and low embodied carbon construction materials, a further study on analysing the impact of the reclassification of the climate of Uttarakhand on building design and construction practices, integration of the findings of this study into building bye-laws, mechanism of code-compliance check and building performance standards and benchmarking in the Uttarakhand region are recommended as the way forward of this study.

shifting from 3-star to 5-star appliances creates annual monetary and carbon saving potential in the range of Rs. 2500-3800 and 416-510 kg CO_2 eq., respectively

1. Introduction

The Indian Himalayan Region (IHR) is one of the most ecologically sensitive regions in the world. The IHR covers approximately 590,000 square kilometres (sq. km.) and is home to over 50 million people. The IHR's ecology is highly sensitive due to its unique topography, fragile ecosystem, and biodiversity, and it is facing various threats due to climate change, greenhouse gas (GHG) emissions, and anthropogenic activities.

The Indian Himalayan Region covers approximately 590,000 sq. km. and is home to over 50 million people

Climate change is the most significant threat to the IHR's ecosystem. The IHR is experiencing changes in temperature, precipitation, and extreme weather events, which are having severe impacts on Himalayan glaciers and causing them to melt at an alarming rate. Melting glaciers, in turn, are affecting the IHR's water resources. Rising temperatures due to climate change are also causing shifts in the distribution of flora and fauna and negatively impacting the IHR's biodiversity. Increased frequency of extreme events such as floods, landslides, and forest fires are causing widespread damage to the IHR's ecosystem.

Anthropogenic activities such as urbanisation, tourism, and agricultural expansion have led to deforestation, soil erosion, and loss of biodiversity. Emissions associated with anthropogenic activities cause global warming and contribute to the melting of glaciers.

Rampant urbanisation and tourism in the IHR have led to haphazard infrastructure development, which, in turn, has contributed to disruptions in the ecosystem. The IHR's steep slopes are prone to erosion and landslides, and haphazard construction of roads, buildings, and other infrastructure can lead to soil erosion and, consequently, landslides, resulting in loss of life and developed infrastructure. The recent Joshimath disaster is a prime example of the impact of haphazard infrastructure development in the IHR.

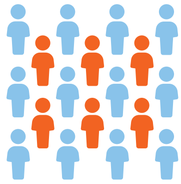
Thermal comfort and energy consumption in the built environment of the residential sector have also been significant concerns in the IHR due to extreme climatic conditions. The buildings need to be designed to provide thermal comfort for occupants while minimizing energy consumption. However, the increasing mismatch between the demand and supply of housing infrastructure has led to a growing need for speedy and cost-effective housing. As a result, many buildings in the region are poorly designed, leading to increased energy consumption and discomfort for occupants. This highlights the need for sustainable and efficient building designs that can provide comfortable living conditions while minimizing energy usage in the IHR region.

To address the critical issues in the urban residential sector in the IHR, there is a need for more sustainable building design practices that prioritise energy efficiency and thermal comfort. This could include using passive building design strategies, like optimising building orientation, high performance building materials, use of natural ventilation, utilisation of natural ventilation, etc. By prioritising sustainable building design practices, the IHR can achieve greater energy efficiency and thermal comfort while reducing its environmental footprint. Keeping this objective in mind, Uttarakhand, a state falling in the IHR, was selected for the development of comprehensive sustainable, energy-efficient building design guidelines.

1.1 Background of Uttarakhand

Uttarakhand, with a geographical area of 53,483 sq. km., constitutes approximately 1.6% of mainland India. As per the 2011 census[1], the population of Uttarakhand is approximately 100.86 lakh, of which approximately 30% constitute the urban population and approximately 70% rural population. Even though the urban area constitutes approximately 1.7% of the total geographical area of Uttarakhand, it is occupied by approximately 30% of the total population of Uttarakhand.

In 2011, urban and rural housing in Uttarakhand stood at 7,85,398 and 22,44,519 units, respectively. The urban population growth in Uttarakhand, at 4.2%, is much higher than the rural population growth of 1.2%[2]. The rising population in Uttarakhand and urbanisation contribute to the accelerated pace of infrastructure development and rise in construction activities, primarily owing to the demand for housing.



The urban population growth in Uttarakhand, at 4.2% is much higher than the rural population growth of 1.2%

Uttarakhand has a unique building construction style that reflects the local climate, culture and tradition[3]. The traditional buildings are made of local construction materials such as wood, stone, and mud, and they are constructed using traditional architectural techniques that have been passed down through generations. However, the modern trend towards cement, brick and concrete based construction has led to increase in the use of contemporary construction materials, e.g., cement and steel which have significant impact on the environment[4]. The rampant increase in contemporary construction materials has led to the destruction of natural habitats and ecosystems[5].

In addition to this, traditional buildings made of local construction materials provide better insulation against extreme temperatures, thus reducing the need for active heating and cooling systems[6]. On the contrary, modern construction practices with contemporary construction materials, such as reinforced concrete structure, has lower insulation properties and require more energy to maintain thermal comfort. Additionally, the trend toward modern architecture has led to a shift toward more energy-intensive building designs.

The housing infrastructure in the IHR requires strategic interventions not only for building design and construction, but the sector needs a more holistic approach to adapt and mitigate the climate change impacts. The design, construction, and operation of residential buildings in cold regions must resist heat loss and promote heat gain to enhance indoor thermal comfort while optimizing energy use.

1 2011 Census of India. Registrar General and Census Commissioner of India.
2 https://udd.uk.gov.in/
3 Juyal, M. (2017). Traditional Building Practices and Sustainability in Uttarakhand, India. Journal of Sustainable Development, 10(5), 65-77.
4 Sarkar, A., & Sathaye, J. (2013). Carbon footprint analysis of cement production: emissions from the Indian cement industry. Mitigation and Adaptation Strategies for Global Change, 18(7), 1059-1081.
5 http://ukdisasterrecovery.in/Docs/Uttarakhand-SAPCC.pdf
6 Gupta, S., & Bhardwaj, P. (2019). Energy efficiency in building construction and design: a review of Uttarakhand. International Journal of Sustainable Energy, 38(11), 1074-1094.

As per the Uttarakhand government statistics[7], the overall residential sector electricity consumption in Uttarakhand is approximately 24% of the regional total. The monthly household electricity consumption is 22.5 kWh/person in urban areas[8], which is expected to grow at a rate of 7% per year[9]. The poorly designed buildings would further escalate the future electricity demand, whereas if building construction practices in Uttarakhand were to incorporate more energy-efficient designs and technologies, it could potentially reduce the region's overall electricity consumption. This could help offset the expected growth in household electricity consumption in urban areas and contribute to more sustainable development practices in the region.

The local climate is the dominant factor impacting the energy need of the buildings. The climatic conditions of Uttarakhand vary from cold to composite[10]. Figure 1.1 shows the Köppen Geiger climate zones of Uttarakhand. Depending on the locations and climatic conditions, there is a need for building design guidelines that improve thermal comfort while minimising energy consumption.

The monthly household electricity consumption is 22.5 kWh/ person in urban areas, which is expected to grow at a rate of 7% per year

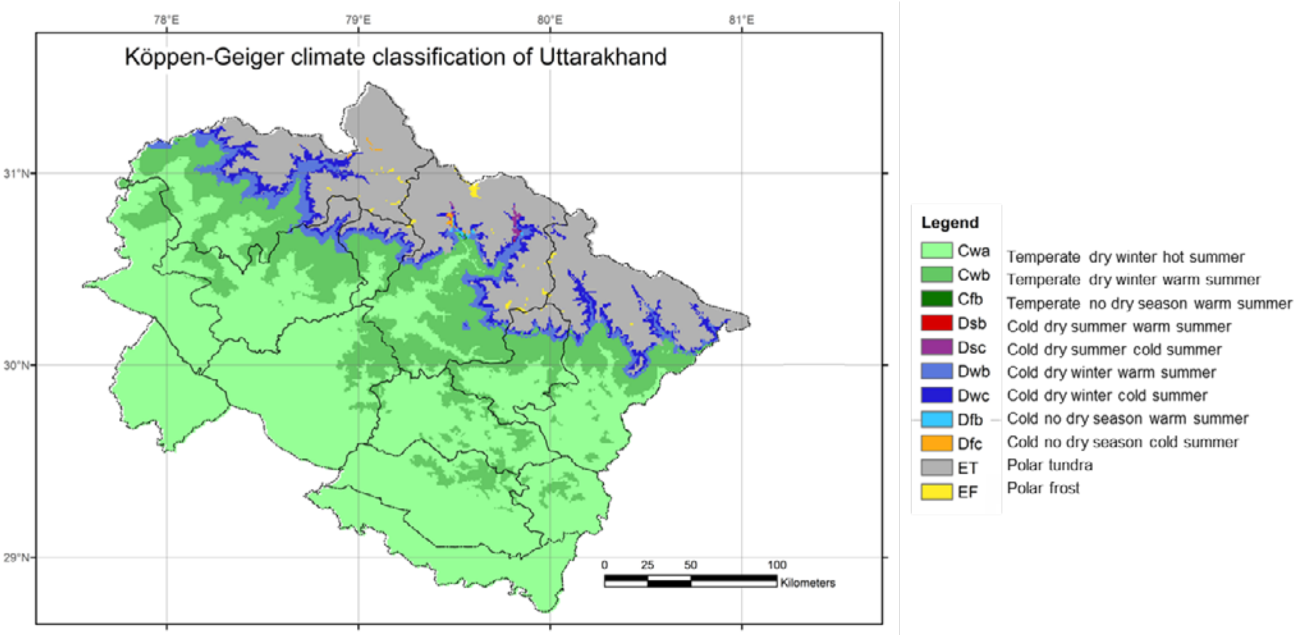


Figure 1-1. Köppen-Geiger classification of the study region[11]

7 MoSPI. (2018). Energy Statistics. Delhi: GOVERNMENT OF INDIA. Retrieved from http://mospi.nic.in/sites/default/files/publication_reports/Energy_Statistics_2018.pdf?download=1

8 National Sample Survey Office. (2014). NSS Report No. 558: Household Consumption of Various Goods and Services in India 2011-12. New Delhi: Ministry of Statistics and Programme Implementation, Government of India. Retrieved August 25, 2020, from http://mospi.nic.in/sites/default/files/publication_reports/Report_no558_rou68_30june14.pdf

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10 Bureau of Indian standards (2016) National building code of India. Retrieved from https://archive.org/details/nationalbuilding01/in.gov.nbc.2016.vol1.digital/

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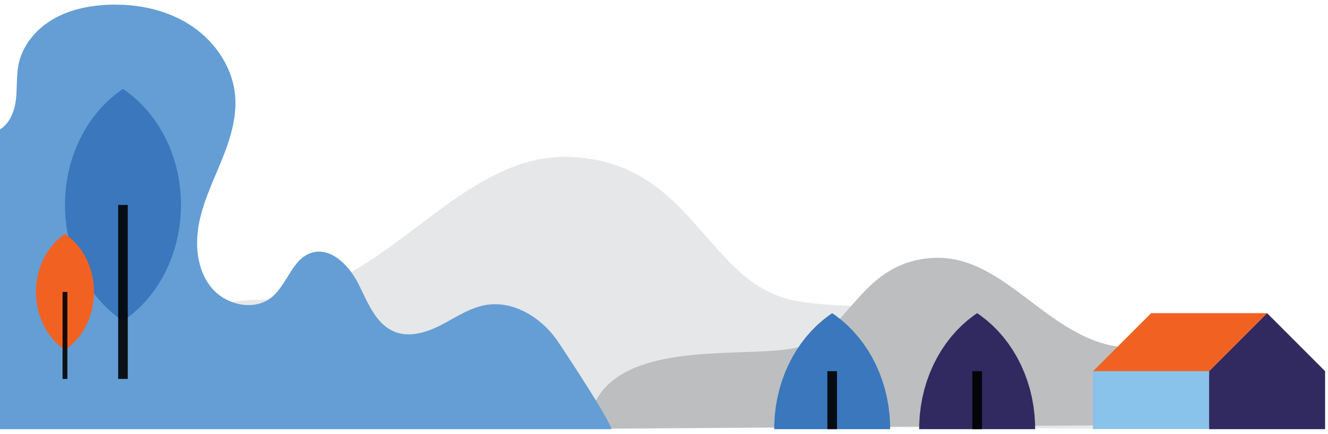


1.2 Need for guidelines

Building construction in Uttarakhand is often done without proper planning and adherence to building codes and standards, which compromises the indoor thermal environment and leads to higher energy consumption[12]. A study reports that buildings constructed with improper use of contemporary construction materials in Uttarakhand lead to poor insulation and air infiltration, decreasing occupants' thermal comfort and increasing the need for heating and cooling, and thus, energy consumption[13]. Similarly, a Bureau of Energy Efficiency (BEE) study noted that there is a lack of compliance with energy efficiency regulations in building construction in Uttarakhand[14]. This results in buildings being constructed without proper insulation and other sustainable design principles, compromising the thermal comfort of the occupants and increasing energy consumption. A report by United Nations Development Programme (UNDP) highlighted the need for energy-efficient building design in Uttarakhand, noting that buildings in the state are not designed to optimise energy efficiency and thermal comfort[15]. The study recommends the use of passive solar design for climate-responsive building construction. While this study is focused on Uttarakhand, many other states in India also suffer from similar problems, and there is a need to address this at a national level.

A Bureau of Energy Efficiency (BEE) study noted that there is a lack of compliance with energy efficiency regulations in building construction in Uttarakhand

Therefore, there is a need for more sustainable and energy-efficient building practices in Uttarakhand to ensure the thermal comfort of occupants and reduce energy consumption. Establishing such practices requires, as a first step, a comprehensive review of the existing residential building infrastructure, construction practices, household energy consumption patterns, solar energy potential, policies, building codes, and standards, as well as identification of the key energy conservation measures and ways to enforce regulations to ensure compliance with energy efficiency standards.

12 http://www.ijcse.com/docs/INDJCSE19-10-05-005.pdf
13 https://www.sciencedirect.com/science/article/pii/S2213138820306027
14 https://beeindia.gov.in/sites/default/files/Report%20on%20Compliance%20Monitoring%20and%20Enforcement%20of%20Energy%20Conservation%20Building%20Code%20in%20India.pdf
15 https://www.in.undp.org/content/india/en/home/library/environment_energy/smart-green-recovery-in-uttarakhand.html

2. Scope and objective of the guidelines

Guidelines for climate-responsive and low-carbon building designs for residential sector will assist the designers, architects, engineers and building owners in constructing buildings for optimised envelope performance. The guidelines provide design flexibility to vary the building orientation along with the building envelope's components, such as wall type, roof type, window size, type of glazing and infiltration level. The guidelines also provide for implementing energy-efficient appliances and integrating renewable energy with buildings. To ensure effective implementation of building design guidelines, the guidelines provide relevant state and national level policies which are conducive for mainstreaming climate-responsive and low-carbon development of residential building sector.

The guidelines have been developed to recommend design interventions and measures in building design, envelope optimisation, choice of construction materials, selection of electro-mechanical equipment for building operation, and on-site renewable energy generation, which can be integrated with building bye-laws.

The design guidelines set recommendations for the following building design parameters:

a. **Building orientation:** To enhance the solar heat gain to keep the residences warm during the winter months

b. **Window-to-wall ratio (WWR):** The optimum WWR to enhance the solar heat gain and daylighting in the buildings and natural ventilation (when needed)

c. **Window glazing types:** To enhance thermal performance of windows

d. **Building envelope**
   - The maximum value of thermal transmittance of wall assemblies (U_{wall})
   - The maximum value of thermal transmittance of roof assemblies (U_{roof})

e. **Infiltration through the building envelope**

Additionally, the guidelines define parameters for:

- Energy-efficient heating appliances and their impact on energy consumption
- Renewable energy (RE) integration with residential buildings and the state's policies to support RE integration.

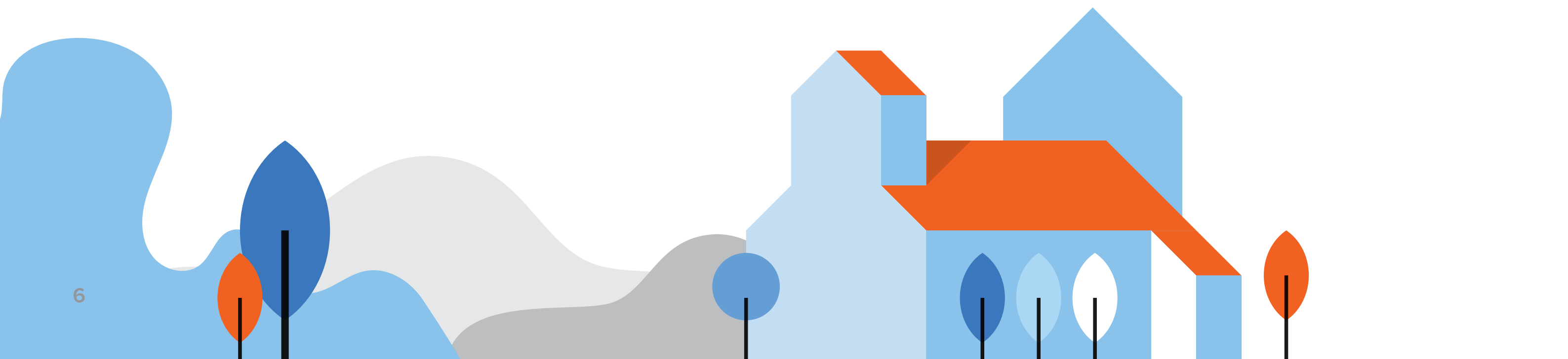
The guidelines also explore the best policies to promote an energy-efficient built environment in the cold climates of the modern world and their applicability in Uttarakhand.

Applicability of guidelines: These guidelines apply to all new residential buildings irrespective of their built-up area and categorisation.

Supporting the existing building codes. To enhance the implementation of existing building codes, such as the Energy Conservation Building Code (ECBC) and Eco Niwas Samhita (ENS), comprehensive guidelines have been developed in alignment with these codes. While ECBC and ENS cater to national and sub-national level activities, the guidelines in this report are specifically tailored to address the cold climatic conditions of IHR. These guidelines provide specific recommendations that complement the existing codes and reinforce their implementation in the IHR. By incorporating the suggested measures for cold climates, the deployment of ECBC and ENS at the grassroots level can be fortified in the region.

... guidelines in this report are specifically tailored to address the cold climatic conditions of IHR.

Exception: The embodied energy of the building construction materials and structural systems is not emphasised while preparing the guidelines. It is noted that structural and fire safety standards and existing building bye-laws precede these guidelines.



3. Methodology

In order to develop climate-responsive and low-carbon building design guidelines, a comprehensive study was conducted through the activities summarised below (a schematic of the study methodology is shown in Figure 3.1):

Context and situation assessment	Characterisation of the existing urban residential sector in Uttarakhand by mapping: • Representative existing residential buildings • Building construction materials • Fuel usage types • Income categories • Energy consumption
Study of international best practices	Mapping existing international best practices for residential building design and review of international policies to promote energy efficiency in buildings. Evaluation of identified best practices and policies for their compatibility to the study area
Review of national and state level policies	The review of national and state laws, policies, and regulations supporting urban governance in terms of housing and energy efficiency, and identification of area of interventions for climate responsive development of urban residential sector
Identification of design intervention and energy conservation measures	Identification of energy conservation measures (ECMs) as interventions for climate-responsive and low-carbon development in the urban residential sector. ECMs are identified for the building envelope by developing an energy simulation model for a base case building and then defining different alternative case scenarios for: • Building orientation • WWR • Glazing types • Wall assembly • Roof Assembly • Infiltration ECMs to tackle the operational phase of buildings are identified through analysis of different options for water and space heating appliances Solar energy utilisation potential as an ECM is identified by analysing Solar PV power output and energy demand
Development of guidelines	Development of roadmap/ guidelines for the urban residential sector to address the present urban transformation as well as climate change resilience

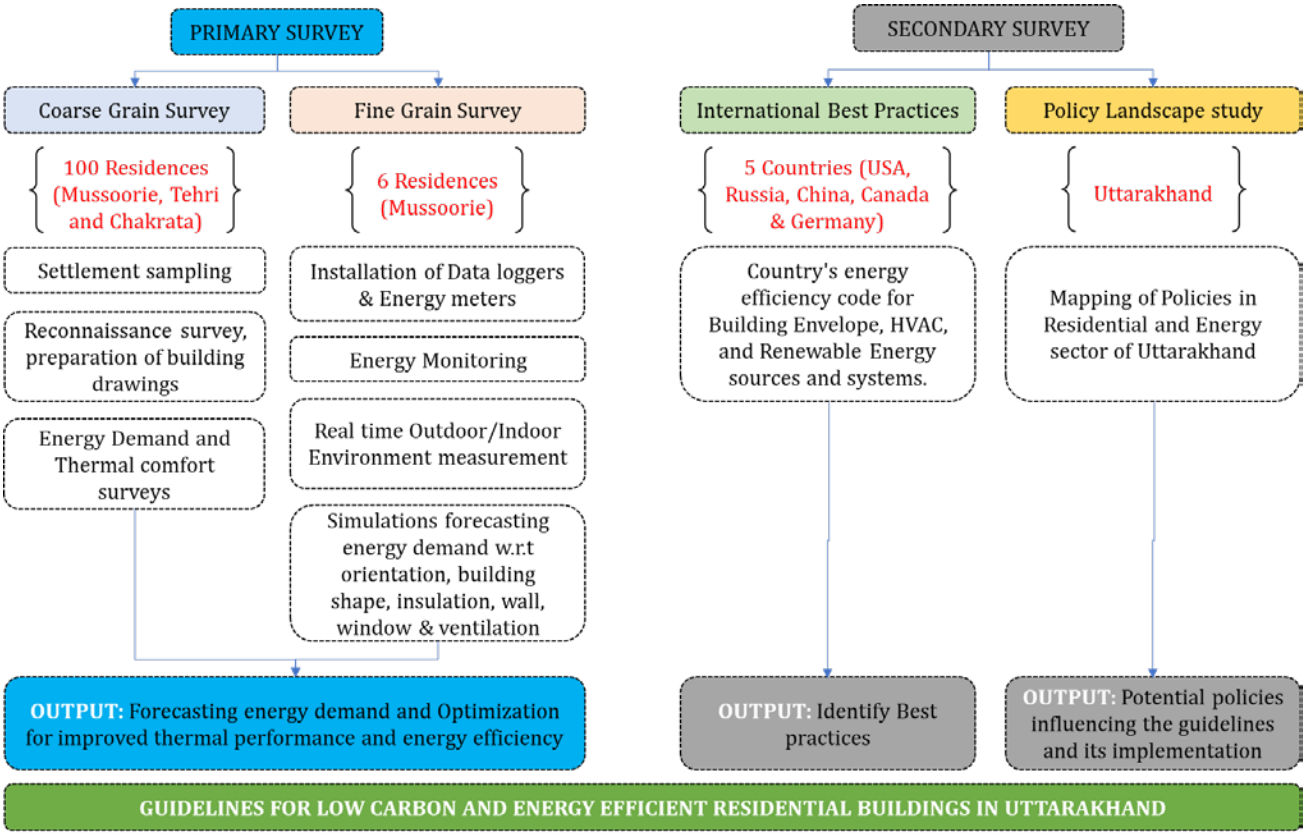
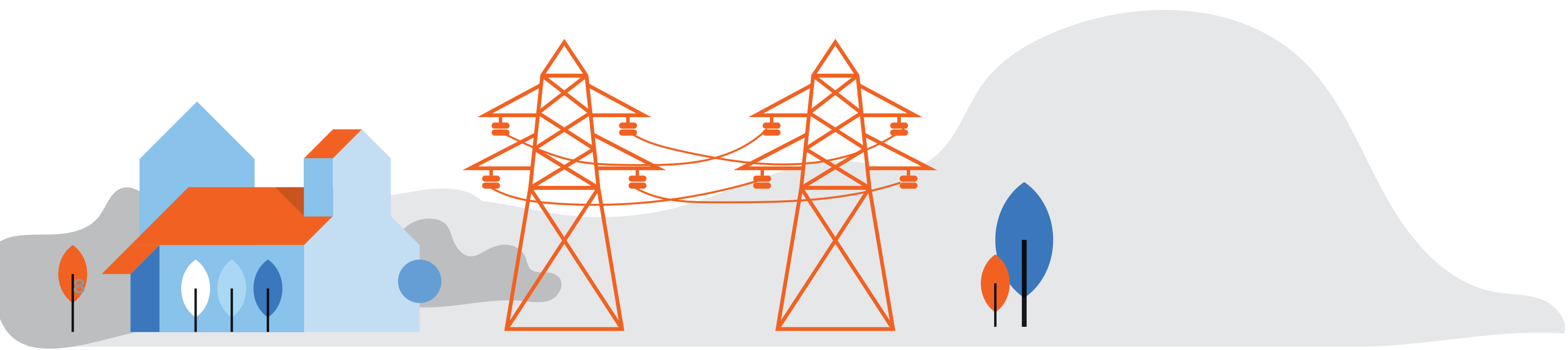


Figure 3-1. Methodology followed to prepare the guidelines



4. Learnings from international best practices

and their applicability in Uttarakhand

Many developed countries/regions that predominantly have cold climates, like the United States (U.S.), Canada, Russia, and the European Union, have pioneered building energy efficiency measures through policy formulation and identification of best practices. The best practices from selected countries, namely, China, the U.S., Canada, Russia, and Germany, have been reviewed, and a mapping exercise has been done to assess their applicability to Uttarakhand. These countries have been selected by doing the Köppen-Geiger classification of Uttarakhand's climate and then matching the classified climate with the world's Köppen-Geiger classified climatic conditions. This chapter provides a summary of the detailed exercise done to review international best practices[16] and how they can be applied to Uttarakhand to promote energy efficiency in the building sector.

The learnings from the international best practices have been divided into two parts. Part I focuses on building code policy implementation, while Part II focuses on energy-efficient construction practices.

Policy and best practices for climate responsive building design from selected countries namely, China, the U.S., Canada, Russia, and Germany have been reviewed to see their applicability in Uttarakhand

4.1 Part I: Learnings from the review of code policy implementation

Building codes are country-specific and are designed based on various factors such as climatic conditions, cultural history, demography, and traditional or contemporary construction practices[17]. Although the fundamental principles of building physics remain constant, the objective of meeting building energy efficiency through these principles may vary based on various factors such as construction practices, availability of building materials, and demographic adaptability to the environment[18]. These factors are reflected in a country's building code, which outlines the necessary standards for construction and design. Therefore, comparing the effectiveness of a country's building code in making buildings energy-efficient to another country's code is not a straightforward task, and as a result, a one-size-fits-all approach to building code policymaking and implementation cannot be adopted. Instead, a framework that caters to India's unique demands and the local market must be developed based on its transformation potential and a carefully assessed policy implementation timeline. Recommendations from international best practices are considered to design the framework for Uttarakhand, as presented in Table 4.1. These recommendations aim to enhance the energy efficiency of buildings in Uttarakhand while also considering the specific local factors that influence the region's building construction practices. By incorporating these recommendations into the framework, the objective is to promote sustainable and efficient building construction practices in Uttarakhand.

Table 4-1. Opportunity to integrate building energy efficiency related recommendations learned from international best practices in existing building codes/guidelines for effective implementation

Opportunity	Relevant Recommendations	Relevant Stakeholders
In Germany, buildings meant to be used for less than four months yearly or temporary facilities for less than two years are not covered under the Building Energy Code. However, they can voluntarily choose to adopt the code. A similar case exists in Uttarakhand, where people prefer to move into their summer homes during the peak of winter, leaving their winter homes empty between November and March.	***Recommendation 1: Establish guidelines defining building size thresholds*** • All new constructions (to be used for more than six months per year) should mandatorily adopt the Building Energy Efficiency Guidelines • All existing constructions and new constructions (to be used less than four months per year) can voluntarily adopt the guidelines	Town and Country Planning Office (TCPO) Urban Local Bodies (ULBs) Ministry of Housing and Urban Affairs (MOHUA) Mussoorie Dehradun Development Authority (MDDA)
Cold climate regions have high energy requirements to meet their space heating demand during the winter peak and the energy needed to meet basic cooking, lighting, and water heating requirements.	***Recommendation 2: Establish guidelines defining energy system requirements*** • Define and draft acceptable thresholds for different energy systems used in a typical household, e.g., building envelope, lighting, heating systems, maintenance schedules, renewables, etc. • Simple structured guidelines will facilitate adopting and implementing the required energy systems.	TCPO ULBs MOHUA MDDA Uttarakhand Power Corporation Limited (UPCL) Uttarakhand Renewable Energy Development Agency (UREDA)
Compliance checks are necessary at multiple project stages—design, construction, post-construction, and post-occupancy—, all of which determine whether the building meets the set criteria under the code/policy/guideline. India lacks the infrastructure to support compliance checks for each building. Based on learnings from China's case, the government can conduct annual compliance assessments where sample cities are randomly selected and given a two-week notification period. It would help make the homeowner accountable for following the imposed guidelines/code/policies and checking the building's operational energy consumption.	***Recommendation 3: Develop a standard compliance check procedure to ensure energy-efficient building construction and operation.*** • **Standardizing compliance procedure:** This will make it easier for contractors, architects, and building owners to understand what is expected and how to comply with energy efficiency standards • **Third-party verification:** this will add an additional layer of credibility to the compliance check process • **Capacity building:** training and education programs for contractors, architects, and building owners to ensure that they have the knowledge and skills necessary to comply with energy efficiency standards	ULBs MDDA Urban Development Directorate (UDD)
For the large-scale implementation of any energy efficiency and low-carbon development initiative, the national government, in alignment with the state government and ULBs, must ensure regular training programmes for design industry professionals. People must repeat their training every time the guidelines undergo revision, a general practice followed in China.	***Recommendation 4: Introduce capacity building and training programmes for professionals*** • Design and material optimisation for better performance • Guidelines use, adoption, and compliance requirements • Passive design measures to enhance user comfort	ULBs MDDA

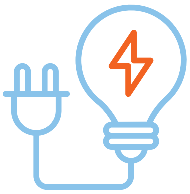
4.2 Part II: Learnings from the review of energy-efficient construction practices

The goal of studying various demonstration projects related to energy-efficient construction practices, appliances, renewables, etc., across the globe was to determine how different countries have benchmarked their energy systems as part of their energy efficiency codes/ guidelines. Understanding these benchmarks is critical to defining thresholds for the Uttarakhand context to ensure easy translation of guidelines to the general public. This also ensures easy adoption and a self-compliance check for the user, making the implementation process accessible. Table 4.2 shows the learnings from the case studies explored across the selected countries.

Table 4-2. Learnings from the case studies studied across the selected countries that can be incorporated into the existing building code/guidelines

S. No.	Intervention	Recommendations
1	**Building Envelope**	• Construct compact houses with a small surface-to-volume ratio ranging between 0.66 and 0.76 m^{-1}, as observed in Germany. • Use local construction materials in Uttarakhand to add thermal mass to the external walls to reduce heat loss. • Keep the U-value range of 0.1-0.4 (W/m^2K) for external walls, 0.05-0.12 W/m^2K for the roof, 0.2-0.7 W/m^2K for windows, and 0.08-0.3 W/m^2K for floors. Though the recommended U-value is very low and difficult to achieve with current construction practices in India, the general recommendation can be to keep the U-value as low as possible. • Use vapour and moisture barriers like adhesive tapes to seal doors and windows. Thermal bridging, a common phenomenon in a cold climate, can be prevented through a weatherproof membrane, which helps in two-way drying in the interior and exterior. • Use of buffer space between living and outside areas to reduce heat loss. • Use ventilated attic spaces to reduce moisture build-up.
2	**Orientation**	• Orient the building towards the south to maximise solar radiation. • Locate living spaces towards the south to maximise sun exposure to capture heat. • Use single, but preferably double-glazed large low-emissivity windows on the southern side and small windows on the northern side.
3	**Shading**	• Use adjustable shading to maximise solar radiation during the winter.
4	**Insulation**	• Proper insulation must be used in the roof, walls, attic, and floor construction, depending on the climate and design demand severity. • Insulation materials like expanded polystyrene (EPS), fiberglass, glass wool, and cellulose should be used with thicknesses of 20-40 centimetres (cm).
5	**Daylighting**	• Use skylights in roofs and clerestory fixed windows for adequate daylighting.
6	**Ventilation**	• Maintain the required air changes to reduce heat loss in a building. The air changes per hour (ACH) at 50-pascal pressure should be in the range of 0.15-2.4 ACH.
7	**Heating system**	• Use a combination of active and passive strategies to achieve a thermally comfortable environment. • Passive heating systems include a solarium, Trombe wall, water wall, air vents in the attic, and heat generation from cooking and cattle/people. • Active systems include heat pumps, solar thermal collectors, standalone heating systems, and heat recovery systems that can be used as per the requirement.
8	**Renewable energy systems**	• Use solar-based systems (e.g., solar PV and solar water heater) for electricity and domestic hot water and reduce utility bills. • The domestic hot water system, like solar collectors, should be based on the capacity and space available at the site.
9	**Appliance**	• Use BEE star-labelled appliances like refrigerators, televisions, geysers, washing machines, dryers, solar water heaters, etc., to reduce energy consumption and increase annual savings.
10	**Water efficiency**	• Low-flow fixtures and flush should be used in washrooms. • Rainwater harvesting can be incorporated.

Learnings from the review of policy guidelines in cold climatic countries reveal a need to adopt a holistic approach towards building design focused on appliances used in the built environment and onsite electricity generation for water heating, to simultaneously match the needs of Uttarakhand and decarbonise the building sector. One meaningful learning from this exercise is that merely formulating an energy-efficient building code policy and setting a threshold for electrical appliances and RE systems is not sufficient. There should also be an established procedure for policy compliance checks and capacity building to keep the building energy-efficient from the design stage to the operational phase and have the skill force required to make buildings climate resilient and sustainable.



Merely formulating an energy-efficient building code policy is not sufficient, there should also be an established procedure for policy compliance check and capacity building

5. National policies to enable sustainable construction practices

and the adoption of energy-efficient appliances

A detailed review of the policy landscape at the national and state levels in Uttarakhand has been conducted to identify interventions for mainstreaming climate change adaptation and mitigation into urban development[16]. A brief description of the potential intervention areas for building construction practices and energy-efficient appliances and the opportunities to achieve energy efficiency and thermal comfort in the urban residential sector in Uttarakhand in terms of policies and recommendations is given in Table 5.1.

Table 5-1. Potential intervention areas, policies, and recommendations to streamline climate-responsive actions in Uttarakhand's residential sector

S. No	Area of intervention	Name of policy/programme/act/rules	Recommended actions for low-carbon development in the existing policy landscape
1	Layout and building design	• Uttarakhand (UP Urban Planning and Development Act, 1973) Amendment Act, 2013 • Smart City Programme	Authorities can make climate change considerations and resilience integration mandatory criteria in the preparation and approval process of the urban development master plan.
2	Building construction materials	Uttarakhand Building Bye-laws and Schedule of Rates (SoR)	• Adopt Central Public Works Department's (CPWD) SoR for new innovative, low-carbon, and sustainable construction technologies for Uttarakhand. • Develop a handbook of locally available materials in Uttarakhand, which includes information on thermo-physical properties, reuse, upgradation, recycled content, embodied energy, emissions intensity, toxicity, sustainability, and safety, and integrate this information into the SoR, to be adopted by the UDD and Public Works Department (PWD).
3	Eco Niwas Samhita (ENS)	Uttarakhand Building Bye-Laws	Adapt the ENS to the local context in Uttarakhand and make provisions in the building bye-laws (through a state notification) to make ENS compliance mandatory for the residential building approval process.

16 Bhadra, J., Garg, T. & Kansal, A. (2020). Mapping of existing residential sector energy efficiency policies and guidelines in Uttarakhand. New Delhi: Alliance for an Energy Efficient Economy

S. No	Area of intervention	Name of policy/programme/act/ rules	Recommended actions for low-carbon development in the existing policy landscape
4	Green Habitat Accomplished Rating (GHAR)	• Awas Niti • All government housing projects • State-funded housing projects • Dehradun Smart City	Make the GHAR system mandatory (housing inspected and rated by CPWD and implemented by PWD/ULBs).
5	Solar water heaters	• Uttarakhand Solar Energy Policy • Uttarakhand Action Plan on Climate Change (UAPCC) • Building bye-laws	• Install solar water heaters in all residential buildings – mandatory for building approval. • Promote and install solar water heaters – UREDA under the Solar Energy Policy. • Encourage micro, small, and medium-sized enterprises (MSMEs) to provide technologies and services through the ESCO financing model.
6	Solar (light-emitting diode (LED)) lighting systems	• Uttarakhand Solar Energy Policy • Vision 2030 • 24X7 Power for all • UAPCC	• Install solar-powered LED lighting systems in all residential buildings – mandatory for all government-funded housing projects. • Promote and install solar-powered LEDs – UREDA under the Solar Energy Policy. • Encourage MSMEs to provide solar LED lighting.
7	Solar-powered (off-grid) heating systems	• Uttarakhand Solar Energy Policy • UAPCC • Smart City Programme	Mainstream and promote solar-powered (off-grid) residential heating systems (pilot projects).
8	Rooftop solar PV	• Uttarakhand Renewable Energy Policy • Vision 2030 • Awas Niti • Smart City Programme	Make rooftop solar PV systems mandatory in all government-funded housing projects and projects under state/central schemes like Pradhan Mantri Awas Yojana – Urban (PMAY-U) and Atal Mission for Rejuvenation and Urban Transformation (AMRUT).
9	Super-efficient household appliances	• Vision 2030 • Sustainable Development Goal (SDG) 7 • UAPCC	• Encourage buyers to buy BEE's star-labelled appliances. • Strict enforcement and market regulations • Financial benefits (like a rebate on the interest rate, green loans, and discount on maximum retail price (MRP) for buyers)
10	Thermal comfort and health	• UAPCC • Vision 2030 • SDGs	Include "Ensure Thermal comfort for all and wellbeing" as an indicator under the UAPCC, SDGs, and Vision 2030.
11	Capacity building and training	• SDGs • UAPCC	Allocate funds for capacity building of state authorities, officials, architects, planners, and developers on energy efficiency and sustainability.
12	Energy efficiency label for residential units	• Vision 2030 • UAPCC	• Promote energy-efficient homes and provide financial incentives to buyers. • Pilot projects for the residential green labelling programme
13	Passive and climate-responsive architecture	• UAPCC • Vision 2030	• (Mandatory) design recommendations and model design strategy should be included in Awas Niti & building bye-laws and adopted by the UDD. • Mainstream energy efficiency and net-zero design strategy in various government projects. • University student education and training
14	Environmental services for residential buildings	• Building bye-laws • Smart City Programme	Guidelines for low-carbon/net-zero/energy-efficient residential building design
15	Climate-resilient residential buildings	• UAPCC • Building bye-laws	Guidelines for resilient and climate-responsive design

The learnings from the review of national policies show that policies and regulations are in place at the national and state level to intervene at the appropriate stages of building design, construction, and operation. There is a need to work with all the government departments, ministries, and implementing agencies in synergy to remove the hurdles and barriers to the seamless implementation of policies at the ground level in order to make construction practices sustainable and enhance climate resilience.

6. Built environment characteristics, construction materials, and energy usage patterns in Uttarakhand

After reviewing the international building code, construction practices, and policies, and national policies to enable sustainable and climate-responsive building design and construction, the next step is to examine the prevailing building construction practices and energy usage patterns in Uttarakhand. To get an idea of the representative built form, demographic character, and energy use patterns to develop a future roadmap for the residential sector in Uttarakhand, 100 residences across three cities, Mussoorie, New Tehri, and Chakarata, all having different climate severities, have been analysed*. Figure 6.1 shows the household data from Census 2011 and selected sampled houses for analysis.

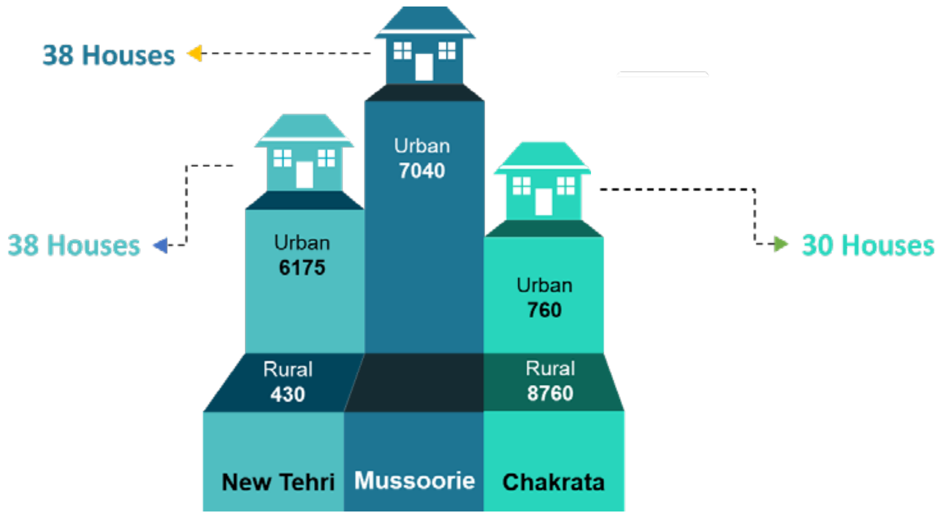


Figure 6-1. **Household data from Census 2011 and selection of sample houses**

The annual heating degree days for Chakrata, Mussoorie, and New Tehri are 3158, 3046, and 2872, respectively. Whereas the annual cooling degree days are 13, 34 and 59 for the respective places

To characterise the climate in the three locations, the monthly average dry bulb temperature (DBT) in Chakrata, Mussoorie, and New Tehri is given in Table 6.1. Chakrata has the most severe climate, while New Tehri has the least extreme. The annual heating degree days for Chakrata, Mussoorie, and New Tehri are 3158, 3046, and 2872, respectively. The annual Cooling Degree days for Chakrata, Mussoorie, and New Tehri are 13, 34, and 59, respectively. Due to the selected cities being in cold regions, residences are heat-dominated.

* Details of survey is mentioned in Appendix 1

Table 6-1. Average monthly outdoor DBT: maximum and minimum for three locations[17]

CITY	DBT (°C)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Chakrata	Min	-0.7	2.05	6.38	11.07	14.41	15.4	15.54	15.17	13.17	8.86	3.33	0.17
	Max	11.23	14.12	19.73	24.93	26.79	25.44	23.11	22.37	22.09	21.1	16.96	12.93
Mussoorie	Min	-0.13	2.52	6.99	11.85	15.26	16.42	16.7	16.01	13.93	9.63	4.08	0.73
	Max	11.75	14.7	20.3	25.68	27.63	26.32	23.96	23.33	22.84	21.78	17.59	13.61
New Tehri	Min	1.27	3.96	8.3	12.93	16.17	17.24	17.55	16.86	14.86	10.76	5.29	2.04
	Max	13.17	16.09	21.6	26.65	28.53	27.3	24.93	24.2	23.75	22.77	18.75	14.86

6.1 Spatial characteristics

The residences surveyed have been categorised as contemporary and composite (traditional + conventional). Figure 6.2 shows the schematic of contemporary and composite buildings prevalent in the residential sector of Uttarakhand. The contemporary buildings (Figure 6.2 (a)) have open spaces on the southern side. The width of these open spaces varies from 2 to 5 m. Living rooms have big windows to allow sunlight and heat to enter. The composite buildings (Figure 6.2 (b)) are built using traditional techniques and locally available materials. These residences have buffer space all around the living spaces for protection against the weather.

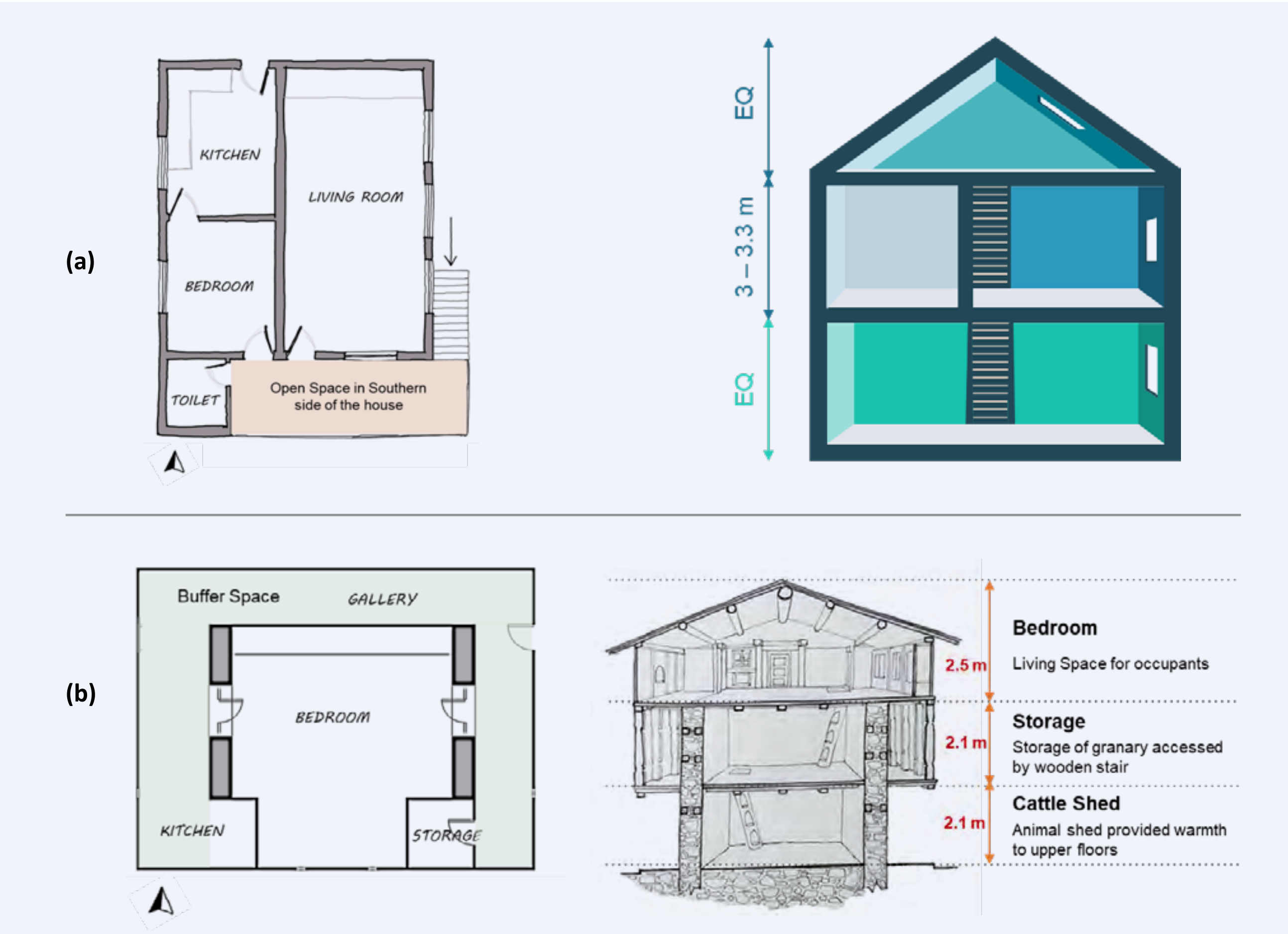


Figure 6-2. Spatial characteristics and building height description of (a) contemporary and (b) composite residential buildings

17 Weather data – ISHRAE

Mussoorie has a combination of attached and detached houses. These are two to three-storied structures with single and multiple families. New Tehri has an affordable middle-income group (MIG) and low-income group (LIG) government housing. The residences are built on contours of the hills facing south. Apartments and gated communities are commonly found here. Chakrata has composite residences built in the Jaunsari architectural style.

6.2 Construction materials

The contemporary residential buildings surveyed have external walls made of 230 mm thick brick with cement plaster on both sides and internal walls of 125-140 mm thick brick with cement plaster on both sides. The flat roofs are made of RCC and laid with galvanised iron (GI) sheets on top for drainage of rainwater and snow. All the residences have eaves extending up to 750 mm for protection against rain and snow. Windows 1.2 m in height have wooden frames with glass panels. Doors 2.1 m in height are made out of wood. The list of different contemporary construction materials used in wall and roof assemblies and windows are shown in Table 6.2 and 6.3. Due to heavy rain and humidity, seepage and moisture are significant problems in contemporary construction. The thermal mass of the materials used in contemporary construction delays the heat transfer by an average of 2 hours in walls and 1.5 hours in roofs.

Table 6-2. Contemporary construction materials used in wall and roof assemblies

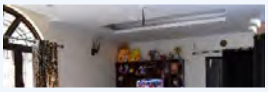
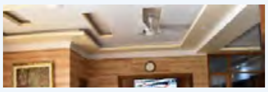
S. No.	Roof assemblies		Wall assemblies	
1	Roof with RCC slab		Brick and cement plaster on both sides	 
2	Roof with GI sheet		AAC block	
3	Gypsum false ceiling	 	RCC wall	
4	Roof tarpaulin sheet			
5	Wooden ceiling panels			

Table 6-3. Description of contemporary window assemblies

Window assemblies			
			
1. Wooden windows	2. Aluminium windows	3. MS Frame windows	4. UPVC windows

The internal walls of the composite houses are made of locally available stone, plastered with mud on both sides and with wood panelling. The external wall is made of wooden boards. The pitched roofs are made with wooden rafters and purlins with slate, pathal, or GI sheets on top. All the residences have eaves extending up to 750 mm for protection against rain and snow. Wooden windows 200 mm in height and wooden doors 2.1 m in height are predominantly used. The list of different contemporary construction materials used in wall and roof assemblies and windows are shown in Table 6.4 and 6.5. The thermal mass of the materials used in composite construction delays the heat transfer by an average of 5 hours in walls and 4 hours in roofs.

Table 6-4. Composite construction materials used in wall and roof assemblies

S. No.	Roof assemblies		Wall assemblies	
1	Roof wooden frames		Stone wall	
2	Roof wooden planks		Mud mortar wall	
3	Slate on roof		Red brick wall	
4	Roof with GI sheet		Wood wall	

S. No.	Roof assemblies		Wall assemblies	
5	Roof with RCC slab		Cement plaster wall	
6	Roof with mud plaster			

Table 6-5. **Description of composite window assemblies**

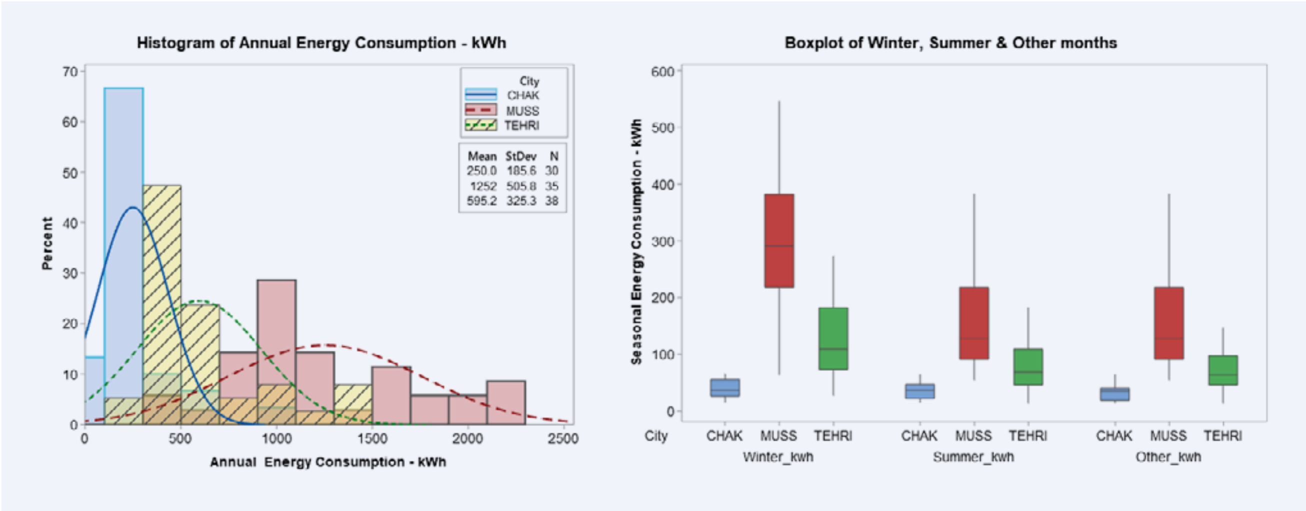
S. No.	Window assemblies			
1	Wooden windows			

It is inferred from the survey that residents are abandoning composite construction techniques due to rapid urbanisation, the emergence of new materials, and the unavailability of skilled labourers. The construction practices have taken a shift from composite to contemporary.

6.3 Energy demand profile

Figure 6.3 shows the annual and seasonal energy consumption characteristics of the surveyed houses from three locations in Uttarakhand. A total of 103 houses were surveyed, with 30 from Chakrata, 35 from Mussoorie, and 38 from Tehri. Figure 6.3 (a) shows that the yearly energy consumption of houses in Mussoorie is in the higher range. In contrast, the annual energy consumption of the homes located in New Tehri and Chakrata is in the lower range. Figure 6.3 (b) shows seasonal energy consumption in three locations. Mussoorie and New Tehri experience higher seasonal electricity consumption. This is due to the more contemporary houses and higher income groups in Mussoorie (35 contemporary houses) and more composite homes and comparatively lower income groups in New Tehri (23 contemporary and 15 composite houses) and Chakrata (7 contemporary and 28 composite houses). Apart from this, variations in energy consumption can also be attributed to the fuel mix used to meet the heating requirements. In Chakrata, residents depend on wood for room heating and domestic water heating.

Annual energy consumption of houses in Mussoorie is in the higher range due to dominance of contemporary constructions, whereas, the annual energy consumption of the houses located in New Tehri and Chakrata is in the lower range due to dominance of composite constructions.



(a) (b)

Figure 6-3. **Energy consumption. (a) annual and (b) seasonal. Out of a total sample size of 103 surveyed houses, 30 were selected from Chakrata, 35 from Mussoorie, and 38 from New Tehri**

Figure 6.4 depicts data on the fuel used for cooking, room heating, and domestic water heating captured from the three locations. Wood is preferred over electricity or gas because it is economical and readily available. Wood is available free of cost in Chakrata from the abutting forests, and the per day consumption of wood is 25-30 kg for room heating, water heating, and cooking. Moreover, the residents cited the factors such as distance to the petrol station in Chakrata, reliability of electricity supply, and health concerns associated with electrical heating devices such as infrared radiators as reasons for their reliance on wood.

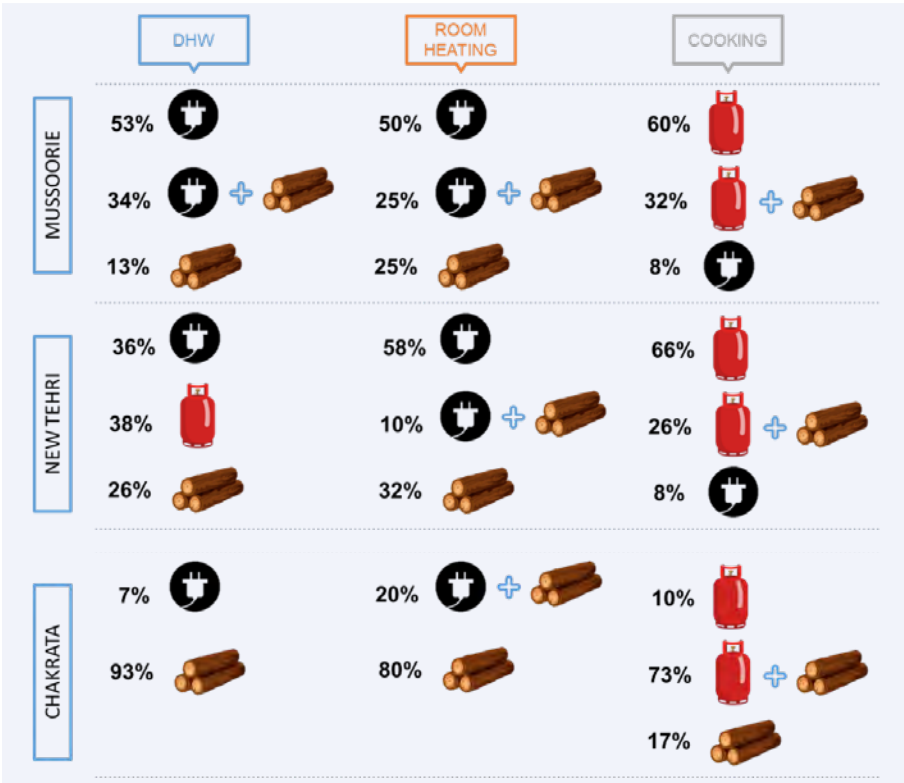


Figure 6-4. **Fuel mix for domestic hot water, room heating, and cooking**

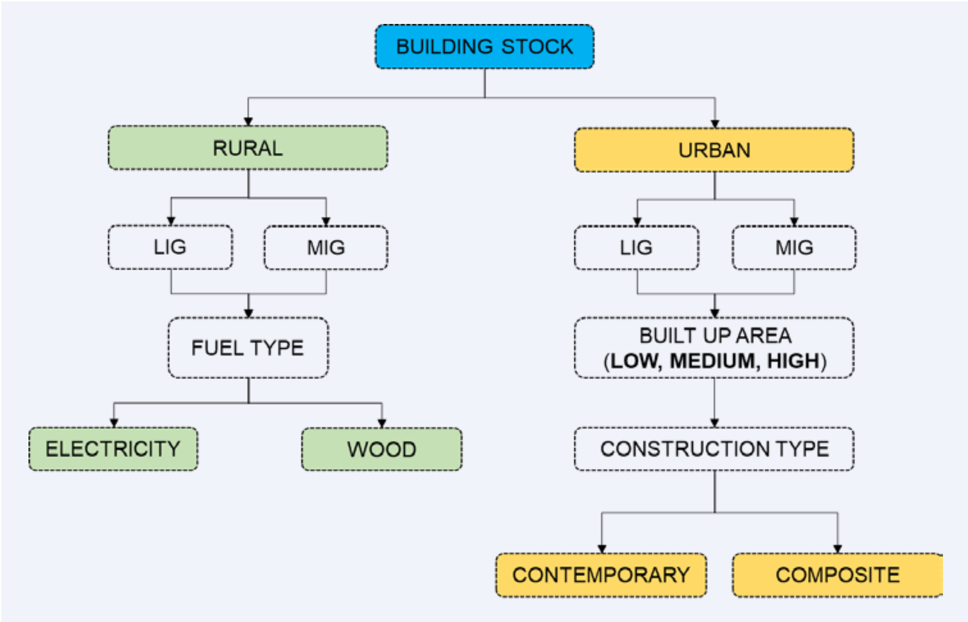


Figure 6-5. Framework for estimating the energy consumption of building stock in Uttarakhand

It is inferred from the survey that, in Uttarakhand, apart from the weather conditions, energy consumption in buildings also depends on multiple factors, such as construction materials, income groups, and the fuel mix used for space heating, cooking, and water heating. Survey analysis revealed that composite houses consume less energy than contemporary houses, and residents in higher-income groups consume more energy than low-income groups. Survey analysis also established a framework to estimate the building sector's energy consumption, considering the type of houses in urban and rural areas, income groups, built-up areas of houses, construction types, and fuel mix usage types. Figure 6.5 shows the framework to estimate the energy consumption of building stock in Uttarakhand.

6.4 Emission profile

The type of fuel mix used in the Uttarakhand region consists of electricity, charcoal, wood, and LPG gas for cooking, room heating, water heating, lighting, and ventilation. This section compares the emission caused due to different fuel mix used in contemporary and composite houses for space heating, cooking, and water heating. The annual energy consumption shown in the previous section does not capture the fuel mix. Therefore, kg CO_2 eq. has been used for each fuel type to estimate the emission. Emissions from using different fuel mix types are calculated using the following equations.

$$\text{Electricity (kg } CO_2 \text{ eq.)} = \text{Monthly electricity consumption (kWh)} \times \text{emission factor (kg } CO_2 \text{ eq./kWh)} \tag{6.1}$$

$$\text{Wood (kg } CO_2 \text{ eq.)} = \text{Monthly consumption (kg)} \times \text{emission factor (kg } CO_2\text{/kg)} \tag{6.2}$$

$$\text{Charcoal (kg } CO_2 \text{ eq.)} = \text{Monthly consumption (kWh)} \times \text{emission factor } (\text{kg}\tfrac{CO_2}{kWh}) \tag{6.3}$$

$$\text{LPG Gas (kg } CO_2 \text{ eq.)} = \text{Monthly consumption (kWh)} \times \text{emission factor } (\text{kg}\tfrac{CO_2}{kWh}) \tag{6.4}$$

Emission factors for electricity, wood charcoal, and LPG gas have been taken as 0.82 (kg CO_2 eq./kWh), 0.80 (kg CO_2 eq./kg), 0.97 (kg CO_2/kWh) and 2.89 (kg CO_2/kWh), respectively. Total annual CO_2 emission has been calculated by adding equations 6.1-6.4. The monthly CO_2 emissions are calculated for the surveyed composite and contemporary houses. A regression plot (shown in Figure (6.6)) is made to compare the monthly emissions of contemporary and composite houses with respect to the monthly average dry bulb temperature.

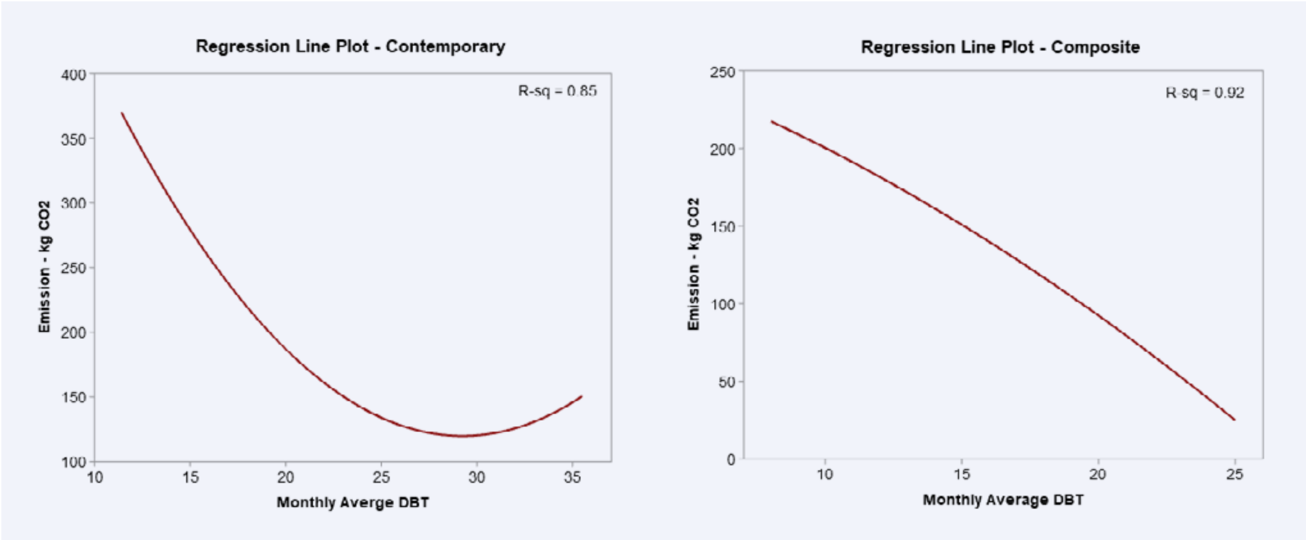
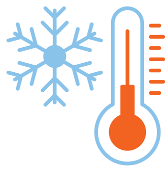


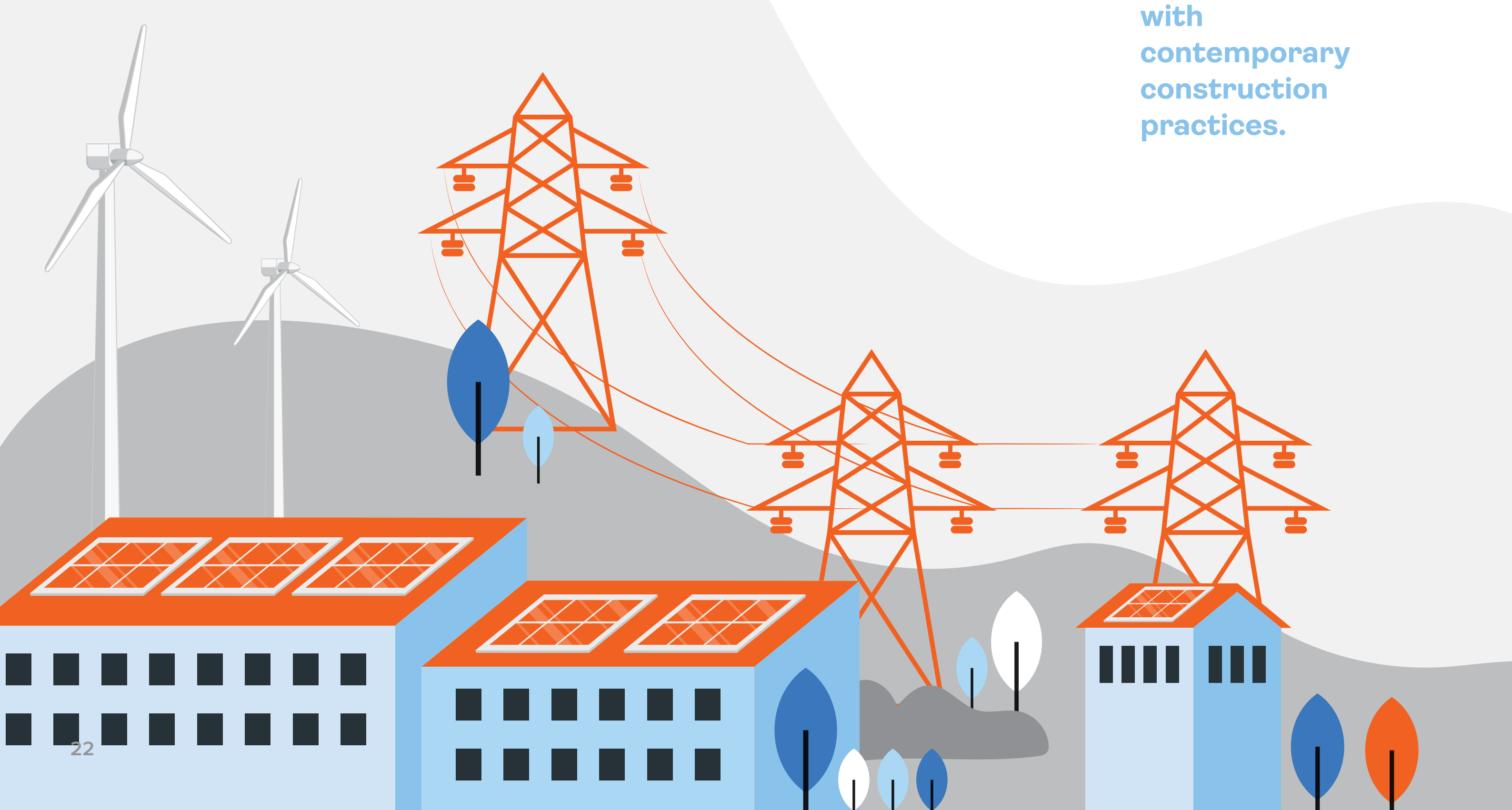
Figure 6-6. Regression plot of monthly DBT and emission for contemporary and composite houses

In contemporary residences which are predominantly dependent on electricity and LPG gas - the monthly carbon emission starts increasing rapidly when the mean outdoor temperature goes below 15 °C. The same trend follows in the composite building, which predominantly depends on wood and charcoal, but the rise is less due to the high thermal performance of the building envelope, due to which less energy is required for space heating.

In summary, this chapter presents the characteristics of the housing types available in the Uttarakhand region, types of construction materials, and fuel mixed usage types. Further, the energy demand profile of the contemporary and composite houses and a comparative analysis of emissions caused due to contemporary and composite houses have also been presented. It can be concluded from this chapter that composite houses demand less energy for space heating requirements compared to contemporary houses and cause less emission. But, composite houses have now become less common in practice, and contemporary construction practices have become prevalent. Contemporary houses, if designed properly, can save space heating related energy requirements. To understand in detail the thermal characteristics of composite and contemporary construction practices, following two chapters describe the thermal characteristics of composite and contemporary construction practices.



The monthly carbon emission starts increasing rapidly when the mean outdoor temperature goes below 15°C in buildings constructed with contemporary construction practices.



7. Composite construction practices and their thermal performance

This chapter documents construction practices that use local materials available in the Uttarakhand region to ensure that this valuable knowledge is not lost completely. The primary survey provides insight that out of total 103 surveyed houses from Chakrata, Mussoorie and New Tehri, 43 houses were constructed using composite construction practices. Composite construction practices include construction materials such as rubble masonry walls, mud and stone walls, wood panelling on the walls and roofs and slate stone plate roofs. Thermal performance analysis of the surveyed houses shows that houses constructed through composite construction practices have better thermal performance due to low thermal transmittance values, and high thermal mass.

However, rampant demand for housing, concentration of the population in the urban regions, unavailability of local construction materials for traditional construction practices, and lack of interest in traditional houses have led to a shift in the construction paradigm towards contemporary construction practices, which has resulted in a loss of traditional building construction knowledge.

In this chapter, the thermal performance of a century-old vernacular style of architecture followed in the Himalayan region (known as Kath-Kuni in Himachal and Koti Banal in Uttarakhand) has been presented. These houses are characterised by double horizontal timber beams filled with dry-stone masonry. The roof consists of slate stone plates nailed with a single nail to the timber purlins. Figure 7.1 shows the materials used and a cross-section of the Kath-Kuni style of architecture. The roof of Kath-Kuni buildings in Himachal Pradesh is shaped in a characteristic curved manner, while in Uttarakhand, the Kath-Kuni buildings have roof on a straight-line slope.

Thermal performance analysis of the surveyed houses shows that houses constructed through composite construction practices have better thermal performance due to low thermal transmittance values, and high thermal mass

Figure 7-1. **Kath-Kuni architectural style in the Himalayan region: a) walls; b) roof; c) cross-section of a typical Kath-Kuni house**[18]

18 https://repository.tudelft.nl/islandora/object/uuid:6eeaa0c7-8d00-4a8e-ae80-79f6abf050bc/datastream/OBJ/download (Last Accessed on 10 Sept. 2022)

7.1 Thermal performance analysis

A simulation was performed using the layout of the base case house (shown in Figure 9.2 of Chapter 9). To show the comparative thermal performance of Kath-Kuni style wall assembly with contemporary wall assembly (e.g., brick wall, brick wall with XPS insulation, AAC wall, AAC wall with XPS insulation, fly ash brick wall and random rubble masonry wall). The details of the Kath-Kuni wall assembly is shown in Figure 7.2. The details of the contemporary wall assemblies used for the simulation are shown in Table 7.1. The simulation was performed for the peak winter (4-5 January) and summer (4-5 June) using the weather data of Mussoorie. The comparison of daily heat gain and loss during peak winter and summer is shown in Figures 7.3 and 7.4, respectively, for the Kath-Kuni wall assembly and other contemporary wall assemblies.

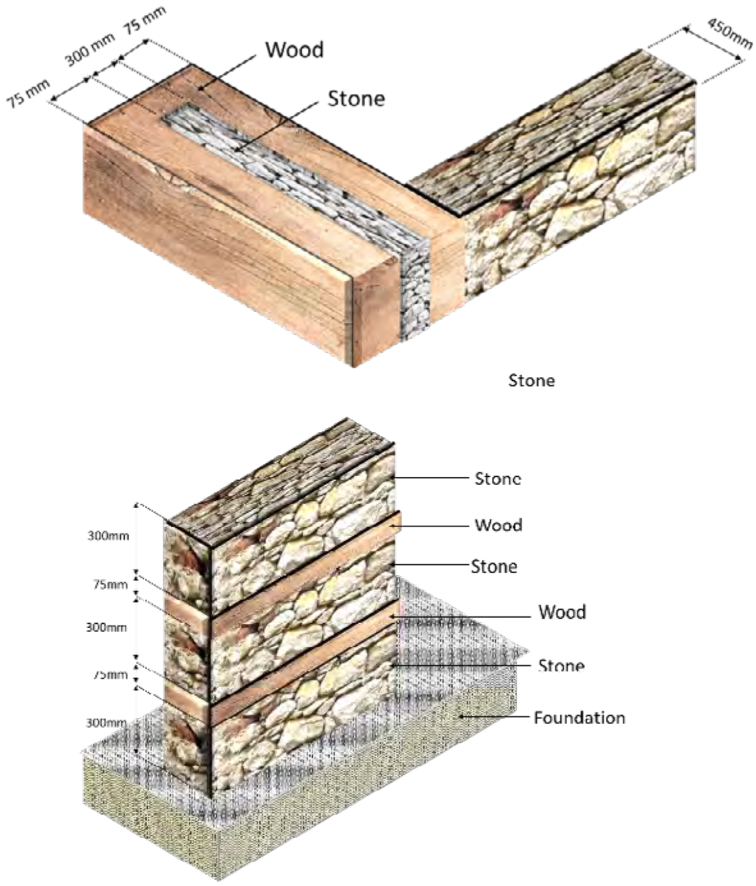


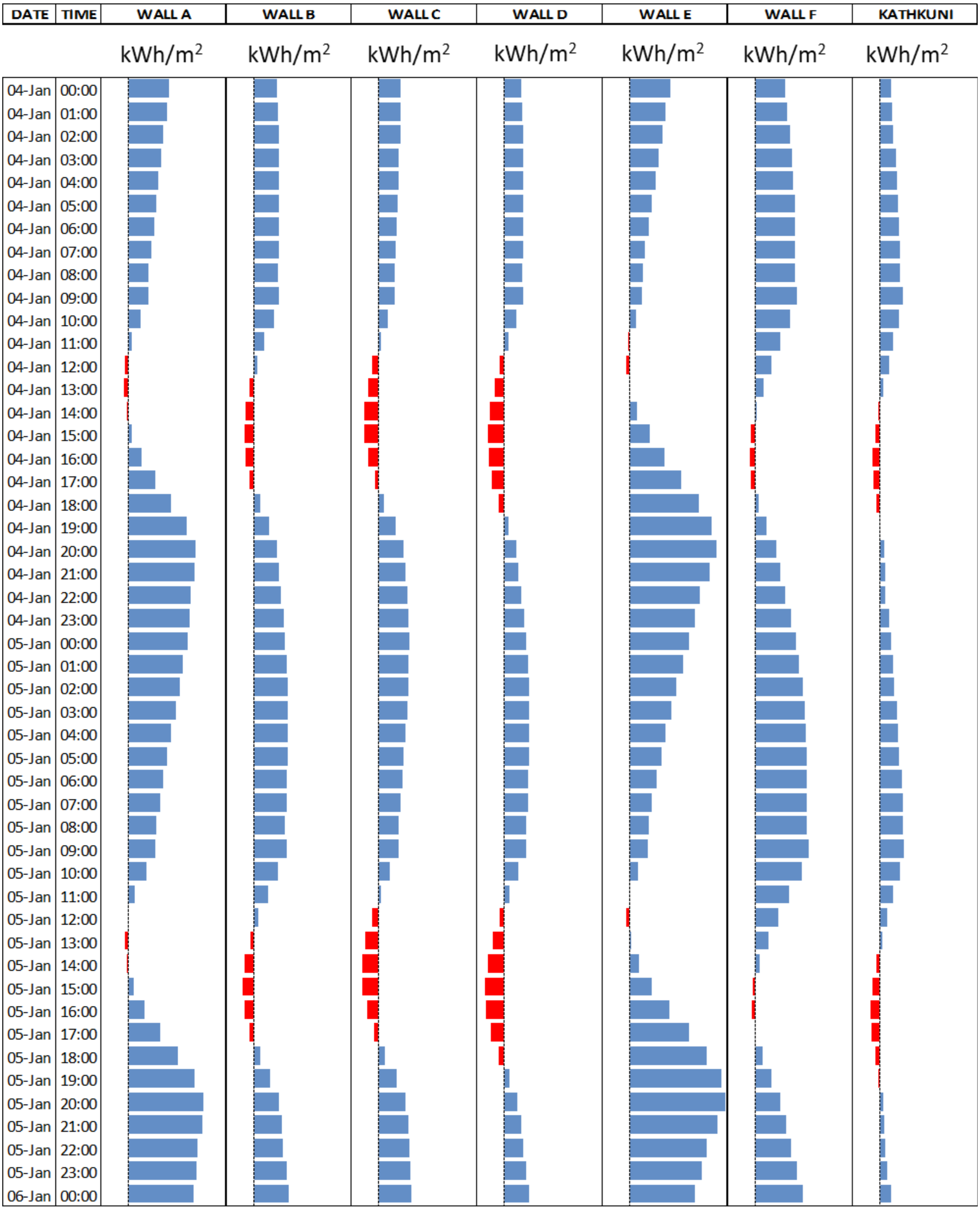
Figure 7-2. Kath-Kuni wall assembly details

Table 7-1. Description of contemporary wall assemblies used in simulation

Wall Assembly Description	Thermal transmittance value (U-Value) (W/m²K)
230 mm Brick + 12 mm interior and exterior cement plaster	2.1
230 mm Brick + 10 mm XPS	0.7
225 mm Fly-ash Bricks + 12 mm interior and exterior cement plaster	2.3
450 mm Random rubble masonry	1.6
200 mm AAC + 12 cement plaster	0.5
200 mm AAC + 10 mm XPS	0.34

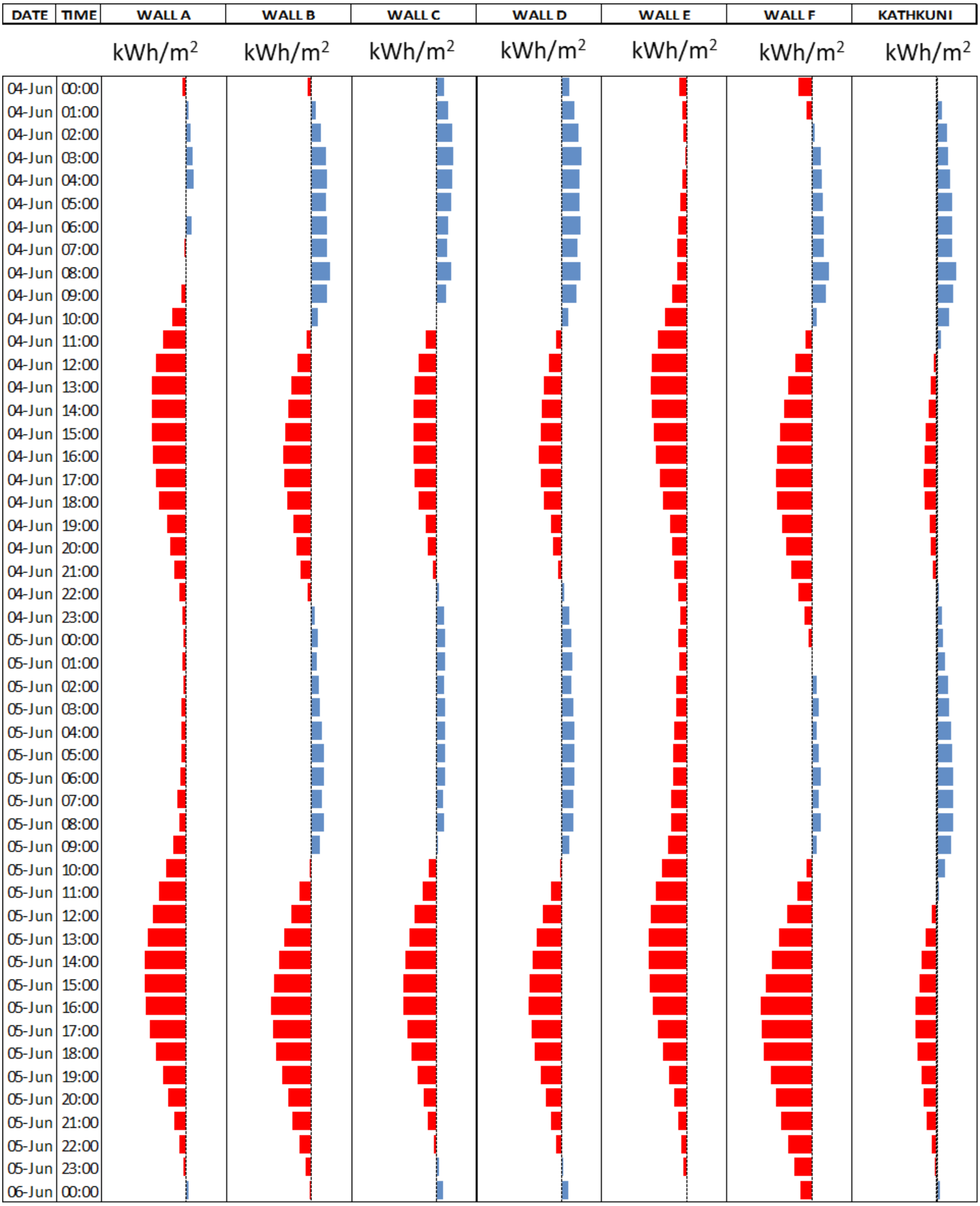
The heat loss is lowest for the Kath-Kuni wall structure in winter, and it gains less heat during summer than other contemporary wall types. The Kath-Kuni structure has higher thermal inertia; hence the time lag is higher compared to other wall types.

The heat loss is lowest for the Kath-Kuni wall structure in winter, and it gains less heat during summer than other contemporary wall types.



Wall A: Brick wall, **Wall B**: Brick wall + XPS, **Wall C**: Aerated concrete wall, **Wall D**: Aerated concrete wall + XPS, **Wall E**: Fly ash brick wall, **Wall F**: Random rubble masonry wall. Gain in **red** and Loss in **blue**.

Figure 7-3. Comparison of heat gain and loss through walls in winter

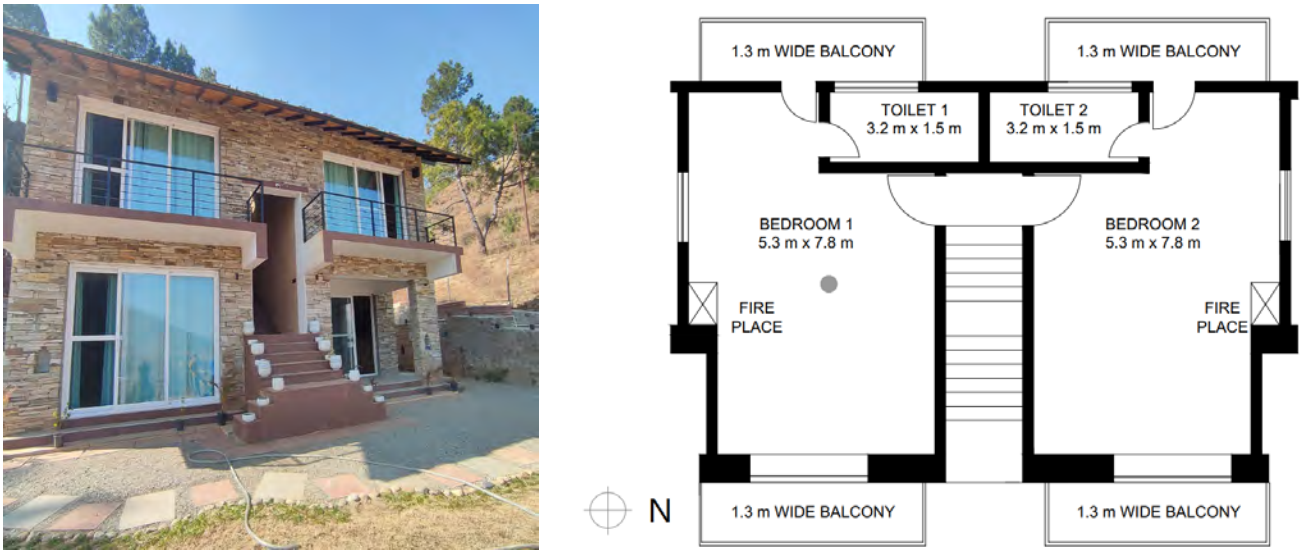


Wall A: Brick wall, **Wall B**: Brick wall + XPS, **Wall C**: Aerated concrete wall, **Wall D**: Aerated concrete wall + XPS, **Wall E**: Fly ash brick wall, **Wall F**: Random rubble masonry wall. Gain in **red** and Loss in **blue.**

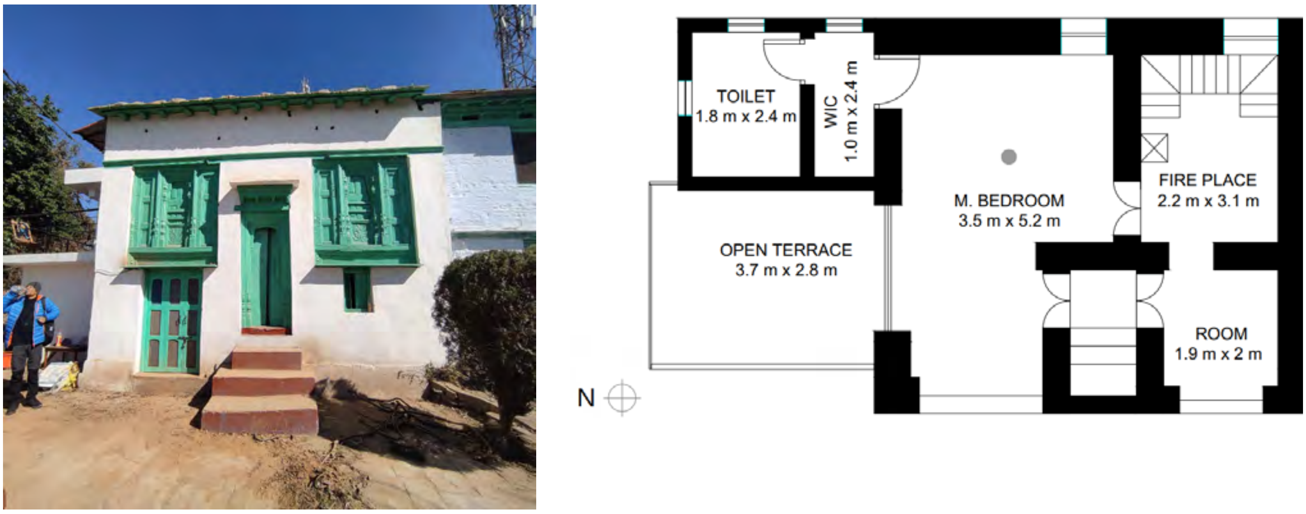
Figure 7-4. Comparison of heat gain and loss through walls in summer

7.2 Measurement based thermal performance analysis of composite houses

This section documents the measurement-based thermal performance analyses of composite houses. The houses are located in the Almora district of Uttarakhand. Indoor and outdoor air temperature data was recorded between January 19 to February 9, 2023. The houses were unoccupied during the measurement period. The layout of the houses with their exterior view is shown in Figure 7.5.



(a)



(b)

Figure 7-5. Exterior image of houses and their first-floor plans (a) House A (b) House B

Table 7.2 compares the materials and architectural features of both houses.

Table 7-2. **Comparative description of House A and House B**

PARAMETERS	HOUSE A	HOUSE B
HOUSE TYPE	Detached	Detached
FAMILY TYPE	Single family	Single family
INCOME CATEGORY	HIG	HIG
HEIGHT	G+1	G+1
PERIMETER (m)	45	34
CARPET AREA (m^2)	93.5	40
VOLUME (m^3)	135	112
FLOOR-TO-FLOOR HEIGHT (m)	4.5	2.8
ORIENTATION	East	West
EXPOSED SURFACE	North, South, East and West	North, South, East and West
WALL ASSEMBLY (U-value, W/m^2K)	600 mm Stone masonry **columns** (1.82 W/m^2K) **East wall** = 12 mm Mud Plaster + 230 mm Brick + 125 mm Stone cladding (1.8 W/m^2K) All other **external and internal wall** = 12 mm Mud Plaster + 230 mm Brick + 12 mm cement Plaster (1.53 W/m^2K)	12 mm Mud plaster + 600 mm Random Rubble Masonry + 12 mm Mud plaster (1.68 W/m^2K) **TOILET BLOCK**: 12 mm Cement plaster + 230 mm brick + 12 mm Cement plaster (1.71 W/m^2K)
ROOF ASSEMBLY (U-value, W/m^2K)	75 mm Iron girder + 50 mm wooden planks + 12 mm mud plaster + 40 mm pathal (slate stone) (1.11 W/m^2K)	100 mm wooden purlin + 40 mm wooden planks + 65 mm thick Pathal (slate) (0.46 W/m^2K)
ROOF FORM	pitched	pitched
WINDOW PANEL TYPE (U-value, W/m^2K)	DGU (2.67 W/m^2K)	Wooden (3.19 W/m^2K) DGU (2.67 W/m^2K)
WINDOW FRAME TYPE	UPVC	Wooden UPVC
SILL HEIGHT (m)	0.9	0.9
LINTEL HEIGHT (m)	2.4	2.1
WWR (%)	14.5	12
WFR (%)	31	28
OVERHANG DEPTH (m)	1.3	0.5

It can be observed that both houses are distinct in terms of their construction materials for walls and roofs. The real-time field measurements are carried out and evaluated in Figure 7.6 to study the impact of these above parameters on the thermal behaviour of both houses.

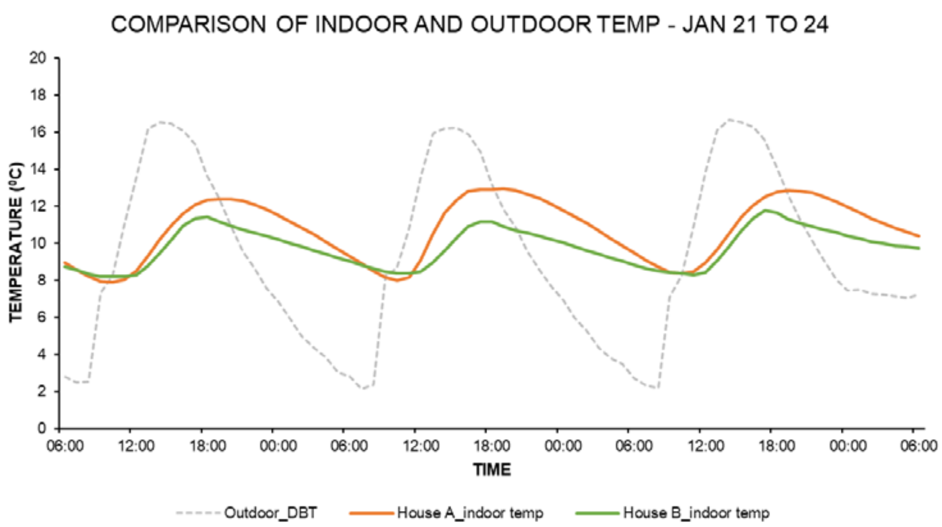


Figure 7-6. **Comparative thermal performance assessment of House A and House B in peak winter**

Figure 7.6 shows that when the outdoor air temperature reaches to minimum 2.1 °C the indoor temperature is maintained at 8.8 °C. Figure 7.6 also shows that diurnal variations in indoor air temperatures are in the range of 4-5 °C, whereas the diurnal variation of outdoor temperature ranges between 12-14 °C. This indicates that the envelope of Houses A and B have low thermal transmittance values, which results in good thermal performance of the houses. It can be inferred from the figure that the average delay between the peak outdoor and indoor air temperature is in the range of 4-5 hours for both houses, which indicates that the high thermal mass of the used construction materials helps in storing the heat during day time and releases it during the late evening.

Simulation and measurement-based thermal performance analysis show that composite construction practices have advantages in retaining heat inside the built environment compared to contemporary construction practices. This would help in reducing heat load in the cold climate of Uttarakhand. However, traditional construction practices have become less common due to high input costs for locally available construction materials, shortage of skilled labourers, and slow construction pace. On the other hand, easy access to contemporary construction materials, availability of labour, low skill requirement, fast construction pace, and rampant urbanisation are boosting contemporary construction practices. But there is a scope for improving the thermal performance of the houses by integrating traditional and contemporary construction materials through innovative architectural design and construction practices, as shown in this chapter. The next chapter describes the thermal performance of houses constructed with contemporary construction materials.

Composite construction practices have advantages in retaining heat inside the built environment compared to contemporary construction practices.

8 Contemporary construction practices and their thermal performance

Contemporary construction practices have now become the norm in the Uttarakhand region. Brick, AAC, and concrete blocks have replaced traditional wall materials. Roofs have become flat, and traditional roofing materials have been replaced by RCC and GI sheets. To characterize the thermal performance of houses constructed with these contemporary construction materials, the indoor air temperature was recorded during the peak summer and winter and compared with the outdoor air temperature. The details of the houses studied, and the measurement procedure is described in the following sections.

The indoor and outdoor temperature and humidity of houses constructed with contemporary construction materials were measured for a year from February 2020 to March 2021.

8.1 Measurement based thermal performance analysis of contemporary houses

To characterize the thermal performance of contemporary residential buildings, real-time field measurements were carried out in six contemporary houses identified in Mussoorie. In this section measurement of peak winter and summer is presented. The seasonal and annual thermal performance of buildings have been mentioned in Appendix 1 (section A.1.3). The houses were chosen based on location, construction materials, and the eagerness of homeowners to participate in the surveys. The indoor and outdoor temperature and humidity measurements were measured for a year from February 2020 to March 2021. The temperature and humidity loggers were placed in living rooms and bedrooms where people moved around frequently.

Figures 8.1 to 8.6 show selected houses' interior and exterior views with their floor plans. The location of the temperature and humidity loggers are shown as grey dots on the floor plans.

Table 8-1 compares the economic group, family type, architectural features, and construction materials used for the six houses.

Figure 8-1. Exterior view, interior view, and floor plan of House A

Figure 8-2. Exterior view, interior view, and floor plan of House B

Figure 8-3. Exterior view, interior view, and floor plan of House C

Figure 8-4. Exterior view, interior view, and floor plan of House D

Figure 8-5. Exterior view, interior view, and floor plan of House E

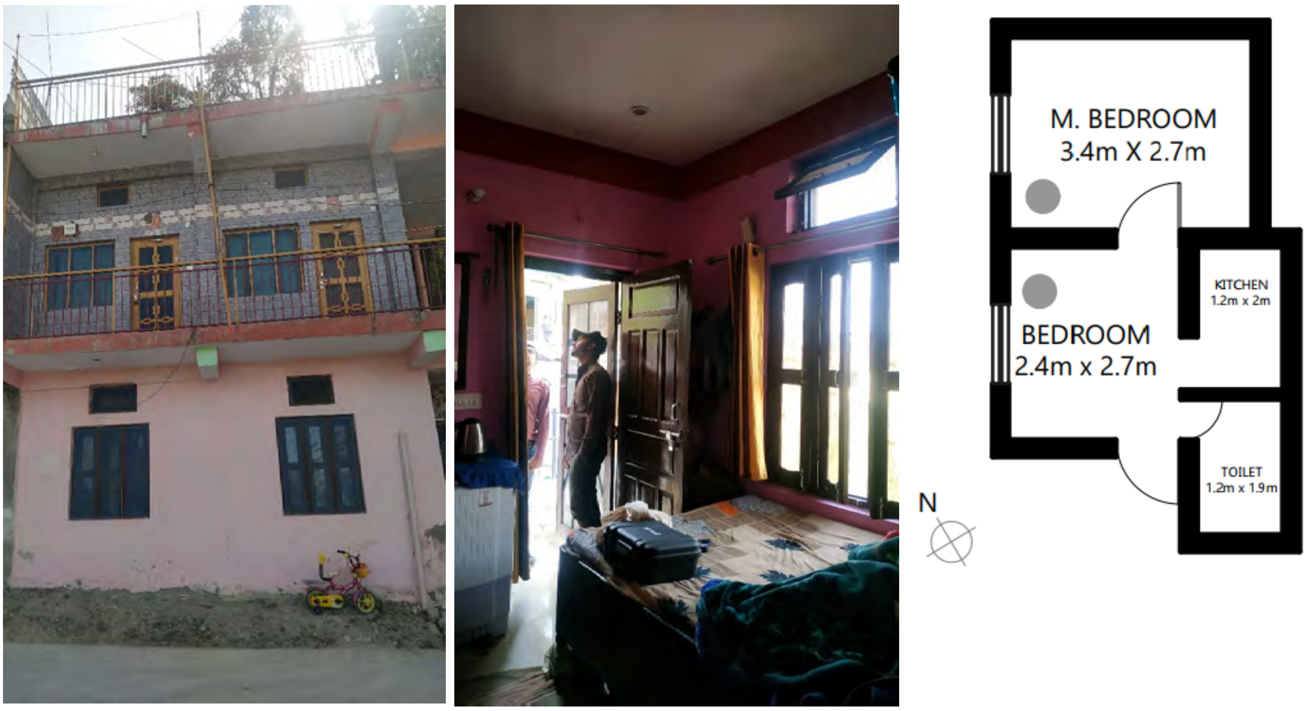
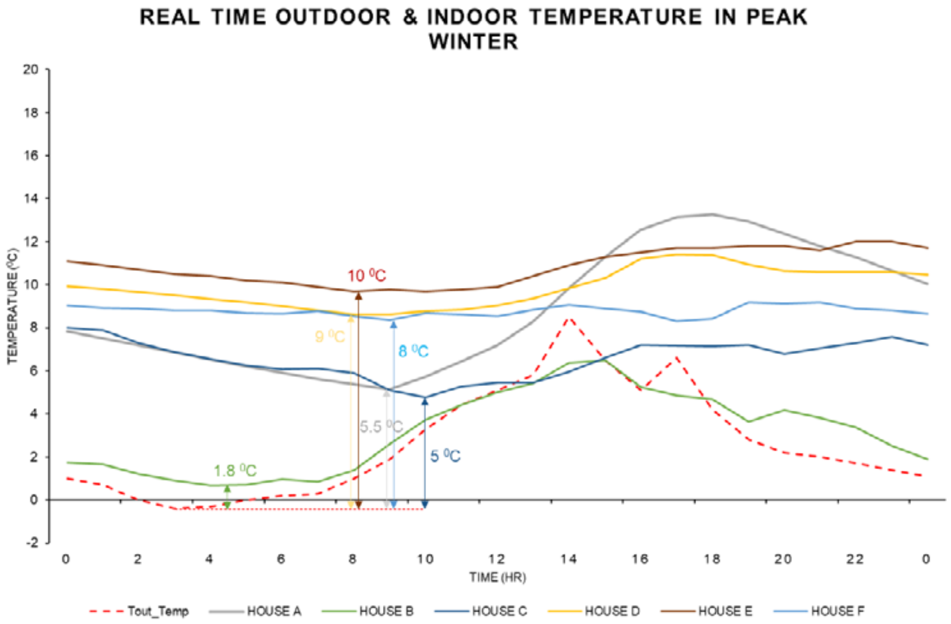


Figure 8-6. Exterior view, interior view, and floor plan of House F

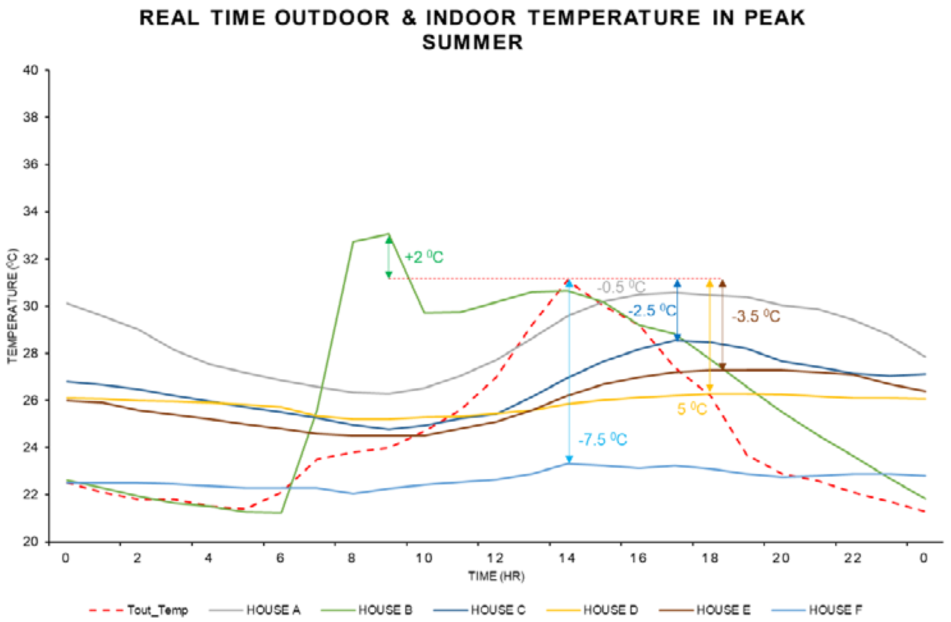
Table 8-1. **Comparative description of House A, B, C, D, E, and F**

PARAMETERS	HOUSE A	HOUSE B	HOUSE C	HOUSE D	HOUSE E	HOUSE F
HOUSE TYPE	Detached	Detached	Duplex	Detached	Detached	Duplex
FAMILY TYPE	Multi-family	Single-family	Multi-family	Single-family	Multi-family	Multi-family
INCOME CATEGORY	MIG	LIG	MIG	MIG	MIG	LIG
HEIGHT	G+2	G	G+1	G+1	G	G+1
PERIMETER (m)	41	22.5	35.5	50.5	38	23.5
CARPET AREA (m^2)	80	20.5	52	66	75	21
VOLUME (m^3)	224	47	182	198	202.5	63
FLOOR-TO-FLOOR HEIGHT (m)	2.8	2.3 - 2.1	3.2	3	2.7	3
ORIENTATION	South	North-East	North-West	South-West	South-East	South-West
EXPOSED SURFACE	East, West, & South	North & East	North, East, & West	East, West, & South	North, East, & South	West & South
WALL ASSEMBLY (U-value, W/m^2K)	Brick + Cement plaster (2.08 W/m^2K)	Brick + Cement plaster (2.08 W/m^2K)	Brick + Cement plaster (2.08 W/m^2K)	Brick + Cement plaster (2.08 W/m^2K)	Brick + Cement plaster (2.08 W/m^2K)	Brick + Cement plaster (2.08 W/m^2K)
ROOF ASSEMBLY (U-value, W/m^2K)	RCC + Cement plaster (3.75 W/m^2K)	GI Sheet (5.82 W/m^2K)	RCC + Cement plaster (3.75 W/m^2K)	RCC + Cement plaster (3.75 W/m^2K)	RCC + Cement plaster (3.75 W/m^2K)	RCC + Cement plaster (3.75 W/m^2K)
ROOF FORM	Flat	Sloping	Flat	Flat	Flat	Flat
WINDOW PANEL TYPE (U-value, W/m^2K)	3 mm clear glass (5.8 W/m^2K)	N. A	3 mm clear glass (5.8 W/m^2K)	3 mm clear glass (5.8 W/m^2K)	3 mm clear glass (5.8 W/m^2K)	3 mm clear glass (5.8 W/m^2K)
WINDOW FRAME TYPE	Wooden	Wooden	Wooden	Wooden	Wooden	Wooden
SILL HEIGHT (m)	0.8	0.9	0.9	0.9	0.8	0.7
LINTEL HEIGHT (m)	2	1.8	2.1	2.1	2	2
WWR (%)	15	5	8	9	12	8
WFR (%)	16	6	11	13	13	13

It was observed that each house is distinct in terms of the parameters mentioned in Table 8.1. The real-time field measurements of indoor air temperature data during the peak winter and summer have been analysed to study the impact of different parameters described in the above table on the thermal behaviour of these buildings.



(a)



(b)

Figure 8-7. Difference between outdoor and indoor temperatures during (a) peak winter and (b) peak summer

Figure 8.7 (a) and (b) show the comparison of real-time indoor and outdoor temperature data of the six houses during peak winter and summer, respectively. Figure 8.7 (a) shows that House E has the maximum peak temperature difference between peak winter, whereas House B has the lowest. The possible reason for the lowest peak difference in the case of house B is the GI sheet roof. The thermal transmittance value of the GI sheet roof is high (5.82 W/m^{2}K), which facilitates the inside heat to go outside through conduction and results in a drop in indoor air temperature. Whereas in the case of House E, the highest temperature difference is due to the south-east facing façade, which facilitates the solar radiation to come inside the room during day time and helps heat up the space. Additionally, the high thermal mass of the brick wall and RCC roof absorb the heat and release it during the night. Comparatively low thermal transmittance value helps reduce the conductive heat loss, which results in the maximum temperature difference during peak winter.

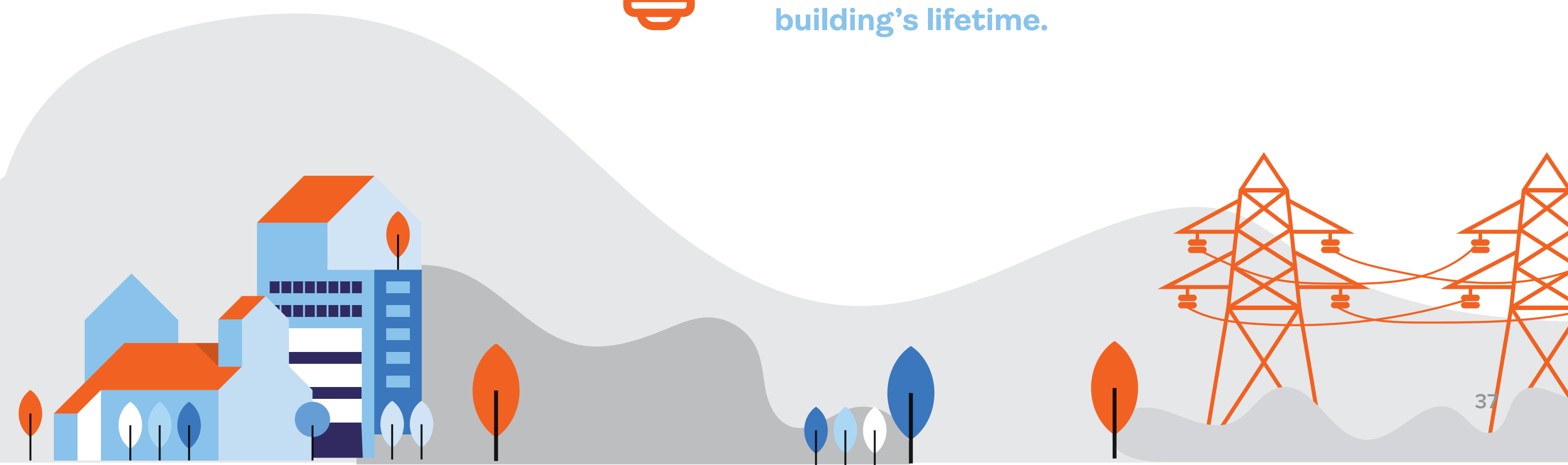
During peak summer, Figure 8.7 (b) shows the minimum peak temperature difference between the indoor and outdoor environments for House B. Again, this is due to the high thermal transmittance value of the GI sheet roof used in House B, which facilitates the outside heat to come inside through conduction and causes heat gain in the house. The maximum indoor temperature of House B is higher than the outdoor maximum temperature because of the heat produced in the kitchen for cooking during the morning hours. Figure 8.7 (b) also shows that House F has a maximum temperature difference between indoor and outdoor environments. This is due to the south-west facing façade and low WWR, which allows heat gain comparatively less compared to the south-east orientation and high WWR as observed in the case of House E. Also, the brick wall and RCC roof have comparatively low thermal transmittance values compared to the GI Sheet roof used in House B, which prevents the conductive heat gain and keeps the indoor air temperature lower compared to the outdoor air temperature during peak summer.

For other houses (A, C, and D) types also, it can be observed that the RCC roof and Brick wall help in maintaining the indoor temperature comparatively better compared to the GI sheet roof (House B) during peak summer and winter. The variations in the indoor temperatures are due to different orientations, WWR, and WFR.

This chapter described how the different parameters of the building envelope, e.g., construction materials, building orientation, WWR, and WFR, affect its thermal performance. It can be concluded from this chapter that if designed poorly, contemporary construction materials result in poor building envelope thermal performance and lock-in energy inefficiencies for the whole building's lifetime.

Since contemporary construction practices have become more prevalent in Uttarakhand compared to composite construction, it has become essential to evaluate the thermal performance of buildings constructed with contemporary construction materials with alternative design solutions which can minimize the thermal discomfort and reduce the energy consumption and associated emissions, and identify the best practices to be followed. Thus, in the next chapter, a whole building simulation-based approach is adopted to analyse the thermal performance of the buildings with multiple building envelope parameters and identify the key interventions in terms of building orientations, WWR, wall and roof assemblies, and infiltration from the perspective of contemporary construction practices. Based on the identified interventions, guidelines have been provided to be followed.

If designed poorly, contemporary construction materials result in poor building envelope thermal performance and lock-in energy inefficiencies for the whole building's lifetime.



The effect of building envelope design parameters, e.g., **orientation, aspect ratio, wall and roof assembly types, infiltration and natural ventilation potential on thermal performance, energy savings and emission reduction potential** has been studied

9. Design interventions for Building envelope

The orientation of buildings, building aspect ratio, WWR, wall and roof assembly types, infiltration, and natural ventilation potential play a significant role in maintaining thermal comfort and energy consumption in the built environment. This chapter investigates the effect of each variable on buildings' thermal performance. Thermal performance has been analysed for each variable using multiple options through simulations, considering a representative building in Uttarakhand*****. The effect of each variable on thermal performance and energy savings has been studied and validated through real-time measured data. Finally, the evidence-based recommendations for different variables are presented in an indicative form to visually understand the comparative benefits of multiple options. Figure 9.1 shows the methodology adopted for simulation studies for evaluating the factors affecting the thermal performance of buildings.

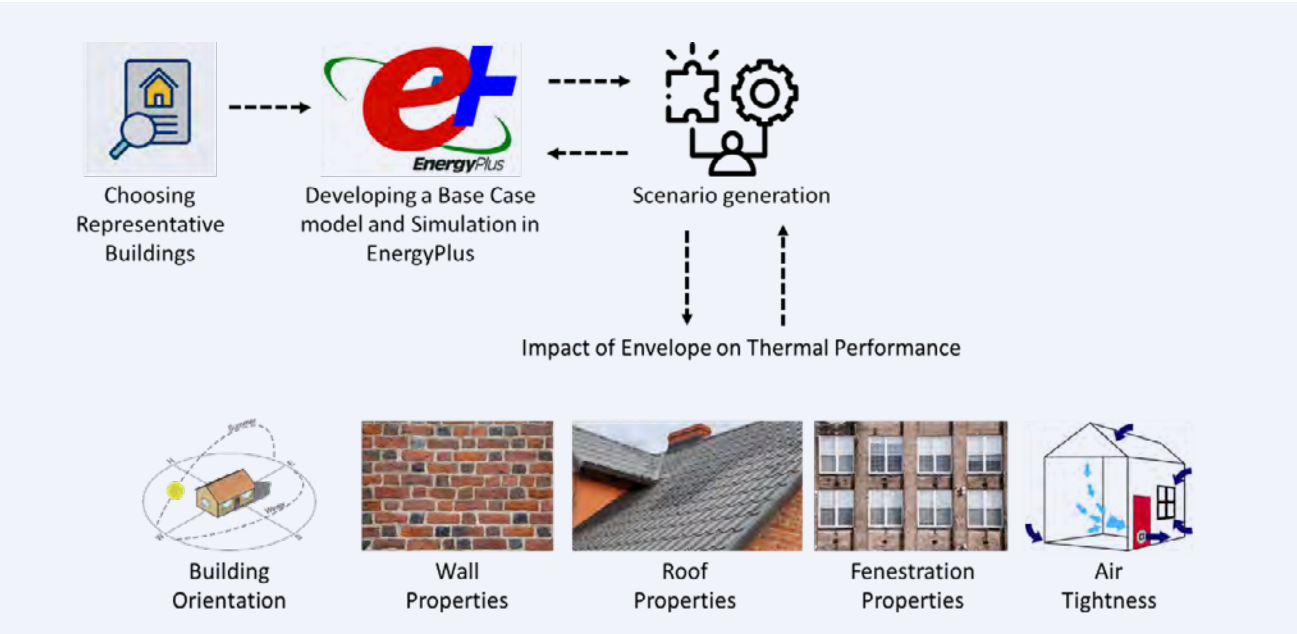


Figure 9-1. **Schematic of the methodology adopted for simulation based analysis**

*Details of simulation-based study is mentioned in Appendix 2

Figure 9.2 shows the representative residential unit chosen from the handbook[19] of replicable designs for energy-efficient residential buildings. Five parameters—building orientation, wall properties, roof properties, fenestration properties, and air tightness—were considered for the scenario generation and performance evaluation. The range for these five parameters was obtained from the coarse grain survey conducted in Mussoorie, New Tehri, and Chakrata from January to March 2020. Table 9.1 shows the assumptions taken for the base case model simulation. Similar simulations were carried out for a 2 BHK, 3 BHK and 4 BHK building to generate energy conservation scenarios and performance evaluation. The details are mentioned in Appendix 2.

Weather files of Mussoorie, Chakrata and Josimath have been selected for the simulation. Josimath is selected to cover the extreme cold climate severity of Uttarakhand, whereas Mussoorie and Chakrata to represent the comparatively milder climatic conditions. In the following sections, HED variations, annual monetary and carbon saving potentials associated with HED have been shown with respect to multiple parameters for different building envelope components. HED has been calculated through whole building simulation model whereas the annual monetary and carbon saving potential have been calculated using equation 9.1 and 9.2, respectively.

Annual monetary saving potential=annual HED savings (kWh) ×electricity tariff (Rs./kWh) (9.1)

Annual carbon saving potential associated with HED=annual HED savings (kWh)×emission factor (kg CO_2 eq./kWh) (9.2)

To calculate the monetary saving potential electricity tariff has been taken as 5.89 Rs./kWh as per the Uttarakhand electricity tariff[20]. For carbon saving potential, national average emission factor has been taken as 0.79 kg CO_2/kWh. The national average emission factor was used to determine Uttarakhand's share of carbon emissions in the country's total carbon stock. This is because the majority of Uttarakhand's electricity generation comes from renewable energy sources, which are supplied to other adjacent states.

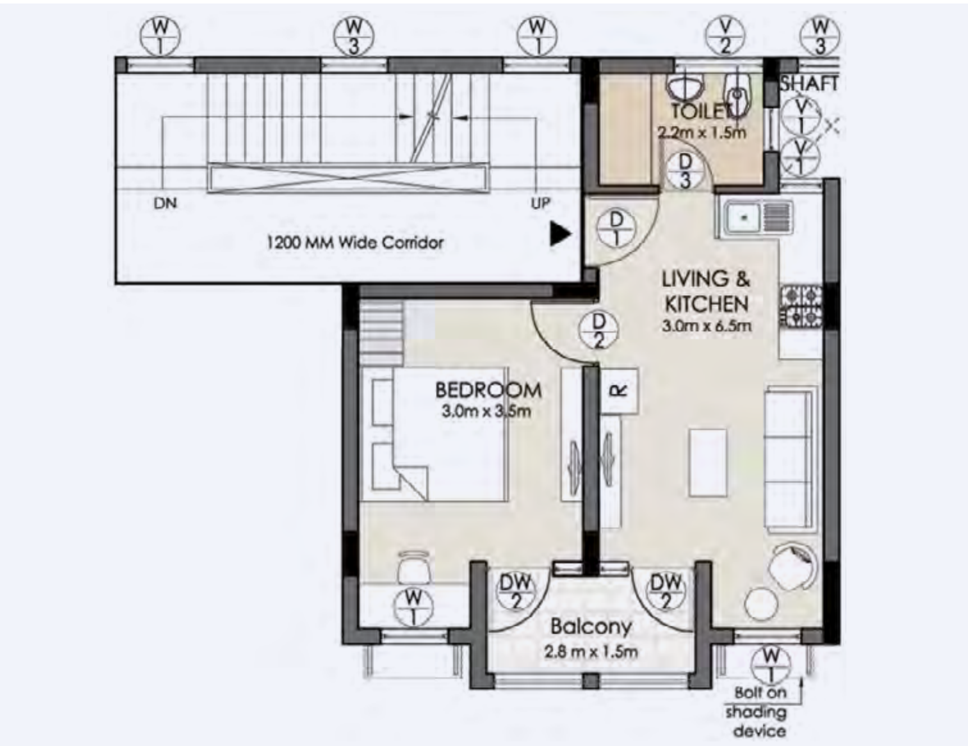


Figure 9-2. Floor plan of multifamily row house used in simulation

Weather files of Mussoorie, Chakrata and Josimath have been selected for the simulation. Josimath is selected to cover the extreme cold climate severity of Uttarakhand, whereas Mussoorie and Chakrata to represent the comparatively milder climatic conditions

19 BEE (Bureau of Energy Efficiency. (2021). Handbook of replicable designs for energy efficient residential buildings
20 https://cercind.gov.in/2022/whatsnew/Draft-RE%20Tariff%20Order-2022-23.pdf

Table 9-1. Inputs and assumptions for base case model

Input	Assumption
Weather file	Mussoorie, Chakrata, and Joshimath
Exposed Wall	Brick + Cement Plaster on both sides (U-value 2.08 W/m²K)
Exposed Roof	Reinforced concrete (U-value 3.1 W/m²K)
Floor (not adjacent to ground)	Reinforced concrete (U-value 3.1 W/m²K)
Windows	Single clear 3mm Glazing (U-value = 5.8 W/m²K and SHGC = 0.87), wooden frame
WWR	10% of the exposed wall
Shafts, corridors, adjacent buildings	are modelled as adiabatic components
Heating setpoint	19⁰C
Cooling setpoint	24⁰C
Heating and cooling schedule	Bedroom [8pm to 8am] Living room [8am to 8pm]
External Window schedule	Always ON (opens when indoor temperature is >24⁰C and closes when outdoor temperature is higher than indoor temperature)
Internal window schedule	Always closed
Internal door schedule	ON [8am to 8pm] OFF [8pm to 8am]
Occupant density	0.0229 (people/m²)
HVAC system used	Split no fresh air to calculate ideal heating and cooling loads
Balcony	Modelled as a zone with a hole in the exposed wall
Infiltration	1.5 ACH

9.1 Building orientation

Orientation affects the building's exposure to solar radiation and hence thermal performance. The typical 1 BHK floor plan was simulated for eight orientations: north, north-east, east, south-east, south, south-west, west, and north-west for the three locations (Chakrata, Mussoorie, and Joshimath) and the heating energy demand (HED) was calculated. Table 9.2 summarizes the impact of orientation on annual HED and corresponding monetary saving potential at the three locations. Table 9.3 summarizes the annual carbon saving potential associated with the HED.

Table 9-2. Impact of orientation on the annual heating energy demand and monetary saving potential

ORIENTATION	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving potential (₹)	HED (kWh)	Variation (%)	Saving potential (₹)	HED (kWh)	Variation (%)	Saving potential (₹)
N (BASELINE)	2288	NA	NA	3006	NA	NA	3226	NA	NA
N-E	2272	-0.7	94	2980	-0.8	153	3203	-0.7	135
E	2095	-9	1137	2779	-7.5	1337	3035	-6	1125
S-E	1907	-16	2244	2573	-14	2550	2877	-11	2056
S	**1791**	**-21**	**2927**	**2465**	**-18**	**3186**	**2794**	**-13**	**2544**
S-W	1900	-17	2285	2591	-14	2444	2885	-10	2008
W	2089	-9	1172	2784	-7	1308	3040	-6	1096
N-W	2269	-0.8	112	2980	-0.8	153	3200	-0.8	153

Table 9-3. **Impact of orientation on the annual carbon saving potential**

ORIENTATION	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Saving potential (kg CO_2 eq.)
N (BASELINE)	1808	NA	NA	2375	NA	NA	2549	NA	NA
N-E	1795	-0.7	13	2354	-0.8	21	2530	-0.7	18
E	1655	-9	152	2195	-7.5	179	2398	-6	151
S-E	1507	-16	301	2033	-14	342	2273	-11	276
S	**1415**	**-21**	**393**	**1947**	**-18**	**427**	**2207**	**-13**	**341**
S-W	1501	-17	307	2047	-14	328	2279	-10	269
W	1650	-9	157	2199	-7	175	2402	-6	147
N-W	1793	-0.8	15	2354	-0.8	21	2528	-0.8	21

Orientation has a significant effect on the annual HED and associated monetary and carbon saving potentials of the building. A south-facing building (fenestrations predominantly facing south orientation) requires about 16% to 21% less heating energy than a north-facing building and can be helpful in saving electricity bill in the range of Rs. 2244-3186 and carbon emission in the range of 300-400 kg CO_2 eq. depending on the locations. Figure 9.3 illustrates the heating energy demand reduction in each orientation for Mussoorie. As the HDD increases, the solar radiation on the surface decreases; hence, HED reduction variation is seen across other locations.

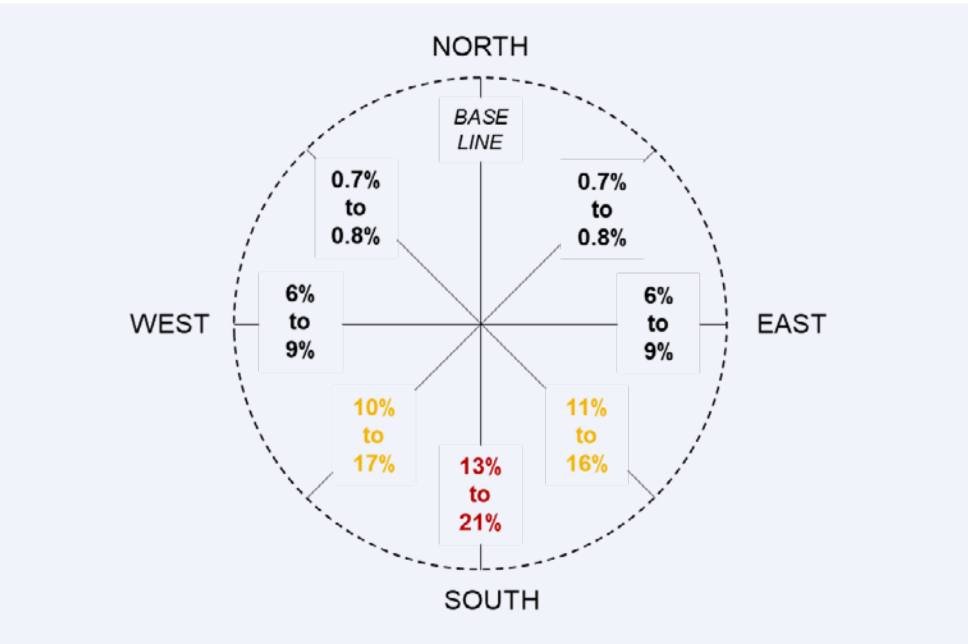


Figure 9-3. **Reduction in heating energy demand for different orientations in Mussoorie**

A south-facing building requires about 16% to 21% less heating energy than a north-facing building and can be helpful in saving electricity bill in the range of Rs. 2244-3186 and abating carbon emission in the range of 300-400 kg CO_2 eq.

9.2 Heat gain and loss due to change in orientation

Change of building orientation affects the heat gains and losses through the building envelope, impacting the heating energy demand. Figure 9.4 presents the summary of heat gains (kWh) and losses (kWh) through the wall, fenestration, roof, and floor on a typical winter day (22nd December) for the north and south-oriented 1 BHK building for Mussoorie.

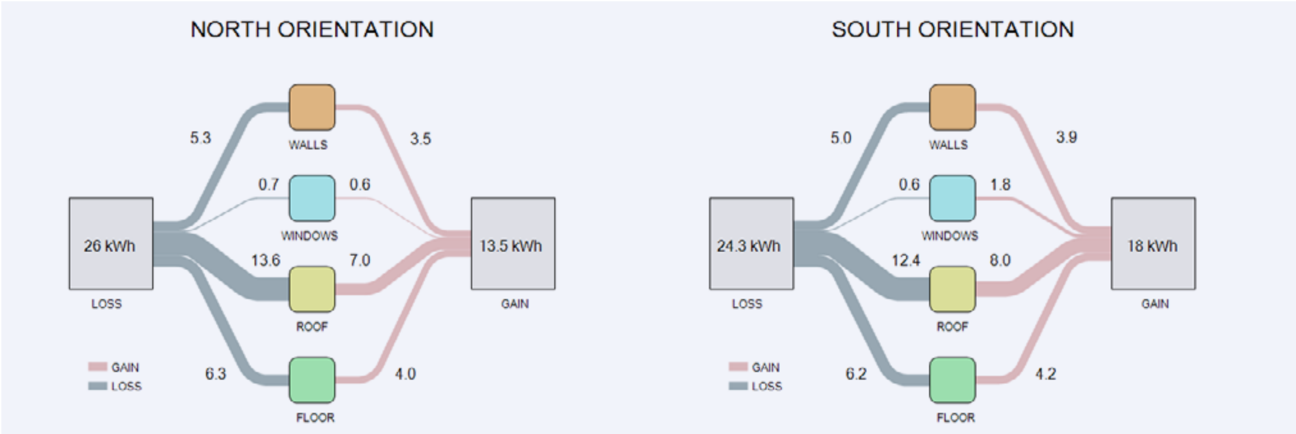


Figure 9-4. Heat gain and loss through the building envelope for north and south orientations in Mussoorie

South-oriented buildings typically illustrate greater heat gains and lower heat losses than north-oriented buildings during the winter. For instance, a south facing building reduced heat loss by 6% over a north facing building in Mussoorie.

9.3 Measurement based analysis of impact of orientation on thermal performance of buildings

The findings of the simulation results were confirmed with the measured data of two houses oriented north-west (House C) and south-east (House D), respectively. The exterior, interior, floor plan and placement of sensors of the houses are shown in Figures 9.5 and 9.6.

Figure 9-5. Exterior view, interior view, and floor plan showing the sensor location in House C

Figure 9-6. **Exterior view, interior view, and floor plan showing the sensor location in House D**

Table 9.4 compares the economic group, family type, architectural features and construction materials used in the two houses.

Table 9-4. **Comparative description of House C and House D**

PARAMETERS	HOUSE C	HOUSE D
HOUSE TYPE	Duplex	Detached
FAMILY TYPE	Multi-family	Single-family
INCOME CATEGORY	MIG	MIG
HEIGHT	G+1	G+1
PERIMETER (m)	35.5	50.5
CARPET AREA (m^2)	52	66
VOLUME (m^3)	182	198
FLOOR-TO-FLOOR HEIGHT (m)	3.2	3
ORIENTATION	North-West	South-West
EXPOSED SURFACE	North, East, & West	East, West, & South
WALL ASSEMBLY (U-value, W/m^2K)	Brick + cement plaster (2.08 W/m^2K)	Brick + cement plaster (2.08 W/m^2K)
ROOF ASSEMBLY (U-value, W/m^2K)	RCC + cement plaster (3.75 W/m^2K)	RCC + cement plaster (3.75 W/m^2K)
ROOF FORM	Flat	Flat
WINDOW PANEL TYPE (U-value, W/m^2K)	3 mm clear glass (5.8 W/m^2K)	3 mm clear glass (5.8 W/m^2K)
WINDOW FRAME TYPE	Wooden	Wooden
SILL HEIGHT (m)	0.9	0.9
LINTEL HEIGHT (m)	2.1	2.1
WWR (%)	8	9
WFR (%)	11	13
OVERHANG DEPTH (m)	1	1

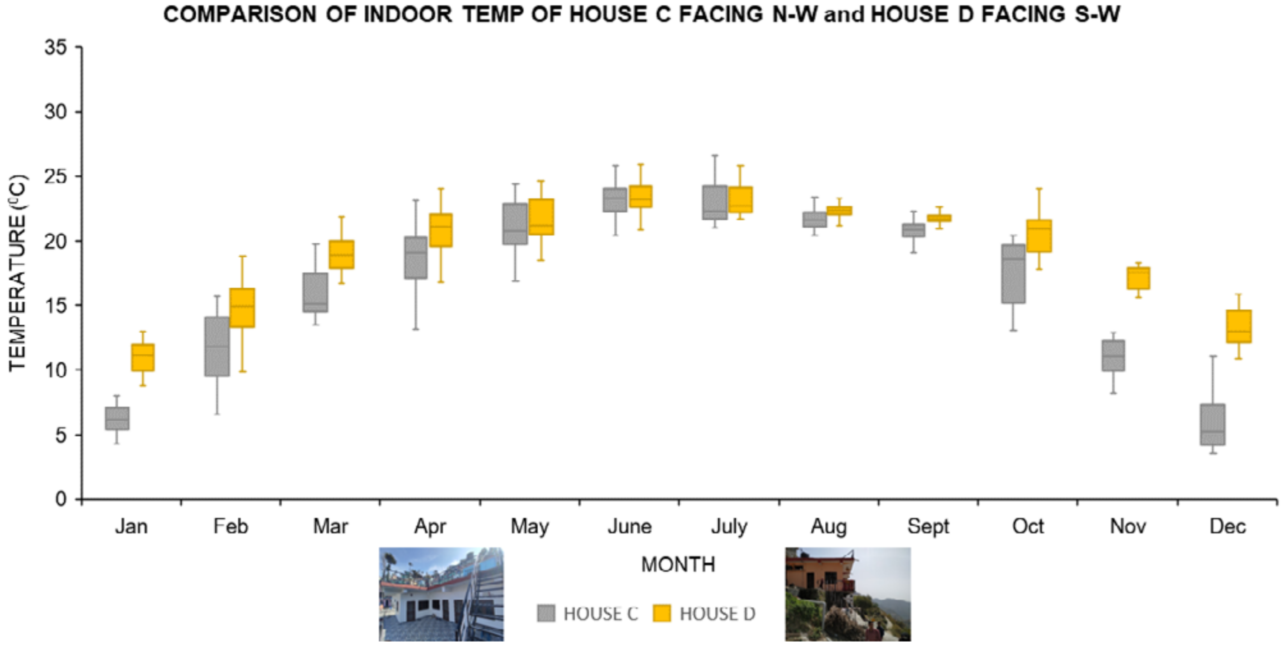


Figure 9-7. Effect of orientation on indoor temperature

Figure 9.7 shows the measured thermal performance of two houses. Figure shows that mean monthly temperature of south-west facing house is higher compared to the north-west facing house throughout the year. From the above simulation results and measured data, it can be concluded that for passive solar design, a building must have the appropriate orientation of openings and spaces to achieve maximum daylight with maximised heat gain, which depends on the location and season. Based on the above finding, a design principle is recommended in the following section for the designers to construct a building Uttarakhand.

9.3.1 Design principles

Exposing the longer face of the building along the sun path allows more control over the heat gain from solar exposure on external walls and increases building surface skin temperature to reduce heat loss. Table 9.5 shows the orientation-wise indicative building thermal performance improvement that the designers can choose from, depending on the site conditions. These orientations will not only ensure indoor thermal comfort but also help reduce HED and maximise daylight.

Table 9-5. Building thermal performance based on orientation

Building Orientation	Long Side	Performance
North	East-West	Baseline
East	North-South	√
South-East	NE-SW	√√
South-West	NW-SE	√√√
South	E-W	√√√√

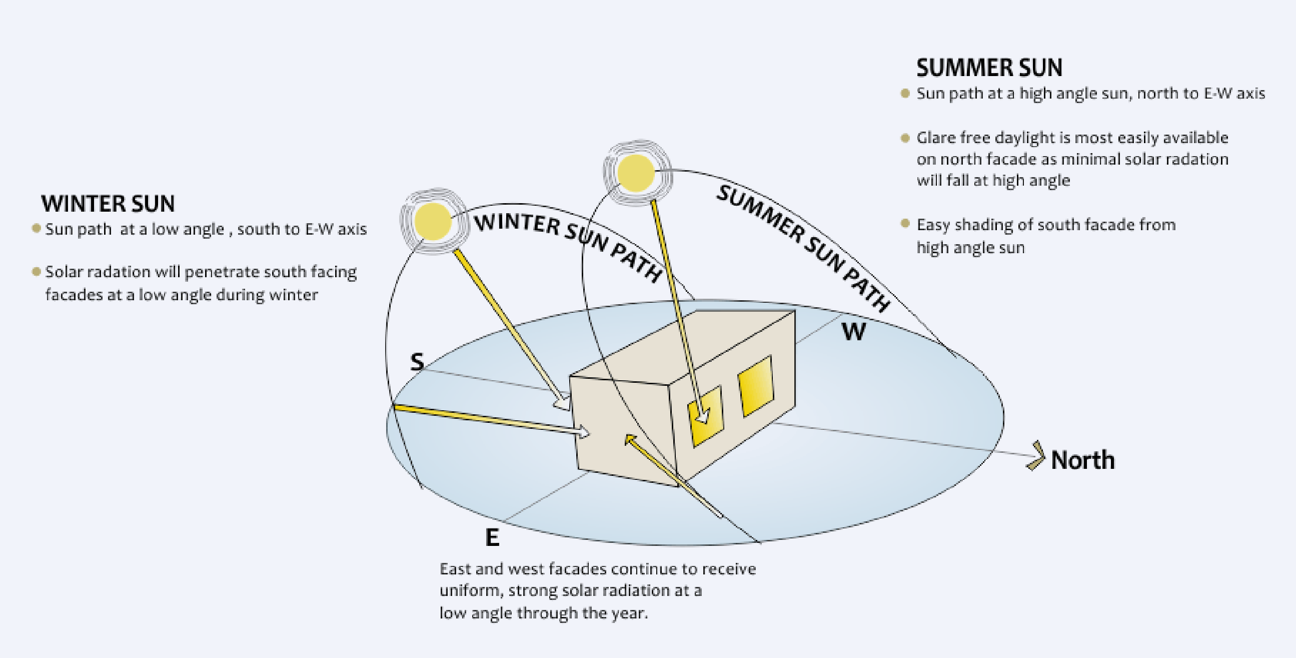


Figure 9-8. **Sun path diagram along with building orientation in northern hemisphere**[21]

The schematic of the building orientation along with the sun path for the Northern Hemispheres is shown in Figure 9.8. The primary living rooms, such as bedrooms and drawing rooms, should be south facing. Seldom-used rooms typically have few windows - such as bathrooms, utility or storage rooms, stairs or attached sheds and garages - which can act as buffer areas and be placed on the north and east sides of the house. This can help reduce heat loss out of the primary living areas.

9.4 Aspect ratio

A building's aspect ratio is defined as the ratio of the building's length to its width. It is one of the most important determinants of energy efficiency in buildings, as it determines the building surface area available for heat transfer between the interior and exterior environment. It also shows the amount of building area that is subject to solar heat gain. Increasing the aspect ratio along the east-west axis, i.e. south-facing, decreases the annual heating energy demand compared to increasing the aspect ratio along the north-south direction. Table 9.6 shows the indicative thermal performance improvement of the building with different aspect ratios.

Increasing the aspect ratio along the east-west axis, i.e. south-facing, decreases the annual heating energy demand

Table 9-6. **Impact of aspect ratio on HED (Heating Energy Demand)**

Aspect Ratio	Shape	Performance
1:4	4x, 1x	√
1:2	2x, 1x	√√
1:3	3x, 1x	√√√

Aspect Ratio	Shape	Performance
4:1	4x, 1x	√√√√
2:1	1x, 2x	√√√√√
1:1	1x, 2x	√√√√√√
3:1	1x, 3x	√√√√√√√

21 https://nzeb.in/knowledge-centre/passive-design/form-orientation/

9.5 Window-to-wall ratio

The optimum WWR significantly reduces heating energy demand in cold climates and improves daylighting and natural ventilation. In this guideline, the term WWR refers to the ratio of the area of non-opaque building envelope components of dwelling units to the envelope area (excluding roof) of dwelling units. This ratio can be expressed mathematically as follows:

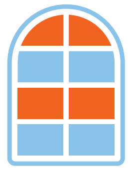
$$WWR = \frac{A_{(Non\text{-}opaque)}}{A_{envelope}} \quad (9.1)$$

Where,

$A_{(Non\text{-}opaque)}$: Openable area (m²): it includes the openable area of all windows and ventilators and opening directly to the external air

Exclusions: All doors opening directly to the external air

$A_{envelope}$: It is the gross external wall area (includes the area of the walls and the openings such as windows and doors)



South-facing windows with 30% WWR reduce annual HED by 3-6% compared to a 10% WWR and provides monetary and carbon saving potentials in the range of Rs.300-583 and 75-78 kg CO_2 eq., respectively.

To demonstrate the effect of different WWR on buildings' thermal performance, the heating energy demand was calculated for the base case building (shown in Figure 9.2). The setpoints to trigger cooling and heating were 240C and 190C, respectively. The WWR of windows in the southern direction was varied as 5%, 10%, 20%, and 30%. The lower limit of WWR was set at 5% based on onsite building surveys conducted in Chakrata. Table 9.7 shows the impact of WWR on the annual heating energy demand and monetary saving potential for the three locations. Table 9.8 shows the impact of WWR on the annual carbon saving potential.

Table 9-7. Impact of WWR on annual heating and cooling energy demand and monetary saving potential

SOUTH-FACING WWR (%)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving potential ( )	HED (kWh)	Variation (%)	Saving potential ( )	HED (kWh)	Variation (%)	Saving potential ( )
5	1820	+1.6	-	2497	+1.3	-	2822	+1	-
10 (BASELINE)	1791	NA	NA	2465	NA	NA	2795	NA	NA
20	1739	-3	306	2404	-2.4	359	2744	-2	300
30	1692	**-5.5**	**583**	2370	**-4**	**560**	2696	**-3.5**	**583**

Table 9-8. Impact of WWR on annual carbon saving potential

SOUTH-FACING WWR (%)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)
5	1438	+1.6	-	1973	+1.3	-	2229	+1	-
10 (BASELINE)	1415	NA	NA	1947	NA	NA	2208	NA	NA
20	1374	-3	41	1899	-2.4	48	2168	-2	40
30	1337	**-5.5**	**78**	1872	**-4**	**75**	2130	**-3.5**	**78**

The effect of window size on HED is significant in the south orientation. South-facing windows with 30% WWR reduce annual HED by 3-6% compared to a 10% WWR and provides monetary and carbon saving potentials in the range of Rs.300-583 and 75-78 kg CO_2 eq., respectively. The impact of window size on HED is less significant in East, West, and North orientations.

Based on the above results, Table 9.9 shows the indicative WWR-wise performance improvement of buildings in Uttarakhand.

Table 9-9. Thermal performance improvement with different south-facing WWR

South Facing WWR (%)	Performance
10	Baseline
20	√
30	√√

9.6 Glazing type

The window's glazing type is another important feature that needs to be considered when designing the windows. Solar insolation is transmitted through the window's glazing in the form of short-wave radiation and absorbed by indoor objects. These objects reradiate in the form of long-wave radiation. The window's glazing is opaque to the long wave radiation, leading to the greenhouse effect. Therefore, the right choice of window glazing type is important for reducing the buildings' heating and cooling energy demand.

To demonstrate the effect of glazing type on HED, two glazing options, a single-glazed unit with 3 millimetre (mm) clear glass (U-value = 5.8 W/m^2K and solar heat gain coefficient (SHGC) = 0.87) and a double-glazing unit (U-value = 2.67 W/m^2K and SHGC = 0.74) with two 6 mm clear glass panels separated by a 12 mm air gap were considered for the simulation. The simulations were performed for the base case building with a south-facing window with a WWR of 10% in Mussoorie. Figure 9.9 shows the heat gain and loss from the different envelope components of a base case building for a typical winter day (22nd December) in Mussoorie. A 10% decrease in heat losses during the winter and gains during the summer through windows is observed when a double-glazed system is used instead of single-glazed windows.

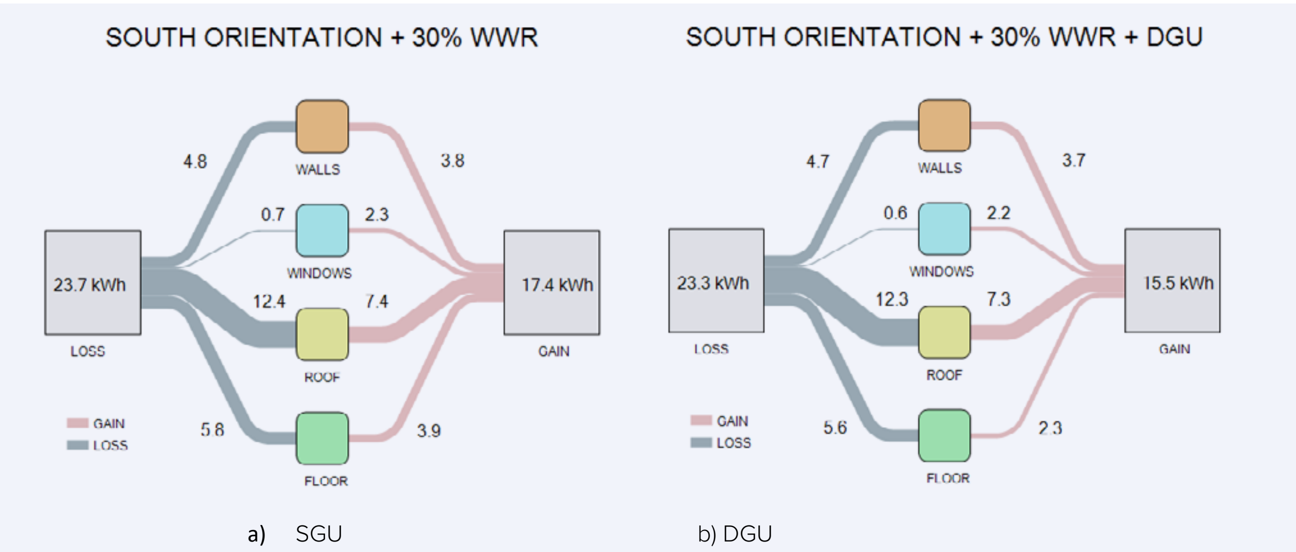


Figure 9-9. Comparison of heat loss and gain in (a) Single glazing unit windows and (b) double glazing unit windows for 30% WWR in Mussoorie on a peak winter day (22nd December)

Based on the simulation results, Table 9.10 shows buildings' indicative thermal performance improvement with the different window's glazing types for Uttarakhand.

Table 9-10. Thermal performance improvement with different window's glazing types

Window's glazing type	Performance
Single	Baseline
Double	√

Apart from double-glazed windows, there are other types of windows that can improve energy efficiency; the descriptions of alternative windows are as follows:

- **Low-emissivity (Low-E) windows:** These windows are coated with a thin layer of metallic oxide that reflects heat back, reducing heat loss in the winter and heat gain in the summer. For the cold climatic conditions low-E coating should be used inner side of the windows. This allows some of the sun's short-wave infrared energy to pass through the glass and helps in heating the indoor environment in the winter and allows the glass to reflect the interior long-wave heat energy back inside

- **Double and triple-pane gas filled windows:** These windows have two or three panes of glass with a layer of insulating gas (such as argon). The insulating gas helps to reduce heat transfer and improve energy efficiency

9.7 Daylighting

To maximise daylighting, designers should consider the following aspects when designing new buildings:

- Consider daylighting strategies that primarily use south-facing glass and secondarily incorporate north-facing glass windows.

- Verify that other exterior design elements or existing site features do not negatively affect the daylighting design.

- Make sure other building elements do not unintentionally shade glazing areas that are designed as daylighting elements.

- Consider the reflectance of the materials in front of the glazing areas. High reflectance can cause glare.

9.8 Wall assemblies

External walls form a major part of the building envelope. The walls gain and lose heat predominantly through conduction. A wall assembly with low thermal transmittance (U-value) will be conducive to lowering the building's heating or cooling energy demand and maintaining indoor thermal comfort. Figure 9.10 shows six wall assemblies chosen to demonstrate the effect of different walling materials on building's annual HED, monetary and carbon saving potential.

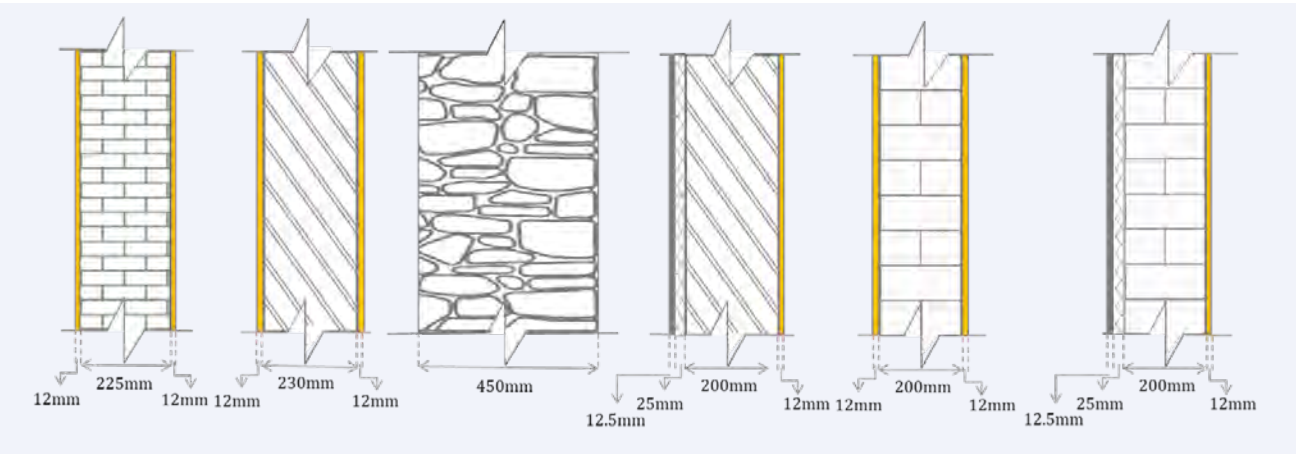


Figure 9-10. **Schematic of different wall assemblies (Insulation can be XPS panel, Polyurethane, Wood cladding, and Glass wool. U-value of the wall assembly will change with different insulating materials)**

Simulations were performed with the shown wall assemblies for the base case building model. Tables 9.11 and 9.12 present the impact of different wall assemblies on the annual HED, monetary and carbon saving potential in the three locations, considering a south-facing building with a WWR of 10% with single clear 3 mm glazing.

The AAC with insulation wall assembly reduces the annual HED by 5-6% over a brick-cement wall, which is predominantly being used in Uttarakhand and provides opportunity of annual monetary and carbon saving potential in the Range of Rs.807-1119 and 108-150 kg CO_2 eq. depending on the locations. The AAC with insulation wall assembly making process is presented in Appendix 3. Based on the above findings, Table 9.13 shows the indicative thermal performance improvement with different wall assembly types in Uttarakhand. Negative sign for Fly-Ash Brick wall shows that it performs poorly compared to the base case, i.e., Brick wall. This is due to high thermal transmittance value of Fly-Ash Brick wall compared to the Brick wall.

Table 9-11. **Impact of different wall assemblies on annual HED and monetary saving potential**

WALL TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving potential ( )	HED (kWh)	Variation (%)	Saving potential ( )	HED (kWh)	Variation (%)	Saving potential ( )
Brick Wall (2.1) (BASELINE)	2288	NA	NA	3006	NA	NA	3226	NA	NA
Brick + Insulation wall (0.74)	2199	-4	524	2895	-3.8	654	3105	-3.7	713
AAC wall (0.5)	2171	-5.1	689	2864	-5	836	3062	-4.7	966
AAC + insulation wall (0.34)	**2151**	**-6**	**807**	**2838**	**-5.8**	**990**	**3036**	**-5.2**	**1119**
Fly-ash Brick wall (2.3)	2314	+1.2	-153	3037	+1	-183	3258	+0.8	-188
Random Rubble Masonry wall (1.7)	2260	-1.2	165	2966	-1.1	236	3190	-1	212

Table 9-12. **Impact of different wall assemblies on annual carbon saving potential**

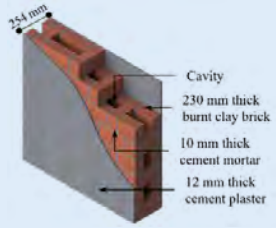
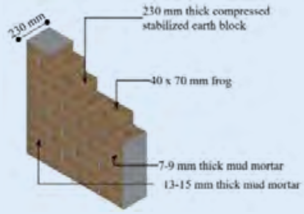
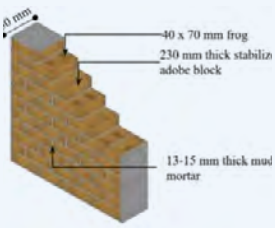
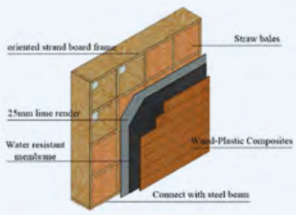
WALL TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)
Brick Wall (2.1) (BASELINE)	1808	NA	NA	2375	NA	NA	2549	NA	NA
Brick + Insulation wall (0.74)	1737	-4	70	2287	-3.8	88	2453	-3.7	96
AAC wall (0.5)	1715	-5.1	92	2263	-5	112	2419	-4.7	130
AAC + insulation wall (0.34)	**1699**	**-6**	**108**	**2242**	**-5.8**	**133**	**2398**	**-5.2**	**150**
Fly-ash Brick wall (2.3)	1828	+1.2	-21	2399	+1	-24	2574	+0.8	-25
Random Rubble Masonry wall (1.7)	1785	-1.2	22	2343	-1.1	32	2520	-1	28

Table 9-13. **Thermal performance improvement with different wall assembly types**

Wall Type (U-value – W/m²K)	Performance
Brick Wall (2.1)	Baseline
Random Rubble Masonry wall (1.7)	√
Brick with Insulation wall (0.7)	√√
AAC Wall (0.5)	√√√
AAC with insulation Wall (0.34)	√√√√
Fly-Ash Brick Wall (2.3)	-√

Apart from the wall assemblies shown in Figure 9.10 there are alternative solutions for wall assemblies with thermal transmittance values lower than those of the brick-cement and RCC wall assembly (business-as-usual construction practice in Uttarakhand) that can be used for the building envelope. Table 9.14 provides information on the thermal transmittance of alternative wall assembly types.

Table 9-14. Alternative wall assembly types and their thermal transmittance values

Wall Type	Thickness	U-value (W/m²K)	Image
Rat-trap bond wall	230 mm thick burnt clay brick + 12 mm thick interior and exterior plaster	1.67	* 
Glass fiber reinforced gypsum panel	15 mm thick GFRP Panel + 94 mm thick cavity	1.56	* 
Compressed Stabilized Earth block wall	230 mm thick compressed stabilized earth block + 13-15 mm thick mud mortar	1.59	* 
Stabilized adobe	230 mm thick stabilized adobe block + 13-15 mm thick mud mortar	1.5	* 
Rammed earth construction	200-250 mm	0.7	** 
Straw bale construction	255-350 mm	0.2	*** 

* https://journals.squ.edu.om/index.php/tjer/article/view/4669/3384
**https://www.firstinarchitecture.co.uk/rammed-earth-construction/
***https://www.researchgate.net/publication/342662121_Multi-case_study_on_the_carbon_emissions_of_the_ecological_dwellings_in_cold_regions_of_China_over_the_whole_life_cycle

9.9 Roof assemblies

The roof receives the largest amount of solar radiation annually. Hence, it is important to account for the heat loss and gain through the roof, and an appropriate design helps reduce the HED in cold climates and facilitates the monetary and carbon saving. Figure 9.11 shows the roof assemblies chosen to demonstrate the impact on HED, monetary and carbon saving potential.

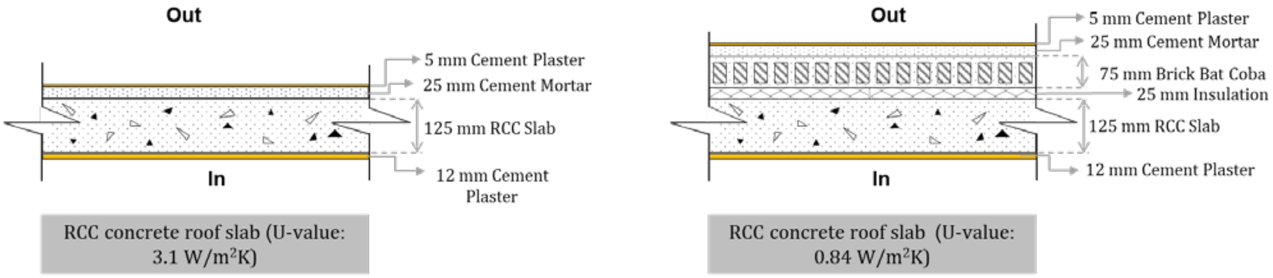


Figure 9-11. **Schematic of different roof assemblies (Insulation can be XPS panel, Polyurethane, Wood cladding, and Glass wool. U-value of the wall assembly will change with different insulating materials)**

Simulations were performed with the shown roof assemblies using the base case building model for the three locations. Tables 9.15 and 9.16 present the impact of roof assembly type on the HED, monetary and carbon saving potential considering a south-facing (fenestrations) brick building with a WWR of 10% with single clear 3 mm glazing. It can be observed from the table that an RCC slab with insulation roof assembly reduces the annual heating energy demand by 11-13% over an RCC roof building and provides monetary and carbon saving potential in the range of Rs.1349-1932 and 181-259 kg CO_2 eq. depending on the locations.

Table 9-15. **Impact of roof assemblies on the annual heat energy demand and monetary saving potential**

ROOF TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving potential ( )	HED (kWh)	Variation (%)	Saving potential ( )	HED (kWh)	Variation (%)	Saving potential ( )
RCC (3.1) (BASELINE)	1791	NA	NA	2465	NA	NA	2795	NA	NA
RCC + insulation (outside) (0.84)	**1562**	-13	1349	2137	-13	1932	2474	-11	1891

Table 9-16. **Impact of roof assemblies on the annual carbon saving potential**

ROOF TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)
RCC (3.1) (BASELINE)	1415	NA	NA	1947	NA	NA	2208	NA	NA
RCC + insulation (outside) (0.84)	1234	**-13**	**181**	1688	**-13**	**259**	1954	**-11**	254

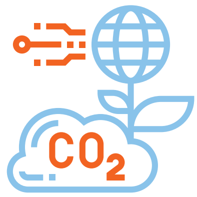
Based on the above findings, Table 9.17 shows the indicative thermal performance improvement with different roof assembly types in Uttarakhand.

Table 9-17. **Thermal performance improvement with different roof assembly types**

Roof Assembly Type (U-value – W/m²K)	Performance
RCC Roof (3.1)	Baseline
RCC Roof with Insulation on Exterior Surface (0.84)	√

9.10 Infiltration

Air gaps between windows and doors are the reasons for infiltration. Infiltration causes overventilation, entry of contaminants or odours, discomfort, and unnecessary wastage of energy. According to EN ISO 52016-1:201725, residential buildings can be classified into three categories for their air tightness at a pressure difference of 50 pascals between the indoor and outdoor air: low with 1.5 ACH, medium with 0.8 ACH, and high with 0.5 ACH. Although it is difficult to measure and ensure a minimum infiltration rate during the operation of buildings, minimising the infiltration rate in buildings can reduce the heating and cooling energy demand. Tables 9.18 and 9.19 demonstrates the impact of air tightness on annual HED, monetary and carbon saving potential for the base case house. It can be inferred from the tables that HED and associated carbon emission decreases with a decrease in infiltration in the three locations. There is an 11-14% reduction in the annual HED. Reduction in annual heating energy demand creates annual monetary and carbon saving potential in the range of Rs.1473-1832 and 197-245 kg CO_2 eq. depending on the locations. This highlights the potential for energy demand reduction, monetary and carbon saving potential through appropriate weather sealing and upkeep of fenestration.



Minimizing infiltration can reduce annual HED up to 11-14% and create annual monetary and carbon saving potential in the range of Rs.1473-1832 and 197-245 kg CO_2 eq.

Table 9-18. **Impact of air tightness on annual HED and monetary saving potential**

AIR TIGHTNESS (ach)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	VARIATION (%)	Saving potential ( )	HED (kWh)	VARIATION (%)	Saving potential ( )	HED (kWh)	VARIATION (%)	Saving potential ( )
POOR (1.5) (BASELINE)	1790	NA	NA	2464	NA	NA	2794	NA	NA
MODERATE (0.8)	1594	-11	1154	2228	-9.5	1390	2550	-8.7	1437
GOOD (0.5)	1540	-14	1473	2164	-12	1767	2483	-11	1832

Table 9-19. **Impact of air tightness on annual carbon saving potential**

AIR TIGHTNESS (ach)	MUSSOORIE			CHAKRATA			JOSHIMATH		
		VARIATION (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	VARIATION (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	VARIATION (%)	Carbon Saving potential (kg CO_2 eq.)
POOR (1.5) (BASELINE)	1414	NA	NA	1947	NA	NA	2207	NA	NA
MODERATE (0.8)	1259	-11	155	1760	-9.5	187	2015	-8.7	193
GOOD (0.5)	1217	-14	197	1710	-12	237	1962	-11	245

Based on the above findings Table 9.20 shows the performance of the different infiltration rates for Uttarakhand.

Table 9-20. **Performance of the different air tightness**

Air Tightness (ACH)	Performance
1.5	Baseline
0.8	√
0.5	√√

Though it is difficult to ensure compliance check for specified ACH, Table 9.21 shows some practical strategies to minimise the infiltration into built environment and simple procedure to measure and prevent unintentional infiltration.

Table 9-21. **Measurement procedure and prevention strategies to limit infiltration into the building**

Measurement procedure		Prevention strategies	
Blower door test	It can be used to measure the air infiltration rate in building. It involves creating a pressure differential between the interior and exterior of the buildings and measuring the rate of air leakage	**Seal air leaks**	Focus on areas where there are gaps, cracks or penetrations (such as around windows, doors, electrical outlets and plumbing) and seal air leaks using weatherstripping and foam sealants
Smoke test	This test involves using a smoke machine to generate smoke, which is then blown into the room to identify areas where the smoke escapes	**High performance windows and doors**	Insulate frames of windows and doors to reduce air infiltration
Thermal imaging	Thermal imaging cameras can be used around windows, doors and utility penetrations to identify areas where air is leaking into the building	**Integration of insulation with building envelope**	Proper insulation helps to reduce air infiltration through wall and roof surfaces

9.11 Natural ventilation

Natural ventilation is considered good during the summer season of Uttarakhand. Naturally ventilated building designs have been widely adopted because they increase user satisfaction and occupants' wellbeing while reducing energy consumption. In the winter, the wind direction affects the heat loss from the building, while in the summer, the change of wind direction and speed affects the building's ventilation and indoor air circulation. Incorporating provisions for natural ventilation into building design is very site-specific, and this can be done with the help of a wind rose diagram of the site. For illustration purposes, wind rose diagrams are presented for Mussoorie for the winter months (December to February) (Figure 9.12 (a)) and the entire year (Figure 9.12 (b)).

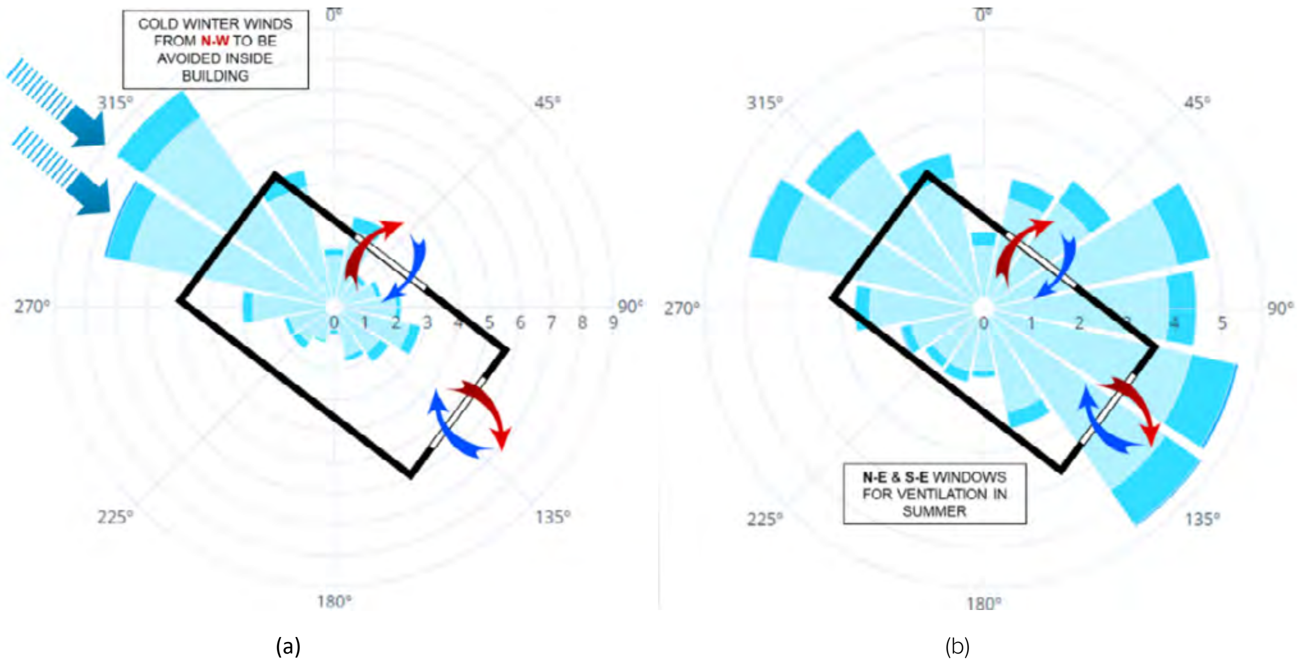


Figure 9-12. **(a) Winter and (b) annual wind rose diagrams for Mussoorie**

The wind rose diagrams suggest that orienting windows in the northwest direction should be avoided to minimise cold winds entering the building in the winter in Mussoorie. Windows should be provided in the northeast and southeast directions to utilise natural ventilation in the summer and transition months.

9.11.1 Natural ventilation potential

The natural ventilation potential (NVP) of a place can be assessed by setting a cut-off range of 22-32 °C for the outdoor DBT and analysing the outdoor temperature throughout the year. For illustration purposes, the NVP potential of Mussoorie is shown in Figure 9.13. Natural ventilation is preferable from April to August from 10:00 am to 8`00 pm in Mussoorie. The annual NVP hours for Mussoorie are 860 hours. To utilize the NVP the minimum window-to-floor ratio (WFR) is defined as 8.33% for the cold climate in ENS[22]. Multiplication of the minimum WFR with carpet area, provides the value of minimum openable area to avail the benefits of natural ventilation in the summer season.

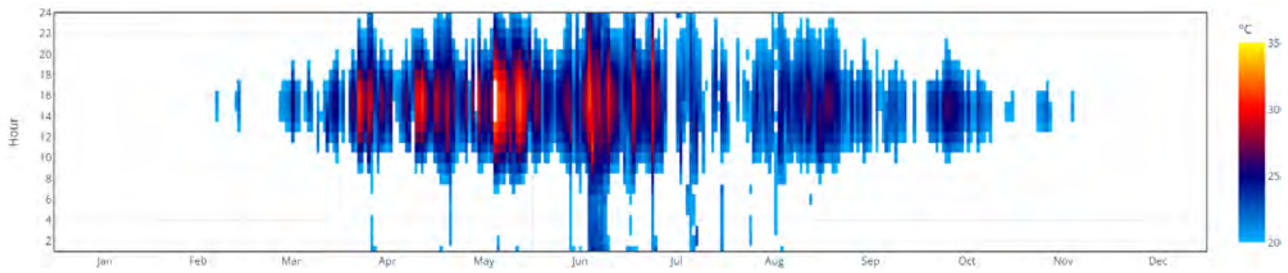


Figure 9-13. **Annual hourly NVP for Mussoorie with DBT range of 22-32 °C**

22 https://www.beepindia.org/wp-content/uploads/2020/06/Eco-Niwas-Samhita-2018_1.pdf

9.12 Incremental impact of energy conservation measures on HED, monetary and carbon saving potentials

In this section the incremental impact of identified energy conservation measures for building envelope such as building orientation, WWR, glazing types, wall assembly, roof assembly and infiltration have been analysed. Further, the incremental impact of energy conservation measures on monetary and carbon saving potentials have also been presented. Incremental impact of energy conservation measures for the base case house is shown in Figure 9.14.

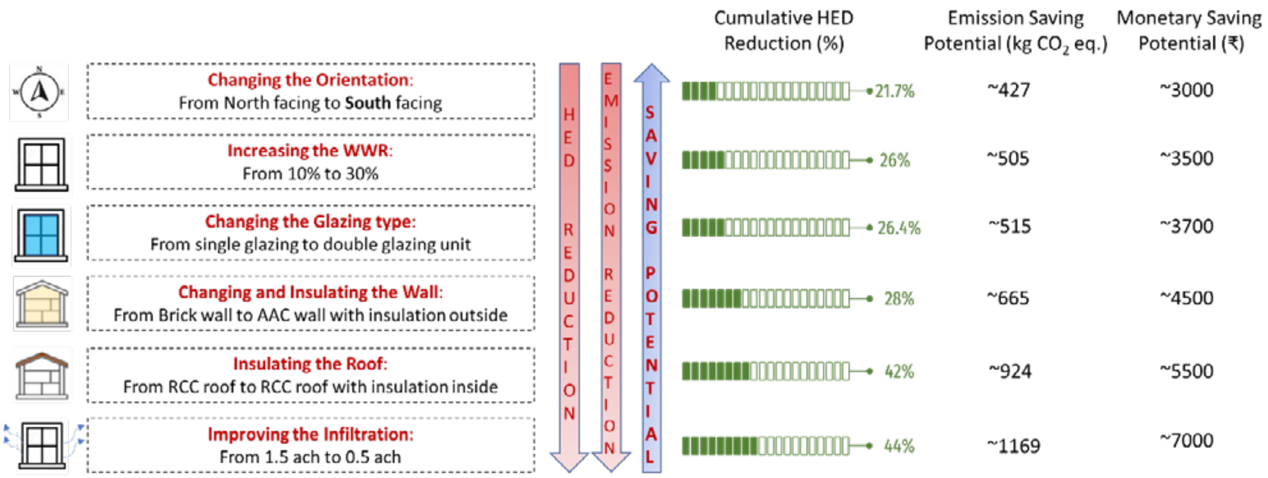


Figure 9-14. **Schematic of incremental impact of energy conservation measures on HED reduction, emission reduction and monetary saving potential**

It can be observed from figure that if all the identified energy conservation measures are adopted during the design phase of the building then approximately 44% reduction in HED can be achieved, additionally it helps in creating annual monetary and carbon saving potential of approximately Rs. 7000 and 1169 kg CO_2 eq. The potential of savings on electricity bills can cover the upfront costs of implementing energy conservation measures after certain time period.

Given the significance of the identified energy conservation measures in reducing HED and increasing monetary and carbon saving potential, it is crucial to make informed decisions regarding their implementation during the building design phase. This approach allows for the integration of energy-saving features into the building's design, resulting in more efficient energy use and lower costs over the long term. By considering these measures early on, building owners and designers can create sustainable buildings that are cost-effective and environmentally friendly.

Through a simulation-based study, this chapter showed the comparative thermal performance analysis of multiple building envelope-related parameters and associated monetary and carbon saving potentials. The simulation results indicated that south or southwest building orientations, higher aspect ratios of buildings along the sun path, higher WWR towards the south or southwest direction, efficient window glazing types, low thermal transmittance values of the wall and roof assemblies, addition of insulating materials, and low infiltration rates help in maintaining thermal comfort and reducing HED in Uttarakhand. These results provide the foundation for a pathway to designing energy-efficient, climate-resilient, and sustainable buildings, keeping in mind the prevalent use of contemporary construction materials and modern construction practices.

If all the identified energy conservation measures are adopted during the design phase of the building, then approximately 44% reduction in HED can be achieved, additionally it helps in creating annual monetary and carbon saving potential of approximately Rs. 7000 and 1169 kg CO_2 eq.

10 Solar energy utilisation potential

The National Solar Mission (NSM) aims to install 100 gigawatts (GW) of grid-connected solar power plants by 2022 (installed capacity has reached around 61.97 GW as on 30th November, 2022), which is in line with India's Intended Nationally Determined Contributions (INDCs) target to achieve 40% cumulative power installed capacity from non-fossil fuel-based energy resources and reduce the emission intensity of its gross domestic product (GDP) by 33% from the 2005 level by 2030. Uttarakhand, richly endowed with solar insolation, can significantly contribute to India's NSM and INDCs. The entire state gets about 4.5-5.5 kWh/m^2 solar insolation. Figure 10.1 shows Uttarakhand's solar PV electricity generation potential. The map reflects the average yearly totals of electricity production from a 1 kW-peak (kWp) grid-connected solar PV power plant, calculated over the period of 1999-2018. The calculation considers solar radiation, air temperature, and terrain to simulate the energy conversion and losses in the PV modules.

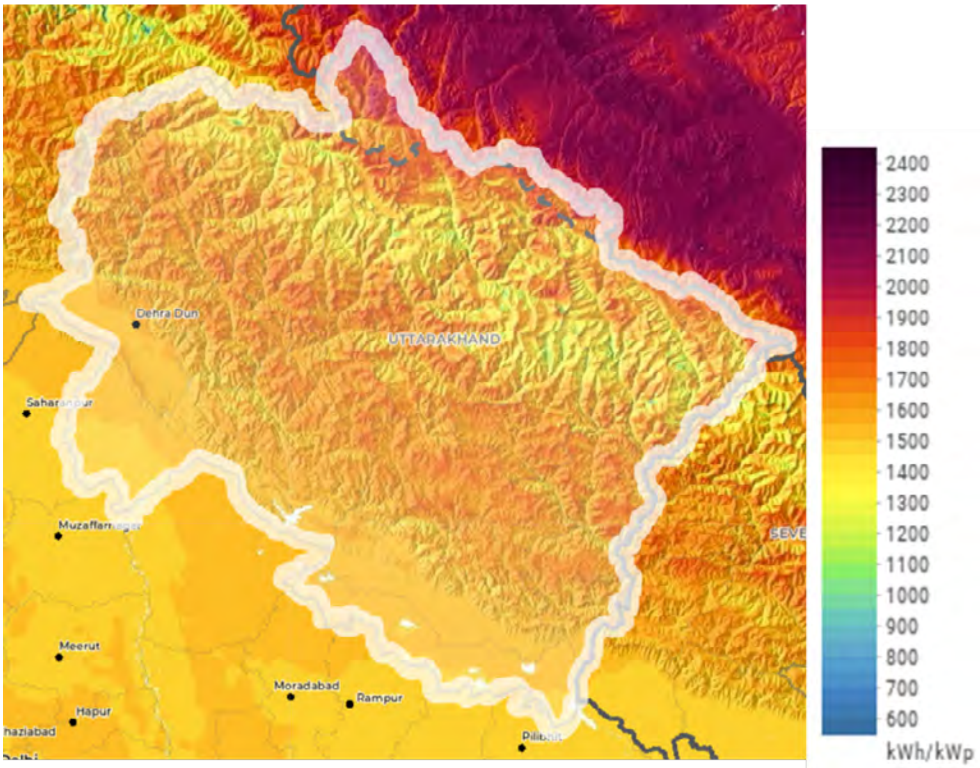


Figure 10-1. Solar PV power potential map of Uttarakhand[23]

Promoting solar PV to fulfil Uttarakhand's power demand has become more significant, considering the gap between the electricity supply and demand in the state. A recent survey carried out by UPCL reports that at present, against the demand of 40 million units

23 Group, W.B. (2018). Global Solar Atlas. Retrieved from https://globalsolaratlas.info/support/about

per day of electricity, the supply is 31 million units per day, and the supply-demand mismatch is being managed by power cuts of 1-6 hours. At the same time, there is still abundant untapped potential to generate solar power using unutilised space on rooftops and around buildings.

To illustrate the potential of solar PV, a study has been conducted on solar rooftop power generation and residential energy consumption in the three selected locations. The average daily solar radiation for Mussoorie, New Tehri, and Chakrata is 5.5, 5.7, and 5.1 kWh/m^2, respectively. Table 10.1 gives the winter PV power output for December and January and the average winter energy consumption of the surveyed houses in these locations.

Table 10-1. PV power output and energy consumption for December and January

Location	PV power output in winter (kWh)	Energy consumption in winter (kWh)
Chakrata	227	40
Mussoorie	279	310
New Tehri	277	110

10.1 Policy landscape to promote solar PV

The Uttarakhand and central governments have introduced various policies and programmes to promote solar energy in the state. The key policies that drive the solar energy sector, their intervention areas, and the relevant implementing authority are summarised in Table 10.2.

Table 10-2. Policies to promote solar energy in Uttarakhand

Area of intervention	Name of policy/ programme/act/rules	Recommended actions for low-carbon development in existing policy landscape	Implementing authorities
Solar (LED) lighting systems	• Uttarakhand Solar Energy Policy • Vision 2030 • 24×7 Power for all UAPCC	• Install solar-powered LED lighting systems in all residential buildings – mandatory for all government-funded housing projects. • Promote and install solar-powered LEDs – UREDA under the Solar Energy Policy. • Encourage MSMEs to provide solar LED lighting.	• UDD • UPCL • UREDA • PTCUL • ULBs
Solar-powered (off-grid) heating systems	• Uttarakhand Solar Energy Policy • UAPCC • Smart City Programme	Mainstream and promote solar-powered (off-grid) residential heating systems (pilot projects).	
Rooftop solar PV	• Uttarakhand Renewable Energy Policy • Vision 2030 • Awas Niti • Smart City Programme	Make these systems mandatory in all government-funded housing projects and projects under state/central schemes like PMAY-U & AMRUT.	
Solar thermal	Solar thermal scheme	• Solar water heating system • Solar cooking system • Solar steam cooking system • Parabolic concentrator	

The state has a huge potential for solar power generation, estimated at 16,800 megawatts (MW), out of which approximately 2% has been tapped. While the state has a policy to mainstream solar energy by installing large-scale solar power plants, there is still no focus on off-grid and building-integrated solar power systems. It is essential for the authorities to promote rooftop solar PV systems, not only for heating water but also to power heating systems, lighting, and equipment. This would also complement the UAPCC implementation.

11 Heating Appliances

11.1 Space heating

As observed in the household survey, electrical heating appliances are the major determinants of buildings' HED in Uttarakhand. In the state, people use an energy mix to meet their heating and domestic water heating requirements (see Chapter 6). The electricity consumption of the households depends on the income group and building envelope type and orientation. Wood is the preferred fuel for space heating, cooking, and water heating due to its abundance and availability in the Uttarakhand region. The reliance on wood is also due to the low reliability of the electricity supply.

In cold climates, the heating equipment causes significant heating energy consumption, especially when it is not energy-efficient. In Uttarakhand, wood, infrared radiators, blowers, oil-filled heaters, and all-weather inverter air conditioners (ACs) are generally used for heating purposes. Table 11.1 shows the performance of the different heating methods based on their carbon dioxide (CO_2) emission potential.

Table 11-1. **Heating equipment performance based on CO_2 emissions**

Type of Space Heating methods	Performance
Fuel-wood	Baseline
Infrared radiators	√
Blowers	√√
Oil-filled heaters	√√√
All weather Inverter ACs.	√√√√

Heat pumps are now being promoted as an energy-efficient heating option in cold regions. Heat pumps offer an energy-efficient alternative to infrared radiators, blowers, oil-filled heaters, and inverter ACs. Heat pumps use electricity to transfer heat from cool spaces to warm spaces, making the cool place cooler and warm place warmer[24]. During the winter, heat pumps move heat from the cool outdoors into the warm indoor environment, and during the summer, heat pumps move heat from the indoor environment to the outdoors.

Three-star, four-star, and five-star rated BEE heat pump systems have been compared to study the corresponding potential reduction in HED in Uttarakhand. The seasonal efficiency ratio (SEER) of the 3-star rated heat pump is taken as 3.4, 3.7 for a 4-star, and 4 for a 5-star[25]. Tables 11.2 and 11.3 show the variation in HED, monetary and carbon saving potential with respect to different star ratings of heat pump for Mussoorie, Chakrata and Joshimath. The reduction of HED from a 3-star rated appliance to a 5-star rated appliance is up to 8% for 12 hours of operation which results in monetary and carbon saving potential in the range of Rs.2500-3800 and 416-510 kg CO_2 eq. depending on the locations.

24 https://www.energy.gov/energysaver/heat-pump-systems (Last accessed on 1st Nov. 2022)
25 BEE (Bureau of Energy Efficiency. (2022) Light Commercial Air conditioners (Issue March)

Table 11-2. Impact of BEE star-rated heat pump on annual heating energy demand and monetary saving potential

Heat pump (SEER) (12 hrs Operation)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving potential ( )	HED (kWh)	Variation (%)	Saving potential ( )	HED (kWh)	Variation (%)	Saving potential ( )
BASELINE	2288	NA	NA	3006	NA	NA	3226	NA	NA
3-star (3.4)	1945	15	2020	2586	14	2474	2840	12	2274
4-star (3.7)	1830	20	2698	2435	19	3363	2646	18	3416
5-star (4.0)	1762	23	3098	2375	21	3717	2580	20	3805

Table 11-3. Impact of BEE star-rated heat pump on annual carbon saving potential

Heat pump (SEER) (12 hrs Operation)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving potential (kg CO_2 eq.)
BASELINE	1808	NA	NA	2375	NA	NA	2549	NA	NA
3-star (3.4)	1537	-15	271	2043	-14	332	2244	-12	305
4-star (3.7)	1446	-20	362	1924	-19	451	2090	-18	458
5-star (4.0)	**1392**	-23	**416**	**1876**	-21	**498**	**2038**	-20	**510**

Based on the above simulation results, Table 11.4 shows the indicative performance improvement of the different BEE rated heat pumps for Uttarakhand.

Table 11-4. Performance of heat pump with different star ratings

BEE star rated Heat Pump (SEER)	Performance
3-star (3.4)	Baseline
4-star (3.7)	√
5-star (4.0)	√√

11.2 Water heating

In Uttarakhand, water heating is an indispensable part of life. Various methods are used for this, such as fuel wood, LPG, electric geysers, and solar water heaters. Table 11.5 shows the performance of different water heating methods based on their potential for CO_2 emissions.

Table 11-5. Water heating equipment performance based on CO_2 emissions

Type of water heating	Performance
Fuel-wood	Baseline
LPG	√
Electric geysers	√√
Solar water heaters	√√√

Heating is a crucial necessity in Uttarakhand. The majority of the population uses wood and oil-filled radiators for heating, which generate a significant amount of CO_2 equivalent (CO_2eq.) emissions and lead to a poor outdoor air quality index (AQI) and low indoor air quality (IAQ). Energy-efficient equipment such as heat pumps are costly and unaffordable for most people. Thus, the focus should be shifted towards large-scale deployment of energy-efficient heat pumps with support via government subsidies.

For water heating, there needs to be a shift away from using fuel-wood, LPG, and electric geysers and towards using solar water heaters. The current relevant policies for large-scale deployment of solar water heaters are mentioned in Chapter 5. There is a need to implement those policies at a faster pace and create awareness of using low-cost and low energy-intensive space and water heating appliances.

12. Key takeaways, conclusion and way forward

Uttarakhand has remained a low carbon emission state due to the absence of fossil fuel-based power plants, relatively low usage of transport vehicles, low emissions from the building sector, and an abundance of forest cover. Currently, Uttarakhand is in the midst of urbanisation, with an urbanisation growth rate of 30.2%[26]. Rapid urbanisation has led to unprecedented demand for housing in some parts of Uttarakhand. Increasing housing demand, an influx of contemporary construction materials, non-scientific construction practices, and higher aspirations for thermal comfort are now increasing the CO_2e emissions from the building sector. Since most of the housing that is going to be needed in Uttarakhand is yet to be built, it is right time to intervene in the building sector to avoid the lock-in of energy inefficiencies and transform the sector from a high energy-intensive sector to a low-carbon, climate-responsive, and sustainable sector.

To drive decarbonisation in the building sector, which is still at is nascent stage in Uttarakhand, a detailed study has been conducted on the international best construction practices and policies followed that can be replicated in Uttarakhand, national policies that can stimulate the decarbonisation of the building sector, science-based building envelope design intervention, scope of on-/offsite RE integration into buildings, and energy-efficient appliances. The key takeaways from the study are divided below into the main areas of inquiry:

International Best Practices

Learnings from the international best construction practices have been categorised into two parts: policy implementation and best construction practices.

Policy implementation

- Establishment of building codes and design guidelines defining building size thresholds
- Establishment of energy-efficient guidelines defining energy system requirements
- Development of a compliance check mechanism for building codes and energy-efficient appliance standards
- Capacity building and training programmes for professionals

Best construction practices

- Thermal transmittance values should be as low as possible for the building envelopes, such as external walls, roofs, and floors
- Building orientation should be towards the south to maximise solar radiation
- Adjustable shading should be used to minimise or maximise solar radiation, depending on the season
- Proper insulation should be used in the building envelope
- Both active and passive systems should be used for space heating purposes
- Solar technologies should be used for water heating, space heating, cooking, lighting, etc.
- Energy-efficient domestic appliances should be used

26 B.R. Pant and R. Chand, (2020). Characteristics of Urban Centres and Urbanization in Uttarakhand, Journal of Urban and Regional Studies on Contemporary India, 6(2).

National policies

The key intervention areas identified in the national policy analysis are as follows:

- Layout for climate-resilient and climate-responsive building design
- Low-carbon building construction materials
- Building code integration into building bye-laws
- Adoption of green ratings or efficiency labelling for buildings
- Solar space and water heating systems
- Rooftop solar PV
- Energy-efficient household appliances
- Mainstreaming of thermal comfort
- Capacity building and training

Building envelope

- Buildings should be oriented in the south or southwest direction to enhance heat gain from the building façade
- The WWR should be a maximum of 30% on the south façade and 10-30% in other directions, depending on the daylighting requirement
- The building aspect ratio should be a maximum of 3:1 and a minimum of 1:1 in the east-west direction
- The thermal transmittance value (U-value) of the wall assemblies should be in the range of 0.7-1.4 W/m^2K
- The thermal transmittance value (U-value) of the roof assemblies should be in the range of 1.36-2 W/m^2K
- Thermal mass should be added to the construction using locally available materials
- Infiltration in buildings should comply with a maximum 0.5 ACH. Though it is difficult to ensure, infiltration can be minimized through integrating insulation, weatherstripping of windows and doors and regular maintenance.
- Natural ventilation should be promoted when the outdoor temperature falls in the range of 22-32 °C

Space heating and water heating appliances

- Heat pump usage should be mainstreamed for space heating
- Energy-efficient heating systems such as energy-efficient oil-filled radiators should be promoted
- The use of energy-efficient electric geysers and solar water heaters such as flat plate collectors should be mainstreamed for water heating

Solar energy utilisation potential

- Uttarakhand gets an average of 4.5-5.5 kWh/m2 solar insolation. Considering the significant potential of solar power generation in Uttarakhand, the following solar technologies should be extensively promoted:
- Building-integrated solar PV
- Solar LED lighting
- Solar integrated heating systems
- Solar thermal systems (water heating and cooking)

12.1 Conclusion

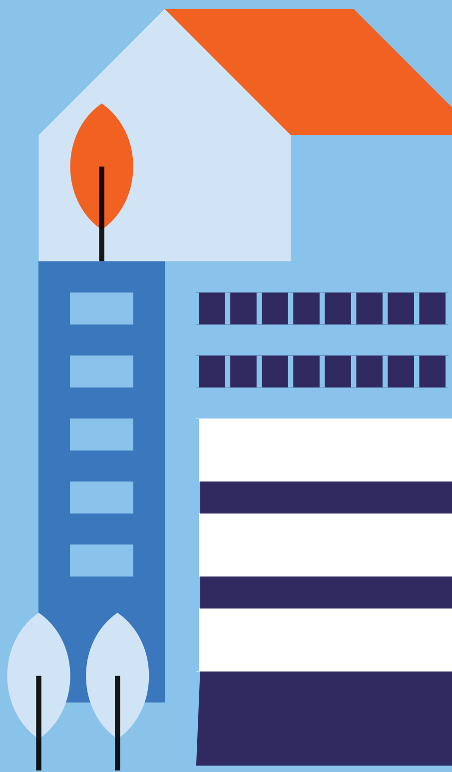
Energy efficiency is the first pillar of the transition in the building sector in Uttarakhand and the larger IHR. As this report highlighted, there is enormous scope for efficiency gains from improved building envelope design, energy-efficient appliances, and low-carbon building construction materials. Future energy demand in the building sector will depend on the efficiency of energy-consuming equipment and the building envelope.

The lifetime of the building stock is typically very long, and the stock is expanding rapidly in the Uttarakhand region. To decarbonise the building sector, mandatory zero carbon-ready building energy codes should be used at least for government buildings in Uttarakhand. Moreover, there is a need to introduce a mechanism for retrofitting existing buildings.

Electrification and switching to low emissions fuels is the second pillar of the transition in the building sector. As this report highlighted, most of the population in Uttarakhand uses wood and energy-inefficient appliances for space heating, water heating, and cooking. There is a need to phase out the use of wood and fossil fuels for cooking and heating. RE-based electricity should become the principal source of energy for decarbonising heating, with high-efficiency electric heat pumps becoming the primary technology choice. Improved biomass cookstoves (ICS) can play a major role in ensuring that the poorest (mainly in rural areas) can use affordable and readily available fuel and contribute to climate change mitigation.

Consumer behaviour change can play an important role in moderating the building sector's energy demand, specifically in space heating and air conditioning—e.g. adjusting thermostats to 19-20 °C in the winter and air conditioning to a maximum of 24 °C in the summer.

The relatively high upfront cost of key technologies to reduce direct emissions and improve energy efficiency, such as heat pumps, insulation, and retrofits, creates economic barriers to their adoption. Therefore, to keep moving forward on the decarbonisation path, Uttarakhand requires a large increase in clean energy investment. Investment in low-emission fuels, biofuels, and green hydrogen should be ramped up. Investment in renewable energy deployment, electricity grids, and solar PV integration with buildings should also be increased to move towards the net zero path in Uttarakhand.



The shortage of skilled labour in clean energy construction projects is a major hindrance to decarbonisation. There is a need to advocate strategic and proactive labour policies to train the workforce needed for the rapid expansion of clean energy technologies. Training and skilling entail long processes, and there is a need to establish partnerships between government, companies, labour organisations, academia, and training institutions to fulfil the future needs of the workforce.

The guidelines presented in this report have been developed in an easy-to-apply format, which requires simple calculations based on the inputs and tick boxes on the options provided by the architects/designers. Although the focus of this study was Uttarakhand, the steps presented in this report to mainstream the low-carbon development of the residential sector are equally applicable to other cold regions in the Himalayan ecosystem, with minor modifications and additions.

In conclusion, the performance-based recommendations, the user-friendly format and adaptable nature of the guidelines outlined in this report offer practical solutions for promoting low-carbon residential development not only in Uttarakhand but also in other cold regions of the Himalayan ecosystem.

12.2 Way forward

The IHR has a very fragile ecosystem, and if not developed carefully, there will be a lock-in of energy inefficiency and increased GHG emissions, which will aggravate the existing environmental deterioration in the region. Through the study on low-carbon and sustainable building infrastructure in Uttarakhand, the following challenges and new areas of investigation have been identified:

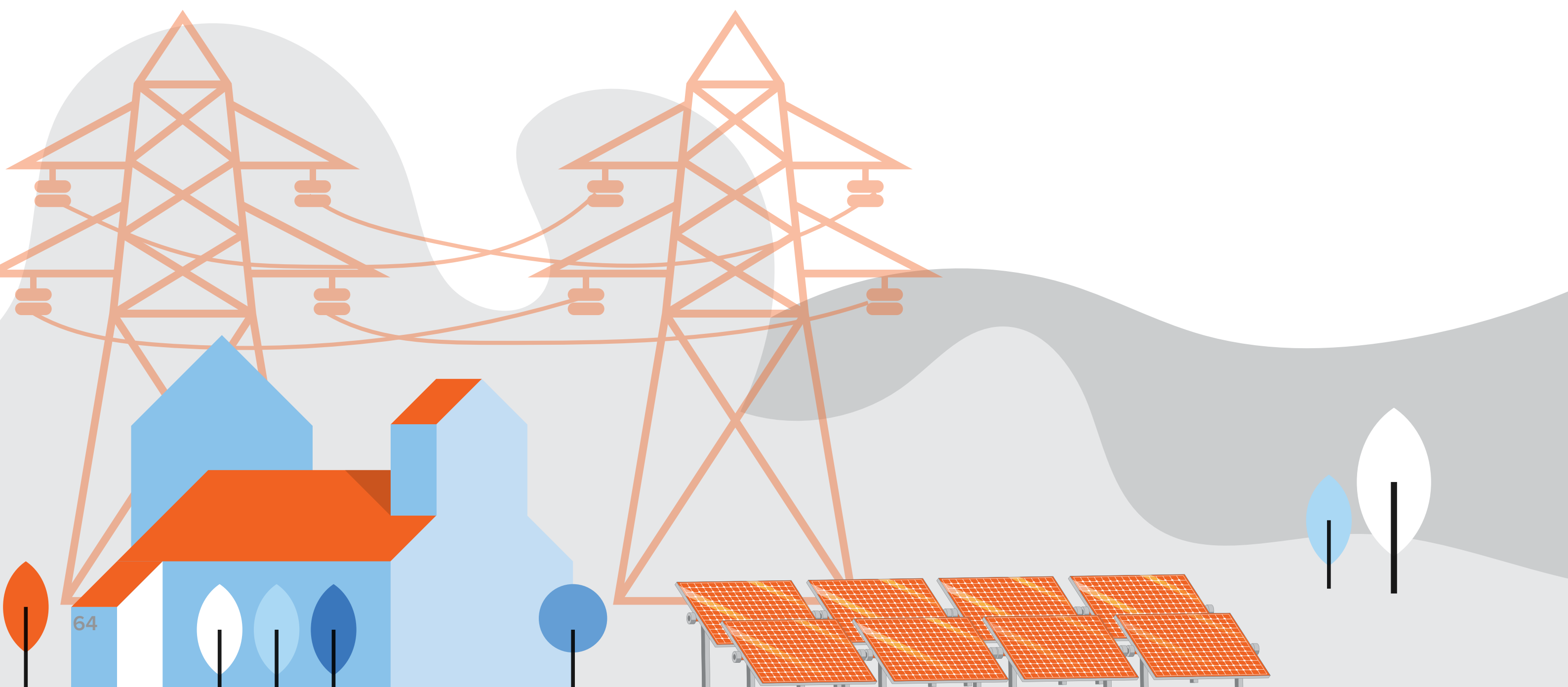
Climate reclassification – At present, Uttarakhand is classified as having a cold climate. While conducting this study, it was discovered that neither the landscape nor the climate of Uttarakhand is uniform. Climatic conditions of Uttarakhand range from composite to very cold, and to implement climate-wise building construction practices, it is essential to properly reclassify the climatic conditions of Uttarakhand.

Integration of findings of these guidelines into building bye-laws – The recommendations outlined in this guidelines report can be seamlessly integrated into building bye-laws, resulting in enhanced code compliance and benchmarking for buildings.

Mechanism to ensure code compliance – Analysis of international best practices revealed that emphasis should be placed on ensuring compliance checks. Uttarakhand currently has no compliance check mechanism to ensure energy-efficient building construction. Therefore, it is recommended that Uttarakhand develop such a mechanism to ensure compliance checks.

Integration of embodied carbon aspect into building bye-laws – When integrating the energy-efficient building codes into the building bye-laws, the Uttarakhand government should also direct municipal officials to document the embodied carbon of construction materials and define structural design with quantities of cement and steel. Inventory of construction materials with embodied carbon help contractor or building designers to choose the best available low-carbon alternative materials.

Benchmarking of Uttarakhand's building sector – There is mixed fuel use in Uttarakhand's buildings to meet energy demand, which hinders the normative building benchmarking. A state-led benchmarking programme is needed to increase awareness of building energy performance, as well as highlight opportunities to improve building efficiency.



Appendices

Appendix 1:
A Survey-based Study to analyse the thermal performance of buildings in the cold climate of Uttarakhand

A.1.1. Approach

Two levels of survey were conducted, viz., coarse grain and fine grain. Coarse gain field surveys were conducted in February and March 2020 in over 100 residences located across the urban settlements identified in the previous phases. This door-to-door survey comprised of two types of questionnaires focusing on the following concepts– (a) appliance ownership and (b) thermal comfort and adaptation. As a first step, the questionnaires were pilot tested for reliability through on-site random sampling. Architects were trained to carry out the surveys. The surveys were accompanied by observational documentation of spatial type, built-form, architectural character, construction materials, and systems. Besides, on-the-spot measurements of outdoor-indoor thermal conditions including T_a, T_g, and RH. The primary outcome of this phase was the thermal performance, comfort, and energy demand profiling of the representative residential buildings.

Fine grain field survey was conducted to study the thermal performance and energy consumption of urban residential buildings made with new emerging materials. The seasonal and annual thermal performance and energy consumption variation is studied through real-time field measurements. The indoor-outdoor temperature, humidity, and energy (kWh) are measured for this purpose in six residential buildings located in the urban settlements of Mussoorie. The six residential buildings are chosen from different income groups

A.1.2. Coarse grain survey

A.1.2.1 Representative locations for coarse grain survey

The representative locations chosen for coarse grain survey are Mussoorie, New Tehri, and Chakrata. Mussoorie and Chakrata are situated in the Dehradun District, while New Tehri is in Tehri Garhwal district Construction of the Tehri Dam submerged the old town of Tehri, and the population was shifted to New Tehri. The residential buildings chosen in Mussoorie belong to the township areas of Barlowganj, Jharipani, Kiyar Kuli, Bhatta Gaon, and Indira Colony. The residential buildings chosen in New Tehri belong to the township areas of Baurari, Sector 8,7,2, 9, Ali Taali, and old Tehri village – Gaumudhar. The residential buildings chosen in Chakrata belong to the township area of the Chakrata market and villages: Jadi and Mohna.

(a)

(b)

(c)

Figure A.1.1. **Residential Settlements in (a) Mussoorie, (b) New Tehri, and (c) Chakrata**

IMAC model is used to calculate the monthly heating and cooling degree days for these representative locations [5][27]. Heating degree days are useful to quantify the demand for the energy needed to heat the building. Table A.1.1 states the monthly heating and cooling degree days. The annual Heating Degree days for Chakrata, Mussoorie, and New Tehri are 3158, 3046, and 2872 respectively. The annual Cooling Degree days for Chakrata, Mussoorie, and New Tehri are 13, 34, and 59 respectively.

Table A.1.1. **Monthly Heating and Cooling degree days**

CITIES	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEPT	OCT	NOV	DEC
CHK_H	420	314	265	194	182	174	140	157	204	300	378	428
CHK_C	0	0	0	0	13	0	0	0	0	0	0	0
MUSS_H	412	310	255	180	168	158	146	145	193	290	366	420
MUSS_C	0	0	0	9	25	0	0	0	0	0	0	0
TEH_H	391	291	238	169	157	149	135	138	180	272	349	401
TEH_C	0	0	0	21	38	0	0	0	0	0	0	0

Census 2011 of Uttarakhand was used to look at the type of buildings, fuel mix, household size, and income group present in these locations. Census 2011 specifies the number of urban and rural households in these locations. So we tried to captured samples from each category. The Occupant profile of the locations will help in selecting a cost-benefit solution for energy consumption. Figure A.1.2. shows the household size, predominant age group, and income category.

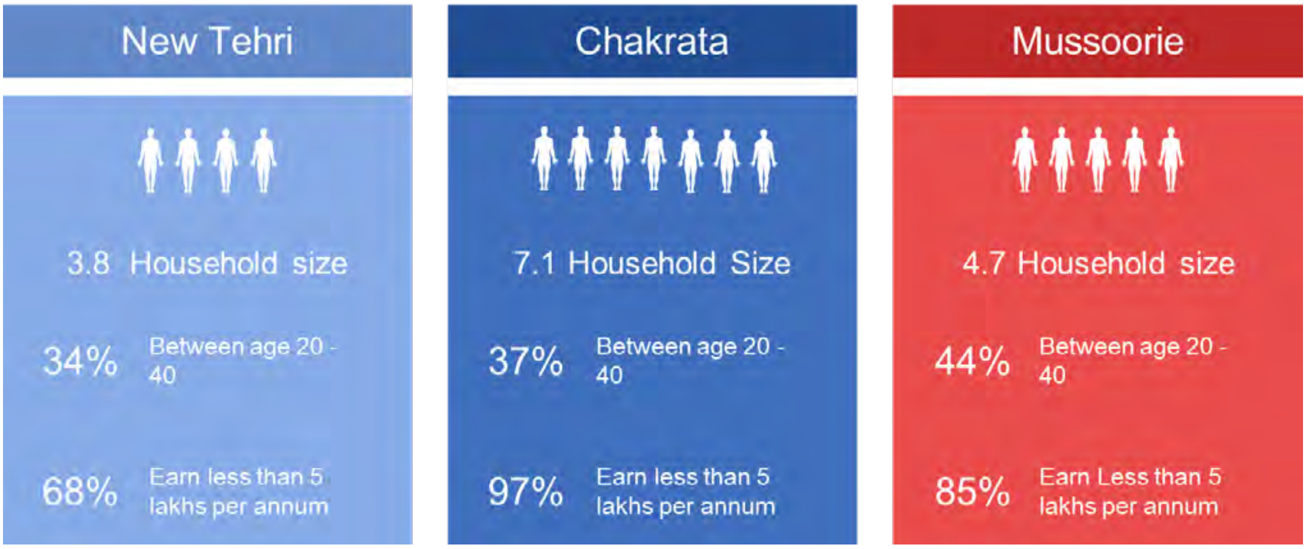


Figure A.1.2. **Occupant profile of representative locations**

27 Manu, S., Shukla, Y., Rawal, R., Thomas, L.E., & de Dear, R., (2016). Fields studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). Building and Environment, 98, 55-70.

A.1.2.2. Environmental conditions

The environmental parameters such as dry bulb temperature, relative humidity, and globe temperatures were measured between February 2020 to March 2020 with the help of handheld comfort meters. The indoor conditions prevailing in the representative locations are given in Table A.1.2. Transverse thermal comfort surveys were taken from 145 respondents through questionnaires on TCV and 7-point TSV. TSV is performed by ASHRAE standard 55 and TCV from the Bedford scale. McIntyre index is a 3-point sensation scale with the responses 'Cooler', 'No change' and 'warmer'. These scales were used to find out the subject's feelings about the environment by casting a vote. Respondents are asked for Yearly, monthly and daily ratings of the residences.

Table A.1.2. Environmental parameters during thermal comfort surveys

Location	Environmental Parameters	Minimum	Maximum	Mean
Mussoorie	Indoor Dry Bulb Temperature	12.8°C	20.3°C	15.3°C
	Indoor Relative Humidity	46.2%	76.6%	63.6%
	Indoor Globe Temperature	10.5°C	19.3°C	12.7°C
	Outdoor Dry Bulb Temperature	7.4°C	23.6°C	15.5°C
	Outdoor Relative Humidity	50%	75%	63%
New Tehri	Indoor Dry Bulb Temperature	14.4°C	24.4°C	18.0°C
	Indoor Relative Humidity	46%	68%	59.5%
	Indoor Globe Temperature	12.2°C	22.1°C	16°C
	Outdoor Dry Bulb Temperature	8.0°C	22.8°C	19.4°C
	Outdoor Relative Humidity	50%	70%	60%
Chakrata	Indoor Dry Bulb Temperature	9.4°C	17°C	13.6°C
	Indoor Relative Humidity	39.5%	77.4%	63.5%
	Indoor Globe Temperature	9.4°C	17.1°C	13.7°C
	Outdoor Dry Bulb Temperature	5.5°C	17.6°C	11.0°C
	Outdoor Relative Humidity	41.8%	90.6%	65.3%

Figure A.1.3. shows the percentage of male and female respondents in each location, TSV, TCV, Response preference for the environment, Rating of the house, and Preference and attitude towards cold stress. Subjects' response to cold stress determines the preference and attitude towards energy saving.

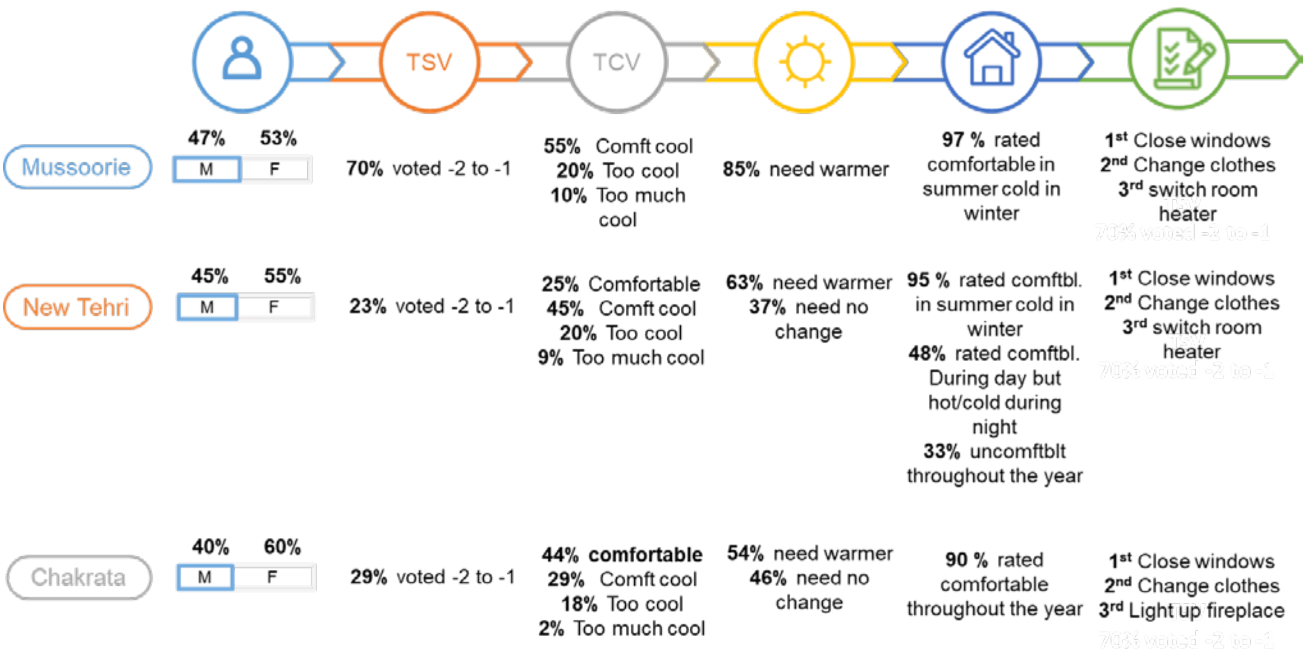


Figure A.1.3. Thermal Comfort surveys of respondents

A.1.2.3. Connected loads

The connected load gives the wattage of ownership of appliances used in the residences. This connected load consists of daily use appliances like room-heaters, geyser, refrigerator, washing machine, laptop, television, lights, iron, mixer/grinder, and electric kettle. Figure A.1.4. compares the connected load range, type of electric heating device used, preference of fuel for room heating, and average electric room heater usage in three locations.

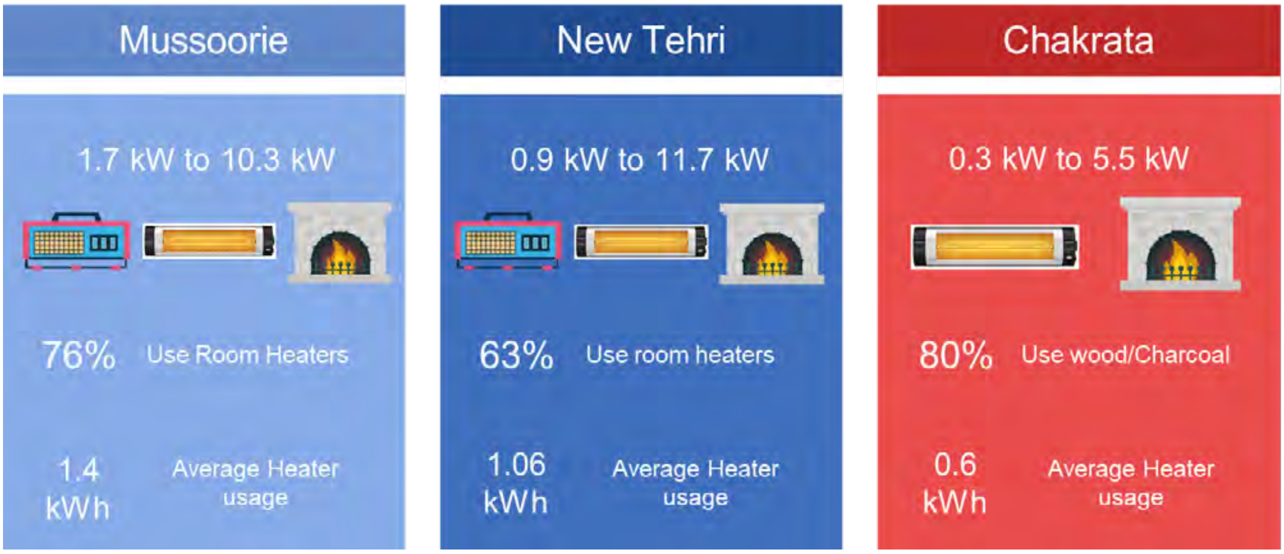


Figure A.1.4. **Connected load and Heater usage in three locations**

The connected load in Mussoorie consists of daily use appliances like room-heaters, geyser, refrigerator, washing machine, laptop, television, lights, iron, mixer/grinder, and electric kettle. The connected load in New Tehri consists of daily use appliances like room-heaters, geyser, refrigerator, washing machine, laptop, television, lights, iron, mixer/grinder, and electric kettle. The connected load in Chakrata consists of daily use appliances like room-heaters, television, lights, iron, and electric kettle. The connected load gives the minimum electrical energy demand of the residences in each location. The electricity demand can be met by using solar PV panels depending on the solar radiation received.

A.1.2.4. Summary of the survey data

Table A.1.3 gives the minimum, maximum, and mean of the following parameters, which were recorded and calculated during fine grain surveys

Table A.1.3 **Minimum, Maximum and mean of Settlement profile parameters**

Parameter		Minimum	Maximum	Mean
Built-up Area (m^2)	Chakrata	11	174	58.82
	Mussoorie	18.58	140	72.07
	New Tehri	25	70	40.87
Age of Building - years	Chakrata	5	400	30
	Mussoorie	2	60	17.2
	New Tehri	3	62	27.18
U value for Wall assembly – W/m^2K	Chakrata	1.47	2.32	1.86
	Mussoorie	2.05	2.12	2.05
	New Tehri	1.9	2.32	2.09
U value for Roof assembly – W/m^2K	Chakrata	0.44	4.21	1.20
	Mussoorie	0.73	5.82	4.07
	New Tehri	0.74	3.75	3.48
Annual Electricity Consumption - kWh	Chakrata	87.36	2292	420
	Mussoorie	382.20	3276	1392.30
	New Tehri	145.60	1456	595.16

Parameter		Minimum	Maximum	Mean
Winter Electricity Consumption - kWh	Chakrata	14.56	273	50
	Mussoorie	63.70	910	344.40
	New Tehri	27.30	364	132.34
Summer Electricity Consumption - kWh	Chakrata	14.56	127.40	39
	Mussoorie	54.60	500	177.41
	New Tehri	13.65	274	85.40
Other non-severe months Electricity Consumption - kWh	Chakrata	14	109.20	36
	Mussoorie	54.60	382.20	169.33
	New Tehri	13.65	218.40	79.84
Occupant size	Chakrata	2	16	5.60
	Mussoorie	2	11	5.70
	New Tehri	2	13	4.20
Electric Heater usage - kWh	Chakrata	46.26	129.6	80.46
	Mussoorie	80.91	590	255.67
	New Tehri	16.30	313.92	115.40
Connected Load - kW	Chakrata	0.3	5.56	1.42
	Mussoorie	1.73	10.30	4.60
	New Tehri	0.93	11.75	5.00

Table A.1.4. presents the percentage for the options provided in the following settlement profile parameters.

Table A.1.4. Percentage of Settlement profile parameters in Three locations

Parameter		Chakrata	Mussoorie	New Tehri
Type of House	Attached	16 %	16 %	13 %
	Detached	84 %	84 %	31 %
	Apartment	-	-	56 %
Number of bedrooms	1	64 %	5 %	8 %
	2	36 %	37 %	63 %
	3	-	24 %	13 %
	4	-	16 %	13 %
	4+	-	18 %	3 %
Residing Since	Less than 2 years	3 %	-	5 %
	2 – 5 years	7 %	23 %	24 %
	5 – 10 years	7 %	11 %	18 %
	10 – 15 years	7 %	11 %	16 %
	More than 15 years	76 %	55 %	37 %
Ownership of residence	Owned	92 %	90 %	47 %
	Rented	8 %	10 %	53 %
Age of Occupants	Below 20 years	32 %	35 %	26 %
	20 – 40 years	38 %	44 %	34 %
	40 – 60 years	20 %	15 %	32 %
	Above 60 years	10 %	6 %	8 %

These parameters give the present scenario of settlements in these locations. This will act as a backbone to prepare guidelines and generating scenarios for the residential buildings in Uttarakhand.

A.1.2.5. Comparative analysis of energy consumption

This section compares the energy consumption between the contemporary and composite types (shown in Figure A.1.5) of residences, across cities, seasons, income groups, and fuel mix. Contemporary buildings are made with construction materials like brick, cement, and RCC. They are built within the past 30 years. On the other hand, composite buildings are made with locally available materials like stone, wood, and slate. The average age of these buildings is 100 years and require renovation seasonally. The roofs of these buildings have eventually been replaced due to the lack of skilled laborers and affordability of GI sheets over Slate. The analysis will help in determining the drivers affecting energy consumption.

(a)

(b)

Figure A.1.5. **(a) Contemporary Construction and (b) Composite Construction**

A.1.2.6. Effect of construction type

The composite and contemporary residences found were compared with each other in terms of annual electricity consumption. New Tehri and Chakrata have both contemporary and composite types of buildings. Whereas, Mussoorie has only contemporary buildings. In Figure A.1.6. the histogram shows the annual energy consumption of modern and composite buildings in three representative locations.

Figure A.1.6. shows that composite construction has annual energy consumption between 100 kWh to 700 kWh. Whereas contemporary construction has higher annual energy consumption ranging from 300 kWh to 2300 kWh. The modern buildings in Chakrata have even lesser annual energy consumption than Tehri and Mussoorie. Figure A.1.7. shows the winter, summer, and non-severe month's energy consumption patterns across cities. The composite buildings have lower seasonal energy consumption below 100 kWh than the modern buildings irrespective of locations. Contemporary buildings of Mussoorie have higher energy consumption during winter than Chakrata, although Chakrata has a more severe cold climate and has higher heating degree days.

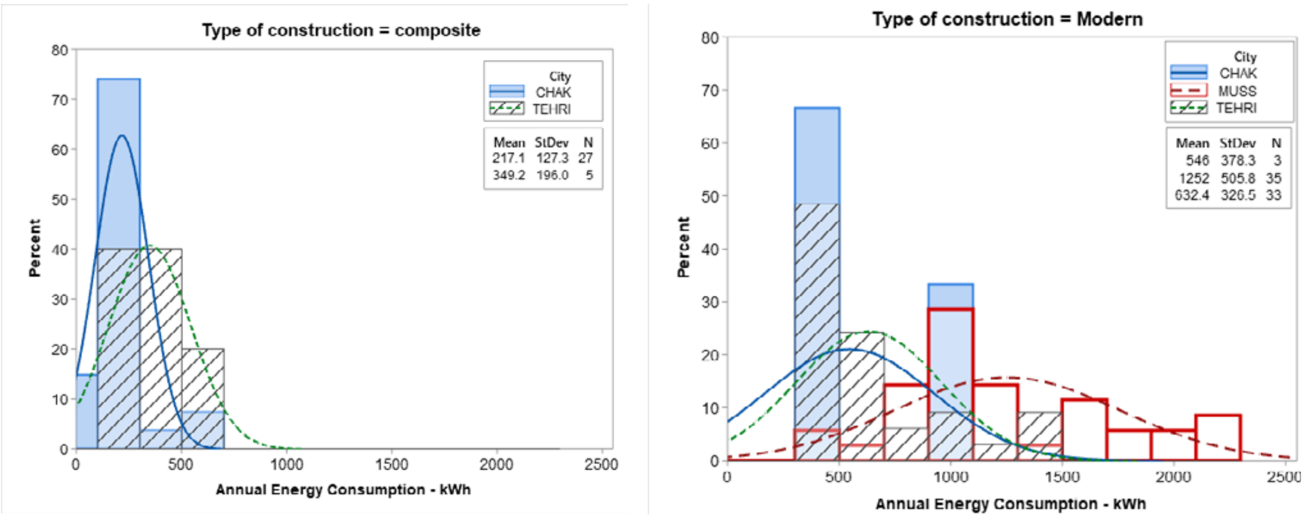


Figure A.1.6. **Annual Energy Consumption of Composite VS Modern buildings in 3 locations**

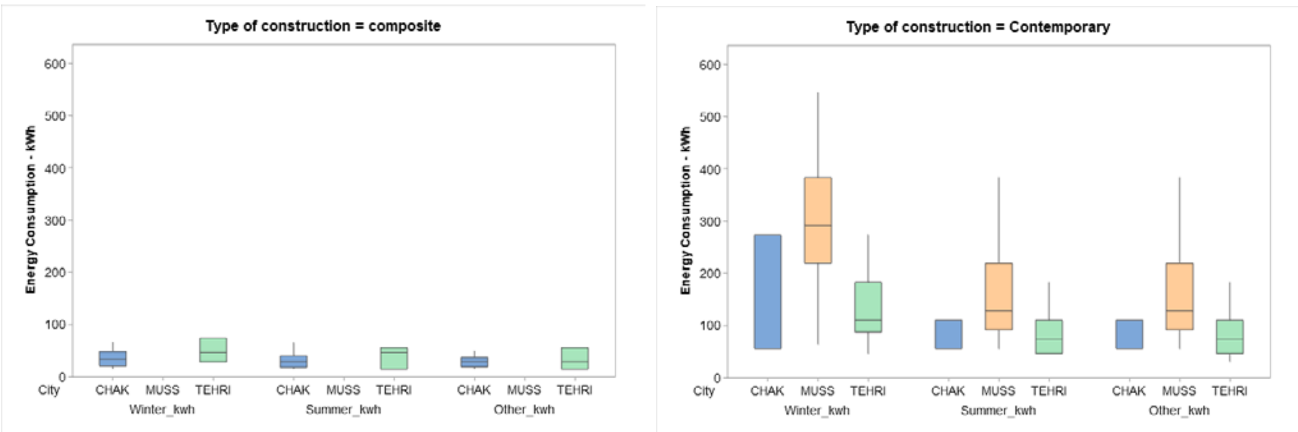


Figure A.1.7. **Energy consumption pattern in Composite VS Modern across seasons**

Winter months have higher energy consumption than summer and non-peak months for all locations. But due to different fuel mix, sole reference to the energy consumption values could be misleading. To find out the reason behind this we further analyze the energy consumption pattern across income groups and fuel type.

A.1.2.7. Across income group

The residences surveyed in the three representative locations were majorly in mid and low-income groups. Here, mid-income is Between 5 to 10 lakhs per annum and low income is below 5 lakhs per annum.

Figure A.1.8. **Annual Energy Consumption based on Income type**

Figure A.1.8 shows the distribution of energy consumption across income groups across different building types. The low-income group resides in Composite buildings. The contemporary building is occupied by both low and middle-income groups. The low-income group consumes average annual energy of 300 kWh. Whereas, in a modern building low-income group consumes higher average annual energy of 800 kWh. The low and middle-income groups in the modern building both consume similar annual energy. So, to study this difference we further analyze the predominant fuel type used across building types.

A.1.2.8. Across predominant fuel types

Figure A.1.9 shows the discrepancy observed in annual energy consumption across seasons, cities, and income groups. This is because of the predominant fuel used in these residences for room heating and domestic water heating. Residences with wood as the predominant fuel have lower annual energy to residences using electricity in similar building typologies. Wood is economical and easily available in hilly areas. Therefore, dependence on wood for heating purposes is higher and residents feel nauseated with the use of infrared radiators. So an equivalent has to be calculated for energy demand due to the fuel mix.

Figure A.1.9. **Annual energy consumption based on predominant Fuel**

A.1.2.9. Effect of construction materials

The building envelope is considered to be effective if it protects the residents from the harsh outside conditions while decreasing energy consumption to maintain comfortable living conditions. A building envelope consists of a wall, floor, fenestrations, shading devices, and roof. Wooden frames with glass panels are commonly found windows in these locations. A major difference in the building envelope was observed in the wall and roof. Figure A.1.10. shows the different wall and roof assemblies available in the representative locations.

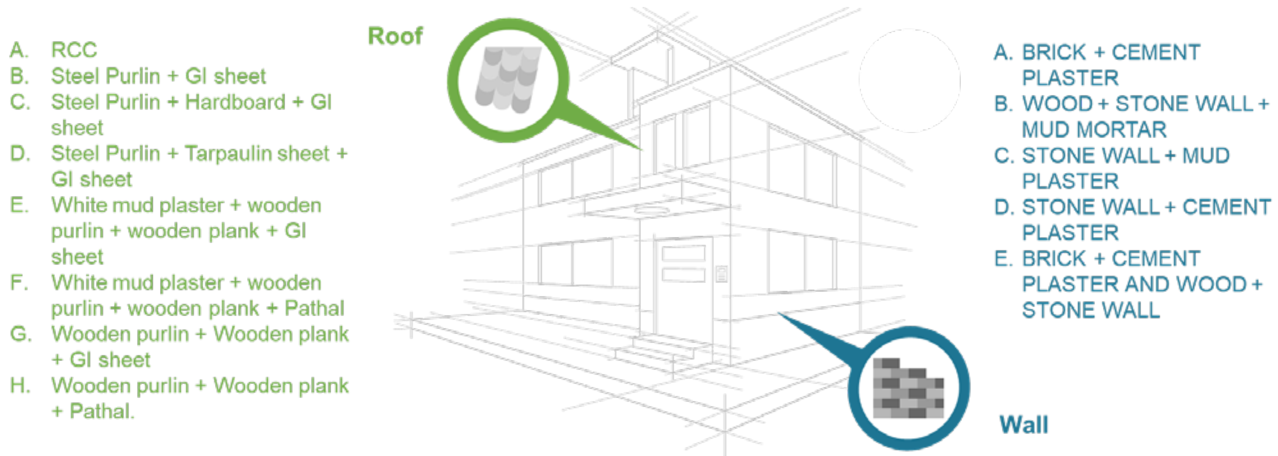


Figure A.1.10 **Roof and Wall assemblies of Residential Buildings**

Figure A.1.11 (a). shows that wall assemblies B and E are effective throughout the year as the annual energy consumption is the lowest. Wall assembly A requires more energy to maintain a comfortable temperature throughout the year. Hence, insulation like wood and mud mortar is useful in addition to brick or stone wall.

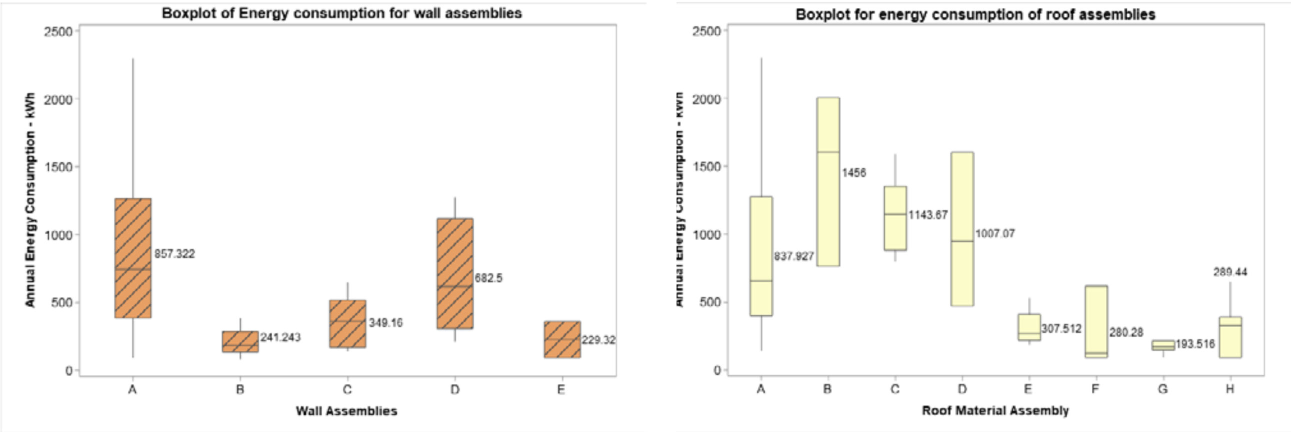


Figure A.1.11 Annual Energy consumption across (a) wall and (b) roof assemblies

Figure A.1.11 (b) shows the annual energy consumption across common roof assemblies found in the representative locations. The roof assemblies E, F, and G perform well throughout the year and use less energy to maintain a comfortable indoor environment. The roof assemblies B, C, and D consume more energy throughout the year. Hence, roof insulation is required in a cold climate.

A.1.2.10. Material market analysis

A market analysis is done for the construction material assemblies used for contemporary and composite walls and roofs. The construction price for wall and roof assemblies (shown in Table A.5) are taken from the Delhi schedule of rates[28] and PWD rates given by districts of Uttarakhand[29]. Table A.1.5 gives the construction price range of wall and roof assemblies found in Uttarakhand. This will help in recommending the material assemblies keeping in mind the affordability of the residents.

Table A.1.5. Construction price of wall and roof assemblies

Assemblies	Price per cubic meter in Rs
Contemporary wall assemblies	502
Composite wall assemblies	5,395 – 7,402
Contemporary roof assemblies	1,770 – 9,840
Composite roof assemblies	3,950 – 10,440

A.1.3. Fine grain survey

A.1.3.1. Methodology

To evaluate the seasonal and annual thermal performance of residential buildings, real-time field measurements were carried out in six contemporary houses identified in Mussoorie. The houses were chosen based on location, construction materials, and the eagerness of homeowners to participate in the surveys. The indoor and outdoor temperature and humidity measurements were measured at 10 minutes intervals. The readings were obtained using a temperature and humidity data logger (shown in figure A.1.12) with a precision of ±0.5°C & ±3% RH and a resolution of 0.1°C & 0.1% RH. The temperature and humidity loggers were placed in living rooms and bedrooms where people moved around frequently.

28 CPWD. (2018). Delhi Schedule of Rates (Vol-1)
29 PWD. (2019). Materials Rates for Block 28 Chakrata Material Rates for Block 28. 20(1), 1-16

Figure A.1.12. **Instrument used to collect indoor and outdoor temperature and humidity**

To study the seasonal and annual energy demand of residential buildings, smart energy meters were installed (shown in Figure A.1.13) at MCB (Main circuit board). The smart energy loggers measured current, voltage, and frequency at 1 second interval.

Figure A.1.13. **Smart energy loggers installed at site**

A.1.3.2. Evaluation of thermal performance

The thermal performance is studied by measuring the real time indoor and outdoor temperature and humidity at 10-minute intervals. Table A.1.6 tabulates the duration of data collection in each house. There is an inconsistency in data logging in House B and F due to the low battery of the temperature and humidity loggers. These could not be replaced on-site due to the onset of the COVID-19 pandemic.

Table A.1.6. **Duration of data collection in 6 Residences in Mussoorie**

	HOUSE A	HOUSE B	HOUSE C	HOUSE D	HOUSE E	HOUSE F
START	JAN 2021	JAN 2021	JAN 2021	JAN 2021	JAN 2021	JAN 2021
STOP	FEB 2022	OCT 2021	FEB 2022	FEB 2022	FEB 2022	OCT 2021
DURATION	14 MONTHS	10 MONTHS	14 MONTHS	14 MONTHS	14 MONTHS	10 MONTHS

To understand the buildings' seasonal thermal behaviour, the indoor and outdoor temperature is compared for the six residences (shown in Figure A.1.14).

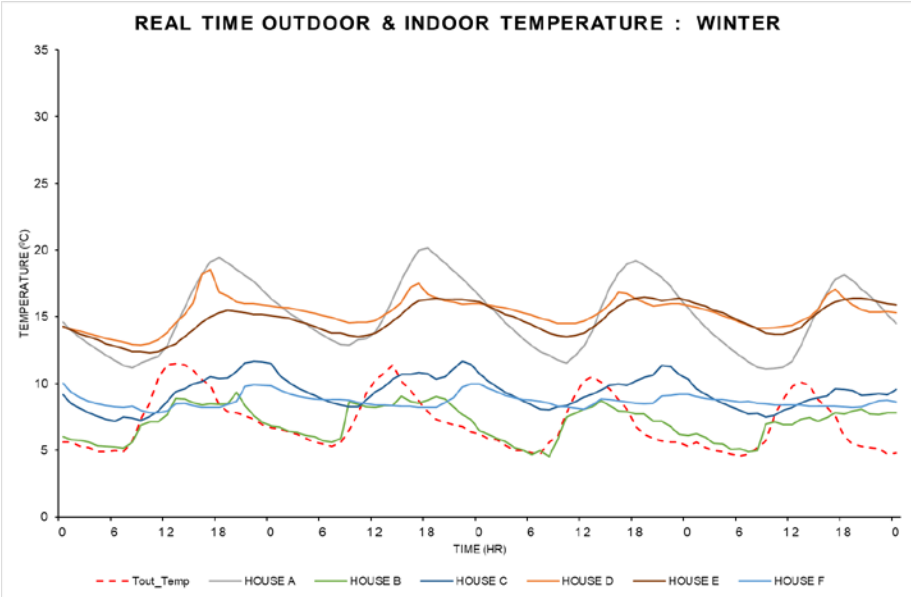


Figure A.1.14. **Comparison of real time indoor and outdoor temperature profile in winter**

The indoor temperature of House B closely follows the outdoor temperature prevailing in the winter season. House B belongs to the low-income category without a permanent roofing structure. Figure A.1.15. Shows House B's thermal image with heat loss through windows and walls due to poor window frame and construction quality.

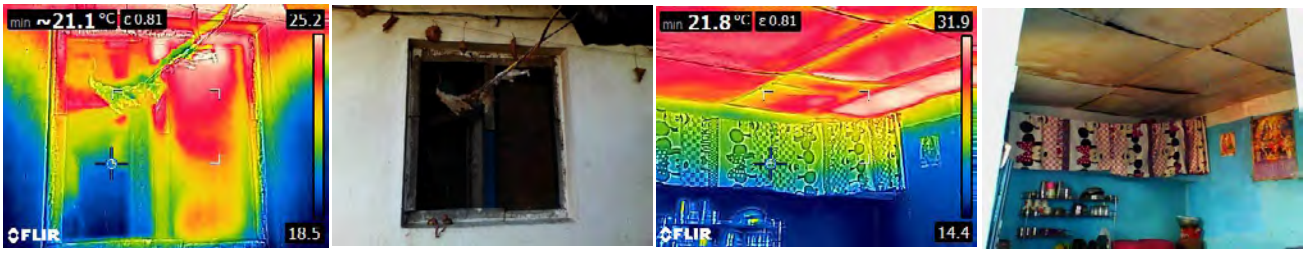
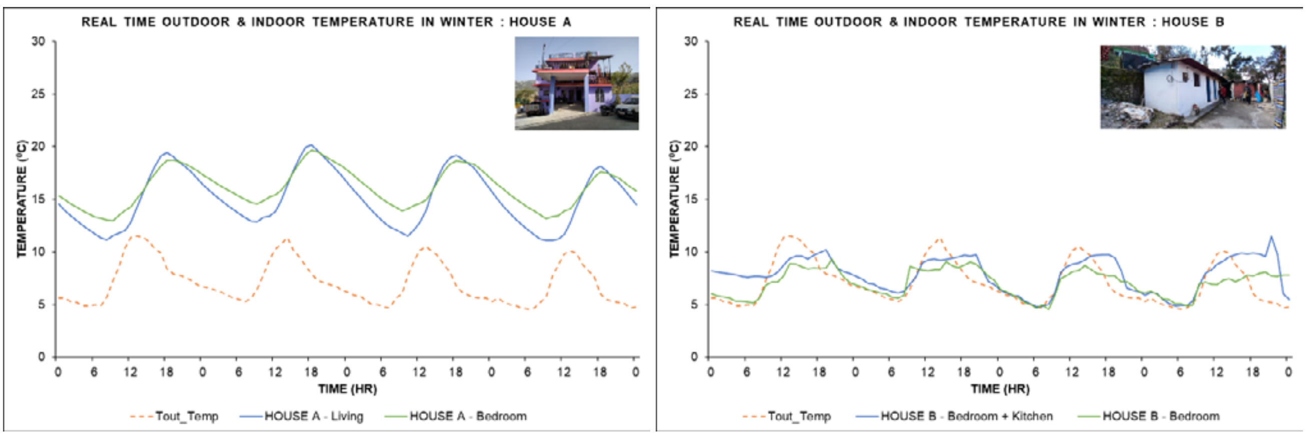


Figure A.1.15. **Thermal image of House B showing poor window design**

The indoor temperature of the bedroom and living room is compared for each house to understand each room's thermal performance (shown in Figure A.1.16).



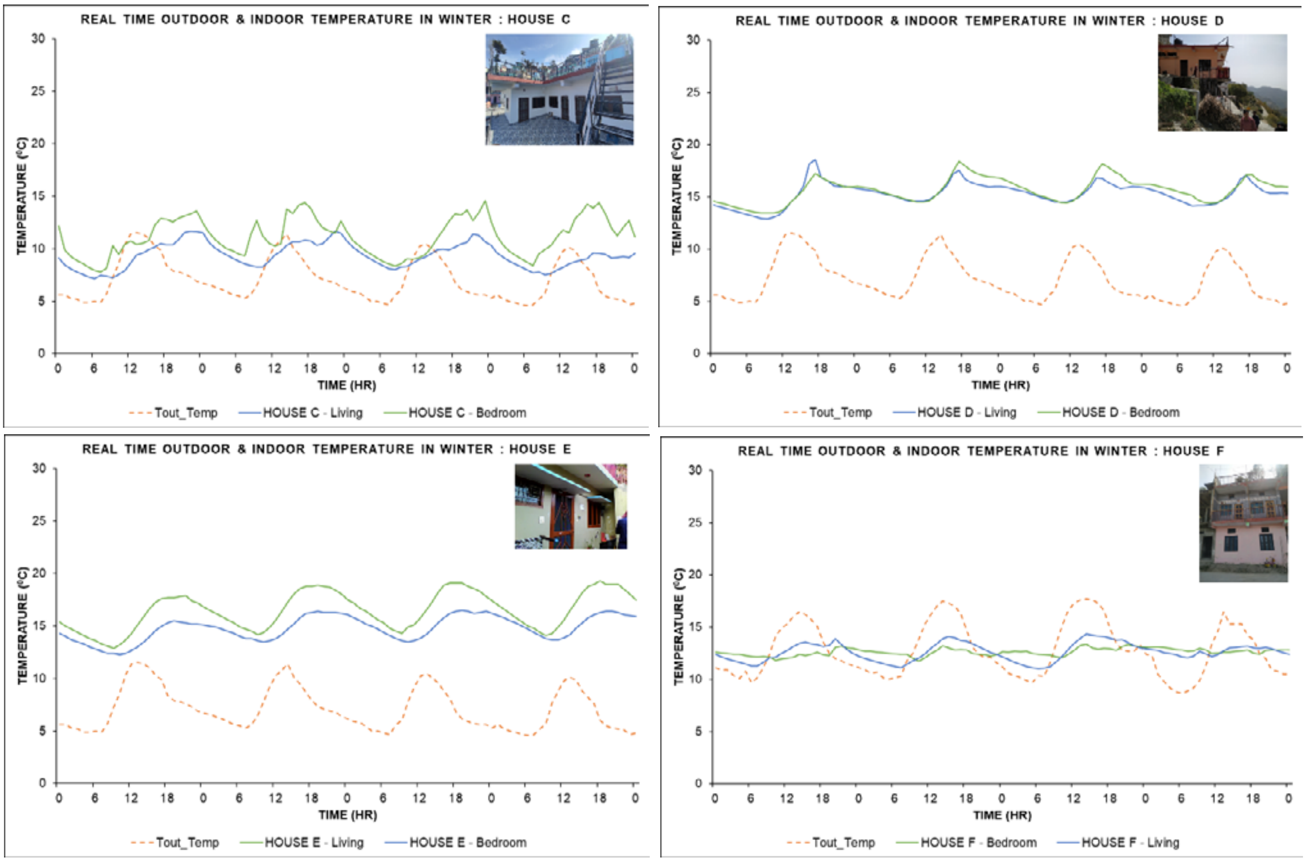


Figure A.1.16. Comparison of indoor and outdoor conditions of each room for 6 residences in winter.

It is observed that there is a difference between the indoor conditions prevailing in each room due to the orientation of the exposed surfaces of these residences. The living room of House A has exposed surfaces facing south and west, hence the indoor temperature is higher during day in comparison to the bedroom which has no exposed walls. The Bedroom + Kitchen in House B has higher temperature than the bedroom as heat is generated in kitchen due to cooking. In House C a stand-alone heating system is used to achieve comfortable conditions in the bedroom at night. In House D, both the bedroom and living room has a stand-alone heating system running during occupied hours; hence there is not much difference in the indoor conditions between the two rooms. The living room of House E has exposed walls facing south and east; hence the indoor temperature is higher than the bedroom, with one wall facing south. In House F, the living room has two exposed walls facing south and west, while the bedroom has one exposed wall facing west. Hence the temperature in living room is higher than the bedroom. House F also uses a stand-alone heating system to achieve comfortable indoor conditions in winter.

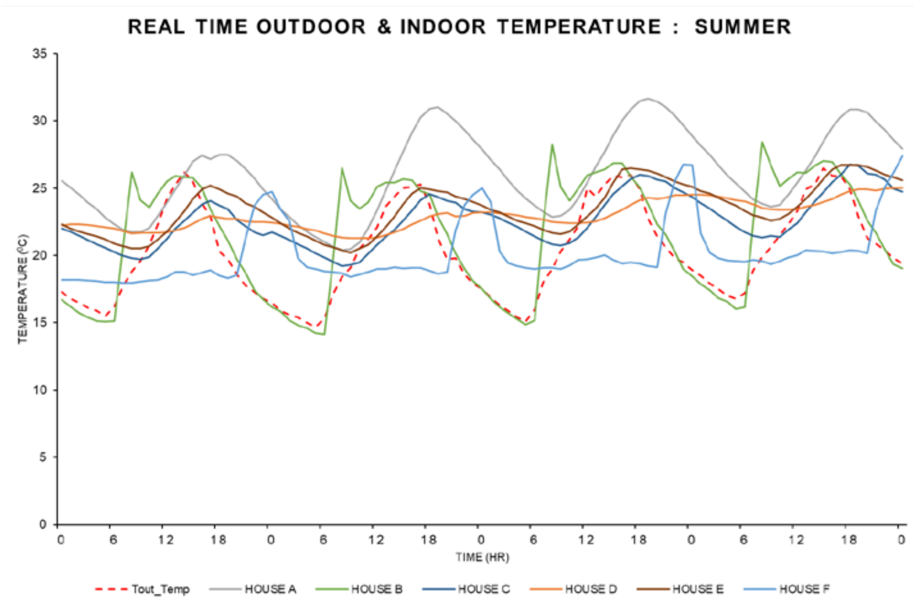


Figure A.1.17. Comparison of real time indoor and outdoor temperature profile in summer

From the above figure, it is observed that House A has a higher indoor temperature in comparison to other residences. House F uses heating system at night when outdoor temperature goes below 18 degrees. There is a peak rise in indoor temperature in House B during the morning because of the heat generated in the kitchen from cooking. House C, D, and E have comfortable indoor conditions during summer.

From the above analysis it can be inferred that construction materials impacts the indoor temperature significantly. Figure A.1.18 compares the daily indoor temperature of House C having RCC roof and brick wall and House B having brick wall and GI sheet roofing.

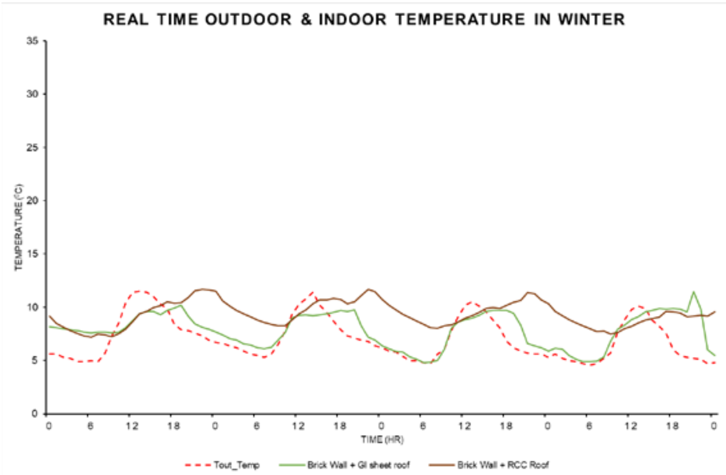


Figure A.1.18. **Effect of Material on indoor temperature in winter**

Figure A.1.19-24 shows the daily average indoor temperature range for all houses for all months

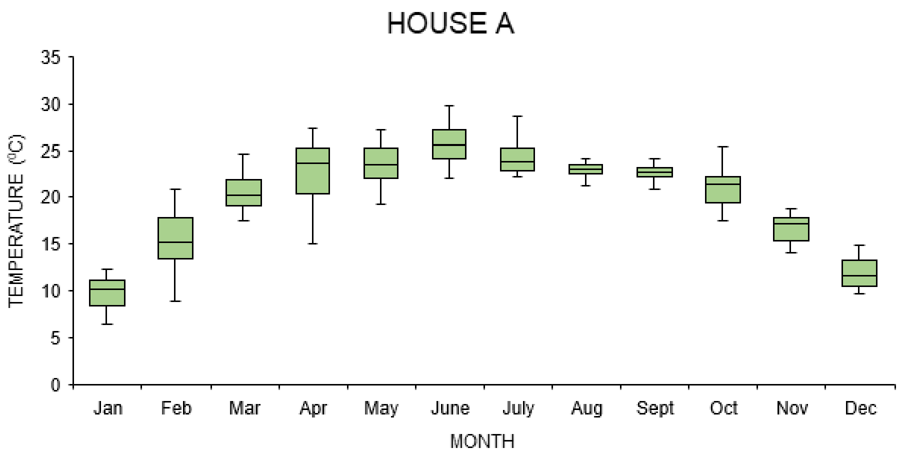


Figure A.1.19. **Daily average indoor temperature range for House A**

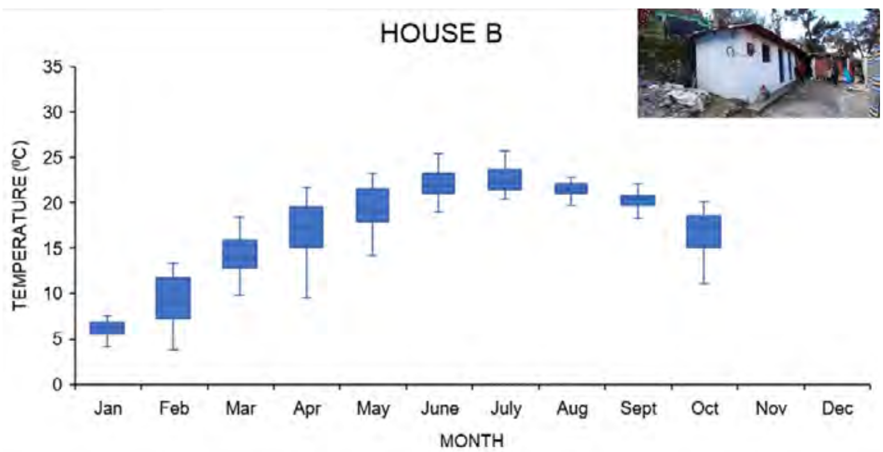


Figure A.1.20 **Daily average indoor temperature range for House B**

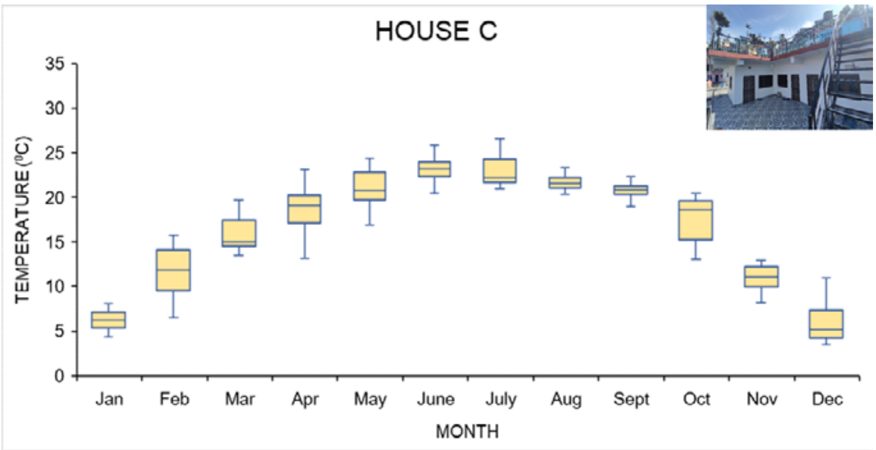


Figure A.1.21. Daily average indoor temperature range for House C

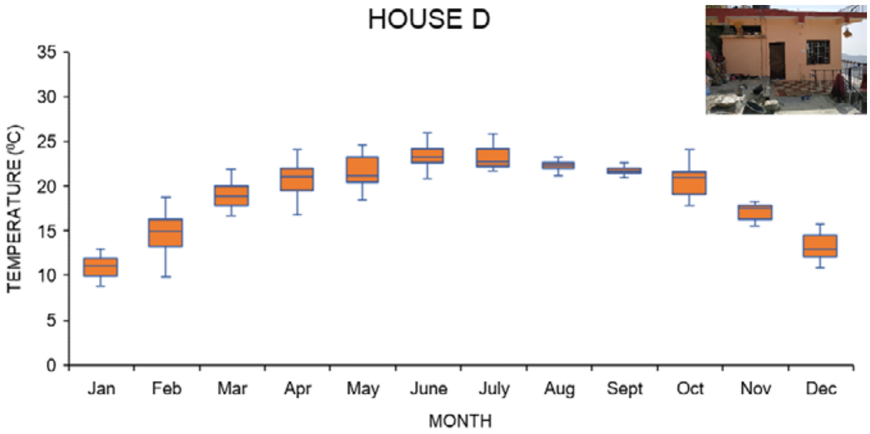


Figure A.1.22. Daily average indoor temperature range for House D

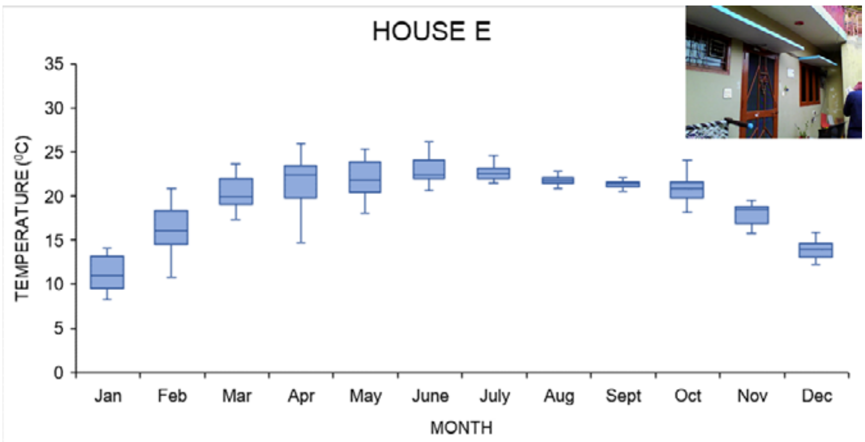


Figure A.1.23. Daily average indoor temperature range for House E

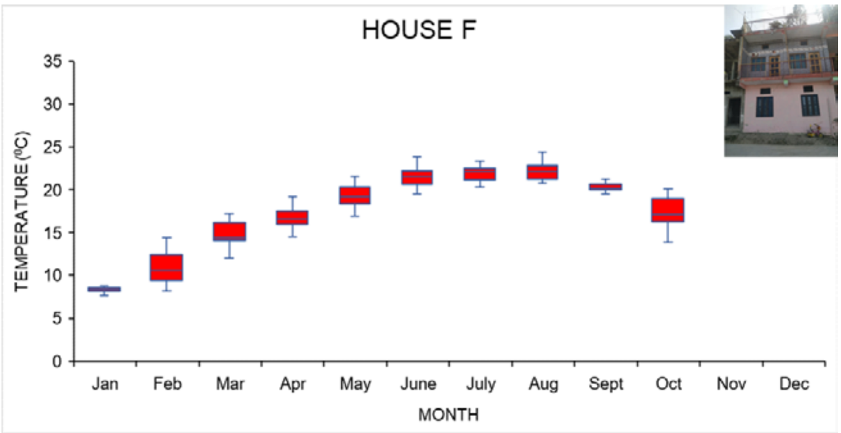


Figure A.1.24. **Daily average indoor temperature range for House F**

In all the houses, the indoor temperature range is lower in August and September. There is not much difference in diurnal temperature. The indoor temperature range is higher for all houses in December, January, and February. Hence the winter months have significant diurnal variations.

A.1.3.3. Evaluation of energy consumption

The energy consumption of each house is measured using a smart data logger, which measures current, voltage and frequency at 1 second intervals. The electricity consumption data offers an opportunity to understand residential energy demand, consumption behavior, and short- and long-term forecasting. The power consumption in watts is given for House E and D for the winter, transition, and summer seasons.

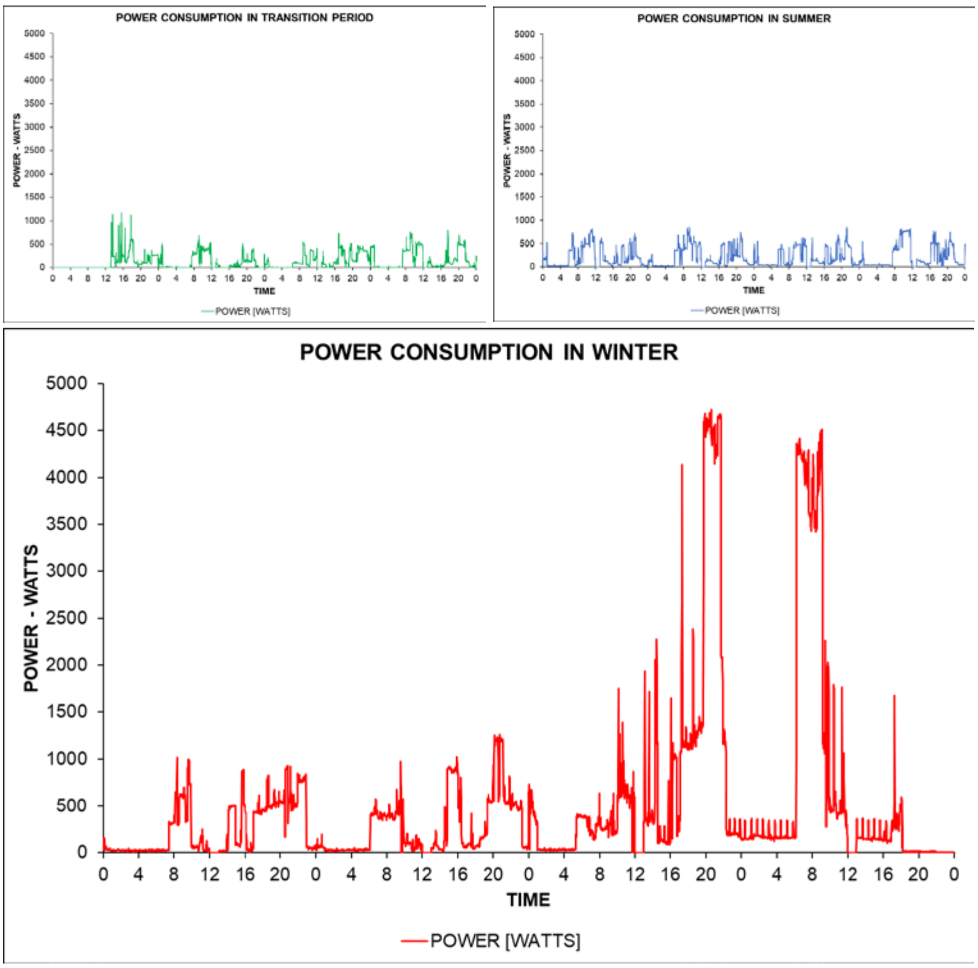


Figure A.1.25. **Energy consumption pattern in House E during transition, summer, and winter season.**

In House E, there is a rise in daily energy demand from 6 am to 11 am and 6 pm to 11 pm during the winter season. The daily energy consumption goes up to 4500 watts in winter, 1100 watts in transition period, and 800 watts in summer. This shows that the energy demand starts increasing in the transition period and peaks in winter.

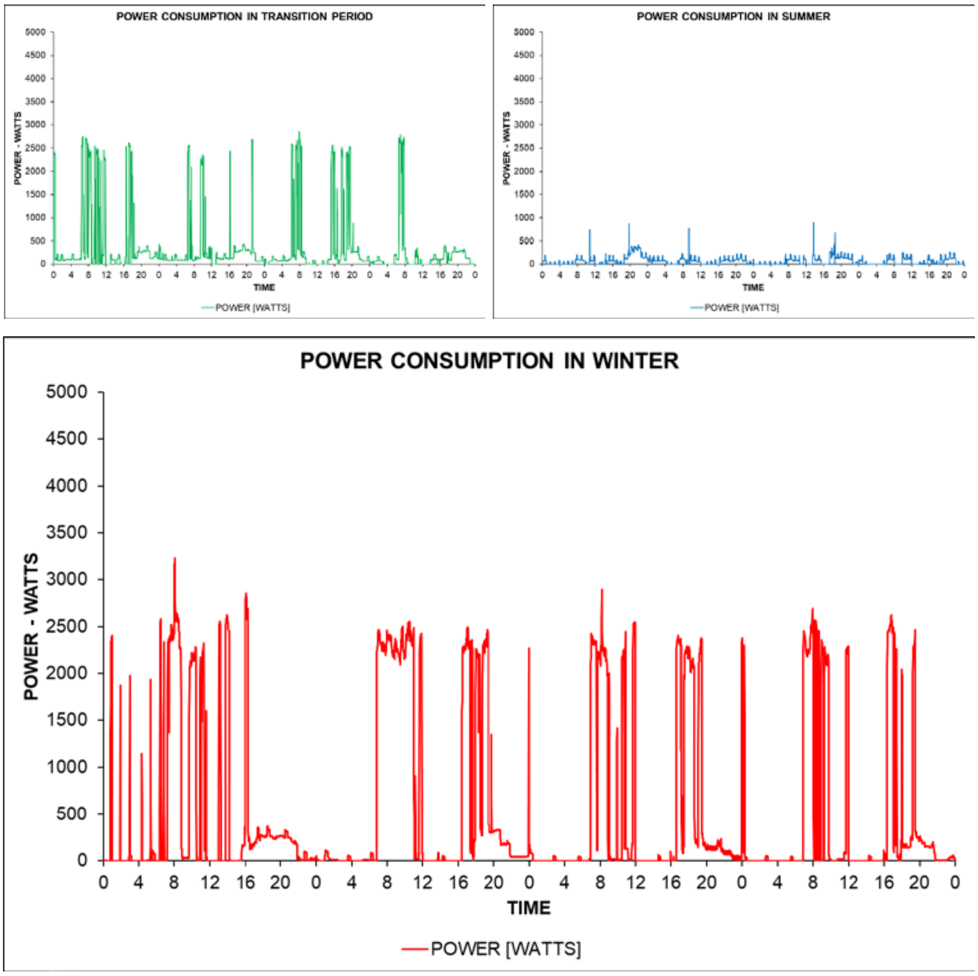


Figure A.1.26. **Energy consumption pattern in House D during transition, summer, and winter season.**

A similar pattern is observed in House D, where the daily energy demand is higher in winter and lower in summer. However, House D's daily energy consumption is higher than House E's in the transition period, but lower in winter. This happens due to the orientation and height of both residences. House E is a single storey building with exposed walls facing north, south, and east. House D is located above the height of 4m with exposed walls facing south, east and west.

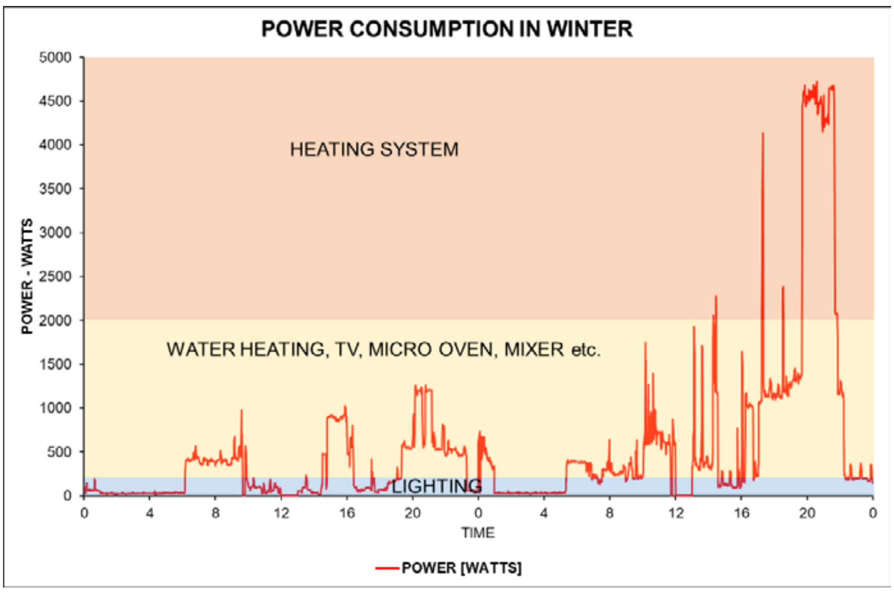


Figure A.1.27. **Appliance-wise energy consumption on a typical winter day in House E.**

Figure A.1.27 shows the appliance-wise energy consumption pattern in House E during a typical winter day. Lighting constitutes between 20 to 100 watts, water heating, and other major appliances fall in the range of 100 to 2000 watts, and room heating systems fall under the range of 2000 to 5000 watts.

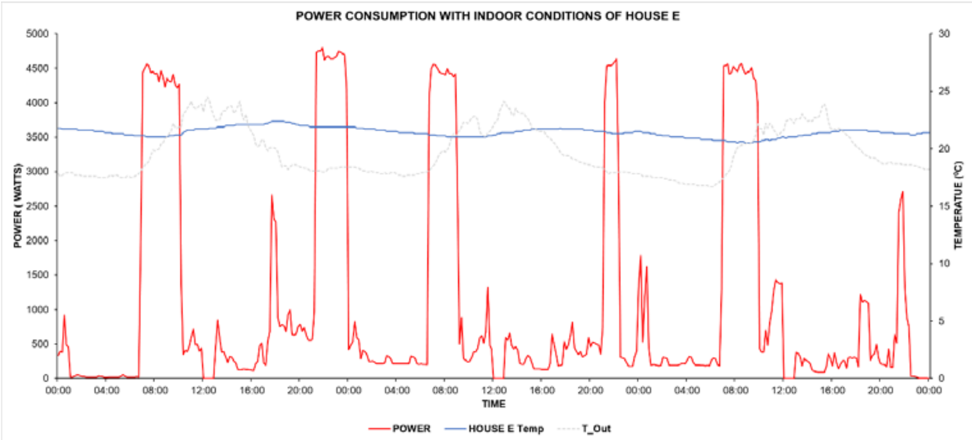


Figure A.1.28. **Power consumption variation with indoor and outdoor temperature in House E in September**

Figure A.1.28 shows the variation in energy consumption pattern for House E. As the outdoor temperature decreases and goes below 18^{0}C, the heating system is turned on to maintain the indoor temperature.

Appendix 2:
Modelling based study to analyse the thermal performance of buildings in the cold climate of Uttarakhand

A.2.1. Methodology

Four representative residential units were chosen from the handbook of replicable designs for energy efficient residential buildings (BEE, 2021)[30]. Of these, three were multi-family row house type units (1 BHK, 2 BHK, and 3 BHK). One is a single-family detached (4 BHK) G+1 residence. The building models were developed and simulated in energy plus. The models were validated using real-time measurements carried out for a year (Jan 2021 to March 2022) in six residences in Mussoorie. Figure A.2.1 shows the building model of a residence in Mussoorie developed in TRNSYS. Figure A.2.2 shows the comparison between simulated data and real-time data; and the validation of simulated data. The model assumptions were kept alike to validate the representative building models for carrying out parametric simulations in three locations – Mussoorie, Chakrata, and Joshimath, based on varying HDD (Heating Degree Days).

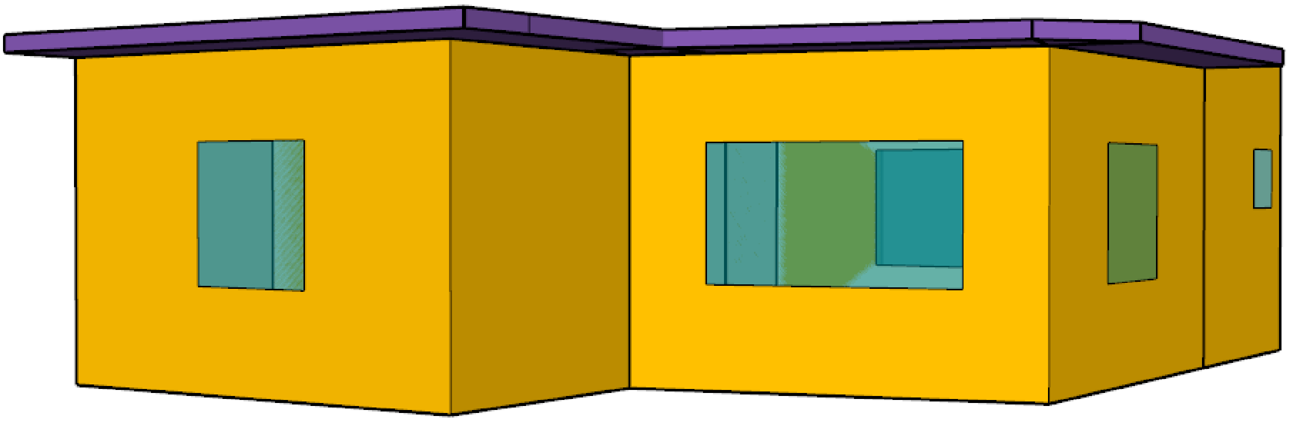


Figure A.2.1. Building simulation model of a surveyed residence in Mussoorie

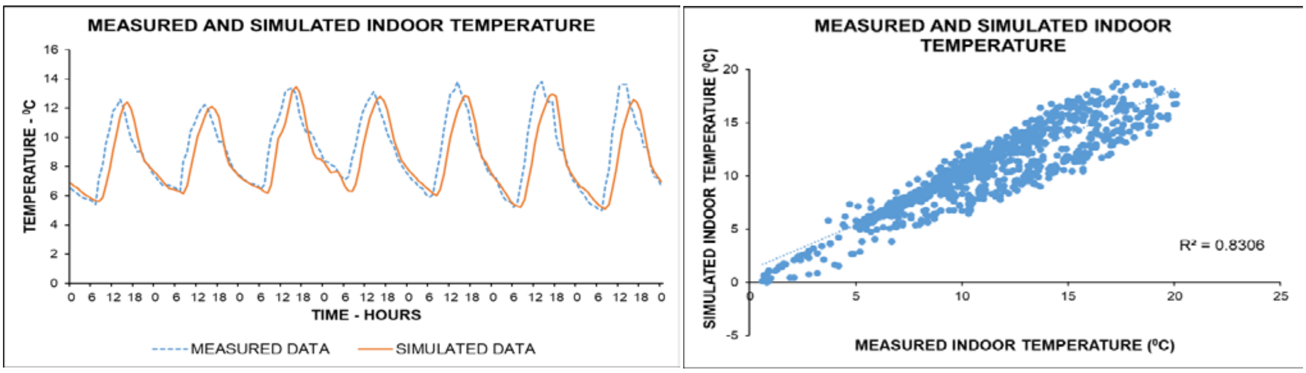


Figure A.2.2. Comparison and Validation of real time data and simulated data

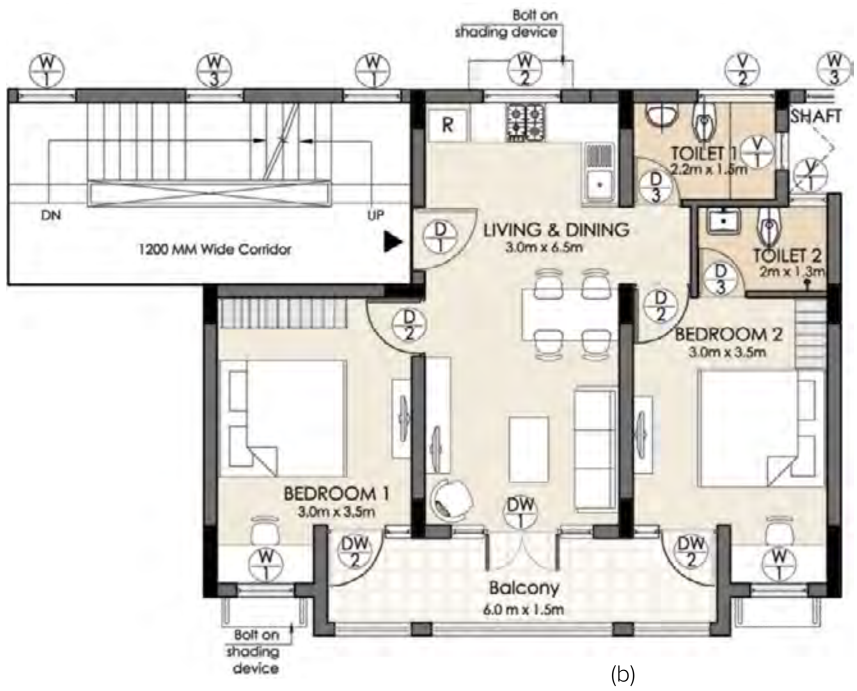
A map of Uttarakhand is developed in GIS to showcase the comparison of the Energy Performance Index (EPI) of the base case and the optimum case throughout varying climate severities.

30 BEE (Bureau of Energy Efficiency) (2021). Handbook of replicable designs for energy efficient residential buildings

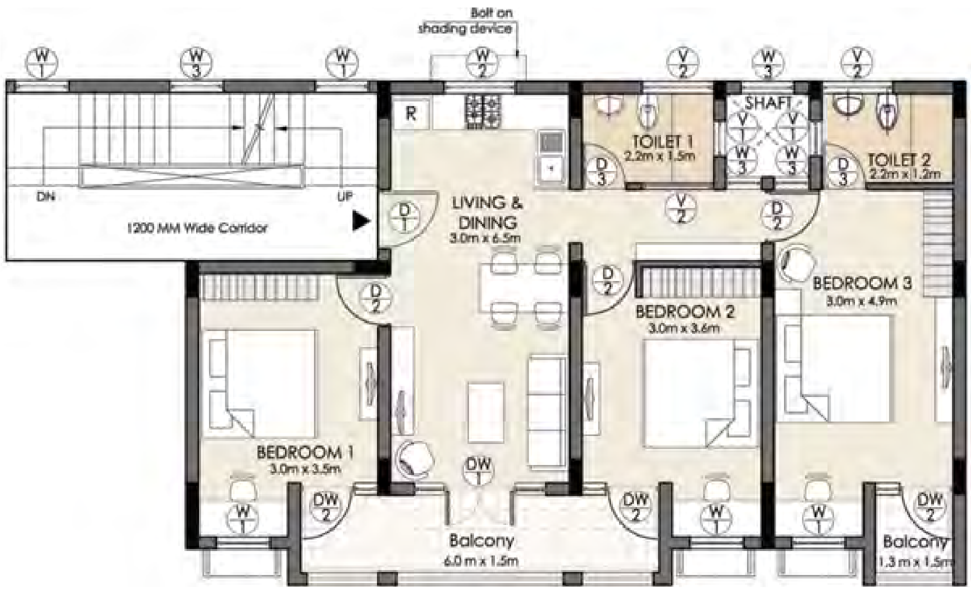
A.2.2. Building model description

Figure A.2.3 shows the floor plan of four representative buildings referred from the Handbook of Replicable Designs for Energy Efficient Residential Buildings. They are chosen based on existing building typologies surveyed in the urban residential sector of Uttarakhand.

(a)



(b)



(c)

Ground Floor Plan

First Floor Plan

(d)

Figure A.2.3. **Floor plan of Multifamily row house a) 1 BHK b) 2 BHK c) 3 BHK d) Detached unit in a cold climate.**

Table A.2.1 gives the spatial details of the four residences. It includes the house type, number of exposed sides, occupant type, building height, and the carpet area.

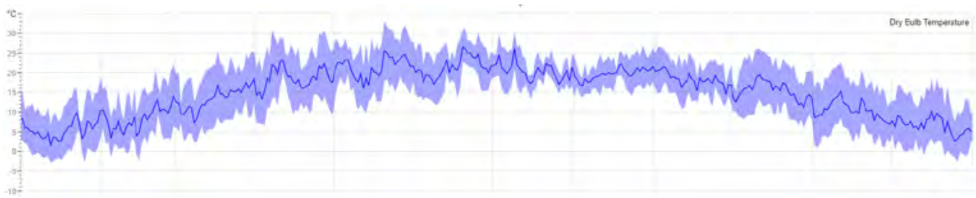
Table A.2.1 Details of representative buildings

PARAMETER	1BHK	2BHK	3BHK	4BHK / DUPLEX
House Type	Row House	Row House	Row House	Detached
Exposed Sides	Two	Two	Two	Four
Family Type	Multi Family	Multi Family	Multi Family	Single Family
Height	G+3	G+3	G+3	G+1
Carpet Area	32 m^2	51 m^2	70 m^2	243 m^2

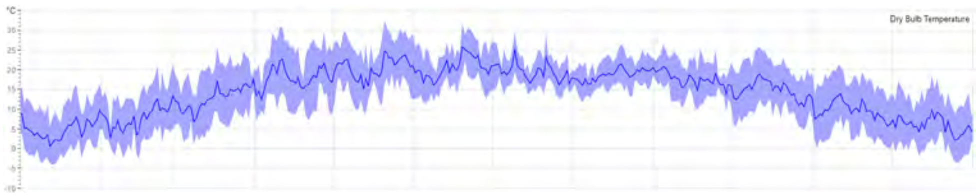
A.2.3. Climatic conditions of study locations

The locations covered in this report are Mussoorie, Chakrata, and Joshimath. They are chosen based on the difference in heating degree days calculated using the IMAC (Indian model for adaptive comfort) model. The heating degree days (HDD) for Mussoorie, Chakrata, and Joshimath are 3046, 3159, and 3520, respectively.

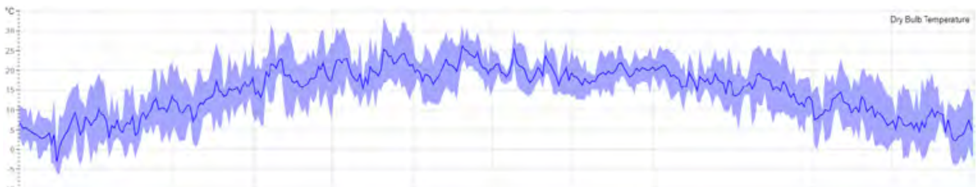
The climatic conditions in the three study locations are described in terms of average monthly dry bulb temperature, relative humidity, wind speed, and global solar radiation. The information for all the climate variables is obtained from the weather files downloaded using Meteonorm.



MUSSOORIE



CHAKRATA

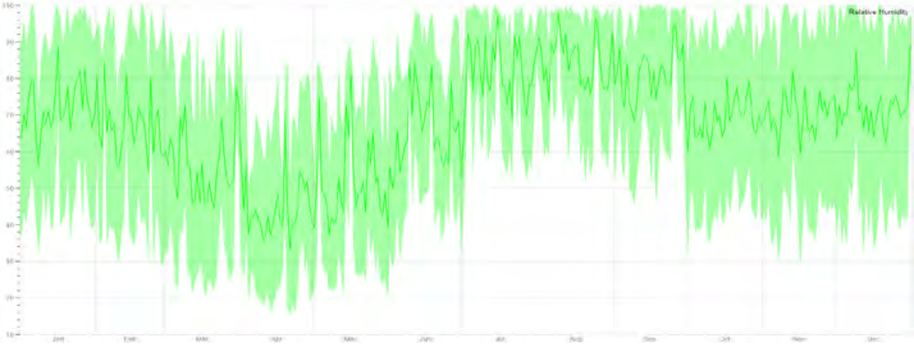


JOSHIMATH

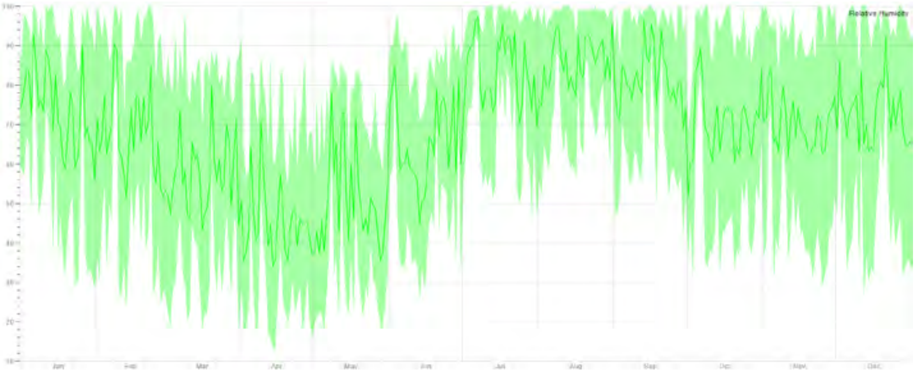
Figure A.2.4. Dry bulb temperature of a) Mussoorie, b) Chakrata and c) Joshimath

The DBT ranges between -2.9°C to 33°C for Mussoorie, -4°C to 32.4°C for Chakrata, and -6°C to 30°C for Joshimath. Figure A.2.5. shows the relative humidity is lowest in April and May and highest in July, August, and September for all three locations. The maximum wind speed goes up to 4.3 m/s in Mussoorie, 5 m/s in Chakrata, and 6 m/s in Joshimath.

MUSSOORIE

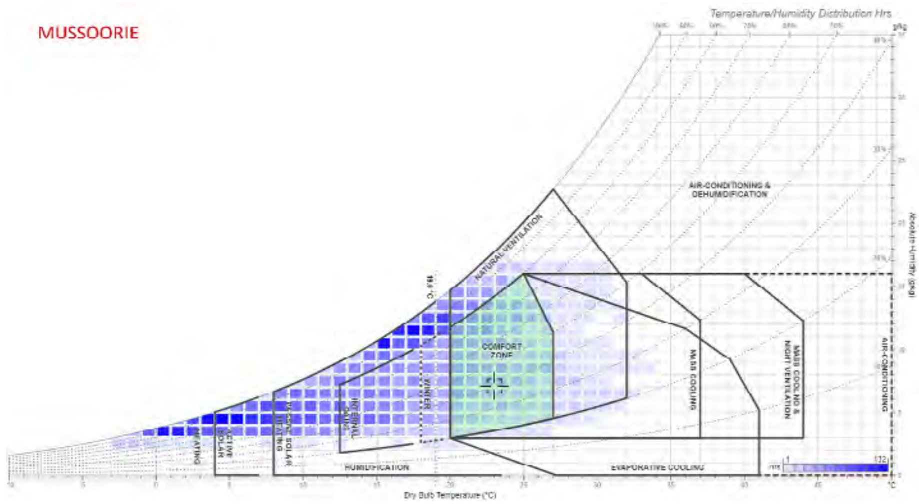


CHAKRATA



JOSHIMATH

Figure A.2.5. **Relative humidity of a) Mussoorie, b) Chakrata and c) Joshimath**



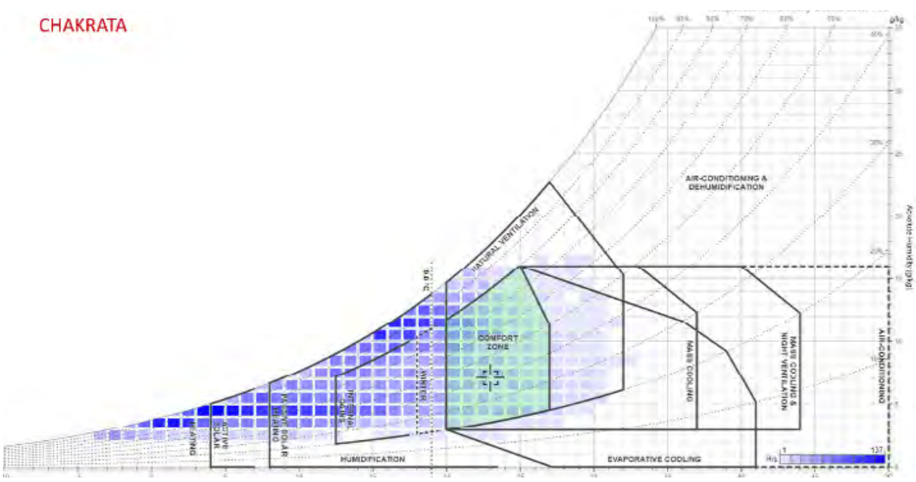


Figure A.2.6. **Psychrometric Chart for Mussoorie, Chakrata, and Joshimath**

Figure A.2.6 shows the psychrometric chart overlayed with Givoni's bioclimatic chart for the three locations. The psychrometric chart suggests internal gains, solar active and passive heating, and heating as the measures to maintain thermal comfort in residential buildings for the three locations.

The sun's relative position is a significant factor in building heat gain. Natural energy gains within a building can be maximized by exploiting the potential contribution to a building's performance offered by the site and its surroundings. The solar radiation received by the three locations is given in Figure A.2.7.

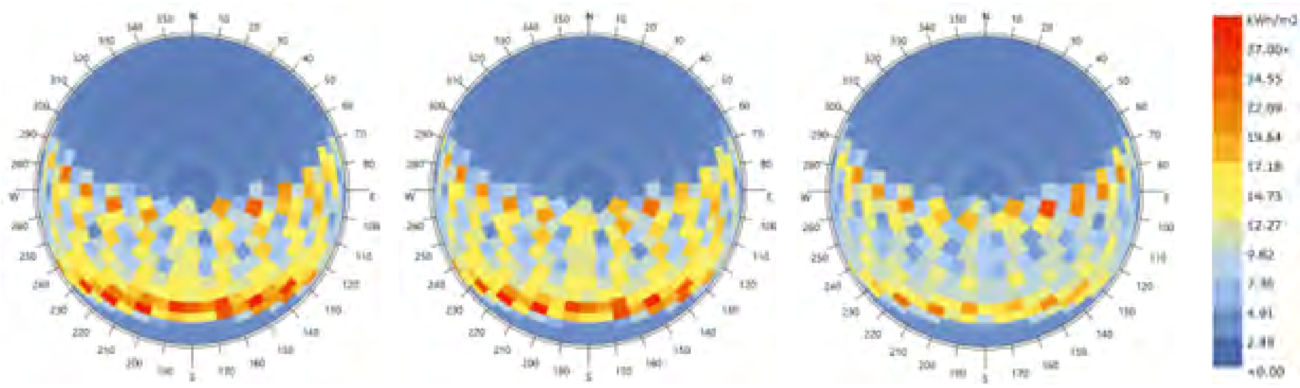


Figure A.2.7. Total Annual Solar radiation (kWh/m2) in Mussoorie, Chakrata and Joshimath.

To maximize the heat gain through direct radiation and minimize heating energy demand of buildings in cold climate, the buildings should be oriented towards the side with maximum solar insolation. Southwest, South, and Southeast orientations receive higher solar radiation in Mussoorie and Chakrata, while Joshimath receives maximum solar radiation in the East, Southwest, and west.

A.2.4. Impact of orientation, WWR, wall assemblies, roof assemblies, infiltration on heating energy demand

The Insulation material mentioned for wall and roof assemblies can be XPS panel, Polyurethane, Wood cladding, and Glass wool.

A.2.4.1 Simulation results for 2 BHK unit

Table A.2.2 Impact of orientation on the annual heating energy demand and monetary saving potential

ORIENTATION	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
N (BASELINE)	4716	NA	NA	5916	NA	NA	6333	NA	NA
N-E	4655	-1.3	359	5870	-0.7	271	6308	-0.4	147
E	4521	-4	1149	5690	-3.8	1331	6135	-3	1166
S-E	4235	-10	2833	5388	-9	3110	5922	-6	2421
S	3999	-15	4223	5155	-13	4482	5756	-9	3399
S-W	4195	-11	3069	5368	-9	3228	5911	-6	2486
W	4475	-5	1419	5644	-4.6	1602	6097	-3	1390
N-W	4677	-0.8	230	5915	-0.02	6	6327	-0.08	35

Table A.2.3 Impact of orientation on the annual carbon saving potential

ORIENTATION	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon [kg CO_2 eq.]	Variation (%)	Carbon Saving Potential (kg CO_2 eq.	Operational Carbon [kg CO_2 eq.]	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
N (BASELINE)	3726	NA	NA	4674	NA	NA	5003	NA	NA
N-E	3677	-1.3	48	4637	-0.7	36	4983	-0.4	20
E	3572	-4	154	4495	-3.8	179	4847	-3	157
S-E	3346	-10	380	4257	-9	417	4678	-6	325
S	3159	-15	566	4072	-13	601	4547	-9	456
S-W	3314	-11	412	4241	-9	433	4670	-6	334
W	3535	-5	190	4459	-4.6	215	4817	-3	187
N-W	3695	-0.8	31	4673	-0.02	1	4998	-0.08	5

Table A.2.4 Impact of WWR on the annual heating energy demand and monetary saving potential

SOUTH FACING WWR [%]	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
5	4051	+1.3		5209	+1.03		5785	+0.5	
10 (BASELINE)	3999	NA	NA	5155	NA	NA	5756	NA	NA
20	3929	-1.7	412	5066	-1.7	524	5687	-1.2	406
30	3857	-3.5	836	4993	-3.1	954	5614	-2.4	836

The annual heating energy demand reduces by 0.5% to 1.1% by using a double-glazing unit over a single glazing unit.

Table A.2.5. Impact of WWR on the annual carbon saving potential

SOUTH FACING WWR (%)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
5	3200	+1.3		4115	+1.03		4570	+0.5	
10 (BASELINE)	3159	NA	NA	4072	NA	NA	4547	NA	NA
20	3104	-1.7	55	4002	-1.7	70	4493	-1.2	55
30	3047	-3.5	112	3944	-3.1	128	4435	-2.4	112

Table A.2.6 Impact of wall assemblies on the annual heating energy demand and monetary saving potential

WALL TYPE (U-Value - W/ m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
Brick Wall (2.08) (BASELINE)	4716	NA	NA	5916	NA	NA	6332	NA	NA
Brick + insulation wall (1.36)	4659	-1.2	336	5855	-1.1	359	6330	-0.5	12
AAC wall (0.77)	4650	-1.4	389	5843	-1.2	430	6282	-0.8	295
AAC + insulation wall (0.62)	4622	-2	554	5833	-1.4	489	6278	-0.86	318
Fly-ash Brick wall (2.27)	4730	0.4	-82	5930	0.3	-83	6344	0.2	-71
Random Rubble Masonry wall (2.04)	4693	-0.5	135	5886	-0.5	117	6307	-0.4	147

Table A.2.7. Impact of wall assemblies on the annual carbon saving potential

WALL TYPE (U-Value - W/ m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
Brick Wall (2.08) (BASELINE)	3726	NA	NA	4674	NA	NA	5002	NA	NA
Brick + insulation wall (1.36)	3681	-1.2	45	4625	-1.1	48	5001	-0.5	2
AAC wall (0.77)	3674	-1.4	52	4616	-1.2	58	4963	-0.8	36
AAC + insulation wall (0.62)	3651	-2	74	4608	-1.4	66	4960	-0.86	43
Fly-ash Brick wall (2.27)	3737	0.4	-11	4685	0.3	-11	5012	0.2	-10
Random Rubble Masonry wall (2.04)	3707	-0.5	18	4650	-0.5	23	4983	-0.4	19

Table A.2.8 Impact of roof assemblies on the annual heating energy demand and monetary saving potential

ROOF TYPE (U-Value - W/m^2K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
RCC (2.08) (BASELINE)	3999	NA	NA	5155	NA	NA	5756	NA	NA
RCC + insulation (outside) (1.7)	3233	-19.2	4512	4176	-19	5766	4676	-18.7	6360
RCC + insulation (inside) (1.7)	3144	-21.4	5036	4095	-20.6	6243	4628	-19.6	6643

Table A.2.9. Impact of roof assemblies on the annual carbon saving potential

ROOF TYPE (U-Value - W/m^2K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
RCC (2.08) (BASELINE)	3159	NA	NA	4072	NA	NA	4547	NA	NA
RCC + insulation (outside) (1.7)	2554	-19.2	605	3299	-19	773	3694	-18.7	853
RCC + insulation (inside) (1.7)	2484	-21.4	675	3235	-20.6	837	3656	-19.6	891

Table A.2.10 Impact of air infiltration on the annual heating energy demand and monetary saving potential

AIR TIGHTNESS (ACH)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	VARIATION (%)	Saving Potential ( )	HED (kWh)	VARIATION (%)	Saving Potential ( )
POOR (1.5) (BASELINE)	3999	NA		5155	NA		5755	NA	
MODERATE (0.8)	3452	-13.6	3222	4540	-12	3622	5140	-11	3622
GOOD (0.5)	3270	-18.2	4294	4334	-16	4836	4942	-14	4789

Table A.2.11. Impact of air infiltration on the annual carbon saving potential

AIR TIGHTNESS (ACH)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	VARIATION (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	VARIATION (%)	Carbon Saving Potential (kg CO_2 eq.)
POOR (1.5) (BASELINE)	3159	NA		4072	NA		4546	NA	
MODERATE (0.8)	2727	-13.6	432	3587	-12	486	4061	-11	486
GOOD (0.5)	2583	-18.2	576	3424	-16	649	3904	-14	642

A.2.4.2 Simulation results for 3 BHK unit

Table A.2.12. Impact of orientation on the annual heating energy demand and monetary saving potential

ORIENTATION	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
N (BASELINE)	7014	NA	NA	8730	NA	NA	9264	NA	NA
N-E	7000	-0.2	82	8725	-0.05	29	9262	-0.02	12
E	6667	-5	2044	8337	-4.5	2315	8950	-3.4	1849
S-E	6299	-10	4211	7948	-9	4606	8637	-6.7	3693
S	5974	-15	6126	7667	-12	6261	8425	-9	4942
S-W	6240	-11	4559	7927	-9	4730	8615	-7	3823
W	6642	-5.3	2191	8325	-4.6	2385	8920	-3.7	2026
N-W	6965	-0.7	289	8695	-0.4	206	9232	-0.3	188

Table A.2.13. Impact of orientation on the annual carbon saving potential

ORIENTATION	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
N (BASELINE)	5541	NA	NA	6897	NA	NA	7319	NA	NA
N-E	5530	-0.2	11	6893	-0.05	4	7317	-0.02	2
E	5267	-5	274	6586	-4.5	310	7071	-3.4	248
S-E	4976	-10	565	6279	-9	618	6823	-6.7	495
S	4719	-15	822	6057	-12	840	6656	-9	663
S-W	4930	-11	611	6262	-9	634	6806	-7	513
W	5247	-5.3	294	6577	-4.6	320	7047	-3.7	272
N-W	5502	-0.7	39	6869	-0.4	28	7293	-0.3	25

Table A.2.14. Impact of WWR on the annual heating energy demand and monetary saving potential

SOUTH FACING WWR (%)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
5	6052	+1.3		7741	+0.9		8488	+0.75	
10 (BASELINE)	5974	NA	NA	7667	NA	NA	8425	NA	NA
20	5873	-1.7	595	7542	-1.6	736	8338	-1.02	512
30	5771	**-3.4**	1196	7409	**-3.3**	1520	8230	**-2.3**	1149

The annual heating energy demand reduces by 0.6% to 0.8% by using a double-glazing unit over a single glazing unit.

Table A.2.15. Impact of WWR on the carbon saving potential

SOUTH FACING WWR (%)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2)
5	4781	+1.3		6115	+0.9		6706	+0.75	
10 (BASELINE)	4719	NA	NA	6057	NA	NA	6656	NA	NA
20	4640	-1.7	80	5958	-1.6	99	6587	-1.02	69
30	4559	**-3.4**	160	5853	**-3.3**	204	6502	**-2.3**	154

Table A.2.16 Impact of wall assemblies on the annual heating energy demand and monetary saving potential

WALL TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
Brick Wall (2.08) (BASELINE)	7014	NA	NA	8,730	NA	NA	9265	NA	NA
Brick + insulation wall (1.36)	6916	-1.4	577	8622	-1.2	636	9164	-1.1	595
AAC wall (0.77)	6874	-2	825	8584	-1.6	860	9145	-1.3	707
AAC + insulation wall (0.62)	6853	-2.3	948	8551	-2	1054	9108	-1.7	925
Fly-ash Brick wall (2.27)	7294	0.4	-1649	8756	0.3	-153	9275	0.1	-59
Random Rubble Masonry wall (2.04)	6972	-0.6	247	8669	-0.7	359	9237	-0.3	165

Table A.2.17. Impact of wall assemblies on the annual carbon saving potential

WALL TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
Brick Wall (2.08) (BASELINE)	3726	NA	NA	4674	NA	NA	5002	NA	NA
Brick + insulation wall (1.36)	3681	-1.4	45	4625	-1.2	48	5001	-1.1	2
AAC wall (0.77)	3674	-2	52	4616	-1.6	58	4963	-1.3	39
AAC + insulation wall (0.62)	3651	-2.3	74	4608	-2	66	4960	-1.7	43
Fly-ash Brick wall (2.27)	3737	0.4	-11	4685	0.3	-11	5012	0.1	-9
Random Rubble Masonry wall (2.04)	3707	-0.6	18	4650	-0.7	24	4983	-0.3	20

Table A.2.18 Impact of roof assemblies on the annual heating energy demand and monetary saving potential

ROOF TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
RCC (2.08) (BASELINE)	5974	NA	NA	7667	NA	NA	8425	NA	NA
RCC + insulation (outside) (1.7)	4840	-19	6679	6287	-18	8128	6993	-17	8434
RCC + insulation (inside) (1.7)	4738	-20.7	7280	6211	-19	8576	6910	-18	8923

Table A.2.19. Impact of roof assemblies on the annual carbon saving potential

ROOF TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
RCC (2.08) (BASELINE)	4719	NA	NA	6057	NA	NA	6656	NA	NA
RCC + insulation (outside) (1.7)	3824	-19	896	4967	-18	1090	5524	-17	1131
RCC + insulation (inside) (1.7)	3743	-20.7	976	4907	-19	1150	5459	-18	1197

Table A.2.20 Impact of infiltration on the annual heating energy demand and monetary savings potential

AIR TIGHTNESS (ACH)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	VARIATION (%)	Saving Potential ( )	HED (kWh)	VARIATION (%)	Saving Potential ( )
POOR (1.5) (BASELINE)	5974	NA		7667	NA		8425	NA	
MODERATE (0.8)	5172	-13.4	4724	6737	-12	5478	7526	-11	5295
GOOD (0.5)	4909	-17.8	6273	6446	-16	7192	7234	-14	7015

Table A.2.21. Impact of infiltration on the annual carbon saving potential

AIR TIGHTNESS (ACH)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	VARIATION (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	VARIATION (%)	Carbon Saving Potential (kg CO_2 eq.)
POOR (1.5) (BASELINE)	4719	NA		6057	NA		6656	NA	
MODERATE (0.8)	4086	-13.4	634	5322	-12	735	5946	-11	710
GOOD (0.5)	3878	-17.8	841	5092	-16	965	5715	-14	941

A.2.4.3 Simulation results for 4 BHK unit

Table A.2.22 Impact of orientation on the annual heating energy demand and monetary saving potential

ORIENTATION	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
N (BASELINE)	6618	NA	NA	8815	NA	NA	9902	NA	NA
N-E	6545	-1.1	430	8752	-0.7	371	9854	-0.5	283
E	5569	-15.8	6179	7667	-13	6762	8989	-9	5378
S-E	5402	-18.3	7162	7482	-15	7851	8827	-11	6332
S	4963	-25	9748	6974	-21	10843	8423	-15	8711
S-W	5406	-18.3	7139	7499	-15	7751	8816	-11	6397
W	5536	-16.3	6373	7623	-13.5	7021	8930	-10	5725
N-W	6580	-0.6	224	8752	-0.7	371	9884	-0.2	106

Table A.2.23. Impact of orientation on the annual carbon saving potential

ORIENTATION	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
N (BASELINE)	5228	NA	NA	6964	NA	NA	7823	NA	NA
N-E	5171	-1.1	58	6914	-0.7	50	7785	-0.5	38
E	4400	-15.8	829	6057	-13	907	7101	-9	721
S-E	4268	-18.3	961	5911	-15	1053	6973	-11	849
S	3921	-25	1307	5509	-21	1454	6654	-15	1168
S-W	4271	-18.3	957	5924	-15	1040	6965	-11	858
W	4373	-16.3	855	6022	-13.5	942	7055	-10	768
N-W	5198	-0.6	30	6914	-0.7	50	7808	-0.2	14

Table A.2.24 Impact of WWR on the annual heating energy demand and monetary saving potential

SOUTH FACING WWR (%)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
5	5237	+5.5	-	7266	+4.2	-	8751	+3.9	-
10 (BASE-LINE)	4964	NA	NA	6974	NA	NA	8423	NA	NA
20	4667	-6	1749	6654	-4.6	1885	8087	-4	1979
30	4518	-9	2627	6464	-7.3	3004	7833	-7	3487

The annual heating energy demand reduces by 0.5% to 1.1% by using a double-glazing unit over a single glazing unit.

Table A.2.25. Impact of WWR on the annual carbon saving potential

SOUTH FACING WWR (%)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
5	4137	+5.5	-	5740	+4.2	-	6913	+3.9	-
10 (BASELINE)	3922	NA	NA	5509	NA	NA	6654	NA	NA
20	3687	-6	235	5257	-4.6	253	6389	-4	265
30	3569	-9	352	5107	-7.3	403	6188	-7	466

Table A.2.26 Impact of wall assemblies on the annual heating energy demand and monetary saving potential

WALL TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
Brick Wall (2.08) (BASELINE)	6618	NA	NA	8815	NA	NA	9902	NA	NA
Brick + insulation wall (1.36)	6122	-7.5	2921	8198	-7	3634	9249	-6.6	3846
AAC wall (0.77)	5735	-12.6	5201	7722	-12.4	6438	8813	-11	6414
AAC + insulation wall (0.62)	5652	-14.6	5690	7555	-14.3	7421	8615	-13	7580
Fly-ash Brick wall (2.27)	6777	+2.4	-937	9011	+2.2	-1154	10099	+2	-1160
Random Rubble Masonry wall (2.04)	6497	-1.8	713	8671	-1.6	848	9788	-1.1	671

Table A.2.27. Impact of wall assemblies on the annual carbon saving potential

WALL TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
Brick Wall (2.08) (BASELINE)	5228	NA	NA	6964	NA	NA	7823	NA	NA
Brick + insulation wall (1.36)	4836	-7.5	392	6476	-7	487	7307	-6.6	516
AAC wall (0.77)	4531	-12.6	698	6100	-12.4	863	6962	-11	860
AAC + insulation wall (0.62)	4465	-14.6	763	5968	-14.3	995	6806	-13	1017
Fly-ash Brick wall (2.27)	5354	+2.4	-126	7119	+2.2	-155	7978	+2	-156
Random Rubble Masonry wall (2.04)	5133	-1.8	96	6850	-1.6	114	7733	-1.1	90

Table A.2.28 Impact of roof assemblies on the annual heating energy demand and monetary saving potential

ROOF TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	Variation (%)	Saving Potential ( )
RCC (2.08) (BASELINE)	4964	NA	NA	6977	NA	NA	8423	NA	NA
RCC + insulation (outside) (1.7)	4617	-7	274	6559	-6	330	8002	-5	333
RCC + insulation (inside) (1.7)	4170	-16	627	5919	-15.3	836	7354	-12.7	845

Table A.2.29. Impact of roof assemblies on the annual carbon saving potential

ROOF TYPE (U-Value - W/m²K)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)
RCC (2.08) (BASELINE)	3922	NA	NA	5512	NA	NA	6654	NA	NA
RCC + insulation (outside) (1.7)	3647	-7	2044	5182	-6	2462	6322	-5	2480
RCC + insulation (inside) (1.7)	3294	-16	4677	4676	-15.3	6232	5810	-12.7	6296

Table A.2.30. Impact of infiltration on the annual heating energy demand and monetary saving potential

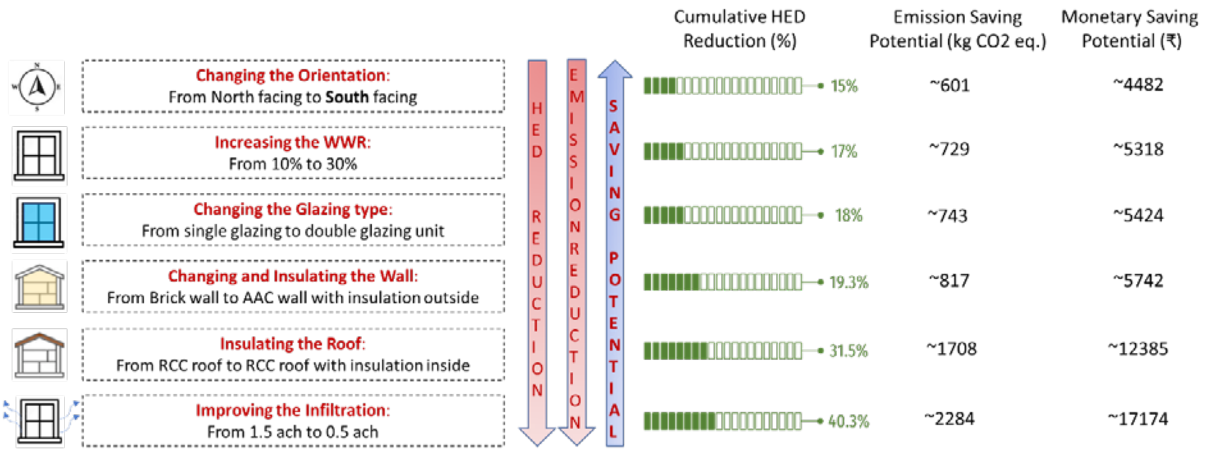
AIR TIGHTNESS (ACH)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	HED (kWh)	Variation (%)	Saving Potential ( )	HED (kWh)	VARIATION (%)	Saving Potential ( )	HED (kWh)	VARIATION (%)	Saving Potential ( )
POOR (1.5) (BASELINE)	4964	NA		6974	NA		8423	NA	
MODERATE (0.8)	4520	-13.4	2615	6474	-12	2945	7885	-11	3169
GOOD (0.5)	4366	-17.8	3522	6270	-16	4147	7689	-14	4323

Table A.2.31. Impact of infiltration on the annual carbon saving potential

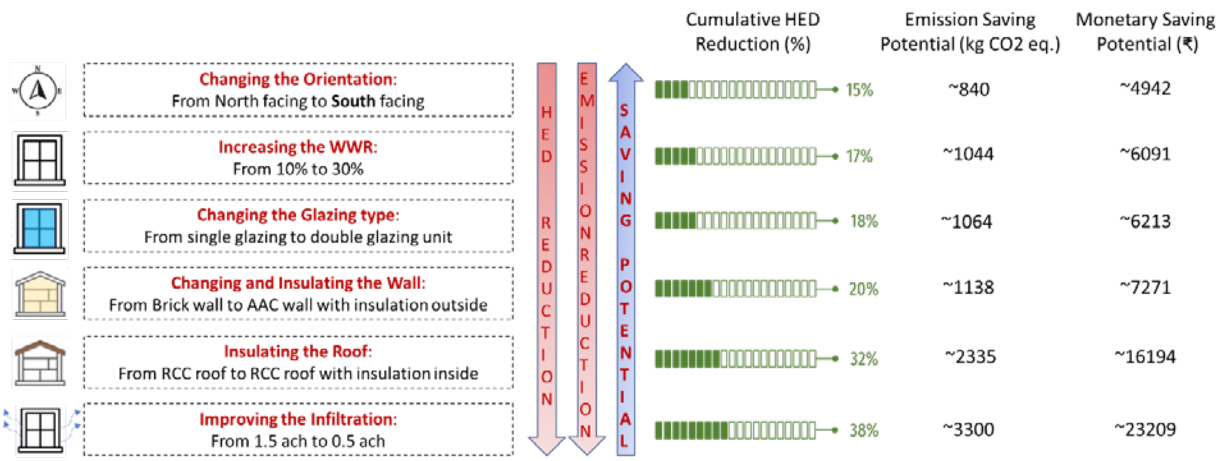
AIR TIGHTNESS (ACH)	MUSSOORIE			CHAKRATA			JOSHIMATH		
	Operational Carbon (kg CO_2 eq.)	Variation (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	VARIATION (%)	Carbon Saving Potential (kg CO_2 eq.)	Operational Carbon (kg CO_2 eq.)	VARIATION (%)	Carbon Saving Potential (kg CO_2 eq.)
POOR (1.5) (BASELINE)	3922	NA		5509	NA		6654	NA	
MODERATE (0.8)	3571	-13.4	351	5114	-12	395	6229	-11	425
GOOD (0.5)	3449	-17.8	472	4953	-16	556	6074	-14	580

A.2.5. Incremental energy conservation measures (ECMs)

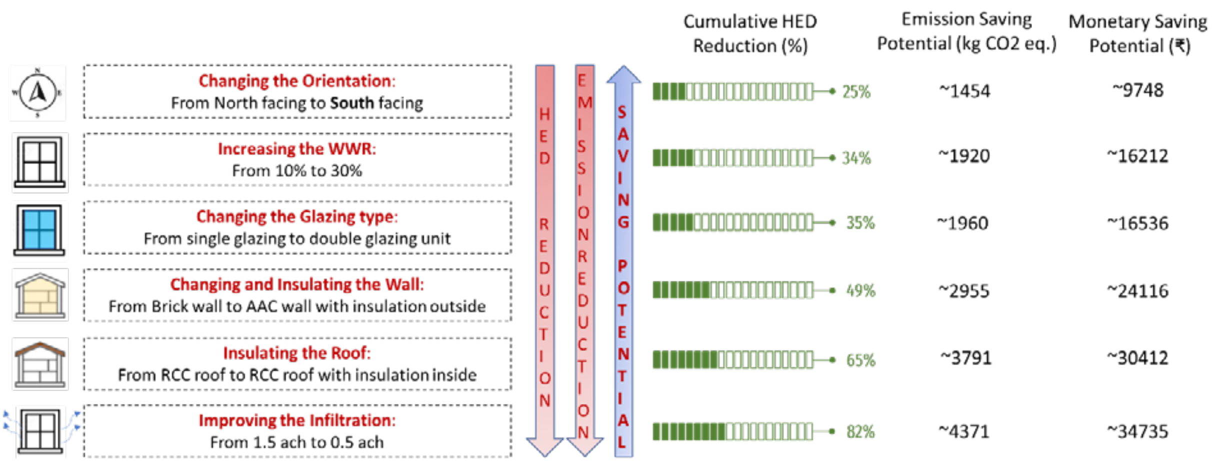
The HED reduction is calculated incrementally to observe the impact of ECMs on HED, monetary and carbon saving potential. The ECMs for a 2 BHK, 3 BHK, and 4 BHK residence are given in Figures A.2.8.



(a)



(b)



(c)

Figure A.2.8. **Schematic of incremental impact of ECM on HED reduction, emission reduction and monetary saving potential for (a) 2-BHK, (b) 3-BHK and (c) 4-BHK**

A.2.6. Parametric evaluation of envelope properties

A parametric analysis of the building envelope was carried out to minimize the heating energy demand. The three independent variables considered for the parametric evaluation are Orientation, WWR, and Wall U-value. The range of these three variables are given in Table A.2.16. The range of wall U-values was calculated by adding XPS insulation of thickness ranging between 5 mm to 50 mm to a 110 mm Brick wall.

Table A.2.16. **Low and High values of the parameters used for parametric evaluation**

PARAMETER	Low	High
ORIENTATION	0 deg	315 deg
WWR	5 %	30 %
Wall U-value	0.6 W/m^2K	3 W/m^2K

Latin hypercube sampling is adopted to obtain 59 combinations for performing the optimization for a typical 1 BHK House. These 59 runs are simulated, and their response for heating energy demand is calculated. Figure A.2.9 explains the impact of the wall U-value on the heating energy demand with 10% WWR facing north, south, east, and west.

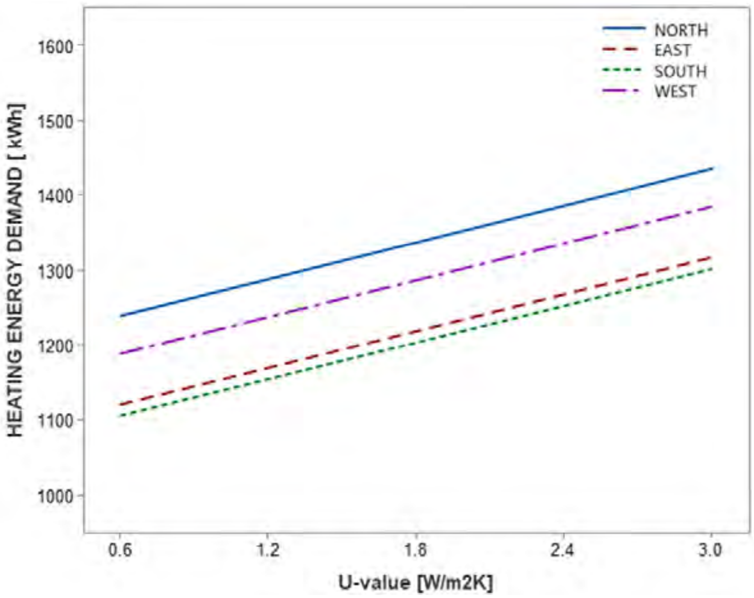


Figure A.2.9. **Impact of Wall U-value on Heating Energy Demand for North, South, East and West façade with 10% WWR**

For the north, south, east, and west façade the wall U-value positively affects the heating energy demand, which means higher the U-value higher the heating energy demand. North and South facades have the highest and lowest heating energy demand. The heating energy demand for a west facade is higher than for an east facade.

For the north, south, east, and west façade, the WWR affects the heating energy demand negatively, which means higher the WWR lower the heating energy demand. Figure A.2.10 shows the impact of WWR on the Heating energy demand for a building with a wall U-value = 0.6 W/m^2K. The combination of a wall U-value of 0.6 W/m^2K, with 30% WWR facing south, is optimal for minimizing the heating energy demand.

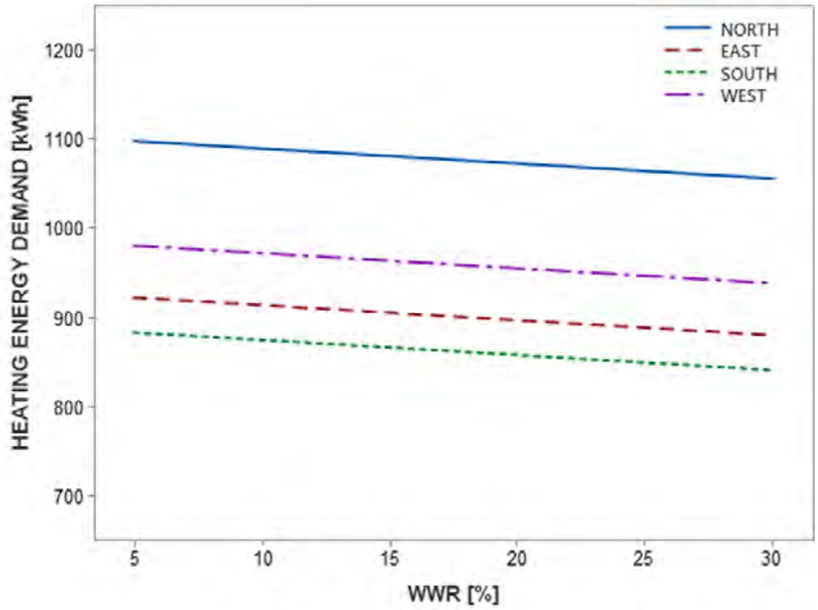


Figure A.2.10. **Impact of WWR on Heating energy demand North, South, East, and West façade with wall U-value = 0.6 W/m²K**

A.2.7. Energy Performance Index (EPI)

The weather data of 54 locations are taken with varying climate severities to evaluate the annual heating and cooling energy demand. The EPI is compared for a base case building and an optimum case building. The following conditions are given in the base case building: The building is oriented north with 5% WWR and the U-value of wall is taken as 3 W/m²K. The following conditions are given in the optimum case building: The building is oriented south with 30% WWR and the U-value of wall is taken as 0.6 W/m²K. Figure A.2.11-12 shows a map of Uttarakhand developed in GIS comparing the Energy Performance Index (EPI) of the base case building and the optimum case building.

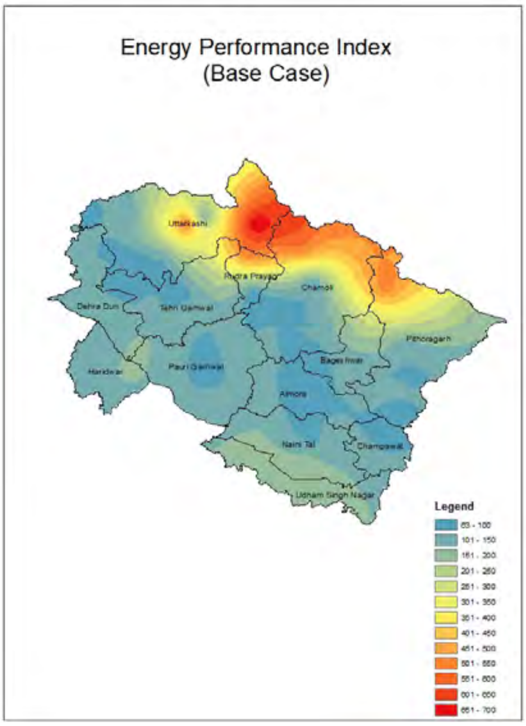


Figure A.2.11. **EPI mapping of base case building in Uttarakhand**

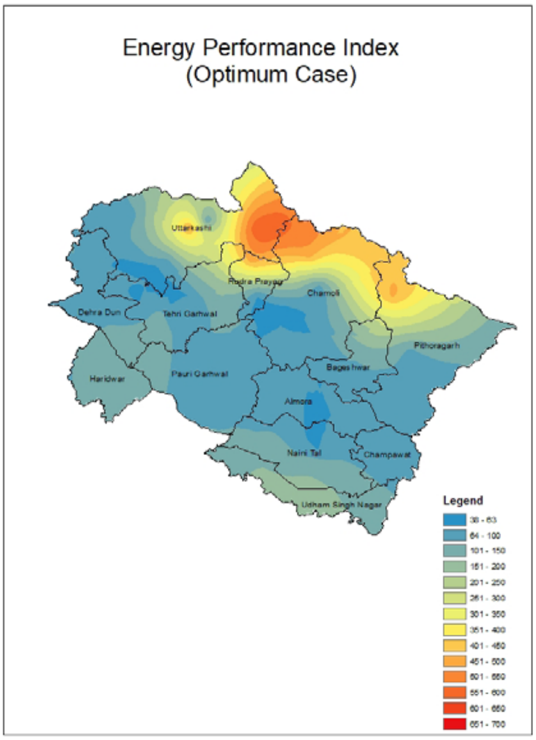


Figure A.2.12. **EPI mapping of optimum case in Uttarakhand**

Appendix 3:
AAC Block with Insulation wall assembly making process

Snapshots shown in Figure A.3.1 have been taken from the videos prepared by the project team to showcase during the capacity building workshop

Step 1: 200 mm thick AAC Block

Step 2: Curing AAC Block

Step 3: 5-10 mm AAC Block ADHESIVE by Laticrete

Step 4: Place the another AAC Block and repeat the process

Step 5: Proper alignment of AAC Block

Step 6: Fill groves between AAC Blocks

Step 7: Wood framing to hold insulation layer on AAC Blocks

Step 8: Insert 25 mm insulation layer (XPS sheet) in the wood frame

Step 9: Preparation of Gypsum Board for exterior finish

Step 10: Attach Gypsum Board with wood frame to complete the wall

Figure A.3.1. **Step by step process of AAC Block with insulation wall assembly making process**

Appendix 4:
Proceedings from the workshops conducted to disseminate project findings

Event 1: Stakeholder Discussion

Program details:

Stakeholder discussion on the Deployment of Climate Responsive and Low Carbon Building Construction Practices in Uttarakhand

Date: February 15, 2023 Time: 10:30 AM to 1:00 PM

Venue: Vichar Hall, Hotel Madhuban, Dehradun

The event started with an overview of the Alliance for an Energy Efficient Economy and an overview of the project. A round table discussion dialogue was held after the same, the key takeaways from which are summarised below:

- Thermal comfort needs to be approached in a multi-pronged and inter-disciplinary way. People need to be sensitized towards the usage of cooling devices and how they approach the ambient temperature required for absolute thermal comfort.
- There is a need to move from reactive to proactive stands regarding climate change. Changes in housing design strategies should be made so that thermal comfort for people is not an afterthought but is integrated into the building envelope. Hence, the house is thermally comfortable and energy efficient in terms of architectural design. An example of rainwater harvesting was given, as how it used to be a recommendation, but now several states have integrated rainwater harvesting into their building bye-laws. Such advances also need to be made in the area of thermal comfort.
- Major advances can be made through behavioural changes, as in hilly areas, people are used to living in a different kind of temperature setting than the plains. Changes on the policy level where there are set ambient temperature settings re-defined for different appliances used for cooling, for different regions can result in a more energy efficient usage of appliances and electricity.
- For the deployment of thermally comfortable and energy-efficient building design, implementing agencies can lead by example with the help of demonstration projects.

Figure A.4.1. **Various stakeholders from Academia, Private sector and Public Sector attended the stakeholder discussion and provided valuable feedback on the findings**

Figure A.4.2. **Stakeholders being presented the project findings from AEEE and IITR**

Figure A.4.3. **Keynote Address by Professor Chandel on climate conscious construction in Uttarakhand**

Event 2: Capacity Building Workshop

Program details:

Capacity Building Workshop on "Deployment of Climate Responsive and Low Carbon Building Construction Practices in Uttarakhand"

Date: March 5, 2023 Time: 10:30 AM to 1:00 PM

Venue: Sunita Elite Hotel, Mall Rd, opposite K.M.O.U Bus Station, near SBI Bank, Paltan Bazar, Dharanaula, Almora

The second event focused on capacity building by creating a near-term deployment plan for climate-responsive and low-carbon building construction practices. The session included group discussions to identify the challenges and opportunities in deploying sustainable construction practices in the Indian Himalayan Region (IHR) states.

A workshop followed by a two-way dialogue was held after the same, the key takeaways from which are summarised below:

- Affordability of alternative solutions is a definite concern. This suggests that while there are benefits to transitioning to climate responsive and low carbon construction methods, such as improved thermal comfort, durability and energy efficiency, the cost of implementing these solutions may be a barrier for some people. This consideration underscores the need for finding cost-effective solutions that balance the benefits of energy-efficient construction with affordability.

- People know the pros and cons of transition in vernacular vs contemporary construction. This suggests that there is a level of knowledge and understanding among the public regarding the advantages and disadvantages of different construction methods. This awareness can help inform decision-making and facilitate a smoother transition.
- There are certain setbacks in the current general practice of construction of houses that need to be addressed. Constructions using vernacular materials are prone to getting dilapidated, suggesting that a mix of contemporary and vernacular construction practices needs to be disseminated in the hilly regions. Capacity building of field level stakeholders like mason can help with the same
- The work of a select group of architects who have successfully blended traditional or vernacular architecture with modern or contemporary design can serve as an inspiration for others in the field and may also be seen as a model for the local population to follow.

Figure A.4.4 **Private and Public Stakeholders who attended the workshop including masons, Contractors and Architects from the Almora region**

Figure A.4.5. **Gathering of stakeholders from the top to bottom of the housing construction process**

Figure A.4.6. **AEEE presenting the findings of the project and demonstrating usage of AAC Blocks**

Event 3: Capacity Building Workshop

Program details:

Capacity Building Workshop on "Deployment of Climate Responsive and Low Carbon Building Construction Practices in Uttarakhand"

Date: March 16, 2023 Time: 10:30 AM to 1:00 PM

Venue: Hotel Tehri Himalaya Residency, New Tehri.

A workshop followed by a two-way dialogue was held after the same, the key takeaways from which are summarised below:

- People have a sense of how ecological impacts have posed many questions on infrastructure development in the region as seen by examples posed by disasters in the Indian Himalayan region. There is a growing awareness of the environmental impact of construction and a need to consider sustainable solutions that minimize ecological impacts. This underscores the importance of sustainability in the construction industry and the need to prioritize environmental considerations in the decision-making process.
- A culture of competition has been instrumental in the increase in the usage of contemporary construction materials in Uttarakhand. As cities like Dehradun have moved to construction practices that involve new contemporary materials, it is important to increase awareness in the rural areas of Uttarakhand that they don't follow the same in light of the ecological balance that needs to be integrated into the construction practices of these areas.
- A common problem in the usage of vernacular materials for making houses is that it is a time-intensive process. People are now opting for RCC and Brick houses because of the ease of Usage and fast-paced delivery of housing using these materials. This can be an area of research.
- Some people in the area are aware of new alternate construction materials like AAC Blocks and the benefits of using them. But there is still a need of awareness generation and capacity building for the deployment of low carbon and constructive materials in the area so that it becomes an integral part of the prevalent construction practices of the state.

Figure A.4.7. Gathering of stakeholders from the Municipal Corporation, Public Schools, Architects, Contractors and Masons

Figure A.4.8. Demonstration by AEEE and IITR

Figure A.4.9. Discussion with the participants

Event 4 Stakeholder Discussion

Program details:

Stakeholder Discussion on "Climate Responsive and Low Carbon Development for Residential and Transport sectors in Uttarakhand"

Date: March 21, 2023 Time: 10:30 AM to 1:00 PM

Venue: Somerset Hall, Keys Prima by Lemon Tree Hotels, Aketa, Dehradun, 113, 1-2, Rajpur Rd, Dehradun.

Context setting

This was the final event of the NMHS Project, with the first half set for stakeholder consultation and capacity building for the deployment of climate-responsive and low-carbon building construction practices in Uttarakhand and second half for Report Launch on Guidelines for Climate responsive and Low carbon building design in the cold climate of Uttarakhand.

Welcome Address

On behalf of the organizing team (AEEE, IIT Roorkee, UITP, and NMHS) Dr. Satish Kumar, President and Executive Director,AEEE welcomed all the experts, stakeholders, and participants to the event. He briefly explained about the energy consumption scenario and need for this project reflecting its importance on the residential sector & transportation sector in the cold climate of Uttarakhand.

Keynote Address

Dr. Anjali Krishan Sharma,Director, DIT emphasized the role of cities in implementing global development and climate goals. She raised questions that provprovokedughts on type of construction practices happening in Hilly areas and peri-urban areas of Uttarakhand and the need for identification of key building construction envelopes. She also emphasized the need for better road networks, the carrying capacity of roads, and need to make junctions for ease of pedestrian traffic. A better action-oriented approach to Land use planning of Uttarakhand and facilities for Electric vehicles were also discussed.

Vipul Kumar from UITP highlighted the significance for the transition to E-buses rapidly and the challenges in the deployment of EV infrastructure in the state.

Dr. Rajashekar, Associate Professor, IIT Roorkee, shared an overview of the methodology followed for the data collection on the NMHS project and selection of study area. He mentioned how thermal Responses of the building were recorded and, based energy profiling was inferred.

Dr. Bhaskar Natrajan, AEEE concluded the session by sharing insights on the study and global scenario of GHG emissions, the impact of climate change, and hence the need for us to conserve ecologically sensitive areas like Himalayan states. He further explained the content of the compendium for the residential and transport sector, including enabling a framework, implementation and technical aspects, and enabling factors/obstacles inferred from the project.

Stakeholder discussion

- Private builders and practicing architects find it challenging in implementing green buildings as the clients, from the government to end users lack awareness on cost to benefit ratio of going for green buildings. They are also unaware of how new technologies, the right combination of building materials & its life cycle analysis can affect the performance of buildings, helping in cutting the cost as residents use it. This is the way forward for green & energy-efficient buildings and better awareness is of prime importance.
- Perceiving the end-user on the benefits of green building are generally through the cost of materials, the life of materials and labor work involved. The key components in deciding materials for building envelopes should be thermal conductivity over aesthetics. A ready reckoner that can provide quick reference/solutions to a client's anticipations on green buildings will be a way forward for private builders/practicing architects.
- Challenges that are preventing authorities like MDDA from including energy efficient materials in Public Works are lack of these materials details in DSR or building codes; Details in ECBC code & Green building chapters in building bye-laws, schedule of rates are submitted for incorporation, DSR is in the process of revision where energy efficient materials will be included.
- Considering aspects of Earthquake resilience while designing a thermally efficient building is the need of the hour, thus interdisciplinary research is the way forward.

Figure A.4.10. Launch of guidelines report titled: "Guidelines for Climate Responsive and Low Carbon Building Design in the Cold Climate of Uttarakhand", "International Best Practices: Energy Efficiency Practices and Policies in Cold Regions" and the "Guidebook for Achieving Thermal Comfort and Energy Efficiency in the Residences of Uttarakhand"

Figure A.4.11. Group of stakeholders that gathered for the stakeholder discussion comprised of academicians from different universities, government officials from UREDA, MDDA, Smart City Mission, private agencies like UITP, UTC, Architects and students.

Figure A.4.12. Gathering of Stakeholders listening to the project findings being presented by AEEE and IITR

Figure A.4.13. The Project Team from AEEE and IITR

Authorship **Contribution Statement**

Brijesh Pandey

Writing - original draft, writing, reviewing and editing

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Primary data collection, simulation analysis, data curation, investigation and visualization, writing, reviewing and editing

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