Study of Effectiveness of Passive Design Methods for Residential Buildings in Pakistan

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出版情報：Kyushu University, 2021, 修士, 修士
バージョン：
権利関係：

Study of Effectiveness of Passive Design Methods for Residential Buildings in Pakistan

A thesis

submitted in fulfillment of the requirements for the degree

of

Master of Engineering [Department of Energy and Environmental Engineering]

at

Kyushu University

by

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九州大学
KYUSHU UNIVERSITY

2021

Contents

ABSTRACT

Pakistan is 6th most populous country of the world. In 2017, the population of Pakistan was 207.7 million with average household size of 6.39. The 6th population census recorded that there are 31.916 million dwellings in Pakistan. Pakistan is facing a shortfall of 0.7 million houses, annually. The private sector of Pakistan is adding 0.3 million dwellings every year. The present government has announced that it is going to construct 5 million houses by 2023. The regulation of housing sector is not centralized, and housing sector is regulated by different regulatory authorities at city and district level. There is no provision for energy efficiency for residential sector in national building codes or the regulations of city / district level building regulatory authorities. Being a developing country, the energy needs of Pakistan are increasing by every year. Also, the country is facing energy crisis which adversely impacted the growth of its economy. The situation calls for an urgent need of introduction of energy efficiency in different consumer sectors. It may be noted that residential sector in Pakistan is major consumer of energy. Hence, introduction of energy efficiency techniques in residential sector is very important. Several energy efficiency techniques can save energy in residential sector while improving the indoor thermal comfort in the sector. Energy efficiency in residential sector is not common in Pakistan neither enforced by the regulators. The houses are constructed with very heavy thermal mass and leaky building envelops. The appliances used in houses are not energy efficient. Use of insulation materials during construction is not common. This resulted into an energy inefficient residential sector in Pakistan.

This study is based on computer simulation of a representative Pakistani house. The simulation model was first developed using a computer program called SketchUp. The developed model was then simulated using another software called EnergyPlus. The focus of this research was to study the impacts of shading on windows, insulation materials, and orientation of the dwelling on indoor climate variables and energy consumption of the house. To study the impact of these parameters, a total of thirteen models were developed in four different categories. These categories were (i) without ventilation (ii) natural ventilation (iii) HVAC and (iv) orientation. Initially, in each category, a model without shading and insulation was developed and simulated. Then shadings were added to the initial model and the effects of shadings were studied. In next step, insulation materials were added to the external walls and roof. This model was simulated and effect of insulation materials on indoor climate variables were studied.

Shading devices do not prove to be effective for improving the indoor comfort variables. The reason behind ineffectiveness of shadings is the position of windows in the model. Windows of both the bedrooms were situated in open verandas where no direct sunlight was incident upon these windows. Addition of insulation materials appeared to be the most effective technique to improve the indoor comfort conditions and energy efficiency. In winter, addition of insulation materials almost vanished the heating load of the house while in summer, a significant decrease in cooling load has been noticed. The orientation of house also has an impact on the indoor thermal comfort of the house. House, whose long axis is oriented in west direction had improved indoor comfort conditions.

ACKNOWLEDGMENT

I would like to extend my gratitude to my supervisor, Prof. Aya HAGISHIMA for granting me the opportunity of working under her supervision and studying in one of the world's best university. She remained a source of support throughout my stay in Japan in academic and general life. Her guidance, help and support enabled me to face the challenges, I encountered during my research and complete my masters' thesis. Her kind and calm nature made it possible to consult with her regarding minutest issues regarding my studies and research. It would not be possible for me to embark on this journey of research without her supervision, guidance, and encouragement.

Also, I am thankful to all the professors and teachers of Energy and Environmental Engineering (EEE) department for sharing knowledge and experience in the field of Energy and Environmental Engineering which equipped me to face the challenges of future. I also acknowledge the support of my fellow students at Urban Architectural Environment Engineering Laboratory. I am obliged to JDS for sponsoring my study in Japan and their continuous support in making my life comfortable and smooth here.

Last but not the least, I would like to thank my parent for being a constant mental and spiritual support. I cannot thank them enough for sacrificing their own comfort and making it sure that I achieve my goals. I am thankful to my spouse for believing in me and pushing me beyond my comfort zone.

Ishtiaq Ahmad

1. INTRODUCTION

1.1. Country Profile

Pakistan is a country spreading over 796,096 km^2 and ranked World's 33rd largest country in terms of area. The 6th Population and Housing Census was conducted in Pakistan in 2017, and the results were approved by the Council of Common Interests (CCI) on 12th April 2021. CCI is a high-power forum in Pakistan having Prime Minister, Provincial Chief Ministers and Federal Minsters for Finance & Revenue, Industries & Production, and Interprovincial Coordination as members. According to the 6th population and Housing Census, the total population of Pakistan was recorded to be 207.77 Million [1], which is the 6th most populous country. Noted that the previous population and housing census was conducted in 1998, and average population growth is 2.4% from 1998 to 2017. The 6th census indicates that 36.44% population of Pakistan was living in urban areas, spread all over the country. The rate of growth of urban population in Pakistan is 3%, which is highest in South Asia, and it is expected that in 2025 half of the population of Pakistan will be living in urban areas. Top ten major cities of the Country are home to 21.8% (45,306,332 people) of the total population of the country.

Table 1.1: Big Cities of Pakistan and their population [2]

Sr. No.	Name of the city	Population (million)
01	Karachi City	14.91
02	Lahore City	11.12
03	Faisalabad M. Corp	3.20
04	Rawalpindi	2.09
05	Gujranwala M. Corp	2.02
06	Peshawar City	1.97
07	Multan City M. Corp	1.87
08	Hyderabad	1.73
09	Islamabad M. Corp	1.01
10	Quetta City	1.00

The yearly population data of Pakistan could not be found on website of Pakistan Bureau of Statistics (PBS). Therefore, data from World Bank website is used for Fig.1.1 and Fig.1.2. As per World Bank's data, there is a steady raise in population of Pakistan from 1998 to 2020. In 2020, World Bank estimates the population of Pakistan at 221 million. However, the annual growth rate of population has decreased from 2.85% in 1998 to 1.98% in 2020.

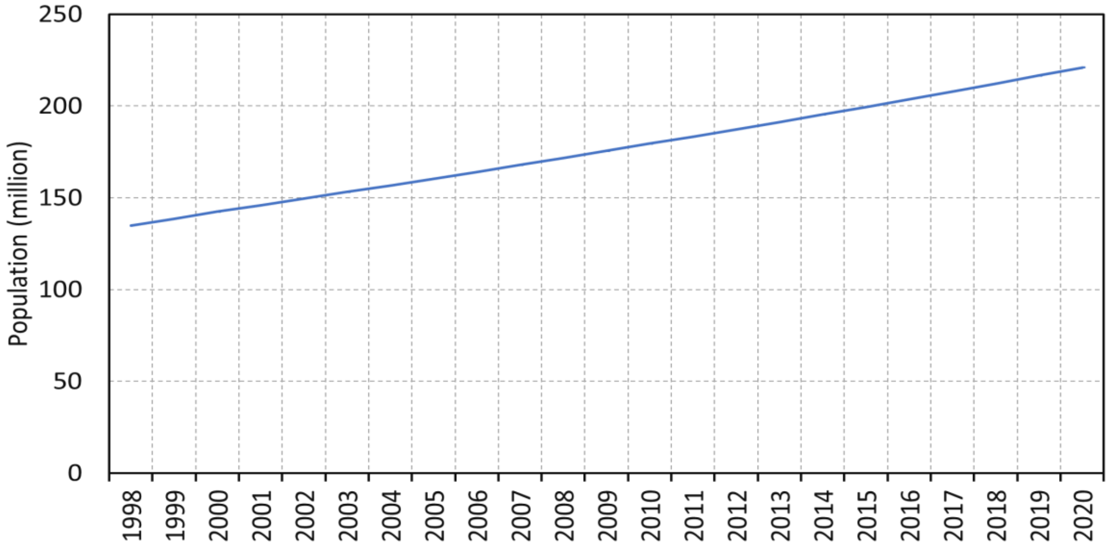


Fig. 1.1: Growth of population of Pakistan from 1998 to 2020 [3]

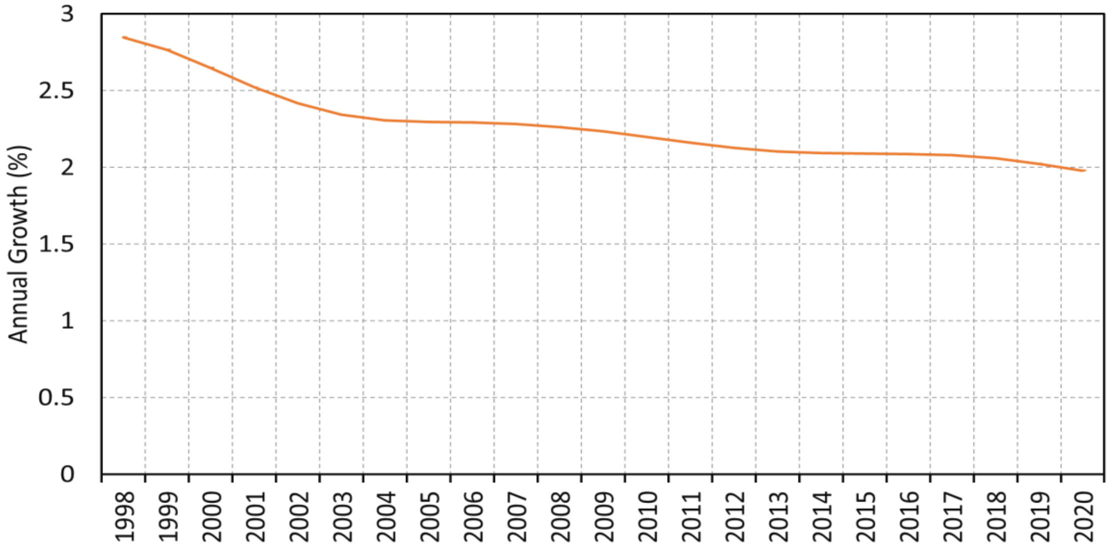


Fig. 1.2: Annual growth rate of population in Pakistan from 1998 to 2020 [3]

1.2. Economy of Pakistan

A country's economy is primarily measured with the Gross Domestic Product (GDP) of the country. GDP is the monetary measure of the market value of all the final goods and services produced in a country. World Bank's website provides a detailed data of different social and economic indicators for countries of the world. In previous section, the population of Pakistan has been considered for the period from 1998 to 2020, therefore, data for economic indicators for the same period is considered. As per World Bank's data, from 1998 till 2020, the GDP of Pakistan increased from 62.19 billion US $ in 1998 to 314.568 billion US $ in 2018. The growth in economy is the result of political stability and continuation of policies. This statement can be verified from the sudden drop in GDP of Pakistan in 2019. From 314.568 billion US $ in 2018, Pakistan's GDP dropped to 278.222 US $ in 2019. In July 2018, a new government came into power in Pakistan and there was a major shift in different policies. This change in policies resulted in a sudden drop in GDP of Pakistan. In 2020, the already struggling economy was hit by COVID-19 and GDP further decreased to 263.686 billion US $.

Fig. 1.4 shows the growth rate in GDP of Pakistan for the same period. It is observed that the growth rate in GDP of Pakistan does not remained constant in last two decades. Over the years, Pakistan has shown that when there is a continuation in policies, there happens a boom in the economy of the country. this can be observed from the growth rate in GDP from 1998 to 2005 when the country was ruled by military leader and there was political stability. However, from 2005, the growth rate falls rapidly. Main reason behind this drop was terrorism in the country, which was ultimately controlled, and the growth rate started increasing in 2011 and 12. In 2018, a new government was formed and there was a change in policies. This change resulted into a drop in growth rate. In coming years, COVID-19 further affected the already declining growth rate, and it touched all times low of 0.52%. However, there are reports that the economy of Pakistan is recovering, and we hope to see increased growth rates in future.

GDP per capita of Pakistan also followed the patterns of GDP and its growth rates. In 1998, per capita GDP of Pakistan was 461.22 US $ which increased to 1482.213 US $ in 2018 and then fell to 1193.73 US $ in 2020. Fig. 5 shows trends of GDP per capita for Pakistan for the period starting from 1998 till 2020.

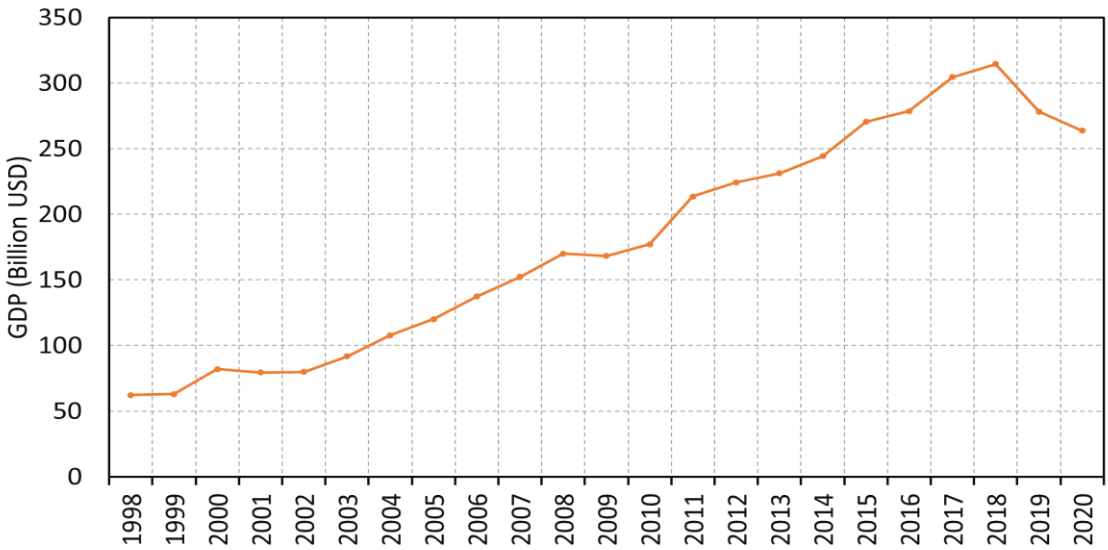


Fig. 1.3: GDP of Pakistan from 1998 to 2020 [3]

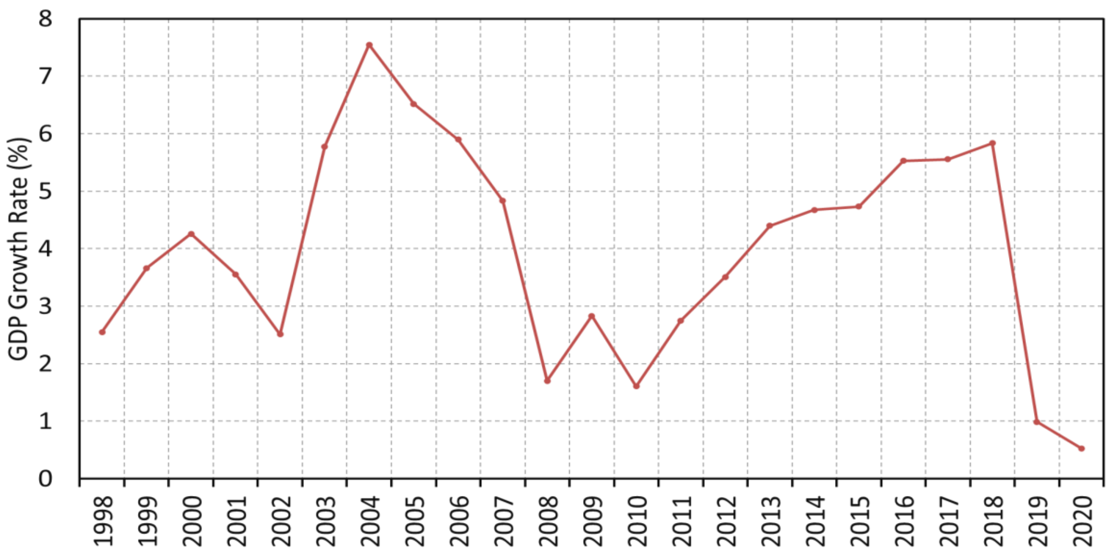


Fig. 1.4: GDP Growth Rate of Pakistan from 1998 to 2020 [3]

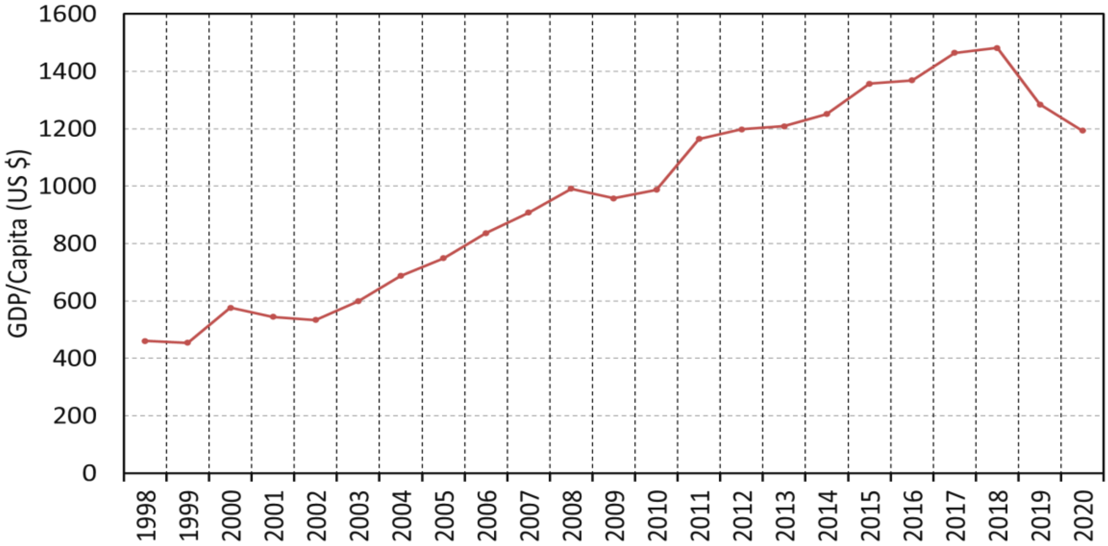


Fig. 1.5: Per Capita GDP of Pakistan from 1998 to 2020 [3]

GINI Index is a measure of inequality of distribution of wealth in a society. Its value ranges from zero to 1. Zero value of GINI index means the equal distribution of wealth in a society while a value of one for GINI index for a society means that all the wealth of the society is accumulated with one person. World Bank's data bank does not have a complete set of values of GINI index for the period under consideration i.e 1998-2020 for Pakistan. However, the graph (Fig.1.6) of available data shows an irregular pattern of GINI index for Pakistan. In 1998, the GINI index for Pakistan had a value of 0.331. While in 2018, it had a value of 0.316.

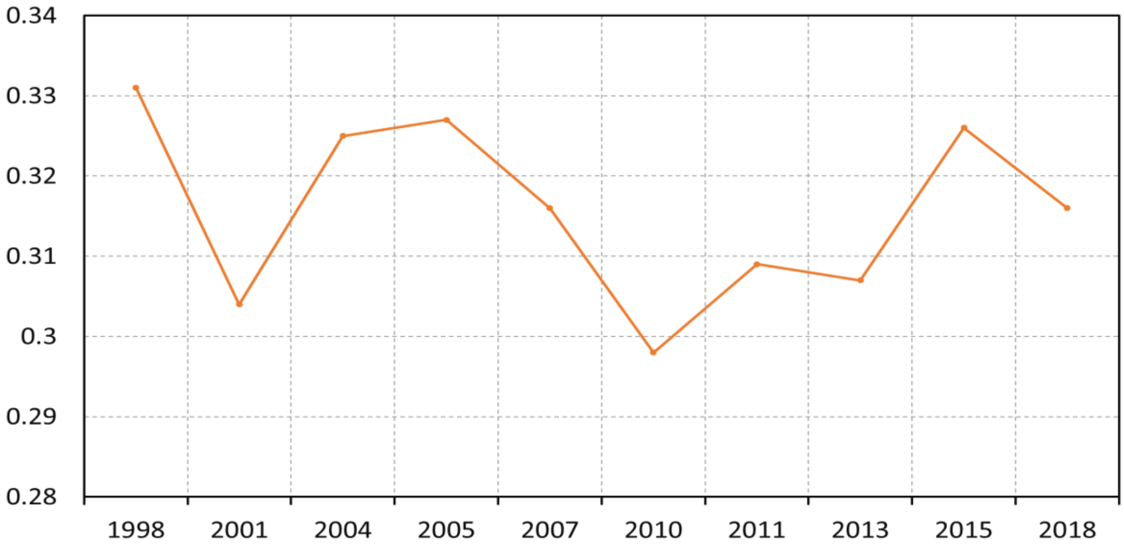


Fig. 1.6: GINI Index for Pakistan from 1998 to 2018 [3]

1.3. Energy

Pakistan is a developing country and trends of its final energy consumption indicates that its energy needs are growing. As per World Bank's data, Pakistan used 1,923,664.909 TJ (tera joules) of primary energy in 1998. The consumption of primary energy increased year after year and this consumption reached 3,111,795.097 TJ in 2015. Fig. 1.7 shows this trend of increase in final energy consumption.

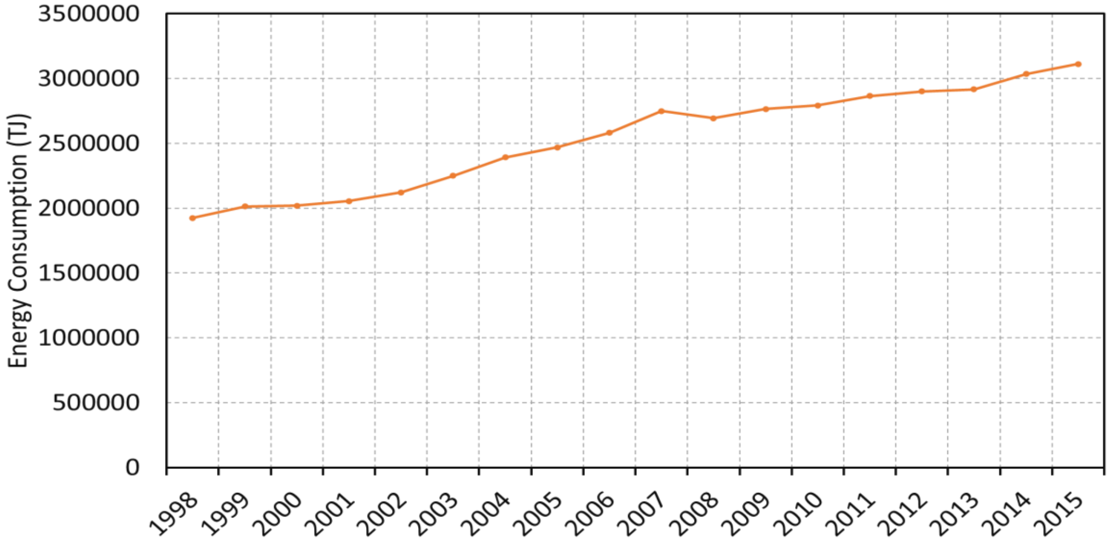


Fig. 1.7: Trend of increase in final energy consumption of Pakistan from 1998 to 2015 [3]

Energy Intensity is a measure of the efficiency of the energy consuming infrastructure. It is a ratio between energy supply and GDP (measured at PPP) and indicates how much primary energy is consumed to produced one unit of GDP. In 1998, one unit of GDP was produced by consuming 5.52 MJ of primary energy. This ratio has decreased with time and in 2015, Pakistan was using 4.42 MJ of primary energy to produce one unit of GDP. Fig. 1.8 show this decreasing trend of energy intensity.

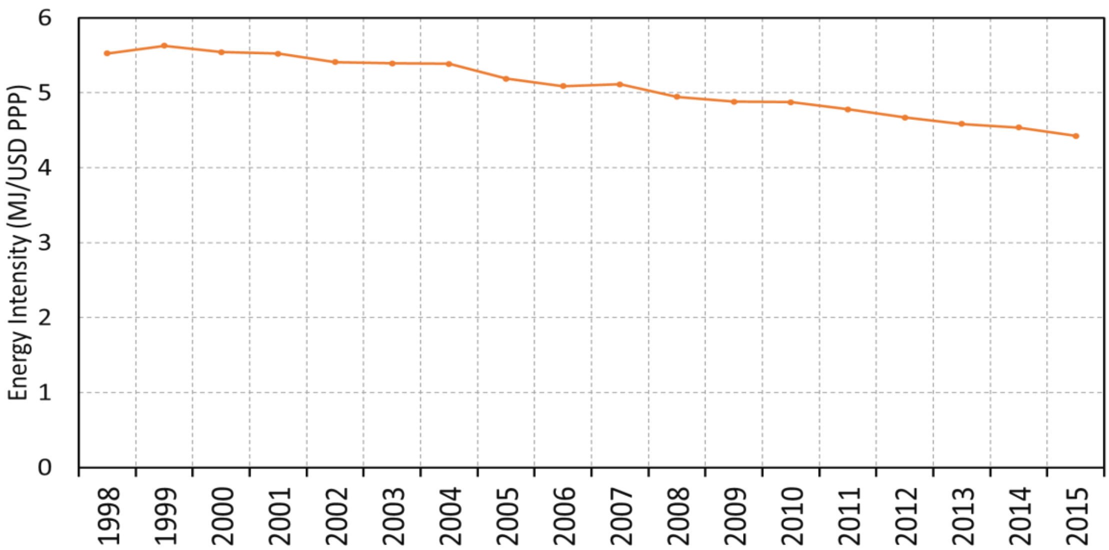


Fig. 1.8: Trend of Energy Intensity in Pakistan [3]

Economic Survey of Pakistan 2018-19 gives details of sectoral energy consumptions of Pakistan. In financial year 2000-01, Pakistan used a total of 17,647.898 Kt (kilo ton) of petroleum products. The major consumer of petroleum was the transport sector. The consumption of petroleum products in Pakistan is increasing. In financial year 2017-18, this consumption was recorded to be 24,677.9 Kt. The residential Sector was using 450.96 Kt of petroleum products in 2000-01 which reduced to 66.075 Kt in 2017-18. Fig. 1.9 shows the consumption of different sectors from 2000 to 2018.

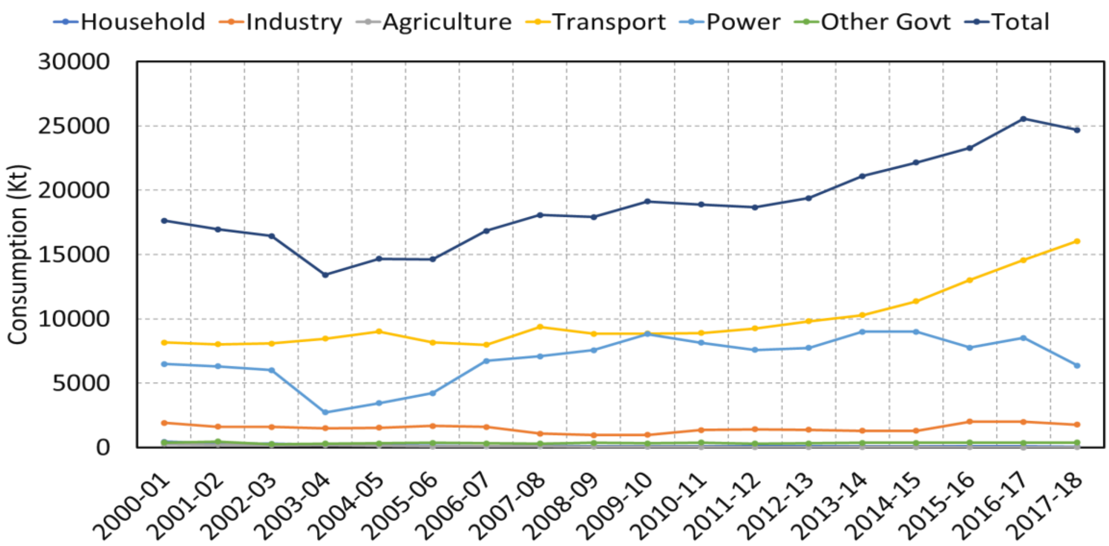


Fig. 1.9: Consumption of petroleum in different sectors [4]

In 2000-2001, Pakistan consumed 768.068 bcf (billion cubic feet) of natural gas. Consumption of natural gas has increased over time and in 2017-2018, this consumption was 1454.697 bcf. In 2000-2001, power sector was the major consumer sector for natural gas in Pakistan. It was consuming 281.26 bcf. A number of electricity producing power plants are consuming natural gas. The second and third largest consumer sectors were the fertilizer sector and household sector with 175.393 bcf and 140.899 bcf. In 2017-2018, the industrial sector was consuming 274 bcf while the residential sector was consuming 284.428 bcf. Interestingly, the industrial sector started consuming more natural gas during 2004 to 2011. However, the domestic use of natural gas surpassed the industrial use in 2013. In 2017-2018, the power sector consumed 544.65 bcf. The residential sector became the second largest consumer of natural gas in 2017-18 with a consumption of 284.428 bcf. Fig. 1.10 shows the natural gas consumed by each sector.

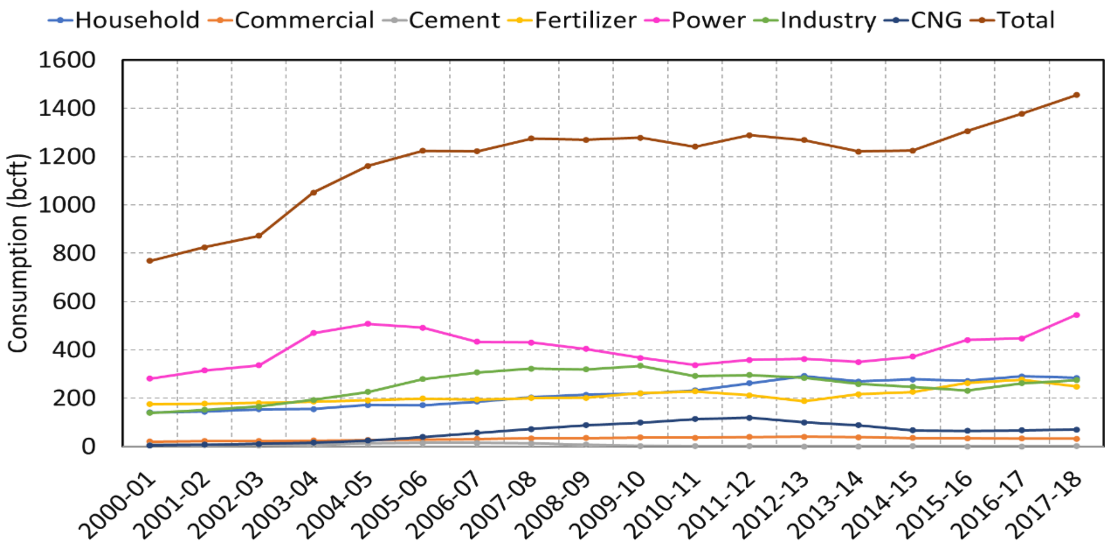


Fig. 1.10: Sectoral consumption of Natural Gas [4]

Pakistan's electricity consumption in 2000-2001 was 48.585 Twh. This consumption continuously increased and in 2017-2018, it became 106.927 Twh. The residential sector remained the major consumer during this period. In 2000-2001, it was consuming 22.765Twh, which increased to 54.028 Twh in 2017-18. The share of the residential sector in total electricity consumption was 47% in 2000-

2001. This share increased to 50.5% in 2017-18. The second largest consumer sector of electricity in Pakistan is the industrial sector. Therefore, in order to meet the current electricity shortfall, there is a dire need of introduction of efficient electricity use in residential sector in Pakistan. Fig. 1.11 shows consumption of electricity in different sectors.

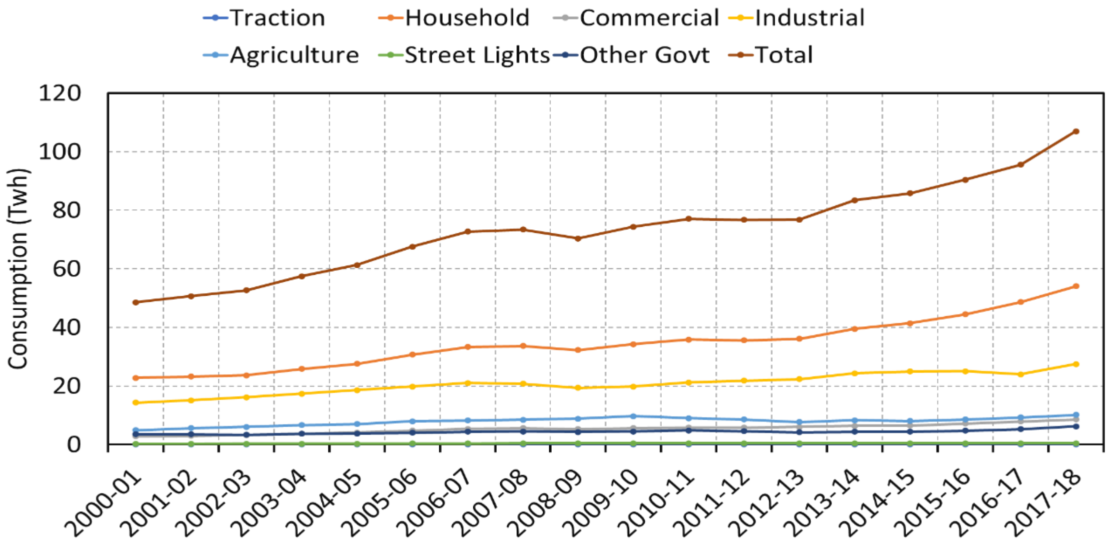


Fig. 1.11: Sector-wise electricity consumption [4]

Coal is another major source of energy in Pakistan. In 2000-2001, Pakistan consumed 4044.7 metric tons of coal. The country tends to increase the use of coal with passage of time. Since large deposits of coal were discovered in district thar of Sind province, this use will further increase in future. This statement can be verified from the surge in coal consumption from 2016-2017. In 2000-2001, brick kilns were the major consumers of coal. However, with passage of time, the country started using coal in power and cement sectors. The use of coal in power sector will further increase in future. In 2017-2018, the cement industry was the major consumer of coal with a total use of 9603.3 metric tons. The residential sector was using 1 metric ton of coal in 2000-01. In 2017-18, the residential sector has no share in coal consumption. Fig. 1.12 shows the consumption of coal in different sectors.

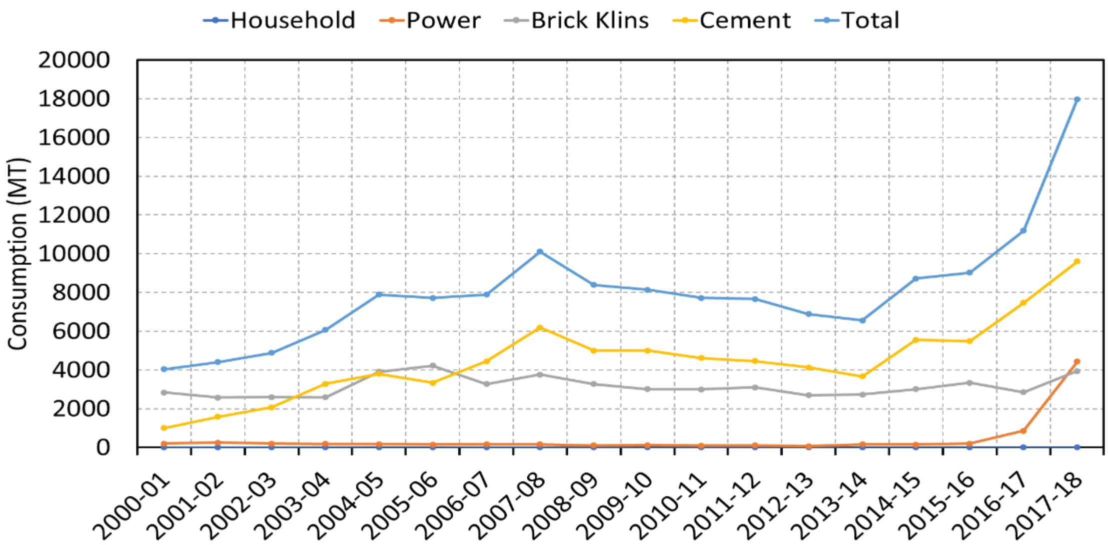


Fig. 1.12: consumption of coal in different sectors [4]

1.4. Housing Stock of Pakistan

The 2017 census states that Pakistan had 31.916 million houses for a population 207.7 million people. 31.37% of houses have one room while 30.23% of the houses have two rooms (Table 30n of 6th Population Census Results). 82.14% of the housing stock (26.215 million) is owned by its residents. 11.53% houses are rented by occupants while 6.33% of the houses is rent without payment. Share of houses with walls made of baked bricks/blocks/stones is 74.25% (23.697 million). Walls of 5.866 million houses (18.38) are made with mudbrick. 8.978 million houses (28.13%) have reinforced cement concrete (RCC)/ reinforced brick concrete (RBC) roof, 12.195 million houses (38.21%) have garder/T. iron as roof while 8.05 million (25.23%) of the houses have roof made of wood/bamboo. Pakistan Bureau of Statistics (PBS) has reported the average size of Household in Pakistan as 6.39. On the other hand, as previously mentioned, the population of Pakistan is increasing at a rate of 2.4% every year. Azra Jabeen [5] estimated that Pakistan needed 8 million houses in 2009 and this shortage was increasing with time. It also points out that Pakistan needs to construct 0.5 million houses annually to overcome the shortage. Table 1.2 shows a breakdown of the housing stock in Pakistan with respect to number of rooms and construction period. Table 1.3 gives construction materials used in houses, while Table 1.4 gives an overview of facilities in the house.

Table 1.2: Details of existing housing stock of Pakistan [6]

Ownership	**1 R* (M**)**	**2 R (M)**	**3 R (M)**	**4 R (M)**	**5 R (M)**	**6 R (M)**	**7 R (M)**	**8 R (M)**	**9& above R (M)**	**Total (M)**	**%age**
Self-Owned	7.944	7.675	4.824	2.861	1.26	0.765	0.361	0.226	0.297	26.215	82.14
Rented	1.017	1.416	0.775	0.285	0.098	0.042	0.024	0.009	0.013	3.681	11.53
Rent Free	1.051	0.557	0.226	0.098	0.036	0.02	0.012	0.006	0.011	2.019	6.33
Total	10.012	9.647	5.825	3.245	1.396	0.828	0.398	0.242	0.322	31.916	100
%	31.37	30.23	18.25	10.17	4.37	2.59	1.25	0.76	1.01	100	
Age of Self-Owned Houses											
Under Construction	0.161	0.142	0.089	0.052	0.022	0.134	0.007	0.004	0.007	0.497	1.9
Less than 5 Years	1.384	1.114	0.647	0.361	0.153	0.095	0.046	0.028	0.036	3.865	14.74
5-10 Years	2.719	2.429	1.388	0.773	0.321	0.190	0.093	0.054	0.072	8.038	30.66
11.-50 Years	3.438	3.769	2.559	1.585	0.724	0.440	0.201	0.130	0.167	13.013	49.64
Over 50 Years	0.242	0.220	0.140	0.090	0.042	0.027	0.014	0.009	0.016	0.8	3.6
Total	7.944	7.675	4.824	2.861	1.26	0.765	0.361	0.226	0.297	26.215	100
%	30.30	29.28	18.4	10.91	4.81	2.92	1.38	0.86	1.13	100	

*: Rooms

**: Million

Table 1.3: Housing Units by construction materials [7]

	Owned Houses (million)	**Rented (million)**	**Rent free (million)**	**Total (million)**	**%**
Materials used in Walls					
Baked Bricks/Blocks/Stones	19.342	3.333	1.023	23.698	74.25
Unbacked Bricks/Mud	5.008	0.248	0.611	5.867	18.38
Wood/Bamboo	1.382	0.048	0.285	1.715	5.37
Others	0.483	0.052	0.101	0.637	1.99
Total	26.215	3.681	2.019	31.916	100
%	82.14	11.53	6.33	100	
Materials used in Roof					
RCC/RBC	6.473	2.112	0.393	8.978	28.13
Cement/Iron Sheets	1.515	0.376	0.089	1.979	6.20
Garder/T. Iron	10.946	0.787	0.463	12.196	38.21
Wood/Bamboo	6.740	0.341	0.971	8.052	25.23
Others	0.543	0.065	0.103	0.710	2.23
Total	26.215	3.681	2.019	31.916	100
%	82.14	11.53	6.33	100	

Table 1.4: Housing Units by facilities [8]

	Owned Houses (million)	**Rented (million)**	**Rent free (million)**	**Total (million)**	**%age**
Kitchen					
Separate	14.334	2.421	0.744	17.500	54.83
Shared	5.114	0.744	0.310	6.168	19.33
None	6.767	0.516	0.966	8.248	25.84
Total	26.215	3.681	2.019	31.916	100
%	82.14	11.53	6.33	100	
Bathroom					
Separate	16.046	2.732	0.839	19.617	61.47
Shared	5.799	0.807	0.349	6.956	21.79
None	4.370	0.141	0.831	5.343	16.74
Total	26.215	3.681	2.019	31.916	
%	82.14	11.53	6.33	100	
Latrine					
Connected with sewerage	7.111	2.477	0.455	10.043	31.47
Connected with septic tank	3.683	0.323	0.160	4.166	13.05
Connected with open drain	4.133	0.350	0.278	4.761	14.92
Pit with slab	6.268	0.393	0.279	6.940	21.74
Others	1.037	0.045	0.129	1.211	3.79

Total	26.215	3.681	2.019	31.916	100
%	82.14	11.53	6.33	100	
Cooking Fuel					
Wood	16.504	0.731	1.417	18.653	58.44
Gas	8.814	2.796	0.473	12.082	37.86
Kerosene Oil	0.048	0.006	0.007	0.061	0.19
Others	0.849	0.148	0.122	1.120	3.51
Total	26.215	3.681	2.019	31.916	100
%	82.14	11.53	6.33	100	
Source of Lighting					
Electricity	22.999	3.566	1.478	28.044	87.87
Kerosene Oil	0.979	0.038	0.153	1.171	3.67
Gas Lamp	0.046	0.004	0.007	0.057	0.18
Others	2.190	0.073	0.381	2.644	8.28
Total	26.216	3.681	2.019	31.916	100
%	82.14	11.53	6.33	100	

Pakistani cities are expanding horizontally. Living in apartments is not popular and people prefer to live in detached houses due number of reasons. In recent years, private firms entered into the Pakistani real estate market and started offering accommodation in gated communities. The concept of gated communities is becoming more and more common with passing time. The target customers of these gated communities also range from upper class to middle class. However, in large cities like Karachi, Lahore, and Islamabad, we can find some areas where people are living in apartments. In small cities, the concept of life in apartments is not popular and almost all the population live in detached houses.

1.5. Legal system for Building Control

Ministry of Housing and Works, Government of Pakistan developed Pakistan Building Code in 1990 to streamline the building sector in the country and to promote energy efficiency in this sector. This code divided the whole country into five thermal zones. Fig. 1.13(a) shows this division of thermal zones while Fig.1.13(b) shows the location of different cities of Pakistan. Table 1.5 gives lists of cities included in each zone. This code was applicable to all the buildings, intended for human habitation e.g residences, offices, shops, schools, hotels, and government buildings. This code stipulates the allowable values of thermal conductance and resistance as shown in Table 1.6 for walls, roof/ceilings, shaded roofs, floors heated slabs on grade.

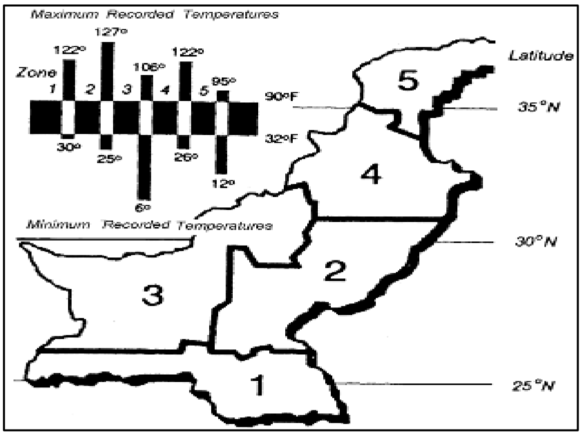


Fig. 1.13(a): Climate Zones of Pakistan

Fig. 1.13(b). Map of Pakistan

Table 1.5: Cities in different climate zones of Pakistan

Climatic Region	**Cities**
1	Karachi, Hyderabad, Badin, Gawadar, Jiuani, Mirpur Khas, Pasni, Sanghar, Thatta, Turbat, Uthal
2	Multan, Bhawalnegar, Bhawalpur, Chichawatni, Chunian, Dadu, D.G. Khan, Hasilpur, Jacobabad, Kabirwala, Kandiaro, Kashmore, Khairpur, Khanewal, Khanpur, Larkana, Leiah, Lodhran, Moro, Muzaffargarh, Nawabshah, Okara, Pak Pattan, Rajanpur, Rahimyar Khan, Sadiqabad, Sahiwal, Shikarpur, Shorkot, Sibi, Sujawal, Sukkur, Toba Tek Sing, Vihari
3	Quetta, Bela, Kalat, Kharan, Khuzdar, Loralai, Muslim Bagh, Nushki, Panjgur, Pishin, Zhob
4	Islamabad, Lahore, Peshawar, Faisalabad, Rawalpindi, Gujranwala, Abbottabad, Bhakkar, Bhalwal, Chiniot, Chakwal, Charsada, Daska, Fateh Jang, Gojra, Gujrat, Hafizabad, Hassansabdal, Haripur, Jaranwala, Jauherabad, Jhang, Jhellum, Kasur, Kharian, Khushab, Kohat, Mansehra, Mardan, Mianwali, Mirpur, Muzaffarabad, Narowal, Nowshehra, Pasrur, Samundri, Sargodha, Shakargarh, Sialkot, Swabi, Talagang, Tangi, Wah, Wazirabad
5	Chitral, Dir, Dassu, Gilgit, Saidu Sharif, Skardu

Table 1.6: Allowable values of conductance and resistance by Pakistan Building Code, 1990

Building Element	Symbol	Unit	Allowable value in different zones				
			Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Walls	U	W/m^2 Btu/hr ft^2	2.67 0.47	2.56 0.45	2.22 0.39	2.50 0.44	2.22 0.39
Roofs / Ceilings	U	W/m^2 Btu/hr ft^2	0.58 0.10	0.58 0.10	0.58 0.10	0.58 0.10	0.58 0.10
Shaded Roofs & Floors exposed to Weather	U	W/m^2 Btu/hr ft^2	1.16 0.20	1.16 0.20	1.16 0.20	1.16 0.20	1.16 0.20
Floors Unheated Spaces	U	W/m^2 Btu/hr ft^2	2.27 0.40	1.70 0.30	1.42 0.25	1.70 0.30	1.42 0.25
Heated Slab on Grade	R	m^2/W hr ft^2/Btu	0.44 2.50	0.63 3.60	0.74 4.20	0.67 3.60	0.74 4.20

This code determines the Overall Thermal Transfer Value (OTTV) as the cooling design criterion for walls, floors and roof/ceilings in order to achieve building envelopes that adequately reduces heat gain by both conduction and solar radiation, resulting in the reduction of the cooling load of the air conditioning system. Table 1.7 gives the upper limit of the OTTV for each thermal zone of the country.

Table 1.7: Maximum Overall Thermal Transfer Values

Climate Zone	Walls		Roofs	
	W/m^2	$Btu/hr.ft^2$	W/m^2	$Btu/hr.ft^2$
1	91	29	26.8	8.5
2	95	30	26.8	8.5
3	95	30	26.8	8.5
4	98	31	26.8	8.5
5	101	32	26.8	8.5

Pakistan Building Code, 1990 also gave the minimum coefficient of performance (COP) and energy efficiency ratio (EER) Cooling for the air conditioning system used in buildings. It states that for an air-cooled system of 19kW and above, the minimum COP must be 2.40 while EER cooling must be 8.2. For a system below 19kW these values must be 2.28 and 7.8 respectively. In 2011, Government of Pakistan updated the Pakistan Building Code, which is called Building Code of Pakistan (Energy Provision-2011). This time the initiative was taken by National Energy Conservation Center (ENERCON), now called National Energy Efficiency & Conservation Authority (NEECA) in coordination of Pakistan Engineering Council (PEC). However, this code is applicable to buildings having a total connected load of 100 kVA or greater, or a contract demand of 125 kVA or greater, or a conditioned area of 900 m^2 or greater or unconditioned buildings of covered area of 1200 m^2 or more. This code is suggesting the following building envelope specifications for the whole country:

Table 1.8: Recommendations of The Building Code of Pakistan (Energy Provisions, 2011)

Components	**Majority**	**Advanced (less than 5%)**
Roof	RC slab and water proofing, covered by topping concrete. No insulation.	Two inches of extruded polystyrene (XPS: U-value 0.035) above the RC slab and water proofing, covered by topping concrete. Then install finish material on the raised frame.
Wall	9-inch brick wall or concrete block. No insulation.	Double brick wall with two-inch insulation in the cavity.
Window	Single-glazed aluminum window. Commercial buildings have tinted glass	Double-glazed aluminum window, for high-end hotels, offices. LOW-E glass must be imported.

For effective implementation of this code, it has to be adopted by different building control authorities of the country. It is worth mentioning that Pakistan is divided into four administrative units, called provinces. At federal level, the Capital Development Authority (CDA) is regulating the residential buildings while in provinces building control authorities are present at district level in the form of Developing Authorities (LDA, PDA, RDA etc.) or Municipal Corporations. All these authorities have their own rules and regulations and understanding of Pakistan Building Code is limited at their level, therefore implementation of the code is facing some hurdles. As the buildings are regulated at district level and the document could not be adopted at the level of districts, therefore, was not much effective.

1.6. Climatic Regions of Pakistan

As mentioned in section 1.5, building code of Pakistan, 1990 divided Pakistan into five different climatic regions. Climate of cities located in these regions can serve as a representation of the climate of these regions. Pakistan Meteorological Department (PMD) publish a monthly climate summary of Pakistan with the title "Pakistan's Monthly Climate Summary". This paper gives highlights of the different climatic parameters of different regions of Pakistan. However, the list of cities does not include Islamabad (the capital), Skardu (the coldest place of the country) and Sibbi (the hottest place). This shortcoming was covered by considering the nearest observation station of PMD e.g Rawalpindi for Islamabad, Jacobabad (2nd hottest city) and Drosh for Skardu (the nearest available location). Table 1.9-1.13 gives the monthly maximum temperature, minimum temperature and total monthly precipitation.

Region I: Region-I of Pakistan is a coastal region. Two major cities i.e Karachi and Hyderabad of Pakistan are located in this region. Main characteristics of this region includes high humidity and low precipitation rate. The climate of this region may be arid. Karachi is located at the coast of Arabian sea; therefore, its climate is affected by the sea breeze. In Turbat, a city of this climate region, the temperature reached 54^{o}C on 28th May 2017. As per World Metrological Organization, this the 4th highest temperature ever recorded on earth (source: Pakistan Meteorological Department). Table 1.9 gives monthly maximum and minimum temperatures and precipitation rate of the representative cities of this region. While Figs. 1.14 (a & b) is the temperature and precipitation curves for these cities.

Table 1.9: Monthly temperature and precipitation of region I [9]

Month/City	Karachi			Hyderabad		
	Max. Temp. (^{o}C)	Min. Temp. (^{o}C)	Precipitation (mm)	Max. Temp. (^{o}C)	Min. Temp. (^{o}C)	Precipitation (mm)
Aug 2020	31.9	26.2	60.1	36	26.6	63.1
Sept 2020	32.8	25.4	10.2	36.4	25.3	12.6
Oct 2020	35.1	21.4	2.3	36.8	22.4	2.9
Nov 2020	32.2	16.3	0.9	31.8	17.4	2.3
Dec 2020	27.9	12.2	3.9	26.5	13	1.4
Jan 2021	25.9	10.8	10.8	24.8	11.4	2
Feb 2021	27.9	13	10.4	27.7	13.7	4.3
April 2021	34.5	22.5	3.2	38.8	23	5.1
May 2021	35.3	26.2	0.2	41.4	26.1	4.6
June 2021	35.2	28.1	6.7	40.2	28	6.3

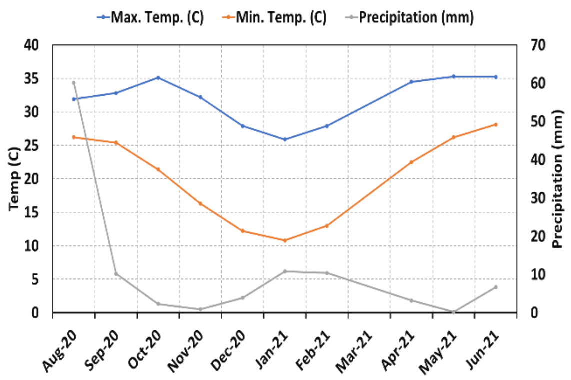


Fig. 1.14(a). Climate of Karachi

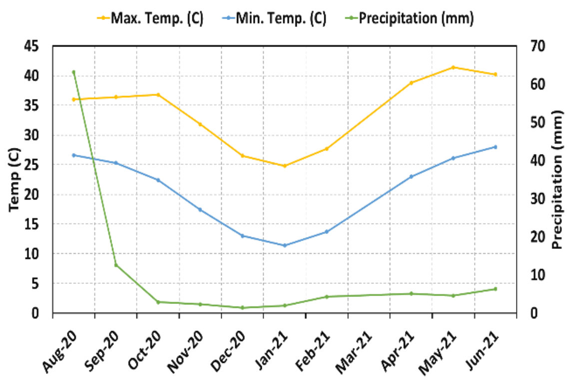


Fig. 1.14(b). Climate of Hyderabad

Region II: This region is the hottest climatic region of Pakistan. Cities of this region experience highest temperatures in summer while the winter in this region is mild. Table 1.10 gives monthly maximum and minimum temperatures and precipitation rate of the representative cities of this region. While Figs. 1.15 (a & b) is the temperature and precipitation curves for these cities.

Table 1.10: Monthly temperature and precipitation of region II [9]

Month/City	**Jacobabad**			**Multan**		
	Max. Temp. (°C)	Min. Temp. (°C)	Precipitation (mm)	Max. Temp. (°C)	Min. Temp. (°C)	Precipitation (mm)
Aug 2020	37.8	28.2	35.4	37.6	27.9	36.4
Sept 2020	36.8	26	11	36.9	24.9	24.9
Oct 2020	35.1	20.2	2.2	34.4	18.2	5.2
Nov 2020	30.2	14.1	1.3	28.8	11.4	2.3
Dec 2020	24.3	8.9	2.9	23	6.3	2.7
Jan 2021	22.5	7.7	3.6	20.9	5	8.2
Feb 2021	25.2	10.3	6.9	23.3	7.8	11.1
April 2021	38.2	22.3	2.1	35.6	19.5	14.6
May 2021	43.3	26.9	3.1	40.8	24.8	11.5
June 2021	44.5	29.5	3	42.2	28.6	15.1

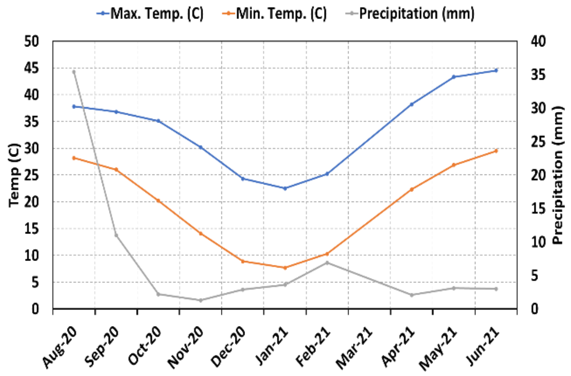


Fig. 1.15(a). Climate of Jacobabad

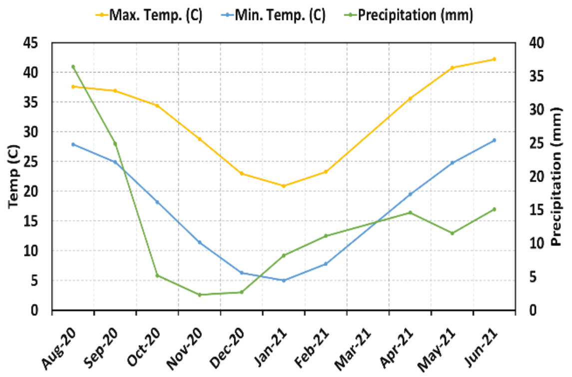


Fig. 1.15(b). Climate of Multan

Region III: This region exhibits arid climate with large variations in winter and summer. This region contains cities from the province of Balochistan. Winter in these cities is wet and cold while summer is dry and moderate. Table 1.11 gives monthly maximum and minimum temperatures and precipitation rate of the representative cities of this region. While Figs.1.16 (a & b) is the temperature and precipitation curves for these cities.

Table 1.11: Monthly temperature and precipitation of region III [9]

Month/City	**Quetta**			**Zhob**		
	Max. Temp. (°C)	Min. Temp. (°C)	Precipitation (mm)	Max. Temp. (°C)	Min. Temp. (°C)	Precipitation (mm)
Aug 2020	35	18.3	13.2	35.4	22.4	49.7
Sept 2020	31.6	11.7	2.5	33.2	19.1	11.5
Oct 2020	25.5	4.7	6.5	28	12.1	6
Nov 2020	19.7	0.1	4.5	22.6	6	3.5
Dec 2020	14	-1.9	37.5	16.3	1	11.5
Jan 2021	10.8	-2.7	64	12.8	-1	20
Feb 2021	12.8	-0.9	49.5	14.6	1.5	25

April 2021	25.3	8.6	22.2	27.2	13.2	31.2
May 2021	30.8	12.4	5.5	32.8	18.2	16.9
June 2021	35.4	16.8	1.5	36.9	22.8	14.7

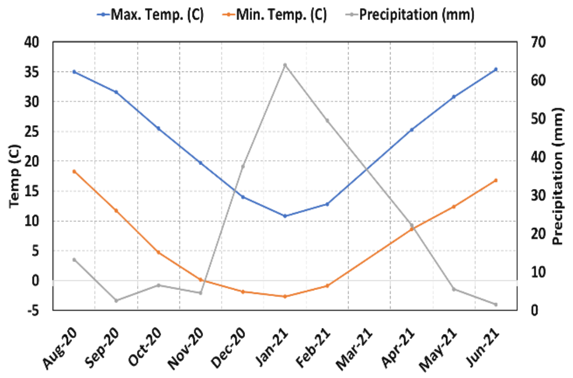


Fig. 1.16(a). Climate of Quetta

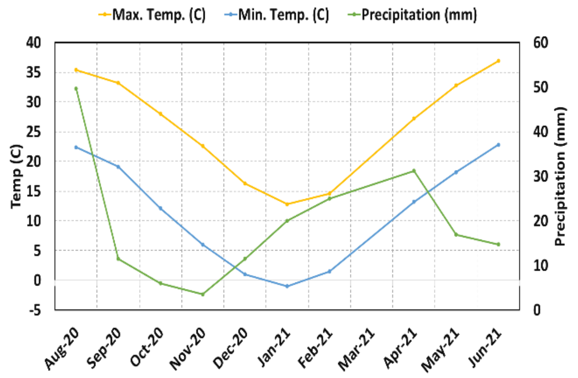


Fig. 1.16(b). Climate of Zhob

Region IV: This region is home to majority of the population of Pakistan. This region has the highest concentration of major cities of the country like Islamabad, Lahore, Faisalabad, Peshawar etc. This region can be called plains of the country with four seasons. Summer in this region is mainly dry with high outdoor temperature. However, this region receives rains during monsoon which lasts from July to August. Table 1.12 gives monthly maximum and minimum temperatures and precipitation rate of the representative cities of this region. While Figs. 1.17 (a & b) is the temperature and precipitation curves for these cities.

Table 1.12: Monthly temperature and precipitation of region IV [9]

Month/City	**Islamabad**			**Lahore**		
	Max. Temp. (°C)	Min. Temp. (°C)	Precipitation (mm)	Max. Temp. (°C)	Min. Temp. (°C)	Precipitation (mm)
Aug 2020	33.4	23.6	348.1	34.9	26.5	194.5
Sept 2020	33.5	20.7	113.2	35	24.6	65.1
Oct 2020	30.9	14	29.8	32.8	18.5	14.8
Nov 2020	25.9	7.9	15.6	27.7	12.4	6.5
Dec 2020	20	4	31.2	21.9	7.8	9.9
Jan 2021	17.6	3.1	59.2	19.6	6.7	22.9
Feb 2021	19.2	5.4	79.7	22.1	9.4	30.3
April 2021	30.2	15.4	63.1	34	20	22.3
May 2021	35.6	20.1	34.1	38.9	24.5	20.8
June 2021	38.4	23.5	70.1	39.9	27.2	51.3

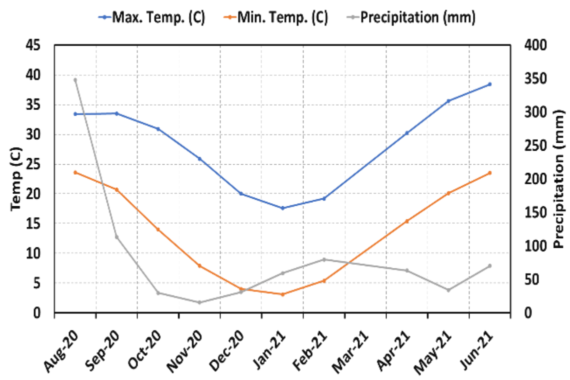


Fig. 1.17(a). Climate of Islamabad

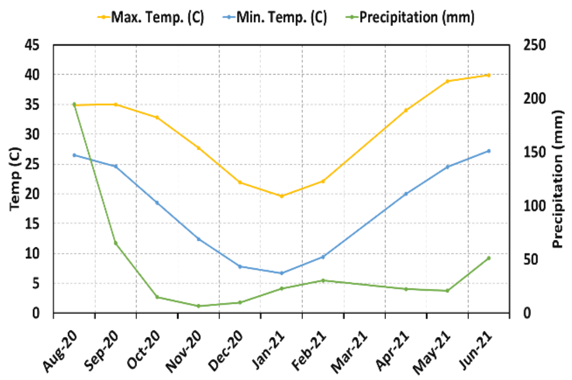


Fig. 1.17(b). Climate of Lahore

Region V: The coldest region of the country has a very cold winter while the summer in this region is mild. This region contains of mountains and glaciers. This region has some of the coldest places of Pakistan which includes Chitral, Dassu, Kalaam and Skardu. Skardu is coldest place of Pakistan where temperature falls to -20 in winter. Winter in this region is harsh and last long. Summer is comparatively moderate. Table 1.13 gives monthly maximum and minimum temperatures and precipitation rate of the representative cities of this region. While Figs. 1.18 (a & b) is the temperature and precipitation curves for these cities.

Table 1.13: Monthly temperature and precipitation of region V [9]

Month/City	**Drosh (Chitral)**		
	Max. Temp. (ºC)	Min. Temp. (ºC)	Precipitation (mm)
Aug 2020	35.9	22.3	20
Sept 2020	33.1	18.2	21.8
Oct 2020	26.7	11.6	5.1
Nov 2020	19.6	6.5	26.8
Dec 2020	12.2	2.3	37.7
Jan 2021	9.2	0.1	6.1
Feb 2021	10.7	1	74.4
April 2021	23.6	10.7	99.2
May 2021	29.4	15.4	67
June 2021	35.8	20.8	19.7

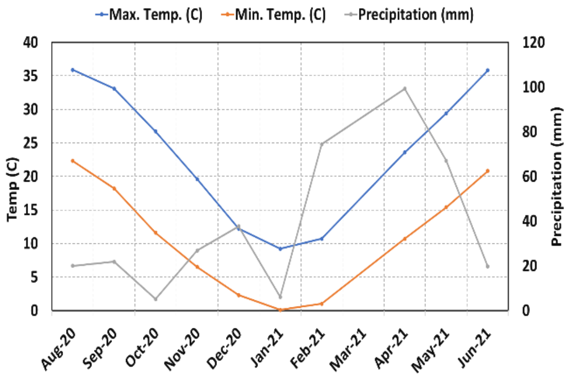


Fig. 1.18: Climate of Drosh

2. BASIC THEORY OF BUILDING ENERGY SIMULATION

EnergyPlus is one of popular computer-based simulation software to conduct building energy analysis. It can provide the prediction of building energy requirement of space cooling, heating, and ventilation under given building designs. It can also simulate the temperature of rooms as well as building envelopes. This chapter mainly describes the basic theory related to heat transfer engineering utilized in the solver of EnergyPlus.

2.1. Heat balance of room air

EnergyPlus solves differential equations, emerged as result of energy and moisture balances of the room, using predictor-corrector approach. The basic heat balance equation (steady system state equation) of the room air can be written as:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \quad (2.1)$$

where:

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$ = sum of the convective internal loads

$\sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z)$ = convective heat transfer from the zone surfaces

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$ = heat transfer due to interzone air mixing

$\dot{m}_{inf} C_p (T_\infty - T_z)$ = heat transfer due to infiltration of outside air

$\dot{Q}_{sys}$= air system output [W]

$C_z \frac{dT_z}{dt}$ = energy stored in room air

$C_z = \rho_{air} C_p C_T$

ρ_{air}= room air density [kgm^{-3}]

C_p = room air specific heat [Jkg-1 K^{-1}]

If the air capacitance of the room is neglected, the steady state system equation shall become as:

$$-\dot{Q}_{sys} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) \quad (2.2)$$

2.2. Heat balance of building envelopes

Assuming one dimensional conductive heat transfer within building envelopes, such as walls and roofs, unsteady heat transfer process inside building materials can be expressed as follows based on the Fourier's law.

$$\rho c_p \frac{\partial T}{\partial x} = \lambda \frac{\partial^2 T}{\partial x^2} + H \quad (2.3)$$

where,
T is the temperature as a function of position and time [K],
x is position [m],
t is time [s],
λ is thermal conductivity [$Wm^{-1}K^{-1}$],
ρ is density of envelope material [kg m^{-3}],
Cp is specific heat of envelope material [J kg^{-1} K^{-1}],
H is heat source term [wm^{-2}]

In EnergyPlus, simultaneous linear equations derived from the above equation by finite difference method are solved for each element of building materials, and time-series temperature variations of each envelope are simulated. Regarding the time discretization, EnergyPlus provides two options, namely Crank-Nicholson scheme, and fully implicit scheme.

The heat source term *H* included in equation (2.3) is basically zero for nodes within building envelopes. On the other hand, term *H* for the calculation nodes on external or internal surfaces of envelopes are determined based on the heat balance as described in the following sections.

2.3. Heat balance at external surfaces

The software considers the three heat transport process on an external surface of building envelopes, namely radiation, convection, and conduction. The heat balance on an external surface is expressed by:

$$q''_{swr} + q''_{lwr} + q''_{conv} - q''_{cond} = 0 \text{ ---------- (1)}$$

where
q''_{swr} = Net solar radiation [W m^{-2}]
q''_{lwr} = Net long wave radiation [W m^{-2}]
q''_{conv} = Convective flux exchange with outside air [W m^{-2}]
q''_{cond} = Conduction heat flux into the wall [W m^{-2}]

In eq (1) all terms are positive for net flux to the face except the conduction term, which is traditionally taken to be positive in the direction from outside to inside of the wall.

i. **Longwave radiation:** EnergyPlus estimates the long wave radiation using the following equation:

$$q''_{lwr} = \varepsilon\sigma F_{gnd}\left(T_{gnd}^4 - T_{surf}^4\right) + \varepsilon\sigma F_{sky}\left(T_{sky}^4 - T_{surf}^4\right) + \varepsilon\sigma F_{air}\left(T_{air}^4 - T_{surf}^4\right) = 0 \text{ ----- (3)}$$

where
ε : long-wave emissivity of the surface
σ : Stefan-Boltzmann constant (=5.67 x 10^{-8}) [W m^{-2} K^{-2}]
F_{gnd} : View factor of wall surface to ground surface temperature
F_{sky} : View factor of wall surface to sky temperature
F_{air} : View factor of wall surface to air temperature
T_{surf}: outside surface temperature [K]
T_{gnd} : ground surface temperature [K]
T_{sky} : sky temperature [K]
T_{air} : Air temperature [K]

ii. **Convective Heat Flux:** For calculation of heat transferred due to convection to the outside surface of the building, EnergyPlus uses the standard equation for convective heat transfer, i.e.

$$q''_{c} = h_{c.\ ext}\left(T_{surf} - T_{air}\right) \text{ -------- (4)}$$

where
$q_c^{"}$: Heat flux of convection on surface of building envelopes [W m^{-2}]
$h_{c.\ ext}$: Convective heat transfer coefficient [W m^{-2} K^{-1}]
T_{surf} : Surface temperature [K]
T_{air} : Outdoor air temperature [K]

Regarding the exterior convective heat transfer coefficient, EnergyPlus provides several methods for estimation. In this study the author selected DOE-2 algorithm which estimates convective heat transfer coefficients for very smooth surfaces using the following equation:

$$h_c = \left\{h_n^2 + \left(a\, V_z^b\right)^2\right\}^{1/2} \text{------ (5)}$$

where
h_c = Convective heat transfer coefficient [W m^{-2} K^{-1}]
h_n = Natural convection heat transfer coefficient [W m^{-2} K^{-1}]
V_z = Local wind speed [m s^{-1}]

For rough surfaces, h_c is determined by the following equation:

$$h_c = h_n + R_f \left(h_{c\, glass} - h_n\right) \text{----------- (6)}$$

where R_f is roughness of the surface.

2.4. Heat balance on internal surfaces

The inside surfaces of walls interact with air of different zones and transfer heat. This heat transfer consists of several components. The heat balance equation on inside face is given by

$$q_{lwx}^{"} + q_{lws}^{"} + q_{cond}^{"} + q_{sol}^{"} + q_{conv}^{"} = 0 \quad \text{-------(8)}$$

where
$q_{lwx}^{"}$: Net longwave radiant exchange flux between surfaces in a zone or group of zones (enclosure) [Wm^{-2}].
$q_{lws}^{"}$: Net longwave radiation [Wm^{-2}].
$q_{cond}^{"}$: Conduction flux through the wall [Wm^{-2}].
$q_{sol}^{"}$: Net short-wave radiation [Wm^{-2}].
$q_{conv}^{"}$: Convective heat flux to zone air [Wm^{-2}].

The software uses the techniques and algorithms described above for calculation of component heat transfers. However, in case of convective heat transfer, the coefficient of heat transfer is calculated by using Thermal Analysis Research Program (TARP) algorithm. This algorithm calculates coefficient of convective heat transfer as:

$$h_c = h_f + h_n \text{-----------(9)}$$

where
h_f = forced convective heat transfer coefficient [Wm^{-2}K^{-1}]
h_n = natural convective heat transfer coefficient [Wm^{-2}K^{-1}]

for conductive heat transfer flux, the following equation is used in EnergyPlus.

$$q_{cond}^{"}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j\, T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j\, T_{o,t-j\delta} + \sum_{j=1}^{nz} \Phi_j\, q_{ki,t-j\delta}^{"} \text{ -----(10)}$$

where
Y_j = Cross CTF coefficient, j = 0,1,…nz. Z_j = Inside CTF coefficient, j = 0,1,…nz.
Φ_j = Flux CTF coefficient, j = 1,2,…nz. T_i = Inside face temperature
T_o = Outside face temperature $q_{cond}^{"}$ = Conduction heat flux on inside face

3. NUMERICAL SETTING OF BASELINE MODEL

Chapter 1 gave an overview of the prevalent housing styles in Pakistan, which indicated various types of houses. In contrast, this chapter describes the details of a baseline model of Pakistan housing, which was assumed for the numerical evaluation of building energy performance of various passive design methodologies.

Unfortunately, there has been little information about the standard designs of houses, including room layout, floor area, and building materials based on large-scale surveys in Pakistan. Therefore, we utilized the data of four types of official residence which were provided from the department of Public Works Department (PWD) of Pakistan. Fig. 3.1 shows the drawings of these 4 houses.

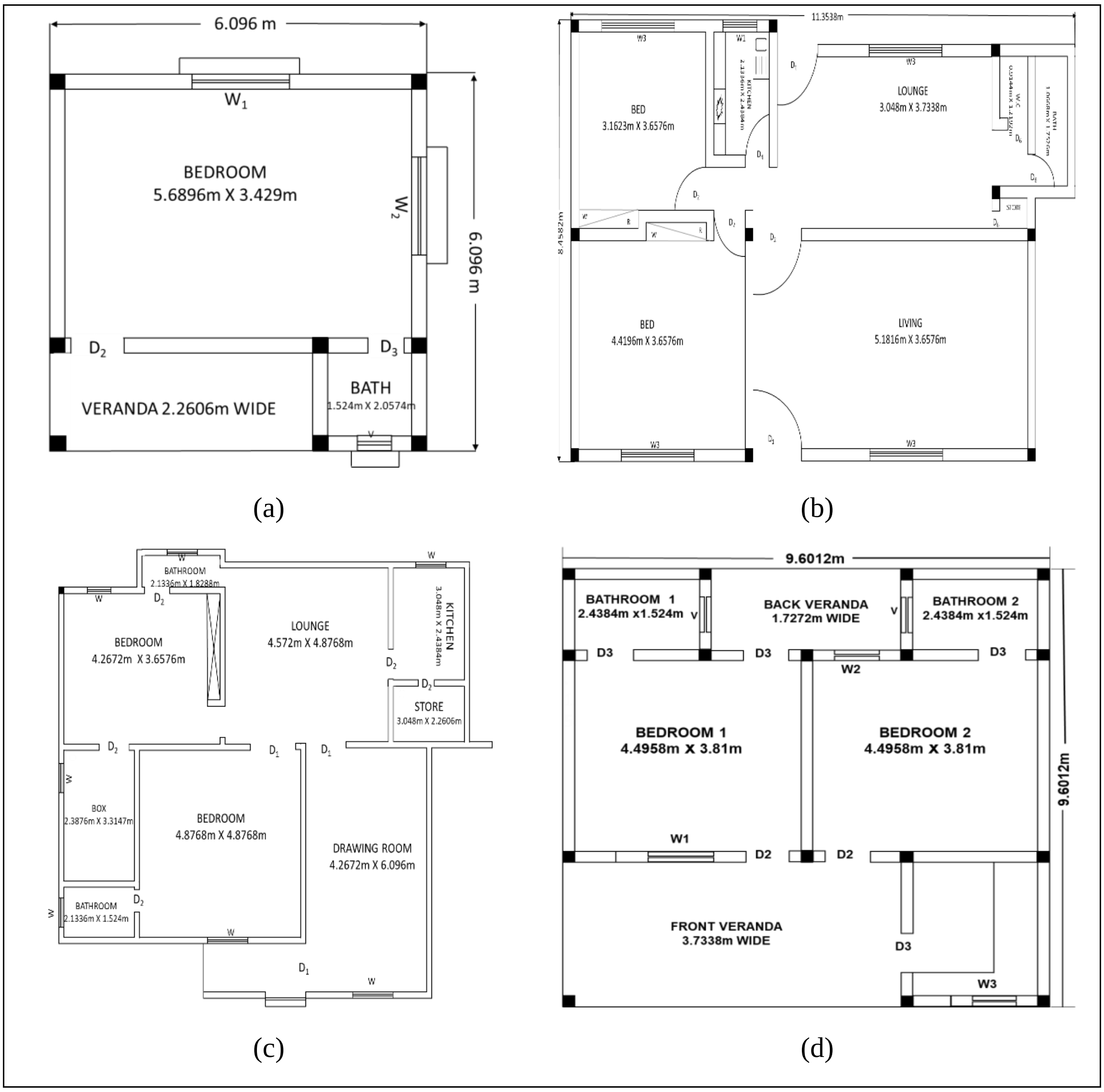


Fig. 3.1: Four types of official residence in Pakistan

3.1. Building Geometry

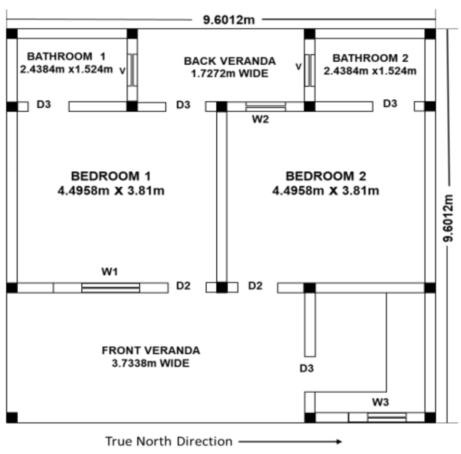
Among four types shown in Fig.1, a two-bedroom detached house (Fig. 3.1d) was selected as a baseline model for the simulation. This has two bedrooms with two attached bathrooms and one kitchen, assuming a small family consisting of four people, i.e husband, wife and two children. This house has verandas on front and back. Normally, in Pakistan such houses are accompanied with an open space called courtyard.

Digital twin of this house was constructed using SkechUp 2017. SkechUp is a free drawing tool that can create building geometry. The areas of different zones of the house are given in Table 3.1. Fig. 2(a) shows the room layout while Fig. 3.2(b) shows the three-dimensional model of the house, constructed using SkechUp.

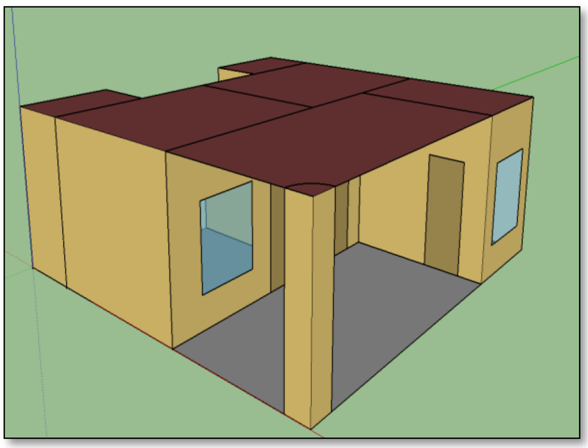
The digital model drawn in SkechUp model was converted into the input file of the EnergyPlus.

Table 3.1: Details of different spaces of the base line model

Sr. No.	**Building Space**	**Length (m)**	**Width (m)**	**Area (m^2)**
01	Bedroom 1	4.5	3.8	17.1
02	Bedroom 2	4.5	3.8	17.1
03	Bathroom 1	2.44	1.5	3.66
04	Bathroom 2	2.44	1.5	3.66
05	Kitchen	2.4	3.5	8.4
06	Front Veranda	6.76	3.7	25.012
07	Back Veranda	3.9	1.7	6.63



(a) Floor plan



(b) North facing SkechUp Model

Fig. 3.2: 3D replica of the house

3.2. Building Materials

In Pakistan, the most common building construction material are backed bricks and a layer of cement and sand (plaster) on both sides of the wall. Therefore, the base-line model considered in this research was assumed to be constructed using backed bricks. The walls are assumed to be composite walls having three layers, i.e 228.6 mm of brick and 9.525 mm of plaster on both sides. The roof of this house consists of reinforced concrete of 152.4mm thickness and 9.525 mm thick layer of plaster. The bedrooms and kitchen are fitted with gypsum ceiling. The roof ceiling is installed below the concrete roof and there is an air gap of 6 inches between roof concrete and roof ceiling. Structures and materials of the building envelope are given in Table 3.2. Thermal transmittance of each component of building envelope, so-called U values are also included. It is noteworthy that the U-values listed are generally large compared to the building standards adopted in many developed countries, suggesting low insulation performance of current houses in Pakistan.

Table 3.2: Materials and depth of building elements

Building envelopes	**Floor**	**Exterior Wall**	**Inter-Zone Wall**	**Roof**	**Window**	**Door**
U value (Given by E+)	1.744 ($Wm^{-2}K^{-1}$)	4.545 ($Wm^{-2}K^{-1}$)	4.545 ($Wm^{-2}K^{-1}$)	3.766 ($Wm^{-2}K^{-1}$)	5.894 ($Wm^{-2}K^{-1}$)	1.951 ($Wm^{-2}K^{-1}$)
Outside layer	Ceramic Tiles (9.5 mm)	Plaster (9.5 mm)	Plaster (9.5 mm)	Plaster (9.5 mm)	Clear glass (3 mm)	Wood (50.8 mm)
Layer 2	Concrete (50.8 mm)	Brick (228.6 mm)	Brick (228.6 mm)	Concrete (152.4 mm)		
Layer 3	Brick Masonry (101.6 mm)	Plaster (9.5 mm)	Plaster (9.5 mm)	Air Gap (152.4 mm)		
Layer 4	Sand (101.6 mm)			Gypsum Ceiling (9.5 mm)		
Layer 5	Soil (228.6 mm)					

As shown in Table 3.2, the floor of the house consists of five different layers. The thermal properties for each material are listed in Table 3.3.

Table 3.3: Thermal properties of materials of the floor

Properties/ Name of Material	**Ceramic Tiles**	**Floor Concrete**	**Brick Masonry**	**Sand**	**Soil**
Conductivity [$Wm^{-1}K^{-1}$]	0.309	0.755	0.711	1.711	0.837
Density [kgm^{-3}]	1900	2000	2000	2240	1300
Specific Heat	656	656	836	840	1046

[$Jkg^{-1}K^{-1}$]					
Emissivity	0.9	N/A	N/A	N/A	N/A
Solar Absorptance	0.7	N/A	N/A	N/A	N/A
Roughness	Medium Smooth	N/A	N/A	N/A	N/A

In this study, walls are classified into exterior and inter-zone walls. In the baseline model without insulation, compositions of these two wall types are treated as same as shown in Table 3.2. At the latter stage, insulation materials will be added to exterior walls only. Table 3.4 gives details of thermal properties of each wall layer.

Table 3.4: Thermal properties of materials for wall

Name of Material	**Plaster**	**Brick**	**Plaster**
Conductivity ($Wm^{-1}K^{-1}$)	0.431	1.3	0.431
Density (Kgm^{-3})	1250	1800	1250
Specific Heat ($Jkg^{-1}K^{-1}$)	1088	840	1088
Thermal Absorptance	0.9	0.9	0.9
Solar Absorptance	0.7	0.7	0.7
Roughness	Medium Rough		Medium Rough

In the baseline model, the roof was assumed to consist of four layers. On the other hand, in the latter sensitivity analysis, insulation material will be added to the roof below the outer layer of plaster. Thermal values of different layers of roof are given in Table 3.5 below:

Table 3.5: Detailed thermal values of different layers of roof

Name of Material	**Plaster**	**Roof Concrete**	**Air Gap**	**False Ceiling**
Conductivity ($Wm^{-1}K^{-1}$)	0.431	1.046	2.03	0.42
Density (Kgm^{-3})	1250	2300	1.3	1250
Specific Heat ($JKg^{-1}K^{-1}$)	1088	656	1004	1088
Thermal Absorptance	0.9	0.9	0.9	0.9
Solar Absorptance	0.7	0.7	0.7	0.7
Visible Absorptance	0.7	0.7	0.7	0.7
Roughness	Medium Smooth	Medium Rough	Medium Rough	Medium Rough

In Pakistan, doors are commonly made of wood in residential buildings. Therefore, the doors for this base-line model were assumed to be made of wood. Table 3.6 shows the thermal properties of wood, being used as doors.

Table 3.6: thermal properties of doors

Name of Material	Wood
Conductivity ($Wm^{-1}K^{-1}$)	0.14
Density (Kgm^{-3})	650
Specific Heat ($JKg^{-1}K^{-1}$)	1200
Thermal Absorptance	0.9
Solar Absorptance	0.7
Visible Absorptance	0.7
Roughness	Medium Smooth

The baseline model house is having double pan windows with an air gap of 0.0127 m thickness. Detailed properties of the glass used in the windows are given in Table 3.7.

Table 3.7: Detailed properties of Glass used in Windows

Name of Material	Clear 3mm
Optical Data Type	Spectral Average
Thickness (m)	0.003
Solar Transmittance at Normal Incidence	0.837
Front Side Solar Reflectance at Normal incidence	0.075
Back Side Solar Reflectance at Normal incidence	0.075
Visible Transmittance at Normal Incidence	0.898
Front Side Visible Reflectance at Normal incidence	0.081
Back Side Visible Reflectance at Normal incidence	0.081
Infrared Transmittance at Normal Incidence	0
Front Side Infrared Hemispherical Emissivity	0.84
Back Side Infrared Hemispherical Emissivity	0.84
Conductivity ($Wm^{-1}K^{-1}$)	0.9

3.3. Appliances related to internal heat generation

The author assumed that the baseline model is home for a small family of four members including a husband, wife and two children. It is worth mentioning that the average size of a family in Pakistan is found to be 6.31 persons (Pakistan Bureau of Statistics). Considering the situation in Pakistan, two types of energy, i.e electricity and natural gas were assumed to be used in the baseline model. Electricity is used for lighting, space cooling, television, microwave oven, refrigerator, washing machine, water pump and exhaust fans, while natural gas is used in gas stove for cooking.

Table 3.8 lists electric appliances assumed in each zone of the house. In Pakistan, LED lights are commonly used in residential sector, thus, we assumed that LED lights are installed in baseline model. The occupants of the house are using air conditioners for space cooling in bedrooms. However, we have not considered ceiling fans in our baseline model, which are commonly used in Pakistan.

Table 3.8: Assumed Appliances and energy consumption in each room

Zone Name	**Appliance**	**Power consumption (W)**	**Daily use in hours**	**Remarks (Period of usage, assumed specification)**
Bedroom 1	Lights	50	06	Throughout the year
	Television	130	Weekday: 04 Weekends: 06	Throughout the year
	Clothes iron	1100	3	Only on Saturdays
	Air Conditioner	N/A	14	From 1st May to 30th September
Bedroom 2	Lights	50	06	Throughout the year
	Air Conditioner	N/A	14	From 1st May to 30th September
Kitchen	Lights	50	06	Throughout the year
	Water Pump	400	2	Throughout the year
	Microwave Oven	500	0.5	Throughout the year
	Refrigerator	150	16	Throughout the year
	Exhaust Fan	50	5	Throughout the year when a gas stove is used
	Gas Stove	3428	4	Throughout the year
Washroom 1	Lights	25	6	Throughout the year
	Washing Machine	500	4	Only on Saturdays Capacity: 12kg Spin Speed: 600 rpm
Washroom 2	Lights	25	6	Throughout the year

(a) LED Ceiling light

(b) 42” LCD Television

(c) Water pump

(d) 15 cubic feet conventional refrigerator

(e) Washing machine

(f) Gas Stove

(g) Ceiling fan

(h) Clothes iron

Fig. 3.3 Assumed appliances used in each room

In addition to these appliances, a kitchen gas stove is the main contributor to the increase of the air temperature of the kitchen. Note that 3.428 kW of the energy consumption for the assumed gas stove indicates the fuel consumption other than internal heat generated contributing to increase the room air temperature. In the EnergyPlus simulation, 40% and 20% of this energy were assumed to be transported by convection and radiation to the rooms and remaining 40% was considered to be used for cooking. Meanwhile, in Pakistan, the energy efficiency of gas stoves are generally low, having limited functions to modulate the heating power. On the other hand, in developed countries such as Japan, energy efficiency of gas stoves has been steadily improved by about 25% for last decades based on the due to the Top Runner System implemented by the Ministry of Economy, Trade and Industry. In addition, gas stoves equipped with thermostatic heat adjustment function are becoming popular recently. Furthermore, the assumption of gas stove usage of 4-hour at 3.428 kW per day is much longer and larger in terms of both time and energy consumption compared to the Japanese situation. According to the questionnaire survey conducted on 500 married Japanese female in 2010, the average hours of cooking was 1.37-hour per day. Since frozen and semi-prepared foods are readily available in Japan, a large fraction of the cooking that used to be done at home has been outsourced to food factories, which probably accounts for the difference between Pakistan and Japan.

3.4. Occupants’ behavior schedule related to internal heat generation

Bedrooms are the main places of occupancy. Beside sleeping, bedrooms were assumed to be used as sitting areas. In addition, bedroom 1 was also assumed to be used as RV lounge, dining room and guest room. Bedroom 2 was assumed to be also used as study area. The occupancy schedule of both the rooms is shown in Table 3.9.

Table 3.9: Schedule of occupancy of two bedrooms

Time	Bedroom 1 Occupancy	Bedroom 2 occupancy
00:00 – 08:00	100%	100%
08:00 – 13:00	25%	25%
13:00 – 15:00	75%	75%
15:00 – 19:00	50%	50%
19:00 – 24:00	100%	100%

100% refers to the maximum number of occupants, 2 persons.

3.5. Estimated internal heat generation

Based upon our assumptions in Table 3.8, Energyplus derived the energy consumptions of these appliances. These appliance-wise energy consumptions are given in Table 3.10.

Table 3.10: Annual energy consumption and Heat Energy radiated by different appliances

Sr. No.	Name of the Appliance	Energy source	Energy consumption per day [Wh/day]	Annual energy consumption (kWh/year)
01	Water pump	Electricity	800	292
02	Refrigerator	Electricity	2400	876
03	Television	Electricity	780* 520**	81.12 135.72
04	Iron	Electricity	3300***	171.6
05	Washing Machine	Electricity	2000***	104
06	Microwave Oven	Electricity	250	91.25
07	Exhaust Fan	Electricity	275	100.375
08	Gas Stove	Natural Gas	13,712	5004.88 ****
09	Bedroom 1 Lights	Electricity	275	100.375
10	Bedroom 2 Lights	Electricity	275	100.375
11	Washroom 1 lights	Electricity	137.5	50.1875
12	Washroom 2 Lights	Electricity	137.5	50.1875
13	Kitchen Lights	Electricity	275	100.375
	Total of electric appliances	Electricity	5345* 10905** 5605***	2253.565
	Total of appliances using natural gas	Natural Gas	13,712	5004.88

*: Per day energy consumption of television on weekends.
**: Per day energy consumption of television on weekdays.
***: Energy consumption on every Saturday.
****: The ratio of heat released to indoor air to the entire energy consumption was assumed to be 40%.
ᴥ: Energy consumption on weekdays
ᴥ ᴥ: Energy consumption on Saturdays
ᴥ ᴥ ᴥ: Energy consumption on Sundays

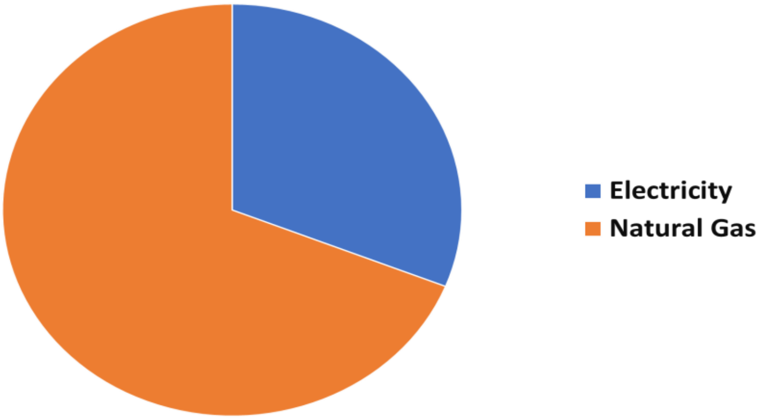


Fig. 3.4: Share of electricity and natural gas in annual energy consumption

Fig. 3.4 shows that the major portion of energy needs of baseline case is met with natural gas. To be precise the share of natural gas in annual energy needs is 70% which amounts to 5004.88 kWh. This huge amount of energy is only used for cooking in kitchen. It may be noted that this share of energy does not include the energy consumed by microwave oven. Hence, improving the energy efficiency of gas stoves in Pakistan can reduce domestic consumption of natural gas, drastically. Remaining 30% (2153.565 kWh) of energy needs of this model are met with electricity. This energy is consumed for different purposes. Fig. 3.5 shows share of different consumptions of electricity by different equipment. From Fig. 3.5, it is apparent that refrigerator consume a major portion of electricity (39%). Water pump (13%) and television (10%) are the next major contributors in the list. Iron is also one of the major contributors on the list with 8% share in electricity consumption.
Economic Survey of Pakistan for the year 2020-21 has mentioned that the household sector of Pakistan is consuming 41,508 GWh of electricity and 915 MMCFD of natural gas.

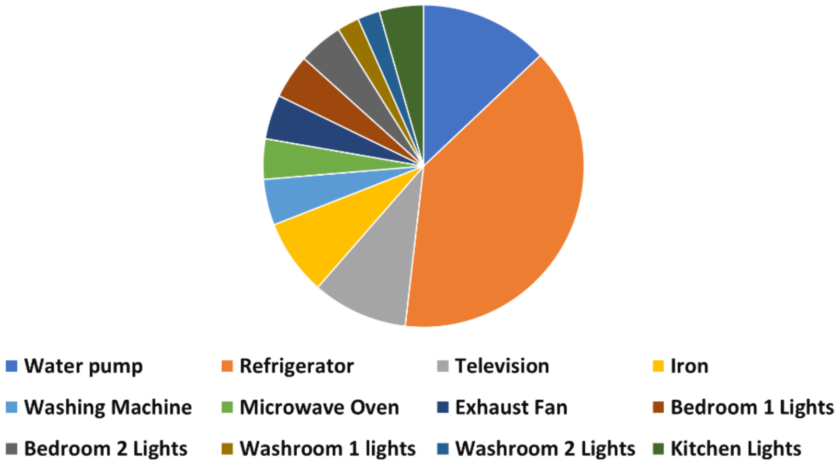


Fig. 3.5: Share of different appliances in electricity consumption

4. SIMULATION RESULT OF BASELINE CASE

4.1. Annual trend of outdoor weather variables

After inputting above detailed data for base line case, the simulations were conducted in EnergyPlus and the results were analyzed. In order to simulate a model in EnergyPlus, local weather data was required. The weather data for this purpose was obtained from Meteonorm 7.3 for year 2002. The weather data extracted from Meteonorm was from 1st January 2002 to 31st December 2002. Fig.4.1 shows different weather variables i.e site air temperature, relative humidity, wind speed, precipitation, direct solar radiation and diffusive solar of Islamabad for the year 2002. As per weather data, the lowest site air temperature was recorded as 1.2ºC on 13th January 2002 at 07:00 a.m. in morning. The highest value of site air temperature was recorded to be 44.6ºC. This temperature was recorded on 18th June at 04:00 p.m. in afternoon. These two dates are treated as extreme weather conditions and the performance of weeks including these two peaks was examined for the baseline model initially. In the baseline case, an infiltration rate of 0.5 ACH was considered for all the zones.

4.2. Daily variation of indoor variables at typical peak days

4.2.1. Outdoor climate variables of selected days

In order to investigate the typical daily patterns of indoor thermal conditions, the performance of baseline model was checked during the coldest week of the year (13th to 19th January 2002) and hottest week of the year (16th to 22nd June). Fig.4.2 shows an overview of the outdoor conditions during the coldest week. The figure shows air temperature, relative humidity, solar radiation, wind speed and precipitation at Islamabad during the week. The site temperature ranges between 1.2ºC and 20.4ºC. The relative humidity ranges from 30% to 100%. The wind speed is calculated at a height of ten meters from ground while B1 wind speed (Bedroom 1 outdoor wind speed) is calculated at a height above the ground equal to zone centroid. In the current study, the height of a zone is considered ten meters, hence, B1 air wind speed is calculated at five meters from ground by EnergyPlus. The pattern of solar radiation indicates that 13th, 17th, 18th and 19th are sunny while 14th, 15th and 16th are cloudy. Major portion of solar radiation received by Islamabad reached the ground directly. The wind speed on a sunny day is larger than that on cloudy or rainy day. As can be seen, there is raining on 16th and nighttime of 14th.

Fig.4.3 gives an overview of the outdoor conditions during the hottest week of the year (16th to 22nd June 2002). the air temperature ranges from 27.0ºC to 44.6ºC. The highest temperature of this week is also the highest temperature of the year. Relative humidity varies from 18% to 77.325%. The solar radiation curve indicates that 16th,17th, 18th, 20th, 21st and 22nd are cloudy, 19th is sunny while 17th is rainy. During the week the almost half of the solar radiation is diffusive. The wind speed on 16th 17th and 18th is lower than rest of the week which is an indication of the presence of clouds in the sky. The precipitation curve shows that there was raining on 17th of June.

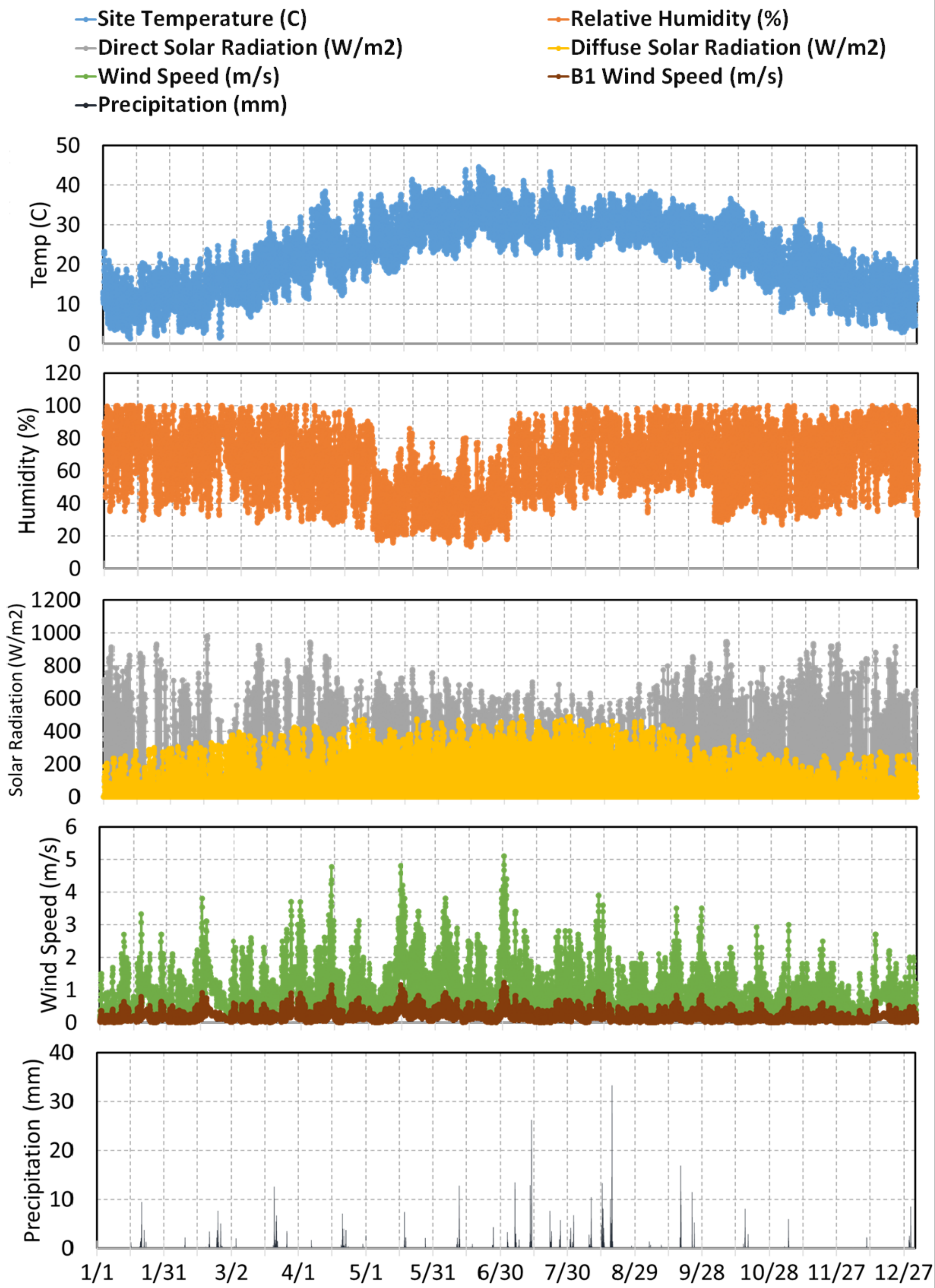


Fig. 4.1: Climate of Islamabad for the year 2002

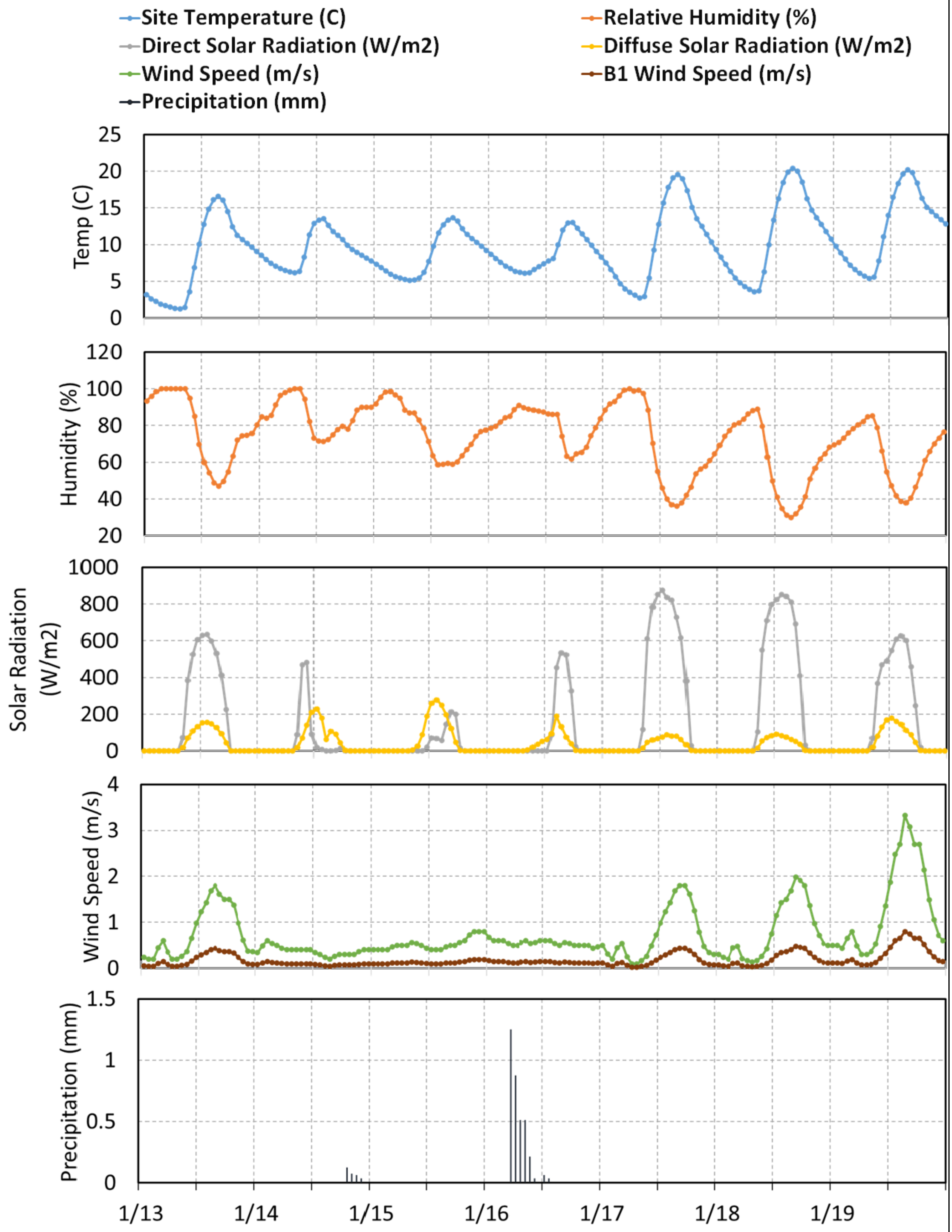


Fig. 4.2: Weekly variation of climate variables during the coldest week

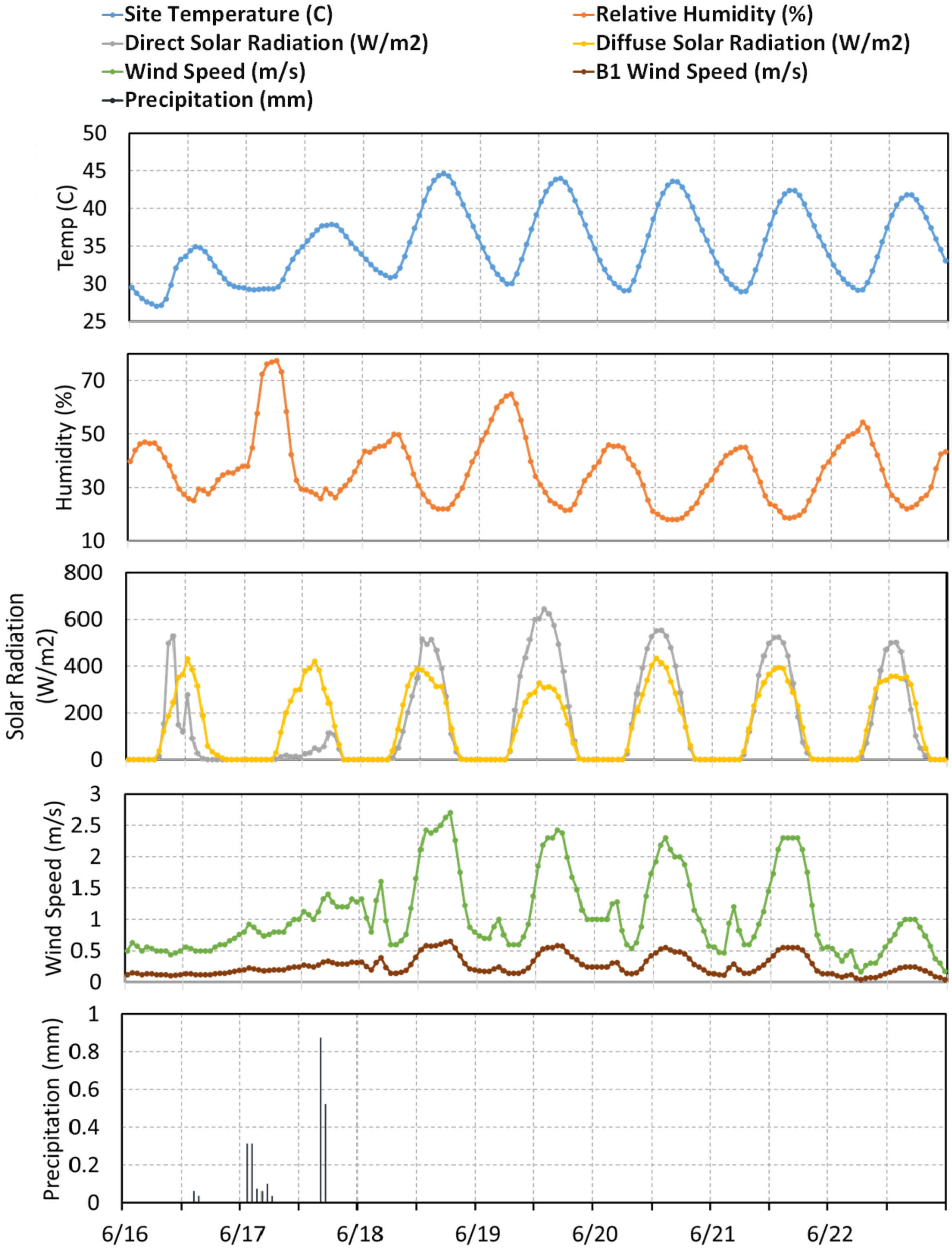


Fig. 4.3: Weekly variation of climate variables during the hottest week

4.2.2. Simulated indoor climate variables of selected days

In Fig.4.4, a comparison between site weather variables and simulated bedroom 1 climate variables for the coldest week of the year is shown. The figure shows that indoor temperature varies in a smaller range as compared to outdoor air temperature. The lowest temperature of bedroom 1 is 10.2ºC while the highest indoor temperature is 23.1ºC. The relative humidity ranges from 45.6% to 86.1%. The smaller range of indoor simulated climate variables indicates that the building envelope is effectively working to attenuate the outdoor environmental oscillation. As shown in Table 3.8, the bedroom was assumed to have heating generation from some home appliances. This is apparent from the graph. During daytime, the zone is only getting heat generation from its occupants. In evening time, heat generation from television also adds up to zone heat generation. In addition, there is a peak of heat generation on 19th January due to the usage of a clothes iron.

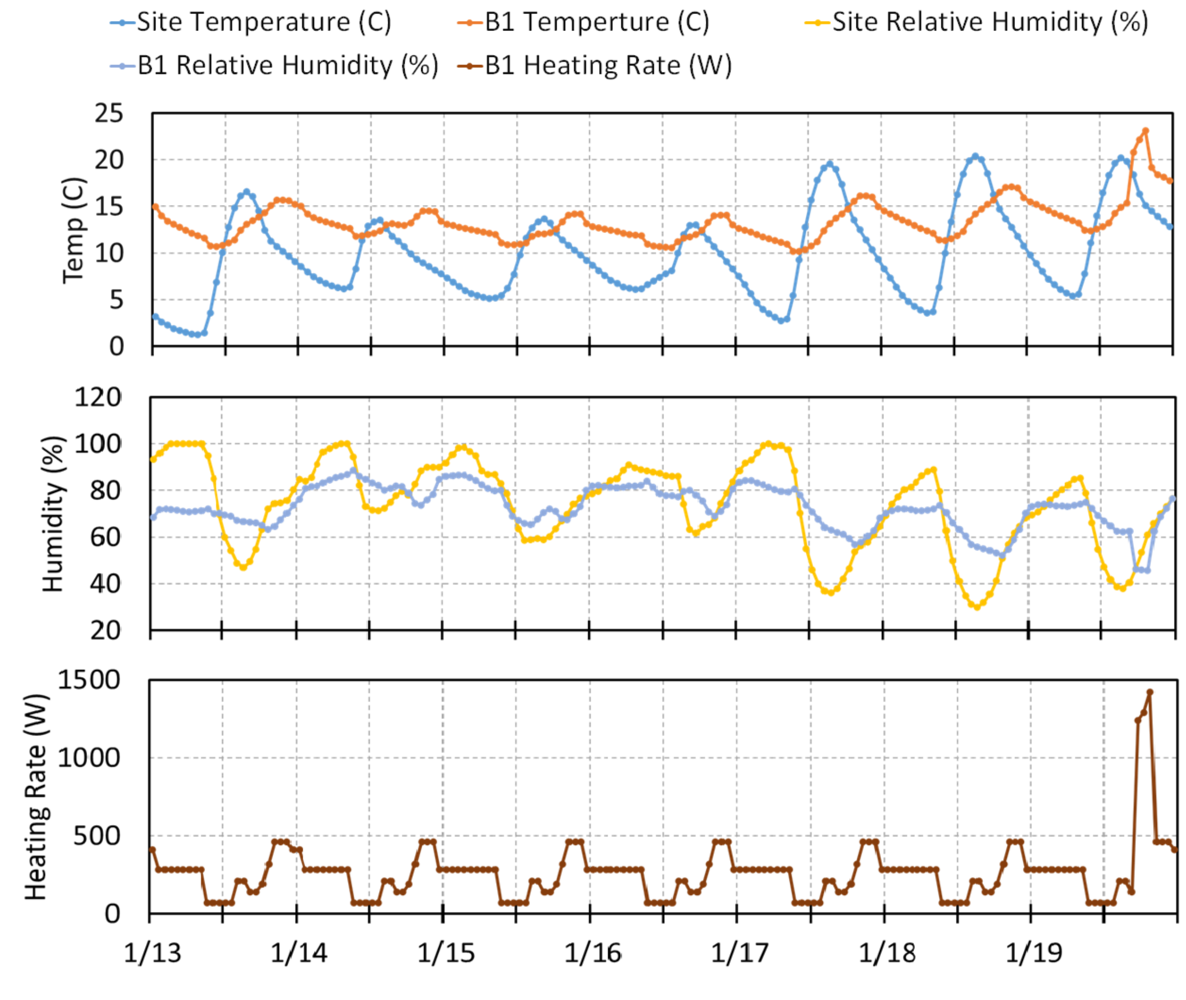


Fig. 4.4: Indoor climate variables of Bedroom 1 (B1) during the coldest week

In Fig.4.5, site weather variables and simulated bedroom 1 climate variables for the hottest week of the year are shown. The figure shows that indoor temperature varies on a smaller range as compared to outdoor air temperature. The lowest temperature of bedroom 1 is 27.9ºC while the highest indoor temperature is 40.1ºC. Relative humidity follows the same pattern as that of site relative humidity but remained higher than site relative humidity. It ranges from 38.7% to 100%. The heat generated in the zone is exactly the same as that of Fig. 4.4 because the equipment usage and occupancy is kept independent of the weather. The peak in indoor temperature on 19th January in Fig. 4.4 and 4.5 is due to heat generated by ironing.

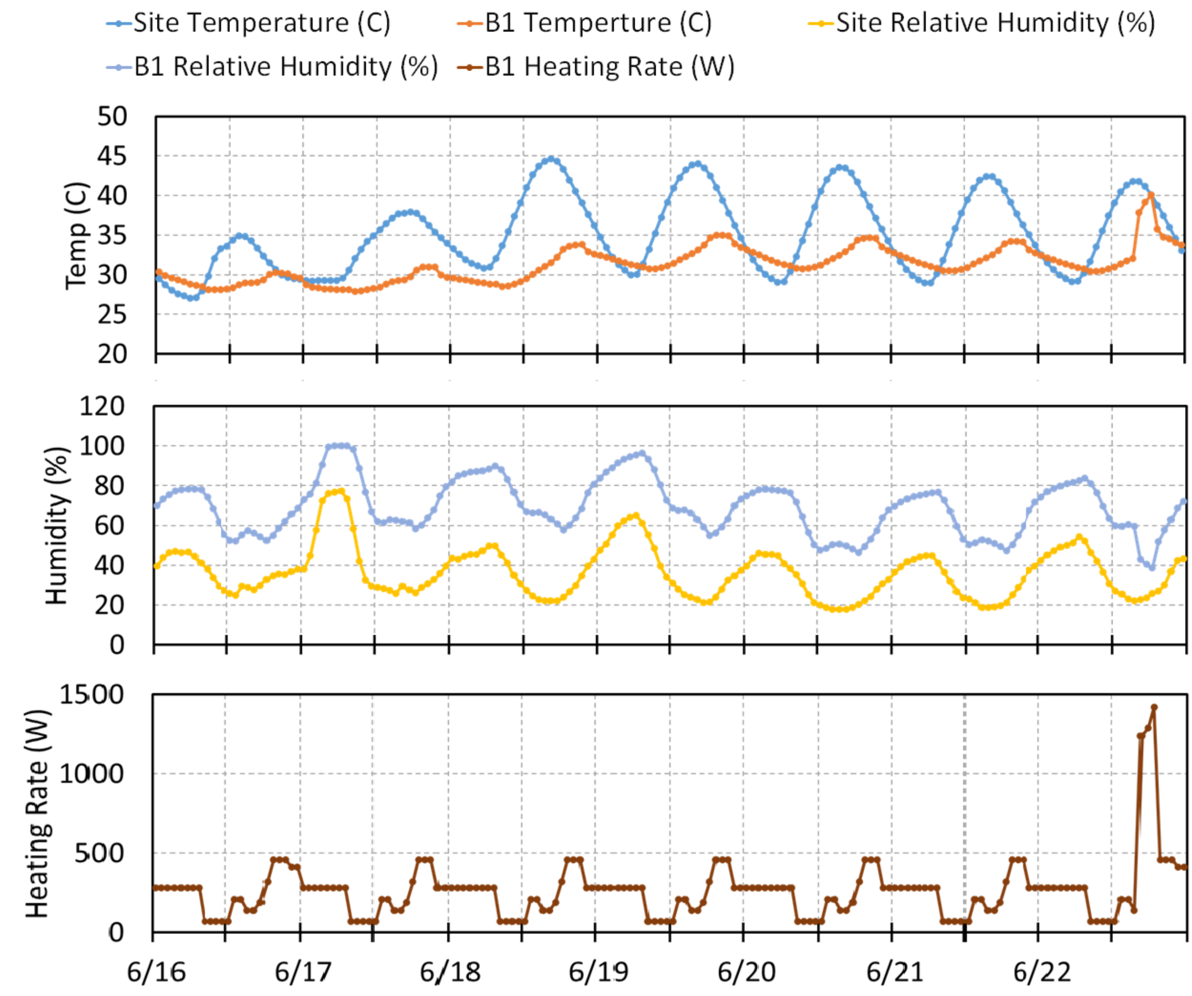


Fig. 4.5: Indoor climate variables of Bedroom 1 (B1) during the hottest week

Fig.4.6 gives the indoor climate variables of bedroom 2 (B2) for the coldest week of the year. Indoor temperature ranges from 10.4ºC to 15.76ºC. The Fig. shows that indoor temperature varies on smaller range as compared to outdoor air temperature. Relative humidity also varies on smaller range as compared to outdoor relative humidity. It ranges from 55.76% to 86.18%. Heat generated in this zone much less than the heat generated in bedroom 1. The greater amount of heat generated in bedroom 1 was due to the presence of a television and clothes iron in the zone. As heat is only generated by lights and occupants in bedroom 2, the amount of heat, generated is much less.

Fig.4.7 gives the indoor climate variables of bedroom 2 (B2) for the hottest week of the year. Indoor temperature ranges from 28.6ºC to 35.6ºC. The Fig. shows that indoor temperature varies on smaller range as compared to outdoor air temperature. However, relative humidity follows variation of outdoor relative humidity. It ranges from 44.8% to 100%. As discussed earlier, the heat generated in the zones is assumed to be the same throughout the year.

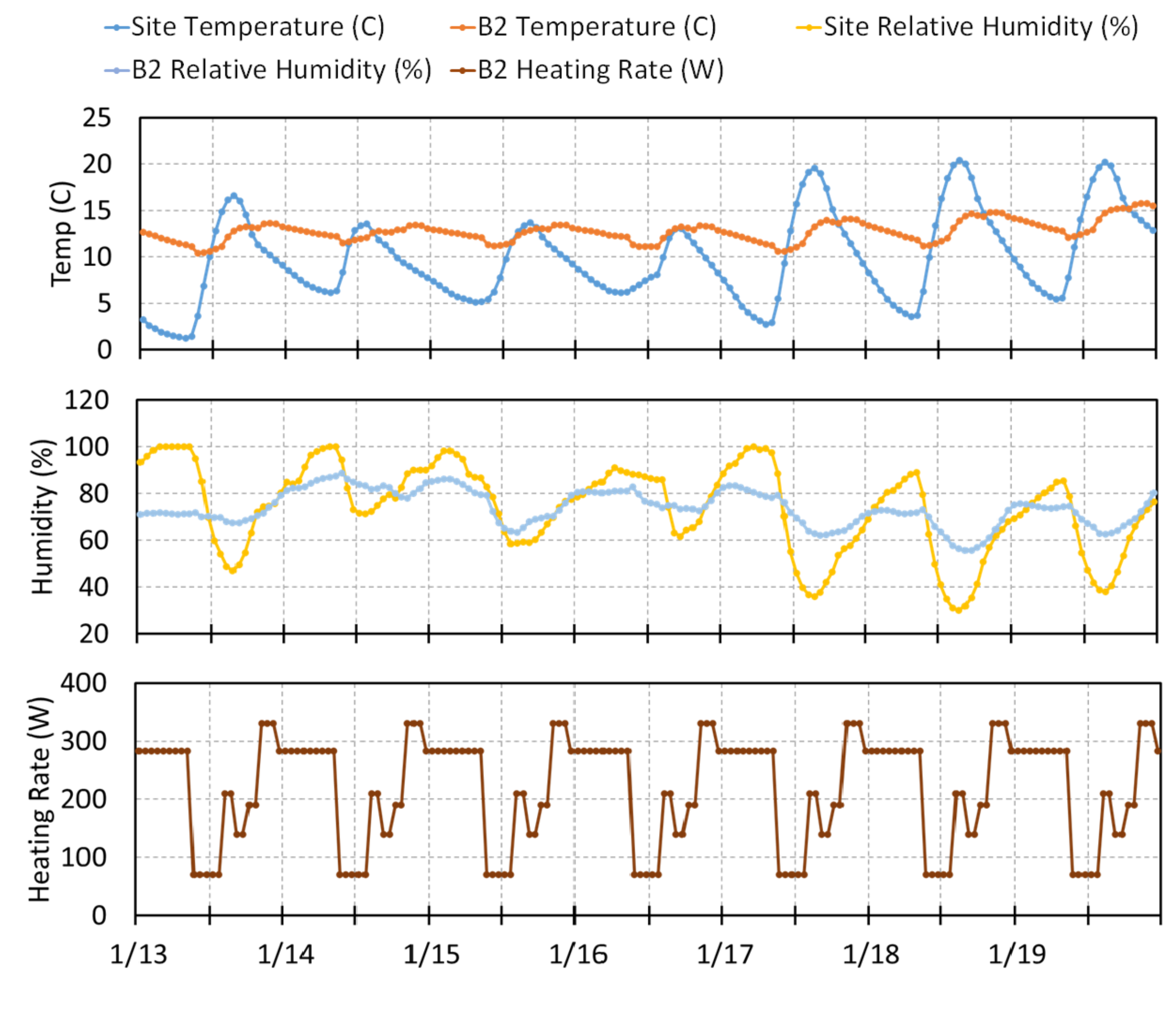


Fig. 4.6: Indoor climate variables of Bedroom 2 (B2) during the coldest week

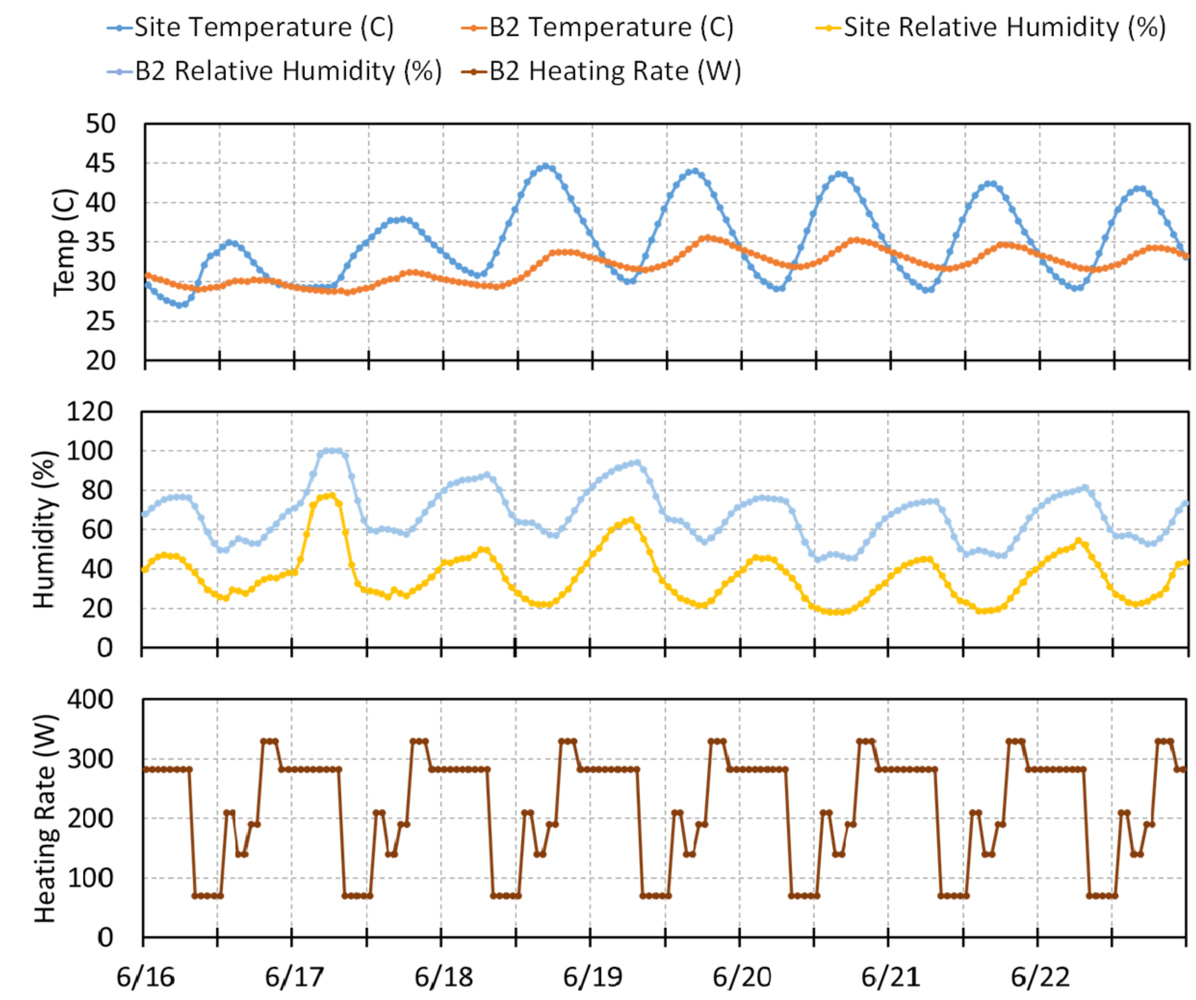


Fig. 4.7: Indoor climate variables of Bedroom 2 (B2) during the hottest week

Fig.4.8 shows the simulated indoor climate variables of kitchen (K) for the coldest week of the year. Indoor temperature ranges from 12°C to 30°C. There are multiple peaks in temperature of the kitchen every day. These peaks are due to the heat generated by a gas stove. As shown in Fig. 3.4, 69% of the energy demand of the baseline model is attributed by natural gas through the use of the gas stove. The hours of operation are shown in Table 3.8. The gas stove is working from 06:30 to 08:00 (1.5 hours), 12:00 to 13:30 (1.5 hours) and 19:00 to 20:00 (1 hour). Fig. 4.8 reveals that these peaks occur during these times. The figure also reveals that whenever there is a peak of temperature, the relative humidity is having a low value. This is due to evaporation of water vapors due to high temperature. The heat generation curve also validates the explanations given in this section. There are peaks of heat generation in the hours of operation of gas stove.

Fig.4.9 is a graphical representation of the indoor simulated variables in kitchen (K) for the hottest week of the year. The lowest temperature in the kitchen during this week is 33.2°C while the highest temperature reached to 53.5°C in kitchen. The relative humidity in the kitchen also increased during cooking time because of the vapor emission during the fuel combustion of the gas stove. The heat generated in the kitchen remained the same as that of the coldest week.

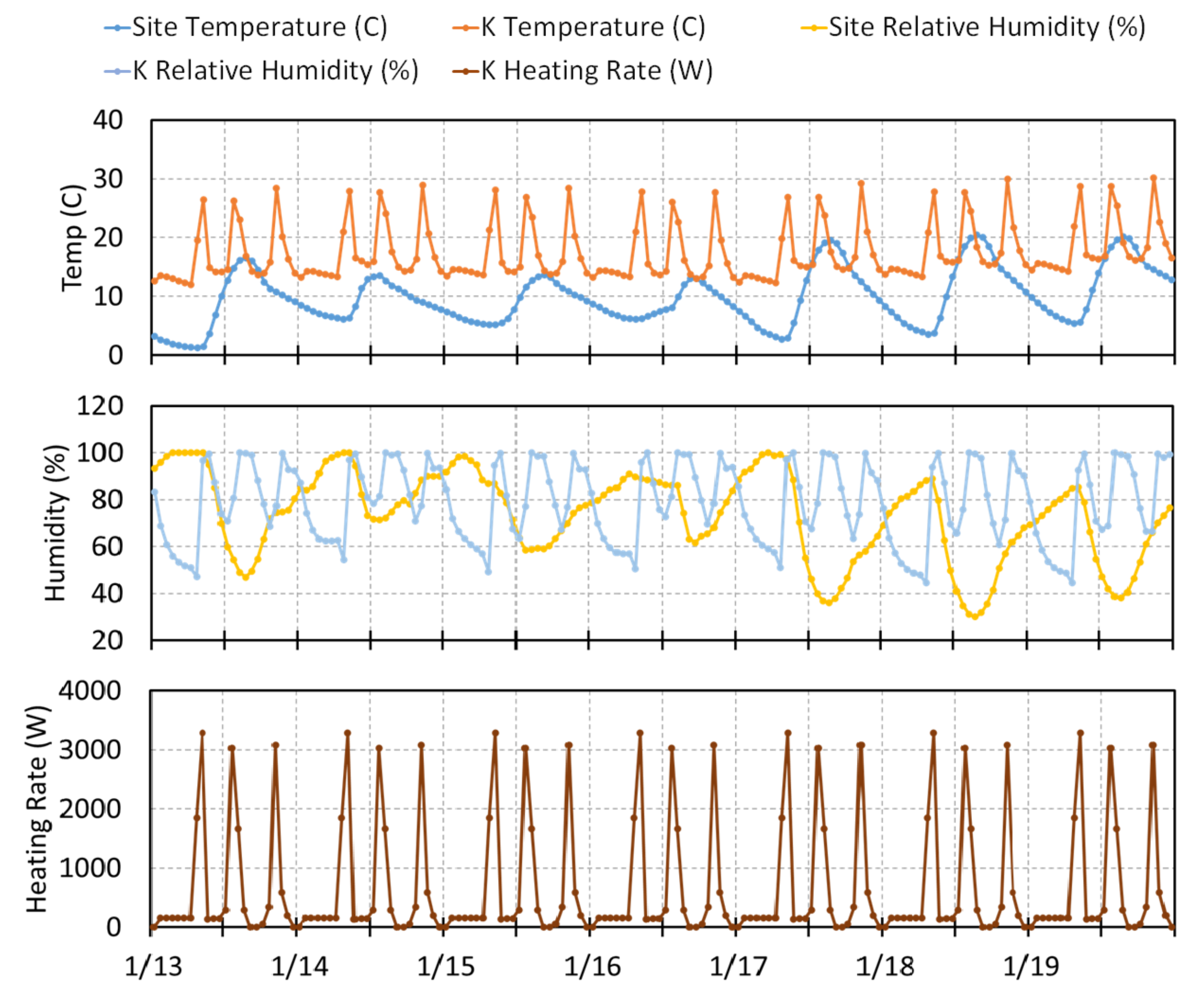


Fig. 4.8: Indoor climate variables of Kitchen (K) during the coldest week

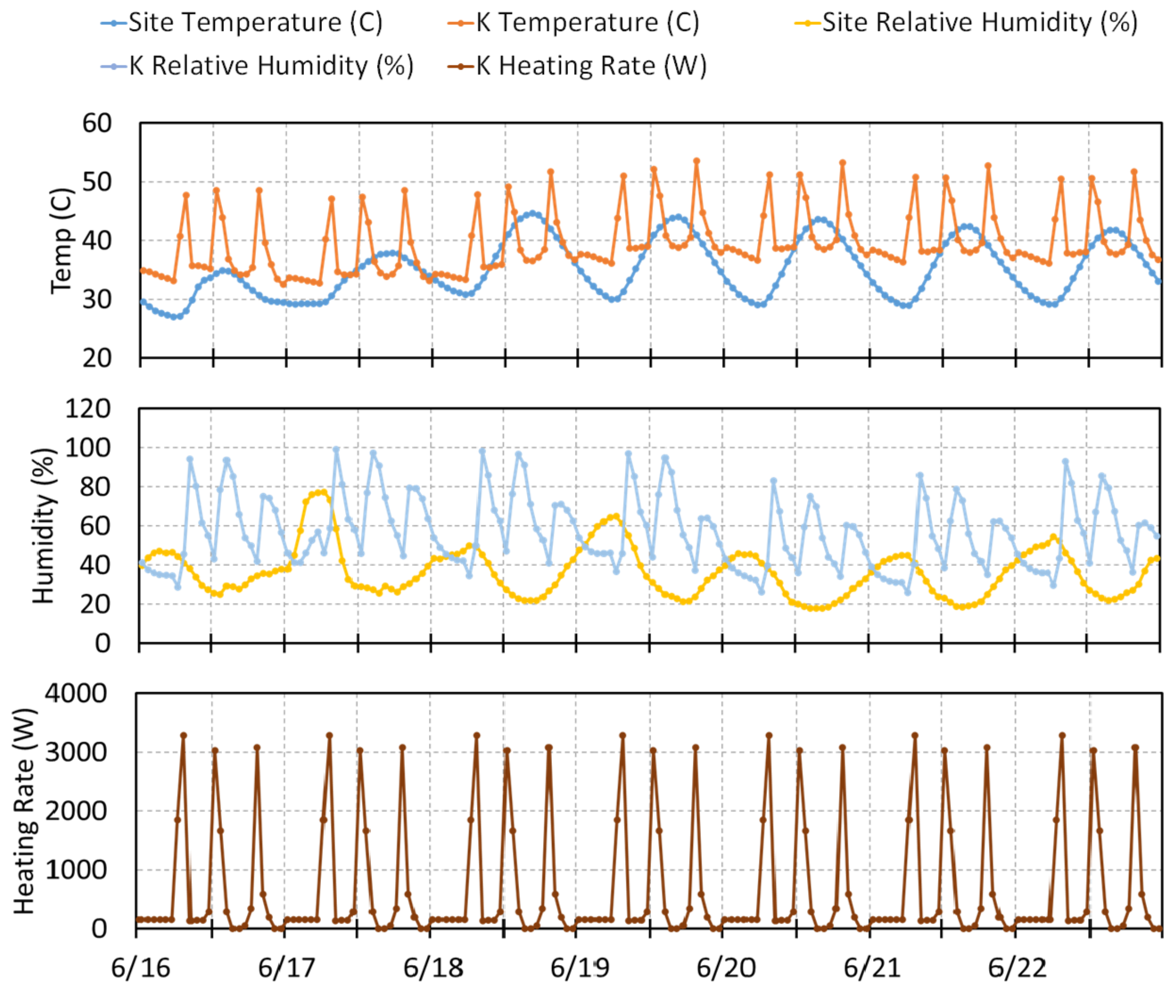


Fig. 4.9: Indoor climate variables of Kitchen (K) during the hottest week

Fig.4.10 gives the indoor climate variables of washroom 1 (W1) for the coldest week of the year. The indoor temperature ranges from 10.05ºC to 20ºC. The Fig. shows that indoor temperature varies on smaller range as compared to outdoor air temperature. There is a peak in indoor temperature of washroom 1 on 19th January. This is because of washing machine which is operated on every Sunday. Relative humidity also varies on smaller range as compared to outdoor relative humidity. It ranges from 32.49% to 74%. Heat generated in this zone is due to lights and washing machine on Sundays. This zone is not allotted any occupancy as washrooms are occupied for relatively smaller durations.

Fig.4.11 gives the graphical representation of indoor climate variables of washroom 1 (W1) for the hottest week of the year. Indoor temperature ranges from 29.57ºC to 41.95ºC. Relative humidity follows variation of outdoor relative humidity. It ranges from 24.9% to 71.4%. As discussed earlier, the heat generated in zones is independent of the weather, so it remains the same throughout the year.

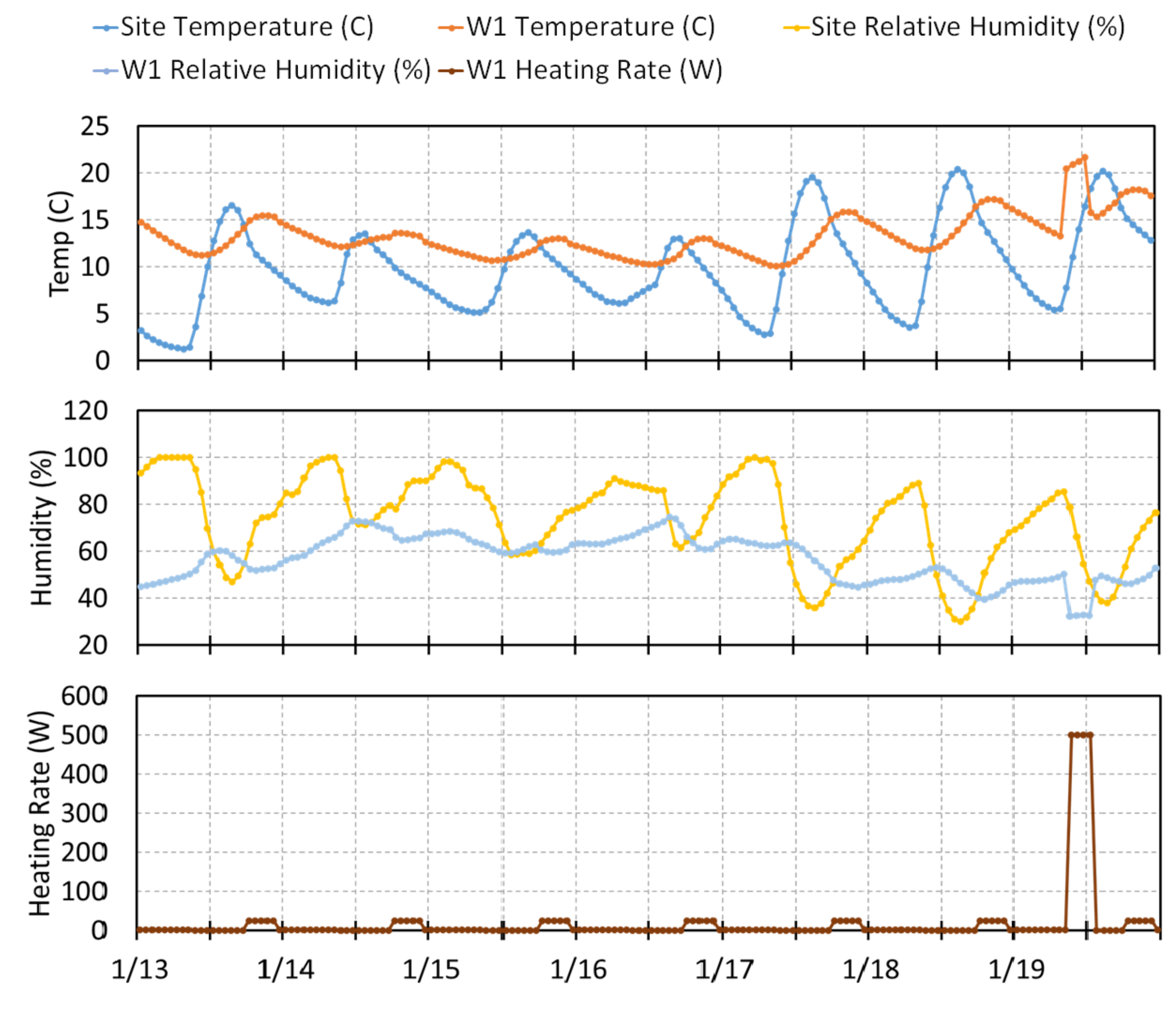


Fig. 4.10: Indoor climate variables of Washroom 1 (W1) during the coldest week

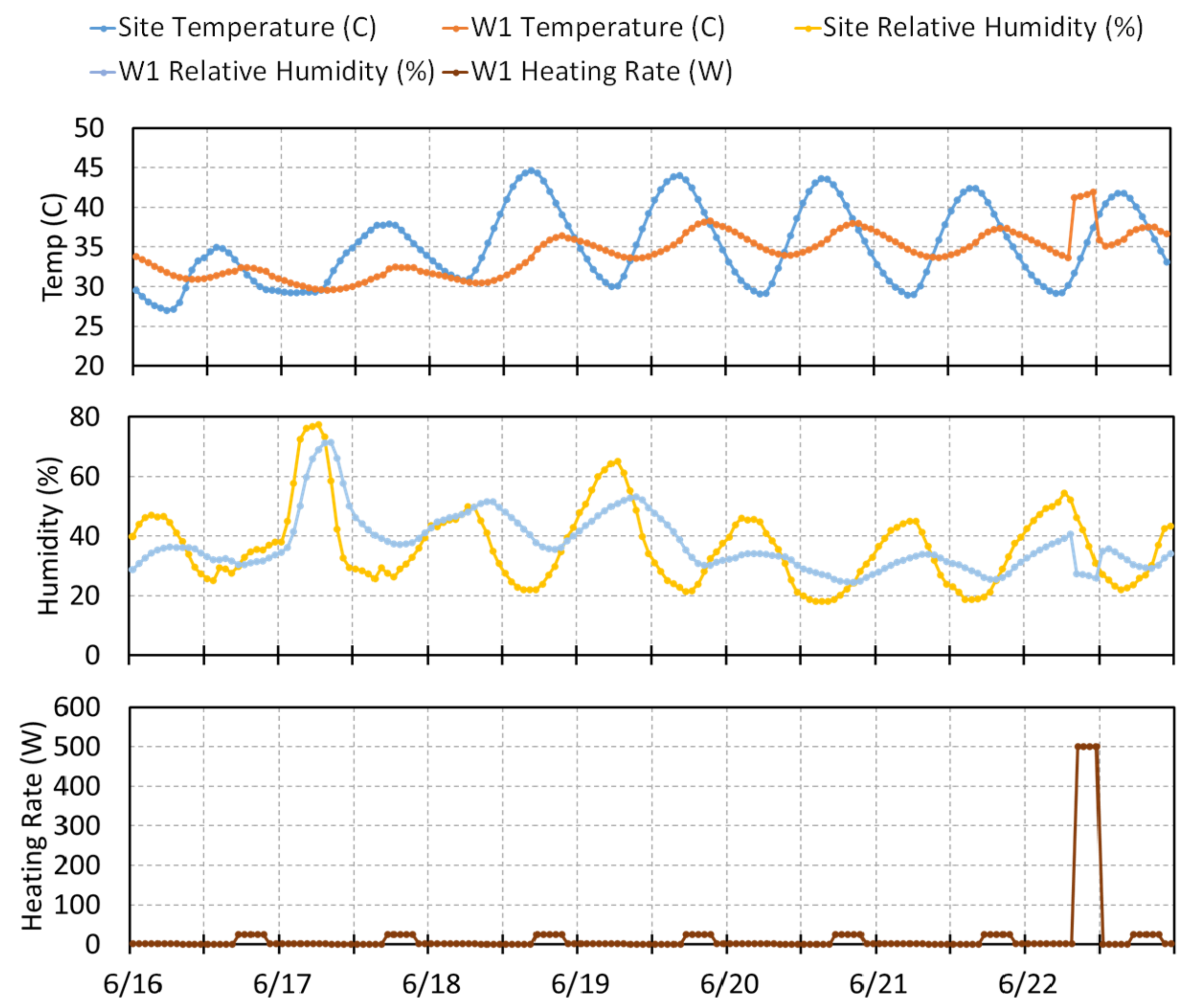


Fig. 4.11: Indoor climate variables of Washroom 1 (W1) during the hottest week

4.2.3. Simulated indoor thermal comfort of selected days

This section deals with the thermal comfort conditions of different zones. In the current study, thermal comfort conditions for three zones i.e bedroom 1, bedroom 2 and kitchen were analyzed. based on two variables, namely Predicted Mean Vote (PMV) and Predicated Percentage Dissatisfaction (PPD), which were calculated by EnergyPlus using Fanger Model. PMV is widely used thermal comfort index, ranging from -3 to 3. A zero value of PMV is considered as thermally neutral condition, indicating that occupants are neither feeling cold nor warm. In the calculation of PMV, mean radiant temperature was estimated by surface temperatures of walls, ceiling, and floor. Wind speed, clothing insulation and metabolic rate were assumed as 0.2 m/s, (0.61-1.3) clo, and 2.5 Met, considering the standard situation of Pakistan housing. PPD can be determined by PMV, indicating the percentage of occupants who feels discomfort with the thermal conditions of a zone. In addition to PMV and PPD, the operative temperature, which is often used as adaptive thermal comfort index, was also calculated.

Fig.4.12 gives a brief overview of the thermal comfort of Bedroom 1 during the coldest week of the year. The PPD for this week ranges from 5.4% to 49.2%. On the other hand, the PMV for this week ranges from -1.4 to 0.3. It means that the occupants are feeling cold during this week. However, comfort conditions can be achieved with the use of warm clothes.

Fig. 4.13 shows the PPD and PMV of bedroom 1's occupants during the hottest week of the year. The PPD during this week remained nearly 100% which means all the occupants felt too hot during this week in bedroom 1. PPD for the hottest week ranged between 35.6% and 100%. The PMV for this week varies between 1.2 and 3.6. The PMV clearly shows that the occupants are not feeling comfortable, and cooling is required to achieve comfort temperature.

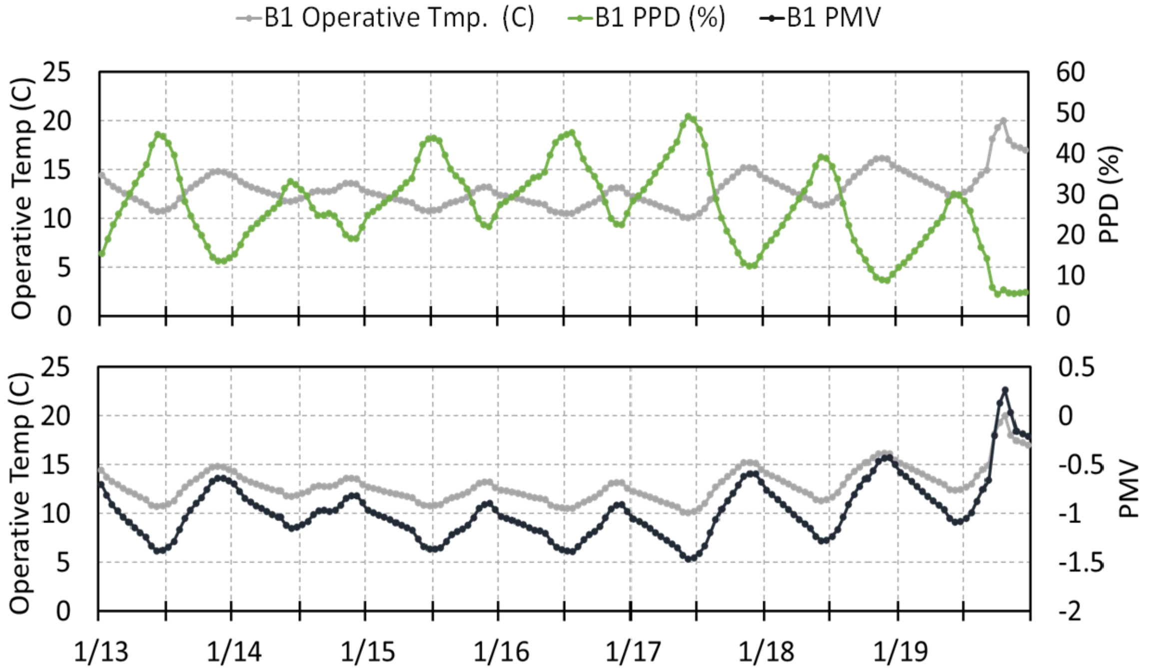


Fig. 4.12: Indoor thermal comfort variables of Bedroom 1 (B1) during the coldest week

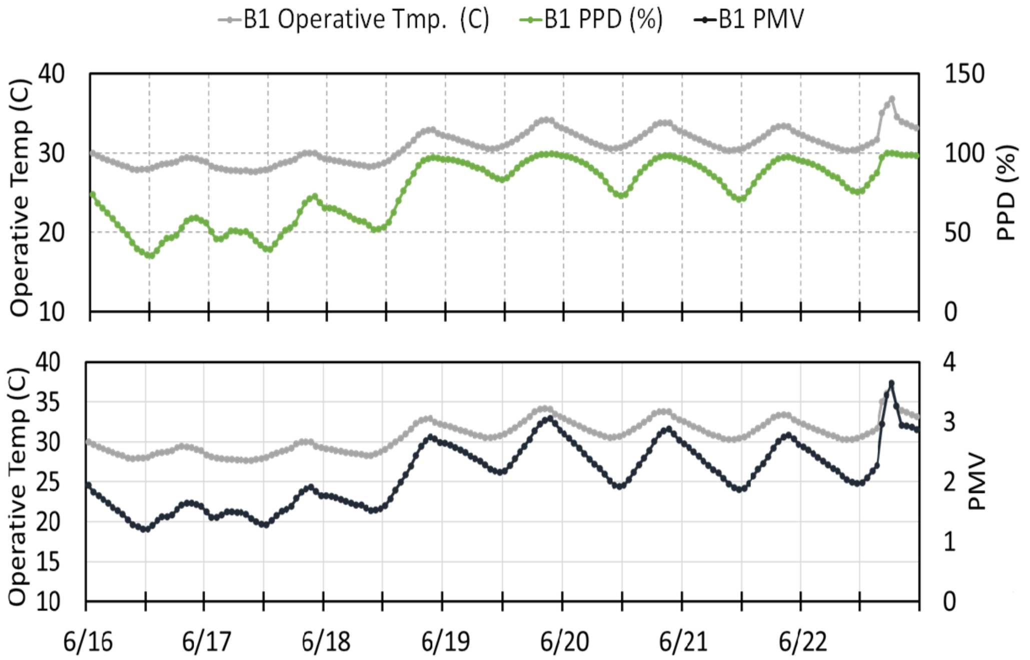


Fig. 4.13: Indoor thermal comfort variables of Bedroom 1 (B1) during the hottest week

Fig.4.14 gives a brief overview of the thermal comfort of Bedroom 2 during the coldest week of the year. The PPD for this week ranges from 11.7% to 46%. The PMV for this week ranges from -1.4 to -0.6. It means that the occupants are feeling cold during this week. However, comfort conditions can be achieved with the use of warm clothes.

Fig. 4.15 shows the PPD and PMV of bedroom 2's occupants during the hottest week of the year. PPD for the hottest week ranged between 51.6% and 100%. The PMV for this week varies between 1.5 and 3.2. The PMV clearly shows that the occupants are not feeling comfortable, and cooling is required to achieve comfort temperature.

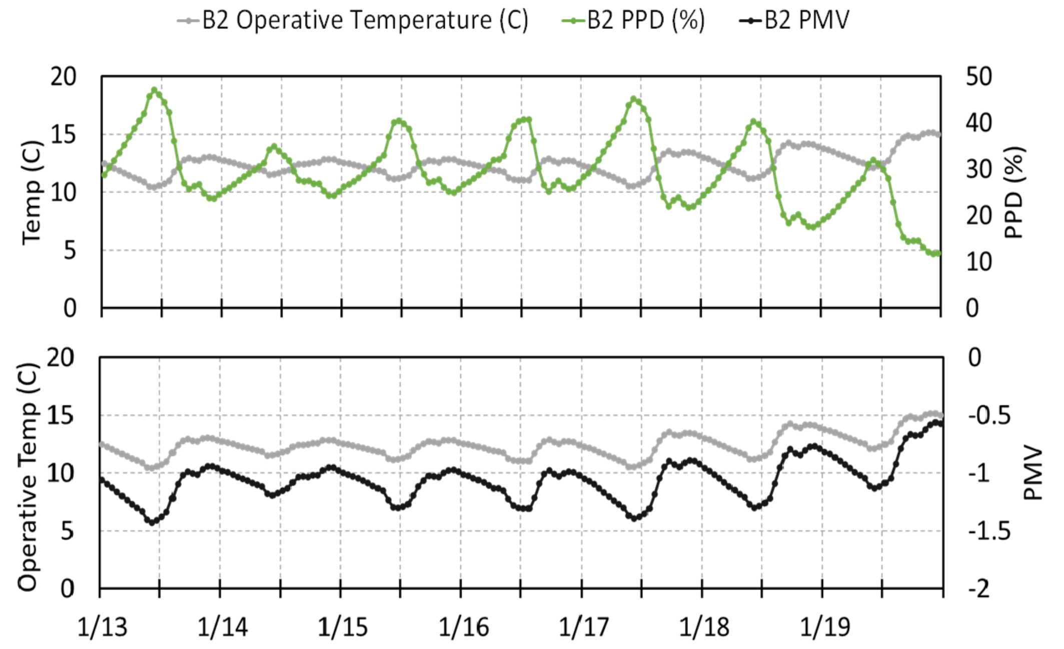


Fig. 4.14: Indoor thermal comfort variables of Bedroom 2 (B2) during the coldest week

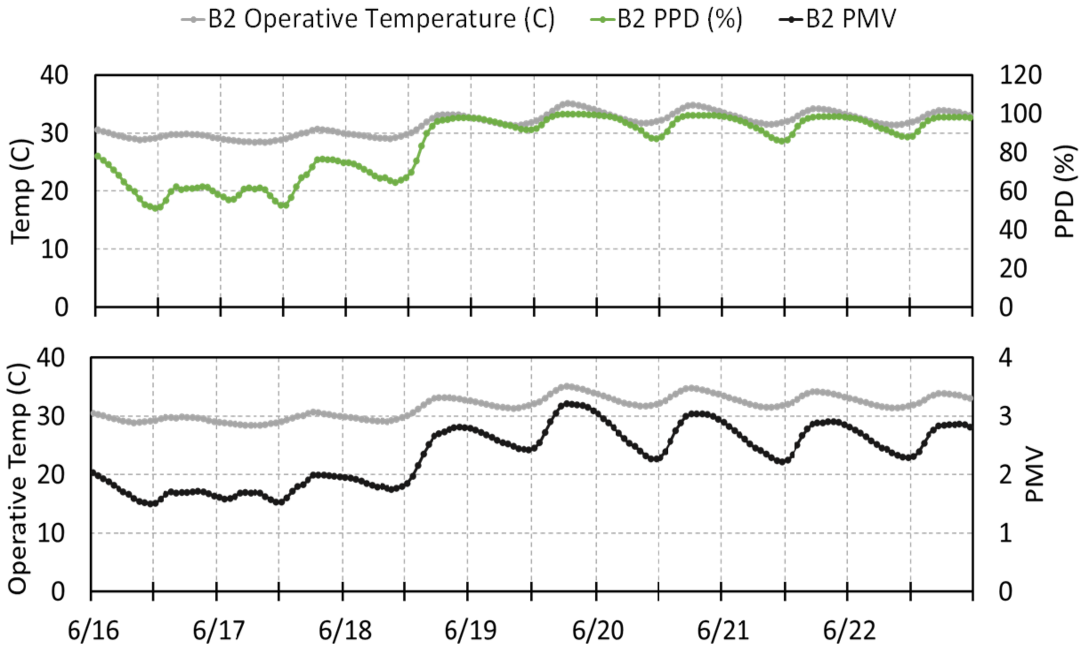


Fig. 4.15: Indoor thermal comfort variables of Bedroom 2 (B2) during the hottest week

Fig.4.16 gives a brief overview of the thermal comfort of kitchen during the coldest week of the year. The PPD for this week ranges from 5.15% to 40.6%. The PMV for this week ranges from -1.3 to 1.2. It means that the occupants are feeling neutral during cooking and cold during rest of the week.

Fig. 4.17 shows the PPD and PMV of kitchen's occupants during the hottest week of the year. PPD for the hottest week ranged between 87.8% and 100%. The PMV for this week varies between 2.3 and 6.8. The PMV of this zone is much higher than permissible range which means the indoor conditions are not suitable for occupants.

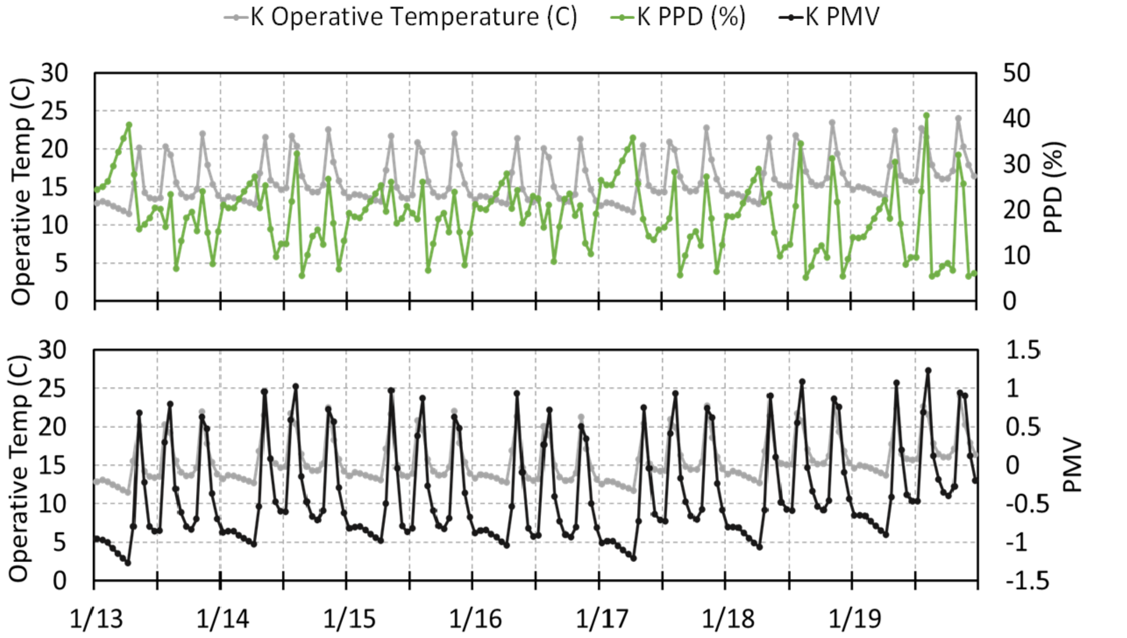


Fig. 4.16: Indoor thermal comfort variables of Kitchen (K) during the coldest week

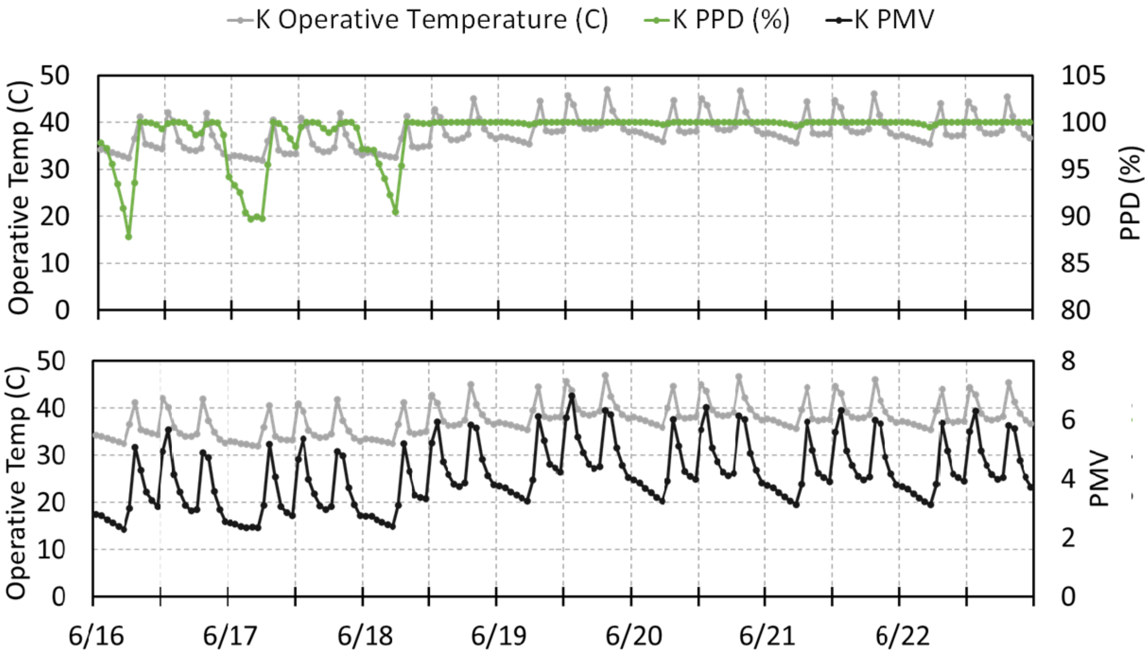


Fig. 4.17: Indoor thermal comfort variables of Kitchen (K) during the hottest week

4.2.4. Probability density distribution of PMV

Time patterns of PPD and PMV at specific periods are not enough to grasp the representative picture of indoor thermal comfort conditions all through the year. Therefore, a probability density distribution (PDD) of PMV was drawn in Fig.4.18 for bedroom 1, 2 and kitchen.

For bedroom 1 and 2, it can be noticed that there are two peaks of PMV occurrence which indicates that majority of PMVs lies in these two regions. In case of kitchen, the frequency of PMV at a certain point is lower however, the range of PMV is extended on higher side. It is caused by the excessive internal heat generation used by the gas stove, resulting in higher temperature in the kitchen.

Fig. 4.19 illustrates the cumulative probability of PMV, showing that in bedroom 1, 24% of PMV lies between -0.5 and 0.5. For bedroom 2, 21.3% of the PMV lies in the comfortable range of -0.5 to 0.5. The cumulative probability curve of kitchen indicates that 22% of the PMVs are in comfortable range. For bedroom 1, 2 and kitchen, the PMVs above 0.5 are 61%, 61.5% and 77.5% respectively. Percentage of PMVs, below -0.5 for bedroom 1, 2 and kitchen are 15%, 17% and 5% respectively.

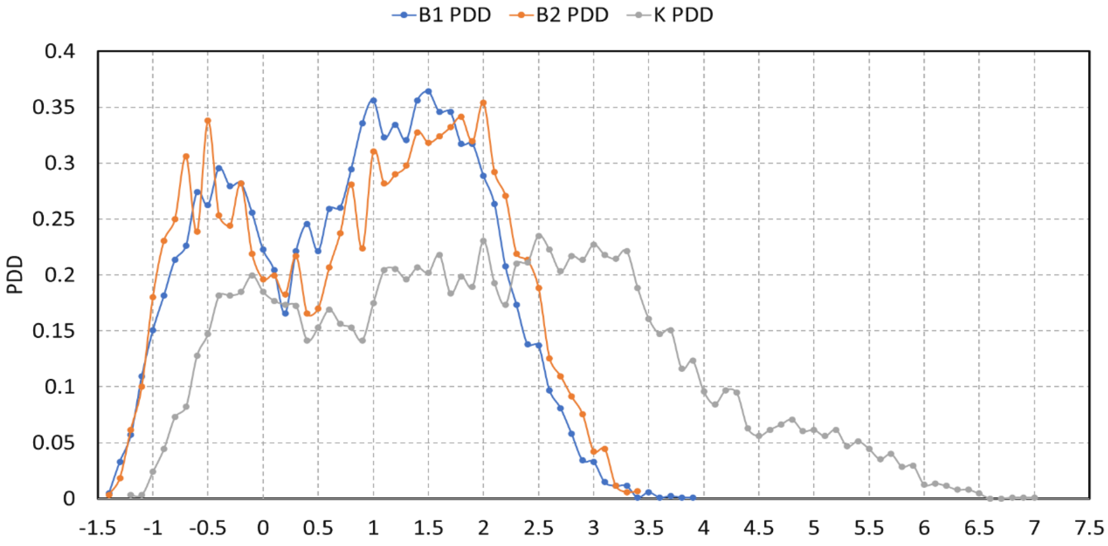


Fig. 4.18: Probability Density of PMV for different zones

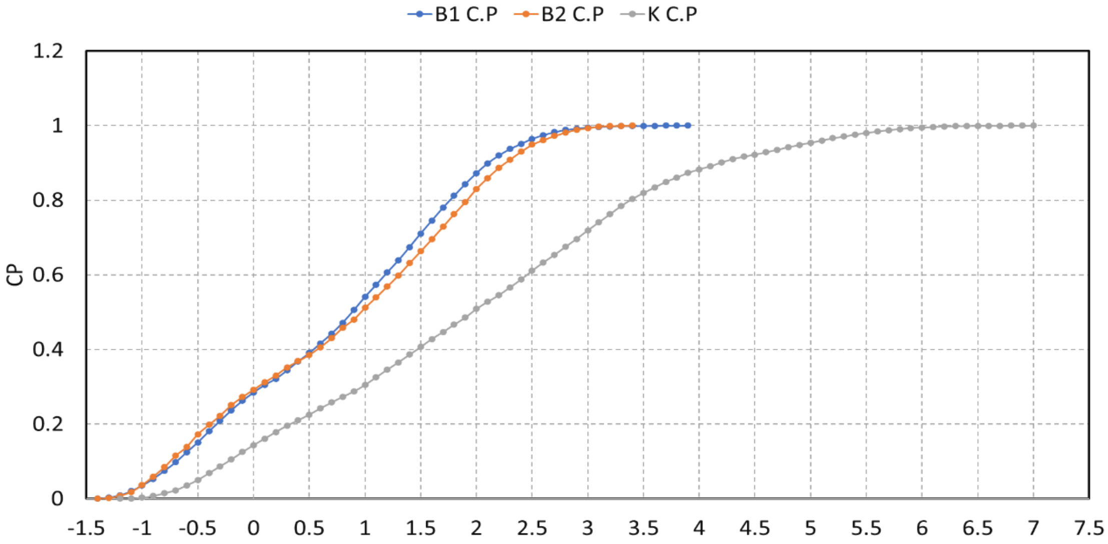


Fig. 4.19: Cumulative Probability of PMV for different zones

4.3. Energy consumption of the baseline model

EnergyPlus calculates the annual energy demands of the model as well. In the case of baseline model, EnergyPlus calculated that the baseline model consumes 2153.19 kWh of energy while 5004.88 kWh of energy is provided by natural gas. The electricity consumption of baseline model can be divided into two components i.e electric energy used for lighting and electric energy used for operating home appliances. Fig. 4.25 shows the monthly consumption of electric energy used for home appliances except for lighting. As listed in Table 3.8, majority of the appliances are stationed in the kitchen so the share of kitchen in this graph is higher. Two appliances i.e TV and clothes iron are stationed in Bedroom 1, and its share in electric energy consumption due to appliances is second highest. Washing machine is placed in Washroom 1, so washroom 1 has also a share in this graph.

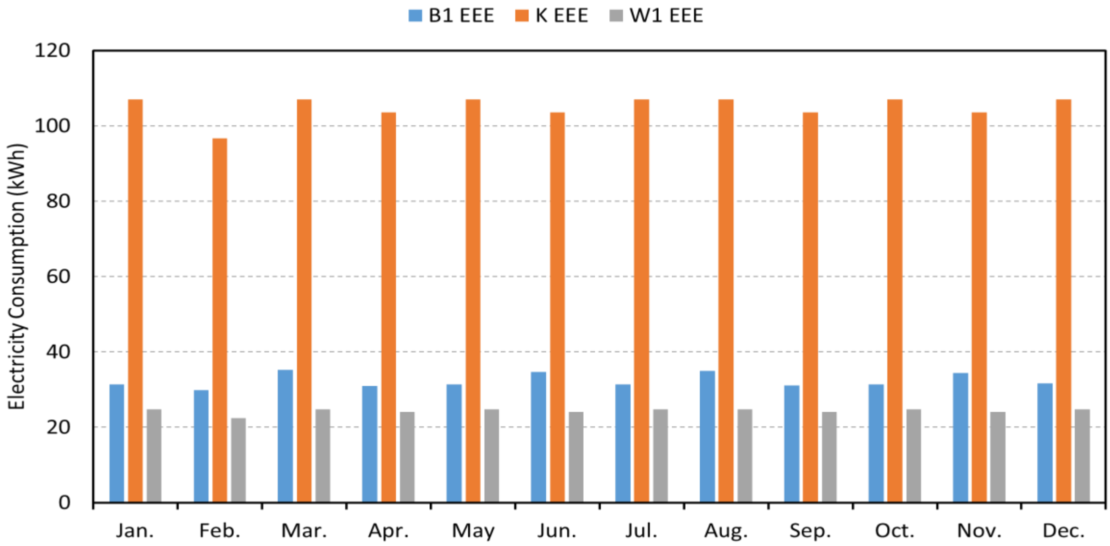


Fig. 4.25: Monthly electricity consumption of appliances

Fig. 4.26 is the graphical representation of consumption of electric energy for space lighting. As 50 watts lights are installed in bedroom 1, bedroom 2 and kitchen while both washroom 1 and 2 are installed with 25 watts lights, the share of electric energy consumption for bedroom 1, 2 and kitchen are the same while that of washroom 1 and 2 are the same. Table 3.8 gives details about the operation hours of these lights. Fig. 4.26 is in good agreement with Table 3.8.

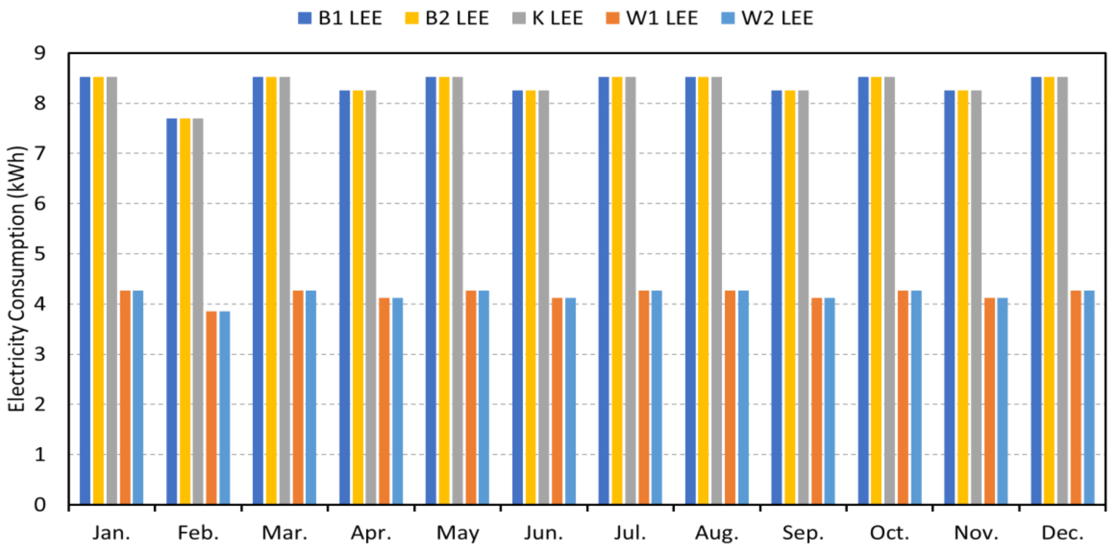


Fig. 4.26: Monthly electricity consumption for space lighting

In Fig.4.27 total monthly electricity and gas consumption of baseline model are shown. As the schedule of operation of lights and equipment is same through the year, the difference in electricity and gas consumption in different months is due to the number of days in a month. Natural gas is used for cooking purposes in the baseline model. Common gas stove is shown in Fig. 3.3(f). Such gas stoves do not have any thermostat. The energy efficiency of such gas stoves is very low. Major portion of energy extracted from natural gas is transferred to the zone and increases its temperature. It has been calculated that the baseline model consumes 5004.88 kWh (18.0 GJ) of energy from natural gas which amounts to 70% of total energy consumptions. Electricity consumptions of the model are 2153.19 kWh (7.75GJ, 30% of total energy). Note that the energy consumption in Japan was reported 33.4 GJ per household in 2016 in the report of the Ministry of the Environment of Japan.

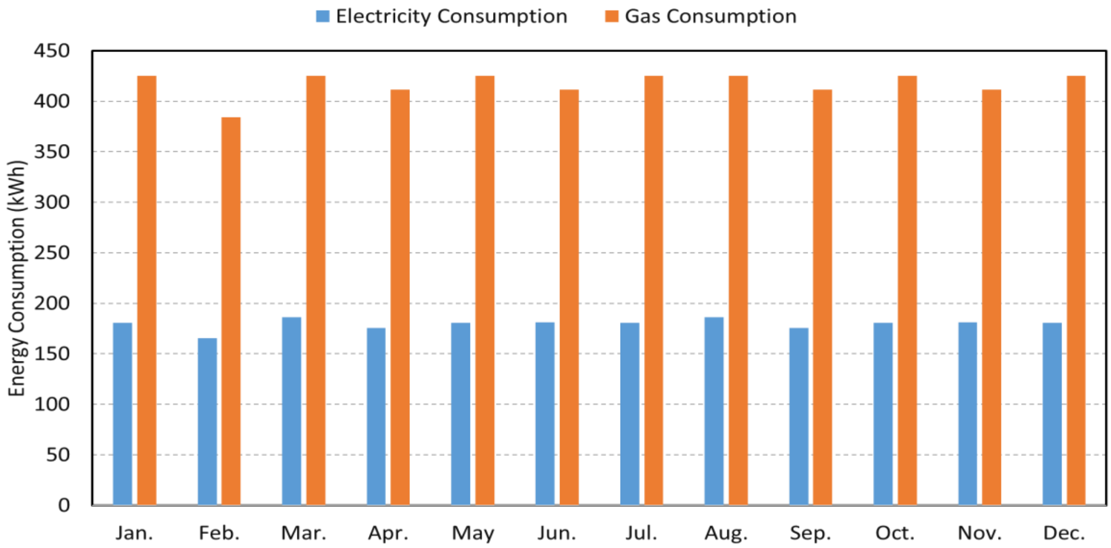


Fig. 4.27: Monthly energy consumption

5. SIMULATION RESULTS OF DIFFERENT SCENARIOS

The thermal performance of the target dwelling was evaluated under the various scenarios. These scenarios are mainly divided into four categories, namely (i) Without Ventilation (ii) Natural Ventilation (iii) HVAC and (iv) Orientation. Categories (i), (ii) and (iii) are further divided into three cases as shown in Table 5.1. In this chapter, simulation results of all these scenarios will be discussed. For simplicity, a comparison is drawn between indoor climate conditions of zones in each category.

Table 5.1: Different simulation scenarios of the model

Category Name	**Case Name**	**Design Variables**
Without Ventilation	WV **(Baseline Case)**	North Direction, No Ventilation, No HVAC, No Insulation, No Shadings
	WV+Sh	Addition of Shadings on windows
	WV+Sh+Ins	Addition of shading on windows and insulation on exterior walls and roof
Natural Ventilation	NV	Baseline setting except for conditions of infiltration/ ventilation rate ✓ 4 ACH in all zones ✓ Additional 10 ACH in a kitchen for exhaust fan during gas stove usage
	NV+Sh	NV case with shading on windows
	NV+Sh+Ins	(NV+Sh) case with insulation material in exterior walls and roof.
HVAC	HVAC	NV Case +HVAC Input the schedule/season of air-conditioning for heating and cooling
	HVAC+Sh	(NV+Sh) Case +HVAC
	HVAC+Sh+Ins	(NV+Sh+Ins) Case +HVAC
Orientation	North	North + 0°, NV Case
	East	North + 90°, NV Case
	South	North + 180°, NV Case
	West	North + 270°, NV Case

5.1. Simulation results of Without Ventilation cases

Without ventilation category has three cases. The first case of this category was discussed in chapter 4 of this thesis in detail. This section will give a comparison of the indoor climate conditions between WV case, (WV+Sh) case and (WV+Sh+Ins) case. In the case of (WV+Sh) and (WV+Sh+Ins), the shades were assumed on the internal face of the window. On the other hand, in (WV+Sh+Ins) case, insulation materials were added as the second outermost layer of roof and walls. Detailed properties of the interior shades are given in Table 5.2.

Table 5.2: Detailed properties of the shades

Solar Transmittance {dimensionless}	0.2
Solar Reflectance {dimensionless}	0.7
Visible Transmittance {dimensionless}	0.2
Visible Reflectance {dimensionless}	0.7
Infrared Hemispherical Emissivity {dimensionless}	0.85
Infrared Transmittance {dimensionless}	0
Thickness {m}	0.001
Conductivity {$Wm^{-1}K^{-1}$}	1.442
Shade to Glass Distance {m}	0.05
Top Opening Multiplier	0.5
Bottom Opening Multiplier	0.5
Left-Side Opening Multiplier	0.5
Right-Side Opening Multiplier	0.5
Airflow Permeability {dimensionless}	0

Addition of insulation materials modifies the thermal transmittance of roof and external walls as shown in Table 5.3.

Table 5.3: Materials and depth of building elements

Building envelopes	U value (Given by E+)	Outside layer l	Layer 2	Layer 3	Layer 4	Layer 5
Roof	0.404 ($Wm^{-2}K^{-1}$)	Roof plaster (9.5mm)	Polyurethane expanded (50.8 mm)	Roof concrete (152.4 mm)	Airgap (152.4 mm)	Gypsum Ceiling (9.5 mm)
Exterior Wal		Plaster (9.5 mm)	Polyurethane expanded (9.5 mm)	Brick (228.6 mm)	Plaster (9.5 mm)	

Fig. 5.1 shows a comparison of the indoor climate variables of bedroom 1 for the coldest week of 2002 (13th January to 19th January) among the three cases. As explained in section 4.1, the outdoor temperature ranges between 1.2ºC and 20.4ºC. Fig. 5.1 shows that indoor temperature remained almost the same for WV case and (WV+Sh) case. A reason behind ineffectiveness of shades is that the shades are active when there is large solar radiation arriving at the window. The window in bedroom 1 is in front of the veranda, hence, most of direct solar radiations is already obstructed by the roof of veranda. On the other hand, the addition of insulation materials to walls and roof shows great improvement of the indoor thermal comfort conditions. The addition of insulation materials increased the indoor temperature of bedroom 1 by almost. The range of Predictive Mean Vote (PMV) increased from (-1.5 to 0.1) to (-1.03 to 0.1) when insulation materials are introduced. Similarly, the range of Predicted percentage dissatisfaction (PPD) decreased (5.23%-53.63%) to (5.23%-27.36%) when insulation materials are added to (WV+Sh) case.

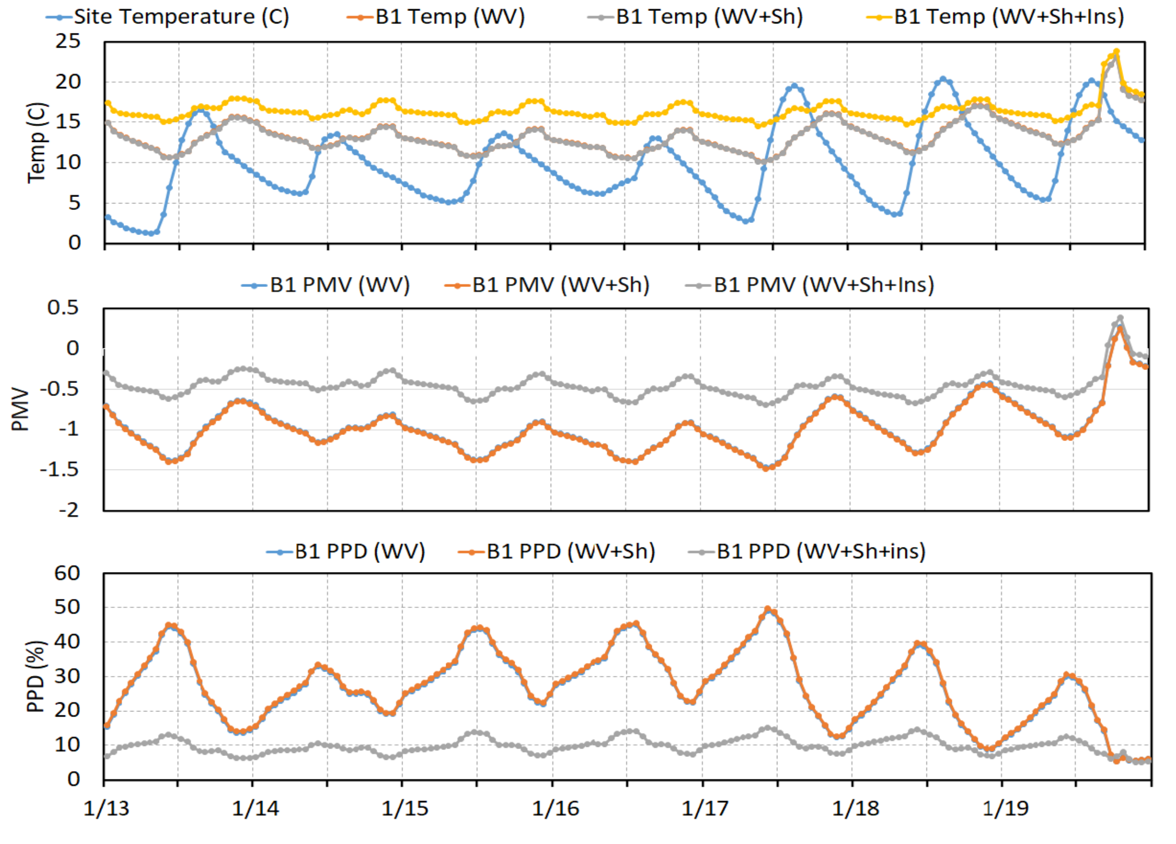


Fig. 5.1 Indoor climate variables of bedroom 1 during the coldest week

Fig. 5.2 shows a comparison of indoor climate variables at bedroom 1 for the hottest week of 2002 (16th June to 22nd June). The outdoor temperature ranges between 27.0ºC and 44.6ºC (section 4.1). Fig. 5.2 shows that the indoor temperatures for WV and (WV+Sh) are almost the same as in Fig. 5.1. The reason behind this trend is explained earlier in this section. The indoor temperature for (WV+Sh+Ins) is generally lower than those of WV and (WV+Sh) cases by 2-3 ºC except for the data of June 16 and 17.A sharp temperature rise observed in the evening on June 22 is caused by the assumption of the internal heat generation due to ironing, which takes place once a week on Saturday. The small difference in the indoor air temperature between (WV+Sh+Ins) and the other two cases on June 16 and 17 might be caused by the cloudy weather condition as shown in Fig.4.3. Under the condition of the relatively weaker solar heating on the roof and walls, the effect of the improved building envelopes is supposed to be small compared to the clear sky condition with strong solar heating.

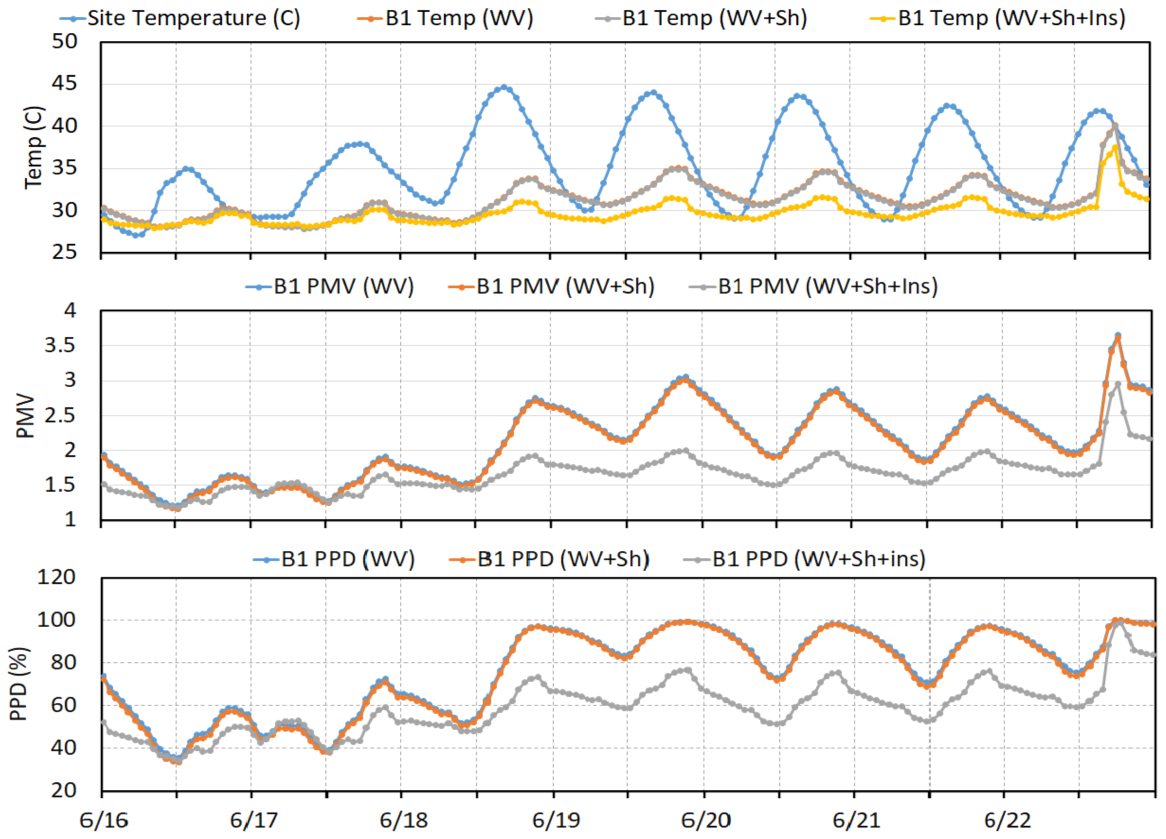


Fig. 5.2 Indoor climate variables of bedroom 1 during the hottest week

Fig. 5.3 shows a comparison between indoor climate variables of bedroom 2 for the coldest week of 2002 (13th January to 19th January). As explained earlier, the outdoor temperature ranged from 1.24ºC to 20.43ºC. Indoor temperature for WV case and (WV+Sh) case remained the same while the indoor temperature of (WV+Sh+Ins) case remained high as compared to other two cases. Indoor temperature range increased from (10.4ºC to 15.8ºC) to (15.8ºC-18.8ºC). As expected, addition of insulation materials to walls and roof can greatly improve the comfort conditions. Addition of insulation materials increased the indoor temperature of bedroom 2 by almost 5 ºC. PMV range increased from (-1.4 to -0.6) to (-0.5 to -0.1) when insulation materials are introduced. Similarly, the PPD range decreased from (11.7% to 47%) to (5.2% to 9.7) when insulation materials are added to (WV+Sh) case.

In Fig. 5.4, a comparison of indoor climate variables is shown for bedroom 2 for the hottest week of 2002 (16th June to 22nd June). On 16th, 17th and 18th June, the outdoor temperature remained comparatively low. On these temperatures, the indoor temperatures for three cases are relatively close. In contrast, on 18th, 19th,20th, 21st and 22nd of June, the outdoor temperature was generally high. This increase in outdoor temperature is reflected as an increase in indoor temperature as well. During this period, a difference in indoor temperatures among different WV cases is obvious. The indoor temperature for WV case ranged between 28.6ºC and 35.53ºC while the temperature range for (WV+Sh+Ins) case remained between 29.36ºC and 32.87ºC. There is a clear decrease in PMV on 18th and onwards. The PMV range changed from (1.5 to 3.2) to (1.6 to 2.4) while the PPD range decreased from (51% to 99.7%) to (57% to 91%) when insulations are introduced. In sum, the effectiveness of the insulation for thermal mitigation can be significant for hotter outdoor environment.

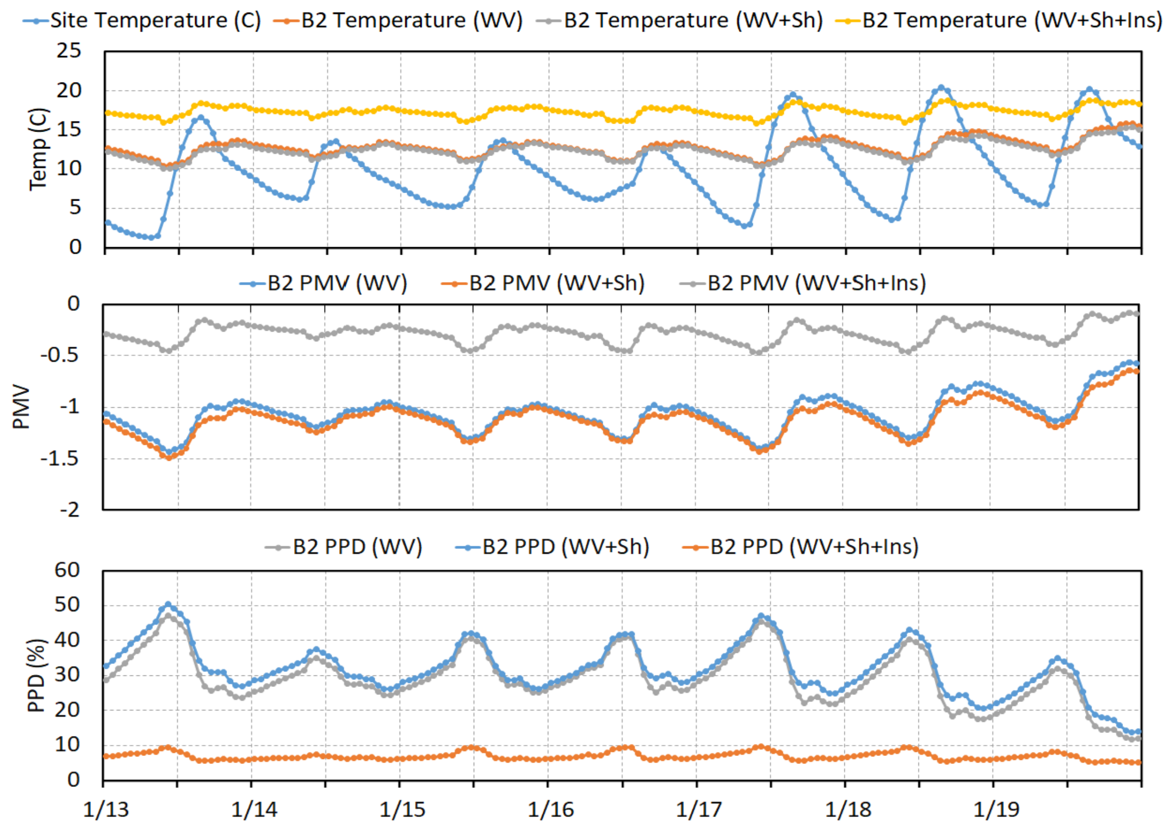


Fig. 5.3 Indoor climate variables of bedroom 2 during the coldest week

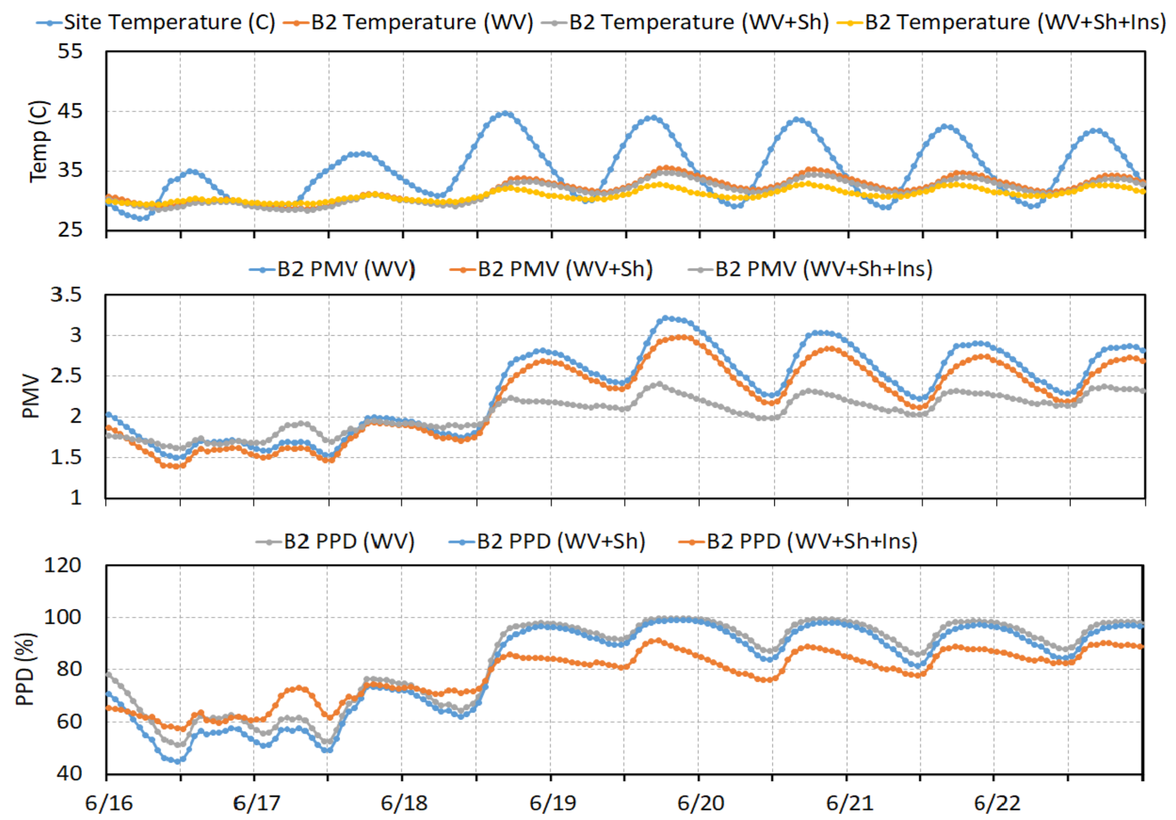


Fig. 5.4 Indoor climate variables of bedroom 2 during the hottest week

Fig. 5.5 is a graphical representation of indoor climate variables of the kitchen for three WV cases during the coldest week of 2002 (13th January to 19th January). Indoor temperature curves for WV case and (WV+Sh) case remained the same while the indoor temperature of (WV+Sh+Ins) case remained high as compared to other two cases. The peaks in temperature curves indicates that gas stove is working during these hours. As insulation materials makes the conduction heat transfer between zone and outdoor more difficult, the effect of insulation materials is a rise in indoor temperature in the coldest week. In the hottest week, this effect is a decrease in indoor temperature. Indoor temperature range increased from (12ºC to 30ºC) to (20.45ºC to 36.8ºC). PMV range increased from (-1.3 to 1.2) to (0.2 to 2.6) when insulation materials are introduced. The PPD exhibited a random behavior. It decreases when the gas stove is not operational and when gas stove is operational, the PPD increased exponentially. On average, the range of PPD changed from (5% to 40.6%) to (6% to 93.8%) when insulation materials are added to (WV+Sh) case.

Fig. 5.6 shows a comparison of indoor climate variables of kitchen for the hottest week of 2002 (16th June to 22nd June). The indoor temperature of WV case and (WV+Sh) case are relatively similar, but in (WV+Sh+Ins) case, the temperature is higher than the other cases. In case of bedroom 1 and 2, the indoor temperature of the zone in WV case and (WV+Sh) case during the hottest week was higher than the indoor temperature in (WV+Sh+Ins) case. The reason behind this increase of temperature in (WV+Sh+Ins) case is that the heat generation in the zone is significant and the presence of insulation materials limited the heat transfer between zone and outdoor. This increase in temperature decreased the comfort conditions inside the zone. Indoor temperature range for WV case was (32.5ºC to 53.6ºC). Indoor temperature range for (WV+Sh+Ins) case became (35.6ºC to 53.3ºC). Observation of PMV curve reveals that it increased from (2.3 to 6.8) to (3.1 to 7). The PPD curves indicates that throughout the week, the occupants are showing 100% dissatisfaction over the indoor climate variables. However, in WV case and (WV+Sh) case, there are some instances where the PPD is less than 100%. The range of PPD increased from (88% to 100%) to (99.6% to 100%)

In Fig. 5.7, a comparison of outdoor temperature and indoor temperature of washroom 1 for the three cases of WV category is presented. The indoor temperature followed the patterns of bedroom 1 and 2. During the coldest week, the indoor temperature of (WV+Sh+Ins) case remained higher than the two cases and during the hottest week, the same remained low than the other two during the hottest week. The reason for this change is explained earlier. Introduction of insulation materials increased the indoor temperature range from (10ºC to 21.7ºC) to (13.8ºC to 23.3ºC). During the hottest week, range of indoor temperature changes from (29.4ºC to 42ºC) to 28.4ºC to 38.3ºC) with introduction of insulation materials.

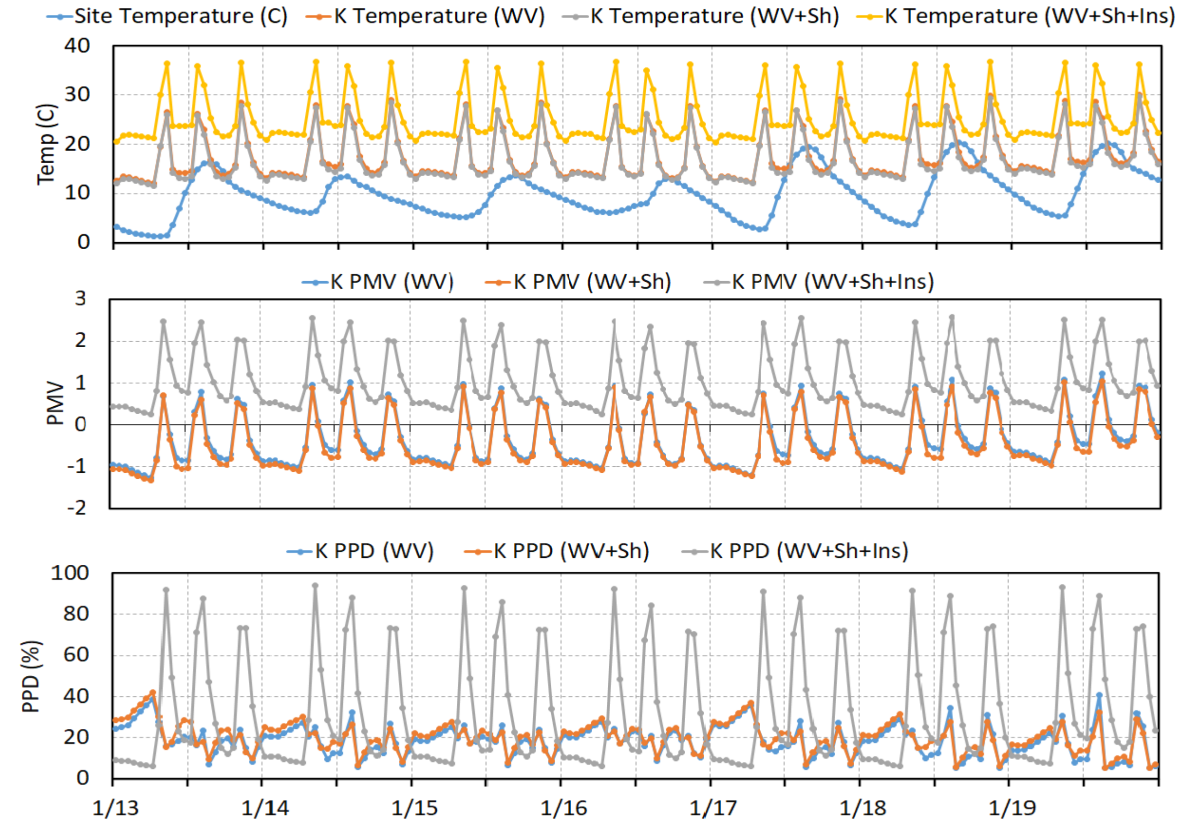


Fig. 5.5 Indoor climate variables of Kitchen during the coldest week

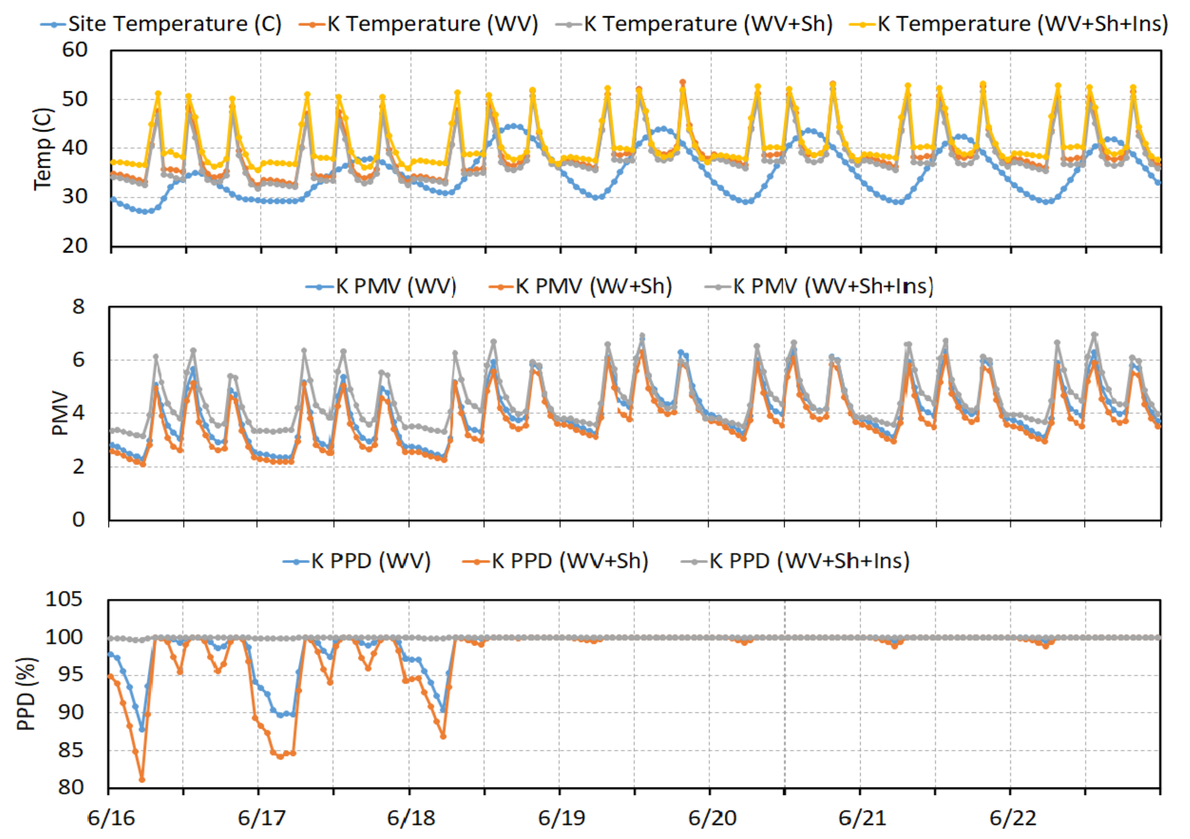


Fig. 5.6 Indoor climate variables of Kitchen during the hottest week

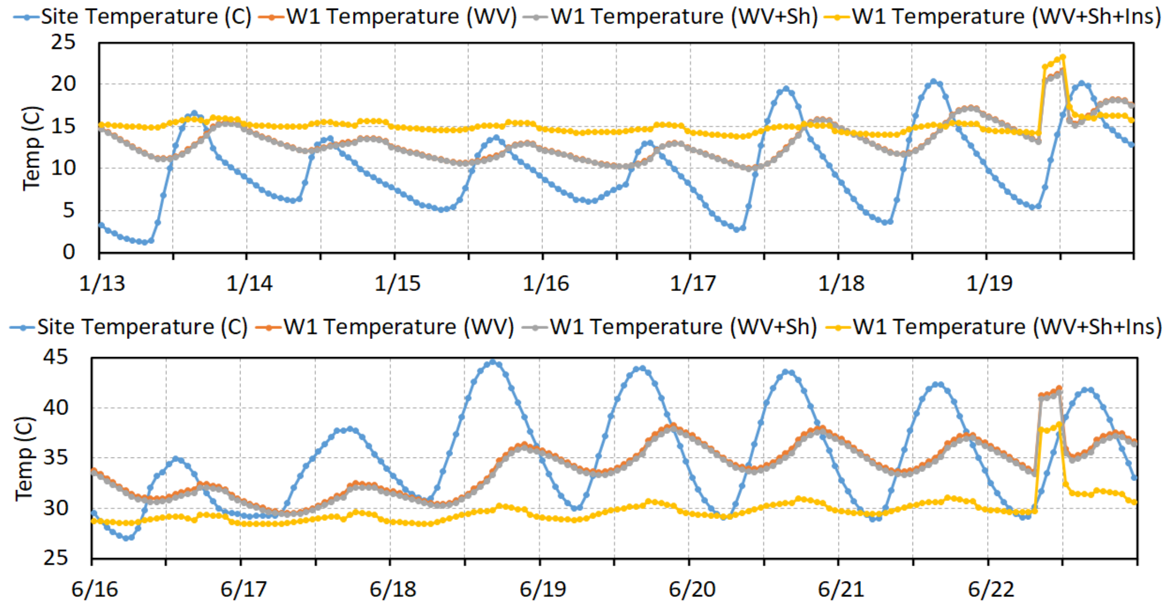


Fig. 5.7 Indoor climate variables of washroom 1 during the coldest and hottest weeks

5.2. Probability density distribution and cumulative probability of WV cases

Fig. 5.8 shows the probability density and cumulative probability of PMV for bedroom 1, bedroom 2 and kitchen for three cases of WV category. The probability density curve for WV and (WV+Sh) cases for bedroom 1 and bedroom 2 remained almost the same as it did for the temperatures and PMVs. Probability curve for kitchen is of irregular shape. The probability density curves of (WV+Sh+Ins) case differs from the curves of mentioned cases. In case of bedroom 1, the PMV for WV and (WV+Sh) cases ranged from -1.4 to 3.8. For bedroom 2, PMV for WV and (WV+Sh) cases ranged from -1.5 to 3.35. For kitchen, the PMV ranges between -1.3 to 6.9. For (WV+Sh+Ins) case, the PMV ranges between -0.7 and 2.9 in bedroom 1, from -0.5 to 2.57 in bedroom 2 and from 0.2 to 7 in the kitchen.

The cumulative probability curves indicates that (i) for bedroom 1, 52.2% of the PMVs lies below 1 (ii) for bedroom 2, 47.3% of the PMVs below 1, and (iii) 9.6% of the PMVs lies below 1 for (WV+Sh+Ins) case. In case of bedroom 1, 29% of the PMVs are over 1.5 for WV and (WV+Sh) case. For (WV+Sh+Ins) case, 19.5% of PMVs are over 1.5. For bedroom 2, 33.7% for WV case, 30% for (WV+Sh) case and only 0.2% for (WV+Sh+Ins) case of PMVs are over 1.5. For kitchen, 56% of PMV for WV and (WV+Sh) cases, and 80.2% of the PMVs for (WV+Sh+Ins) case are over 1.5.

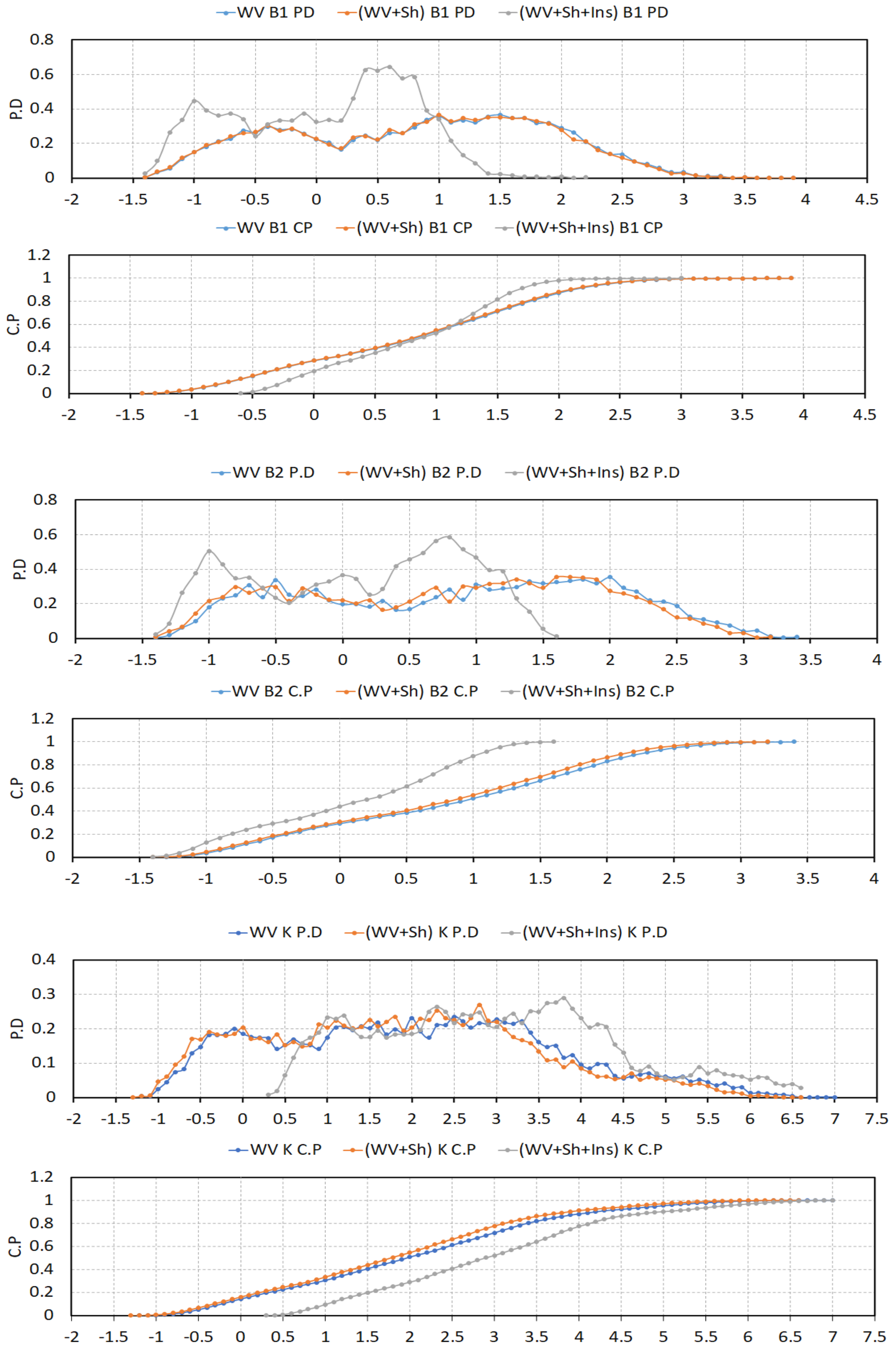


Fig. 5.8 Probability density and cumulative probability of PMV for different WV cases

5.3. Simulation results of Natural Ventilation cases

Natural ventilation category has three cases. i.e NV case, (NV+Sh) case and (NV+Sh+Ins) case. When baseline case is introduced with a ventilation of 4ACH in all the zones, the resultant model is termed as Natural Ventilation (NV) case. An additional 10 ACH ventilation is also introduced for exhaust fan in kitchen. Table 5.3 gives schedules of ventilations for different zones.

Table 5.3: Ventilation schedules for different zones

Zone / appliances	Period	Hours	Ventilation Rate (ACH)
Bedrooms	Jan-Feb	00:00-08:00	0
		08:00-10:00	2
		10:00-16:00	4
		16:00-18:00	2
		18:00-24:00	0
	Mar-Apr	00:00-08:00	0
		08:00-18:00	4
		18:00-24:00	0
	May-Sept.	00:00-12:00	4
		12:00-16:00	0
		16:00-24:00	4
	Oct-Nov	00:00-08:00	0
		08:00-18:00	4
		18:00-24:00	0
	Dec	00:00-08:00	0
		08:00-10:00	2
		10:00-16:00	4
		16:00-18:00	2
		18:00-24:00	0
Kitchen	Jan-Feb	00:00-24:00	0.8
	Mar-Apr	00:00-24:00	2
	May-Sept	00:00-24:00	4
	Oct	00:00-24:00	2
	Nov-Dec	00:00-24:00	0.8
Washrooms	Jan-Feb	00:00-24:00	0
	Mar-Oct	00:00-24:00	4

	Nov-Dec	00:00-24:00	0
Exhaust Fan	Throughout the Year	00:00-06:00	0
		06:00-09:00	10
		09:00-12:00	0
		12:00-14:00	10
		14:00-19:00	0
		19:00-21:00	10
		21:00-24:00	0

Ventilation was assumed to be introduced at each zone as per given schedules and resulting climate variables were examined. A comparison of climate variables for each zone is drawn for the three cases of natural ventilation category. Fig. 5.9 shows a comparison between indoor climate variables of bedroom 1 for the coldest week of 2002 (13th January to 19th January). Indoor temperature for NV and (NV+Sh) cases is almost the same and it ranges from 9.4^{o}C to 23.1^{o}C. Indoor temperature of (NV+Sh+Ins) case is comparatively higher and remained between 12.1^{o}C to 23.3^{o}C. the peak in indoor temperature on the evening of 19th January corresponds to ironing in the zone. the PMV for (NV+Sh+Ins) case was higher than NV and (NV+Sh) case. The PMV for the earlier case ranged between -0.9 and -0.3 while PMV for the later cases ranged from -1.6 to -0.6. During coldest week, it is expected that an increase in indoor temperature and PMV will decrease PPD. Fig. 5.9 validates this assumption as it is observed that the PPD in (NV+Sh+Ins) case had values from 6.4% to 24.7%. It is worth mentioning that PPD for NV and (NV+Sh) cases ranged between 11.5% and 54.2%.

Fig. 5.10 shows indoor climate variables of bedroom 1 during the hottest week of 2002 (16th June to 22nd June). The temperature curve can be divided into two parts i.e indoor temperature from 16th to 17th June and indoor temperature from 18th to 22nd June. Indoor temperature was the same on 16th and 17th for NV (NV+Sh) and (NV+Sh+Ins). From 18th June, the indoor temperature of (NV+Sh+Ins) case lagged from the indoor temperature of NV and (NV+Sh) cases by 1^{o}C. Reasons of this lagging are explained earlier in this chapter. Indoor temperature for NV and (NV+Sh) ranged between 28.2^{o}C and 40.4^{o}C. temperature range of (NV+Sh+Ins) case is from 28.1^{o}C to 39^{o}C. The PMV for NV and (NV+Sh) case was recorded between 0.9 and 3.9 while it remained between 0.9 and 3.5 for (NV+Sh+Ins) case. the range of PPD for NV and (NV+Sh) case was 24% to 100%. Range of PPD for (NV+Sh+Ins) case was between 23.6% and 99.9%.

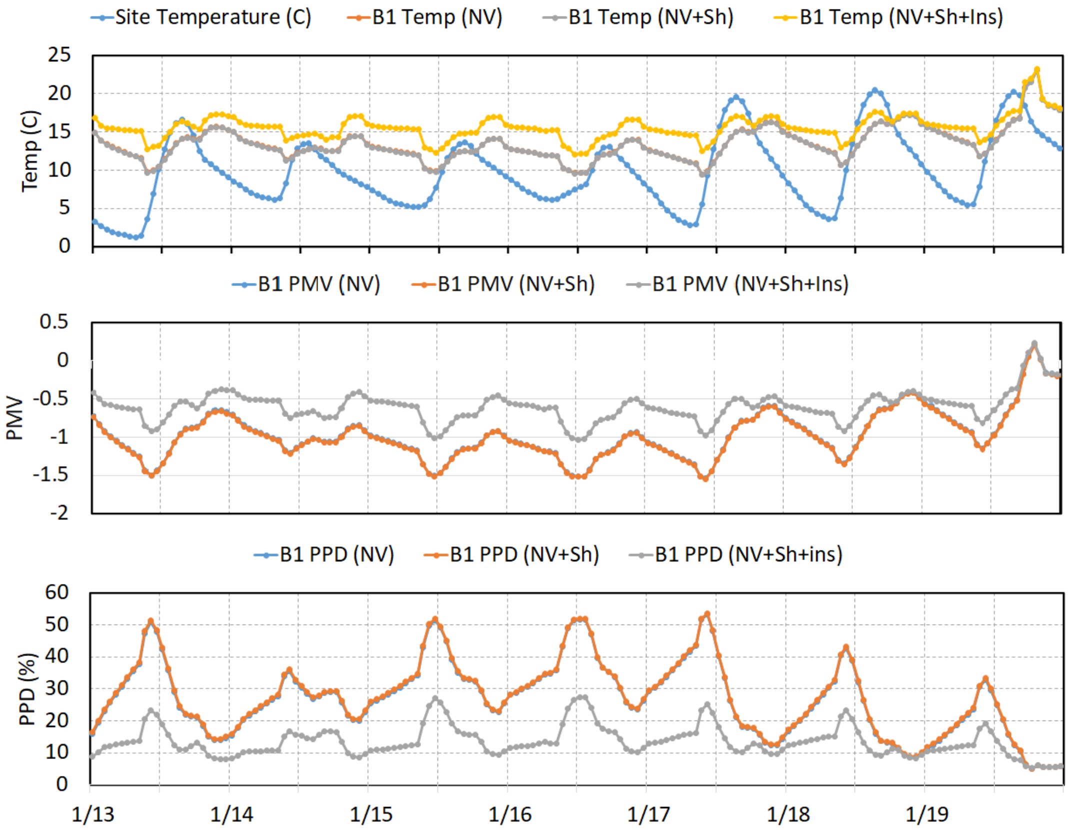


Fig. 5.9 Indoor climate variables of bedroom 1 during the coldest week

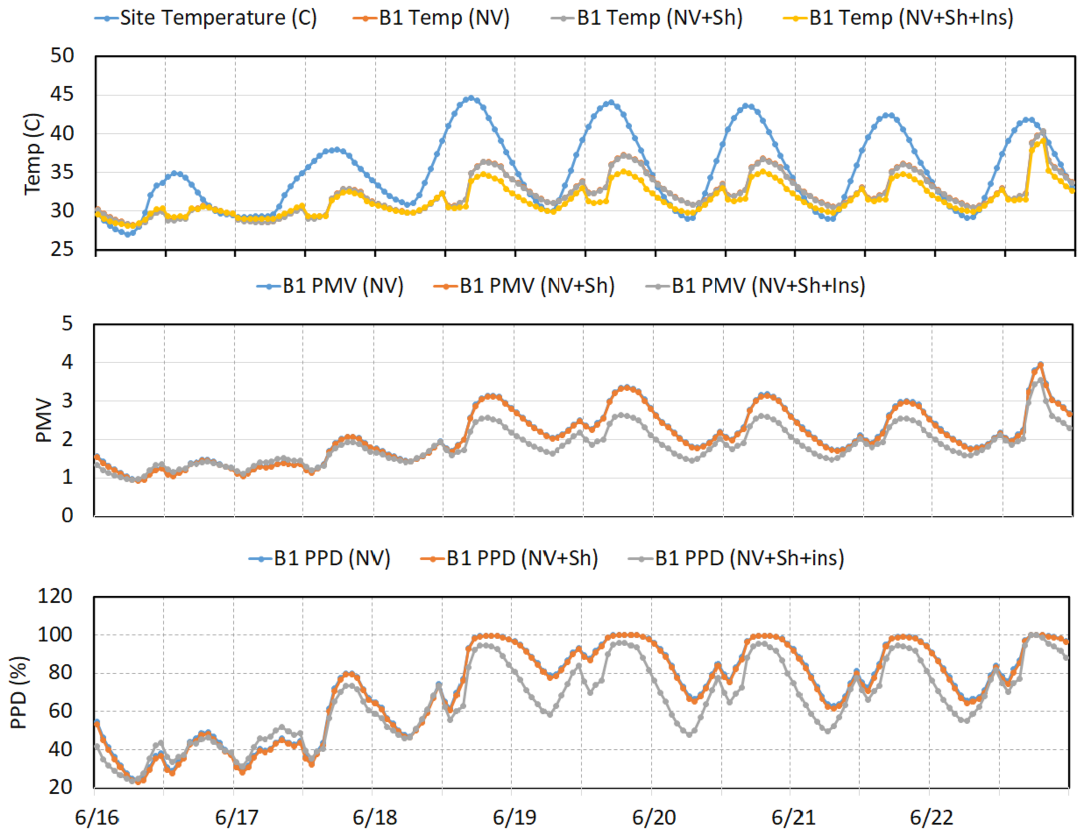


Fig. 5.10 Indoor climate variables of bedroom 1 during the hottest week

In Fig. 5.11, a comparison between indoor climate variables of bedroom 2 for the coldest week of 2002 (13th January to 19th January) is depicted. Indoor temperature for NV case and (NV+Sh) case remained the same while the indoor temperature of (NV+Sh+Ins) case remained high as compared to other two cases. Indoor temperature range increased from (9.3°C to 16.5°C) to (9°C to 16°C). As expected, addition of insulation materials to walls and roof can greatly improve the comfort conditions. PMV range increased from (-1.6 to -0.5) to (-0.9 to -0.26) when insulation materials are introduced. Similarly, the PPD range decreased from (11.5%-54.2%) to (6.4%-24.7%) when insulation materials are added to (NV+Sh) case.

In Fig. 5.12 a comparison is shown between indoor climate variables of bedroom 2 for the hottest week of 2002 (16th June to 22nd June). It may be noted that on 16th and 17th June, the outdoor temperature remained comparatively low. On these days, the indoor temperatures for three cases remained the same. On 18th to 22nd of June, the outdoor temperature remained high. This increase in outdoor temperature is reflected as an increase in indoor temperature as well. During this period, a difference in indoor temperatures of different NV cases is very clear. The indoor temperature for NV case ranged between 28.6°C and 38°C while the temperature range for (NV+Sh+Ins) case remained between 28.33°C and 32.3°C. There is a clear decrease in PMV on 18th and onwards. The PMV range for NV case is 1.1 to 3.6 while that of (NV+Sh+Ins) case is 1.1 to 2.9. The PPD decreased for (NV+Sh+Ins) in comparison of NV case. PPD range for NV case is (30.3%-99.9%) while the same for (NV+Sh+Ins) case is (30%-98.8%).

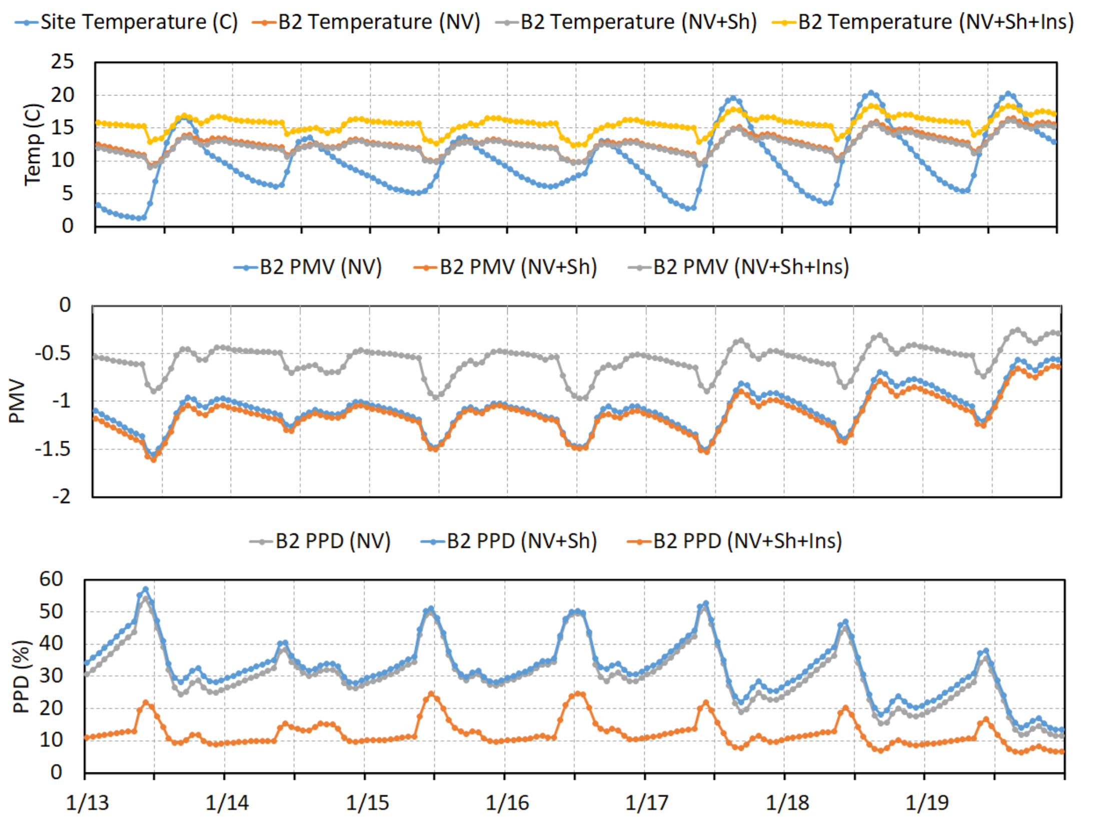


Fig. 5.11 Indoor climate variables of bedroom 2 during the coldest week

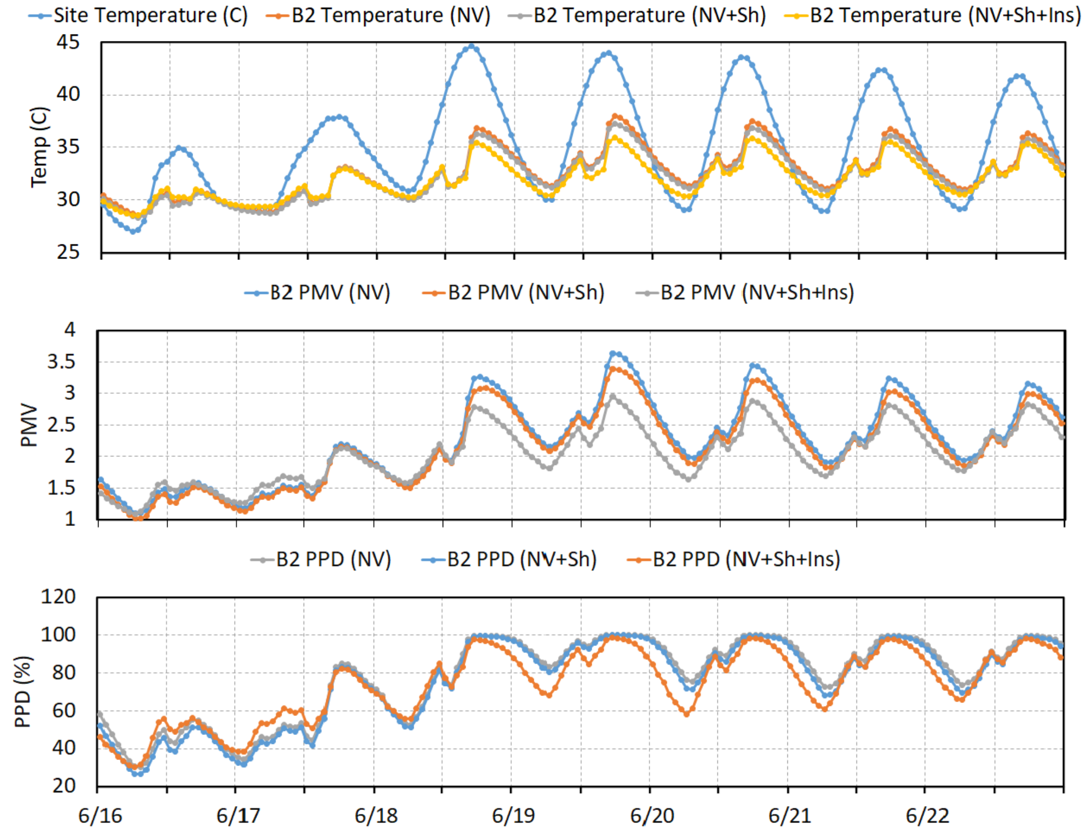


Fig. 5.12 Indoor climate variables of bedroom 2 during the hottest week

Fig. 5.13 is a graphical representation of indoor climate variables of kitchen for the coldest week of 2002 (13th January to 19th January). Indoor temperature for NV case and (NV+Sh) case remained the same while the indoor temperature of (NV+Sh+Ins) case remained high as compared to other two cases. The peaks in temperature curves indicates that gas stove is working during these hours. Indoor temperature range increased from (8.3°C to 24.23°C) to (11.3°C-26.57°C). PMV range increased from (-1.54 to 0.27) to (-0.85 to 0.67) when insulation materials are introduced. There is clear decrease in PPD for (NV+Sh+Ins) case. PPD range decreased from (6.6%-53.9%) to (5%-22.5%) when insulation materials are added to (NV+Sh) case.

Fig. 5.14 shows a comparison of indoor climate variables of kitchen for the hottest week of 2002 (16th June to 22nd June). It may be noted that the indoor temperature for the three cases remained the same during the hottest week. The indoor temperature ranged between 30.7°C to 47.9°C for the 1st two cases while for (NV+Sh+Ins) case, it remained between 31°C and 46.3°C. Similarly, the change in PMV for NV and (NV+Sh) case remained between 1.7 to 5.7. PMV for (NV+Sh+Ins) case remained between 1.9 to 5.3. PPD for NV and (NV+Sh) cases ranged between 61.9% and 100% while PPD for (NV+Sh+Ins) case ranged between 72.6% to 100%. Indoor comfort conditions became worse in kitchen with introduction of insulation materials. Insulation materials decrease the heat losses from zone and hence the indoor temperature increases.

In Fig. 5.15, a comparison of outdoor temperature and indoor temperature of washroom 1 for the three cases of NV category is drawn. As evident from Table 5.2, during the coldest week, no ventilation is provided to the zone. The indoor temperature in case of NV and (NV+Sh) fluctuated on smaller amplitude while the indoor temperature in (NV+Sh+Ins) case almost remained constant. The indoor temperature in NV and (NV+Sh) case remained between 10°C and 21.7°C while it remained between 13.5°C and 23°C in (NV+Sh+Ins) case. The peaks in indoor temperatures of the zone are due to the heat generated by washing machine, present in the zone. During hottest week, the indoor temperature of

(NV+Sh+Ins) case remained lower as compared to NV and (NV+Sh) cases. The range of temperature for (NV+Sh+Ins) case is from 28.82ºC to 39ºC while for NV and (NV+Sh) case it is from 29.54ºC to 41ºC. Weekly average change in temperature is 7%.

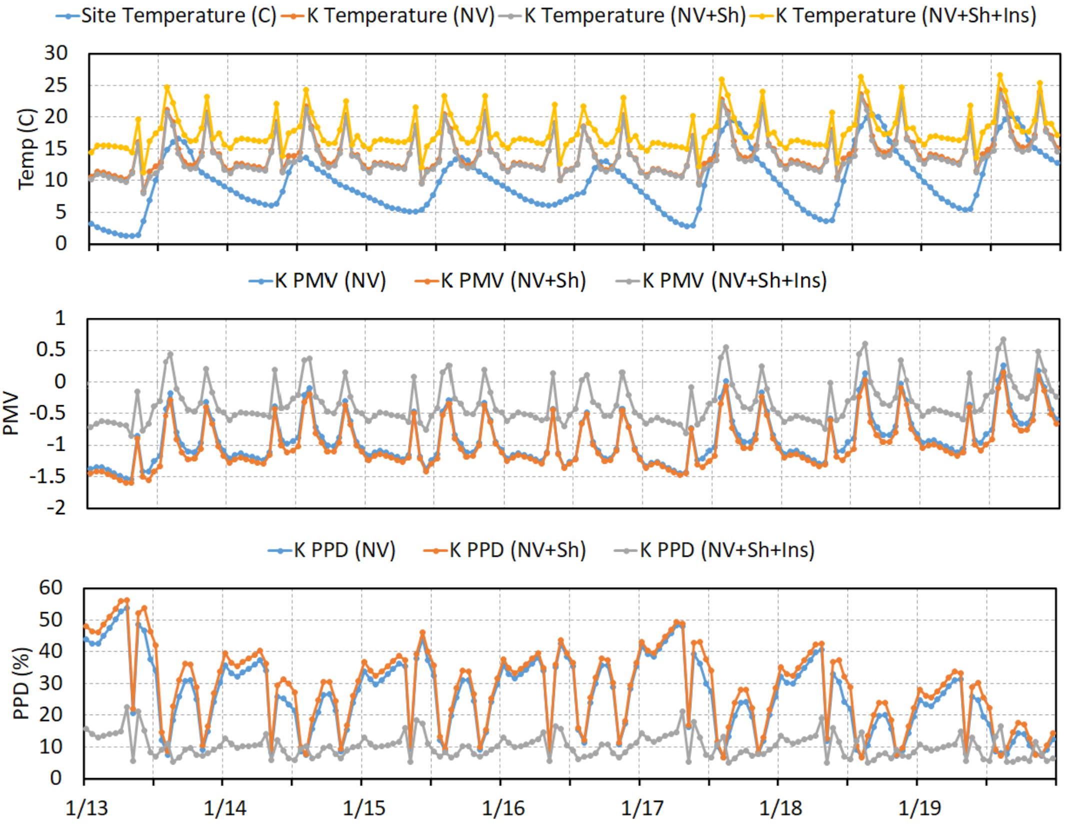


Fig. 5.13 Indoor climate variables of Kitchen during the coldest week

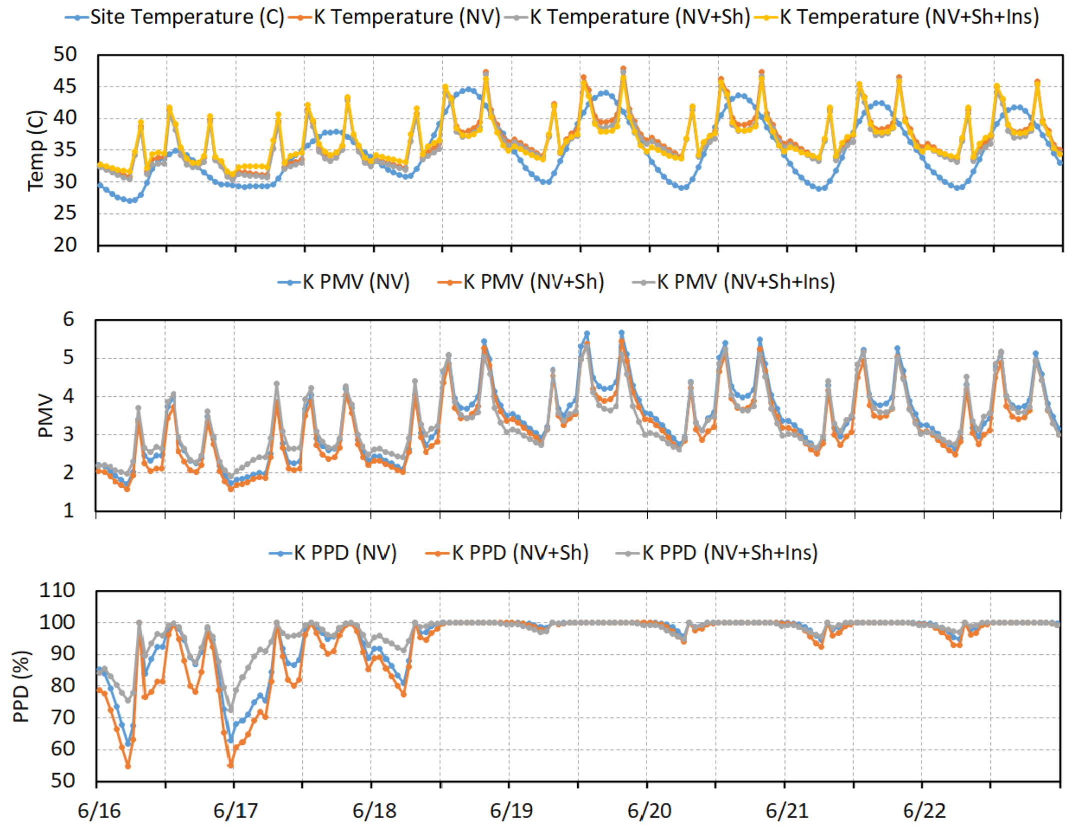


Fig. 5.14 Indoor climate variables of Kitchen during the hottest week

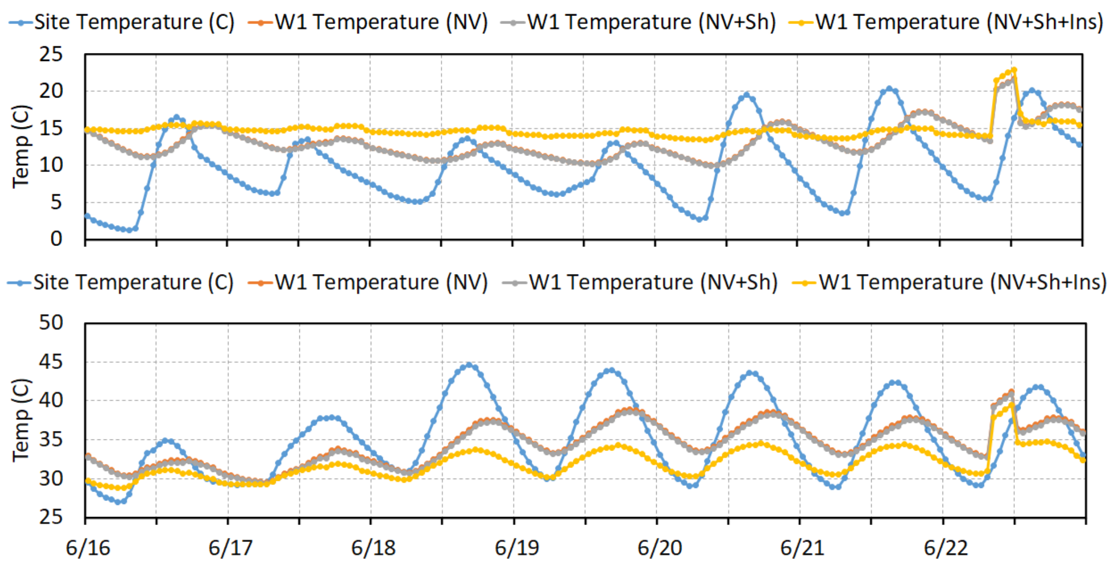


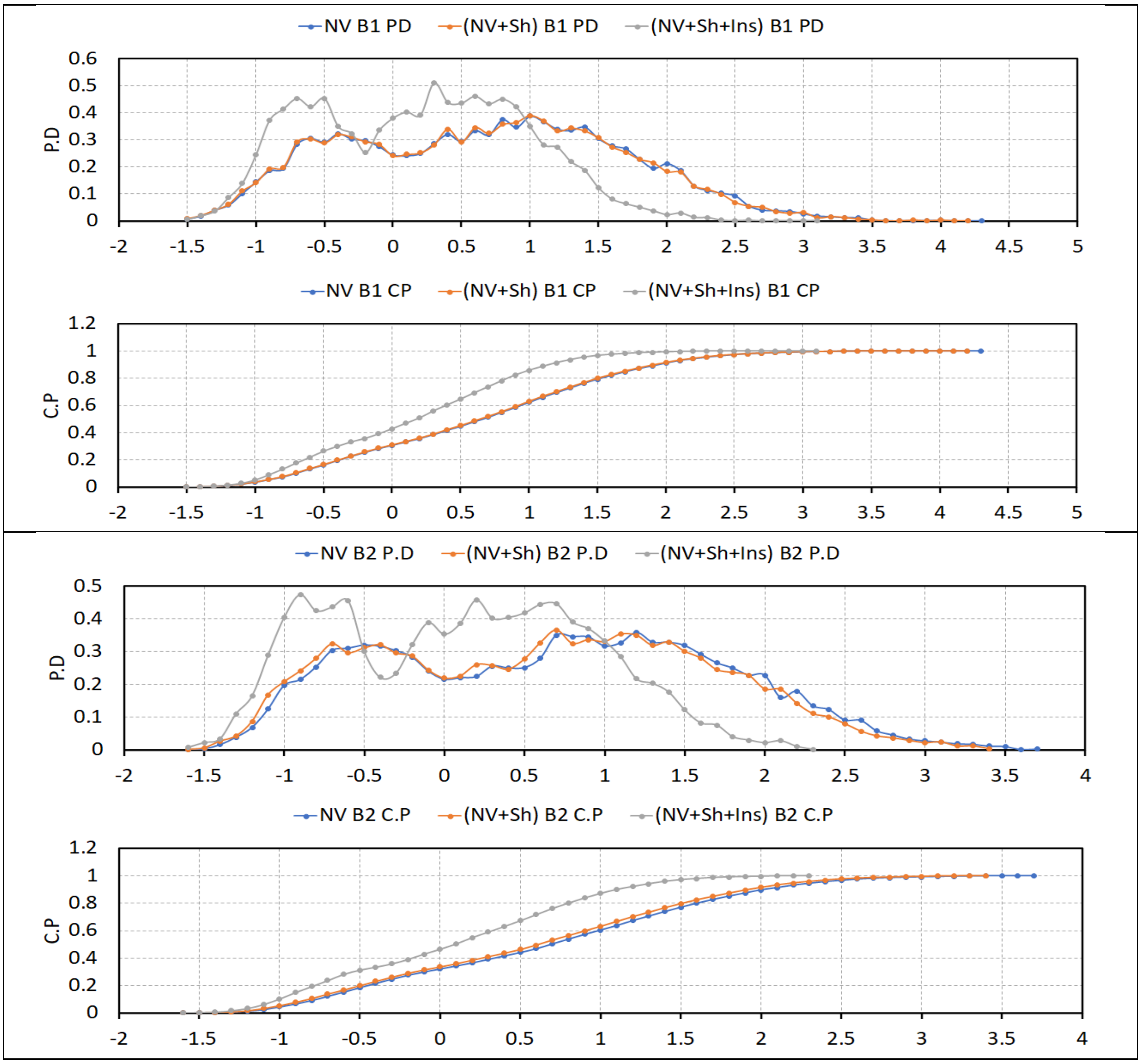
Fig. 5.15 Indoor climate variables of washroom 1 during the coldest and hottest weeks

5.4. Probability density distribution and cumulative probability of NV cases

The probability density and cumulative probability of PMV in bedroom 1, 2 and kitchen is shown in Fig. 5.16. The probability density curve for NV and (NV+Sh) cases remained almost the same as it did for the temperatures and PMVs. The probability density curve of (NV+Sh+Ins) case differs from the curves of mentioned cases. The PMV in bedroom 1 for NV and (NV+Sh) cases ranged from -1.5 to 4.2. PMV for (NV+Sh+Ins) case ranged from -1 to 3.5. In bedroom 2, the PMV for NV and (NV+Sh) ranged between -1.6 to 3.6 while PMV in bedroom 2 for (NV+Sh+Ins) lies between -1 to 2.9. In case of kitchen, the PMV for NV and (NV+Sh) has values between -1.5 and 5.6. For (NV+Sh+Ins) case, the PMV has values -0.8 to 5.3 in the same zone.

The cumulative probability curve indicates that in bedroom 1, 62.3% of PMV for NV case, 63% of PMVs for (NV+Sh) case and 64.7% of PMVs in (NV+Sh+Ins) case are less than or equal to 1. For bedroom 2, 60.4% of PMV for NV case, 63% of PMV for (NV+Sh) case and 59% of PMV for (NV+Sh+Ins) case are less than equal to 1. In case of kitchen, 46.6% of PMV for NV case, 50% of PMV for (NV+Sh) case and 40% of PMV for (NV+Sh+Ins) case are less than or equal to 1.

The cumulative probability curve of bedroom 1 show that 20% of the PMVs for NV and (NV+Sh) cases while only 3.3% of the PMVs for (NV+Sh+Ins) case are over 1.5. The cumulative probability curve of bedroom 2 indicates that 23% of PMVs for NV case, 20.3% of PMV for (NV+Sh) and 2.9% of the PMVs for (NV+Sh+Ins) cases are over 1.5. Similarly, the curve for kitchen shows that 38% of PMVs for NV and (NV+Sh) cases and 26.9% of PMVs for (NV+Sh+Ins) case are over 1.5.



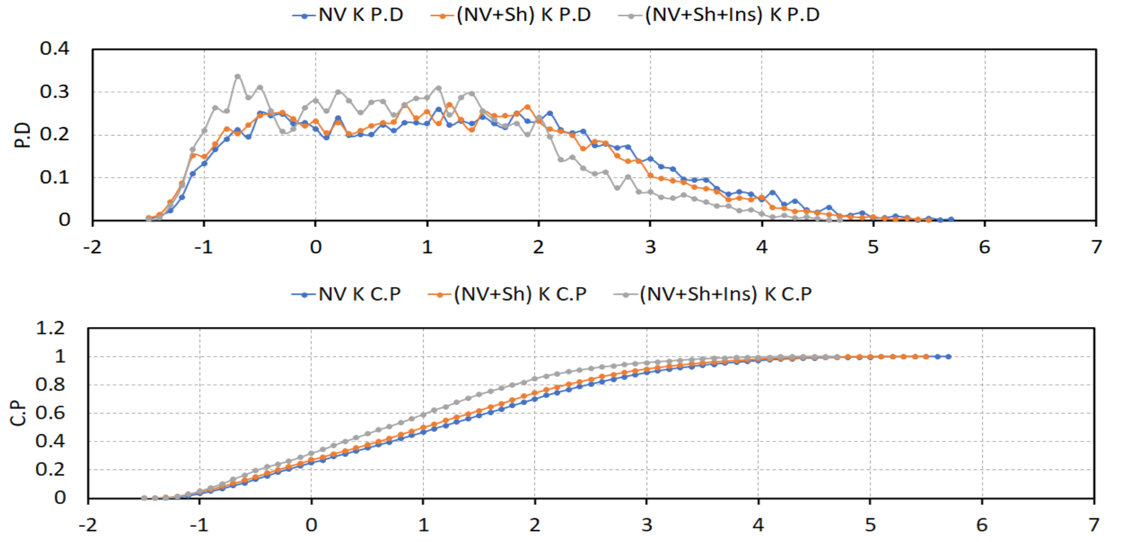


Fig. 5.16 Probability density and cumulative probability of PMV for different NV cases

5.5. Simulation results of HVAC cases

HVAC category has also three cases. i.e HVAC case, (HVAC+Sh) case and (HVAC+Sh+Ins) case. When NV case is added with HVAC system, the resultant model is termed as HVAC case. It may be noted that in current study, bedroom 1 and 2 are conditioned spaces while kitchen and washrooms are non-conditioned spaces. Hence, Figs. 5.13-5.16 can represent the climate variables of these zones. In this section, only the climate variables of conditioned spaces will be discussed. Table 5.4 gives schedules of heating and cooling set points.

Table 5.4: Heating and cooling setpoints

Period		**Heating (set point)**	**Cooling (set point)**
Month	Hours		
Jan-Feb	00:00-07:00	Yes (15ºC)	No
	07:00-22:00	No	No
	22:00-24:00	Yes (15ºC)	No
Mar-Apr	00:00-24:00	No	No
May-Sept	00:00-07:00	No	Yes (26ºC)
	07:00-12:00	No	No
	12:00-17:00	No	Yes (26ºC)
	17:00-22:00	No	No
	22:00-24:00	No	Yes (26ºC)
Oct	00:00-24:00	No	No

Nov-Dec	00:00-05:00	Yes (15°C)	No
	05:00-22:00	No	No
	22:00-24:00	Yes (15°C)	No

By conditioning the indoor climate of bedroom 1 and 2, the indoor temperature of both the zones is kept in comfortable range. Fig. 5.17 shows a comparison between indoor climate variables of bedroom 1 for the coldest week of 2002 (13th January to 19th January). Indoor temperature for HVAC and (HVAC+Sh) cases is same and ranged from 10°C to 23°C. Indoor temperature of (HVAC+Sh+Ins) case is comparatively higher (11.8°C to 22.9°C). The PMV values remained between -1.4 and 0.2 for HVAC and (HVAC+Sh) case. For (HVAC+Sh+Ins) case, the PMV ranged between -1.1 and 0.2. It is worth mentioning that as per Table 5.4, there are some hours of day when HVAC is not working. In such hours, the model behaves like NV model and this is the reason of PMV lower than -0.5. PPD for HVAC and (HVAC+Sh) cases remained between 5.4% to 48%. For (HVAC+Sh+Ins) case, the PPD remained between 5.4% to 30%. As the temperature of zone is mechanically controlled, so to identify the best suitable scenario, looking into the energy, required to be removed from or provided to the zone to achieve comfort temperature is a good tool. A careful study of Fig.5.17 reveals that the heating load for HVAC and (HVAC+Sh) cases is 13.25 kW while that of (HVAC+Sh+Ins) case is only 0.42 kW.

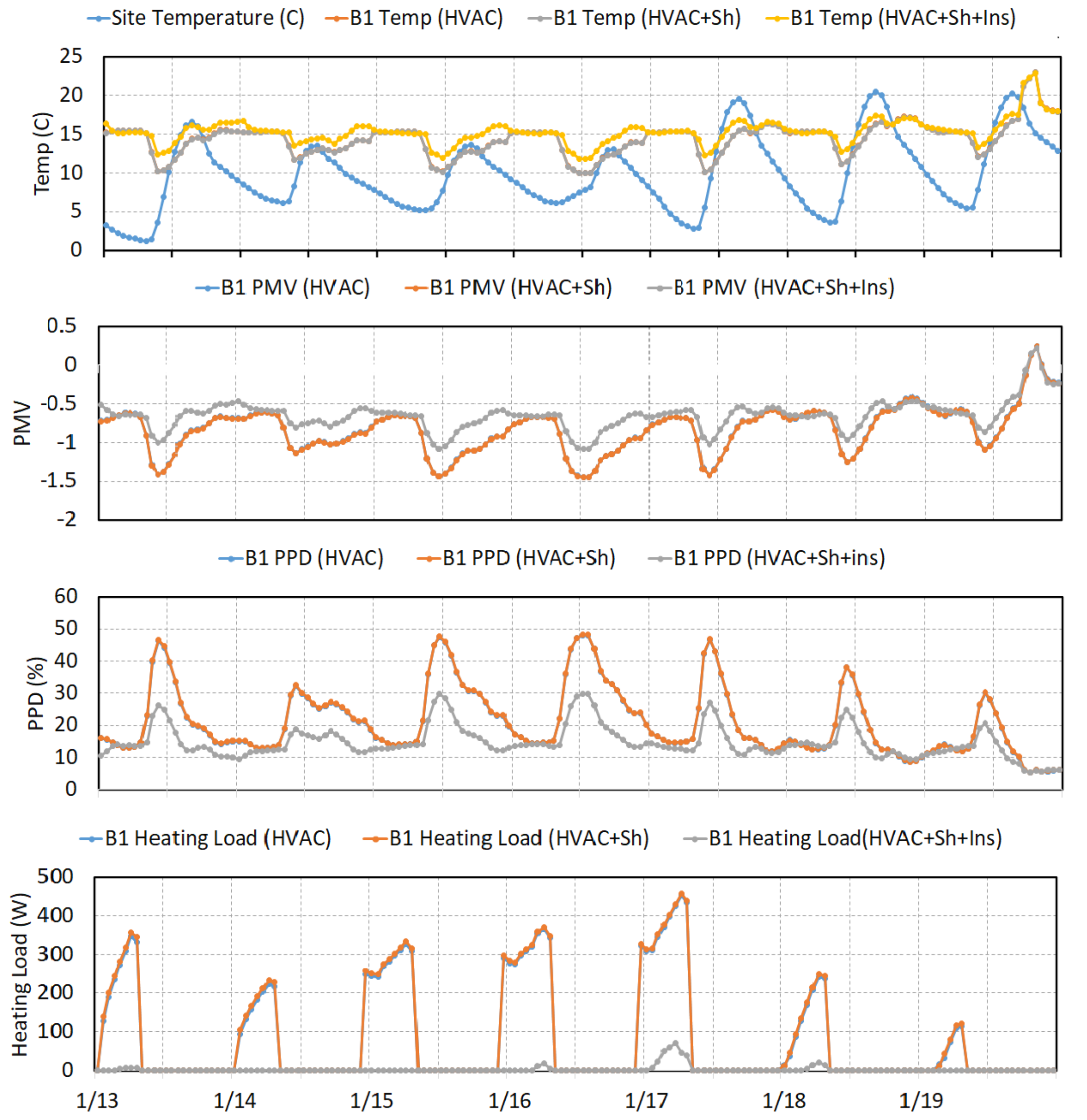


Fig. 5.17 Indoor climate variables of bedroom 1 during the coldest week

Fig. 5.18 shows a comparison between indoor climate variables of bedroom 1 for the hottest week of 2002 (16th June to 22nd June). The indoor temperature for HVAC and (HVAC+Sh) remained between 25.5ºC and 38.6ºC. Indoor temperature tends to remain the same in all the three cases of during the operation of HVAC. Further, the indoor temperature in three cases also remained the same on 16th and 17th June because the outdoor temperature is comparatively low. The difference in indoor temperature of HVAC cases became visible on 18th and onwards when HVAC is not operational and when the outdoor temperature is highest. However, it can be noticed that the indoor temperature for (HVAC+Sh+Ins) case remained lower than the other two cases. The range of indoor temperature for HVAC and (HVAC+Sh) cases is 25.5ºC to 38.6ºC while for (HVAC+Sh+Ins), it is from 25.4ºC to 36.9ºC. Similarly, PMV for the prior cases had values from 0.3 to 3.3 while the PMV for the latter case remined between 0.3 and 2.8. PPD for HVAC and (HVAC+Sh) cases can be noticed between 7.5% and 99.7%. PPD for (HVAC+Sh+Ins) case is having its value between 6.7% and 96.8%. In HVAC case, the cooling load of bedroom 1 is 75.5 kW while in (HVAC+Sh+Ins) case the amount of energy, required to be removed from the zone is 48.7 kW.

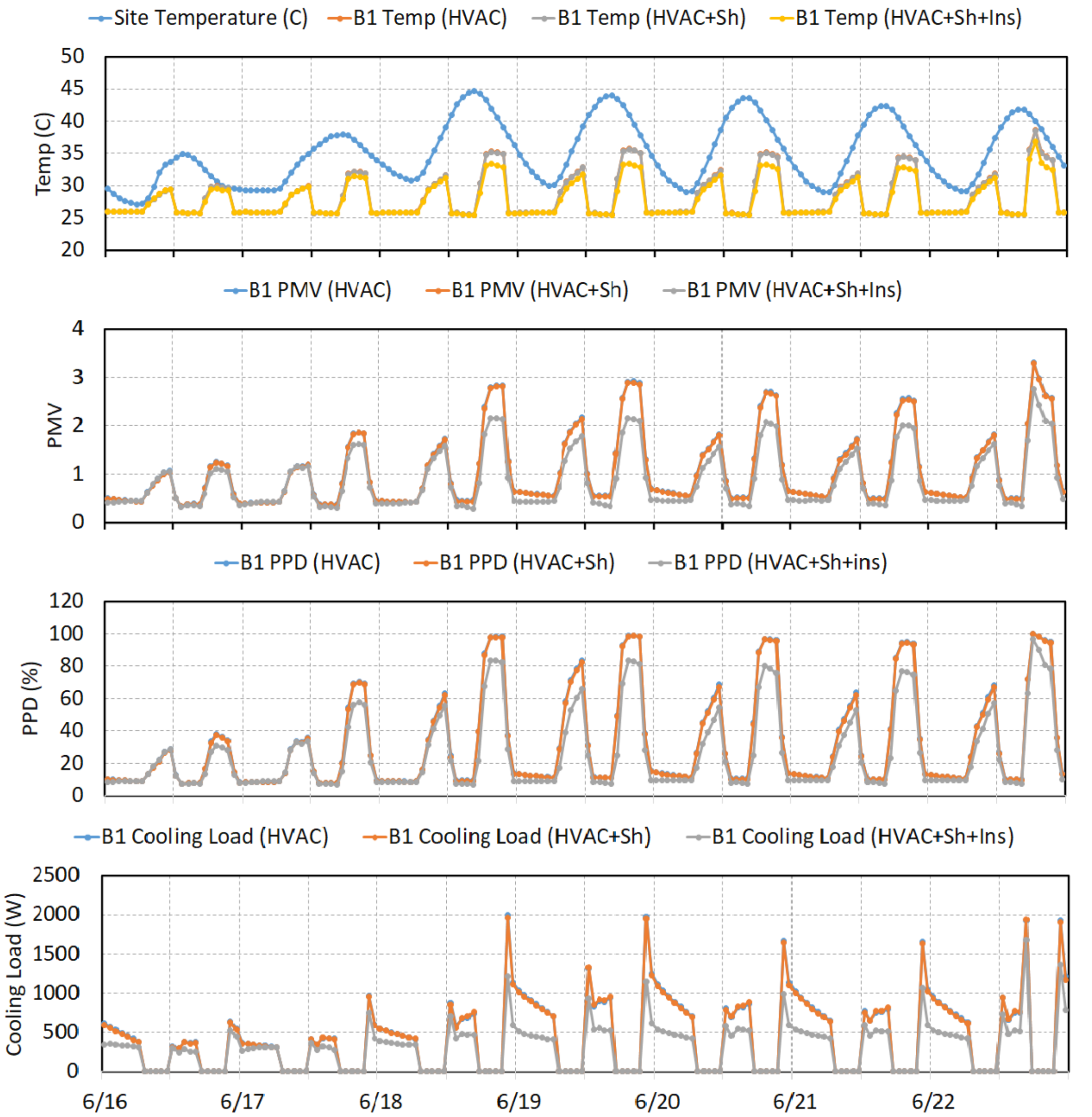


Fig. 5.18 Indoor climate variables of bedroom 1 during the hottest week

Fig. 5.19 shows a comparison between indoor climate variables of bedroom 2 for the coldest week of 2002 (13th January to 19th January). Indoor temperature for HVAC case and (HVAC+Sh) case remained between 10°C and 16.7°C while the indoor temperature of (HVAC+Sh+Ins) case remained between 12.2°C and 18.2°C. PMV for HVAC and (HVAC+Sh) case ranged between -1.4 and -0.5. PMV for (HVAC+Sh+Ins) case was in the range of (-1 to -0.3). PPD for the prior two cases was between 10.8% and 47.9% while PPD for the latter case remained between 6.8% and 26.7%. The heating load of bedroom during the coldest week was 17.8 kW for HVAC case. In (HVAC+Sh+Ins) case, this load became 0.035 kW.

Fig. 5.20 shows a comparison between indoor climate variables of bedroom 2 for the hottest week of 2002 (16th June to 22nd June). The indoor temperature for HVAC and (HVAC+Sh) cases stayed between 25.5°C and 36°C while that of (HVAC+Sh+Ins) case remained between 25.5°C and 33.7°C. The PMV of HVAC and (HVAC+Sh) cases ranged between 0.4 and 3.1, while that of (HVAC+Sh+Ins) case was between 0.4 and 2.3. The PPD for earlier two cases had it values between 8.6% and 99.3%. For the latter case, this range was 7.8% to 88.1%. The cooling load of bedroom 2 in HVAC and (HVAC+Sh) cases was 85.89 kW while this value decreased to 61 kW in (HVAC+Sh+Ins) case.

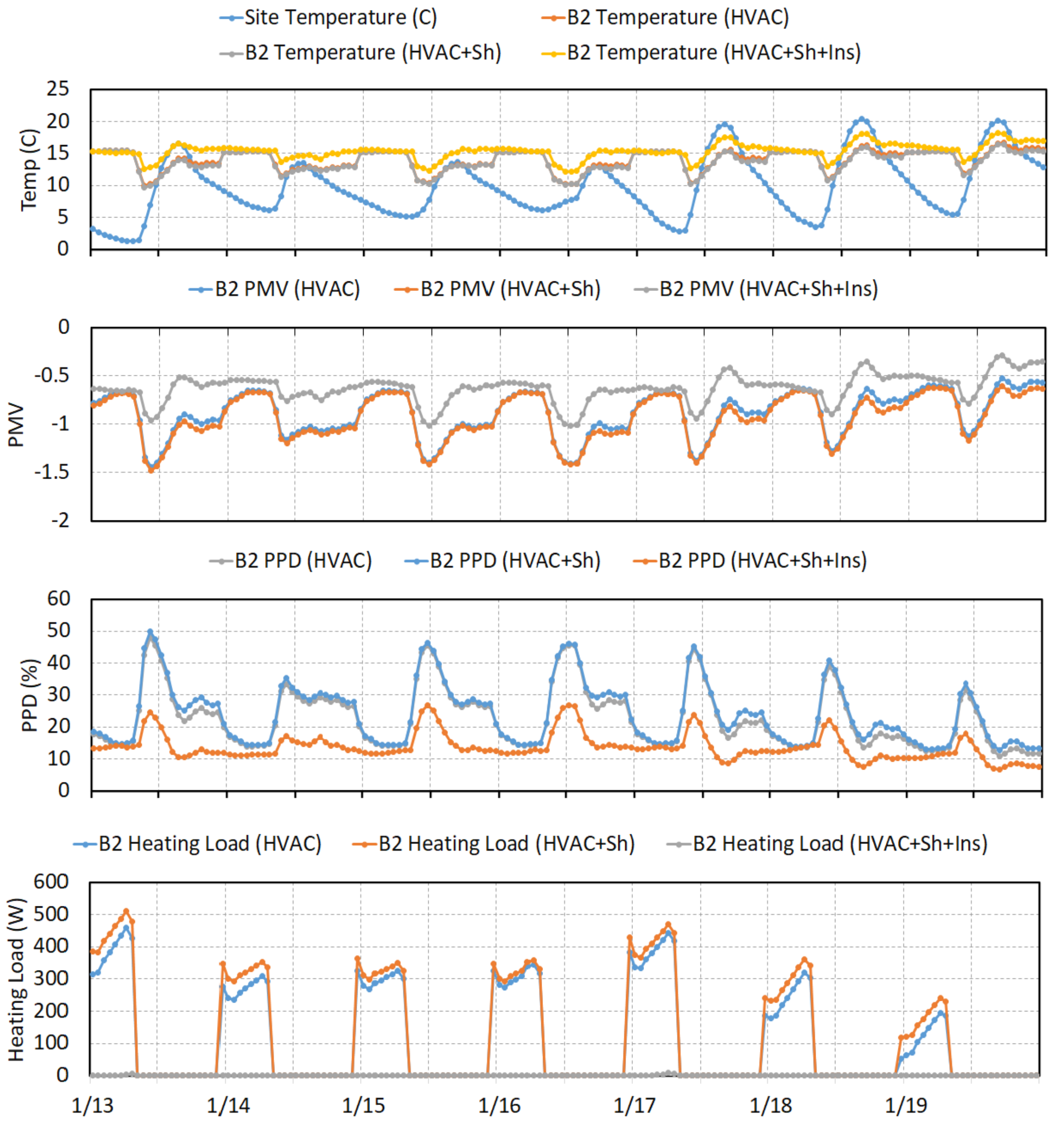


Fig. 5.19 Indoor climate variables of bedroom 2 during the coldest week

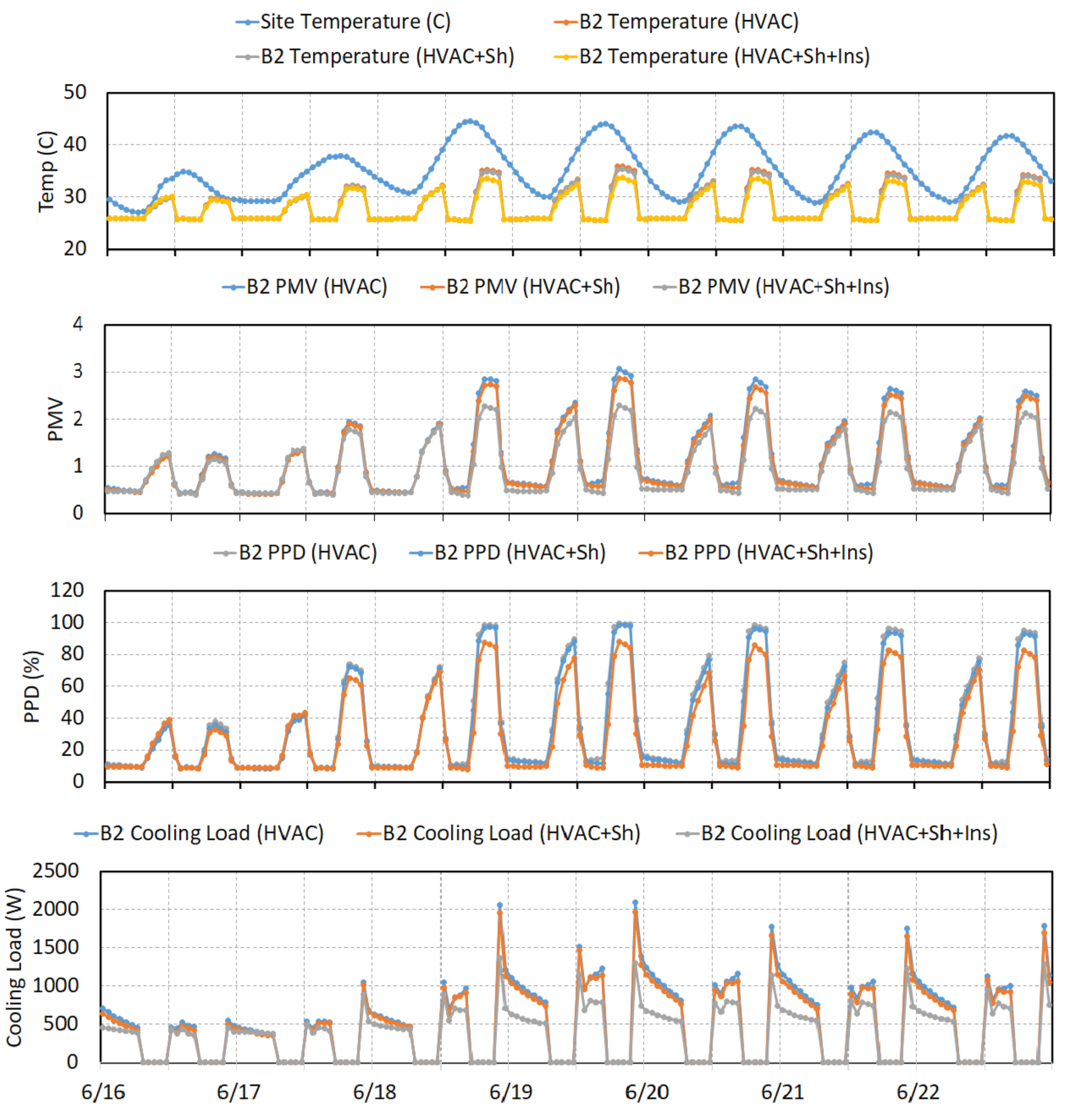


Fig. 5.20 Indoor climate variables of bedroom 2 during the hottest week

5.6. Probability density and cumulative probability of HVAC cases

Fig. 5.21 shows the probability density and cumulative probability of PMV for bedroom 1, 2 and kitchen for three cases of HVAC category. For bedroom 1, the probability density curve for HVAC and (HVAC+Sh) cases are the same. It is in agreement with indoor temperatures and PMVs of the zone. The PMV range of for these cases is (-1.4 to 3.6). PMV for (HVAC+Sh+Ins) case remained between -1.1 and 2.8. For bedroom 2, the PMV range in HVAC and (HVAC+Sh) case (-1.4 to 3). The PMV range in (HVAC+Sh+Ins) case is (-1 to 2.4).

The cumulative probability curve of bedroom 1 reveals that for HVAC and (HVAC+Sh) cases, 17.5% of PMVs while for (HVAC+Sh+Ins) case only 6% of the PMVs are over 1. The cumulative probability curve of bedroom 2 indicates that in HVAC, (HVAC+Sh) and (HVAC+Sh+Ins) cases 16.6% of the PMVs are over 1.

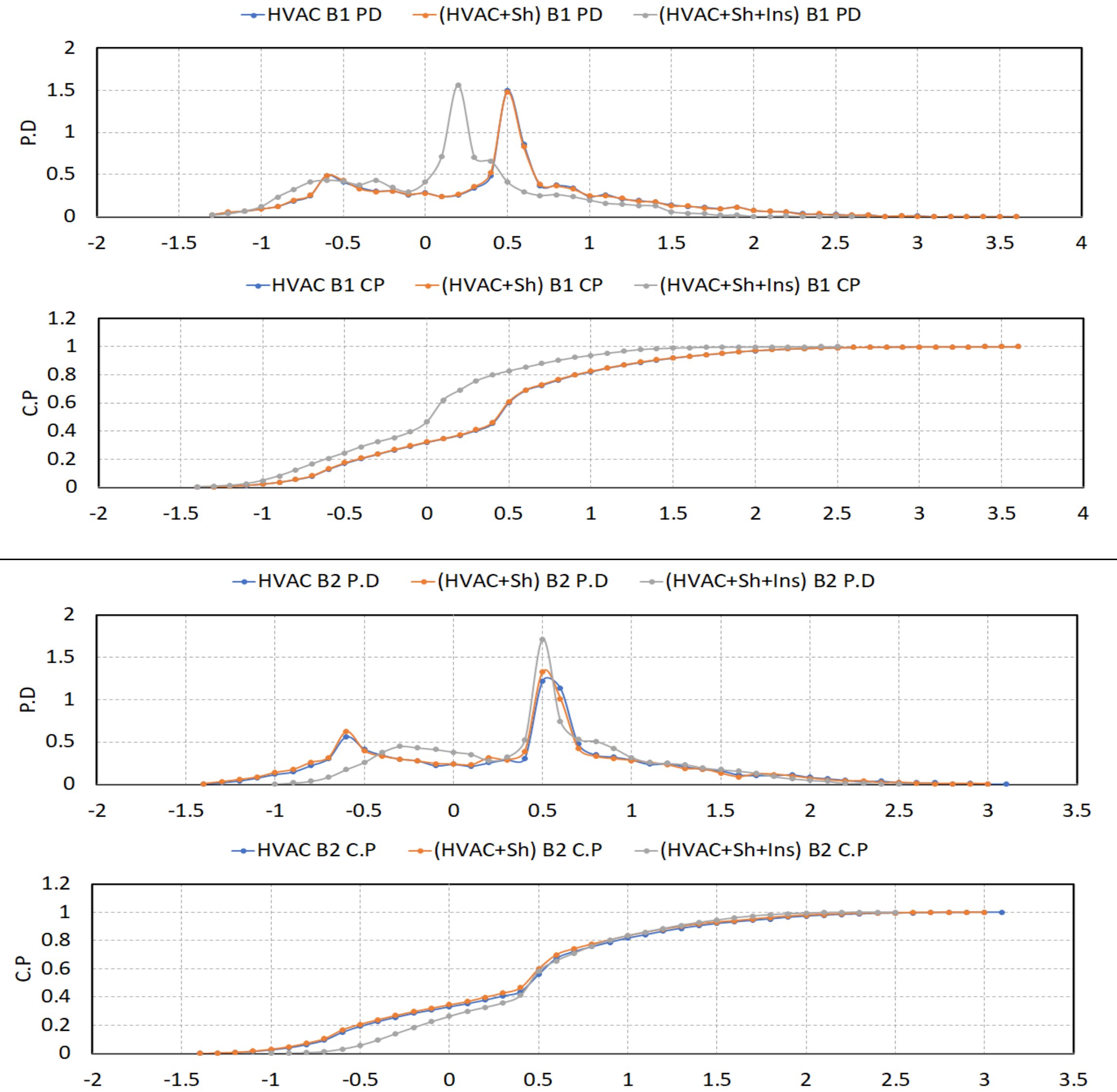


Fig. 5.21 Probability density and cumulative probability of PMV for different NV cases

5.7. Energy consumptions of HVAC cases

The most important aspect of sustainability of residential buildings are the energy efficiency of these buildings. In baseline model, energy is being consumed for (i) space heating, (ii) operating appliances, and (iii) cooking. Section 4.3 described the monthly energy consumption of baseline model. Fig. 4.25 shows monthly consumption of electricity for appliances. Fig. 4.26 gives details of electricity consumptions for space lightening on monthly basis. Fig. 4.27 is the monthly consumption of natural gas and total electricity. As the schedules of electricity and natural gas consumption remains the same for all the categories, the energy consumption of the model remains the same for different cases of different categories. Hence, Figs. 4.25 to 4.27 are valid for all the cases. However, in HVAC category, additional energy is consumed for space conditioning. In HVAC category, the assumed settings are Ideal Load Systems which is the simplest of all the available HVAC templates in EnergyPlus. However, with the use of ideal Load System, the energy consumption for space conditioning do not appears in electricity consumption outputs. It must be calculated indirectly by working out the cooling and heating loads of the zones. Then dividing the heating / cooling load by Coefficient of Performance (CoP) of the HVAC system, can yield into the electricity consumed by HVAC for space conditioning. In this section, a comparison of the monthly heating /cooling loads is presented so that most energy efficient model can be identified. Fig. 5.22 shows the monthly heating and cooling load of bedroom 1 and 2. It may be noted that heating load of both the zones in (HVAC+Sh+Ins) case is very small and is not visible in the graph. For bedroom 1, heating load for HVAC case is 18.6 MWh, for (HVAC+Sh) case is 19.3 MWh and for (HVAC+Sh+Ins) is only 0.32 MWh in the month of January. Similarly, for bedroom 1, the cooling load is 212 MWh for HVAC case, 210 MWh for (HVAC+Sh) case and 140.5 MWh for (HVAC+Sh+Ins) case for the month of July. For bedroom 2, the heating load is 26.8 MWh for HVAC case, 32 MWh for (HVAC+Sh) case and 0.03 MWh for (HVAC+Sh+Ins) case for the month of January. The cooling load is 242 MWh for HVAC, 228 MWh for (HVAC+Sh) and 177 MWh for (HVAC+Sh+Ins) case for the month of July. Fig. 5.22 clearly indicates that adding insulation materials to the model improved its energy efficiency in terms of space conditioning.

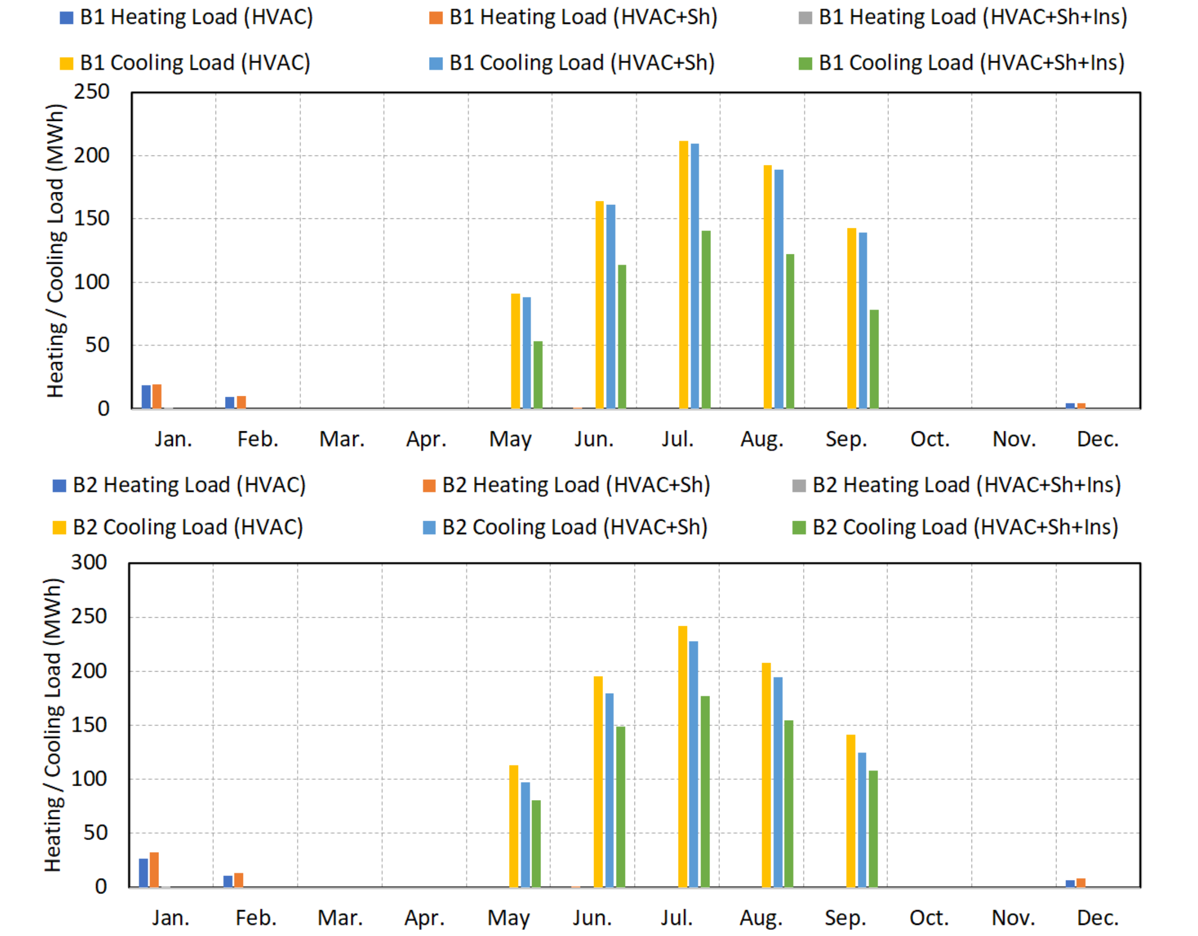


Fig. 5.22. Heating and cooling load of the zones in HVAC category

5.8. Simulation results of orientation cases

In this study, the impact of orientation on building's thermal performance has also been studied. Possible orientations are 360. However, checking the performance of model on all the 360 orientations was not possible. For simplicity, only four orientations are selected in this study i.e north, south, east and west. EnergyPlus takes true north direction as the default direction and all other orientations are determined relative to north axis. Hence, if a building is supposed to be orientated in east direction, 90° are to be mentioned in "North Axis" object in EnergyPlus. the performance of NV case of Natural Ventilation category was checked in these four orientations.

Fig. 5.23 shows a comparison between indoor climate variables of bedroom 1 for the coldest week of 2002 (13th January to 19th January). Indoor temperature for east and south cases is almost the same. Maximum indoor temperature for the coldest week for these two cases is 21°C. Minimum indoor temperature for these two cases is 8.5°C. Maximum indoor temperature for north orientation is 23°C while minimum temperature is 9.4°C. The best performance in terms of indoor temperature during the coldest week is exhibited by west orientation where minimum indoor temperature is 12°C while the maximum temperature is 23.7°C. The trends of indoor temperatures for these orientations are also reflected in PMV and PPD curves. The PMVs of east and south was between -1.7 and -0.1. The PMV for north direction had its values between -1.5 and 0.2. PMV of west orientation increased ranged between -1 and 0.2. The PPD of east and south orientation was between 5.4% and 60.6% while that of north orientation was between 5% and 53.3%. PPD of west orientation ranged between 5.2% and 27.5%.

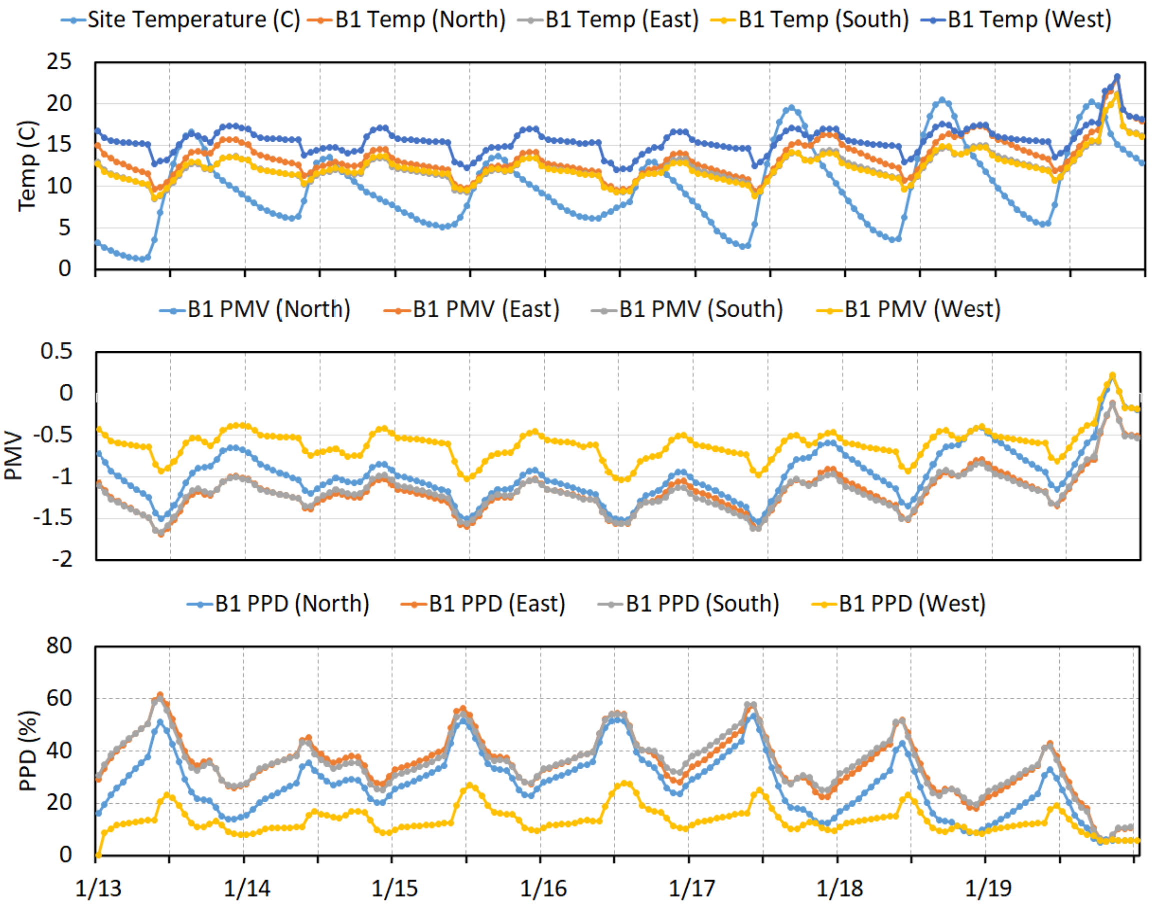


Fig. 5.23 Indoor climate variables of bedroom 1 during the coldest week

Fig. 5.24 represents the indoor climate variables of bedroom 1 for the hottest week of 2002 (16th June to 22nd June). Indoor temperature for north, east and south cases is almost the same. Maximum indoor temperature for the hottest week for these cases is 40ºC. Minimum indoor temperature for these cases is 28ºC. The indoor temperature for west orientation is almost same on 16th and 17th June as the outdoor temperature is lower on these days. From 18th June, when the outdoor temperature is high, the indoor temperature of west orientation is lower as compared to the other three cases. The minimum indoor temperature for west orientation is 28ºC while the maximum temperature is 39ºC. The PMV of north, east and south had values between 0.9 and 3.9. PMV of west orientation was between 0.9 and 3.5 during the hottest week. PPD of prior three cases were between (24%-99.9%), (26.6%-99.9%) and (22.5%-99.9%) respectively. PPD of west orientation was between 23.5% and 99.9%.

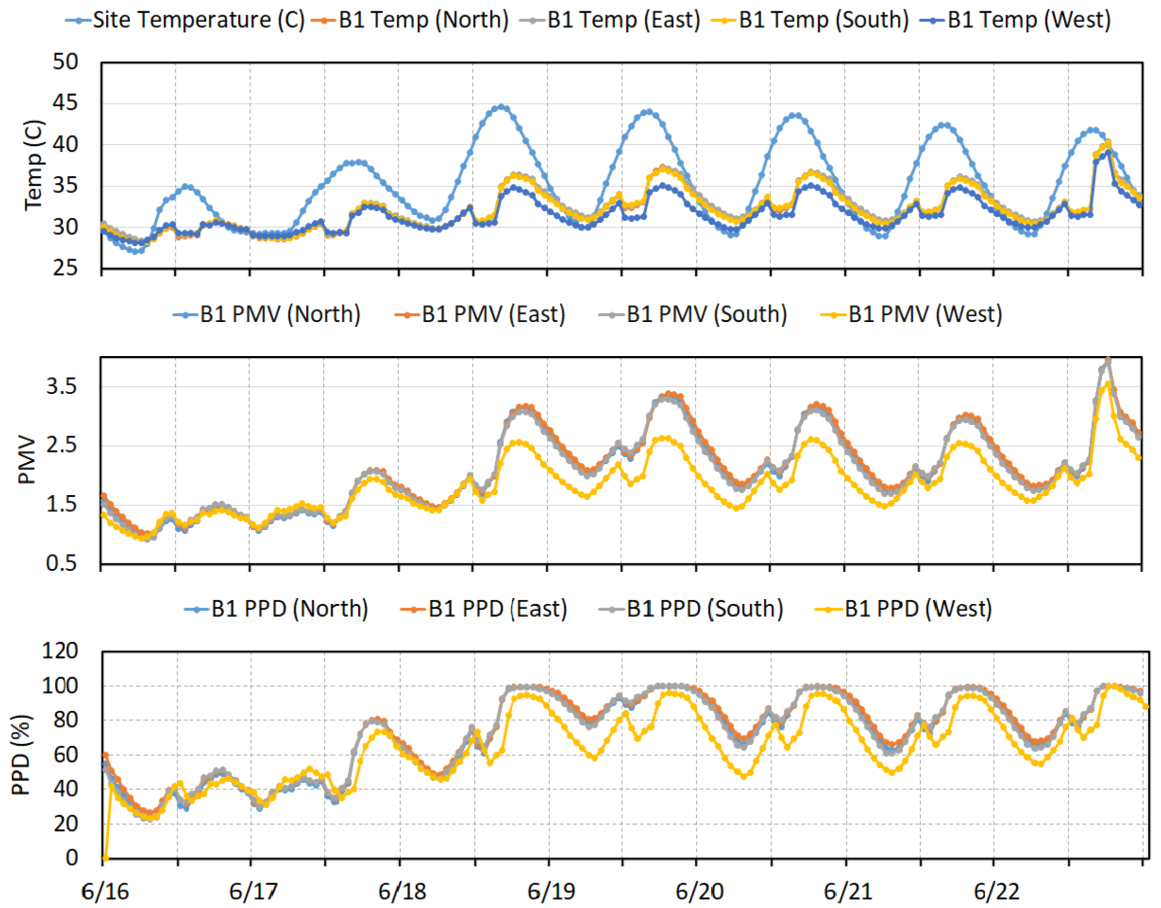


Fig. 5.24 Indoor climate variables of bedroom 1 during the hottest week

Fig. 5.25 shows a comparison between indoor climate variables of bedroom 2 for the coldest week of 2002 (13th January to 19th January). Indoor temperature for north, east and south cases is almost the same. Temperature ranges for these orientations are (9.3ºC-16.5ºC), (9ºC-16.1ºC) and (10ºC-17.6ºC) respectively. Maximum indoor temperature for west orientation is 18.4ºC while minimum indoor temperature is 12.4ºC. The PMV ranges for north, east and south are (-1.6 to -0.6), (-1.6 to -0.6) and (-1.4 to -0.3). For west orientation, PMV lies between -0.9 to -0.3. The PPD ranges for north, east and south orientations are (11.5%-54.2%), (13.1%-56.4%) and (6.4%-47.4%). The PPD in west orientation case is from 6.4% to 24.7%.

In Fig. 5.26 is the graphical representation of indoor climate variables of bedroom 2 for the hottest week of 2002 (16th June to 22nd June). Indoor temperature for all the four cases remained the same on 16th and 17th of June. On 18th June and onwards, indoor temperature of north orientation, east orientation and south orientation cases is almost the same. However, on 18th June and onwards, when the outdoor temperature is high, the indoor temperature of west orientation is lower as compared to the other three case. The ranges of indoor temperatures for north, east and south orientations are (28.6°C-38°C), (28.5°C-37.5°C) and (28.5°C-37.5°C) respectively. The minimum indoor temperature for west orientation is 28.5°C while the maximum temperature is 36°C. The PMV ranges for north, east and south orientation cases are (1.1-3.6), (1.1-3.5) and (1.1-3.5), respectively. The PMV for west orientation has a minimum value of 1.1 and maximum value of 2.9. The PPD ranges of prior three cases are (30.3%-99.9%), (29.3%-99.9%) and (29.3%-99.9%), respectively while PPD range for west orientation is from 30.1% to 98.8%.

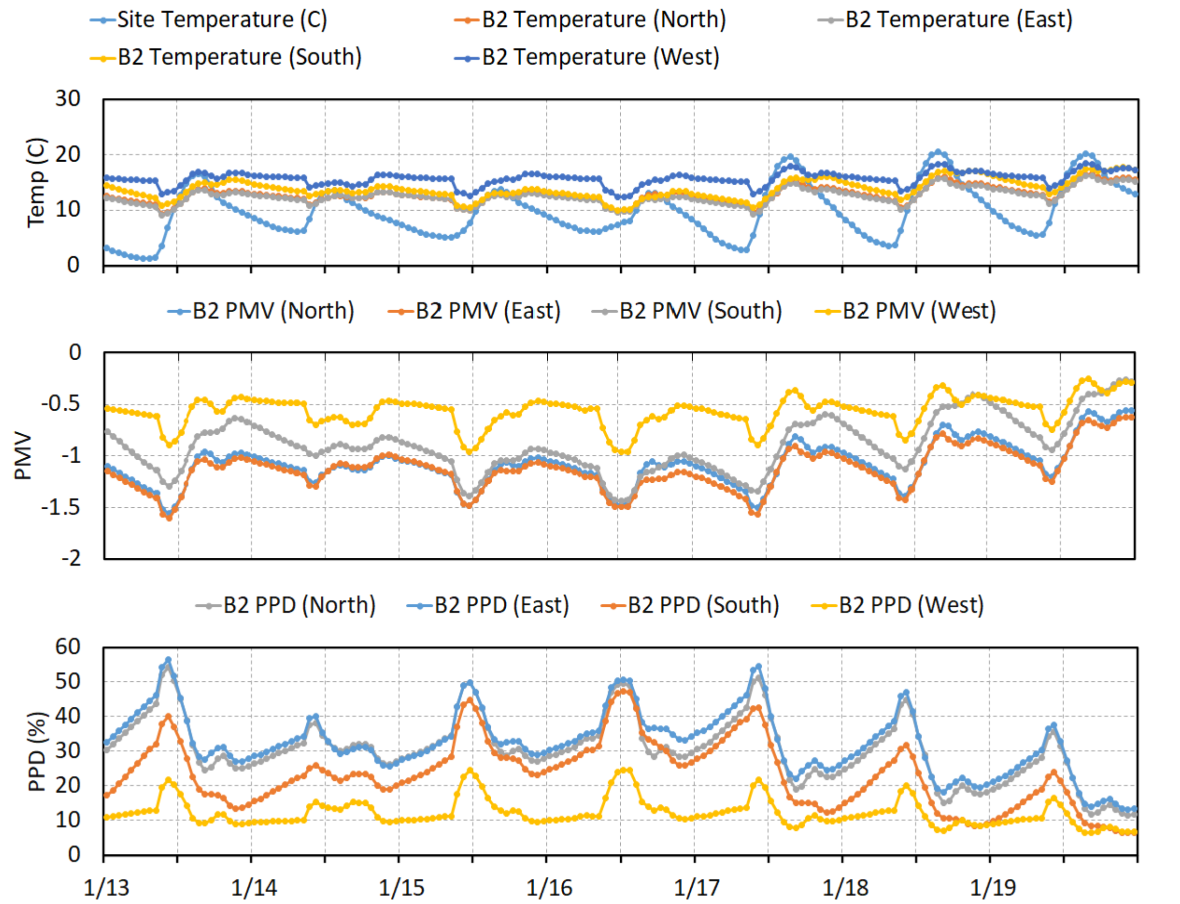


Fig. 5.25 Indoor climate variables of bedroom 2 during the coldest week

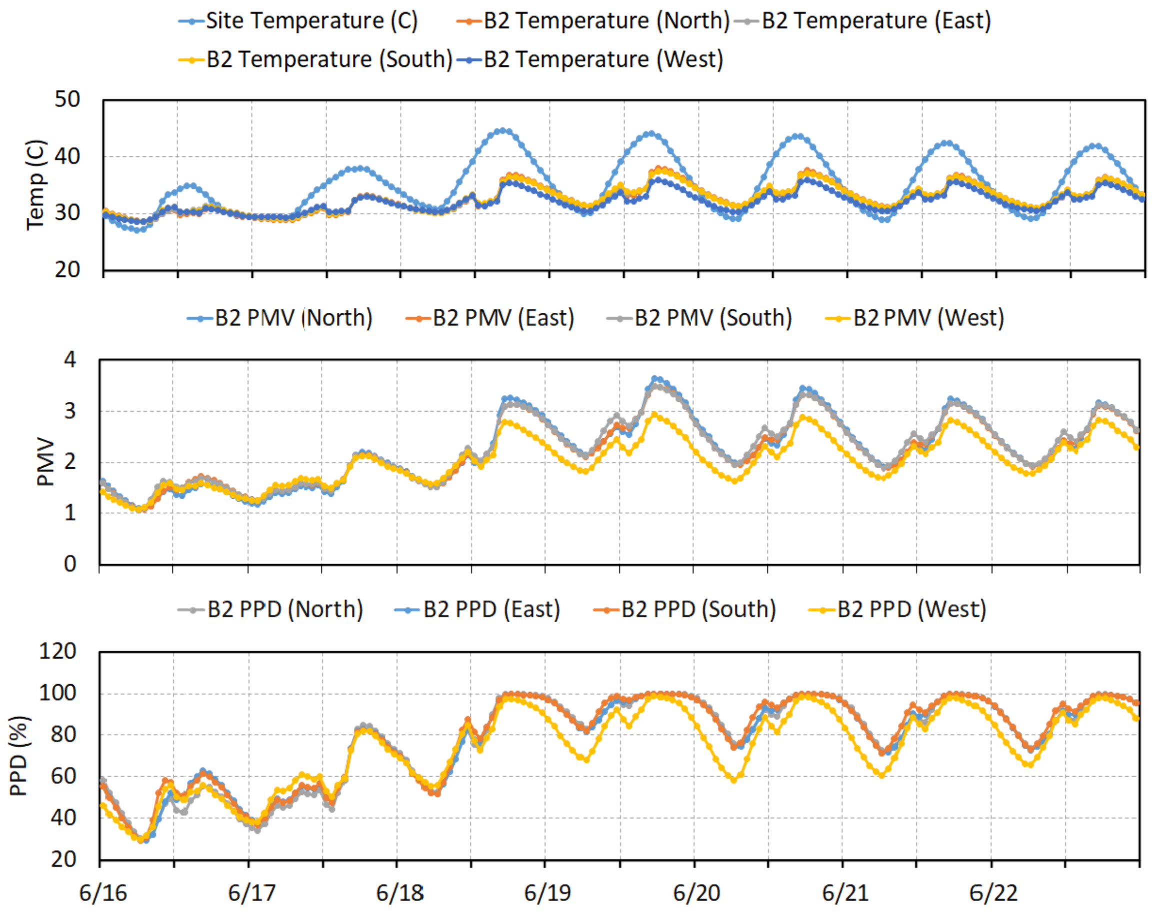


Fig. 5.26 Indoor climate variables of bedroom 2 during the hottest week

Fig. 5.27 is a graphical representation of indoor climate variables of kitchen for the coldest week of 2002 (13th January to 19th January). As internal heat generation from gas stove and other appliances in kitchen is very high, it seems that orientation has no effect on indoor temperature of kitchen. However, a careful observation of Fig. 5.27 reveals that the temperature in case west is relatively high as compared to other orientations. Indoor temperature of kitchen remained between 8°C and 24°C for north orientation, 9°C and 26.7°C for east orientation, 9°C and 26.3°C for south orientation and 22°C and 26.6°C for west orientation. Hence, the west orientation is best performer in case of kitchen as well. The ranges of PMV for north, east and south orientations are (-1.5 to 0.3), (-1.3 to 0.8) and (-1.3 to 0.7), respectively. The PMV of west orientation ranges from -0.8 to 0.7. The PPD for first three cases are (6.6%-54%), (5%-42.9%) and (5%-40%). The PPD of west orientation ranges from 5% to 22.5%.

Fig. 5.28 exhibits the indoor climate variables of kitchen for the hottest week of 2002 (16th June to 22nd June). Due to high internal heat generations of zone, the orientation seems no longer effective. However careful examination of the Fig.5.28 declare west orientation as the best performer. The range of indoor temperature for north, east and south orientations are (30.7°C-47.9°C), (30.7°C-48°C) and (31.2°C-48.7°C). The range of indoor temperature for west orientation is from 31.3°C to 46.3°C. Study of PMV charts reveals that PMV fluctuates on smaller amplitude for west orientation. The range of PMV for north, east, south, and west orientation are (1.7-5.7), (1.7-5.7), (1.6-6) and (1.9-5.3) respectively. The PPD for these orientations' ranges between (61.9%-100%), (61.5%-100%), (58.3%-100%) and (72.6%-100%).

In Fig. 5.29, a comparison of outdoor temperature and indoor temperature of washroom 1 for four orientations is drawn. During coldest week, the indoor temperature for north, east and south orientations have almost the same temperature while the indoor temperature for west orientation is relatively higher. The range of temperatures for north, east, south, and west are (10ºC-21.7ºC), (9,2ºC-20.1ºC), (9.3ºC-22.6ºC) and (13.5ºC-23ºC). During the hottest week, indoor temperatures of north, east and south remained the same while the indoor temperature of west orientation is lower. The ranges of indoor temperatures for north, east, south, and west are (29.5oC-41.2oC), (29.9oC-41.2oC), (29.9oC-41.3oC) and (28.8oC-39.4).

Form above discussion, the west orientation appears to be performing best in terms of indoor temperature, PMV and PPD of different zones of the model.

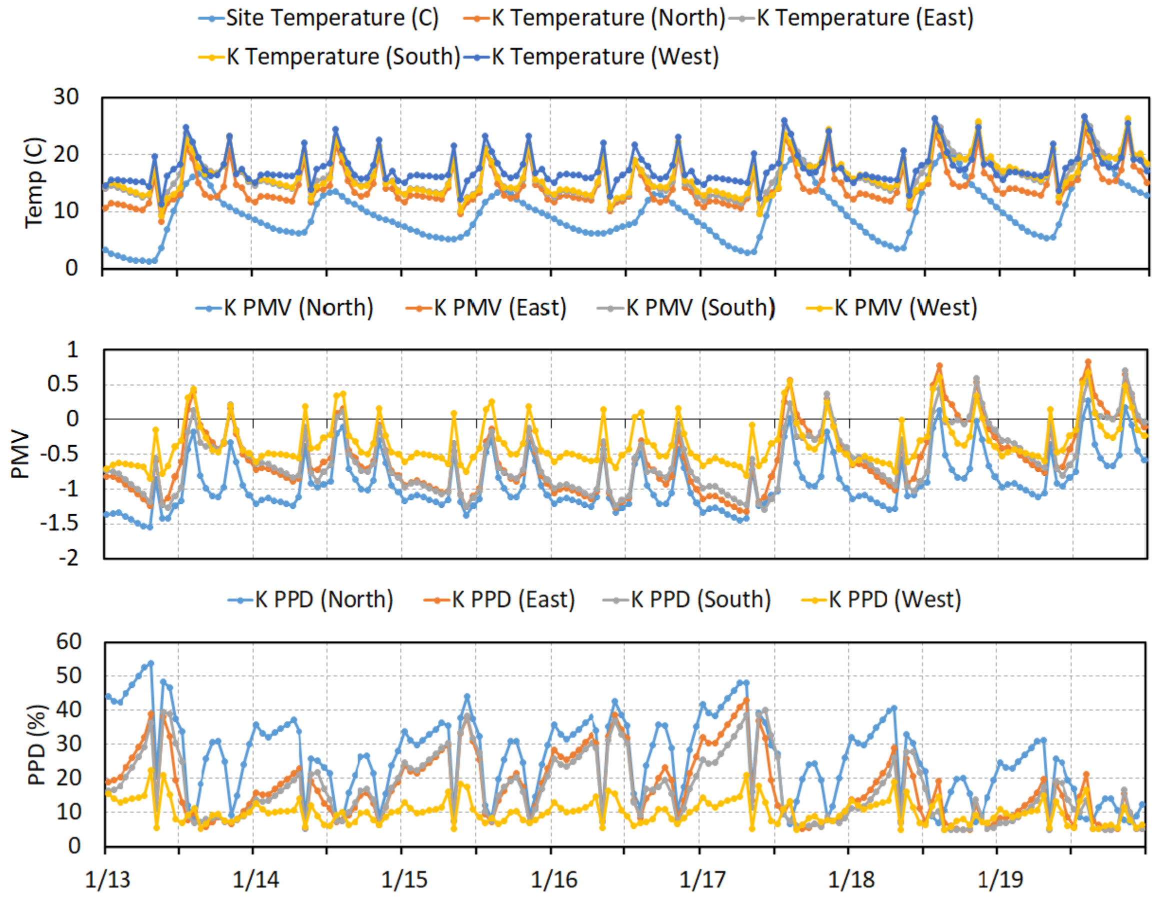


Fig. 5.27 Indoor climate variables of kitchen during the coldest week

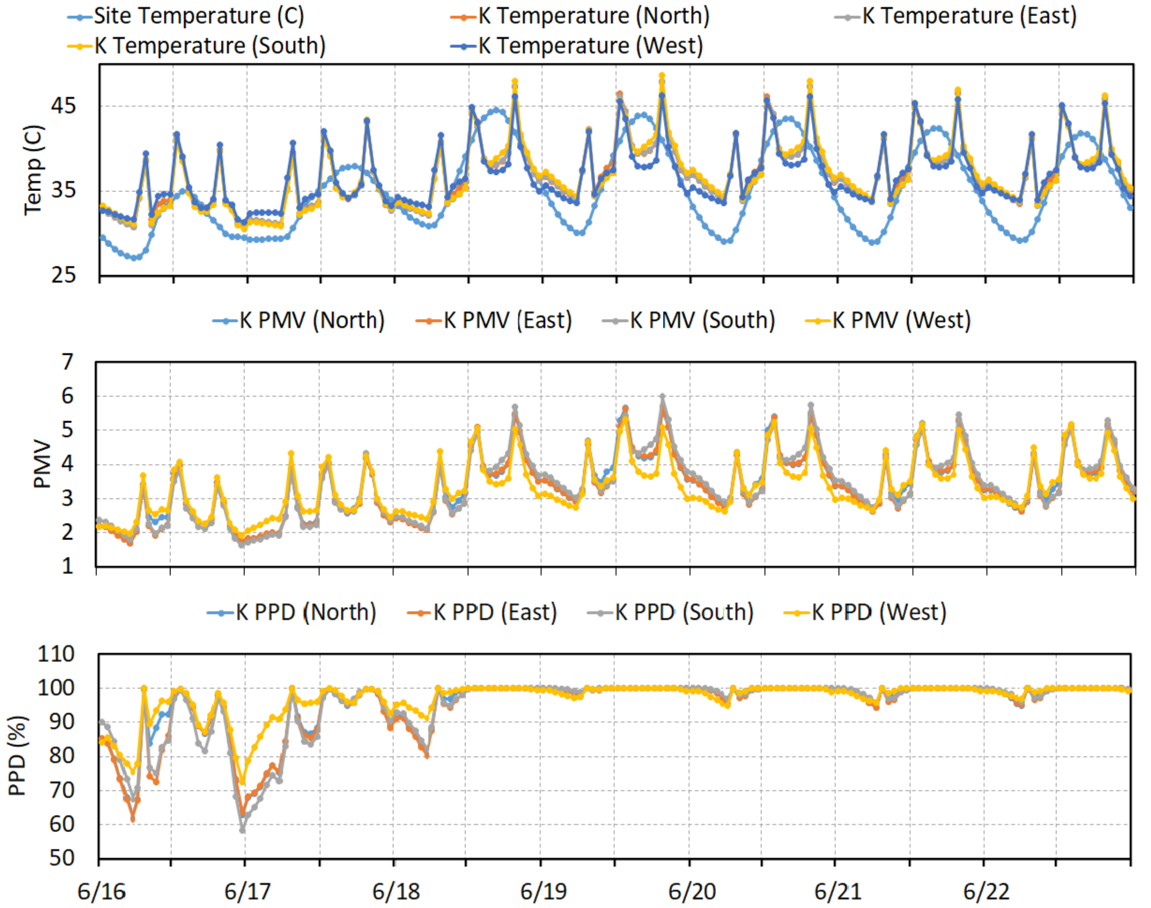


Fig. 5.28 Indoor climate variables of Kitchen during the hottest week

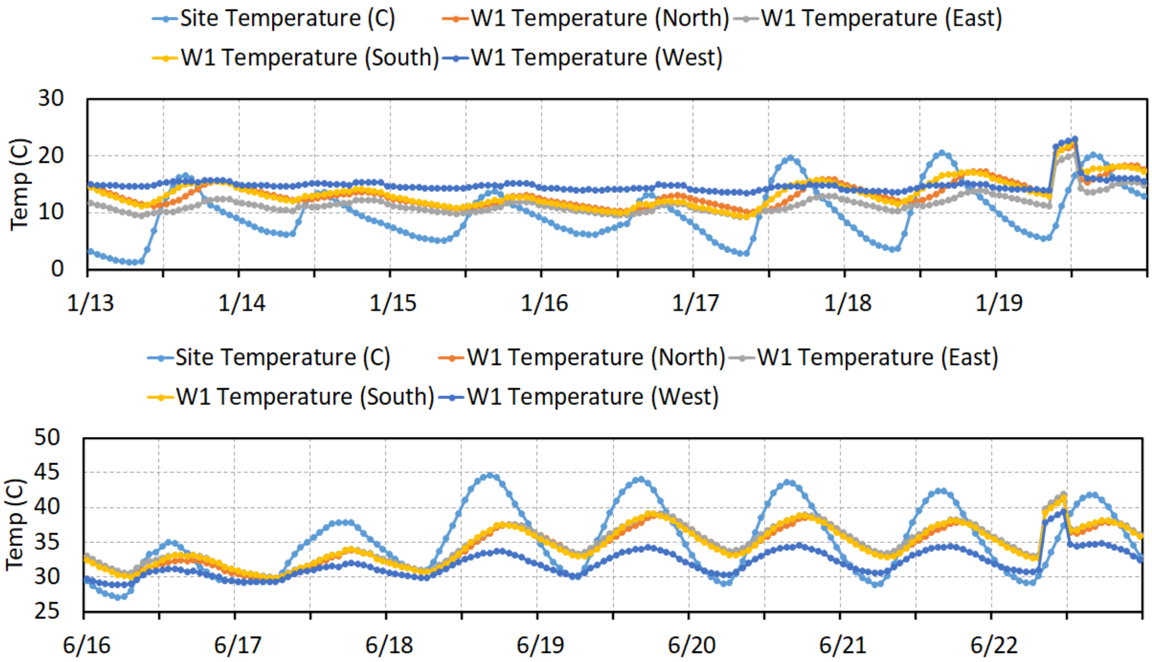
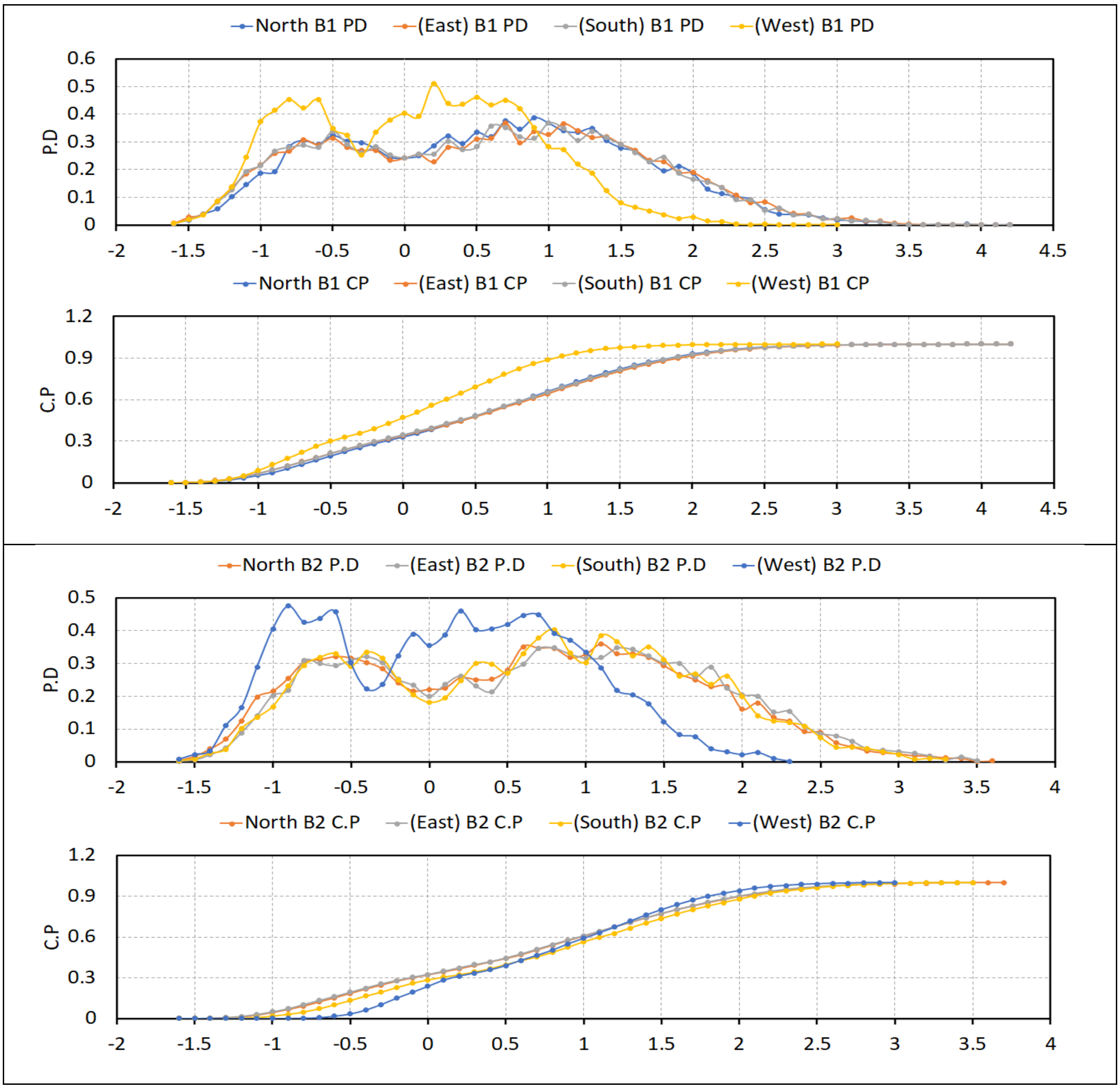


Fig. 5.29 Indoor climate variables of washroom 1 during the coldest and hottest weeks

5.9. Probability density and cumulative probability of PMV under various orientation cases

Fig. 5.30 shows the probability density and cumulative probability of PMV for bedroom 1, bedroom 2 and kitchen. For bedroom 1, the PMV range for north, east, south, and west orientations are (-1.5 to 4.2), (-1.7 to 4.2), (-1.6 to 4.1) and (-1 to 3.5). For bedroom 2, the PMV ranges for these orientations are (-1.6 to 3.6), (-1.6 to 3.5), (-1.4 to 3.5) and (-1 to 2.9) while these ranges of PMV for kitchen are (-1.5 to 5.7), (-1.3 to 5.7), (-1.3 to 6) and (-0.8 to 5.3).

The cumulative probability curve of bedroom 1 shows that for 34.5% of the PMVs for north, east and south orientations while 11.4% of the PMVs for west orientation are above 1. The cumulative probability curve for bedroom 2 reveals that 39.2% of the PMVs for north and east orientations, 43.6% of the PMVs for south orientation while 41.1% of the PMVs for west orientation are above 1. Cumulative probability curve of kitchen shows that 53.2% of PMVs for north and east orientations, 51.1% of PMVs for south orientation while 40.9% of the PMVs for west orientations are above 1.



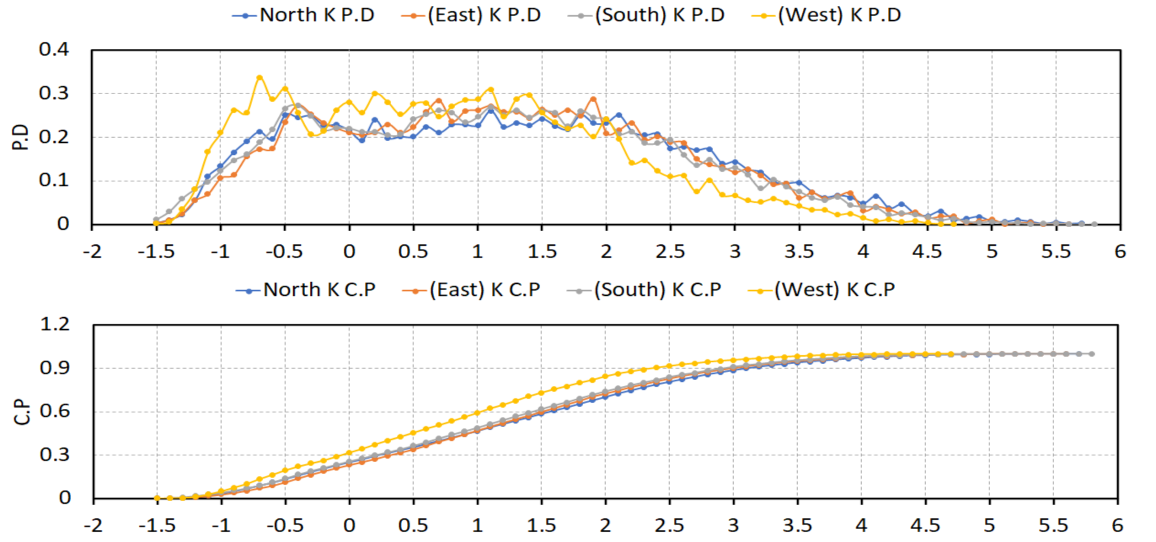


Fig. 5.30 Probability density and cumulative probability of PMV for different NV cases

6. Conclusion

Pakistan has 31.916 million houses for a population of over 207.7 million. The country is facing an annual shortage of 0.7 million houses while the country can only add 0.3 million houses, annually to its existing stock. There is no provision for energy efficiency in national building codes or the regulations of regional building regulatory authorities. Being a developing country, the energy needs of Pakistan are increasing by every year. Also, the country is facing energy crisis which adversely impacted the growth of its economy. The situation calls for an urgent need of introduction of energy efficiency in different consumer sectors. It may be noted that residential sector in Pakistan is major consumer of energy. Hence, introduction of energy efficiency techniques in residential sector is very important. Several energy efficiency techniques can improve the indoor thermal comfort in the residential units, however, this research focused on three parameters i.e shading on windows, insulation materials, and orientation of the unit.

Due to restrictions of COVID-19, the questionnaire surveys could not be conducted to get information about the most common house designs, schedules of usage of electric and gas equipment and air conditioners in Pakistan. However, some drawings of government residence were received from Pakistan. The most representative design was selected based on literature survey and the design was simulated using EnergyPlus software. Different simulation settings were developed and simulated indoor climate variables were developed. Based upon the analysis of those climate variables, the following results were found:

(i) Addition of shadings on windows does not prove effective as in without ventilation, natural ventilation and HVAC categories, the indoor climate conditions for base case (WV, NV and HVAC) case and shading case (WV+Sh, NV+Sh, HVAC+Sh) case appeared to be the same. The reason behind this is the presence of window of bedroom 1 and bedroom 2 in front and back verandas. If direct solar radiations fall on windows, it is expected that window shadings will prove effective.

(ii) It is found that orientation of house impacts indoor climate variables. The west orientation has been proved to be the most effective. However, the impact of orientation in summer is less than its impact in winter.

(iii) Addition of insulation materials to external walls and roof proves to be the most effective tool of achieving the indoor thermal comfort. Addition of insulation materials decreases the heat transfer between zone and outdoor. This results into higher temperature during winter and lower temperature during summer. However, addition of insulation materials to kitchen makes it more uncomfortable for occupants. Therefore, it is suggested that insulation materials may be added while keeping in view of the utility of the zone.

References

1. Table 1.1, 6th Population Census Results, Pakistan Bureau of Statistics.
2. Pakistan Economic Survey 2017-18
3. World Bank Data bank, https://databank.worldbank.org/source
4. Economic Survey of Pakistan 2018-19
5. Housing crises in Pakistan: Review of population growth and deficiencies in housing laws and policies, Azra Jabeen, Huang Zi Sheng and Muhammad Aamir. International Journal of Sciences: Basic and applied research.
6. Table 30n & 32n of 6th Population Census Results, Pakistan Bureau of Statistics.
7. Table 33n, of 6th Population Census Results, Pakistan Bureau of Statistics.
8. Table 35n & 37n of 6th Population Census Results, Pakistan Bureau of Statistics.
9. Pakistan's Monthly Climate Summaries (August 2020 to May 2021), Pakistan Metrological Department (PMD).