TOKYO CITY UNIVERSITY

Thermal improvement of Nepalese houses based on the evaluation of energy use and adaptive comfort

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Abstract

Energy use is required for securing a certain living standard. The rationality of household energy use is important not only for improving individual living conditions but also for the economic growth of a nation. The current energy-policy scenario showed that if humans continue taking the present path without any change, the energy demand would rise by 1.3% each year. Since approximately 40% of total global energy is used in the building sector, and it is important to seek a rational path that does not sacrifice human well-being. Nepalese households have been so far using energy at almost the least rate among other countries. Residents are adjusting their indoor environment relying on very primitive methods. In the context of Nepal, the researchers have so far conducted a study on overall energy sectors such as firewood, fossil fuels, biomass, electricity, and solar PV system. But no studies have focused yet on the household sector in particular. Some researchers have focused, either, on the current indoor thermal condition and or, on the thermal improvement, but not on both. Therefore, we need to study on energy use, thermal comfort of residents and thermal improvement of houses.

The objectives of this research are to investigate the current energy use condition including electricity use. This study also estimates the comfort temperature of residents in each region. Finally, this study examines a possible improvement of the houses that allows the residents to have a better indoor thermal environment during night time.

We have collected the data in winter in the form of electricity bills, family income, family size, the number of electric appliances, and energy use for lighting, cooking, heating and cooling from 442 households of cold, temperate and sub-tropical regions in Nepal. The indoor thermal environment was measured in three climatic regions and 839 thermal sensation votes were collected from three regions.

The monthly rate of firewood consumption was found 2.08 GJ/household/month in rural areas, which is higher than in other developing countries. The average electricity use of all areas in Nepal was 2.06 GJ/household/year, which is low compared to developed and even other developing countries. The electricity is used mainly for lighting purpose in the rural area, while it was also used to run other electric appliances in semi-urban and urban areas. It was found that the amount of electricity use related to household income level, occupation, family size and education level of the household responsible person.

The proportion of cold side vote increases as the indoor globe temperature decreases in each region. The mean comfort temperature was 17.2 °C, 20.9 °C and 21.7 °C in cold, temperate and sub-tropical regions, respectively. The comfort temperature has a large regional difference.

The average measured indoor air temperature were 10.9 ºC, 18 ºC and 20 ºC in cold, temperate and subtropical regions, respectively and they were 6.3 ºC, 2.9 ºC and 2 ºC lower

than average comfort temperature estimated. The results showed that the indoor globe temperature of the cold region was significantly lower than comfort temperature, and thus it needs to be increased to avoid the thermal discomfort. If we improve the thermal insulation and reduce the infiltration based on simple heat balance model, the indoor air temperature was found to be increased by 1.1 to 1.8 °C, which is speculated to be equivalent to 10 to 20% of energy saving.

In overall, we found that rural households use more firewood and the rate of electricity use in Nepal is one of the least in the world. The access to electric appliances is significantly low. In cold region, people are not satisfied in the present indoor thermal condition. The enhancement of thermal insulation and the reduction of infiltration was effective to increase the indoor air temperature in winter nighttime. The findings of this study might be useful for energy-saving building design and thereby hopefully help to provide a comfortable indoor thermal environment in Nepalese houses.

論　文　要　旨(和文)

報 告 番 号	甲 第号	氏　　名	サヒ ディネス クマル
論 文 主 題	Thermal improvement of Nepalese houses based on the evaluation of energy use and adaptive comfort (エネルギー使用と適応的快適性の評価に基づくネパールの住宅の温熱環境の改善)		

一定の生活水準を確保するためには、エネルギーの使用が必要である。家庭における合理的なエネルギー使用は、個人の生活環境を改善するだけでなく、国の経済成長にとっても重要である。現在のエネルギー政策のシナリオは、我々が現在のような生活を継続するならば、エネルギー需要は毎年 1.3%増加するといわれている。全世界のエネルギーの約 40%が建築部門で使用されており、人間の生活を損なわない合理的な政策を模索することが重要である。ネパールの家庭は他の国に比べてエネルギー使用量が少ない。居住者は薪燃焼など伝統的な方法に基づいて室内温熱環境を調整している。ネパールでは、これまでに多くの研究者が薪、化石燃料、バイオマス、電気、太陽光発電など全体的なエネルギー使用に関する研究を行ってきたが、特に家庭部門に関する研究は殆ど行ってない。一部の研究者は、現在の室内温熱環境、熱的快適性と温熱環境の改善のいずれかについて研究を行っているが、総合的に着目した研究がみられない。従って、エネルギー使用、居住者の熱的快適性、住宅の温熱環境の改善について研究を行う必要がある。

本研究の目的は、現在のエネルギー使用の実態把握、居住者の快適温度の解明、住宅の温熱環境の改善策を示すことである。そのため、ネパールの冷帯、温帯、亜熱帯地域における冬季に 442 世帯からデータを収集した。主な収集データは電気代、収入、家族の規模、電化製品の数、照明、調理器具、冷暖房のエネルギー使用量などである。室内の温熱環境は 3 つの気候地域で測定し、839 の温冷感申告を収集した。

データを分析した結果、薪の消費率は、農村地域で 2.08GJ /世帯/月であり、他の開発途上国より高い。ネパールの全地域の平均電力使用量は 2.06GJ /世帯/年であり、他の開発途上国や先進国より低い。電気は農村部では主に照明に使用されているが、都市部などでは電化製品にも使用されている。電気使用量は、家庭の代表者の社会的経済的な要因に関連していた。

各地域の室内グローブ温度が下がると、寒い側の申告の割合が増加する。平均快適温度は、冷帯、温帯、亜熱帯地域でそれぞれ 17.2° C、20.9° C、21.7° C であり、快適温度に地域差

が大きい。冷帯、温帯、亜熱帯地域の平均室温は 10.9ºC、18ºC、20ºC であり、平均快適温度よりもそれぞれ 6.3ºC、2.9ºC、2ºC 低かった。

冷帯地の室内グローブ温度は快適温度よりも低いことから、熱的快適性を実現するために気温を上げる必要がある。単純な熱収支モデルに基づいて断熱・気密化を行って室温を予測すると、室温が 1.1～1.8℃上昇することが分かった。これは 10～20％の省エネルギーに相当する。

以上のことから、農村部の世帯では多くの薪を使用しており、ネパールの電力使用率は世界で最も低いことが分かった。電化製品の利用もかなり低い実態が明らかになった。冷帯地の居住者現在の室温に満足していないことから、断熱・気密化は室温上昇に効果的である。本研究の成果は、ネパールの住宅で快適な室内熱環境を実現し、エネルギー消費の少ない住宅を設計するのに役立つと思われる。

Abbreviations

AC	:	Air Conditioning unit
AEPC	:	Alternative Energy Promotion Centre
ANSI	:	American National Standards Institute
ASHRAE	:	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	:	Carbon dioxide
DHM	:	Department of Hydrology and Meteorology
E	:	Energy
E_H	:	Education of Family Head
GDP	:	Gross Domestic Product
GHG	:	Green House Gas
GJ	:	Giga Joule
HRP	:	Household Responsible Person
HVAC	:	Heating, Ventilation, and Air Conditioning
I	:	Income
IEA	:	International Energy Agency
IEO	:	International Energy Outlook
I_H	:	Household Income

JICA	:	Japan International Cooperation Agency
kWh	:	Kilowatt Hour
LEAP	:	Long-range Energy Alternatives Planning System
LED	:	Light Emitting Diode
LPG	:	Liquefied Petroleum Gas
MARKAL	:	Market Allocation
MEAD	:	Model for Analysis of Energy Demand
mTSV	:	Modified Thermal Sensation Vote
MW	:	Mega Watt
N	:	Number
NEA	:	Nepal Electricity Authority
NOC	:	Nepal Oil Corporation
NRs	:	Nepalese Rupee
OECD	:	Organization for Economic Co-operation and Development
PJ	:	Petajoule
P_{LED}	:	Proportion of LED
PMV	:	Predictive Mean Vote
PPD	:	Predicted Percentage of Dissatisfied

PV	:	Photo Voltic
RH	:	Relative Humidity
SD	:	Standard Deviation
T_c	:	Thermal Comfort
T_g	:	Globe Temperature
T_i	:	Indoor Air Temperature
T_{mrt}	:	Mean Radiant Temperature
T_o	:	Outdoor Air Temperature
TP	:	Thermal Preference
TPES	:	Total Primary Energy Supply
UN	:	United nation
WECS	:	Water and Energy Commission Secretariat

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Chapter 1: Introduction

1.1 Overview

Nepal is a Himalayan landlocked country bounded by India to the east, south, and west and China to the north. The territory from east to west is roughly 800 kilometers and from north to south is 150 to 250 km. The total area of Nepal is 147,181 square kilometers. It lies between latitudes 26° and 31°N, and longitudes 80° and 89°E. Nepal is divided into three principal physiographic belts known as Himal-Pahad-Terai. “Himal” is the hilly region containing snow and situated in the Great Himalayan Range up the northern part of Nepal. The world highest mountain called Mount Everest (Sagarmatha in Nepali) lies in Himal on the border with China. Its altitude is 8,848.86 meters. “Pahad” is the mountain region that does not generally contain snow. The mountains vary from 800 to 4,000 meters in altitude, with progression from subtropical climates below 1,200 meters to alpine climates above 3,600 meters. The Lower Himalayan Range, reaching 1,500 to 3,000 meters, is the southern limit of this region, with subtropical river valleys. “Terai” is the lowland region containing some hill ranges. The plains were formed and are fed by three major Himalayan rivers: the Koshi, the Narayani, and the Karnali as well as smaller rivers rising below the permanent snowline. This region has subtropical to tropical climate. The altitude of Terai is 700 to 1,000 meters. Nepal has four seasons such as autumn (September to November), winter (December to February), spring (March to May) and monsoon (June to August). Nepalese climatic conditions vary from one place to another in accordance with its geographical features as shown in Fig. 1.1. Nepal is one of the least developed countries with 81% of its households residing in rural areas. The Gross Domestic Product (GDP) per capita in Nepal was last recorded at 1,071.05 US dollars in 2019 (World Bank, 2020).

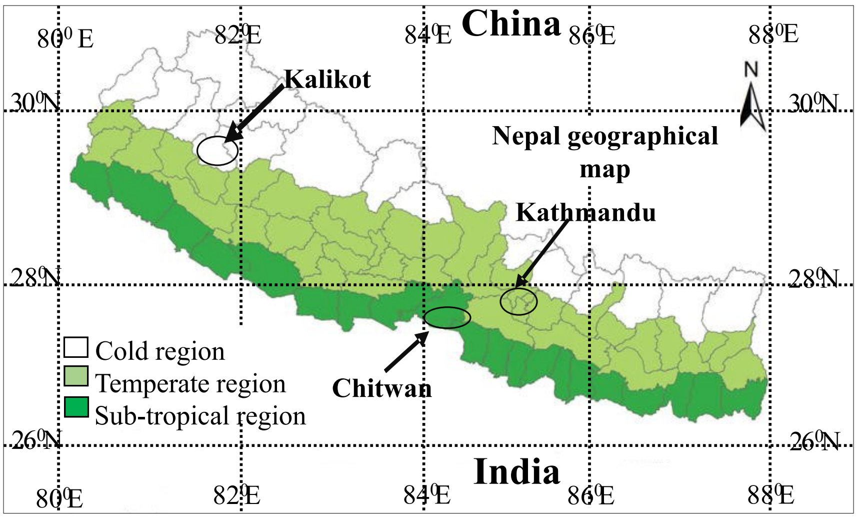


Fig. 1.1 Three regions focused in the research

1.2 Energy use situation

Energy is important for economic development, but it also plays a major role in improving conditions at the household level. Availability of energy source is one of the rational basic requirements for the quality of life and development of nation. It's also one of the basic factor, for the development of any civilized society and it is required to upgrade the quality of life style, socio-economic growth and human development of the country. The structure of energy use in rural and urban areas has a huge impact on the household income and on the well-being of residents (Wang and Jiang 2017). According to the United Nation (UN) the energy access as one of its sustainable development goals (SDG) to be achieved by 2030 (UN sustainable development). But in Nepal, many rural area have no access of electricity and the rate of electricity is very low compared to other developing countries (Shahi et al. 2020).

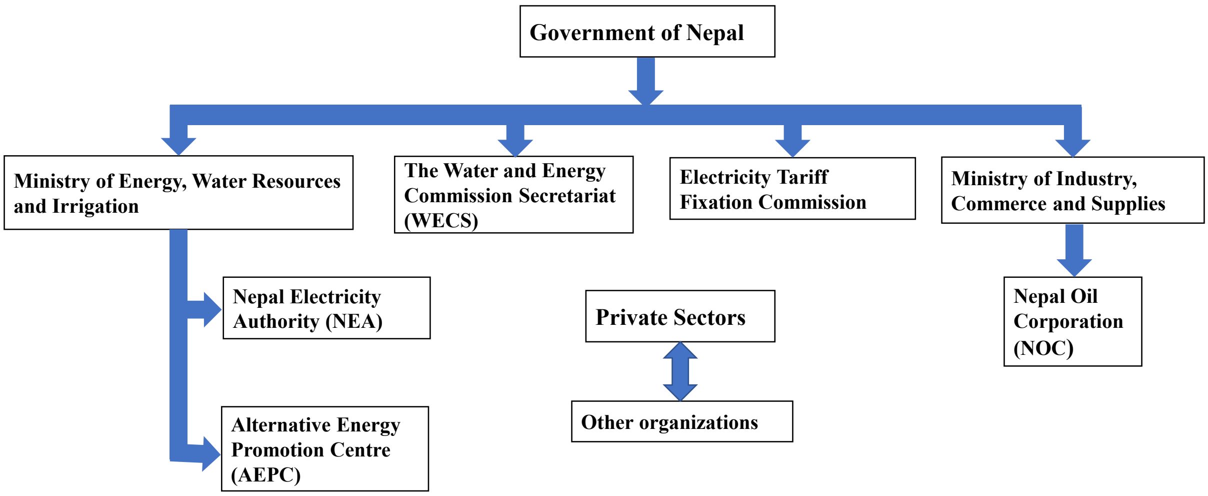


Fig. 1.2 Major stakeholders of energy sector in Nepal

As shown in Fig. 1.2, many stakeholders have been working on the energy production, supply and distribution in Nepal. Government and private sectors are the two key stakeholders in Nepal's energy sector. Mainly, the two ministries and the two committees are directly involved in the energy sector, including: (ministry of energy, water resources and irrigation) and (ministry of industry, commerce and supplies), (the water and energy commission secretariat) and (electricity tariff fixation commission). The main works of the Ministry of Energy, Water Resources and Irrigation are the management of energy resources, energy conservation, the formulation of plans and policies on the regulation and utilization of energy sources, the investigation and construction of multipurpose hydropower projects, the operation and maintenance, and the implementation of monitoring. It also supervises private hydropower companies. There are two other agencies, such as the Nepal Electricity Authority (NEA) and the Alternative Energy Promotion Center (AEPC). The major works of NEA is to establish a supply chain of electricity in overall Nepal, vertically integrated with the responsibility of generation, transmission and distribution and regulation to the private sector. The major works of the AEPC is the government agency promoting energy sources other than large-scale hydropower, the modernization of traditional energy, micro and mini-hydropower, solar and wind energy, and rural electrification. It supports the promotion of rural and less income people. The major fields of (Ministry of Industry, Commerce and Supply) are monitoring and supervision of the supply status of petroleum products and supervision of price fixing of petroleum products. The Nepal Oil Corporation (NOC) has a public enterprise under the supervision of Ministry of Industry, Commerce and Supply, that imports petroleum products, stores petroleum products, and fixes the prices of petroleum products. The petroleum sector in Nepal is a monopoly. NOC is a state-owned enterprise in charge of importing, storing and distributing all petroleum products in Nepal. These products and the liquefied petroleum gas (LPG) for cooking are imported from India. According to Khanal (2019), Nepal imported 2.07 million kL (kilo-liters) of petroleum in 2017/18, and the demand has been rising at a rate of 13.8% annually. The present storage capacity of 71,622 kL is just enough for 15 days (NOC, 2019). The water and energy commission secretariat makes the energy planning and policy designing and give guidance to line ministries on energy planning and policy designing. Accordingly, electricity tariff fixation commission fixes the tariff of electricity in Nepal.

According to Abid et al. (2019), In Nepal, energy policy formulation and regulation is a relatively centralized process, administered by the Ministry of Energy. Realizing the huge potential for hydropower, first hydropower development Policy was announced in the year 1992. Since then, the policy has been successful in attracting the private sector to hydropower development. However, many aspects, such as emerging international markets and their impact, the possibility of exporting hydropower, foreign investment and commitment to environmental protection are still unaddressed. It appears that the formulation of the Hydropower Policy 2001 was built on the lacunae of the earlier policy, incorporating all new criteria to make it more comprehensive and inclusive (and it remains relevant at the date of writing). Setting high goals for rural electrification, expanding grid-based electricity and developing hydropower as an exportable commodity, the policy also emphasized generating electricity at low cost by using the country's water resources. Learning lessons from previous policies, Nepal formulated Renewable Energy policies 2006 and 2009, Renewable Energy Subsidy Delivery Mechanism 2010 and Renewable Energy Subsidy Policy 2013. Subsidy mechanism and policy were designed with key objective of expanding the power sector in sustainable and environmental-friendly manner. Subsidy provision has promoted community participation, and tax-free incentives have helped micro-hydro technologies to develop into exemplars. However, there is still some room for improvement in the management of off-grid rural electrification from micro-hydropower.

1.2.1 Major energy sources

There are not any sources of fossil fuel, gas and coal reserves in Nepal. These energy sources were imported from India, they were difficult to reach in rural areas and very remote communities had no access to good transportation. As a result, most rural populations use biomass, imported kerosene, and or traditional water-powered vertical axis mills, so per capita energy use is very low compared to other areas of Nepal. In 2010, 12.5 million people lived without electricity and 76% relied on firewood for cooking (that is, 20.22 million stressed Nepalese forests due to fuel demand). Now days, access to electricity has improved significantly, but a few years ago, imbalances in electricity production, supply and demand resulted in load shedding occurred up to 18 hours per day. However, Nepal needs to improve the current energy situation in order to avoid these problems. Placing the emphasis on alternative energy sources, nationally improved cooking stoves, biogas digester, there is a large market of solar lantern.

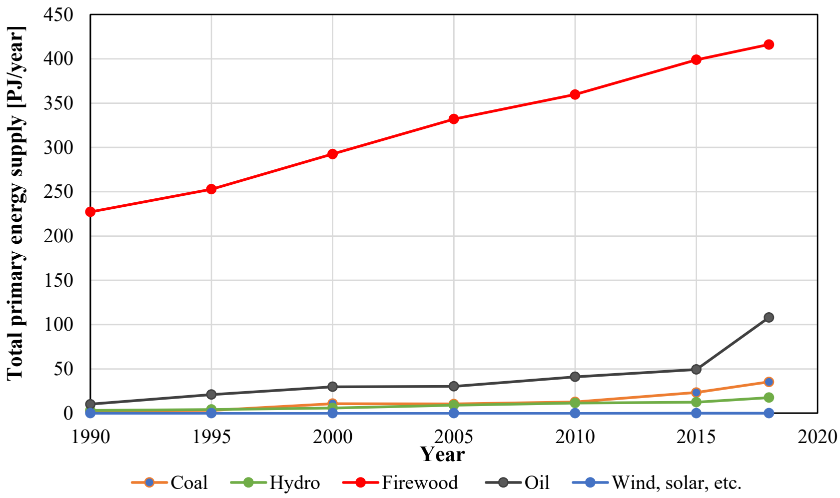


Fig. 1.3 Total primary energy supply in Nepal from 1990 to 2018 (IEA 2020)

According to IEA (2020) and World bank (2015) south Asian counties, about 80% of the rural population still depends on traditional energy resources such as biomass. Statistics of energy data from Bangladesh, India, Pakistan and Nepal also show that biofuels and waste contribute substantially to Total Primary Energy Supply (TPES) in these countries. According to Abid et al. (2019) biofuels and waste account for around one-quarter of primary energy supply in India and Bangladesh. In Pakistan, one-third of the TPES is contributed by this source. Nepal depends predominantly on biofuels and waste, which constitute 82% of TPES. Among other resources of TPES, natural gas contributes 56% in Bangladesh, and coal contributes 45% in India. Crude oil and oil products also contribute one-quarter to TPES in India. Pakistan depends heavily on natural gas, crude oil and oil products for more than half of its TPES. In all four countries, nuclear, geothermal and solar either has no contribution or has a very tiny share. Most importantly, hydropower contributes a very small share to their TPES. In Bangladesh, hydropower contributes the least (0.1%), and in Pakistan it contributes the most (3.1%). In India, it contributes 1.4%, to TPES. Fig. 1.3 shows the total primary energy supply from 1990 to 2018 in Nepal. The horizontal axis represents the years, the vertical axis shows the sources of energy supply in Nepal. Firewood is the highest sources of total primary energy sources. The other energy sources such as coal, hydro, fossil fuels and renewable have increased in recent years. Still, firewood is the main energy sources of total primary energy sources in Nepal.

Fig. 1.4 shows the total energy use percentage in sector-wise in Nepal. The horizontal axis shows a portion of energy use, and the vertical axis shows the energy use sector of Nepal. Over 80% of energy is used in the residential sector of total energy use. Energy use in the industrial and transportation sectors is used in less than 20%, the commercial and agricultural sectors use in less than 10%, and the rest is used in non-category sectors.

Fig. 1.5 shows the types of energy sources and the relative numbers of energy use in the residential sector in Nepal. The horizontal axis shows the relative energy use, and the vertical axis shows the energy use in the housing sector of Nepal. It shows that 84% of energy is used in the residential sector from firewood. Electricity, biogas solar cells, liquefied petroleum gas, kerosene, agricultural residues and animal waste are also used in the residential sector at 1.7%, 1.5%, 0.0003%, 1.9%, 0.4% and 4.4%, respectively. It shows that almost all energy is used from the traditional energy sources.

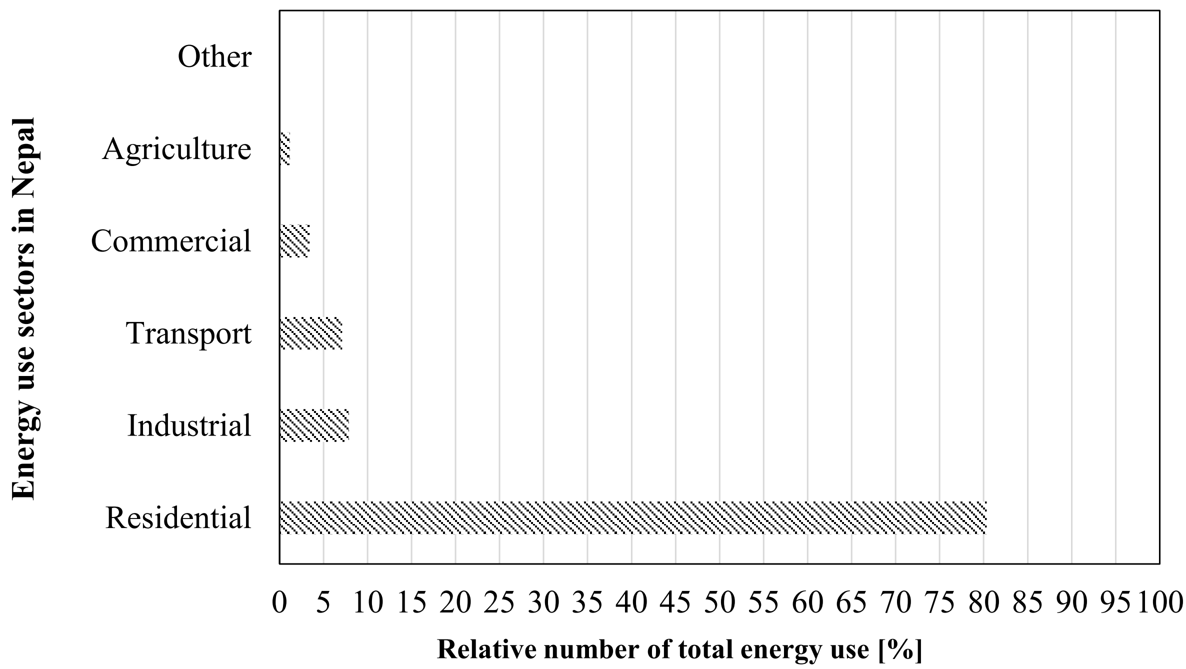


Fig. 1.4 Total energy use sectors in Nepal (WECS 2014)

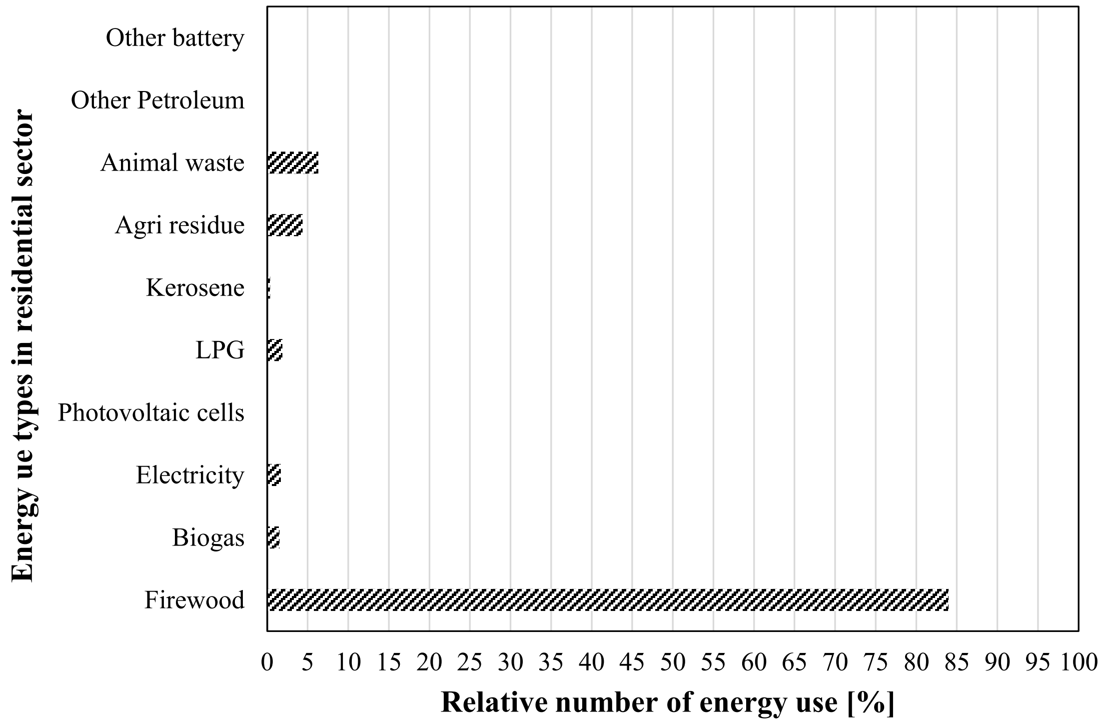


Fig. 1.5 Types of energy sources and relative number of energy use in residential sector in Nepal (WECS 2014)

1.2.2 Electricity production, supply and distribution

The history of electricity development in Nepal is not so old. The Pharping (500 kW) is the first hydropower plant, which was made in 1911. Currently, the total population with access to grid electricity reaches about 70% and 45% of the population has access to the National Grid (NEA 2019/2020).

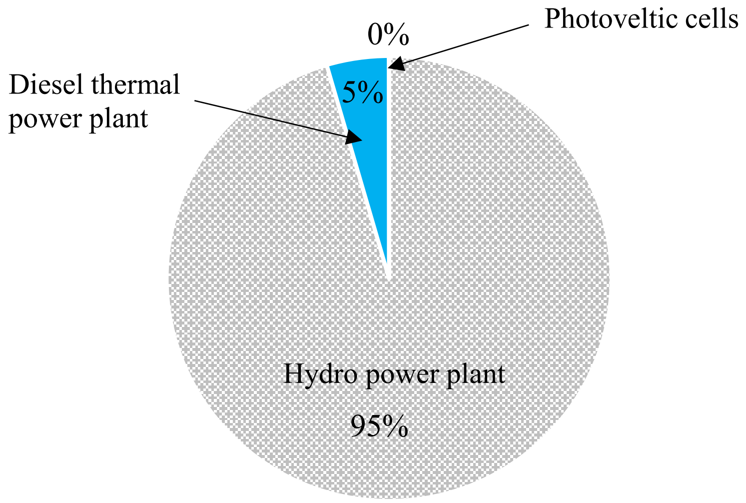


Fig. 1.6 Sources of electricity in Nepal (NEA 2018/19)

As shown in Fig. 1.6, hydropower is the main source of electricity in Nepal. The percentage of electricity generation from hydroelectric power plants, diesel thermal power plant and renewable energy sources are 95, 5 and 1, respectively. Nepal has large geographical variation, almost covered by mountains and hills, and the access of transportation and grid electricity is very limited. In such a case, government needs to focus on local energy sources such as; small water mills, micro hydro, PV cells and wind. But, still the electricity generation from renewable sources is very limited.

According to Toman & Timilsina (2015) and IEA (2014), South Asian countries have hydropower potential, but this electricity generation potential is unevenly distributed across countries and seasons. According to Abid et al. (2019), three countries (Pakistan, India and Nepal) have hydroelectricity potential of 333,000 MW. Out which, nearly 60% is commercially feasible. However, only one-third of commercially feasible potential has actually been harnessed so far. Pakistan has harnessed only tiny proportions of their commercially feasible hydropower potential, at 12%. India has done remarkably well with installed capacity by harnessing about 62% of feasible potential. If hydropower is developed sensibly, it can result in multiple benefits as a source of clean electricity, and also as a strategic approach of water management for irrigation, industry, flood control, and domestic uses. Electricity generated through hydropower has slightly increased in the last ten years but not sufficiently. The hydro potential in Nepal is 83,290 MW according to the theoretical prospective, the technical and economic potentials are 45,610 MW and 42,133 MW respectively as shown in Table 1.1 (K.C. et al. 2011). The electricity generated from large hydropower has increased from 645 MW in 2009/10 to 1128.71 MW in 2018/19 (Fig.1.7). Electricity generated from mini and micro hydropower has increased from 18 MW in 2009/10 to 33 MW in 2014/15 with a growth rate of 12.88 % as shown Fig. 1.8 (NEA 2016/2017). Nepal needs to focus more on the current energy situation and the potential for improvement in the production, supply and distribution sectors to achieve the United Nations Sustainable Development Goals.

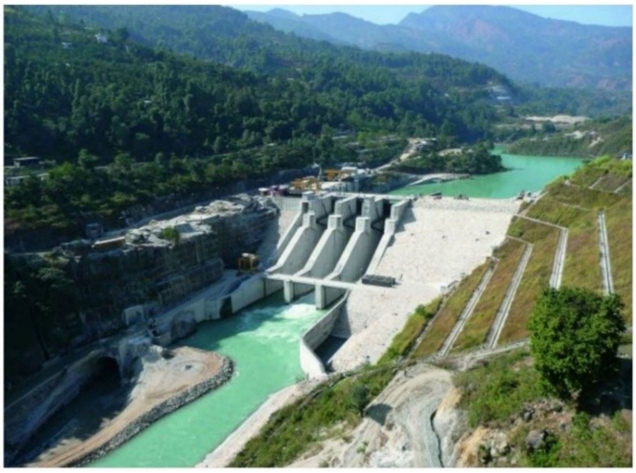


Fig. 1.7 Big hydroelectric power plant (Middle Marsyangdi, Udipur, Nepal) (Source: https://www.strabag-international.com)

Fig. 1.8 Micro hydro power plant (Potmara, Kalikot, Nepal)

Table 1.1 The hydro potential and major rivers in Nepal (K.C. et al. 2011).

River	Theoretical potential	Technical potential		Economic potential	
	(MW)	Number of projects	(MW)	Number of projects	(MW)
Sapta Koshi	22,350	53	11,400	40	10,860
Sapta Gandaki	20,650	18	6,660	12	5,270
Karnali and Mahakali	36,180	34	26,570	9	25,125
Southern Rivers	4,110	9	980	5	878
Total	83,290	114	45,610	66	42,133

The government has produced 563.39 MW electricity from large and small hydropower plants which are connected to national grid and 4.54 MW from small hydro power plant which are not connected to national grid as shown in Table 1.2 (NEA annual report 2018/19). The government has produced 5.341 MW from diesel power plant and 0.1 MW form photovoltaic cells. 560.77 MW electricity has been produced by private sectors which is named as Independent Power Producers (IPP). It is encouraging to note that, share of private producers are increasing in energy sector in Nepal. 957.1 MW is under construction through 7 hydroelectric power plants. 2285.2 MW electricity is planned to be generated constructing by hydroelectric power plants (NEA annual report 2018/19). AEPC had installed 33 MW micro hydropower plants and 7 MW capacity solar power plant up to 2014/15 (AEPC 2015/16). It is also helping to improve traditional energy-using technologies, such as installing biogas plants and improving cook stoves as shown in Fig. 1.9, Fig. 1.10 and Fig. 1.11.

Table 1.2 Hydropower plants situation in Nepal (NEA 2018/19)

S.N.	Large hydropower plantsb conneceted grid	Capacity (KW)	S.N.	Small hydropower plants not connected grid	Capacity (KW)
1	Kaligandaki A	144000	1	Dhankuta***	240
2	Middle Marsyandi	70000	2	Jhupra (Surkhet)***	345
3	Marsyandi	69000	3	Gorkhe (Illam)***	64
4	Trishuli	24000	4	Jumla**	200
5	Sunkoshi	10050	5	Dhanding***	32
6	Gandak	15000	6	Syangja***	80
7	Kulekhani I	60000	7	Helambu	50
8	Devighat	14100	8	Darchula**	300
9	Kulekhani II	32000	9	Chame**	45
10	Puwa Khola	6200	10	Taplejung**	125
11	Modi Khola	14800	11	Manag**	80
12	Chameliya	30000	12	Chaurjhari (Rukum)**	150
13	Upper Trishuli 3A HEP	60000	13	Syaprudaha (Rukum)**	200
Sub-total		549150	14	Bhojpur**	250
S.N.	Small hydropower plants		15	Bajura**	200
1	Sundarijal	640	16	Bajhang**	200
2	Panauti	2400	17	Arughat (Gorkha)	150
3	Fewa	1000	18	Okhaldhunga	125
4	Seti (Pokhara)	1500	19	Rupalgad (Dadeldhura)	100
5	Tatopani	2000	20	Achham	400
6	Chatara	3200	21	Dolpa	200
7	Tinau	1024	22	Kalokot	500
8	Pharping***	500	23	Heldung (Humla)	500
9	Jomsom**	240	Total		4536
10	Baglung***	200	S.N.	Thermal power plants	Capacity (KW)
11	Khandbari**	250	1	Duhabi Multifuel	39000
12	Phidim**	240	2	Hetauda Diesel	14410
13	Surnaiyagad	200	Total		53410
14	Doti***	200	S.N.	Solar Power Plants	Capacity (KW)
15	Ramechhap	150	1	Simikot	50
16	Terhathum**	100	2	Gamgadhi	50
17	Gamgad	400		Total	100
Sub total		14244			
Total		563394			

Total large hydro produced by government connecetd to grid	563394
Total small hydro produced by government not connected to grid	4536
Total hydro produced by government	567930
Total hydro produce by private sector	560775.4
Total hydro produced in Nepal	1128705
Total diesel thermal plant generated by government	53410
Total solar generated by (NEA)	100
Total installed capacity by government and private connected to grid	1177679.4
Total installed capacity in Nepal	**1182215**

Under construction		Capacity (KW)	Planned and proposed		Capacity (KW)
1	Upper Tamakoshi Hydropower Project	456000	1	Upper Arun HEP	1061000
2	Tanahu Hydropower Project	140000	2	Upper Modi A HEP	42000
3	Kulekhani III HEP	14000	3	Upper Modi HEP	18200
4	Rahuganga HEP	40000	4	Dudhkoshi Storage HEP	635000
5	Upper Sanjen	14600	5	Tamor Storage HEP	762000
6	Sanjen	42500	6	Uttar Ganga Storage HEP	828000
7	Rasuwagadi	111000	7	Tamakoshi V HEP	95000
8	Madhya Bhotekoshi	102000	8	Aandhikhola Storage HEP	180000
9	Upper Trishuli 3B	37000	9	Chainpur Seti HEP	210000
			10	Begnas Rupa Pump Storage HEP	150000
	Total	**957100**			**2285200**

** Leased to private sector, *** Not normal operation

Fig. 1.9 Using firewood from modified cook stove in rural area of Nepal

Fig. 1.10 Using firewood from traditional cook stove in rural area of Nepal

Fig. 1.11 Making bio gas from bio gas plant in Nepal (Source: Alternative Bio-Energy Pvt. Ltd)

Fig. 1.12 shows the electricity use percentage by sector wise. Domestic, commercial, non-commercial, and industrial users accounts 93%, 1%, 1% and 1%, respectively. It shows the household is the main electricity use sector in Nepal. So, it is very important to seek the electricity use patterns in household sectors, such as; rate of electricity use, electricity use for heating, cooling, cooking and lighting, access of electricity appliances and the factors affecting the energy use in Nepal. Table 1.3 shows the electricity prices of domestic users in Nepal. Charges fall into single-phase, two-phase, and three-phase categories. Energy charges are categorized by two types: minimum service charges and energy charges, it depends on phase, ampere, and energy used per month. For domestic users, the minimum service charge starts from NRs 30 and the minimum energy charge starts from NRs 3 up to 20 kWh electricity use. The highest service charge is NRs 10,000 and the maximum energy charge is NRs. 13.50 and above for 1000 kWh. Electricity is priced at $0.90/kWh for end-users in 2018 which is among the highest in the world. Such high electricity costs in developing countries required financial subsidies (Poudyal et al. 2019).

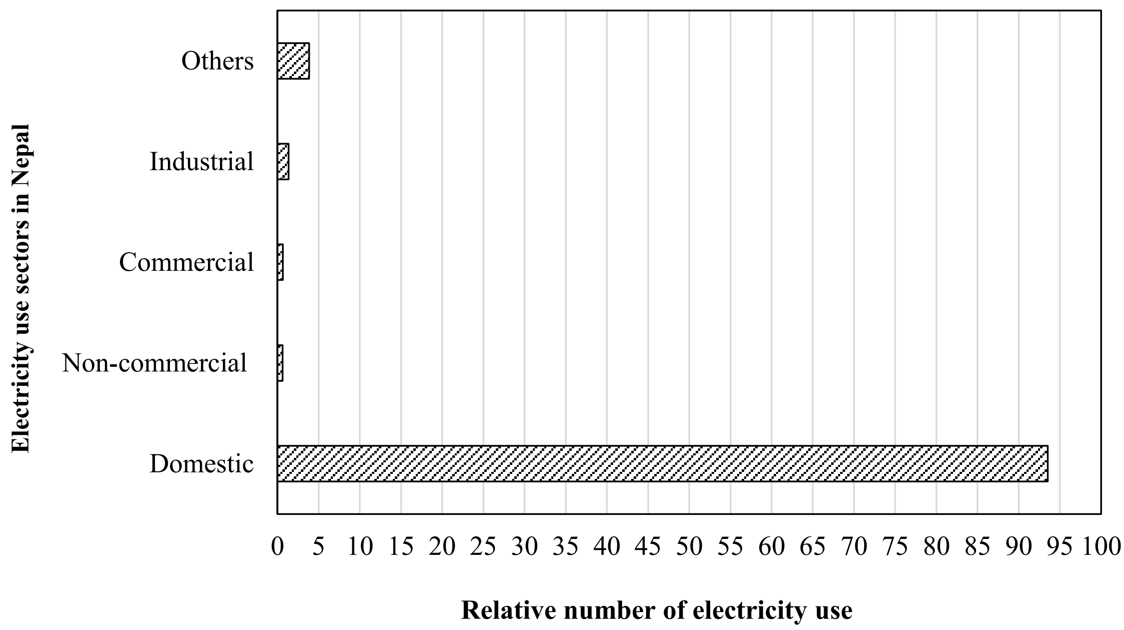


Fig. 1.12 Sector wise electricity use in Nepal (NEA 2019/20)

Table 1.3 Electricity tariff for domestic users in Nepal (NEA 2019/20)

Single phase

Energy (kWh/month)	5 Ampere		15 Ampere		30 Ampere		60 Ampere	
	Minimum charge	Energy charge	Minimum charge	Energy charge	Minimum charge	Energy charge	Minimum charge	Energy charge
0-20	30	3	50	4	75	5	125	6
21-30	50	7	75	7	100	7	150	7
31-50	75	8.5	100	8.5	125	8.5	175	8.5
51-150	100	10	125	10	150	10	200	10
151-250	125	11	150	11	175	11	225	11
251-400	150	12	175	12	200	12	250	12
Above 400	175	13	200	13	225	13	275	13

Three phase, Low voltage (230/400V)

Energy (kWh/month)	Up to 10 KVA		Above 10 KVA	
	Minimum charge	Energy charge	Minimum charge	Energy charge
Up to 400	1100	12.5	1800	12.5
Above 400	1100	13.5	1800	13.5

Three phase, Medium voltage (33/11 KV)

Energy (kWh/month)	Above 10 KVA	
	Minimum charge	Energy charge
Up to 1000	10000	11
1001-2000	10000	12
Above 2001	10000	13

1.3 Thermal environmental

Nepal is one of the least developed countries in the world. Natural resources such as land and forests are open access as the primary livelihood for most people. In Nepal, the household sector is the main energy use sector. Also, as shown in Fig. 1.5, the use of firewood at home accounts for the majority. Socio-economic factors are closely linked to environmental degradation, and the loss of various lives can lead to the disruption of the functioning of a declining ecosystem. Lower income people have no choice but to engage in the unsustainable use of natural resources. Government of Nepal, Multidimensional poverty index, 2018 shows that 28.6% of Nepal's population is multidimensionally poor. The indicators that contribute most to multidimensional poverty in Nepal are undernutrition and households that lack any member who has completed five years of schooling. 7% of the urban population and 33% of the rural population are multidimensionally poor in Nepal. Most of the people in poor groups collect and sell forest products to daily survive as shown in Fig. 1.13. In efforts to increase production, poor farmers expand cultivation into highlands that are not suitable for agriculture.

Fig. 1.13 Selling firewood in local market from local people

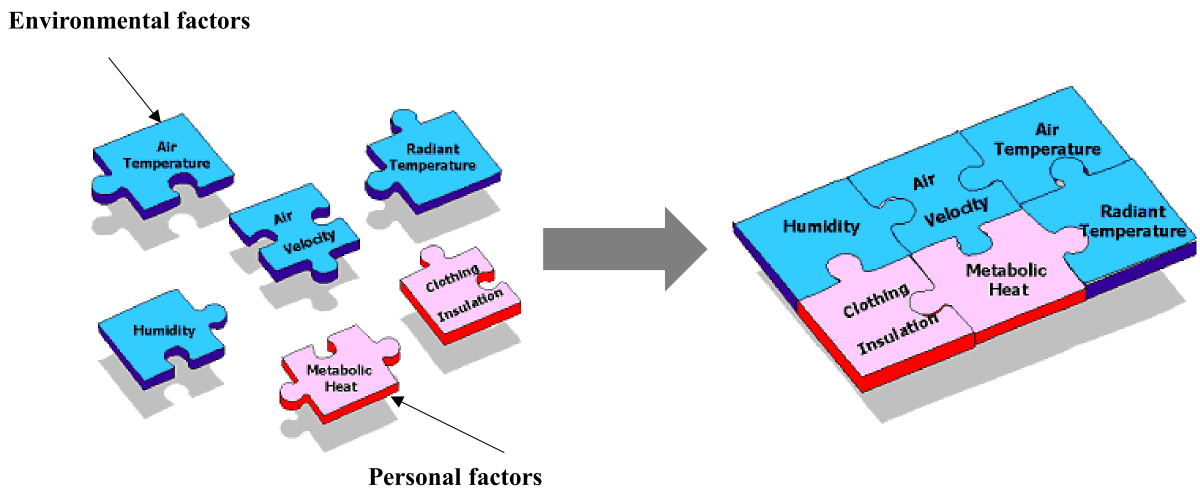
The result is accelerated soil erosion, land degradation, declining productivity of farmland and sedimentation in downstream areas. On the other hand, the hydroelectric dams are under construction in Nepal, not only Nepal mainly in developing countries. These enormous structures are one of the world's largest sources of renewable energy, but they also cause environmental problems. Hydropower dams degrade water quality along rivers and can cause soil erosion. The firewood collection, grazing, deforestation, hydropower plant construction, low level of public awareness, lack of research and development, lack of integrated land and water use planning and inadequate policies and strategies for environmental protection are the major reasons for environmental degradation (Chhetri and Shakya 2016).

1.4 Thermal comfort

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55). However, academic researchers are arguing whether thermal comfort is associated with well-being, productivity, and human health. Although it is a big public debate, concrete evidence shows that the aforementioned aspects of human "mortality" is inherent in thermal comfort (Ramsey et al. 1983). The human body functions as a system of machines where food is fed as a fuel. It tries to maintain a core body temperature of 37 °C so that heat transfer is proportional to the temperature difference. In a cold climatic environment, human body loses more heat to the surrounding environment, and in a hot environment, the body does not produce enough heat. In general, we eat more food in the cold season and less in the hot season. Our bodies feel uncomfortable when the surrounding temperature is either hot or cold.

1.4.1 Factors affecting thermal comfort

The thermal balance of the body is of great importance in thermal comfort, and this balance is affected by several parameters. According to the (ASHRAE 2013, Fanger 1970) the factors are categorized into two groups such as: personal and environmental factors. These experiments were conducted in a closed room for students, given a 7-point thermal comfort scale, and so called the Predicted Mean Voter - Percentage Predicted Dissatisfaction (PMV-PPD) model. The environmental factors are air temperature, mean radiation temperature, relative humidity and air velocity. And, clothing and the level of activity as shown in Fig. 1.14.



1.14 Environmental and personal factors that affect the thermal comfort (Source: Healthy and safety accusative, https://www.hse.gov.uk/temperature/thermal/factors.htm).

(a) Environmental factors

According to the (Fanger 1970, McIntyre 2002 and Li 2007) the environmental factors are as follows:

1. Air velocity (*V*): As long as the temperature is lower than the temperature of the skin, thermal comfort effect due to the convection process from the skin. There are some conditions such as: moving air in warm or humid conditions can increase heat loss through convection without any change in air temperature. People's physical activity also increases the movement of air, so air velocity can be changed to the active level of physical activity. Small air movements in cool or cold environments can be perceived as drafts, as people are particularly sensitive to these movements.

2. Mean radiant temperature (T_{mrt}): The mean radiant temperature affects the exchange of radiant heat with the body in all surroundings. The mean radiant temperature determines how much the human body loses or gains from radiation to the surrounding surface.

3. Air temperature (T_i): This is the temperature of the air surrounding the body. In most situations, this is the most important parameter that directly affects the heat exchange between the environment and the occupants. The air temperature at which the human body is exposed determines the amount of heat lost by convection or conduction, primarily during contact from the surface of the body. This gives a person a sense of warmth and coolness.

4. Relative humidity (*RH*): Relative humidity is the ratio between the vapor pressure of the water in the air to that at the air-water interface at that temperature. According to the ASHRAE guidelines recommend a relative humidity is better between (*RH*) of 30 to 60 percent in the indoor environment. When the relative humidity is low, the mucous membrane becomes dry and feels dry. However, at the high relative humidity the rate of evaporation of sweet from the skin decrease and thus the person feel sticky apart for impediment to the essential process of losing heat from the human body.

(b) Personal factors

According to (Fanger 1970, McIntyre 2002 and Li 2007) the personal factors, which can be controlled to some extent by occupant:

1. Activity level or metabolic rate (*met*): The more physical work we do, the more heat we produce. The more heat we produce, the more heat needs to be lost so we don't overheat. The internal metabolic heat production of the body is dependent of activity level of people. It needs to dissipate from the human body. The metabolic activity determines the rate of heat produced in the body and thus it affects the thermal comfort. As the human body begins to shake in the cold climate and its metabolic rate rises, it is

common for more heat to be generated and balanced with the heat lost from the human body. Similarly, in warm and humid climates, people often take afternoon siesta, resulting in less heat generated in the body and less heat lost due to higher environmental temperatures. This balance between the heat lost from the human body and the heat generated in the human body is essential to keep the temperature in the center of the human body constant.

2. Clothing insulation (*clo*): Various types of clothing insulation affect heat exchange by convection between the environment and the body surface. Increasing the insulation of clothing slows the heat loss from the human body, which is comfortable in cold climates and uncomfortable in warm climates.

1.4.2 Models of thermal comfort

Generally, in HVAC buildings, the temperature is fixed at a comfortable point in terms of outdoor conditions. It was called the "set point" temperature. If we set the temperature in this way then the energy use increases for heating and cooling, and increases the size of the electrical appliances that needs to be installed. Then, the initial investment increases and the running cost arising such as utility fees and maintenance change. In addition, such type of power plants are costly and they necessarily cause environmental problems to be avoided. The indoor thermal environment improvement by improving the building envelope system is very important, since it could be realized without energy use. Generally, two methods are used for the thermal comfort such as; Predict Mean Vote - Percentage Predicted Dissatisfied (PMV-PPD) and adaptive thermal comfort models.

(a) Predicted Mean Vote- Percentage Predicted Dissatisfied (PMV-PPD) Model

According to Fanger in 1970s, obtained a thermal index and it possible to predict the thermal sensation for the combination of personal factors; activity level, clothing and environmental factors; air temperature, mean radiant temperature, air velocity and humidity. In his experiment, subjects were placed under control in a climate chamber equipped with equipment to measure the temperature of various parts of the body. The activity and clothing levels were observed and thermal sensation votes were recorded with the use seven points scales shown in Fig. 1.15. The scale ranging from -3 (cold) to +3 (hot) with 0 (as neutral) and it is known as the predicted mean vote (PMV) model. Furthermore, ASHRAE Standard 55 and ISO 7730s standards are based on the Fanger PMV - PPD model.

Fig. 1.15 Fanger's seven point thermal sensation scale (Source: http://danieloverbey.blogspot.com/2013/02/evaluating-human-thermal-comfort.html)

The equation of predicted mean vote (*PMV*) is given by as follows:

$$PMV = (0.303e^{-0.036Met} + 0.028)L_t \tag{1.1}$$

where, *Met* is the metabolic rate and L_t is the thermal load which is difference between the internal heat production and the actual heat lost to the environment.

British Standards Institute determined in 1995, the a correlation between the *PMV* and the predicted percentage of dissatisfied people (*PPD*) in a given indoor environment. The equation was derived as follows:

$$PPD\ = 100 - 95e^{(-0.03353PMV^4 - 0.2179PMV^2)} \tag{1.2}$$

The dissatisfaction rate (*PPD*) obtained from equation (1.2) above varies between 5% and 100% when the predicted average varies between 0 and ± 3. Therefore, even in neutral thermal conditions (PMV = 0), at least 5% of people are dissatisfied. Respondents cannot meet 100 % satisfy this method.

The PMV-PPD model was the first model to combine environmental and personal factors. This model has some limitations, including: this model determines thermal sensation through a laboratory-type it called "chamber methodology". It does not include cultural, climate and social contextual dimension of comfort in the engineering approach. High levels of dissatisfaction also occur in air-conditioned office buildings. This is not related to the "current research methods" of comfort standards, but to expectations, "cultural and clothing norms". According to (Singh et al. 2011) adaptive model is more appropriate compared to PMV-PPD method as this model considers the local climate, culture and social setup, behavior and lifestyle etc.

According to Nicol and Humphreys (2002), the PMV-PPD model cannot handle the various adaptive approaches that residents may take to make them more comfortable. They developed the adaptive thermal comfort model.

(b) Adaptive thermal comfort model

According to Nicol and Humphreys (2002), thermal comfort cannot determine only through the four environmental and two personal factors. They was influenced by people perception, expectations, past history, opportunities to change clothing level and adjust the current environment oneself, etc. Every people have a natural behaviors to adapt to changing conditions in their surrounding environment. If people feel discomfort, people react in many ways which helps to restore their thermal comfort, for e.g., changing the level of clothing, changing position to increase or decrease the surface area to lose body heat, open or close the windows or switching "on" or "off" of fans, reducing and increase the activity level, drink water etc. Such types of activities makes oneself comfortable is expressed in the adaptive approach to thermal comfort. Basically, adaptive thermal comfort is introduced and influenced by three physiological, psychological and physical factors.

Behavioral adaptation

In this type of adaptation, every action a person takes consciously or unconsciously that affects the heat and mass flux that governs the human body. Basically, behavioral adaptation can be divided into three levels. First one is the individual level, at the level, the people take actions with respect to individual variables, such as changing clothing levels, changing activity levels, changing posture, eating, drinking, and moving to another location. The second one is the technological level, at the level, the surrounding environment changes depending on the opening and closing the windows and doors, and the on/off of fans etc. The third is cultural adjustments, this includes scheduling activities according to socio-cultural priorities and traditional manners such as post-lunch siesta and dressing according to social norms and value.

Physiological adaptation

This is the type of change that would result from long-term exposure to a particular thermal environment factor and as a result, makes the occupant habituated. They are either (i) generic, which is a slow process and extends beyond the life of the individual; or (ii) acclimatization, which is obtained in a short period of time by constant exposure.

Psychological adaptation

They are the effects of cognitive and cultural variables on an individual's warmth and coldness, and how much their perceptions and expectations of the thermal environment change. These are expectation and preferences.

We can improve the indoor thermal comfort thought two ways one is active system and other way is passive system. The question arise how the indoor thermal environment to be obtained by rationalizing the range of air temperature, radiant temperature and others by either passive or active systems. Passive systems are working as non-mechanical system through the improvement of building envelopes. In order to improve the overall thermal environment indoors, it is necessary to improve the thermal performance of windows, walls, roof and floor. Active systems function to maintain the thermal environment by the use of biomass, electricity from fossil fuels, hydro, photovoltaic cell and wind turbine through mechanical devices. Using fossil fuels and biomass mainly to maintain the indoor thermal environment leads to a variety of environmental problems locally and globally.

1.5 Rational for this research

There are some possible factors which are also responsible for energy use in rural and urban areas such as different tariff, household income, family size, occupation, using different electrical appliances, housing structure, location or climate, demographic characteristics and variation in the intensity of use of electricity using devices (Petersen 1992). The demand of the electricity is different in rural to urban because in rural areas people depend on fuel wood, charcoal, kerosene to meet their energy requirement and use small amount of electricity for lighting (Sinha and Biswas 2009). Biomass-based fuels are being steadily replaced with modern fossil fuels and electricity in developing countries (Alam at al. 1998). The income level and access of energy of households also effects to the choice of energy. Income is an important factor determining the choice of fuel preferences at household level (Joon et al. 2009). The patterns of electricity use changes when there is change in income level (Khandker et al. 2010). In developing countries, access and use of energy is essential to reduce poverty. The household's choice of cleaner fuels for lighting, cooking, and heating is driven by level of income, age, education and gender of household, access to electricity and location. Households with a better-education, those with a higher level of income, and urban households, have a higher probability of using of clean energy, while poor households and those with a low level of education are constrained by these factors to continue using traditional energy (Rahut et al. 2014). The previous researches (Mullaly 1998, Jaber 2002, Westergren 1999, Chen 2006, Pachauri and Jiang 2008, Zhang et al. 2009 and Petersen 1982) have focused on household energy use, household size, income, access of electricity, climate, energy price, and ownership of appliances in developed countries and other developing countries. Nepal has its own unique climatic regions, income levels, lifestyle and occupants' behaviors that are different from other developing countries as they have their own unique cultures as well.

Energy use is required for securing a certain living standard. The rationality of household energy use is not only for improving individual living conditions, but also for the economic growth of a nation. The current energy-policy scenario shows that if the humans continue taking the present path without any change, the energy demand would rise by 1.3% each year. Since, approximately 40% of total global energy is used in building sector, and it is important to seek a rational path that does not sacrifice human well-being. Nepalese households have been so far using energy at almost the least rate among other countries. Residents are adjusting their indoor environment relying on very primitive methods. In the context of Nepal, the researchers have so far conducted researches on overall energy sectors such as firewood, fossil fuels, biomass, electricity, and solar PV system. But no any study has focused yet on household sector in particular. Some researchers have focused, either, on current indoor thermal condition and or, on the improvement, but not on both. Therefore, this study focus on thermal comfort condition of residents in houses in winter, and thermal performance improvement of these houses.1.6 Research questions

1. What are the major energy resources and its rate of energy use, access of electric appliances and the relationship between energy use and social economic factors ?
2. What are the average indoor globe temperature and comfort temperature and is there any regional differences of comfort temperature in cold, temperate and sub-tropical regions ?
3. How is variation of indoor temperature, relative humidity, CO_2 emission of houses in the three regions ?
4. Are thermal insulation and the reduction of infiltration the effective way to increase the indoor air temperature during nighttime ?

1.7 Research objectives

1. To estimate the rate of electricity use and the current situation of energy use, the availability of energy resources (firewood, electricity, LPG and solar PV), and the use of electric appliances.
2. To analyze the relationship between energy use and social economic factors such as, household income, household size, the use of light emitting diode (LED) and the educational level of household responsible person.
3. To estimate the comfort temperature of residents in each region.
4. To know the effect of regional difference on comfort temperature.
5. To evaluate the thermal performance of the houses.
6. To examine a possible improvement of the houses that allows the residents to have better indoor thermal environment during night time.

1.8 Thesis structure and outline of thesis

Chapter 1: Introduction

Geographical variations, environmental and general information about Nepal are presented at the beginning of this chapter. Information about energy situation, the environmental issues and introduction about thermal comfort is provided in second parts. The necessity of this research, research question and purpose of this study is shown in the last part of this chapter.

Chapter 2: Literature review

The first part is introduces a literature review. Second part, I reviewed papers on energy use in the world and Nepal. In last section, reviews the literatures on thermal comfort, thermal environment, and thermal improvement in world as well as Nepal.

Chapter 3: Methodology

In first part presents the general information about the study area. Information on climatic conditions, home structure, lifestyle and socio-economic conditions is describes as cold, temperate and subtropical regions. The reasons for the selected survey area, the questionnaire format of the survey, the data collection procedure, information on the equipment used give in the last section.

Chapter 4: Energy use patterns in Nepal

We try to clarify the household energy use patterns and mainly focus on electricity use in rural, semi-urban and urban areas in Nepal. We estimate the current situation of energy use, the availability of energy resources (firewood, electricity, LPG and solar PV), and the use of electric appliances. We analyze the relationship between energy use and social-economic factors such as household income, household size, the use of light-emitting diode (LED) and the educational level of household responsible persons.

Chapter 5: Thermal comfort

We estimate the comfort temperature of people residing in cold, temperate and sub-tropical regions. We compare the comfort temperature of this study with other studies. We also try to find the "comfort zone" and "discomfort zone" of people. We estimate the preferred temperature of the residents and its compare to comfort temperature in all regions.

Chapter 6: Thermal environment

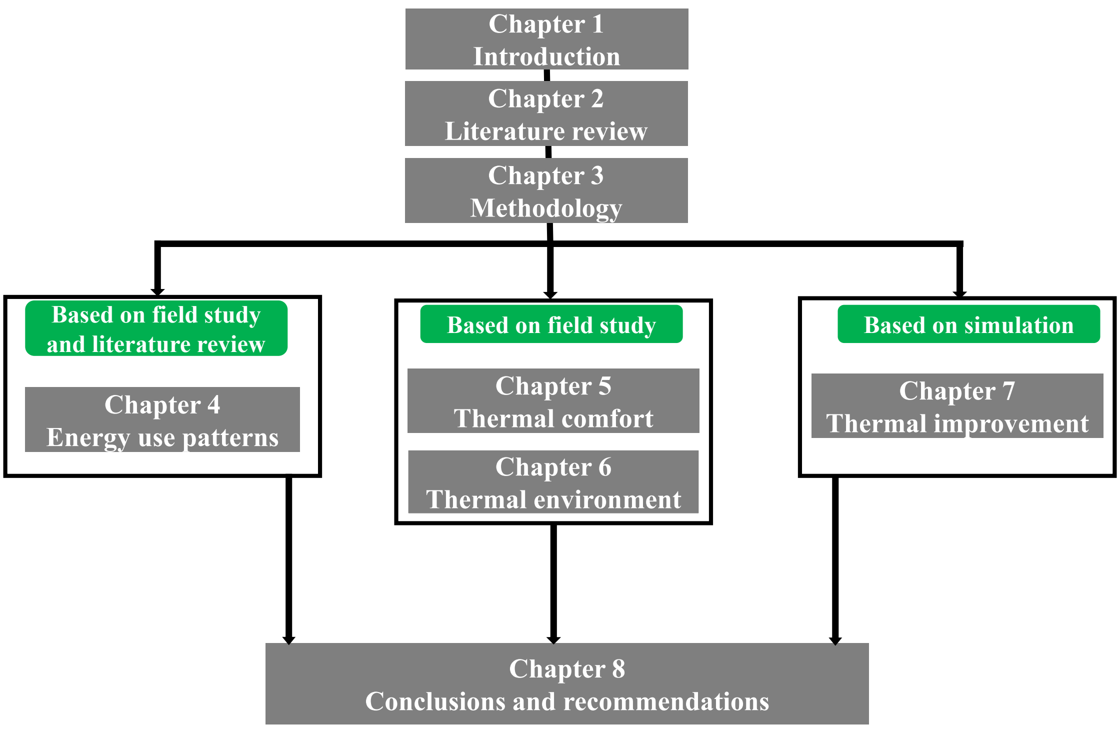
We present the wintry indoor thermal environment of houses in the three investigated area such as cold, temperate and sub-tropical regions. We discuss the wintry thermal environment, relative humidity, CO_2 concentration, indoor and outdoor air temperature of three regions.

Chapter 7: Thermal improvement

First we evaluate the thermal performance of the houses. Then we examine a possible improvement of the houses that allows the residents to have better indoor thermal environment during night time. We assessed the possibility of improvement of houses, we use simplified mathematical modeling for the calculation of indoor air temperature. In order to clarify how much effective the enchainment of thermal insulations would be rather than merely installing mechanical heating systems. We first analyzed the actual indoor air temperature based on measured data and then we estimated the indoor air temperature based on theoretical base model. By improving the thermal insulation in building walls and reducing the infiltration, we should be able to increase the indoor air temperature and also internal surface temperature.

Chapter 8: Conclusions and Recommendations

The results of the above chapters summarize and give the further recommendations to Nepalese government and other developing counties.



1.15 Structure of thesis

Chapter 2: Literature review

Preface: A literature review is needed to find the research gap between current and past research. For this purpose, it is very important to know the national and international researches and to identify the actual problem in depth in this fields. This chapter presents a categorical review of the previous researches identified after being conducted during the study.

2.1 Introduction

Energy use is required for securing a certain living standard. Availability of energy sources, electricity in particular, is the basic requirement for the quality of living. The rationality of household energy use is not only for improving individual living conditions, but also for the economic growth of a nation. The current energy-policy scenario shows that if the humans continue taking the present path without any change, the energy demand would rise by 1.3% each year. Since, approximately 40% of total global energy is used in building sector, it is important to seek a rational path that does not sacrifices human well-being. Global energy use is projected to increase by 60% by 2030, with developing countries accounting for two-thirds of this growth (Schröder at al. 2011). The energy use, the building sector contributes as much as one third of greenhouse gas emissions, primarily through the use of fossil fuels during, 80% of which is used during building operation, heating, cooling and lighting, etc. (Mardiana et al. 2015). Human being spends a large portion of time indoors. A good indoor environment thus, necessary for the buildings, which not only occupants thermal comfortable to love. Thermal comfort is one of the most important parameters when designing buildings (Douvlou 2003). Therefore, it is important to reduce the energy use in the building by achieving thermal comfort in the most natural way possible and incorporating energy efficient strategies into the thermal improvement (Aldawoud 2013).

2.2 Energy use patterns

2.2.1 General trends of energy production and distribution in world

Globally, 1.06 billion people do not have access to electricity and more than 3 billion still use fuels like wood, charcoal, coal and dung for cooking and heating (IEO 2017). The world energy use increases by 28% in the IEO 2017 reference case, with more than half of the increase attributed to non-OECD Asia (including China and India) in between 2015 and 2040. Energy use in non-OECD countries will increased 41% between 2015 and 2040 in contrast to a 9% increase in OECD countries. Most of the increase occurs in large, emerging non-OECD countries, where population continues to shift from rural to urban areas. Energy is one of the main sources of sustainable economic growth and basic requirement of human development. Non-OECD countries for the increasing the demand of appliances, personal equipment, and commercial services. (IEA 2011). According to the (IEA 2019), the major energy supply by sources in the world are coal, crude oil, oil products, natural gas, wind, solar, biofuels and waste, hydroelectricity, thermal energy (heat).

Fig. 2.1 shows the major energy supply by sources in the world from 1990 to 2018. Oil products, electricity, natural gas, biofuels and waste, coal, heat from thermal and crude oil are shared 40.4%, 19.2%, 16.1%, 10.1%, 10%, 9%, 1%, 0.5% and 0.1% respectively. Supply from renewable sources is increased by 125.7% in 2018 than in 2010. Electricity is increased by 24.8% in 2018 than in 2010 but coal and crude oil are decreased in 2018 than in 2010. The increased rate of oil products and heat from thermal, natural gas and biofuel is very small compared to renewable energy and electricity sources in the world. It indicates that the energy supply from renewable energy is increased in the world.

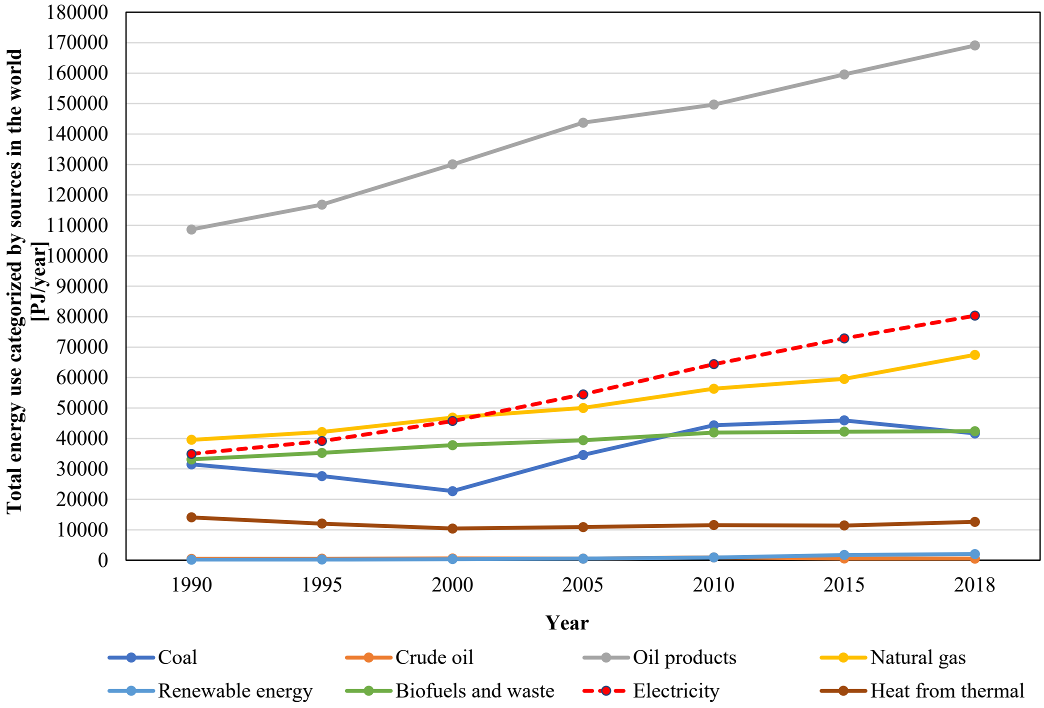


Fig. 2.1 Major energy supply by sources in the world from 1990 to 2018 (IEA 2019).

Fig. 2.2 shows the share of total energy use by sector wise in the world (IEA, world energy balance 2019). The horizontal axis shows the year and the vertical axis shows the total energy use by sector wise in the world. Industry, transport, residential, commercial and agriculture are categorized. The industry, transport, residential, commercial and agriculture are shared 28.4%, 28.9%, 21.1%, 8.1% and 2.2% of the total energy use in the world. Energy use has increased in the all sectors in 2018 rather than 2010. (Nejat et al. 2016) claimed that the building sector, which accounts for 27% and 17% of global energy use and CO_2 emissions, respectively, plays a significant role in mitigating global climate change. Ten countries, including China, the United States, India, Russia, Japan, Germany, South Korea, Canada, Iran and the United Kingdom, account for two-thirds of global CO_2 emissions. Therefore, the energy use and GHG emissions of building in these countries have a direct and significant impact on the global environment. The current trends of energy use, CO_2 emissions and energy policies in the residential sector, both globally and in those ten countries. Global residential energy use increased by 14% from 2000 to 2011. Most of this increase is occurring in developing countries, where population, urbanization and economic growth are the main reasons.

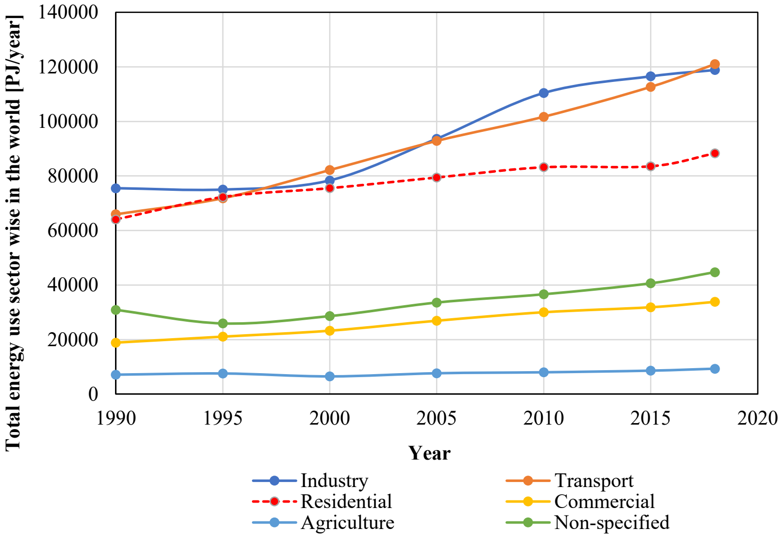


Fig. 2.2 Total energy use by sector wise in the world from 1990 to 2018 (IEA 2019).

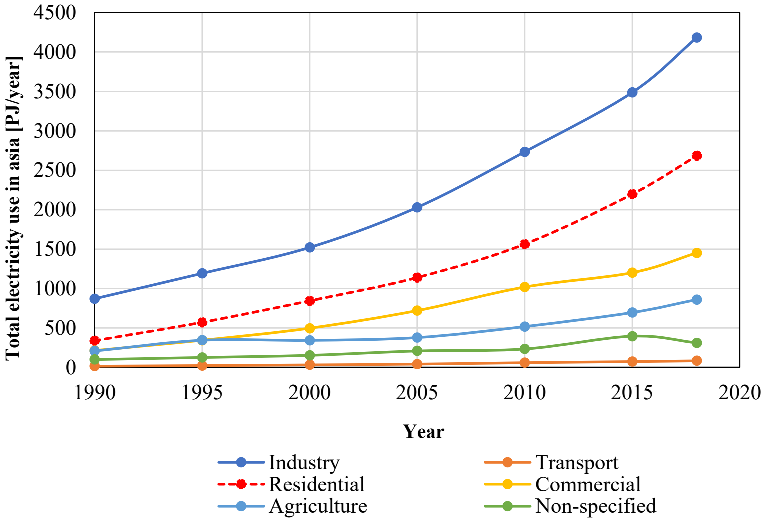


Fig. 2.3 Total electricity use in Asia by sector wise from 1990 to 2018 (IEA 2019).

Fig. 2.3 shows the electricity usage of Asian countries by sector. The total electricity use of Asian countries is 11591.87 PJ per year which is increased by 42% in 2018 rather than in 2010. Energy use in the industrial, residential, commercial, agricultural and transport sectors is 36%, 23%, 13%, 7% and 1%, respectively. The energy use in building sector will increase by 2% annually between 2015 and 2040 as rising the standards but electricity usage in the residential sector is growing rapidly, at 72% in 2018 than of 2010 in Asian countries. This trend is the opposite in the world due to the Asian country are rapidly developing.

Most of the developed and developing countries follow the conventional path of development that a developing country follows to become a developed country. Most of the developed countries use fossil fuel to meet the high energy demand of various sectors. Many countries use the verities of the energy sources that one of their energy produced from nuclear power plants.

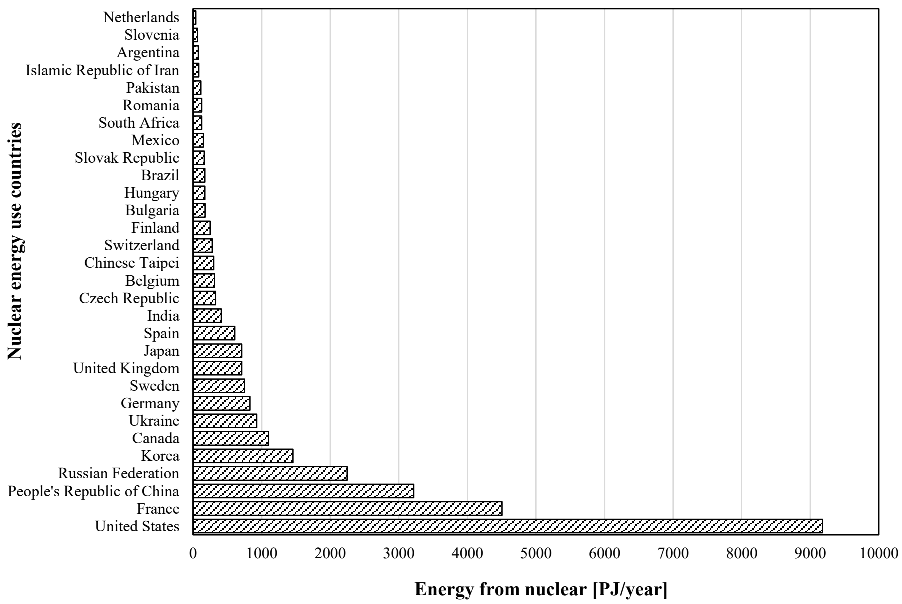


Fig. 2.4 Nuclear energy use countries in the world (IEA, 2019).

Fig. 2.4 shows the countries where energy is produced from nuclear power plants around the world. According to (IEA 2019) 30 countries are produced energy from nuclear power plant. Around 10% of the world's electricity is generated by about 440 nuclear power reactors. About 50 more reactors are under construction, equivalent to approximately 15% of existing capacity (World Nuclear Association, 2020). 70% of the world's nuclear energy is produced by the top five countries: United States, France, People's Republic of China, Russian Federation and South Korea. The United States shares 31% of the world's total nuclear energy and 10% of the total energy of country. Nuclear power reactors do not produce direct carbon dioxide emissions. Unlike fossil fuel-fired power plants, nuclear reactors do not produce air pollution or carbon dioxide while operating. However, the processes for mining and refining uranium ore and making reactor fuel all require large amounts of energy (EIA 2020). The Fukushima nuclear accident, which was caused by a huge tsunami after a magnitude 9 under sea earthquake in March 2011, was extraordinary in terms of its significant and extensive damage and its negative effect on local and global environments (Kim et al. 2013). The Fukushima disaster also had a significantly impact on policies making to reduce the nuclear production in many countries. Many governments have changed or redirected their investment in nuclear power, suspending the construction of various nuclear power plants (Ramana 2011). The Government of Japan has announced a comprehensive review of its energy policy and has canceled plans to build additional reactors (Ohta 2020). Germany has shut down all 17 operating reactors, and Switzerland has agreed to phase out five aging reactors when they reach the end of their life cycle over the next 25 years. Italy has decided to exclude nuclear energy from its future energy mix (Froggatt and Schneider 2011).

After the Fukusima digester most of the countries focused on renewable energy sources instated of nuclear and fossil fuels. With respect to technology, solar PV and wind become competitive with other types of renewables and nuclear. Moreover, It also decreases the CO_2 emissions by 25% compared fossil fuels (Handayani et al. 2019). So that the energy policies should focus on the development of renewables technologies, upgrading the grid capacity to accommodate variable renewable energy, and enabling faster local learning. According IEA (2019), world total primary energy supply (TPES) was produced 13.5% from renewable energy sources, which includes hydro, biofuels, renewable municipal waste, solar PV, solar thermal, wind, geothermal and tidal. The World Energy Outlook 2016 by the International Energy Agency (IEA) interlinks energy, air pollution, and health issues. In order to reduce atmospheric emissions, the IEA recommends avoiding traditional fuels, improving energy efficiency and energy conservation, transitioning towards renewable energy sources, and developing low-carbon and carbon-capture technologies. It is estimated that renewable energy can cover 10% of the total energy use in the world.

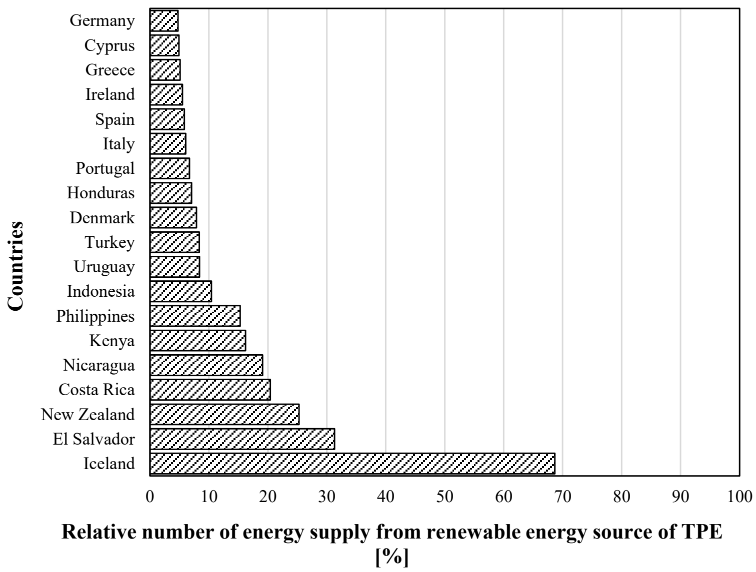


Fig. 2.5 Relative number of energy supply from renewable energy sources above 5% (IEA, 2019).

Fig. 2.5 shows the relative numbers of renewable energy producing and using countries, with 5% of the country's energy from renewable energy sources excluding the hydro. Iceland produces only 177 PJ/year and shares about 70% of the total energy supply of country, while China is the largest renewable energy producer with 3396 PJ/year which accounts only 2% of total energy supply of country. Iceland, El Salvador, New Zealand, Costa Rica, Kenya, Philippines, Indonesia and Nicaragua share more than 10% of their total energy supply of each countries. Developing countries also need to develop policies on promoting renewable energy sources (Ahuja and Tatsutani 2009).

Fig. 2.6 shows the relative number of energy supplies from the share of hydropower plants share large than 10% of total energy supply. Paraguay produces only 213 PJ/year and shares about 70% of the total energy supply of country, while China is the largest energy producer from hydro with 4317 PJ/year which accounts only 3% of total energy supply of country. Paraguay, Tajikistan, Norway, Lao People's Democratic Republic, Albaniya, Kyrgyzstan, Indonesia and Iceland share more than 20% of their total energy supply of each countries.

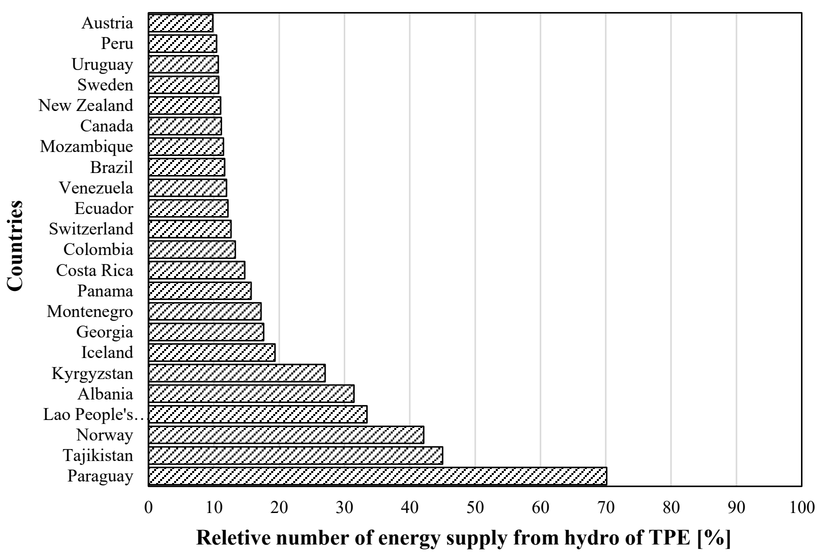


Fig. 2.6 Relative number of energy supply countries from hydro sources above 5% of TPES (IEA, 2019).

2.2.2 Household energy use patterns in world

The buildings sector is one of the main sectors for energy use. Electricity is used for lighting, cooling, and electric appliances are the fastest-growing source of energy use in buildings between 2015 and 2040 (IEO 2017). The building sector is comprised of two categories; (a) commercial and (b) residential. According to Kavgic et al. (2010), 22% of energy is absorbed by the domestic buildings, with the rest 18%, used by commercial sector. A breakdown of residential energy use according to Lapillone and Wolfgang (2009), reveals that the conditioning of spaces requires approximately two thirds of this energy, whilst the remaining third is consumed by cooking and electric appliances. This trend is particularly noticeable in modern societies, where the evolution of mechanization coupled with the poorer building envelopes has led to the use of artificial cooling or heating to maintain thermal comfortable conditions (Roaf et al. 2010). Clements-Croome (2000) claimed that buildings cannot provide adaptive opportunities, maintaining a moderate indoor climate. Further to this Roaf et al. (2010) reported that in warmer regions where cooling was necessary for the summer period, a bad design could contribute to the extended use of mechanical cooling.

Some studies regarding the energy use patterns were conducted in the different counties in the world as shown in Table 2.1. Foysal et al. (2012) revealed that 95% of the households use biomass, 72% kerosene, 53% electricity, 23% LPG and 60% candle as fuel types. Also revealed that rural households use fire wood, cow-dung, leaves & twigs, branches, straw and rice husk as biomass energy mainly for cooking (98.3%). The average electricity use in household was 56.73 kWh and firewood was 82.49 Kg. They found that rural households collect 42.6% of biomass from their own homestead and agricultural lands. Households mean expenditure for total energy was US$ 6.17 per month with total income US$ 148.11. The ratio of the total monthly energy expenditure to the total monthly income was 4.34%. found that the per capita energy expenditure of households is US$ 1.29 with explicit and implicit costs. Sakah et al. (2019) conducted the residential electricity use survey (RECS) with electricity end-use monitoring of 60 between June and September 2017 in Ghana. They found the average electricity use per household is 3234 kwh/year. They found the ownership of air conditioner, freezer, fan, refrigerator and television; and changes in socio-economic and building factors such as energy efficiency awareness and practice; income; household size and floor space show high statistical significance, and collectively explain 57% variance in households' total electricity use. The presence of dependent children increases ownership of television, iron, washing machine and small kitchen appliances. Singh et al. (2018) conducted questionnaire survey in three different climate zones of India. Utilizing micro level primary data obtained through the household survey, they have analyzed the variation in the electricity use and the factors such as demographic and dwelling attributes. They found the electricity use 279.7 kwh per month per house. Ownership of major home appliances like air conditioner, refrigerator and electric water heaters (geyser) have seen a significant rise over the years in households. They are found to contribute high electricity use in Indian urban households. Electricity use in the Indian urban household is observed more responsive to ownership of air conditioner rather than demographic variables and other appliances. They observed that, electricity use in air conditioning could be reduced by 15% to 31%; if existing household air conditioners, older than 7 years were replaced by new energy efficient air conditioners, subject to all other parameters like tonnage and usage remain constant. Hu et al. (2017) conducted an online survey in 2015 to study the urban residential energy and usage behavior. A total of 4964 Chinese urban households participated in survey. The average electricity use of urban residential buildings is

1690 kWh per year per household in 2015 and it continues to grow as home electronics become more widespread and the demand for higher quality of life increases. China urban residential buildings energy use has the following characteristics: steady growth in size and energy use of the buildings associated with rapid urbanization, decentralized and individual equipment with diversified energy usage behavior, and relatively low energy use level compared to other countries. In addition they suggested to the current energy efficiency programs, China should focus on energy use and intensities target of building sector, and the key for urban residential building energy efficiency is to retain traditional behaviors and lifestyles, as well as promoting outcome-based energy conservation policies and technology systems to improve indoor environment and comfort.

McLoughlin et al. (2012) conducted on dwelling and occupant characteristics on domestic electricity use patterns by analyzing data obtained from a smart metering survey of a representative cross section of approximately 4200 domestic Irish dwellings. A multiple linear regression model was applied. The total mean electricity use in household was found 2261 kWh per year. They also found the dwelling type, number of bedrooms, head of household (HoH) age, household composition, social class, water heating and cooking type all had a significant influence over total domestic electricity use. Maximum electricity demand was significantly influenced by household composition as well as water heating and cooking type. A strong relationship also existed between maximum demand and most household appliances but, in particular, tumble dryers, dishwashers and electric cookers had the greatest influence over this parameter. Time of use (ToU) for maximum electricity demand was found to be strongly influenced by occupant characteristics, HoH age and household composition. Younger head of households were more inclined to use electricity later in the evening than older occupants. The appliance that showed the greatest potential for shifting demand away from peak time use was the dishwasher. Firth et al. (2008) were presented from a monitoring study of the electricity use of a sample of UK domestic buildings. Five-minutely average whole house power use was recorded for 72 dwellings at five sites over a 2-year monitoring period. They found that total average use increased overall from 1770 kWh to 1964 kWh (11.0%) for the low energy group and from 4841 kWh to 5088 kWh (5.1%) for the high-energy group. The mean annual electricity use for the households increased significantly by 4.5% from the first to the second year of monitoring. New techniques are developed which estimate the electricity use of different appliance groups, based on analysis of the five-minutely monitored data. The overall increase in electricity use is attributed to a 10.2% increase in the use of ‘standby’ appliances (such as televisions and consumer electronics) and a 4.7% increase in the use of ‘active’ appliance (such as lighting, kettles and electric showers).

The Korea Energy Economics Institute conducted an interview survey of 2,250 households nationwide in order to establish data to identify the electricity use of the whole household sector. This data used by Kim (2018) and found the monthly average electricity use was 286.54 kWh per month. He/she reviled the differences in socio-demographic, dwelling, and electricity use characteristics between two groups. Next, the factors affecting the household electricity use are investigated. Factor affecting the household electricity use for two groups is only the number of electrical appliances. There were also the differences in major determinants of the household electricity use for two groups. He/she suggests that this study would be useful for understanding socio-demographic, dwelling, and electricity use characteristics for two groups. Onuma et al. (2020) used microlevel data from the Survey on Carbon Dioxide Emission from Households (SCDEH) of Japan. They analyzed that many countries have promoted the replacement of conventional lamps with next-generation lamps to reduce electricity usage for lighting. The monthly average electricity use in household found 411.07 kWh per month. In Japan, the majority of the lamps sold at home appliance mass merchant shops have been changed from incandescent lamps to energy-saving lamps. Although the energy-saving effect of LEDs has been stressed in many engineering studies, the amount of electricity that is actually saved by the installation of LEDs has not been examined. They compared monthly electricity usage between households using conventional lamps and those using LEDs. Households can reduce their electricity usage by an additional 6.99% when LEDization is completed. They suggests that the empirical results further demonstrate that middle-income households have higher price elasticity of electricity demand and are more likely to receive greater benefit from LED installation. Chen (2017) conducted field survey on socioeconomic perspective electricity and use patterns. He/she found the gross domestic product (GDP), employment rates, residential space, and the implementation of energy labelling schemes provide significant impacts on residential electricity use. However, the impacts of electricity price and the energy efficiency standards do not receive significant support. He/she analyzed of the direct use approach finds that air conditioners consume the largest portion of electricity, amounting to 1470 kWh for each household and accounting for 26.81% except for lighting. Refrigerators and rice cookers follow, using 815.83 kWh (14.88%) and 343.85 kWh (6.27%) of electricity. The correlation analysis reveals that GDP keeps a high relationship with the installation of electrical appliances and eventually leads to an increase in residential electricity use. The residential electricity demand in Taiwan was investigated using survey data of 7677 households between 2014 and 2017 by Su (2017). They used right-skewed regression models to study key determinants affecting the household and appliance-specific electricity use. He/she found that a representative household in Taiwan uses 7175 kW h electricity annually, including 2625 kW h for AC, 1432 kW h for lighting, 593 kW h for TV, and 505 kW h for refrigerator. Appliances covered air conditioner, lighting, television, and refrigerator. The difference of electricity use between appliances with and without energy efficiency label was also studied; thus rebound effects were obtained. He/she concluded the results indicate that household income, indoor floor area, and owning the house had positive influences on electricity use. Electricity use behavior was different among age groups and appliances. Moreover, rebound effect was large for air conditioner and refrigerator in Taiwan. Heinonen and Junnila (2014) used the primary data set from Household Bud-get Survey (HBS) 2006 by Statistics Finland. They find out the overall average energy use per household increases from approximately 12,600 kWh/year in apartment buildings in rural areas and 15,500 kWh/a in urban areas for the same building type to 22,500 kWh/year and 23,300 kWh/ year, respectively. They found key findings: (1) behavioral differences seem significant between different housing modes; (2) each housing mode appears to be less energy-intensive in rural areas; (3) including indirect energy purchases is essential when comparing different housing modes; (4) unit-of-analysis (m^2, capita, household) selection strongly affects the results; and (5) the energy mixes vary significantly between the studied building types, changing from the pre-dominance of non-renewables in apartment buildings to that of renewables in detached houses, which in turn has interesting carbon footprint implications.

2.2.3 Household energy use patterns in Nepal

Quite a lot of research works on energy use and economy in Nepal were conducted. Fox (1984) conducted field survey in Nepal and found that the firewood use in rural areas is 0.96-1.75 kg/capita/day in rural households. It is affected by family size, caste and seasons. Similarly, Rijal (2018) has investigated the firewood use in traditional houses in Nepal and found that the firewood use rate was 235-1130 kg/capita/year. Pokharel (2007) used econometric approaches for forecasting energy demands till 2012 and 2015. Malla (2013) employed the long-range Energy Alternatives Planning System (LEAP) modelling framework for developing scenarios to study household energy use patterns till 2040. Several studies were also conducted on the status and assessment of renewable energy potentials in Nepal in the context of reducing the greenhouse gas (GHG) emissions. (Pokharel 2007, Gewali & Bhandari 2005) and Parajuli (2014). Shrestha & Rajbhandari (2010) studied the energy and environmental impacts due to the CO_2 emissions from 2005 to 2050 in the Kathmandu valley using Market Allocation (MARKAL) modelling framework. Similarly, Shakya et al. (2012) and Nakarmi et al. (2016) analyzed the integrated Model for Analysis of Energy Demand (MEAD) and MARKEL based analysis of future energy use scenario of Nepal. Bhandari & Stadler (2011) and Gurung et al. (2012) analyzed the rural electrification and the use of solar photovoltaic system in rural and urban areas in Nepal. Household energy use depends on family size, climate, appliance ownership, life style, physical characteristics of the houses and occupants' behavior (Mullaly 1998, Jaber 2002 and Westergren 1999). It is also considered to depend on such characteristics as educational level, cooking habits and lifestyle, accessibility to energy sources, energy price, demographic characteristics and geographical variation (Chen 2006, Pachauri and Jiang 2008, Zhang et al. 2009 and Craig Petersen 1982).

Table 2.1 Various household energy use patterns in the different country (continue)

Country	Reference	Building type	Survey method	Key findings
Bangladesh	Foysal et al. 2012	Residential	Field survey	The household used 95% biomass, 72% kerosene, 53% electricity, 23% LPG and 60% candle as fuel types. The average electricity use in household was 56.73 kWh and firewood was 82.49 Kg. They found that rural households collect 42.6% of biomass from their own homestead and agricultural lands. The ratio of the total monthly energy expenditure to the total monthly income was 4.34%. found that the per capita energy expenditure of households is US$ 1.29 with explicit and implicit costs.
Ghana	Sakah et al. 2019	Residential	Field survey (multiple linear regression)	They found the average electricity use per household is 3234 kwh/year. The ownership of air conditioner, freezer, fan, refrigerator and television; and changes in socio-economic and building factors such as energy efficiency awareness and practice; income; household size and floor space show high statistical significance, and collectively explain 57% variance in households' total electricity use.
India	Singh et al. 2018	Residential	Field survey	The average monthly electricity use 279.7 kwh per house. Ownership of major home appliances like air conditioner, refrigerator and electric water heaters (geyser) have seen a significant rise over the years in households. Electricity use in the Indian urban household is observed more responsive to ownership of air conditioner rather than demographic variables and other appliances.
China	Hu et al. 2017	Urban residential	Online survey	The average electricity use of urban residential buildings is 1690 kWh per year per household in 2015 and it continues to grow as home electronics become more widespread and the demand for higher quality of life increases.
Ireland	McLoughlin et al. 2012	Domestic	Smart metering survey	The total mean electricity use in household was found 2261 kWh per year. The dwelling type, number of bedrooms, head of household (HoH) age, household composition, social class, water heating and cooking type all had a significant influence over total domestic electricity use.
UK	Firth et al. 2008	Domestic	Monitoring and recorded	The total average use increased overall from 1770 kWh to 1964 kWh (11.0%) for the low energy group and from 4841 kWh to 5088 kWh (5.1%) for the high-energy group. The mean annual electricity use for the households increased significantly by 4.5% from the first to the second year of monitoring.

Country	Reference	Building type	Survey method	Key findings
Korea	Kim 2018	Domestic	Interview survey by KEEI	The monthly average electricity use was 286.54 kWh per month. Factor affecting the household electricity use for two groups is only the number of electrical appliances. Urged that the results would be useful for understanding socio-demographic, dwelling, and electricity use characteristics for two groups.
Japan	Onuma et al. 2020	Domestic	Survey on (SCDEH)	The monthly average electricity use in household found 411.07 kWh per month. In Japan, the majority of the lamps sold at home appliance mass merchant shops have been changed from incandescent lamps to energy-saving lamps. Households can reduce their electricity usage by an additional 6.99% when LEDization is completed.
Taiwan	Chen 2017	Residential	Field survey (regression analysis)	The gross domestic product (GDP), employment rates, residential space, and the implementation of energy labelling schemes provide significant impacts on residential electricity use. However, the impacts of electricity price and the energy efficiency standards do not receive significant support. He/she analyzed of the direct use approach finds that air conditioners consume the largest portion of electricity, amounting to 1470 kWh for each household and accounting for 26.81% except for lighting. Refrigerators and rice cookers follow, using 815.83 kWh (14.88%) and 343.85 kWh (6.27%) of electricity.
Taiwan	Su 2019	Residential	Field survey (Regression models)	A representative household in Taiwan uses 7175 kW h electricity annually, including 2625 kW h for AC, 1432 kW h for lighting, 593 kW h for TV, and 505 kW h for refrigerator. Appliances covered air conditioner, lighting, television, and refrigerator. The results indicate that household income, indoor floor area, and owning the house had positive influences on electricity use. Electricity use behavior was different among age groups and appliances.
Finland	Heinonen and Junnila 2014	Residential	Household Bud-get Survey (HBS) 2006 by Statistics Finland	They find out the overall average energy use per household increases from approximately 12,600 kWh/year in apartment buildings in rural areas and 15,500 kWh/a in urban areas for the same building type to 22,500 kWh/year and 23,300 kWh/ year, respectively. Key findings: (1) behavioral differences seem significant between different housing modes; (2) each housing mode appears to be less energy-intensive in rural areas; (3) including indirect energy purchases is essential when comparing different housing modes; (4) unit-of-analysis (m^2, capita, household) selection strongly affects the results.

2.3 Thermal comfort

2.3.1 Overview

Thermal comfort is defined as the, "condition of mind that expresses satisfaction with the thermal environment" (ANSI/ASHRAE Standard 55-2017) standards that define the local thermal comfort in an indoor environment, and its main indices and measuring procedures are described" (Orosa and Oliveira 2012). In addition to thermal comfort, acceptable environments, such as quiet service equipment, and visual comfort, including artificial and natural lighting, are also human comfort categories that require attention when designing buildings (Bansal at al. 1994). However, this study is primarily related to the thermal comfort of people with traditional and contemporary materials using Nepalese houses.

Thereafter, some studies was published, based on findings from environmental chambers and field studies with different climates, genders, ages, cultures and building types. The majority of the studies were mainly driven by the investigation and establishment of criteria, thresholds and standards to define the range of conditions that people are satisfied by their thermal environment. There seem to be two lines of thought with regards to the perception of thermal comfort. The first relies on the globally accepted predicted mean vote (PMV), so-called static approach, which is based on a study carried out by (Ole Fanger) in a climate chamber (Fanger 1970). The PMV was governed by controlled indoor conditions, neglecting the transient conditions of real life scenarios. On the other hand, a group of people accepted that people are not passive recipients of the environment, but tend to interact with it Roaf et al. (2010). The principle of adaptive model, dynamic method, was initially defined by Humphreys and Nicol (1970) as: "if a change occurs that produces discomfort, people will tend to act to restore their comfort". The method was founded by field studies carried out in 'real' buildings during 'real' environmental conditions, without marginalizing the pragmatic activities and actions of the subjects.

2.3.2 Thermal comfort study in other countries

Many previous thermal comfort studies have been conducted on different types of countries, climates, seasons, and building as shown Table 2.2. de Dear et al. (1991) were conducted field survey in Singapore in both naturally ventilated high-rise residential buildings and air conditioned office buildings. Each of the 818 questionnaire responses was made simultaneously with a detailed set of indoor climatic measurements, and estimates of clothing insulation and metabolic rate. They concluded that in the naturally ventilated apartments the mean operative temperature of 29.6 °C, mean RH of 74%, mean air velocity of 0.22 m/s, mean occupant clothing insulation level of 0.26 clo, and an average metabolic rate of 70 W/m^2. The comfort temperature was found 28.5 °C in naturally ventilated building. They also notified for the air conditioned sample indicated that office buildings were overcooled, causing up to one-third of their occupants to experience cool thermal comfort sensations. These observations in air conditioned buildings were broadly consistent with the ISO, ASHRAE and Singapore indoor climatic standards. Indoor climates of the naturally ventilated apartments during the day and early evening were on average three degrees warmer than the ISO comfort standard prescriptions, but caused much less thermal discomfort than expected. de Dear and Barger (2002) conducted the on naturally ventilated buildings during summer and in warmer climate zones. They revised ASHRAE Standard 55-thermal environmental conditions for human occupancy. The adaptive comfort standard was based on the analysis of 21,000 sets of raw data compiled from field studies in 160 buildings located on four continents in varied climatic zones. They summarized the earlier adaptive comfort research, presents some of its findings for naturally ventilated buildings, and discusses the process of getting the ACS incorporated into Standard 55. They suggested the ways the adaptive comfort standard could be used for the design, operation, or evaluation of buildings, and for research applications. They also used GIS mapping techniques to examine the energy-savings potential of the ACS on a regional scale across the US. Nicol and Roaf (1996) conducted a field survey in July 1993 and January 1994 of five climatic regions of Pakistan based on thermal comfort in summer and winter. They found the comfort temperature 26.7 ~ 29.9 °C. The use of such a temperature standard allows the saving of energy by buildings with air-conditioning and can be used to suggest the most appropriate method of passive or low-energy control of indoor conditions in any given climate and season. Heidari and Sharples (2002) conducted two field survey of naturally ventilated buildings in Iran. The first study consisted of two short-term surveys carried out during two climatically extreme periods a hot summer and a cold winter in 1998. The second study consisted of a long-term survey that collected data throughout the whole of 1999. They found the neutral temperatures for hot season 28.4 ~ 26.7 °C and for the cold season 20.8 and 21.2 °C. They urged that the main points of interest from the studies were the variability of acceptable conditions, a good relationship between neutral temperature and room temperatures and also, more importantly, between indoor comfort and outdoor conditions. These findings revealed that the people in the study could achieve comfort at higher indoor air temperatures compared with the recommendations of international standards such as ISO 7730.

Feriadi and Wong (2004) field survey conducted in naturally ventilated residential buildings in Indonesia, 525 sets of data had been gathered. The data analysis revealed that the PMV equation had predicted warmer thermal perception as compared to what people actually felt. They observed that under hot and humid tropical climate, people indicated preference to cooler environment as compared to what the neutral temperature has shown. And, they investigated the occupant's adaptive control preferences in creating a more thermally comfortable living environment. The reciprocal effects of occupant's thermal perception and behavioral adaptation were explored. In tropical free-running buildings where the air temperature and humidity might not be modified easily without mechanical means, the people seemed to prefer higher wind speed. The mean and the recorded indoor range temperatures seem to have effect in the prediction of comfort temperature. Wang (2006) visited on 66 residential units in two communities and he collected 120 data sets with 61 females (50.8%) and 59 males (49.2%). He found the neutral operative temperatures for the Harbin males and females are 20.9 and 21.9 °C, respectively. The neutral operative temperature for the Harbin males was 1 °C lower than that of the Harbin females, although the Harbin women wore heavier clothes than the Harbin men. He summarized the Harbin females would prefer a slightly higher temperature. The comfort temperature was closed to the mean air temperature.

Ogbonna and Harris (2008) conducted this survey in a total of 29 residential buildings in the city as well as in three classrooms/studio spaces at the University of Jos with a total of 200 respondents. All were conducted in naturally-ventilated (NV) buildings between July and August 2006. They found the physiological and adaptive factors were equally important in the perception and interpretation of thermal comfort. The comfort range was 2 ~ 3 °C less than that suggested by the ASHRAE standard, probably due to higher relative humidity. Han et al., (2007) investigated the thermal environment and comfort of residences in the central southern China with collected votes 110 from 26 residences in the summers in 2003 and 2004 in the hot humid cities of Changsha, Guangzhou and Shenzhen in the central south of China. They found the average clothing insulation for seated subjects was 0.54 clo and 0.15 clo for chairs. The operative temperature denoting the thermal environment accepted by 90% of occupants is 22.0 ~ 25.91 °C. In the ASHRAE seven-point sensation scale, thermal neutral temperature occurs at 28.61 °C. Preferred temperature, mean temperature requested by respondents, is 22.81 °C.

Nicol and Humphreys (2010) conducted the physical measurements and subjective responses recorded in 26 European office reported. They derived the adaptive equations for thermal comfort in free running buildings in European standard EN15252 described that how the indoor comfort conditions were related to the running mean of the outdoor temperature, and addresses the effect of air movement and humidity. Indraganti (2010) conducted field survey in India in May, June and July 2008 and collected a data set of 3962 including 113 subjects living in 45 apartments belonging to 5 apartments. She found the respondents living in top floor flats had a higher thermal sensation and thermal preference votes than those respondents who were living lower floor flats. The clothing adaptation to be impeded by many socio-cultural and economic aspects. She used the regression analysis yielded the comfort band to be between 26 and 32.45 °C. The neutral temperature was at 29.23 °C, lying way above the temperature limits (23-26 °C) set in standards. As the adaptation mechanisms of the subjects were ignored, the PMV was always found to be much higher than the actual sensation. Singh et al. (2011) performed a study on the adaptive model of comfort for different climatic zones in India and concluded that the occupants adopt different manners of adaptation based on the types of climatic zones. They also concluded from the study that if dynamic control of the set temperature (based on adaptive model) of the air conditioning system can be done then there is a huge potential of energy saving. However, for this it is required to adopt the adaptive model in real buildings for assessment of actual energy savings potential. This model is more appropriate compared to PMV-PPD method as this model considers the local climate, culture and social setup, behavior and lifestyle etc.

Yun et al. (2012) conducted in field survey on office building in Korea. They found the occupants would feel comfortable even at 28 °C depending on the previous running mean outdoor temperature, 2 °C higher than the 26 °C stipulated in the Korean Standard. Liang at al. (2012) conducted on field survey in naturally ventilated school buildings in hot-and-humid climate of Taiwan and found the building envelope energy regulation had a significant impact on the level of thermal comfort in naturally ventilated buildings. Adaptive comfort model was developed and suggested to be integrated with other building design variables in the energy regulation. Djamila et al. (2013) did field study in Malaysian naturally ventilated houses for the prediction and evaluation of the effect of the indoor thermal environment on occupants' thermal comfort. They gathered 890 in hot-humid indoor climates. The revealed the predicted neutral temperature using least squares linear regression was found to be nearly 30 °C regardless of the adopted approach. From statistical analysis, it was concluded that the predicted indoor neutral temperature in residential buildings was 30.2 °C ± 0.2 °C. Imagawa and Rijal (2015) measured the air temperature and relative humidity in the 26 bedrooms of 10 houses, and conducted a thermal comfort, depth of sleep and occupant behavior survey with 31 residents, obtaining 1176 votes. They found the mean indoor air temperature in the rooms during the survey period was 26.3–27.9°C. The residents sleep in the bedrooms, where the indoor air temperature is high. The mean comfort temperature was 26.4 - 27.1°C. The thermal comfort of residents is high and the depth of sleep is normal for the given thermal environment. They revealed that residents are thermally satisfied and slept well in the bedrooms using various thermal adjustments, such as cooling, fans, windows and clothing insulation.

Manu et al. (2016) conducted the field studies of thermal comfort across multiple climate and 6330 responses were gathered from naturally ventilated, mixed mode and air-conditioned office buildings using instantaneous thermal comfort surveys. They found the occupants in naturally ventilated Indian offices were found to be more adaptive than the prevailing ASHRAE and EN models would suggest. The neutral temperature in naturally ventilated buildings was varied from 19.6 to 28.5 °C and outdoor running mean air temperatures ranging from 12.5 to 31 °C. They suggested the IMAC study models for neutral temperatures and acceptability limits for naturally ventilated and mixed mode buildings, as derived through an empirical field study specific to the Indian context, offer an energy efficient pathway for its commercial building sector without compromising occupant comfort. Damiati et al. (2016) field survived on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan in free running (FR), mixed mode (MM), and mechanical cooling (CL) during hot and humid season in 2015 and collected 2049 responses from 325.

They found the comfort range differed for each group of occupants under the different ventilation modes. The comfort operative temperatures in tropical climates are 25.7 °C, 24.9 °C, and 27.5 °C for the CL, FR, and MM ventilation modes respectively, whereas in Japan was 25.8 °C for both CL and MM. They suggested the high comfort temperature with MM ventilation could be influenced by the strong air movement and a wide range of adaptive options, such as opening windows and utilizing air-conditioning systems. Ning et al. (2016) conducted a study on thermal history and adaptation in Harbin, China and suggested that a thermally comfortable zone with a higher indoor temperature was formed in the case of people exposed to warmer climatic conditions. They also observed that the neutral temperature for people with warm exposure was 1.9 ◦C higher than that for people with cold exposure. They also found the indoor air temperature should be increased gradually to avoid human inadaptability in EH period. During space heating, if participants felt hot, they would mainly open windows to release heat which wastes a huge energy. The current indoor heating temperature in winter should be decreased properly and occupants' climatic adaptation should be considered in this region. If so, a healthier and more energy-efficient indoor environment would be achieved. Yu et al. (2017) were conducted subjective questionnaire survey Tibetan houses in an area covering Lhasa, Shigatse, Qamdo, Nagqu, Nyingchi, Lhoka and Ngari. They summarized the findings such as: indoor air temperatures in residential buildings fluctuate greatly within the range 0 °C–26 °C during the daytime when the outdoor temperature is between −20 °C and 0 °C. Thus, the indoor thermal environments are highly variable due to the great variety of heating measures that are in use. The clo value in winter was (1.19–2.67clo and summer was (0.43-1.71) clo. The indoor temperature is higher than the outdoor temperature when the outdoor temperature is between 0 and 20 °C; while the indoor temperature is mostly lower than the outdoor temperature when the outdoor temperature exceeds 20 °C. This phenomenon reflects the active behavioral adaptation. The acceptable thermal comfortable zone for the indoor environment of residential buildings in Tibet has been identified within the temperature range between 10.18 °C and 22.91 °C under a low relative humidity of 30% and between 9.79 °C and 21.74°Cunder a high relative humidity of 70%.

Field studies on thermal comfort in 120 residential buildings in summer and winter have been conducted in 12 cities, representative of four climate zones in eastern China by Yan et al. (1017). The results showed the clothing was mainly affected by the indoor temperature in the severe cold climate; however, it was affected by the outdoor temperature in the warmer climates. Clothing adjustment was more obvious in the warmer climate than in the colder climate. They also found neutral temperature in cold season is 20.8 °C. The neutral temperature of the occupants is greatly close to the indoor temperature in the SC zone. But in other three climate zones, the neutral temperatures are slightly higher than the indoor temperature in winter, and vice versa in summer. The outdoor climate is the colder, the clothing adjustment is mainly affected by the indoor temperature, and the outdoor climate is the warmer, the clothing adjustment is mainly affected by the outdoor temperature. Thapa et al. (2018) did field survey on residential buildings at two different locations, Kurseong and Tiger Hills in the Darjeeling and found the comfort temperature 20.8 ~ 26.1 °C. He also found the subjects were highly satisfied with the indoor condition. The mean clothing insulation for women was 0.742 and that for men was mean 0.860, respectively. Rijal et al. (2018) conducted field survey on Japanese dwelling in urban areas ok Kanto region. They found that the constraint of the window opening in dwellings is smaller than those in the office buildings. The indoor comfort temperature was found 17.6 °C. The indoor comfort temperature correlated well with the running mean of the outdoor temperature. They also found the indoor comfort temperature was found 17.6 °C. The indoor comfort temperature correlated well with the running mean of the outdoor temperature.

Xu et al. (2018) conducted a field study of thermal comfort and thermal adaptive behaviors of residents in a traditional residential settlement in Nanjing in summer and winter. They found the thermal neutral temperature (15.8 °C) is lower than the ASHRAE standard and the neutral temperature of residents of modern dwellings in winter. Because of their long-term thermal experiences, the traditional dwellings' residents' thermal sensitivity is also lower than that of residents of modern dwellings, and the range of indoor operative temperatures that they regarded as acceptable 10.6 ~ 28.5 °C in winter. Although their thermal neutral temperature in winter was low, the residents of traditional dwellings still preferred a temperature (16.2 °C) that is higher than their thermal neutral temperature, which indicates the necessity of improving their living environment by warming the indoors in winter. Thermal comfort survey, and an occupant behavior survey were conducted by Rijal et al. (2019) for 4 years in the living and bedrooms of dwellings in the Kanto region of Japan. They had collected 36,114 thermal comfort votes from 244 residents of 120 dwellings. They found the residents are highly satisfied with the thermal environment of their dwellings. People are well-adapted to the thermal condition of their dwellings, and thus the comfort temperature has large seasonal differences in free running mode (FR): 9.4 K. They was derived an adaptive model for housing from the data to relate the indoor comfort temperature to the prevailing outdoor temperature, and the regression coefficient in the FR mode is notably higher (0.48) than that in office buildings. They urged the such a models would useful for the control of indoor temperatures. And, the adaptive model of thermal comfort is strongly supported by the various adaptive actions reported by the residents.

Rate of urbanization in Nepal is significantly increasing day by day. The traditional houses were replaced by modern houses. The increasing standard of living of the population has led to an increase in the installation of comfort devices such as air conditioners. However, due to the geographical variations and complicity in a third world country like Nepal, a small rise in the per capita energy use. In Nepal, buildings account for 84 % of the total energy used and very limited of this energy is used for providing the thermally comfortable conditions of indoors. Further, the building energy use in Nepal is growing. Secondly, Nepal being a small

Table. 2.2 Various thermal comfort study in various climate and seasons in the world (continue)

Country	Reference	Building type	Climate	Key findings
Global	de Dear 2002	General	Different	They summarized the earlier adaptive comfort research, presents some of its findings for naturally ventilated buildings. They suggested the ways the adaptive comfort standard could be used for the design, operation, or evaluation of buildings, and for research applications.
Netherlands	Van der Linder 2006	Office	-	The 90% acceptability is allowed to exceed in 10% of the occupancy time (i.e. at least 90% satisfied for at least 90% of the time), and indoor temperature limits are given as a function of mean outdoor temperature.
Nigeria	Ogbonna and Harris 2008	Classrooms and residential	Tropical region	The physiological and adaptive factors are equally important in the perception and interpretation of thermal comfort. The comfort range was 2 ~ 3 °C less than that suggested by the ASHRAE standard.
Global	Nicol and Humphreys 2009	General	Many	New standards are needed that put the sustainable buildings at a premium, and the adaptive thermal comfort approach is conducive to defining conditions compatible
Europe	Nicol and Humphreys 2010	Offices	Mix	They derived the adaptive equations for thermal comfort in free running buildings in European standard EN15252 and the indoor comfort conditions were related to the running mean of the outdoor temperature, and addresses the effect of air movement and humidity.
Korea	Yun 2012	Office	Summer, autumn, winter	Occupants would feel comfortable even at 28 °C depending on the previous running mean outdoor temperature, 2 °C higher than the 26 °C stipulated in the Korean Standard.
Taiwan	Liang 2012	School	Hot-and-humid	Building envelope energy regulation had a significant impact on the level of thermal comfort in naturally ventilated buildings. Adaptive comfort model was developed and suggested to be integrated with other building design variables in the energy regulation.

Country	Reference	Building type	Climate	Key findings
Japan	Rijal et al. 2018	Dwelling	Cold	The indoor comfort temperature was found 17.6 °C. The indoor comfort temperature correlated well with the running mean of the outdoor temperature.
Japan	Imagawa and Rijal 2015	Japanese houses	Hot and humid season	The mean comfort temperature is 26.4 ~ 27.1°C. The residents were thermally satisfied and slept well in the bedrooms using various thermal adjustments, such as cooling, fans, windows and clothing insulation.
Japan	Rijal et al. 2019	Dwelling	Cold	People are well-adapted to the thermal condition of their dwellings, and thus the comfort temperature has large seasonal differences in free running mode. They was derived an adaptive model for housing from the data to relate the indoor comfort temperature to the outdoor temperature.
Different	Damiati et al. 2016	Offices	Hot and humid	The comfort operative temperatures in tropical climates are 25.7 °C, 24.9 °C, and 27.5 °C for the CL, FR, and MM ventilation modes respectively, whereas in Japan it was 25.8 °C for both CL and MM. The high comfort temperature with MM ventilation could be influenced by the strong air movement such as opening windows and utilizing air-conditioning systems.
Iran	Heidari and Sharples 2002	Residential buildings	Hot and Cold	They found the neutral temperatures for hot season 28.4 - 26.7 °C and for the cold season 20.8 and 21.2 °C. They urged that the good relationship between neutral temperature and room temperatures and also, more importantly, between indoor comfort and outdoor conditions.
Singapore	de Dear et al. 1991	Residential buildings	Humid tropics	The mean operative temperature of 29.6 ~ C, mean RH of 74%, mean air velocity of 0.22 m/s, mean occupant clothing insulation level of 0.26 clo, and an average metabolic rate of 70 W/m2. The comfort temperature was found 28.5 °C in naturally ventilated building.

Country	Reference	Building type	Climate	Key findings

Malaysia	Djamila et al. 2013	Residential building	Hot-humid	The neutral temperature was found to be nearly 30 °C regardless of the adopted approach. From statistical analysis, it was concluded that the predicted indoor neutral temperature in residential buildings was 30.2 °C ± 0.2 °C.
Indonesia	Feriadi and Wong 2004	Residential building	Hot and humid tropical climate	Investigated the occupant's adaptive control preferences in creating a more thermally comfortable living environment. The reciprocal effects of occupant's thermal perception and behavioral adaptation were explored. The mean and the recorded indoor range temperatures seem to have effect in the prediction of comfort temperature.
China	Wang 2006	Residential buildings	Humid	The neutral operative temperatures for the males and females are 20.9 and 21.9 °C, respectively. Women wore heavier clothes than the men. It shows that the females would prefer a slightly higher temperature. The comfort temperature is close to the mean air temperature.
China	Han et al. 2007	Chinese dwelling	Hot-humid climate	They found the average clothing insulation for seated and chairs peoples were 0.54 clo and 0.15 clo, respectively. Thermal neutral temperature occurs at 28.61 °C. Preferred temperature, mean temperature requested by respondents, is 22.81 °C.
China	Xu et al. 2018	Naturally ventilated houses	Winter and higher in summer	Their thermal neutral temperature (15.8 °C) is lower than the ASHRAE standard and the neutral temperature of residents of modern dwellings in winter. Although their thermal neutral temperature in winter is low, the residents of traditional dwellings still preferred a temperature (16.2 °C).
China	Yan et al. 1017	Modern building	Summer and winter	The clothing was mainly affected by the indoor temperature in the cold climate; however, it was affected by the outdoor temperature in the warmer climates. The neutral temperature in cold season is 20.8 °C.
Country	Reference	Building type	Climate	Key findings

Taiwan	Liang 2012	School	Hot-and-humid	Building envelope energy regulation had a significant impact on the level of thermal comfort in naturally ventilated buildings. Adaptive comfort model was developed and suggested to be integrated with other building design variables in the energy regulation.
Tibet	Yu et al. 2017	Traditional residential building	Winter	The clo value in winter was (1.19–2.67) clo and in summer was (0.43-1.71) clo. The comfortable zone has been identified within the temperature range between 10.18 °C and 22.91 °C under a low relative humidity of 30% and between 9.79 °C and 21.74 °C under a high relative humidity of 70%.
China	Ning et al. 2016	-	Winter, autumn, spring	The neutral temperature in warm was 1.9 °C higher than that for people with cold exposure.
India	Singh et al. 2011	Houses	Different climatic	The set temperature (based on adaptive model) of the air conditioning system can be done huge potential of energy saving. It required to adopt the adaptive model in real buildings for assessment of actual energy savings potential.
India	Indraganti 2010	Residential	Composite climate	Temperature range was based on adaptive model 26 ~ 32.5 °C, far higher than the Indian Standard 23 ~ 26 °C.
India	Thapa et al. 2018	Residential buildings	Cold	The subjects were highly satisfied with the indoor condition. The mean clothing insulation for women was 0.742 and that for men was mean 0.860 respectively. The comfort temperature found 20.8 ~ 26.1 °C.
India	Manu et al. 2016	Indian office	Different climate	Indian NV offices were found to be more adaptive than the prevailing ASHRAE and EN models would suggest. The neutral temperature in naturally ventilated buildings was varied from 19.6 to 28.5 °C for 30-day outdoor running mean air temperatures ranging from 12.5 to 31 °C.
Pakistan	Nicol and Roaf 1996	Natural ventilated buildings	Five climatic regions	The comfort temperature found 26.7 ~ 29.9 °C. The use of such a temperature standard allows the saving of energy by buildings with air-conditioning and can be used to suggest the most appropriate method of passive or low-energy control of indoor conditions in any given climate and season.

Table. 2.2 Various thermal comfort study in various climate and seasons in the Nepal

Country	Reference	Building type	Climate	Key findings
Nepal	Rijal et al., 2010	Houses	Cold, temperate and sub-tropical	The indoor neutral temperature is highest in sub-tropical climate, medium in the temperate climate, and lowest in the cool climate areas both in summer (21.1 ~ 30.0 °C) and winter (13.4 ~ 24.2 °C). The indoor neutral temperature has large seasonal differences (4.9 ~ 13.8K). These differences might be due to the seasonal difference in clothing insulation, wind velocity and the physiological or psychological adaptation of the residents to the seasons.
Nepal	Thapa et al., 2018	Shelter	Temperate	The mean indoor globe temperature varied between 12.1 and 18.5 °C in winter. The lowest value of mean comfort temperature among the four districts was 15.0 °C and the highest was 28.6 °C; that is, the seasonal difference is 13.6 °C. The range of indoor globe temperature, within which 80% of the respondents would accept, was found from 11 °C to 30 °C.
Nepal	Gautam et al., 2019	Houses	Cold, temperate and sub-tropical	The mean indoor globe temperature was 12.2 °C in the cold region, which was 4.7 °C and 10.0 °C lower than that in the temperate and sub-tropical regions, respectively. The estimated mean comfort globe temperature was 13.8 °C in the cold region, which was 4.1 °C and 9.3 °C lower than that in the temperate and sub-tropical regions, respectively. The mean preferred temperature in the cold region was 14.7 °C, which is slightly higher than its mean comfort temperature.
Nepal	Rijal, 2021	Houses	Cold	Passive heating effects were found in houses with thick brick walls and mud roofs. Residents of these houses were highly satisfied with the thermal environment, with 10.7 °C being the mean comfort temperature, which was related to the indoor temperature of the investigated indoor spaces.
Nepal	Pokharel et al. 2020	Houses	Sub-tropical region,	About 90% of the measured indoor air temperature was found below the comfort temperature of all three regions. Average measured indoor air temperature was 8.0 °C, 13.9 °C and 12.8 °C, respectively.
Nepal	Gautam et al., 2020	Residential houses	Sub-tropical region	There is a significant difference in the preferring lower temperature between local and migrant peoples under the condition of indoor globe temperature lower than 31 °C. This indicates that it is more difficult for the migrant people to maintain thermal comfort than local people. At globe temperature above 31 °C, the difference gradually decreases, and the difference ceases as the indoor globe temperature reaches 35 °C.

country but wide climatic and cultural diversity. However, the thermal comfort standards in Nepal are not well defined. Indoor air temperature is not defined in the National Building Code (NBC Nepal 2015) but they are assumed to equivalent to India, the ranges of temperature, 23 - 26 °C for summers and 21 - 23 °C for winters, irrespective of all types of buildings and climate (NBC, India 2005). In addition, these conditions in Nepal are not compulsory.

2.3.2 Thermal comfort study in Nepal

However, despite the real condition of Nepal's climatic and cultural variations, both can affect thermal comfort and comfort expectations, very few research have been conducted in Nepal. Rijal et al. (2010) conducted a survey on traditional houses during summer and winter seasons of cold, temperate and sub-tropical regions of Nepal. Thermal comfort survey was conducted and 7116 responses were gathered. They found that the residents were highly satisfied with the thermal condition of their houses. They also found the indoor neutral temperature was highest in sub-tropical climate, medium in the temperate climate, and lowest in the cool climate areas both in summer (21.1 ~ 30.0 °C) and winter (13.4 ~ 24.2 °C). The indoor neutral temperature has large seasonal differences (4.9 ~ 13.8K). They claimed that the comfort temperature differences might be due to the seasonal difference in clothing insulation, wind velocity and the physiological or psychological adaptation of the residents to the seasons. Thapa et al. (2018) investigated the thermal environment in temporary shelters after earthquake 2015 in temperate region. They found the mean indoor globe temperature varied between 12.1 and 18.5 °C in winter. The lowest value of mean comfort temperature among the four districts was 15.0 °C and the highest was 28.6 °C; that is, the seasonal difference is 13.6 °C. The range of indoor globe temperature, within which 80% of the respondents would accept, was found from 11 °C to 30 °C. Gautam et al. (2019) investigated the thermal comfort of traditional Nepalese houses in the cold, temperate and subtropical regions. The mean indoor globe temperature was 12.2 °C in the cold region, which was 4.7 °C and 10.0 °C lower than that in the temperate and sub-tropical regions, respectively. The estimated mean comfort globe temperature was 13.8 °C in the cold region, which was 4.1 °C and 9.3 °C The mean comfort temperature in cold region was lower than that in temperate and sub-tropical regions. Rijal et al. (2021) conducted on cold climate in Nepal. Passive heating effects were found in houses with thick brick walls and mud roofs. Residents of these houses were highly satisfied with the thermal environment, with 10.7 °C being the mean comfort temperature, which was related to the indoor temperature of the investigated. Gautam et al. (2020) investigated two groups of people, local and migrant, living in sub-tropical region of Nepal and collected votes of thermal perception from 395 individuals living in 122 houses. They try to clarified whether such thermal history exists and if it does, then it is important to clarify how it is associated with their thermal adaptability. They found the significant difference in the preferring lower temperature between local and migrant peoples under the condition of indoor globe temperature lower than 31 °C. At globe temperature above 31 °C, the difference gradually decreases, and the difference ceases as the indoor globe temperature reaches 35 °C. There is a significant difference in the preferring lower temperature between local and migrant peoples under the condition of indoor globe temperature lower than 31 °C. This indicates that it is more difficult for the migrant people to maintain thermal comfort than local people. At globe temperature above 31 °C, the difference gradually decreases, and the difference ceases as the indoor globe temperature reaches 35 °C. Pokharel et al. (2020) investigated indoor thermal environment and its associated energy use in cold, temperate and sub-tropical regions in Nepal. About 90% of the measured indoor air temperature was found below the comfort temperature of all three regions. Average measured indoor air temperature was 8.0 °C, 13.9 °C and 12.8 °C, respectively.

2.3.3 Well-being and productivity

It is internationally accepted that thermal comfort is defined as a condition of mind. Indoor thermal comfort is among the most important factors affecting occupant well-being, health and productivity in buildings (Frontczak and Wargocki 2011). This is important since people spend up to 87% of their time in enclosed buildings, especially in developed countries (Klepeis et al. 2001). However, in an ordinary building, there is a significant energy cost to heat or cool the building to the desired level of comfort. In developed countries, where energy demand is nearly increased, this is estimated to be 20-40% of total final energy use and about 30% of total CO_2 emissions (Pérez-Lombard et al. 2008). However, academic researchers debate whether thermal comfort is related with well-being, productivity and human health. Although it is an open debate, concrete evidence indicates that the aforementioned aspects of human 'mortality' are inherent with thermal comfort. For example, Parson (2014) stated that the performance of children in schools was reduced when they were subjected to uncomfortable. In addition, a study carried out by Ramsey et al. (1983) shows that temperature higher or lower than the preferable influenced the safety-related behavior of workers. Moreover, Niemelä et al. (2002) observed that productivity in telecommunication centers decreased by 5-7% when the workers are sensing high indoor temperatures. Seppanen et al. (2006) wrote that the performance in offices is reduced by about 9% when occupants are subjected to a temperature of 30 °C.

Considering performance (or productivity) in a workplace as the output of the system, the well-being of each individual person is substantially contributing to the quality and quantity of the productivity. For instance, Warr (2002) concluded that high levels of performance are coherent with greater well-being. Apart from personal or social-economic factors, Clement-Croome (2000) pointed out that the environment is considered as another determinant factor of well-being. In essence, the previous studies presented that the performance (output) of workers was negatively affected, as a consequence of indoor thermal discomfort which is directly reflected on the well-being of people. To this effect, the provision of thermal comfortable environments are associated with higher levels of performance, as health and well-being are enhanced (Clements-Croome 2000).

Evidently, well-being and health are important factors on the mortality of people. Since workplaces are conditioned to maintain moderate climates in order to enhance well-being and health, people indisputably have the same expectations of thermal comfort at home. In the case of residential buildings, a range of adaptive opportunities (siesta, open/close window, clothing, etc.) might be undertaken to maintain the indoor thermal environment. The adaptivity and control of environment, gives more "forgiveness" on the fluctuation of indoor thermal environment.

2.4 Thermal improvement and energy saving

Thermal comfort is one of the most important parameters when designing buildings (Douvlou 2003). The role of natural ventilation in buildings in different climates, efficient design parameters and their application to improvement of thermal performance and decrease of energy use (Moosavi et al. 2014). Mainly, after the 1973 oil crisis, the focus was shifted to reducing energy usage in buildings as much as possible by considering the energy-efficient strategies into the passive design without decrease the level of comfort in the building (Aldawoud 2013). It is therefore important to try to achieve thermal comfort via natural means as much as possible and to lower the energy usage of buildings by incorporating energy efficient strategies into designs (El-Darwish and Gomaa 2017, Aldawoud 2013). Emphasis on thermal comfort in terms of energy efficiency. Some of the important measures used in the retrofitting process of the building envelope include: external walls' insulation, windows' glazing type, air tightness (infiltration) and solar shading (El-Darwish and Gomaa 2017). Increasing populations, increasing levels of service and comfort in buildings, and increasing time spent in buildings ensure that energy demand continues to grow. For this reason, building energy efficiency is today a major goal of energy policy at the regional, national and international levels (Pérez-Lombard 2008). Many studies show in Table 2.3 energy use can be reduced by many strategies and can be improved the indoor thermal condition with less energy use.

Few studies have been conducted on thermal improvement and saving energy of the buildings in the context of Nepal. Fuller et al. (2009) investigated comfort levels in a traditional house located at high altitude area of Nepal and found that the reduction of infiltration was likely to be more effective than increasing the insulation level in the ceilings. They pointed out that this strategy increased average internal temperature by 1.7 to 2.3 °C. Combining increased insulation levels, the level of discomfort in the sunspaces was reduced by more than 50%. Rijal (2012) conducted the structural improvements on the thermal performance of a traditional house in Nepal. To increase the indoor air temperature in winter, three kinds of sealants were used to make openings airtight, and three kinds of insulation were used in the roof, floor and

Table 2.3 Reduction of energy use applying various strategies in the world.

Country	Reference	Building	Strategy	Key findings and energy use
Hong Kong SAR	Chow and Lam 1992	Office	Raise SST from 21.5 °C to 25.5 °C (SST = summer set point temperature)	Cooling energy reduced by 29%.
Montreal	Zmeureanu and Doramajian1992	Office	Raise SST from 24.6 °C to 25.2 °C (during 09:00 ~ 15:00) and up to 27 °C (during 15:00 ~ 18:00)	Chilled water use reduced by 34 ~ 40% and energy budget for HVAC by 11%.
Singapore	Sekhar 1995	Office	Raise SST from 23 °C to 26 °C	Cooling energy reduced by 13%.
Pakistan	Nicol and Roaf 1996	Office	Change the 26 °C SST to a variable indoor design temperature (Tc = 17 + 0.38To; Tc = comfort temperature, To = mean monthly outdoor temperature)	Potential energy savings of 20 ~ 25%.
Hong Kong SAR	Mui and Chan 2003	Office	Change SST from 24 °C (average) to adaptive comfort temperature (Tc = 18.303 + 0.158To)	Energy use by cooling coil reduced by 7%.
Riyadh	Al-Sanea and Zedan 2008	No specific	Change yearly-fixed Thermostat setting (21 ~ 24.1 °C) to optimized monthly fixed settings (20.1 ~ 26.2 °C)	Energy cost reduced by 26.8 ~ 33.6%.
Australia	Roussac et al. 2011	Office	Static (raise SST 1 °C higher) and dynamic (adjust SST in direct response to variations in ambient conditions)	HVAC electricity use reduced by 6% (static) and 6.3% (dynamic).
Las Vegas	Sadineni and Boehm 2012	Home	Raise SST from 23.9 °C to 26.1 °C (during 16:00 ~ 19:00)	Peak electrical energy demand reduced by 69%.
Egypt	Radwan et al. 2016	Commercial, Hospital	Experiment, a case study	Air conditioning system in buildings used 56% of total energy use in buildings
Egypt	Darwish and Gomaa 2017	University	The simple retrofit strategies such as solar shading, window glazing, air tightness then insulation	Reduce energy use by 33%.
World	Urge-Vorsatz 2015	Dwelling and office	Improve thermal efficiency of the building	Reduce energy use by 18 ~ 73%
China	Tong et al. 2016	Office	Raising set point temperature	Reduce energy use by 8 ~78 %
China	Xu et al. 2020	Dwelling	Set temperature of the air conditioning systems	Reduce energy use by 26.87 ~ 36.51%

Country	Reference	Building	Strategy	Key findings and energy use
South Korea	Yun et al. 2016	Office	Adaptive comfort models	Reduce energy use by 22%
Australia	Roussac et al. 2011	Office	Dynamic (adjust set point temperature in direct response to variations in ambient conditions)	Reduce energy use by 6.3%
Spain	González-Lezcano and Hormigos-Jiménez 2016	Dwelling	Natural ventilation	Reduce energy use by 13%
Spain	Sánchez-Guevara et al. 2017	Dwelling	Shifting from the conventional fixed thresholds to the adaptive energy demand	Reduce energy use by 20 ~ 80%
Netherlands	Kramer 2017	Museum	Set point algorithm	Reduce energy use by 53 ~ 74%
Spain	Barbadilla-Martín et al. 2018	Office	Adaptive control algorithm	Reduction of energy use by 11.4 ~ 27.5%
USA	Walker 2016	-	Natural ventilation	Reduce energy use by 10 ~ 30%
UK	Nicol 2012	Building	A simple method used to assess heating requirements for building is to find from weather data the number of heating degree-days in the cooling season.	25% in the heating energy used for a drop of 2.5 k in the internal temperature- or a saving of about 10% for every degree.

walls. The nighttime indoor air temperature of the improved house was 4.4 to 12.7 °C higher than the base model. Firewood use was reduced by 60% in the improved house, while at the same time the nighttime indoor air temperature was 1.0 to 4.0 °C higher than the base model. Thapa et al. (2019) studied wintry thermal improvement to examine the thermal improvement of the shelters. They did not consider the effects of miscellaneous heat generation and infiltration. They found that, if the total heat loss coefficient per floor area was reduced, then a significant improvement of indoor air temperature could be realized. It was shown that the heat loss coefficient could be reduced by adding cellular polyethylene foam sheets for the walls and roof of temporary shelters.

2.5 Conclusions

We reviewed previous studies on energy use, thermal comfort, thermal environment, and thermal improvement. We found the followings results.

1. In the context of Nepal, the researchers have so far conducted on overall energy sectors such as firewood, fossil fuels, biomass, electricity, and solar PV system. But no studies have focused yet on household sector in particular.

2. Adaptive thermal comfort model is effective method than the PMV-PPD model for implementation on Nepalese homes due to its variation of climate, unique culture, socio-economic factors and adoption behaviour.

3. Nepal is a developing country with very low income levels and poor access to electricity. When Nepalese people use mechanical heating and cooling appliances, the energy demand increases, so that the indoor thermal environment model can be effective model than other energy use model.

4. Many researchers have focused, either, on current indoor thermal condition and or, on the improvement, but not on both. Therefore, this study need to focus on thermal comfort condition of residents in houses in winter, and thermal performance improvement of these houses.

Chapter 3: Methodology

3.1 Introduction

The altitude ranges in Nepal from a minimum of 64 meters to a maximum of 8848 meters above sea level whereas the climate varies with its topography. Nepal is topographically divided into three main regions. There are Himalayan region, hilly region and Terai region. Basically, it has three climate regions: i.e. cold lies in Himalayan region, temperate in hilly region and subtropical in Terai region. We selected the three districts such as Kalikot lies in cold climate, Kathmandu lies in temperate climate and Chitwan lies in sub-tropical climate. for the field study.

Kalikot

Kalikot District a part of Karnali province, is one of the seventy-seven districts of Nepal. The district consists of nine municipalities, out of which four are urban municipalities and five are rural municipalities. It has an altitude 300 to 5,000 m. The total area of the Kalikot district is 1741 square kilometers. It has a population of 136,948 and it has 23,013 households, with 5.95 family members (CBS, 2011). The literacy rate is 48% of the total population. Farming is the main occupation of peoples. The access to transportation has not covered all area and no good access to electricity Table 3.1.

Kathmandu

Kathmandu is the capital and largest city of Nepal. It is located in a valley surrounded by the Himalayan mountains. The city is located in a bowl-shaped valley in central Nepal at an altitude of about 1,400 meters (4,600 feet) and is surrounded by four major mountains: Shivapri, Purchoki, Nagarjun and Chandragiri. The total area of the Kathmandu district is 395 square kilometers. Kathmandu has a population of 1,744,240, and it has 436,344 households, with four family members (CBS 2011). According to CBS (2011), the literacy rate is 81% of the total population. Service and business are the main occupations of their peoples. The access to transportation covered all area and good access to electricity as shown in Table 3.1. The Kathmandu valley with its three districts including Kathmandu District accounts for a population density of only 97 per square kilometers whereas Kathmandu metropolitan city has a density of 13,225 per square kilometers. Kathmandu, as the gateway to Nepal Tourism, is the nerve center of the country's economy. With the most advanced infrastructure among urban areas in Nepal, Kathmandu's economy is tourism centric accounting for 3.8% of the GDP in 1995-96 (had declined since then due to political unrest but has picked up again). The city's rich history is nearly 2000 years old, as inferred from an inscription in the valley. Nepali is the common language of the city, though many speak the Nepal Bhasa Newari as it is the center of the Newar people and culture. English is understood by all of the educated population of the city. Kathmandu is now the premier cultural and economic hub of Nepal and is considered to have the most advanced infrastructure among urban areas in Nepal. From the point of view of tourism, economy and cultural heritage, the sister cities of Patan (Lalitpur) and Bhaktapur are integral to Kathmandu (KMCO, 2012).

Chitwan

Chitwan District is one of district of Nepal, and takes up the southwestern corner of Bagmati Province. Bharatpur is the largest city of Nepal after Kathmandu, is its administrative center. Chitwan is semi-urban area it has the altitude 300 to 2,000 m. It covers 2,218 square kilometers, and in 2011 had a population of 579,984 (279,087 male and 300,897 female) people. It has 132,462 household, with average 4.38 members per family. The literacy rate is 71% of the total population. Farming, Service and business are the main occupations of their peoples. The access to transportation covered all area and good access to electricity as shown in Table 3.1. Bharatpur is the commercial and service center of South Central Nepal and a major destination for higher education, health care and transportation in the region. Chitwan lies in the Terai region of Nepal. It is in the drainage basin of the Gandaki River and is roughly triangular, taking that river as its meandering northwestern border, and a modest watershed border, with India, as the basis of its southern limit.

3.2 Plan view of houses

Fig. 3.1 shows the photographic external and plan views of the three houses cold, temperate, and sub-tropical regions of Nepal. In cold region, all investigated houses were made by local materials such as stone, wood and mud. In cold region, the traditional houses have thick walls. These houses are multi-storied and the ground floor rooms are used to keep livestock, while the middle and upper storeys often consist of living rooms and store rooms. Mainly, firewood was used for cooking and heating purpose through traditional cookstove in the cold region. Access to transportation and national electricity was poor. The size of room, window and door was very small. Residents want to maintain indoor temperatures during the winter because the outside temperature is very low. Since this field survey was conducted in urban areas in temperature region, all the houses surveyed used the latest materials, including: cement, brick, wood, zinc. The wall is thinner than cold region. Access to transportation and national electricity grid was very good. LPG was used for cooling and electricity was used for lighting, but less energy source for heating purposes was used. Since this field survey was conducted in semi-urban areas in sub-tropical region, almost all houses used the modern materials similar to temperate region but some houses was made by using local materials such as; wood and mud only those houses were single storey.

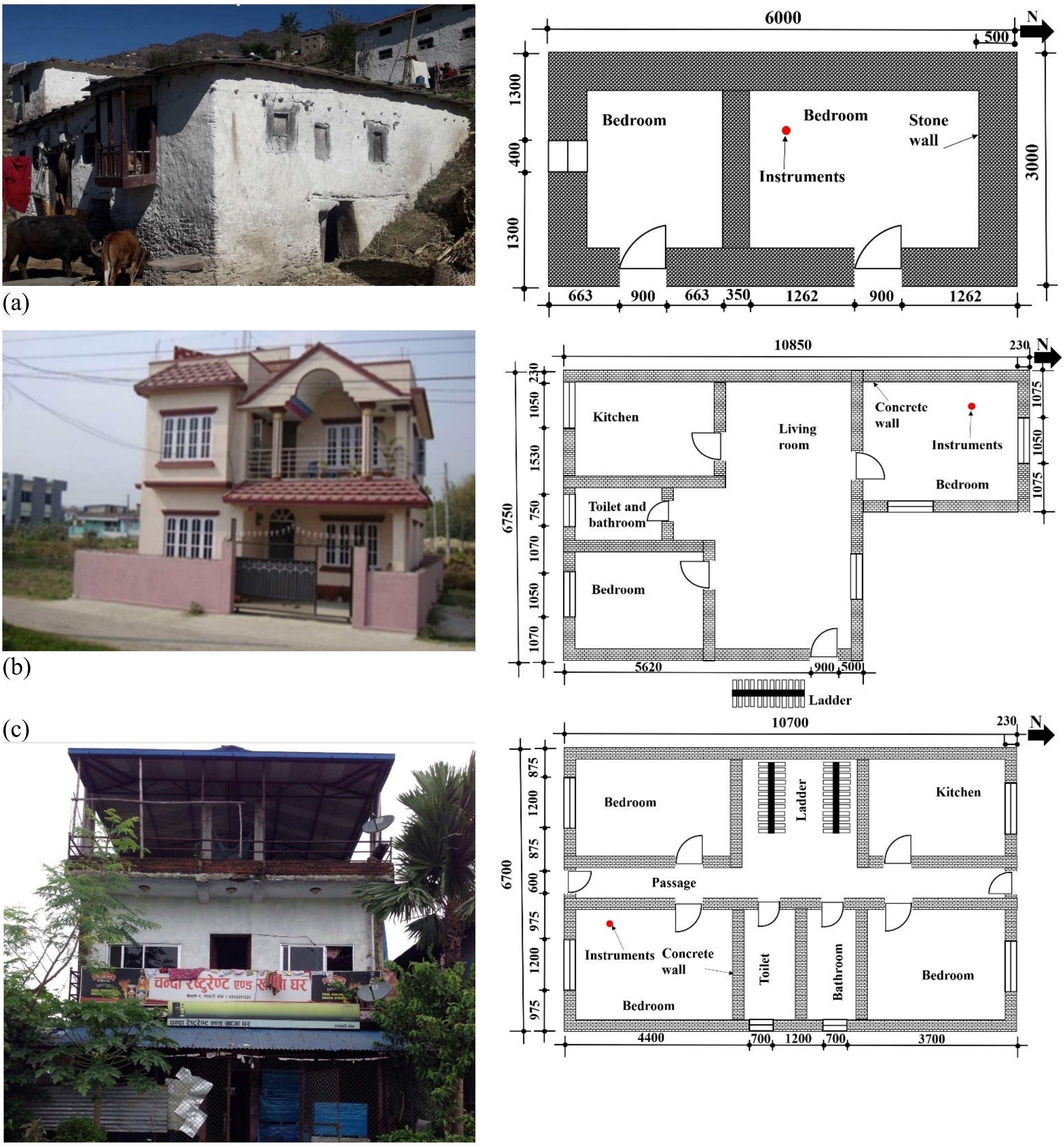


Fig. 3.1 Photographic external and plan views of the three houses: (a) Cold, (b) Temperate, and (c) Sub-tropical regions (Unit: mm)

Table 3.1 General information of the study areas and the houses surveyed

Information	Study area	Rural	Semi-urban	Urban
General	District	Kalikot	Chitwan	Kathmandu
	Climate	Cold	Sub-tropical	Temperate
	Total population	136948	579984	975453
	Male	68833	279087	913001
	Female	68155	300897	831239
	No. of household	23013	132462	436344
	Family member/ household	6	4	4
	Literacy rate [%]	48	71	81
	Major occupation	Farmer, service	Farmer, service, business	Service, business
	Transportation access	Not good	Good	Good
	Grid electricity access	No	Yes	Yes
	Area [km²]	1741	2218	395
	Altitude [m]	300-5000	300-2000	up to 1400
	Average temperature in winter from December to February [°C]	10.6	16.5	10.9
Surveyed	No. of houses	114	112	216
	Survey period (2018)	23rd-29th Jan.	5th-9th Feb.	13th-23rd Feb.
	Building materials used	Stone, soil, wood, straw, zinc	Cement, brick, iron, zinc, wood	Cement, brick, iron, zinc, wood

3.3 Household energy use survey

The field survey for energy use patterns was conducted for one month from 23rd January to 23rd February, 2018. We choose survey area based on rural, semi-urban and urban. The households were randomly selected. The energy use data was collected from 442 houses. The houses were randomly selected: 114 households from rural area, 112 from semi-urban area, and 216 from urban areas. The questionnaire survey was conducted all these houses. The interview was conducted with the occupants. Data were recorded by the interviewer. The questionnaires were designed based on previous studies (Hu 2017) and (Sukarno et al. 2017), and modified in the context of Nepal. Table 3.2 shows the data collection and questionnaire patterns, which were divided into five categories. We have collected household information such as the number of family members (above 10 years old only), household income and occupation and the educational level of household responsible person. We prepared the list of electric appliances such as electric lamp, radio/music system, computer, electric fan, air-conditioning unit and so on, as shown in the detail of second row of primary item. They were checked upon their use. The energy use data was collected through monthly electricity bills, firewood use per month (Bundel: "Bhari" in local language) with price, the sources of firewood and liquefied petroleum gas (LPG) cylinder (14.5 kg/cylinder). We also collected the data of photovoltaic cell, candles and kerosene use. The whole questionnaire sheet was structured so that socio-demography data, household energy use and the household energy use patterns are obtained.

Fig. 3.2 Landscape and houses structure: Cold; (a) landscape, (b) house build; Temperate: (c) landscape, (d) house build; Subtropical; (e) landscape, and (f) house built

Table 3.2 Items of questionnaire and their details

Primary items	Details of collected data
Household information	Number of family members, household income, occupation, education level, marital status, sex of household responsible person.
Access to household appliances	Electric lamp, radio/music system, computer, electric fan, ac, electric heater, micro oven, vacuum cleaner, refrigerator, washing machine, mobile phone, electric iron, TV, electric rice cooker, electric water pump, electric mixer
Amount and source of energy	Electricity, LPG, firewood, candle, kerosene, solar panel, residue
Purpose of energy use	Lighting, cooking, heating and cooling
Types of lamp	Incandescent, fluorescent, or LED

3.4 Thermal comfort survey

The thermal comfort survey was conducted for one month from 23rd January to 23rd February, 2018 (Table 3.3). Firstly we visited a cold region, secondly sub-tropical region, and lastly temperate region. Random sampling method was applied for choosing the houses in all regions. In cold region, data were obtained within 3864 m in length and 3640 m in height. The distance from the one surveyed house to another was 15-180 m. In temperate region, data were obtained within 2896 m in length and 1526 m in breadth. The distance from the one surveyed house to another is 10-47 m. In subtropical region, data were obtained within 2656 m in length and 1710 m in breadth. The distance from the one surveyed house to another was 20-50 m as shown in Fig. 3.3 (a-c). We collected 203, 407 and 229 votes from 114, 216 and 112 households in cold, temperate and sub-tropical regions, respectively. We took 839 votes from 442 households from the people whose age ranging from 15 to 65 years. The voting was made for 20 minutes from 7:20 to 20:40 in all regions. All interviews were conducted in living room as shown in Fig. 3.4 (a). We used modified thermal sensation scale and thermal preference scale which was translated into Nepali language as shown in Table 3.4.

Table 3.3 General information of the surveyed houses

Survey information	Cold	Temperate	Sub-tropical
Survey period (2018)	23rd -29th Jan.	5th -9th Feb.	13th -23rd Feb.
No. of houses	114	112	216
No. of respondent	203	407	229
Average indoor air temp. [°C]	12.7	19.2	20.6
Average outdoor air temp. [°C]	11.7	20.7	21.9
Age range	10-85	10-73	10-84

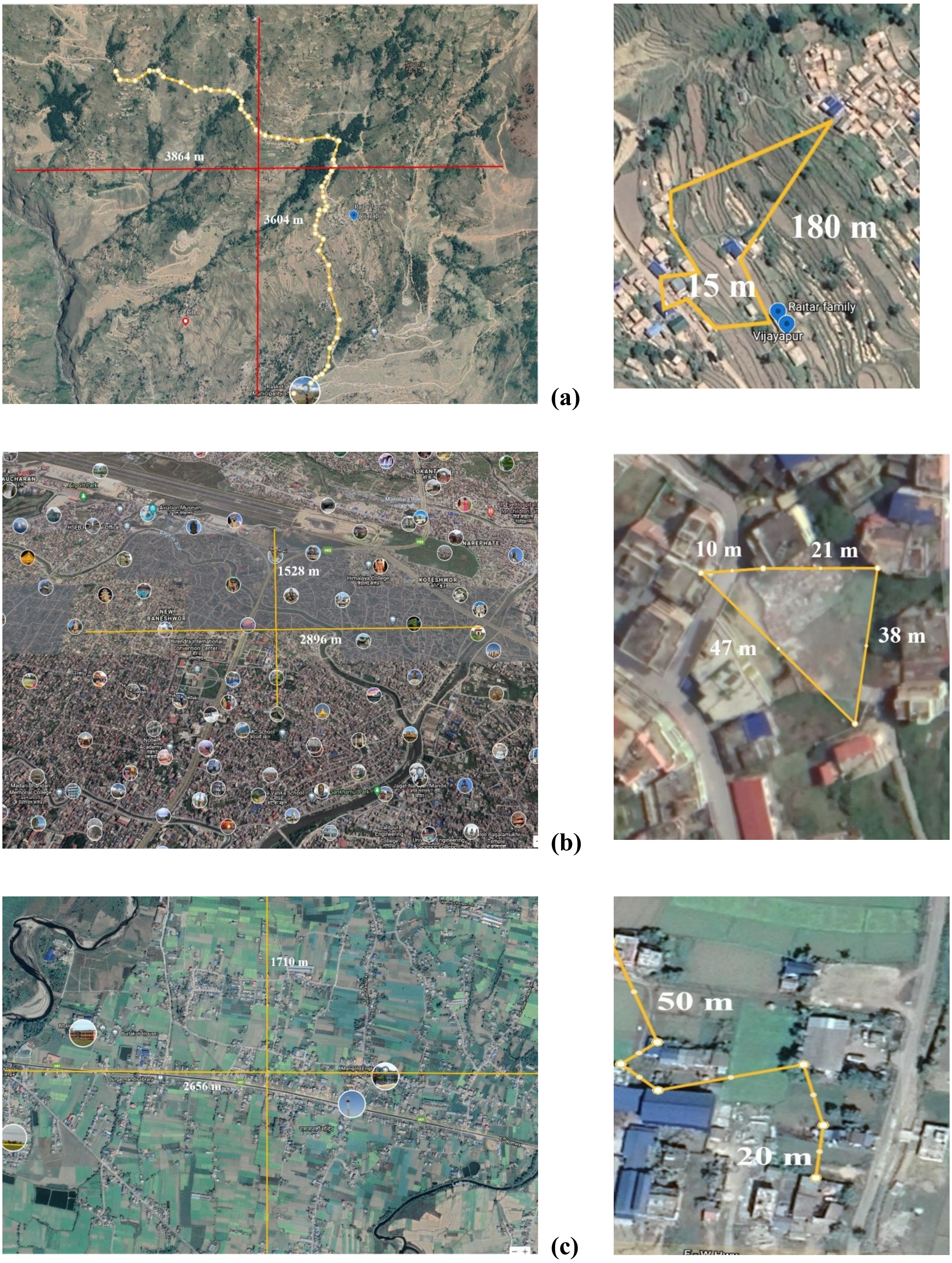


Fig. 3.3 Photographic view of study area: (a) cold, (b) temperate, and (c) subtropical regions

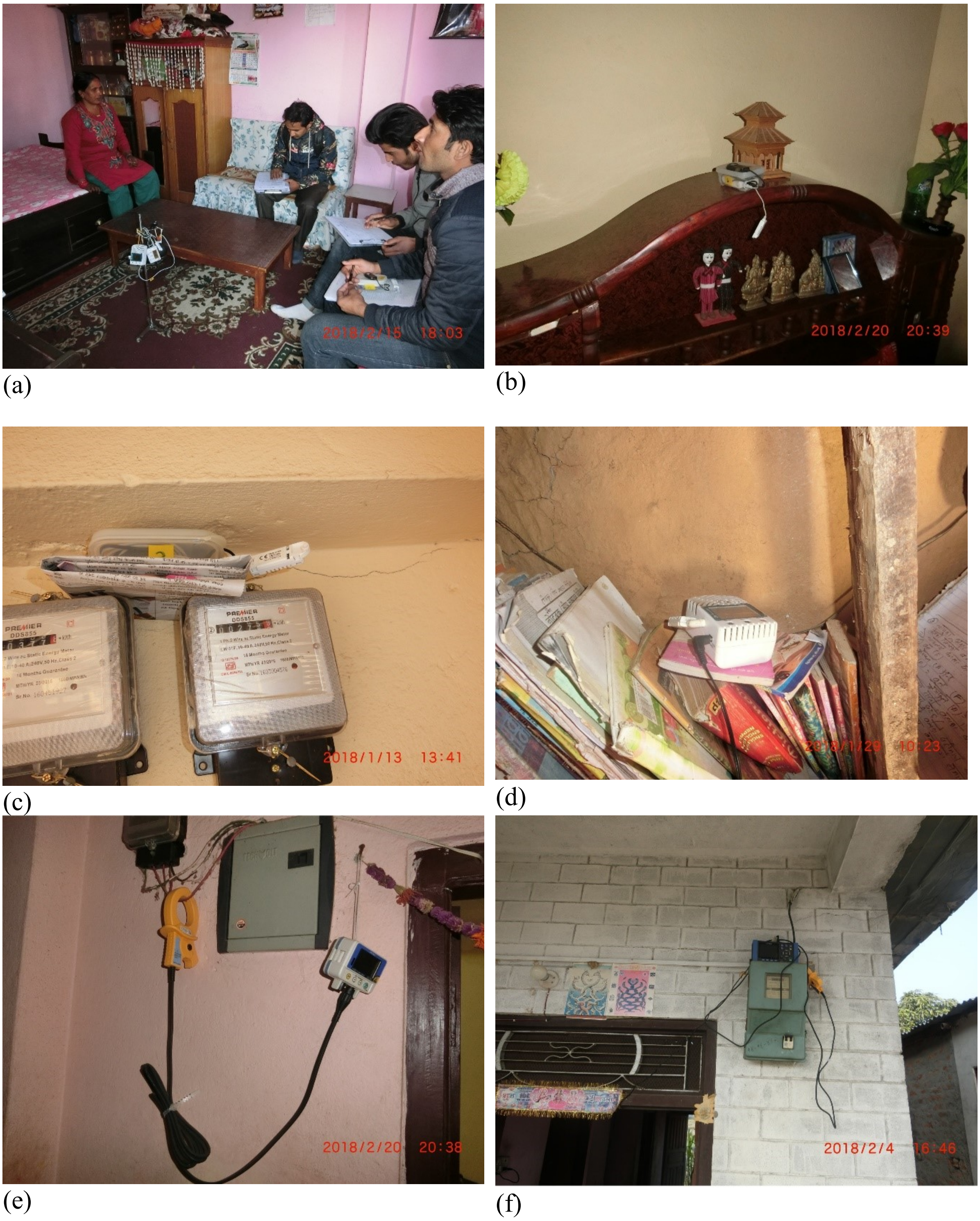


Fig. 3.4 Interview and data recording scene: (a) taking thermal sensation vote, (b) recording indoor air temperature, (c) recording outdoor air temperature, (d), recording the indoor CO_2, (e) recording the electricity by small data logger, and (f) recording the electricity by big data logger with voltage

Table 3.4 Thermal sensation scale used (Rijal et al. 2010).

English		Nepalese	
Modify thermal sensation vote (mTSV)		चिसो तातोको अनुभव:	
1.	Very cold	१.	जाडो
2.	Cold	२.	चिसो
3.	Slightly cold	३.	अलिकति चिसो
4.	Neutral (Neither cold nor hot)	४.	ठिक्क (चिसो पनि छैन तातो पनि छैन ।)
5.	Slightly hot	५.	अलिकति तातो
6.	Hot	६.	तातो
7.	Very hot	७.	गर्मी
Thermal preference		तापक्रमको चाहना :	
1.	Much warmer	१.	धेरै न्यानो चाहिन्छ ।
2.	A bit warmer	२.	अलिकति न्यानो चाहिन्छ ।
3.	No change	३.	यत्तिकै ठिक्क छ ।
4.	A bit cooler	४.	अलिकति शीतल चाहिन्छ ।
5.	Much cooler	५.	धेरै शीतल चाहिन्छ ।

3.5 Description of instrument used

Field and continuous measurements of indoor, outdoor air temperature, indoor global temperature, and indoor relative humidity were measured by the instruments and data loggers named in Table 3.5 and the photographs shown in Fig. 3.5. The instruments were set in the middle of the rooms. While vising the houses, we first set the instruments outdoors and then indoors. The data were recorded after 15-20 minute had passed since the instruments were set up. The instruments were placed about 1.1 m above the floor level for indoors and about 1.5 m above the ground surface for outdoors. The effect of solar radiation is avoided to the senso

Table 3.5 The instruments used for this study.

Parameter measured	Name of instruments	Sensors	Range	Accuracy
Air temperature, relative humidity	TR-74 Ui	Thermistor and polymer membrane	0.55 °C, 10-95%	± 0.5 ºC, ± 5% RH
Globe temperature	TR-52i, SIBATA, 080340-75	Black painted, 75 mm-diameter globe	-60 to 155 °C	± 0.3 ºC
Surface temperature	Custom, IR-300	Infrared sensor	-55 °C to + 220 °C	± 2% rdg or ± °C
CO_2 recorder	TR-76Ui	Infrared sensor	0 to 9999 ppm,	±(50 ppm + 5 % of reading)
Air velocity	Trust Since Innovation (TSI) 9535	Hot-wire anemometer	0-30 m/s	± 0.15 m/s

Fig. 3.5 The use of instruments for thermal measurement: (a) instrument for globe temperature, (b) that for globe temperature (globe diameter), (c), that for air temperature and relative humidity (d) that for air velocity (e) that for surface temperature, and (f) that for CO_2.

Chapter 4: Energy use patterns in Nepal

4.1 Introduction

4.1.1 Overview of this study

Some rate of energy-use is necessary for human being to realize a certain required living standard. It can be an indicator to know about the household living condition. Availability of energy source is one of the human basic requirements for a better quality of life and thereby the development of a whole nation. Energy use at a certain rate is necessary for the development of any society to upgrade the quality of life, to achieve socio-economic growth and thereby to realize rational modernization. Electricity is a clean energy source at least at the demand site and its accessibility is a determining factor for the improvement of the quality of life. In general, people tend to believe that the more one uses energy, the better his/her quality of life becomes and so-called energy saving simply decreases the quality of life. However, it is important to seek the way of life that can realize the reasonably better quality of life with the least possible rate of energy use in dwellings.

Fig. 4.1 shows the general trends of energy use both in developing and developed countries at present and also the future goal to be designated. Two boxes in the left are representing the low energy-use countries (LOW) and high energy-use countries (HIGH) at present on the earth. One box on the right indicates the future target (MEDIUM). In low energy-use countries, so-called developing countries, a large portion of people live in rural areas and the lifestyle has to rely very much on local animal and plant powers due to less accessibility to electricity. Developing countries are facing two serious problems in the energy sector. The first is too-much dependency on the use of traditional energy sources such as firewood and agricultural residues, which cause economic, environmental, and health threats. The second is the highly uneven access to modern energy sources such as petroleum products, and liquefied natural gas, which can be used for electric power production that would help solve the issues of equity and the quality of life, both of which are much dependent on the level of societal economic activities (Barnes and Floor 1996). High energy use countries are so-called developed countries with more or less high rate of energy use.

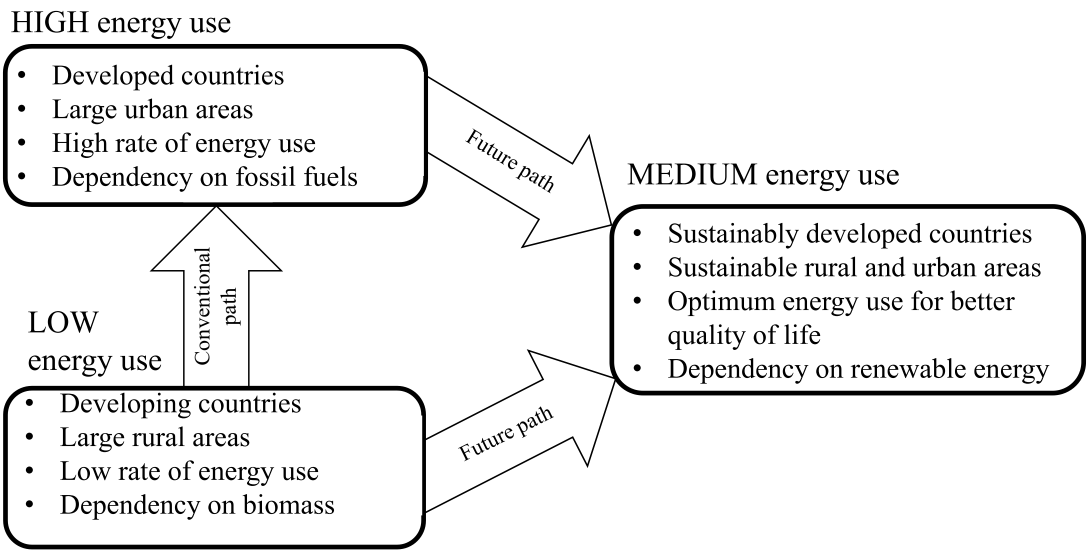


Fig. 4.1 Energy-use status of developing and developed countries and the future target to be sought for the equity of wellbeing

A path from "LOW" to "HIGH" indicates the conventional path of development that a developing country follows to become a developed country. Most of the developed countries use fossil fuel to meet the energy demand of various sectors. "MEDIUM" represents a futuristic rational path of energy use to follow for reasonably good quality of life for both developed and developing countries. There are two possibilities for developing countries: one path from "LOW" to "HIGH" or the other from "LOW" to "MEDIUM". The path to be sought is, of course, the latter. This is considered to become possible by introducing, for example in building sector, the design of thermally well-insulated building envelopes and the associated construction methodology. Most of the developing countries are focusing more energy use for development, but they need to decrease fossil fuel and biomass energy demand (Ahuja and Tatsutani 2009). One reason is that the renewable energy is now cheaper than oil and it is about the same price as oil and coal are included in fossil fuels. However, they are expensive than coal. The other reason is that electricity can offer various opportunities such as efficient transportation with rationally, high energy efficiency and low impact to local environment (Kaberge 2018). The current energy supply system can be improved with the implementation of commercialized renewable energy system such as small micro hydraulic, solar photovoltaic, wind turbine plants for electricity production (Lund 2007). The path for developed countries, from "HIGH" to "MEDIUM", does not imply that the people living there decreases their quality of life but rather increase it by reducing the fossil-fuel demand for running conventional mechanical heating/cooling systems. Then the energy use will be balanced rationally both in developed and developing countries. The present status of energy use patterns in least developed countries such as Nepal has to be searched in order for them to develop their respective rational energy policies that meet the path from "LOW" to "MEDIUM" as shown in Fig. 4.1 and hence to clarify the goal of overall national macro-economic development strategy.

Globally, 1.06 billion people do not have access to electricity and more than 3 billion still use fuels like wood, charcoal, coal and dung for cooking and heating (World Bank). The average rate of electricity use increases by 28% in the world and the rate of electricity use in buildings grow 2% annually because of the increasing demand for electric appliances, personal equipment, and commercial services (IEO 2017). Nepal is the least developed country with the population of 26.5 million and 5.6 million households in 2010 and 81% of people live in rural area (CBS 2011). The rate of electricity use and the number of consumers increase at the rate of approximately 9% per year (NEA 2018). Nepal has indigenous natural energy resources such as hydro, solar and wind. The hydropower potential is 83 GW, but Nepal has so far 1.07 GW has succeeded marginally in producing the electricity from hydro (Shrestha 2016). The 1.02 GW is under construction and 9.92 GW purposed for future planning. The electricity use in residential sector accounts for nearly 87% of total electricity use in Nepal and 94% are domestic consumers (Nakarm et al. 2016), (WECS 2014). The total population with access to grid electricity has reached about 70% and 45% of the population has the access to national grid (NEA 2018).

Nepal is a developing country and we speculate easily that the rate of electricity use is much lower than developed countries. But, for the sake of formulating the rational energy use in order to achieve a certain benign quality of life in the future in Nepal, it is necessary for us to know the current and previous energy situations. The development of easier access to electricity at households in Nepal as a whole is no doubt necessary. For this purpose, we have reviewed the Nepal Electricity Authority report 2017/2018 (NEA 2018). We extract from this report, the required electricity, electricity use and sources of electricity (its own generation from hydro-power stations and purchased portion from India) from year 2009 to 2018 (World Bank).

Fig. 4.2 shows the annual average rate of electricity use per capita in respective countries from 2000 to 2014. The vertical axis denotes the rate of electricity use and the horizontal axis the year from 2000 to 2014. In India, the rate of electricity use is the highest in these years. In Nepal, the rate of electricity use is the lowest in the South-Asian countries. Other South-Asian countries such as Sri-Lanka, Pakistan and Bangladesh have higher electricity use than Nepal. The increase in the rate of electricity use is increasing in India and Bangladesh looks obvious than other countries. The average rate of electricity use in South-Asian countries is 5 times larger than Nepal. The main reason is due to the insufficient production of electricity in Nepal.

Fig. 4.3 shows the annual total rates of electricity use and peak demand by year from 2009 to 2018 in Nepal (NEA 2018). The vertical axis on the left denotes the annual rate of total electricity use and the vertical axis on the right denotes the peak electricity demand occurred each year. The horizontal axis is the years from 2009 to 2018. In Nepal, almost all of electricity has been generated by hydro power plants and the rest was purchased from India. The peak demand looks to have grown steadily. If this trend is assumed to continue, then the solution to meet the growing peak demand is to construct more and more power plants. But what we need to be careful is how often such peak demand occurs throughout the whole year. That is, to take the frequency distribution of demands is important. If the peak demand that is much larger than the average demand, it is definitely much better to mitigate such peak demand and thereby manage the whole of the demands to remain within a certain narrow range so that the construction of rational sized power plants to be socially and environmentally friendly becomes possible. Such a way is, as shown in Fig. 4.1, necessary for the sustainable devolvement that seek a better quality of life with the optimum energy use. If the peak demand tends to occur early in the afternoon, then the installation of PV cells on the roof of a house becomes reasonable. Anyway, we need to make a good management of the demand in additional to build a rational sized power plants in future.

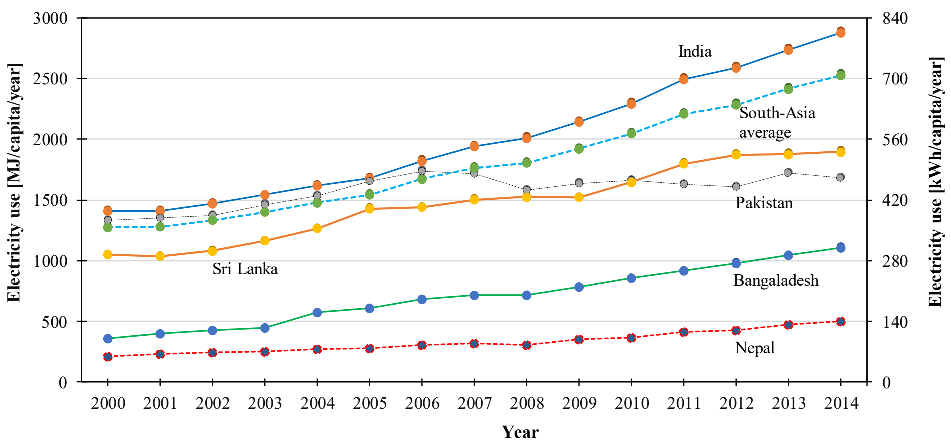


Fig. 4.2 Electricity-use trend in South-Asian countries from 2000 to 2014 (World Bank)

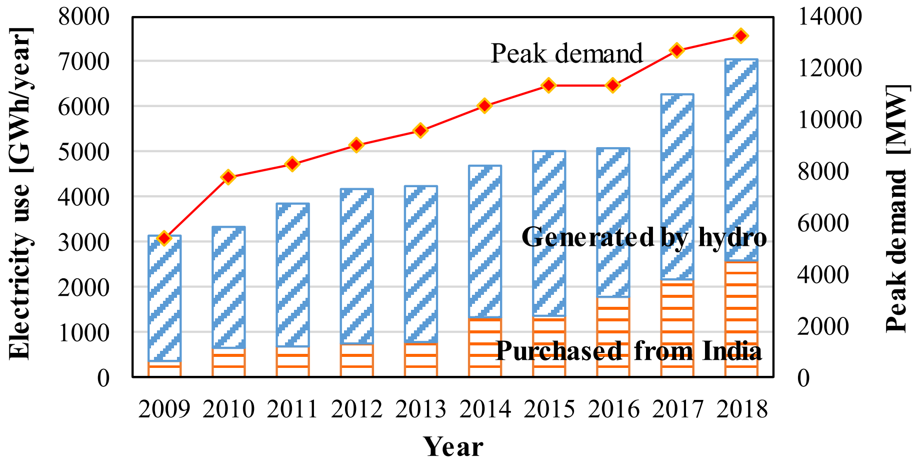


Fig. 4.3 Peak demand and electricity use in Nepal from 2009 to 2018 (NEA 2018)

The previous researches (Mullaly 1998, Jaber 2002, Westergren 1999, Chen 2006, Pachauri and Jiang 2008, Zhang et al. 2009 and Craig Petersen 1982) have focused on household energy use, household size, income, access of electricity, climate, energy price, and ownership of appliances in developed countries and other developing countries. Nepal has its own unique climatic regions, income levels, lifestyle and occupants' behaviors that are different from other developing countries as they have their own unique cultures as well. In the context of Nepal, the researchers have so far conducted on overall energy sectors such as firewood, fossil fuels, biomass and electricity, energy demand model and forecasting, rural electrification and solar PV system. But no studies have focused yet on household sector in particular.

4.1.2 Objectives

Under such circumstances so far of the researches on energy use in Nepal, we try to clarify the household energy use patterns and mainly focus on the electricity use. It is important to know the current situation of energy use, the availability of energy resources (firewood, electricity, LPG and solar PV), and the use of electric appliances. We also analyze the relationship between energy use and social economic factors such as, household income, household size, the use of light emitting diode (LED) and the educational level of household responsible persons. This research is to estimate the rate of electricity use in rural, semi-urban and urban households of Nepal and thereby to make comparison with previous studies for the future planning of Nepalese household energy policy.

4.2. Method of household energy use patterns

4.2.1 Field survey

Field survey was conducted for one month from 23rd January to 23rd February 2018 in the following districts: Kalikot, Chitwan and Kathmandu, which are located in cold, sub-tropical and temperate climate as shown in Fig. 1.1, respectively. Kalikot is a rural area in the western part of Nepal. Chitwan is semi-urban area lying in Terai region. Kathmandu is capital city of Nepal. Fig. 4.4 (a)-(c) show three typical houses in respective districts. Those houses are not equipped with any contemporary types of heating and cooling systems. We conducted the questionnaire survey in similar houses. Fig. 4.4 (d) shows the interview being taken place with the occupant during questionnaire based survey in present study. Data were recorded by the interviewer. Fig. 4.4 (e) shows the interview made while a respondent was at cooking. Fig. 4.4 (f) shows a firewood bundle ready to use in rural households.

(a)

(b)

(c)

(d)

(e)

(f)

Fig. 4.4 Surveyed houses and data collection: (a) Rural house, (b) Semi-urban house, (c) Urban house, (d) A interviewing seen, (e) Firewood use seen for cooking in rural area, and (f) Firewood bundle ready for use in rural household.

Table 3.1 shows the households of three regions surveyed. The houses were randomly selected: 114 households from rural area, 112 from semi-urban area, and 216 from urban areas. The houses are made by stone, wood, soil, straw and zinc in rural area, while on the other hand, they are made by cement, bricks, iron and zinc in urban areas. The questionnaires were designed based on previous studies (Hu 2017 and Sukarno et al. 2017), and modified in the context of Nepal. Table 3.2 shows the data collection and questionnaire patterns, which were divided into five categories. We have collected household information such as the number of family members (above 10 years old only), household income and occupation and the educational level of education of household responsible person. We prepared the list of electric appliances such as electric lamp, radio/music system, computer, electric fan, air-conditioning unit and so on, as shown in the detail of second row of primary item. They were checked upon their use. The energy use data was collected through monthly electricity bills, firewood use per month (Bundel: "Bhari" in local language) with price, the sources of firewood and liquefied petroleum gas (LPG) cylinder (14.5 kg/cylinder). We also collected the data of photovoltaic cell, candles and kerosene use. The whole questionnaire sheet was structured so that socio-demography data, household energy use and the household energy use patterns are obtained.

4.2.2 Logistic regression analysis

To estimate the relationship between the relative number of LED lamps used and the educational level of household responsible person, logistic regression analysis was used. The relationship between the relative number of LED lamps used (p) and the level of education and the income of household responsible person (X) is expressed as the following equations:

$$p = \exp(aX + b) / \{1 + \exp(aX + b)\} \tag{4.1}$$

where, exp (aX + b) represents Napier number (2.718…) powered by (aX + b), a and b are the constants in the regression equation.

4.3. Results and discussion

4.3.1. Nepal's current energy use and its comparison to other countries

In this survey, the types of household energy use are electricity, LPG and firewood. The use of firewood was estimated by the respondents in the unit of Bundel. The mass of one Bundel was weighted in 5 houses with the unit of kg and then the average value was found to be 30 kg/Bundel. The firewood energy use was calculated assuming 16.6 MJ/kg (Rijal 2001). Similarly, energy use with LPG was calculated assuming 49 MJ/kg (Hahn).

Fig. 4.5 shows the monthly average rates of energy use per household in respective areas in terms of firewood, electricity and LPG. The vertical axis denotes the rate of energy use and the horizontal axis the percentage of surveyed households that use the corresponding energy sources. In rural area, all households use firewood and in semi-urban area, nearly 50 % of households; but in the urban area, no household use firewood. The use of firewood is 2080 MJ/household/month in rural areas, which is twice higher than that in other developing countries such as Bangladesh (Foysal 2012). It is necessary to reduce the dependence on firewood by promoting the use of alternative energy source such as PV cells. Access to clean and modern electricity as the secondary energy source is crucial for the well-being of humanity. In all areas, almost all households use electricity; the rate of its use is lower in rural area than semi-urban and urban areas. Similarly, in urban and semi-urban areas, all households use LPG; but in the rural area, only fewer than 15% of households use LPG. The rate of LPG use is the highest in urban followed by semi-urban and the lowest in rural areas in Nepal.

Access to clean and modern energy sources can transform the future of people for better in various ways. For example, the use of LPG for cooking instead of firewood can save millions of women from health issues such as respiratory diseases and a better access to electricity at home can facilitate education to many more millions of children. Moreover, collecting firewood has been recognized as the task of women in the absence of LPG; it is the issue to be solved for the basic human right such as education and security (Acharya and Sadath 2018). The gender discrimination is one of the problems in most rural areas in developing countries. The firewood needs to be replaced by clean and modern energy sources in rural areas in Nepal.

Kerosene was used to be in use before, but as seen in Fig. 4.5, it seems that the kerosene has been totally substituted by electricity and LPG in urban and semi-urban areas. In general, the number of LPG users has increased not only in urban and semi-urban areas but also in rural areas. The use of LPG was increasing at the annual growth rate of 17% during the period of 1995 to 2010 (NOC 2012). This trend is similar to other developing countries (Bhandari and Pandit 2018).

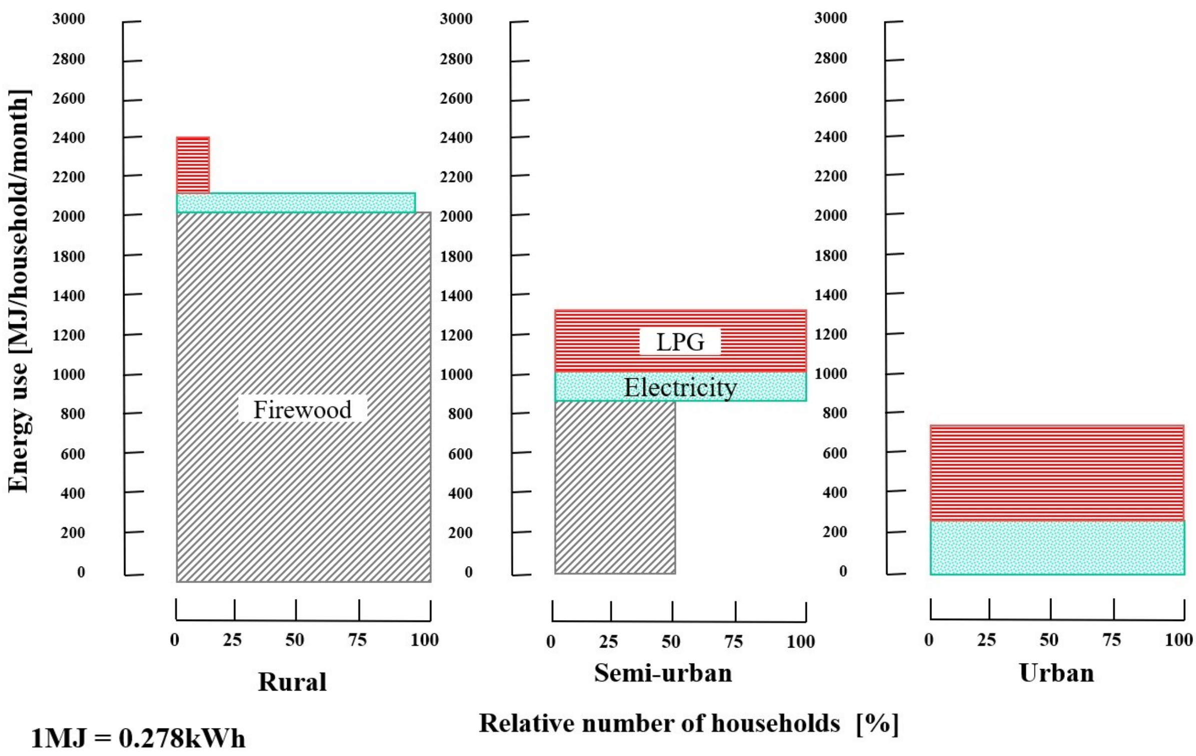


Fig. 4.5 Energy use in rural, semi-urban and urban areas

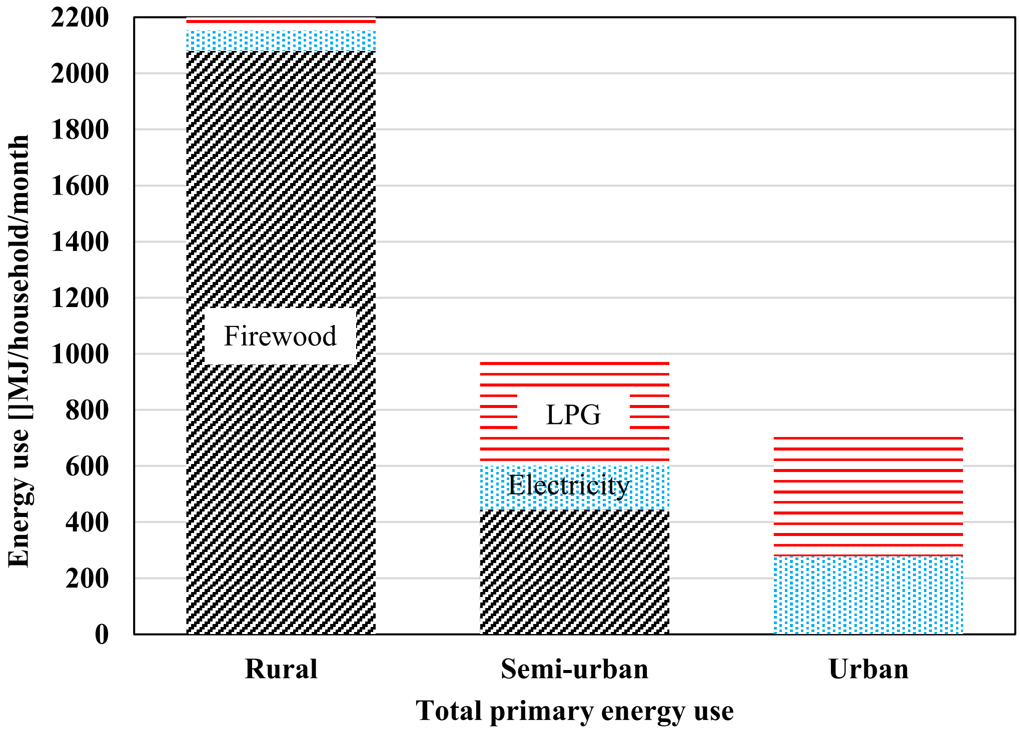


Fig. 4.6 Toral primary energy use in rural, semi-urban and urban areas of Nepal

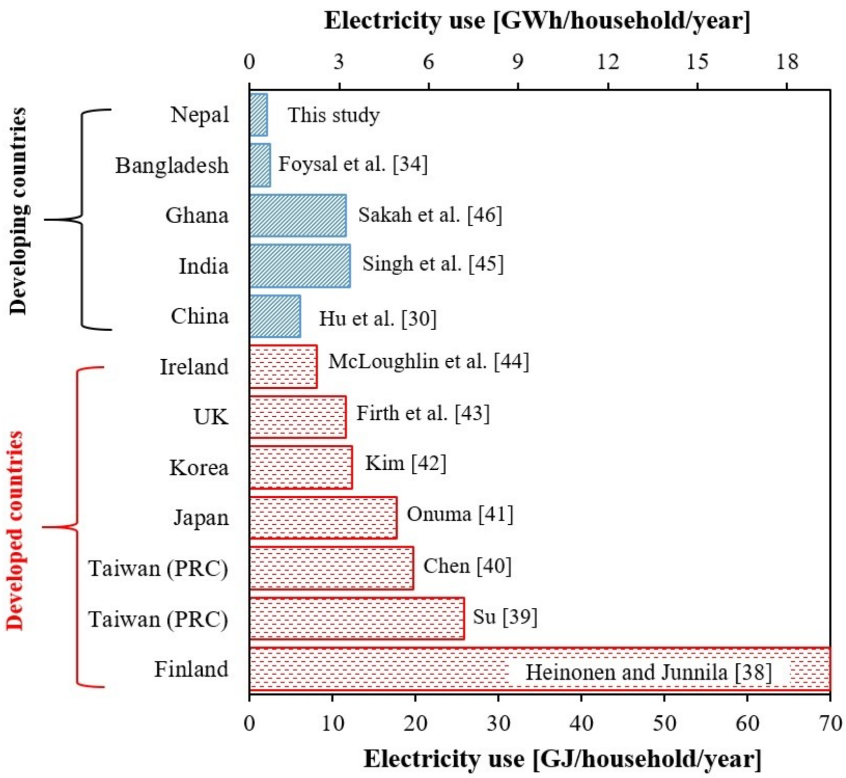


Fig. 4.7 Electricity use in developed and developing countries

Fig. 4.6 shows the monthly average rates of energy use per household in respective areas in terms of firewood, electricity and LPG. The vertical axis denotes the rate of energy use and the horizontal axis the areas of surveyed households that use the corresponding energy sources. The total primary energy use in rural, semi-urban and urban areas are 2199.6, 980.1 and 711.9 MJ/household/month, respectively. The total primary energy use in rural area is more than two times higher than semi-urban area and three times than urban area. This is due to the large amount of firewood use in rural area in winter season with using traditional cook stove. On hand, they need not buy firewood, and they can collect firewood easily from the public jungle, and other hand the efficiency of traditional cook stove by using firewood is much less than other energy types. Pandey et al. (2019) conducted the field survey in India to develop the multiport cookstove, which was compared against the popular cookstove by conducting a set of experiments. The parameters evaluated during the experimentation were specific fuel use, burning rate, thermal efficiency, time taken to do a specific cooking task and CO_2 emissions. They found that the modifications to the popular stove resulted in increase in thermal efficiency, decrease in burning rate and specific fuel consumption but a decrease of firepower and turn-down ratio. The activity resulted in developing a better cookstoves for the targeted community. Boy et al. (2000) reports on the fuel efficiency of a modified cook stove in western Guatemala, in comparison with the traditional cook stove. Modify cook stove reduce levels of indoor air pollution, and the traditional cook stove consumed more fuel and took longer than the traditional cook stove. After the modification 12% improvement in overall thermal efficiency, bringing it up to the value for the traditional cook stove. They found 39% less fuel wood than the traditional cook stove. This indicates that reducing the total amount of primary energy use in rural areas requires replacing traditional cookstoves by modern cookstoves.

According to JICA (2018) reports the northern part of Hokkaido, Shimokawa town. Shimokawa town has covered about 90% by forests. Taking advantage of this geographic feature, the town has created a 60-year-cycle sustainable forest management system and worked with local residents to build a society that coexists with forests. The future city initiative as its primary goal, the town is working to create an integrated forest industry and promote energy independence through the use of local forest biomass. By 2050, the town plans to reduce its CO_2 emissions by 66% from 1990 levels using local woody biomass and other means. The village has two 550-kW boilers manufactured by Schmid, a Swiss company. These boilers use wood chips produced by the woody raw material production facility. When wood chips are brought into the fuel bunker, they are supplied by automatic conveyors to the boilers. The community reactivating cooperator squad is in charge of the routine maintenance of these automatically operated boilers. While installing the heat supply facility, the town made efforts to attract companies to the district. With the supplied heat, a medicinal plant research facility, a forest product cultivation research facility, and other facilities are conducting corporate activities, providing employment opportunities to 30 to 40 local residents. These efforts have promoted the creation of a low-carbon society and contributed greatly to community revitalization. From 2010 when the discussions for the village plan started, to 2015, the population stopped declining and the proportion of elderly people lowered drastically (from 52% to 28%). The idea can be a very effective way to reduce CO_2 emissions, make better use of firewood and improve people's socio-economic status.

Fig. 4.7 indicates annual average rate of electricity use per household in respective countries with respect to developed and developing countries. The vertical axis represents countries and horizontal axis the rate of electricity use. The average electricity use in Nepal was 2.06 GJ/household/year, which is lower than any of developed and developing countries. In developed countries, all countries use electricity at higher rate; but in developing countries only Ghana and India use electricity at as high rate as that in some developed countries (Hu et a. 2017, Foysal et al. 2012, Heinonen and Junnila 2018, Su 1019, Chen 2017, Onuma et al. 2018, Kim 2018, Firth et al. 2008, McLoughlin et al. 2012, Singh et al. 2018, Sakah et al. 2019). The use of electricity in India and Ghana is 6 times higher than in Nepal (Singh et al. (2018, Sakah et al. 2019). The rate of electricity use in Bangladesh is a little higher than that in Nepal (Foysal et al. 2012). The development of industry and economy is very slow in Nepal and thus the level of energy use is the least in the world (Pokharel 2007). Such a low rate of electricity use does not seem to be rational as mentioned above; therefore, the current state of life in Nepal is to be improved. The government needs to make the policy to minimize the firewood use in rural houses. Simultaneously, they also need to promote the renewable energy use by providing subsidy to each community.

3.3.2 Energy use for lighting, cooking and heating

Fig. 4.8 shows the relative number of households in respective areas with respect to energy sources for cooking lighting, heating and cooling. The vertical axis denotes the purpose of energy use, and the horizontal axis the percentage of surveyed households that use the corresponding purpose of energy use. In urban and semi-urban areas, almost all households use LPG for cooking; but in the rural area, very small number of households use LPG for cooking. In rural area, all households use firewood and almost all households use residue (dried animal dung) for cooking. The firewood is mainly used for boiling water in semi-urban area. However, in urban area, no household uses firewood and residue (dried animal dung) for cooking. In urban and semi-urban areas, the use of electricity for cooking is higher than that of rural area.

In all areas, households use electricity for lighting. Rural households use PV cells for the production of electricity only for electric lamps other than the supply from hydro-power stations, because they were donated by non-governmental and governmental organizations. In semi-urban areas, almost 100% of households surveyed use electricity for heating and cooling and in urban area less than 30% households use electricity for those purposes. The reason for high percentage in semi-urban area is due to its very hot summer climatic characteristics. In rural area, almost no households use electricity for heating and cooling. In rural area, all households use firewood for space heating. In urban and semi-urban areas, some households use PV cells for hot-shower purpose. It shows that, in rural area, the use of LPG and electricity are smaller than semi-urban and urban area. The reason is the household low income level. The results so far presented here are similar to some previous studies (Wang and Jiang 2017, Rahut et al. 2014, Joon et al. 2009, Sinha and Biswas 2009, Alam et al. 1998). It is important that developing countries including Nepal need to emphasize the renewable energy use as much as possible instead of the use of fossil fuels and firewood use.

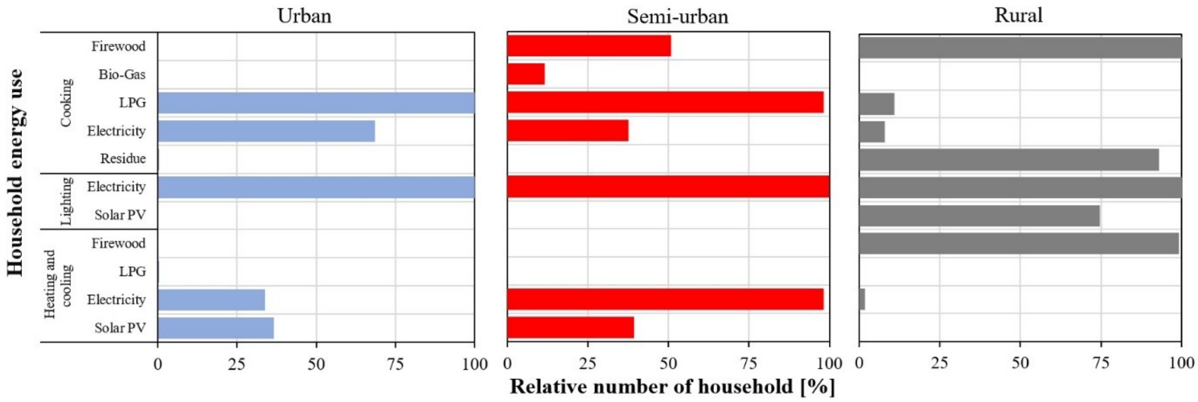
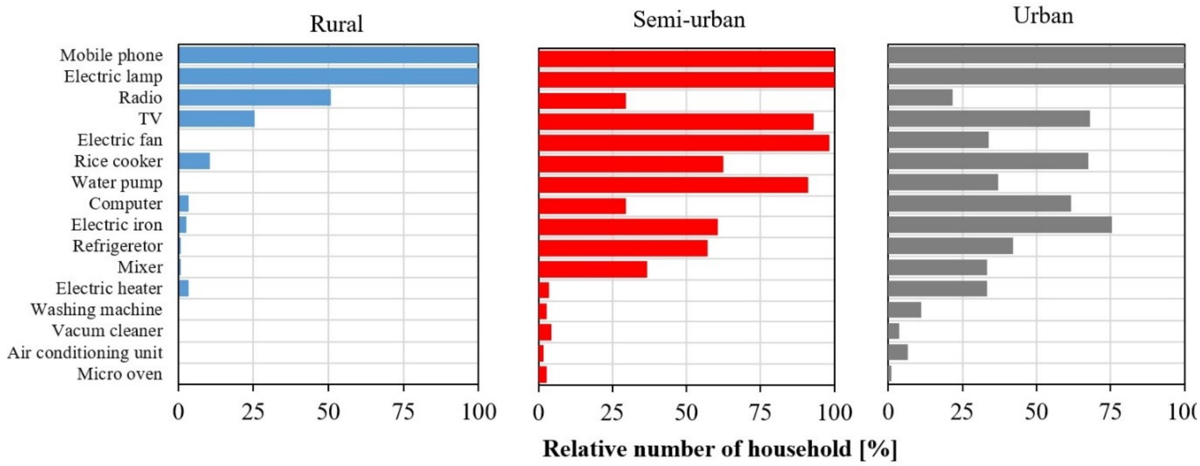


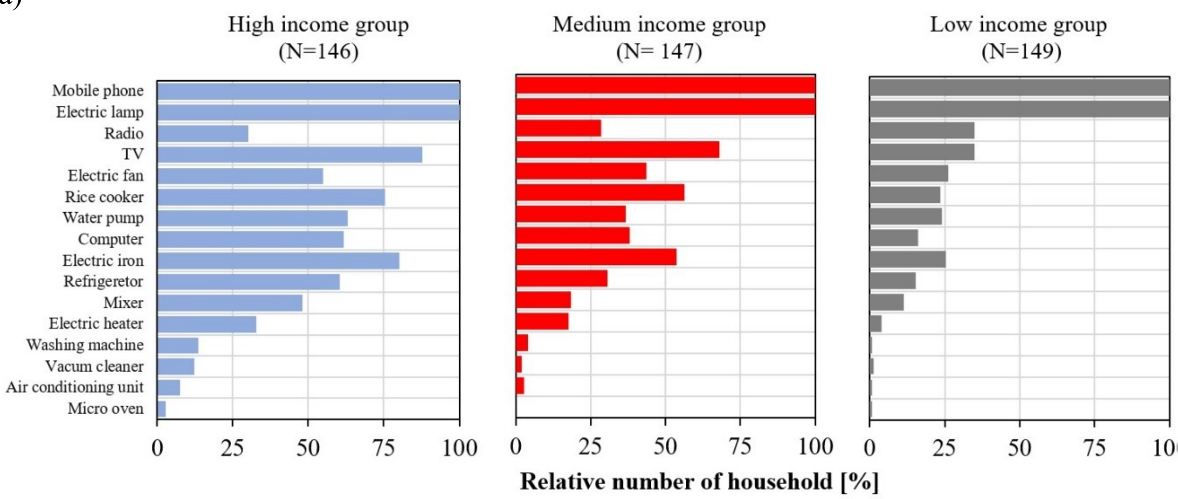
Fig. 4.8 Household energy use in cooking, lighting, heating and cooling in urban, semi-urban and urban area

4.3.3 Possession of electric appliances

The kinds of electric appliances to possess are considered to relate to the access to electricity, household income and climate condition. Fig. 4.9 (a) indicates the relative number of households in three areas with respect to the possession of electric appliances. The vertical axis denotes the household electric appliances and the horizontal axis the relative number of surveyed households that use respective electric appliances. The placement of appliances along the vertical axis is quoted from the questionnaire list that we used in the survey. All households use mobile phones and electric lamps in any of three areas. In urban and semi-urban areas, radio, TV, electric fan, rice cooker, water pump, computer, electric iron and refrigerator are used in most of households; but in rural area, almost no use of appliances such as micro oven, air-conditioning unit, vacuum cleaner, washing machine and electric heater.



(a)



(b)

Fig. 4.9 Relative number of households using electric appliances comparisons of (a) three study areas and (b) three income group

Fig. 4.10 indicates the relative number of all households in Nepal with respect to the possession of electric appliances and that in Hong Kong and Afghanistan (Wan and Yik 2004, Mohammad 2013). The vertical axis denotes the household electric appliances and the horizontal axis the relative number of surveyed and literature reviewed countries that use respective electric appliances. Some electric appliances data could not be collected for Hong Kong and Afghanistan so that we have written "No data" in such cases. The ownership percentage of electric appliances in Hong Kong is the highest among the three countries. Nepal is the least electric-appliance ownership country among others, both developing and developed countries. It is self-evident that lowering the number of electric appliances could decrease the amount of energy use. However, it may create inconvenient lifestyle. Therefore, in the context of Nepalese houses, the rational use of electric appliances is needed to improve the quality of life.

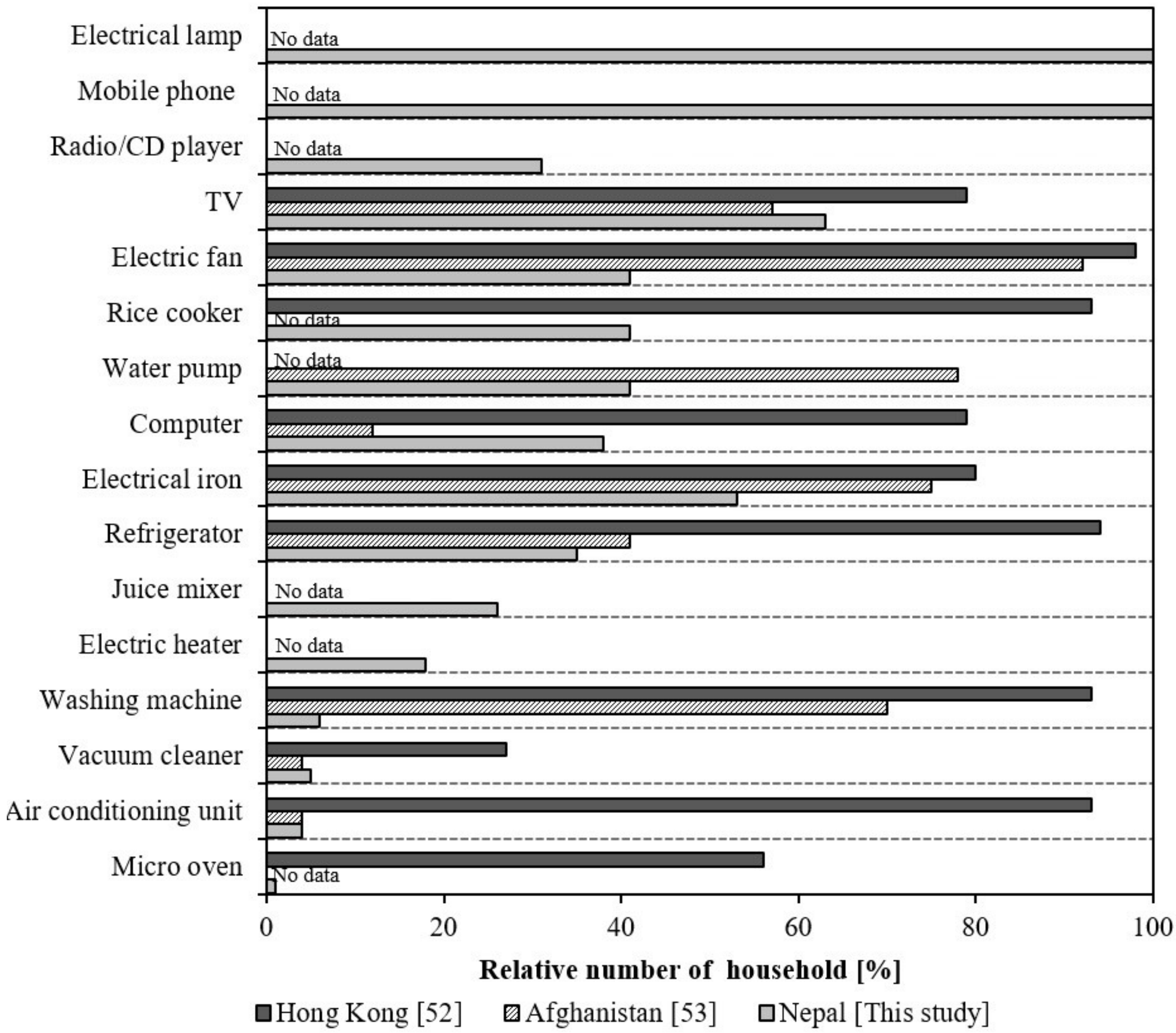


Fig. 4.10 Relative number of household and the use of electric appliances in this study and other studies

4.3.4 Electricity use and socio-economic factors

4.3.4.1 Electricity use, GDP and household income

(The World Bank 2013) recorded the electricity use and GDP of Nepal from 2006 to 2014. Fig. 4.11 shows the relationship between GDP per capita and electricity use. The total electricity use in Nepal (448 MJ/capita/year) is far smaller compared to global (11.17 TJ/capita/year) electricity use rate and GDP per capita of Nepal (from 2006 to 2014).

Fig. 4.12 represents the monthly average rates of electricity use per capita in relation to GDP of five countries including Nepal. The vertical axis denotes the rate of electricity use and the horizontal axis the GDP of those countries for the period of year 2000 to 2014. We took these data of per-capita electricity use and GDP of five South-Asian countries from the world bank data book (World Bank) and converted the unit of electricity use into MJ per household per year. Electricity use looks being well correlated linearly with GDP in any of these five countries. The linear regression equation for each of the five countries is

$$E = a(GDP)+b \tag{4.2}$$

where, E is annual electricity use per capita, GDP is gross domestic product per capita, a is the slope of the regression line, and b is the intercept. Nepal has the least GDP and annual electricity use per capita among the five countries. The slope is quite different. India and Bangladesh are similar and Pakistan, Nepal and Sri Lanka are similar. The rate of electricity is very small in Nepal as seen in Fig. 4.3. Taking the trend in Fig. 4.3 into consideration, GDP increases year by year. But its rate of electricity use is very small in Nepal. Whether the slope is larger or smaller seems to depend on whether the increase of power plants constructed and resultant electricity use is fast or not.

(Kantar et al. 2016) conducted hierarchical structure of the countries based on electricity use and economic growth 64 countries on the based three-income group from 1971 to 2008 as shows in Fig. 4.13. They have been found different clusters of countries according their geographical location and economic growth, strong relationship between energy use and economic growth for all the income groups. They have given data in paper and we have plotted as shown in Fig. 4.12. We have excluded three countries (Iceland, Norway and Luxemburg) because of different characteristics to respects GDP and electricity use. The electricity use and GDP was highly correlated. From the regression equation we can estimate the relationship of them.

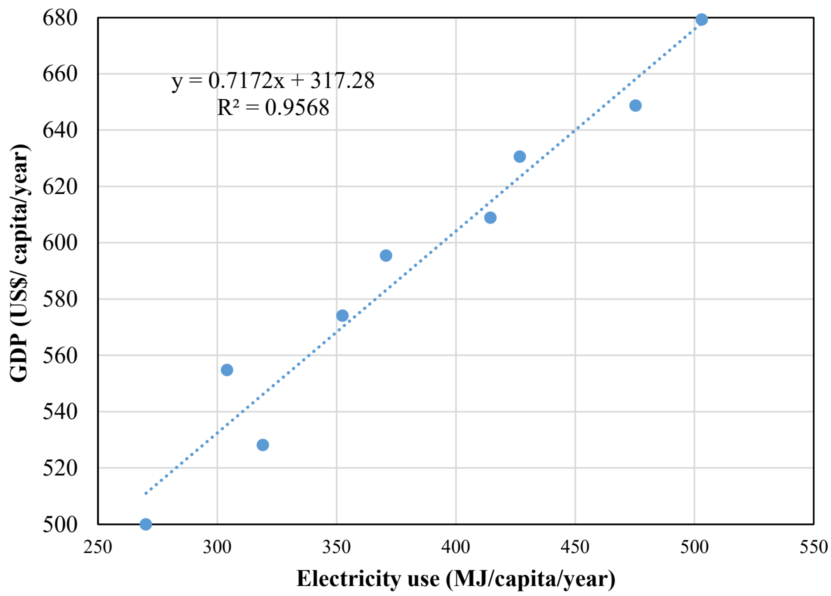


Fig. 4.11 The relationship between electricity use and GDP per capita of Nepal (from 2006 to 2014)

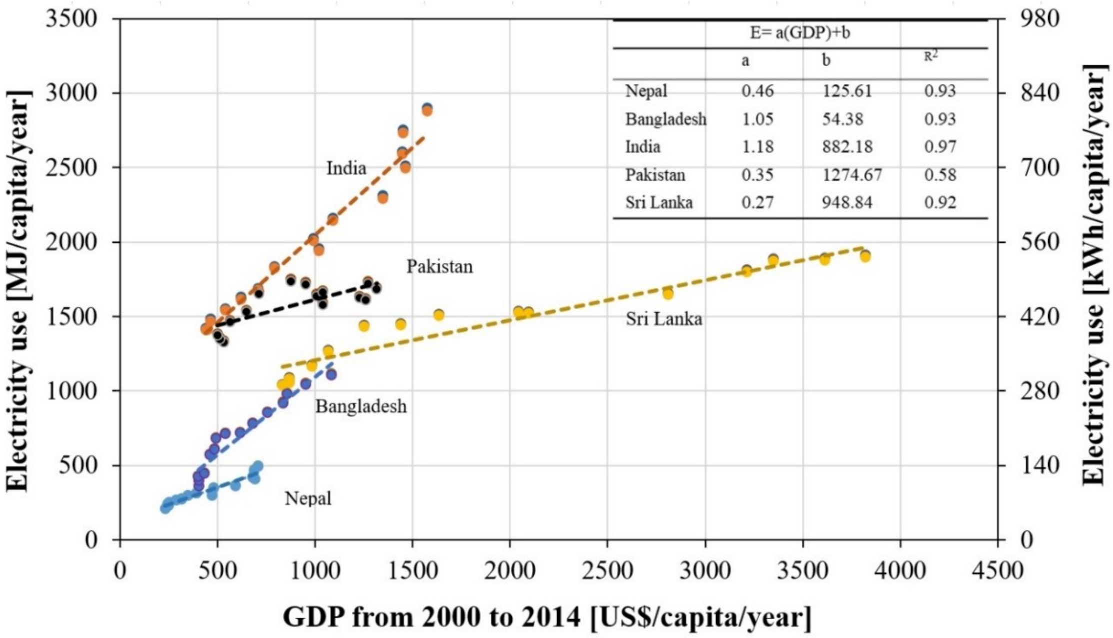


Fig. 4.12 Relationship between electricity use and GDP per capita per year of five South-Asian countries (World Bank)

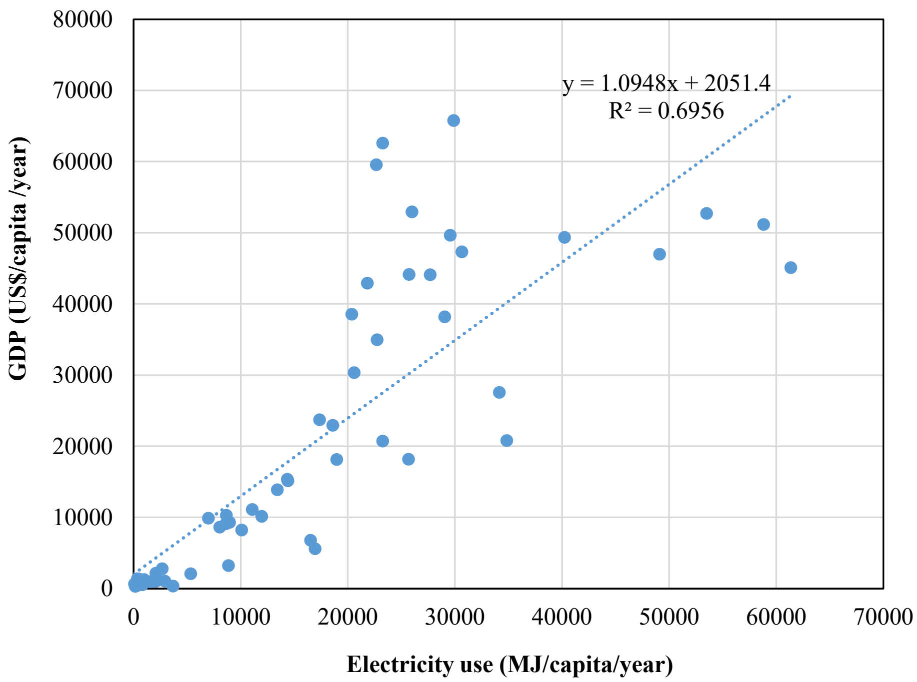


Fig. 4.13 Relationship between electricity use and GDP per capita in world

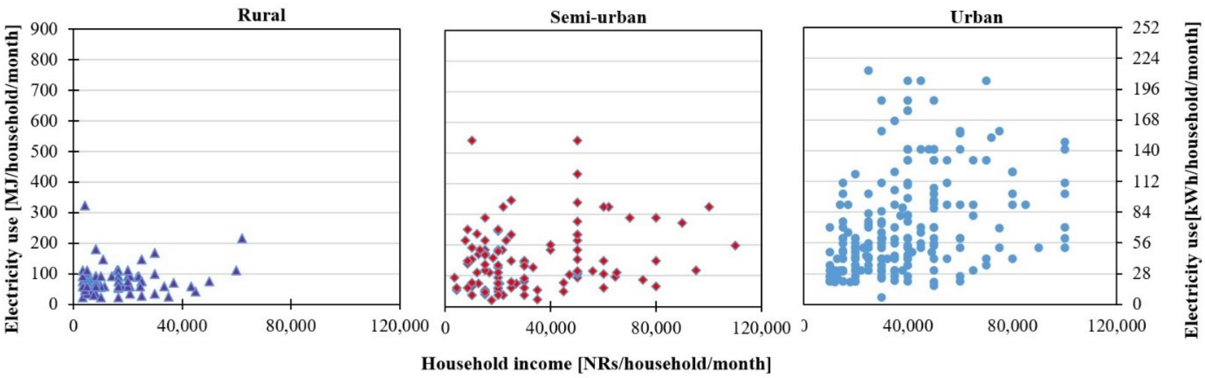


Fig. 4.14 Relationship between household income and electricity use

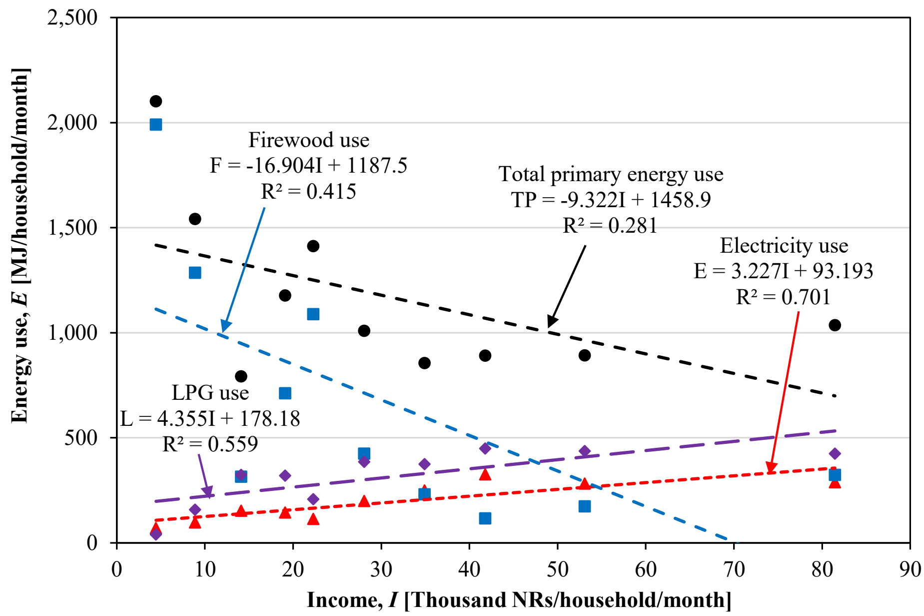


Fig. 4.15 Relationship between total primary energy use, electricity use and income group

The household income is an important indicator of living standard. Fig. 4.14 shows the monthly average rate of electricity use per household in respective areas with respect to the income level of households. From the left graph to the right, urban, semi-urban, and rural areas, the vertical axis of each graph denotes the monthly rate of electricity use and the horizontal axis the household income. In urban area, the least income is 10,000 NRs and the least electricity use is about 50 MJ/household/month. It looks that some of those having the income higher than 30,000 NRs may become using more electricity. In semi-urban area, some of high income seem to use electricity more, but its rate of electricity use is moderate if compared with urban area. In rural area, the scattering pattern of the plots looks similar to that in semi-urban area, but the rate of electricity use and also the income are much smaller.

Fig. 4.14 does not show any clear trend of electricity use and household income. Therefore, we divided the income into ten groups and calculated the average electricity use.

Fig. 4.15 shows the monthly rate of total primary energy use; firewood, electricity and LPG use and household income per income group of all areas. Each plot represents the average calculated from 16 to 61 data. We have conducted weighted linear regression analysis for these plots. The result shows that the household electricity and LPG use are positive correlation with household income. The total amount of firewood and primary energy use has a negative correlation with household income. In rural areas, they have low incomes and high rate of firewood use. As shown in Fig. 4.9, high income households have more electric appliances and they use high rate of electricity use, which means household income is the primary factor for choosing household energy. Previous studies (Wiesmann et al. 2011 and Yohanis et al. 2008) also found a similar trend to this result.

4.3.4.2 Electricity use and the occupation of household responsible person

As Fig. 4.8 (b) has indicated, the level of income is related to the possession of electric appliances. The income and occupation are considered also to be related to each other. Fig. 4.16 shows the monthly average rates of electricity use per household in respective areas with respect to the occupation of the household responsible person. The vertical axis denotes the monthly average electricity use per household and the horizontal axis the monthly average income of per household. We have conducted weighted linear regression analysis and found the following regression equation.

$$E = 6.51I - 4.13 \qquad (4.3)$$

where, E is monthly average electricity use per household, and I is monthly household income of each occupation group. The use of electricity of household is affected by the income of households. The use of electricity is correlated with household income. The occupation is either farmers, employees of government or business firms, or self-business persons. In rural area, all occupational households have less income and less electricity use, even if they are employees of government and a business firm or self-business persons. In semi-urban area, self-business person households have quite high incomes, but the rate of electricity is not high. In urban areas, the rate of electricity use increases as the income of household responsible person increases. The possession of electric appliances is affected by household income, which is affected by the occupation of household responsible person. The household social class is associated with the use of electricity in urban area. As found in a previous study (McLoughlin et al. 2012), high class uses more electricity than middle and lower classes as the reflection of possible income effect.

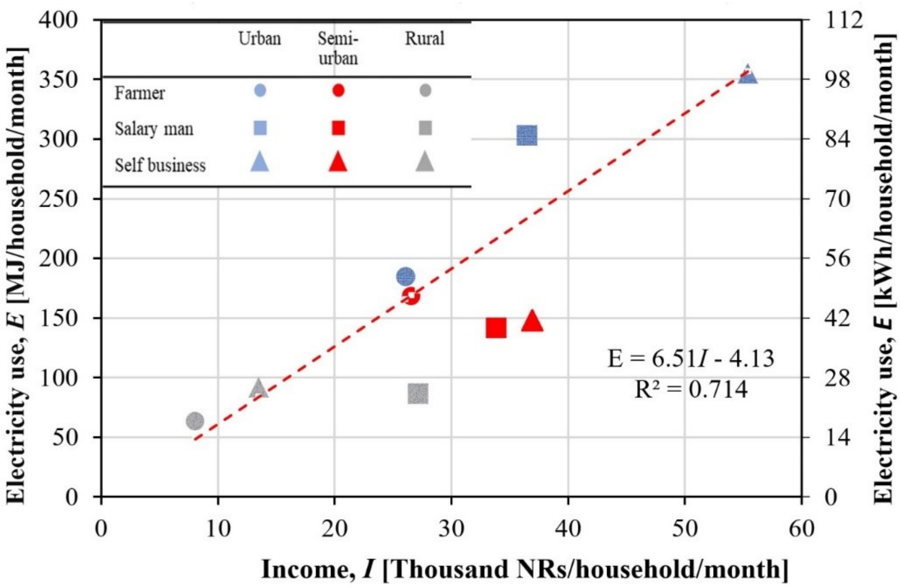


Fig. 4.16 Occupation of household responsible person and electricity use in urban, semi-urban and rural areas

4.3.4.3 Electricity use and family size

Family characteristic such as family size is also an important factor influencing household energy use. Fig. 4.17 and Fig. 4.18 show the monthly average rates of electricity use per household and per capita in respective areas. The vertical axis denotes the electricity use and the horizontal axis the family size of the surveyed households. The families are divided into three categories according to the number of family members. Small family group is defined to be with 1 to 3 members, medium family group with 4 to 5 members, and big family group with 6 members or more. In all of three areas, as the family size increases, the rate of electricity use also increases. For each additional family member, energy use increases by 7.7%, which is similar to the one shown by (Jones et al. 2015). By sharing household appliances by family members, the per-capita electricity use decreases as the family size increases. It is consistent with previous studies (Wiesmann et al. 2011 and Yohanis 2008).

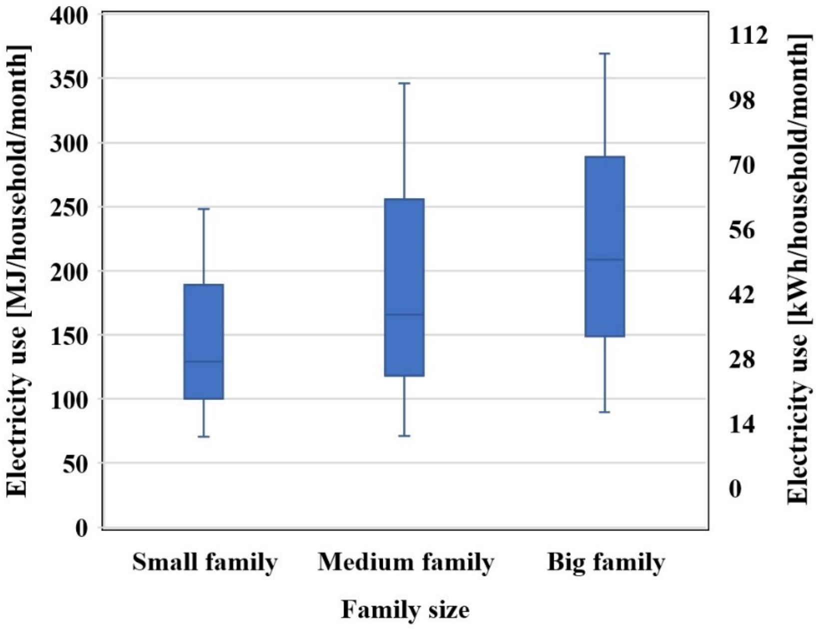


Fig. 4.17 Family size and electricity use per household

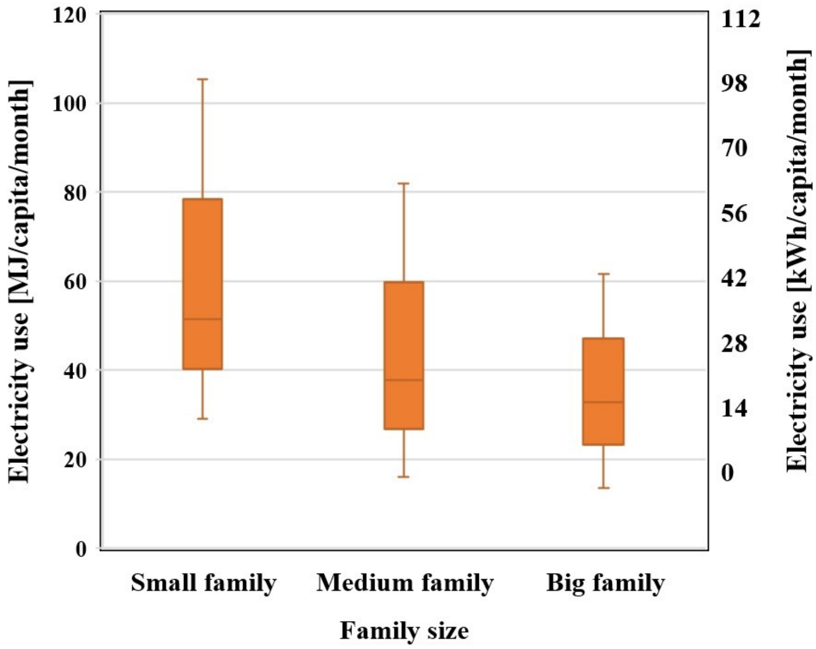


Fig. 4.18 Family size and electricity use per capita

4.3.4.4 Household electricity use and the education level of household responsible person

Education is one of the key indicators representing the quality of life as well as the income level of households. Education of household responsible person may play an important role for the selection of energy sources, electric appliances and also for the reduction of electricity use. As shown in Fig. 4.8, electricity is used mainly for lighting in Nepal. The use of LED lamps instead of incandescent or fluorescent lamps can result in reducing the rate of electricity use because of its high luminous efficacy in comparison to those of fluorescent or incandescent lamps (Shukuya 2019). The use of LED lamps can be dependent on its awareness, which must be highly dependent on the level of education.

Fig. 4.19 shows the relationship between the electricity use and the income level of household by plotting them according to the educational level. As the income of household increases, the electricity use also increases; this is similar to a previous study (Inglesi-Lotz and del Corral Morales 2017). According to (McLoughlin et al 2012) the educational level of household responsible person has a significant effect on the electricity demand. As found in the previous study (Inglesi-Lotz and del Corral Morales 2017), the literacy of the household responsible person is associated with lower household electricity requirement. But some other researchers found that the educational level of households doesn't affect the household electricity use (Leahy and Lyons 2010 and Gram-Hanssen et al. 2013). Considering the context of Nepal, the rate of electricity use is still very low and the level of education is also low, and thus the rational energy use should be realized by helping the people realize what rational use of electricity is by increasing the opportunity of education.

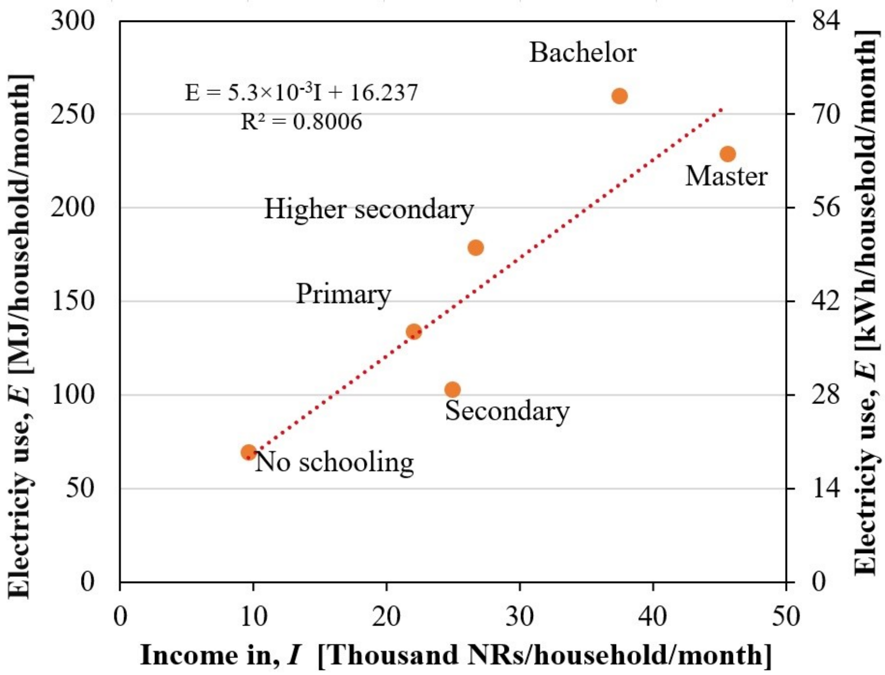


Fig. 4.19 Relationship between income and the electricity use by grouping them to the education level

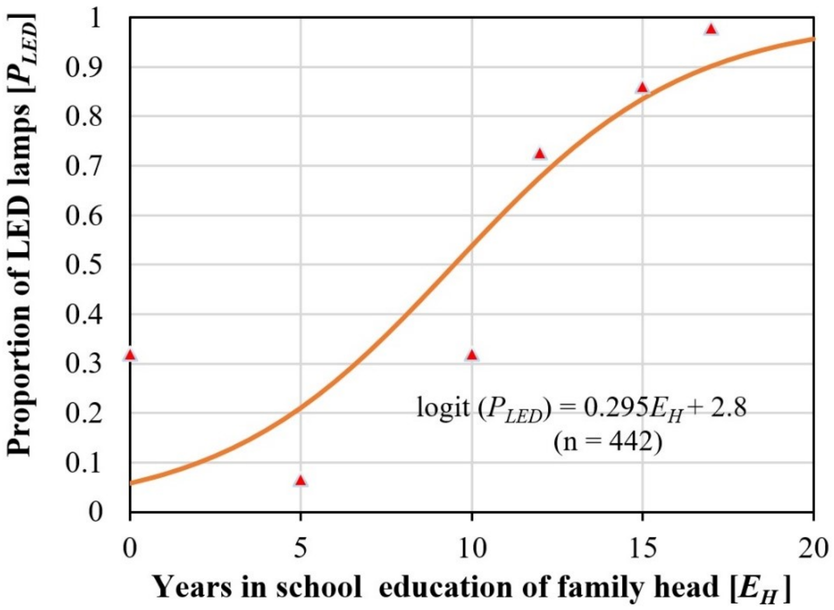


Fig. 4.20 Number of years in school education and the proportion of LED lamps used

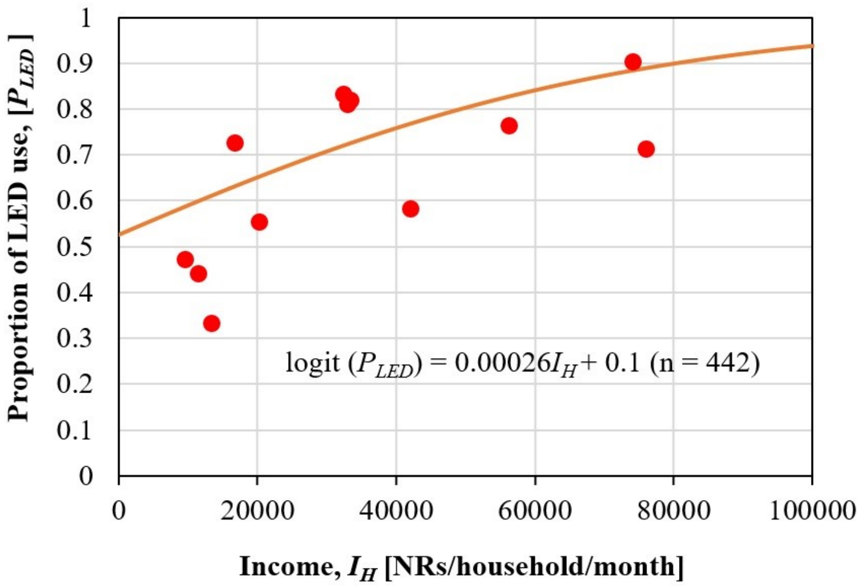


Fig. 4.21 Household income and the proportion of lamps used. (The data were divided into 15 income groups, and income groups with the samples ≤3 were omitted)

Fig. 4.20 shows the relationship between the proportion of LED lamps to all types of lamps used in households and the number of years in public-school education of household responsible person. The year 0, 5, 10, 12, 15 and 17 denote no schooling, primary, lower-secondary school, higher-secondary school and university educations, respectively. The proportion of LED lamps looks increasing as the level of education becomes higher. The manner that the plots scatter looks following the characteristics of a logistic curve; the line shown in the graph is the one obtained from regression analyses as shown in Fig. 4.20. According to this line, the households of 32% change from conventional lamps to LED lamps even if they are illiterate. It might be due to the informal educational effect given from radio, television, government awareness program and other literate people. The households of 55% do such change if they complete the secondary level that is 10 years. Almost 90% households do that change if they complete the bachelor degree that is 17 years of education. It seems that the education level of household responsible person affects the use of LED lamps. It suggests the necessity of higher education in order to rationalize the individual energy use.

Fig. 4.21 shows the proportion of families using LED lamps to all families in a certain income level and also the logistic curve representing the relationship between the proportion of LED use to all lamps used and the binned group of household income. Each plot represents the ratio of LED use families and total number of families, which are grouped into 15 bins representing the corresponding household incomes. Even if they are at low income, 50% of them change the lamps to LED on average, but the high income household have more LED lamps than the low-income households. It is considered that the higher use of LED may lead to mitigating the increase of electricity use by higher income households.

4.3.5 Daily use patterns of household electricity

One of the most important aspects to a better understanding of demand for electricity in the domestic sector is the daily electricity using patterns, because most of the energy is used in domestic sectors. Fig. 4.22 and Fig. 4.23 shows that the daily electricity use patterns in rural, semi-urban and urban areas respectively. There is no heating and cooling devices used in these three areas. A rural household surveyed used less energy than semi-urban and urban households. Very basic electric appliances used in rural areas of Nepal are electric lamp, radio/music system, mobile phones and televisions. Fig. 4.23 shows that the trends of electricity use are constant during night time. The semi-urban household used more electricity than others. The semi-urban household has a chicken farm. They used high wattage electric bulbs for heating and lighting purposes for chicken breeding. The electricity is used from 18:00 to 5:00 at almost constant rate of 80 W. From at 5:00 to 11:00 and from at 18:00-21:00 more electricity is used than other time; this is probably the electricity use for cooking and using electric appliances such as, television, rice cooker and other appliances. But, during day time from 11:00 to 18:00 they used less electricity. This must be due to the fact they do not have any activities, out of household or maybe they used solar light. Fig. 4.22 shows that the electricity load patterns in second and third days together with the first day these days have similar patterns.

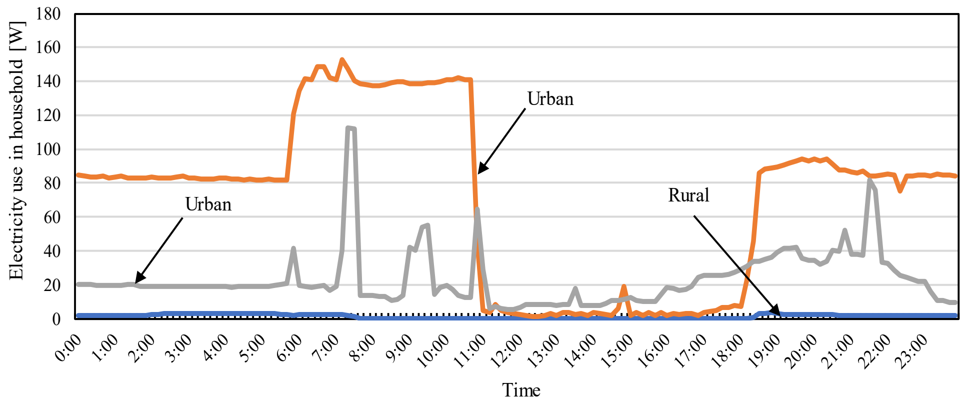


Fig. 4.22 Daily electricity loading pattern for one day

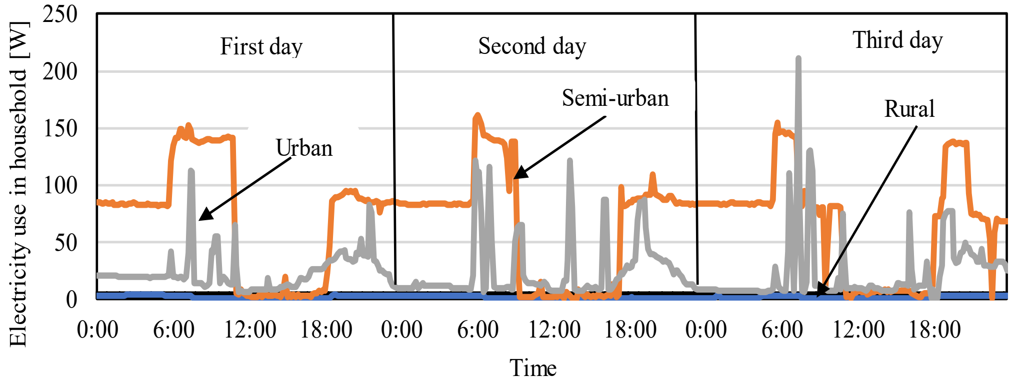


Fig. 4.23 Daily electricity loading pattern for three day

4.3.6 Relation between energy use and CO_2 emission

(Chen et al. 2007) conducted on the relationship between GDP and electricity use in 10 newly industrializing Asian countries in 2003. The total population of ten those countries was 2.8 billion, which accounts for 45% of the world's population. The GDP and electricity use in the region and US$3572.71 billion and 3174.14 TWh (Terawatt per hour), which accounts for about 10.7 % and 20.9% of the world`s GDP and electricity use, respectively. Also they found to be the combined CO_2 emissions for those countries accounted for 25.1% of global emission in 2003, while China, India and Korea were among the world's top 12 polluting countries in terms of CO_2 emissions. Since in China, India and Indonesia GDP per capita and electricity use per capita were so far below the world average. Those countries were account for a significant proportion on the world population, GDP and electricity use. They have given data and we have plotted as shown in (Fig. 4.24 and Fig. 4.25). The electricity use and CO_2 emission were highly correlated. The equation can be used to estimate the relationship of them (Wang et al. 2017) also described China's use of energy source is highly geographically dependent a large rural population still reside in areas where carbonate composites are major energy source, consequently the resulted carbon pollution has been an increasingly serious environmental problem.

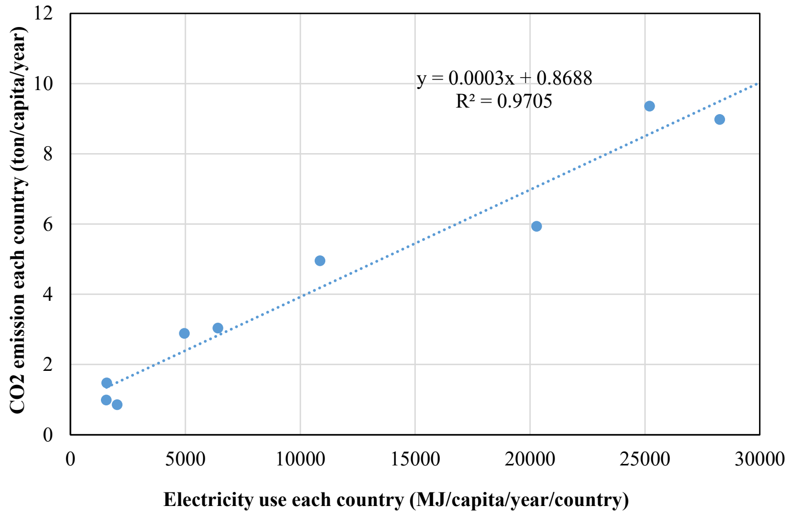


Fig. 4.24 The relationship between electricity use and CO_2 emission per capita per year

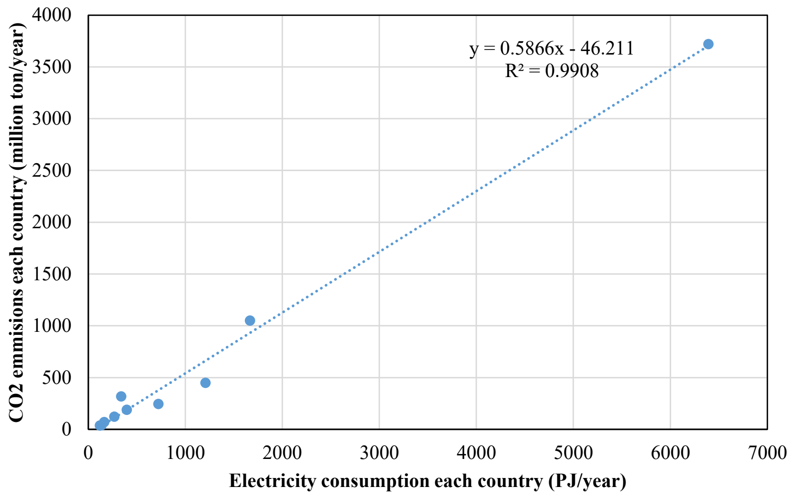


Fig. 4.25 The relationship between electricity use and CO_2 emission per country per year

4.4. Conclusions

We have investigated the structure of rural, semi-urban and urban household's energy use in Nepal by field survey combined and identified the current Nepalese situation of household energy use. The findings are summarized as follows.

1. The main energy source in rural and urban area is firewood, while on the other hand, that in semi-urban and urban areas is LPG and electricity. The use of electricity in rural area is smaller than that in semi-urban and urban areas. The average electricity use of all areas in Nepal was 2.06 GJ/household/year, which is lower than that in other developing countries. The use of firewood is 2.08 GJ/household/month in Nepalese rural areas, which is twice higher than other developing countries.

2. The access to electricity and the household income were associated with the possession of electric appliances. Nepal is in the least state of electric appliance ownership among developing countries. A higher income level of household tends to bring about an increase of the home-appliance ownership.
3. The rate of electricity use is correlated with the income levels. There is a strong linear relationship between GDP and per-capita electricity use in Nepal and also in other South-Asian countries.
4. The use of electricity in households is affected by the household income in urban area. It is correlated with household income. The social class of households affects the total electricity use in urban areas, but it doesn't affect much in rural and semi-urban areas.
5. In all of three areas, as the family size increases, the rate of electricity use also increases. But the per-capita electricity use decreases as the family size increases.
6. There is a significant relationship between electricity use and income regarding to the education level of household responsible person. As their level of education and income of household increase, the electricity use tends to increase.
7. The education level of household responsible person affects the use of LED lamps. It was correlated with the use of LED lamps, although its mechanism is not ascertained.
8. The use of electricity from 5:00 to 11:00 and from 18:00-21:00 were more than other time. The household electricity demand is very high at these period of time. The electricity load patterns in second and third day were similar to that of first day.
9. The GDP and CO_2 emission were highly correlated worldwide.

We found that rural households use more firewood and the rate of electricity use in Nepal is one of the least in the world. The access to electric appliances is very low. The findings identified in this study should be useful for the improvement of the life of people in Nepal. The GDP is increasing in Nepal and the energy use will definitely increase in the future. Thus, the government needs to plan for the sustainable energy use in Nepal.

Chapter 5: Thermal comfort

5.1. Introduction

The current energy-policy scenario shows that if the humans continue taking the present path without any change the energy demand would rise by 1.3% each year (WEO 2019). Energy use in buildings forms a significant part of global and regional energy requirement; about 40% of total global energy is used in building sector (UNDP). The portion of heating and cooling in total building energy use is from 18 to 73% (Urge-Vorsatz 2015). It is mainly for the operation of mechanical heating and cooling devices.

Fig. 5.1 shows the relationship between indoor thermal environment to be obtained by rationalizing the range of air temperature, radiant temperature and others by either passive or active systems. Passive systems are working as non-mechanical system through the improvement of building envelopes. In order to improve the overall thermal environment indoors, it is necessary to improve the thermal performance of windows, walls, roof and floor. Active systems function to maintain the thermal environment by the use of biomass, electricity from fossil fuels, hydro, photovoltaic cell and wind turbine through mechanical devices. Using fossil fuels and biomass mainly to maintain the indoor thermal environment leads to a variety of environmental problems locally and globally.

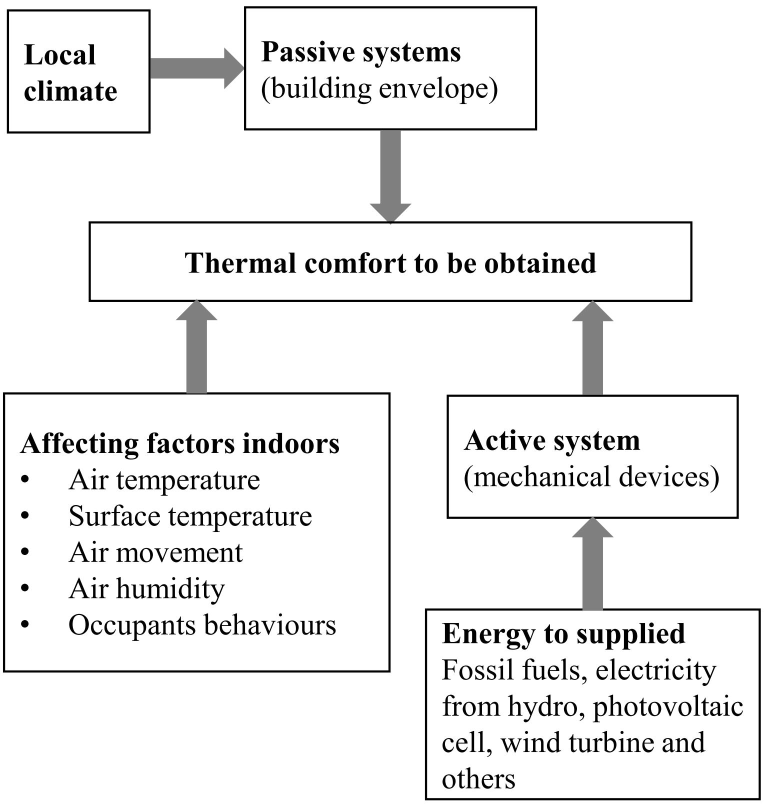


Fig. 5.1 Thermal improvement and energy use path for obtained the thermal comfort

Approximately 87% of total final energy use is for household sector and biomass, it originates from LPG, hydro-electricity and photovoltaic cells in Nepal (GON, Economic survey, 2015). Nepal is one of the least developed countries and its gross domestic product (GDP) is the lowest in the world (Nepal economy 2020). Nepalese households used less energy than other countries. Firewood can be the main source of energy in rural areas but electricity and LPG are used in semi-urban and urban areas (Shahi et al. 2020, Pokharel et al. 2020, Shahi et al. 2019). The population with the access to electricity has reached 70% of the whole of population and 45% of the population has reached national grid (NEA 2017/18). Nepal experienced 18 hours of power cut 5 years ago but now it is significantly improved. It happened to show that Nepalese grid electricity has been so far very fragile and the people do not have a good access to electricity. Nepal has diverse in geographical variation. The average maximum outdoor air temperate in summer is 37.4 °C and average minimum outdoor air temperature in winter is -5 °C (DHM). But as mentioned above very few mechanical systems are being used for the improvement of indoor environment (Shahi et al. 2020) and Nepalese people were satisfied in day time thermal condition of their traditional houses, and residents wore more clothing and used firewood for heating to adjust the thermal environment in night time (Rijal et al. 2010). The income level of many households is still quite low to purchase electric appliances and then pay electricity bills. However, if they have a good access to energy and high level of income, they may start using more fossil fuels for mechanical heating and cooling appliances to obtain better indoor thermal environment. Then the energy demand will increase in the future. A large electric-power plants could be required to fulfil the increasing energy demand. Such type of power plants are costly and they necessarily cause environmental problems to be avoided, although some rate of energy is definitely necessary to upgrade their lifestyle. The indoor thermal environment improvement by improving the building envelope system is very important, since it could be realized without energy use.

Very few researches have been so far conducted in Nepal. (Rijal et al. 2010) conducted a survey on traditional houses during summer and winter seasons of cold, temperate and sub-tropical regions of Nepal. Thermal comfort survey was conducted and 7116 responses were gathered. They found that the residents were highly satisfied with the thermal condition of their houses and there were reginal and seasonal differences in comfort temperature. (Thapa et al. 2018) investigated the thermal environment in temporary shelters after earthquake 2015 in temperate region. The mean comfort temperature was 15.0 ºC in winter and the 28.6 ºC in summer. (Gautam et al. 2019) investigated thermal comfort in traditional houses. The mean comfort temperature in cold region was lower than that in temperate and sub-tropical regions. (Pokharel et al. 2020) investigated indoor thermal environment and its associated energy use in cold, temperate and sub-tropical regions in Nepal. About 90% of the measured indoor air temperature was found below the comfort temperature of all three regions. Average measured indoor air temperature was 8.0 °C, 13.9 °C and 12.8 °C, respectively.

The previous researches have focused, either, on current indoor thermal condition (Pokharel et al. 2020, Rijal et al. 2010, Thapa et al. 2018, Gautam et al. 2019) and or, on the improvement (Thapa et al. 2019, Fuller et al. 2009, Rijal 2012), but not on both. There is one trail on both current thermal condition and the improvement, but it was on temporary shelters (Thapa et al. 2019). Therefore, this study focus on thermal comfort condition of residents in ordinary houses, and thermal performance improvement of these houses during night time in particular. For this purpose, we have conducted a thermal comfort survey together with indoor and outdoor thermal environment measurement and made a simple analysis on thermal improvement in cold, temperate and sub-tropical regions of Nepal. The objectives of this research are: 1) to estimate the comfort temperature of residents in each region, 2) to evaluate the thermal performance of the houses; and 3) to examine a possible improvement of the houses that allows the residents to have better indoor thermal environment during night time.

5.2. Research methodology

5.2.1 Investigated regions and houses

Nepal has diverse climate variation because of the topography ranging from 60 m above the sea-level to 8,848 m. It has three climatic regions; i.e. cold, temperate, and sub-tropical. Generally, from April to August is summer and from November to February is winter. We have selected three areas in accordance with its geographical features: Kalikot (Cold); Kathmandu (Temperate); and Chitwan (Sub-tropical) districts as shown in Fig. 1.1 (a). Fig. 5.2 shows the mean outdoor air temperature of the year of 2014 in three regions (Rijal et al. 2012). The mean outdoor air temperature during the winter months ranges from 10 to 14°C in cold, 11.3 to 18°C in temperate and 16 to 22°C in sub-tropical region, respectively.

The cold region lies in a rural area and income and education level are low compared to the temperate and sub-tropical regions. The electricity grid in temperate and sub-tropical regions is much more developed than in cold region. The access to the electric appliances is also low in cold region compared to other regions (Shahi et al. 2020). In cold region, the traditional houses have thick walls. These houses are multi-storied and the ground floor rooms are used to keep livestock, while the middle and upper storeys often consist of living rooms and store rooms. Mainly, firewood was used for cooking and heating purpose through traditional cookstove in the cold region but some households also used firewood in temperate and sub-tropical regions. Mainly, LPG is used for cooking purpose in temperate and sub-tropical regions and some peoples used electric heater for heating. Fig. 3.1 shows three example of chosen houses in cold, temperate and sub-tropical regions.

5.2.2 Thermal comfort survey

The thermal comfort survey was conducted for one month from 23th January to 23th February, 2018. Firstly we visited a cold region, secondly sub-tropical region, and lastly temperate region. We have collected 203, 407 and 229 votes from 114, 216 and 112 households in cold, temperate and sub-tropical regions, respectively. We took 839 votes from 442 households from the people whose age ranges from 15 to 65 years. The voting was made for 20 minutes from 7:20 to 20:40 in all regions. All interview was conducted in living room. In cold region, a large number of residents were participated in survey by wearing the thick cloths compared to temperate and sub-tropical regions (Fig. 5.2 a-c). We used modified thermal sensation scale which was translated into Nepali language as shown in Table 3.2. We didn't use the warm or cool which has comfortable meaning in Nepalese. We used the words which has discomfort meaning is not and cold sides (Rijal et al. 2010). We visited each house and measured the indoor and outdoor air temperature, indoor globe temperature, indoor relative humidity and wind velocity using the devices shown in Table 3.3. While vising the houses, we first set the instruments outdoors and then indoors. The data were recorded after 15-20 minute had passed since the instruments were set up. The instruments were placed about 1.1 m above the floor level for indoors and about 1.5 m above the ground surface for outdoors. The effect of solar radiation is avoided to the sensors.

(a) (b) (c)

Fig. 5.2 Thermal comfort survey and interview scene: (a) cold, (b) temperate, and (c) sub-tropical regions.

5.3. Thermal comfort of residents

5.3.1 Thermal environment during the voting time

Building envelope system is like one of the human body system. In cold season, the heat discharge from our body through the skin to surrounding environment. The clothing insulation will work as the resistance for the heat discharge from body through the skin. In similar way, the heat discharge from the indoor to outdoor through the walls. We need to understand the close infrared relationship between our body and the surrounding surface of the room, expressed in terms of mean radiation temperature (T_{mrt}). Mean radiant temperature is a key component of the thermal comfort, which is an integral part of the quality of the indoor environment and the performance of the building. The mean radiant temperature is a means of expressing the influence of surface temperatures on occupant comfort. It can be calculated many ways. Ironically, most buildings and energy codes are thermal from thermal comfort indicators such as average radiation temperature and operative temperature if the minimum requirements for insulation and air leakage are better than currently specified. It does not explicitly consider comfort (Bean et al. 2010). Walikewitz et al. (2015) found the differences between indoor air temperature [T_i] and mean radiant temperature [T_{mrt}] are negligible during most periods, as stated in previous literature. As T_i increase, however, T_{mrt} exceeds T_i up to 1.3 K. The examination of the surface temperatures indicates that rooms with window walls facing southeast and southwest show the largest disparities between T_i and T_{mrt}. The correlation between T_i and T_{mrt} and the sum of the short and long wave radiation specifies the radiation intensity and duration as the main driver of T_{mrt}. They suggest the future studies on indoor heat stress should hence consider that T_{mrt} and T_i can differ depending on the characteristics of the room and on solar radiation.

Stone, wood and mud are used in traditional houses in cold region and concrete is mainly used in modern houses in temperate and sub-tropical regions. The average indoor globe temperature was 13.2 °C, 19.7 °C and 21 °C in cold, temperate and sub-tropical regions, respectively. The average relative humidity was 42%, 50% and 63% in cold, temperate and sub-tropical regions, respectively. The indoor wind velocity was less than 0.10 m/s in all houses of three regions. The mean radiant temperature was calculated to confirm the radiation effect using the following equation (Thorsson et al. 2007).

$$T_{mrt} = \left\{ \left(T_g + 273\right)^4 + \frac{1.1 \times 10^8 v^{0.6}}{\varepsilon d^{0.4}} \times \left(T_g - T_i\right) \right\}^{0.25} - 273 \tag{5.1}$$

where T_{mrt} is mean radiant temperature [°C], v is air velocity [m/s], T_g is indoor globe temperature [°C], T_i is indoor air temperature [°C], d is diameter of the globe [m] (= 0.075 m), ε is the emissivity of globe surface (= 0.95).

Fig. 5.3 shows the relationship between the mean radiant temperature calculated and indoor air temperature in three climatic regions. In cold region, the mean radiant temperature is high as the indoor air temperature is less than 15 ºC. This might be due to the high thermal mass of thick walls. Indoor air temperature is easily decreased by infiltration but thermal energies stored in the wall is discharged as the air temperature start decreasing. Therefore the indoor air temperature may be lowered. In temperate region, many data points lie above the diagonal line. Similarly, in the sub-tropical region, they lie above the diagonal line; this indicates the mean radiant temperature is higher than air temperature. It is probably due to the effect of solar radiation incident on the walls and transmitted through the windows that could result in the increase of indoor surface temperature.

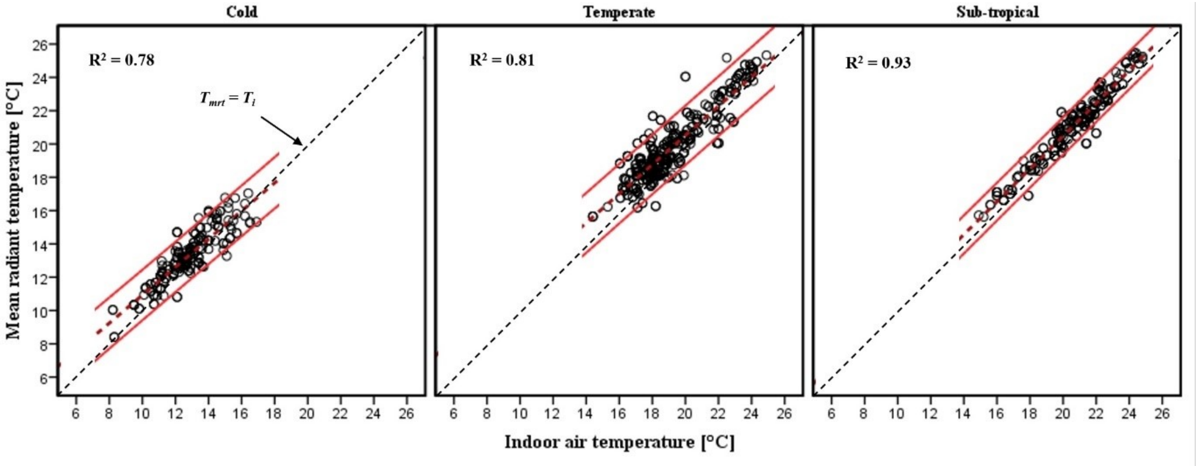


Fig. 5.3 Relationship between mean radiant temperature and indoor air temperature in three climatic regions with regression line and 95% band of data points

5.3.2 Relation between indoor globe temperature and outdoor air temperature

The indoor temperature was low in cold region and high in sub-tropical region as shown in Fig. 5.3. The structure and materials of the houses are different from one region to the others. In this section, we analyze how the relationship between indoor globe temperature and the outdoor air temperature. Fig. 5.4 shows the relation between indoor globe temperature and outdoor air temperature in respective regions during the voting time. Generally, the indoor globe temperature is higher than outdoor air temperature. We have found the following regression equations:

For cold region, $T_g = 0.250\ T_o + 10.253$ (n = 203, $R^2 = 0.20$, S.E. = 0.035, $p < 0.001$) (5.2)

For temperate, $T_g = 0.888\ T_o + 1.402$ (n = 407, $R^2 = 0.71$, S.E. = 0.028, $p < 0.001$) (5.3)

For sub-tropical, $T_g = 0.820\ T_o + 3.118$ (n = 229, $R^2 = 0.78$, S.E. = 0.028, $p < 0.001$) (5.4)

where T_o is outdoor air temperature, n is the number of data, R^2 is the coefficient of determination, S.E. is the standard error of the regression coefficient, and p is the significance level of the regression coefficient. The slope obtained for cold region is smaller than the other regions. The correlation coefficient of the cold region is much smaller than that of the temperate and sub-tropical regions. This is due to high thermal mass of the houses in cold region. The slopes of temperate and sub-tropical regions are similar. These must be due to the similar thermal masses of the houses in the two regions.

The globe temperature lies between 8 and 16 °C for cold region and 15 and 25 °C for both temperate and sub-tropical regions. Assume the outdoor air temperature to be 15 °C, T_g tourns out to be 14 °C for cold region and 15.4 °C for temperate region. The difference between the indoor globe temperatures for two regions is 1.4 °C (= 15.4 - 14). Similarly, if we assume the outdoor air temperature to be 22 °C, T_g turns out to be 21.2 °C for temperate region and 21.5 °C for the sub-tropical region. The difference between the indoor globe temperatures is 0.3 °C (= 21.5 - 21.2) for temperate and sub-tropical regions.

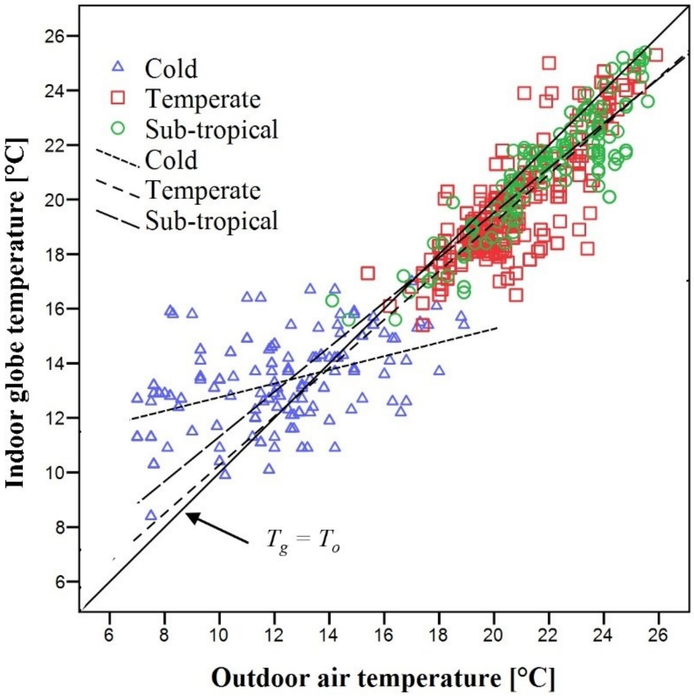


Fig. 5.4 Relationship between indoor globe temperature and outdoor air temperature

5.3.3 Relationship between thermal sensation votes and indoor globe temperature

Nepal has a different climatic region as described above and thus the thermal sensation vote can be different. Thus, in this section, we first describe the thermal sensation votes obtained in each region as shown in Fig. 5.5. We received the largest number of votes for "2. cold" in cold and temperate regions and "4. Neutral" in sub-tropical region. Although on the thermal sensation vote for "4. Neutral" appeared, only 1% of all votes in cold region, 39% in temperate and 59% in sub-tropical regions. Even though (Shahzad et al. 2019), (Shahzad and Rijal 2019) used the overall comfort scale to evaluate the thermal comfort of people, we used the central three thermal sensation votes including neutral as a "comfort zone" or "satisfied" and rest as "dissatisfied" or "discomfort" (ASHRAE Standard-5520, EN 15251, Fanger 1970, Humphreys and Nicol 1970, Rijal 2021). If the thermal sensation votes for 3, 4, and 5 are grouped as "comfort zone", then 15% of the votes are in the "comfort zone" in cold region, 96% in temperate and 93% in sub-tropical regions. The percentage of "comfort zone" in cold region is much lower than the result given in other study (Gautam 2019), and the results in temperate and sub-tropical regions are similar to each other. This is probably due to the low indoor globe temperate (13.2 °C) in cold region which is 6.5 °C and 7.5 °C lower than temperate and sub-tropical regions, respectively.

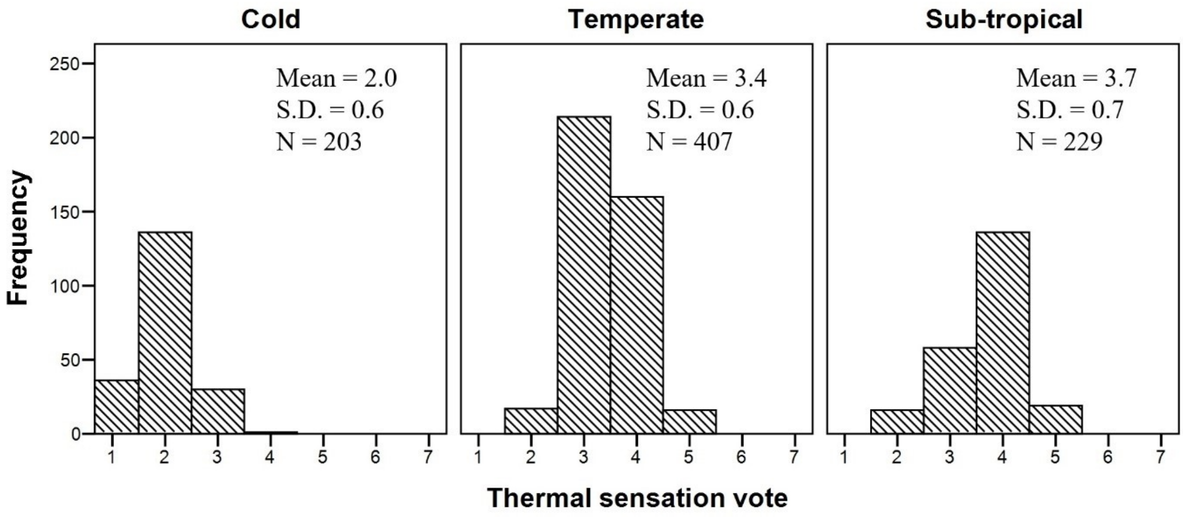


Fig. 5.5 Frequency of thermal sensation vote of residents

The relative number of thermal sensation votes for cold side ("1. Very cold", "2. Clod" and "3. Slightly cold) among all votes may be expressed as a logistic curve with the indoor globe temperature, T_g as the single explanatory variables as follows (Rijal et al. 2018).

logit (P) = 0.63 T_g - 12.64 (n = 839, R^2 = 0.38, S.E. = 0.047, $p < 0.001$) (5.5)

where p is proportion of cold side votes.

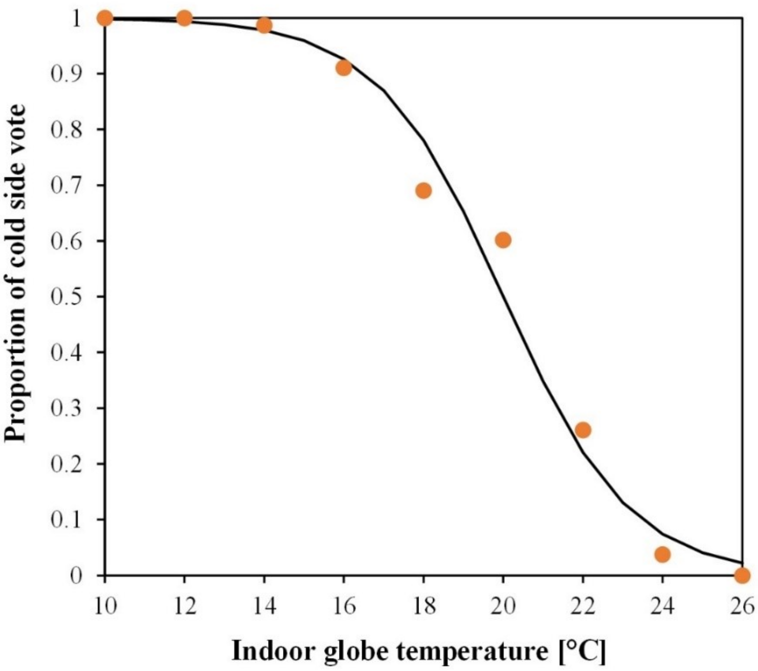


Fig. 5.6 The proportion of cold side votes and indoor globe temperature

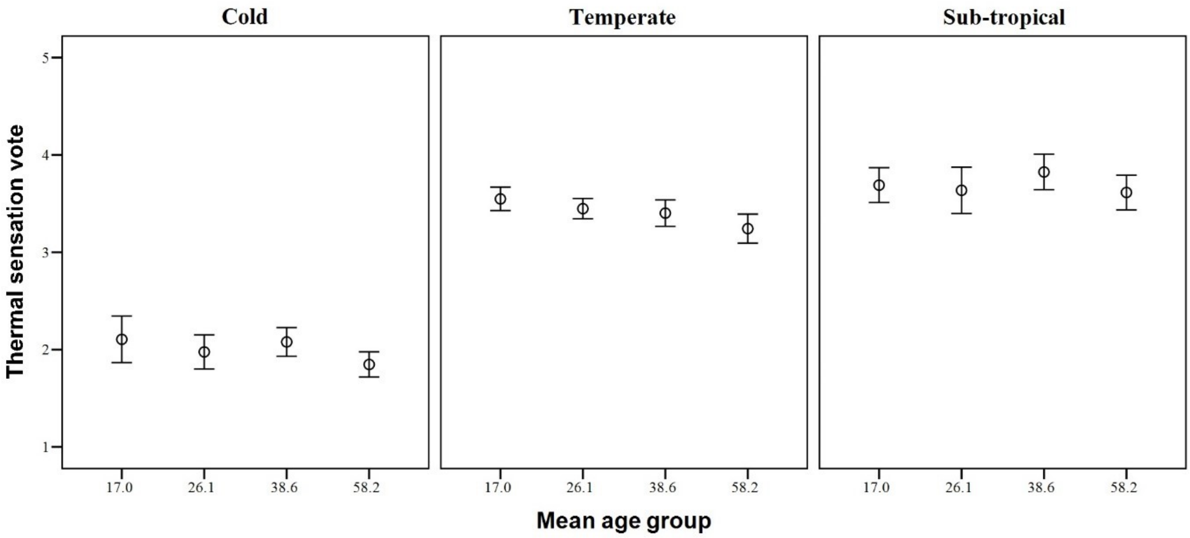


Fig. 5.7 Thermal sensation vote according to age group of three regions

Fig. 5.6 shows the relationship between the proportion of cold side vote and indoor globe temperature. The regression analysis was made for all vote obtained from these regions. The proportion of cold side vote decreases as the indoor globe temperature increases. For the indoor globe temperature at 20 °C, 50% of the votes are in cold side. These result indicates that we need to improve the houses with low indoor globe temperature to the ones with rationally higher indoor globe temperature.

Fig. 5.7 shows the thermal sensation vote by age group in each region. The data was sorted into four age groups so that each group contains the large number of data: 205 to 212. Almost all age groups were voted below the “4. Neutral” in all regions. Generally, the oldest age group voted for colder side than other three age groups in all regions. The thermal sensation vote could be affected by the age group. This trend is similar to other studies (Chen et al. 2018, Lie et al. 2014, Rupp et al. 2019).

5.3.4 Comfort temperature

In this research, the comfort temperature is estimated by Griffiths’ method as shown below (Nicol et al. 2012, Rijal et al. 2020, Griffiths 1990)

$$T_c = T_g + \frac{(4 - TSV)}{a} \tag{5.6}$$

where T_c is comfort temperature [°C], the number 4 indicates “neutral” in the TSV seven-point linear scale, TSV indicates the thermal sensation vote obtained from the survey, and a is the assumed increment of thermal sensation vote corresponding to an increase of 2 °C in globe temperature and we assumed it to be 0.50 referring the previous studies (Humphreys et al. 2013, Rijal et al. 2017). In applying Griffiths’ constant, (Humphreys et al. 2013) and (Nicol et al. 1999) used 0.50. (Thapa et al. 2018, Gautam et al. 2019], Rijal et al. 2019, Wang et al. 2018) and (Kumar and Singh 2019) are also used this constant in residential buildings. (Ryu et al. 2020) found 0.356 of Griffiths constant in residential building. (Rupp et al. 2019) concluded that the Griffiths constant of 0.50 was derived from office building and it's not applicable in different building types. Thus, we have estimated the comfort temperature using three Griffiths' constants simar to other studies (Thapa et al. 2018, Rijal et al. 2019) (Table 5.1). The mean comfort temperature obtained from these three constants in temperate and sub-tropical regions are similar but they are different in cold region. We choose the constant of 0.50 further analysis because the comfort temperature which is estimated by 0.50 is close to the mean temperature when voted "4. Neutral" in all regions as shown in Table 5.1. The mean comfort temperature was 17.2 °C, 20.9 °C and 21.7 °C in cold, temperate and sub-tropical regions, respectively. These values are close to the findings in Japanese houses (Rijal et al. 2018, , Rijal et al. 2019, Rijal et al. 2013). Residents feel comfortable at low comfort temperature in the cold region because the clothing insulation of residents might be high similar to other studies in Nepal (Rijal et al. 2010, Gautam et al. 2019, Rijal 2021, Rijal 2018)

Table 5.1 Mean of neutral temperature and comfort temperature predicted by Griffiths' method

Study area	Regression coefficient	N	Comfort temperature (°C)		N	Temperature for 4. Neutral (°C)	
			Mean	S.D.		Mean	S.D.
Cold	0.25	203	21.3	2.3			
	0.33	203	19.3	1.9			
	0.50	203	17.2	1.6	1	(13.1)	-
Sub-tropical	0.25	407	22.0	2.3			
	0.33	407	21.5	2.0			
	0.50	407	20.9	1.8	160	20.4	2.1
Temperate	0.25	229	22.3	2.0			
	0.33	229	22.0	1.7			
	0.50	229	21.7	1.5	136	21.5	1.6

S.D : Standard deviation

Fig. 5.8 shows the average comfort temperate and indoor globe temperature by time in each region. The thermal comfort survey was conducted at for a period of 20 minutes or so in each house between 7:10 and 20:45. The data was preformed was sorted into four groups so that each group contains the data from 206 to 213. In cold region, the comfort temperature is significantly higher than indoor globe temperature for any time. In cold region, comfort temperatures increase from the morning to the evening. But in the temperate and sub-tropical region, they increased in morning time to early afternoon and decreased to evening time. The result indicates that the comfort temperatures changes according to the time of the day. This result is consistent with the findings by (Gallardo et al. 2016, Gautam et al. 2020).

Fig. 5.9 shows the relationship between comfort temperature and indoor globe temperature in all three regions. Most of data plots lie above the diagonal line. As indoor globe temperature increase, the comfort temperature also increases. The difference between comfort temperature and indoor globe temperature in cold region is large compared to temperate and sub-tropical regions. This trend suggests that the residents of the cold region in particular desire a warmer indoor environment condition for a given indoor environment. This result is consistent with other studies (Rijal et al. 2010, Gautam et al. 2019, Rijal et al. 2017, Nicol et al. 1999, Rijal et al. 2019).

The average indoor globe temperature of cold region is lower than temperate and sub-tropical regions. The difference between the indoor globe temperature in cold and temperate, temperate and sub-tropical regions are large difference. We may say that the indoor globe temperature has a large regional difference; this tendency is similar to the findings in previous studies (Rijal et al. 2010, Gautam et al. 2019, Nicol and Roaf 1996). The mean comfort temperature was 17.2 ~ 21.7 °C and they are different from one region to another region (Figs 5.8 and 5.9). Table 5.2 shows the comparison of comfort temperature obtained in this study and those given in previous studies (Rijal et al. 2010-Gautam et al. 2019, Rijal et al. 2019, Rijal et al. 2013, Wang 2006, Thapa et al. 2017, Heidari and Sharples 2002, Rijal and Stevenson 2010). The mean comfort temperature of cold region is significantly higher than that in previous studies of Nepal. But, the mean comfort temperature of the temperate and sub-tropical regions was consistent with that in other studies.

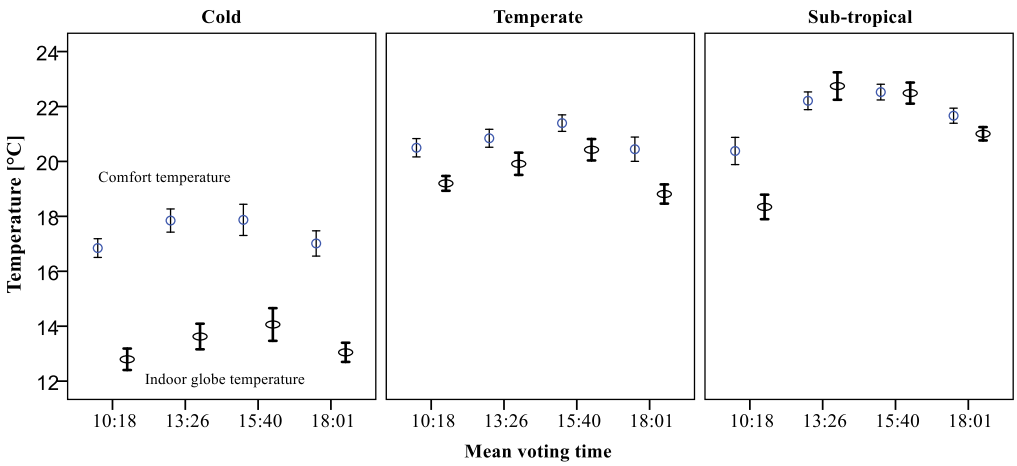


Fig. 5.8 Comfort and indoor globe temperature according to voting time of three region

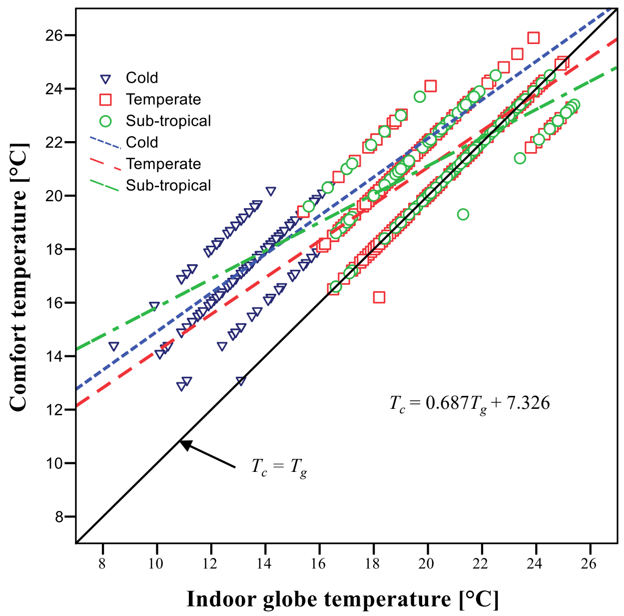


Fig. 5.9 Relation between comfort temperature and indoor globe temperature of three region

Table 5.2 Comparison of comfort temperature in winter with previous studies.

References	Country	Climate	House type	Temp. for T_c (°C)	Comfort temperature range (°C)
This study	Nepal	Cold, temperate and sub-tropical	Traditional, modern	T_g	17.2 ~ 21.7
Rijal et al. [11]	Nepal	Cold, temperate and sub-tropical	Tradiational	T_g	13.4 ~ 24.2
Thapa et al. [12]	Nepal	Temperate	Tempерory shelter	T_g	15.0 ~ 28.6
Gautam et al. [13]	Nepal	Cold, temperate and sub-tropical	Tradiational	T_g	13.8 ~ 23.1
Rijal et al. [35]	Japan	Cold (Kanto)	Dwellings	T_i	17.6
Rijal et al. [39]	Japan	Cold (Gifu)	Dwellings	T_i	15.6
Wang [51]	China	Humid continental	Residential buildings	T_{op}	20.9(M), 21.9(F)
Thapa et al. [52]	India	Cold	Residential buildings	T_i	20.8 ~ 26.1
Heidari and Sharples [53]	Iran	Cold	Residential buildings	T_i	20.8
Rijal and Stevenson [54]	UK	Cold	Residential buildings	T_i	19.4

5.4 Preferred temperature

5.4.1 Indoor and outdoor air temperature during the voting

The structure and materials of the houses differ among the regions. In this section, we analyze the relationship between the indoor air temperature and outdoor air temperature. Fig. 5.10 shows the relationship between the indoor air temperature and outdoor air temperature in the respective regions during the voting time. The indoor air temperature is related to outdoor air temperature and it is higher than the outdoor air temperature. We found the following regression equations:

For cold region, $T_i = 0.676\ T_o + 3.085$ (n = 203, $R^2 = 0.16$, S.E. = 0.011, $p < 0.001$) (5.7)

For temperate, $T_i = 0.746\ T_o + 6.368$ (n = 407, $R^2 = 0.652$, S.E. = 0.027, $p < 0.001$) (5.8)

For subtropical, $T_i = 0.971\ T_o + 1.854$ (n = 229, $R^2 = 0.782$, S.E. = 0.034, $p < 0.001$) (5.9)

where T_o is the outdoor air temperature, n is the number of data samples, R^2 is the coefficient of determination, S.E. is the standard error of the regression coefficient, and p is the significance level of the regression coefficient. The slope obtained for the cold region was smaller than that for the other regions. The correlation coefficient of the cold region was much smaller than that of the temperate and subtropical regions. This is due to the high thermal masses of houses in the cold region. The slopes of the temperate and subtropical regions were similar. This may be due to the similar thermal masses of the houses in the two regions.

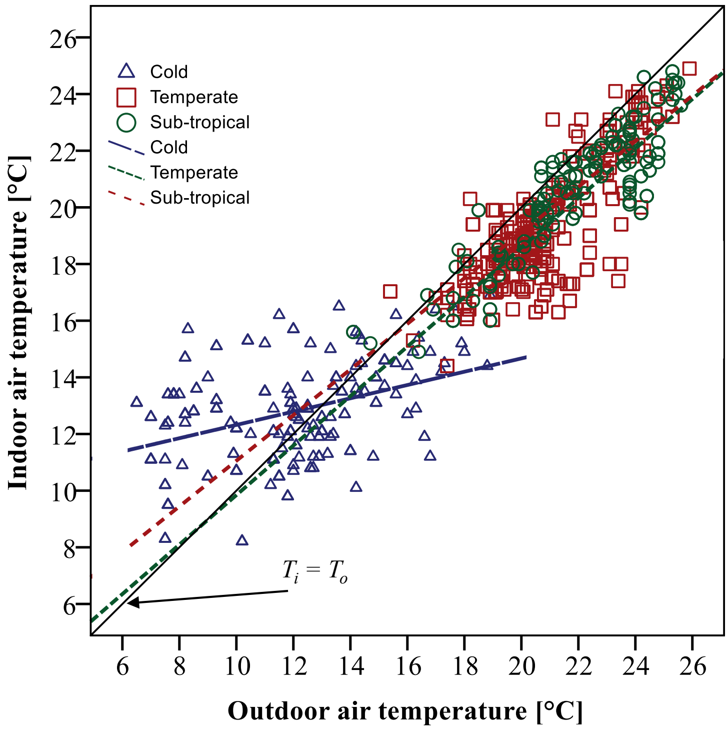


Fig. 5.10 Relation between indoor and outdoor air temperature

Table 5.3 shows the regression equations from Nepal and Japan. The slope obtained from this study is higher than Pokharel et al. (2020) in the cold, temperate and subtropical region. The slope is high in modern houses and low in traditional houses which is similar trends to Pokharel et al. (2020) and Bajracharya (2013). The slope is high in the shelter (Thapa et al. 2018). The slope is low in Japanese dwelling. It shows that the effect of outdoor air temperate is high in modern houses than the traditional houses.

Table 5.3 Comparison of regression equation with previous studies.

Country	Area	References	House type	Season	Regression equation
Nepal	Kalikot	This study	Traditional house	Winter	$T_i = 0.68\ T_o + 3.1$
Nepal	Kathmandu	This study	Modern house	Winter	$T_i = 0.75\ T_o + 6.4$
Nepal	Chitwan	This study	Modern house	Winter	$T_i = 0.97\ T_o + 1.9$
Nepal	Mustang	Pokharel et al. 2020	Traditional house	Winter	$T_i = 0.49\ T_o + 4.8$
Nepal	Panchthar	Pokharel et al. 2020	Traditional house	Winter	$T_i = 0.45\ T_o + 9.1$
Nepal	Jhapa	Pokharel et al. 2020	Modern house	Winter	$T_i = 0.86\ T_o + 2.8$
Nepal	Lalitpur, Kathmandu, Shindhupalchowk, Gorkha	Thapa et al. 2018	Temporary shelters	Summer and winter	$T_i = 0.92\ T_o + 2.7$
Nepal	Kathmandu Valley	Bajracharya 2013	Modern houses	Summer and winter	$T_i = 0.94\ T_o + 1.3$
Nepal	Kathmandu Valley	Bajracharya 2013	Traditional houses	Summer and winter	$T_i = 0.89\ T_o + 1.6$
Japan	Kanto region	Rijal et al. 2015	Japanese houses	All season	$T_i = 0.59\ T_o + 12.6$

5.4.2 Thermal preference vote

Due to the wide climate variation of Nepal, thermal response of residents might be different. Thus, in this section, we first describe the thermal preference in each region as shown in Fig. 5.11 The percentage of "3. No change" is 1%, 39.3% and 59.4% in cold, temperate and subtropical regions, respectively. This tendency is similar to other study in cold region (Rijal 2021). We used the central three thermal preference votes 2 and 3 as a "preference zone"(Rijal et al. 2010, Gautam et al. 2019 and Shrestha et al. 2021). The "preference zone" is 43.3%. 95.1% and 98.7% in cold, temperate and subtropical regions, respectively. The percentage of "preference zone" in cold region is much lower than other two regions. This is probably due to the low indoor globe temperate (13.2 °C) in cold region compared to other regions.

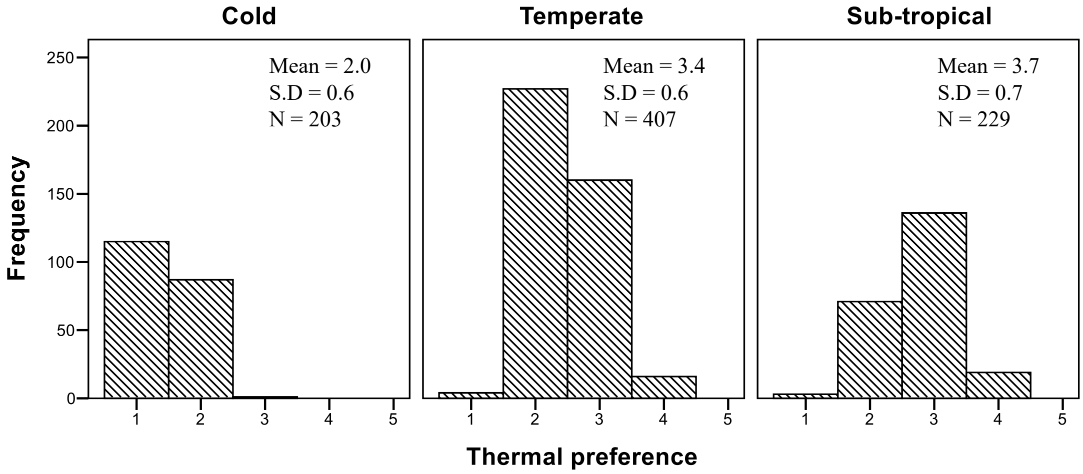


Fig. 5.11 Frequency of thermal preference vote of residents

5.4.3 Relation between thermal preference vote and indoor globe temperature

The proportion of prefer warmer for a given indoor temperature is predicted by using logistic regression analyze. We have classified the binary data for the thermal preference vote: "1. Prefer warmer"(vote 1. Much warmer and 2. A bit warmer) and "0. Others". The following regression equation is obtained from the regression analysis.

$$\text{logit}\,(P_w) = 0.63\ T_g - 12.64\ (\text{n} = 839,\ \text{R}^2 = 0.38,\ \text{S.E.} = 0.047,\ p < 0.001) \qquad (5.10)$$

where P_w is proportion of prefer warmer. T_g: indoor globe temperature (°C); n: number of sample; R^2 : coefficient of determination; S.E.: standard error of the regression coefficient; p: significance level of regression coefficient.

Fig. 5.12 shows the relationship between the proportion of prefer warmer and indoor globe temperature. The proportion of prefer warmer increases as the indoor globe temperature decreases. When the indoor globe temperature is 21 °C, the proportion of prefer warmer is 50%. The result indicates that people are not satisfied with the present indoor thermal condition and thus we need to increase the indoor temperature by improving the houses such as thermal insulation and airtightness.

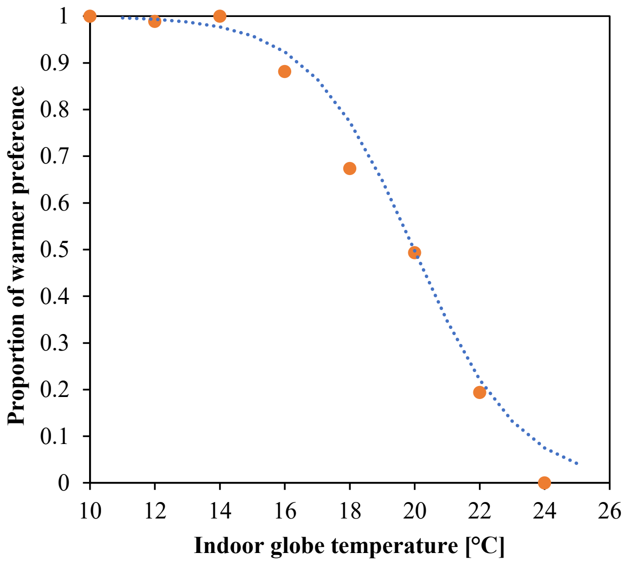


Fig. 5.12 The proportion of prefer warmer and indoor globe temperature

3.4. Distribution of preferred temperature and its relation to indoor globe temperature

The thermal preference might be more suitable than thermal sensation vote of residents. Fig. 5.13 shows the distribution of the estimated preferred temperature in each climatic region. The mean preferred temperature is the lowest in the cold region, middle in the temperate region and the highest in the subtropical region. The preferred temperature has a large regional difference. The the preferred temperature is quite close to the comfort temperature (Shahi et al. 2021). This tendency is similar to that observed in a previous study (Gautam et al. 2019). In all three climatic regions, the preferred temperature is higher than the comfort temperature. The difference between them is largest at 0.7 °C in the cold.

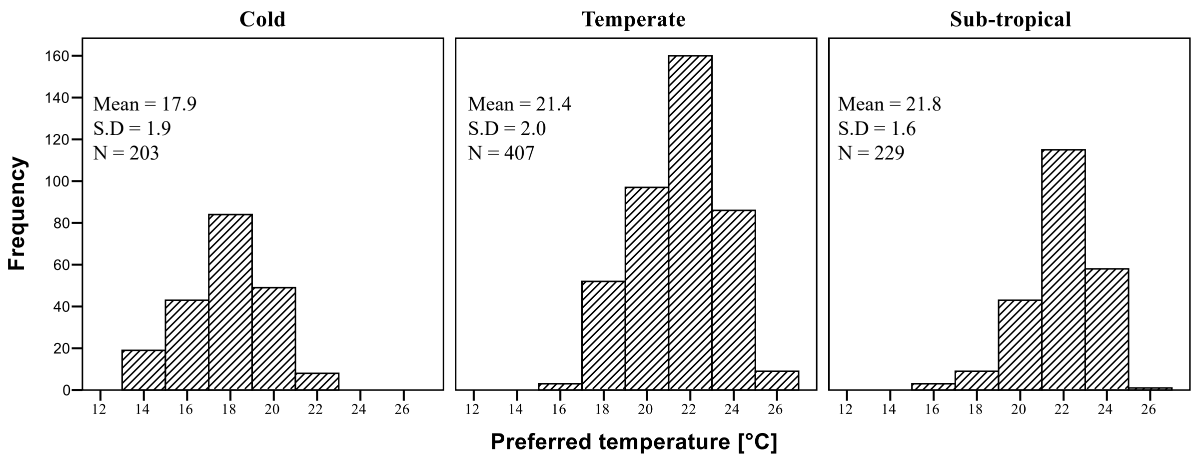


Fig. 5.13 Distribution of preferred temperature in each climate

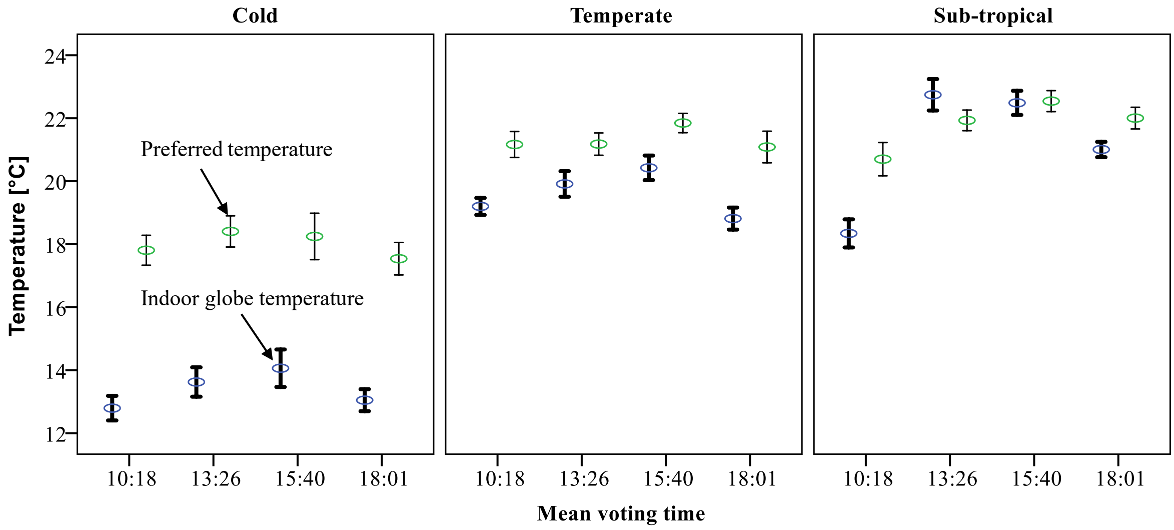


Fig. 5.14 The preferred temperature and indoor globe temperature by time in each climate

Fig. 5.14 shows the preferred temperate and indoor globe temperature by time in each region. The thermal comfort survey was conducted in each house between 7:10 and 20:45. The data ware sorted into four groups so that each group contains the similar number of data: 206 to 213. In cold region, the preferred temperature is significantly higher than that of indoor globe temperature for all given time. In cold region, preferred temperatures increase from the morning to the evening. But in the temperate and subtropical regions, they increased in morning time to early afternoon and decreased to evening time. The result indicates that the preferred temperatures changes according to the time of the day.

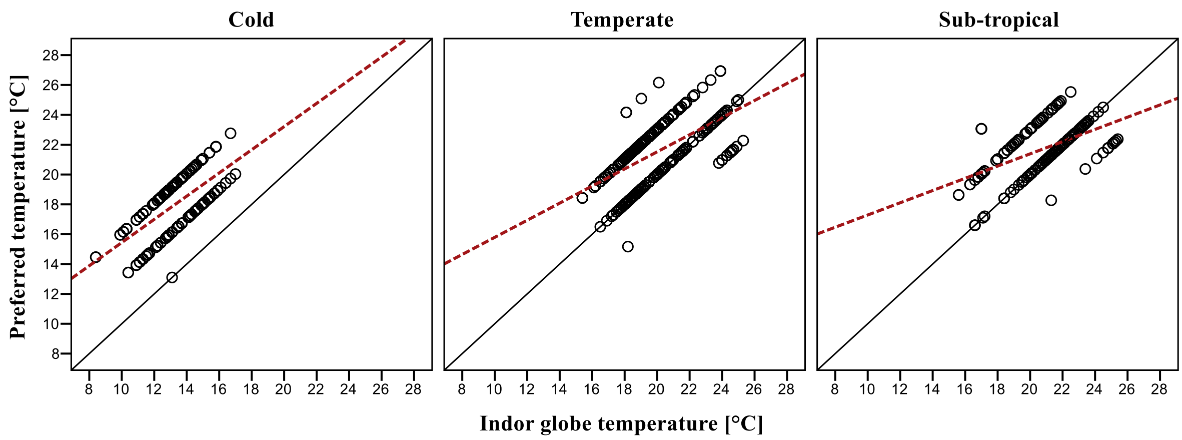


Fig. 5.15 Relation between preferred temperature and indoor globe temperature

Fig. 5.15 shows the relationship between preferred temperature and indoor globe temperature in each region. Most of data plots lie above the diagonal line. As indoor globe temperature increase, the preferred temperature also increases. The difference between preferred temperature and indoor globe temperature in cold region is large compared to the temperate and subtropical regions. The result suggests that the residents of the cold region in particular desire a warmer indoor environment condition for a given indoor temperature. This result is consistent with other studies (Gautam et al. 2019). So, it is necessary to increase the indoor temperature to obtain the preferred temperature of residents. According to Shahi et al. (2020) and Rijal (2012), the thermal improvement of houses by using thermal insulation and reduction of infiltration is effective to increase the indoor air temperature.

3.5. Relationship between preferred temperature and comfort temperature

Currently, most of the studies are used comfort temperature to evaluate the thermal comfort and we may need to consider the prefer temperature of residents. Thus, this study analyzed how the preferred temperature and comfort temperature are related to each other. Fig. 5.16 shows the relationship between the preferred temperature and comfort temperature. We have found the following equations from the regression analysis:

Cold $T_{per} = 0.934\ T_c + 1.835$ (n = 203, $R^2 = 0.58$, S.E. = 0.056, $p < 0.001$) (5.11)

Temperate $T_{per} = 1.023\ T_c + 0.012$ (n = 407, $R^2 = 0.89$, S.E. = 0.018, $p < 0.001$) (5.12)

Subtropical $T_{per} = 0.973\ T_c + 0.737$ (n = 229, $R^2 = 0.83$, S.E. = 0.029, $p < 0.001$) (5.13)

These regression equations can be used to estimate the preferred temperature by comfort temperature. The coefficient of determination of the cold region data is much smaller than the temperate and subtropical regions. The slope of the three regions are similar trends. More of data plots lie above the diagonal line in the cold region. This tendency suggests that people in cold regions especially prefer higher indoor temperature when the comfort temperature is low. The results are similar to other previous study (Gautam at al. 2019, Shahzad & Rijal 2019). This study suggests that we also need to consider "preferred temperature" for thermal comfort of people, especially when the indoor temperature is low.

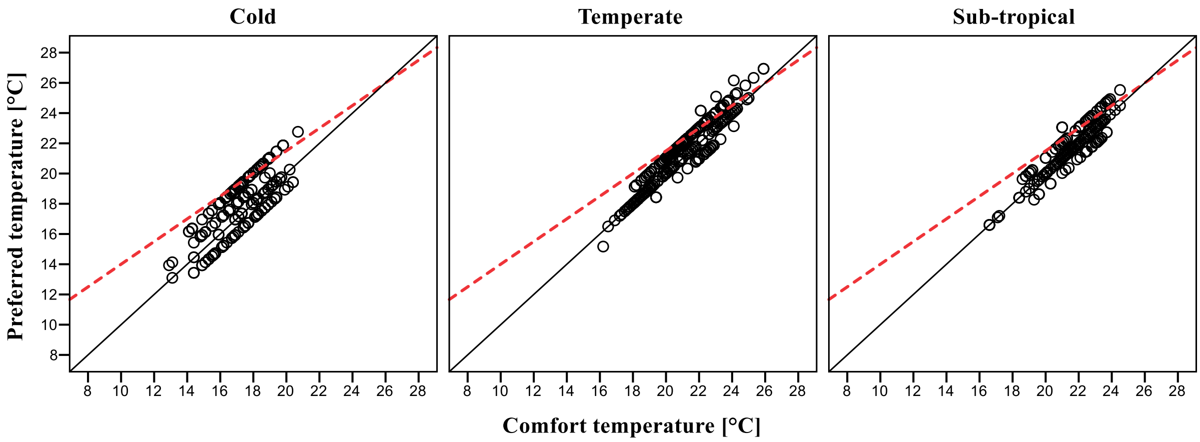


Fig. 5.16 Relation between preferred and comfort temperature

5.4. Conclusions

Focusing on ordinary houses in three climatic regions in Nepal, we have conducted a thermal comfort survey together with indoor and outdoor thermal environment measurement in winter. Then, we analyzed the characteristics of indoor air temperature in cold, temperate and sub-tropical regions, respectively. The major findings are as follows:

1. Thermal sensation votes for “2. cold” was the largest proportion in cold and temperate regions, and those for “4. Neutral” was in sub-tropical region. The proportion of cold side vote increases as the indoor globe temperature decreases. For the indoor globe temperature at 20 °C, 50% of the votes was in cold side.

2. The mean comfort temperature was estimated to be 17.2 °C, 20.9 °C and 21.7 °C in cold, temperate and sub-tropical regions, respectively. The indoor globe temperature of the cold region was significantly lower than comfort temperature. In other two regions, the tendency was similar, but the difference in two temperatures was less significant. The comfort temperature has a large regional difference.

3. The percentage of “3. No change” in thermal preference is 1%, 39.3% and 59.4% in cold, temperate and subtropical regions, respectively. The “preference zone” is 43.3%. 95.1% and 98.7% in cold, temperate and subtropical regions, respectively. The percentage of “preference zone” in cold region is much lower than other two regions. This is probably due to the low indoor globe temperate 13.2 °C in cold region.

4. In cold region, the preferred temperature is significantly higher than indoor globe temperature for different day. In cold region, preferred temperatures increase from the morning to the evening. The result indicates that the preferred temperatures changes according to the time of the day.

5. The mean preferred temperature was estimated to be 17.9 °C, 21.4 °C and 21.8 °C in cold, temperate and subtropical regions, respectively. The preferred temperature has a large reginal difference. The residents of the cold region in particular prefer 0.7 °C higher indoor temperature than comfort temperature.

6. The preferred temperature and comfort temperature was highly related in temperate and subtropical regions but it is less related in cold region, and thus the prefer temperature might be better indication to evaluate the indoor thermal comfort in cold climate.

In cold region, the estimated comfort temperature was significantly higher than the indoor globe temperature measured. In the other two regions, the estimated comfort temperature was higher than the measured indoor globe temperature, but their difference was less significant. The indoor thermal improvement is necessary to improve enhancement of thermal insulation and the reduction of infiltration was effective to increase the indoor air temperature.

Chapter 6: Thermal environment

6.1 Introduction

The indoor thermal environment is one of the important aspects of sustainable building design. This criterion is important in ensuring a healthy indoor environment for the occupants. The consideration of environmental concerns at the early design stage would effectively integrate the sustainability of the building environment. Residents are now more aware of the importance of sustainability for a better quality of life. A good thermal environment is essential for human wellness and comfort. The living environment affects the health and safety of residents (Jamaludin et al. 2014). Most of the time spent is inside the house but the average indoor temperature in winter is low as shown in Fig. 6.1. (Niemelä et al. 2002) observed that productivity in telecommunication centers decreases by 5-7% when the workers are sensing high indoor temperatures. (Seppanen et al. 2006) wrote that the performance in offices is reduced by about 9% when occupants are subjected to a temperature of 30 °C. Similarly, (Cao and Wei 2005) claimed that low temperatures tend to cause aggression, while elevated temperatures have the tendency to cause aggression, hysteria and apathy. Therefore, it is necessary to analyze the indoor thermal environment for further improvement. This knowledge is important when you need to devise a solution to control the indoor environment that maximizes the user comfort of the building. The concern is whether all environmental conditions contribute equally to achieving comfort or rank differently depending on the user of the building. This section describes the indoor environmental conditions of these homes in the cold, temperate and subtropical regions of Nepal.

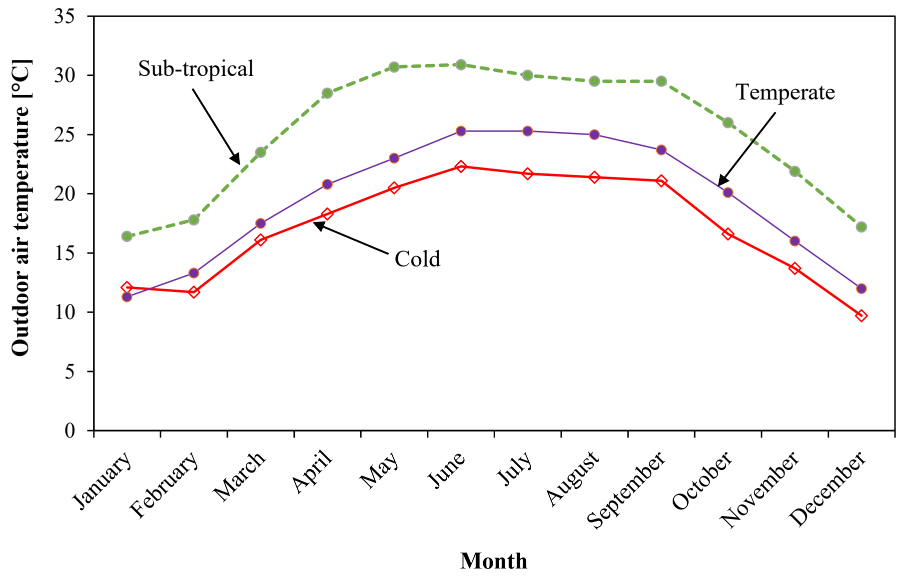


Fig. 6.1 Monthly mean outdoor air temperature in Manma, Kathmandu international airport and Bharatpur meteorological station in 2014.

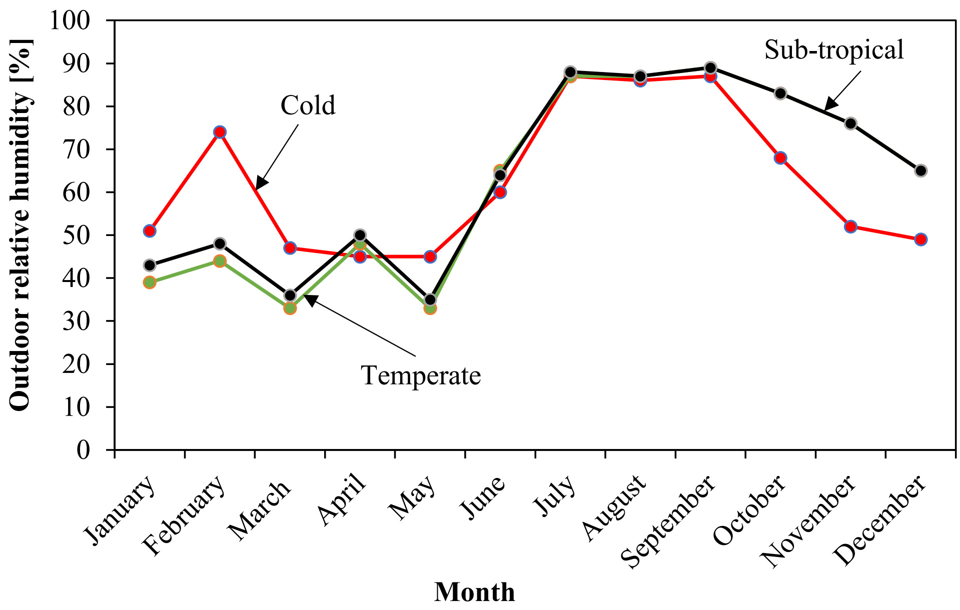


Fig. 6.2 The Monthly mean outdoor relative humidity of cold, temperate and sub-tropical regions (Source: World weather online, https://www.worldweatheronline.com/kathmandu-weather-averages/np.aspx)

Fig. 6.1 shows the monthly outdoor air temperature in cold, temperate and subtropical regions (DHM). Outdoor air temperature trends rise from February, and constant from June to August, decrease from September, and constant from December to February. The cold climate has much lower outdoor air temperature throughout the month than in temperate and sub-tropical regions. Fig. 6.2 shows the average monthly outdoor relative humidity in cold, temperate and subtropical regions. In cold regions, the relative humidity is higher from January to March than in the temperate and subtropical regions, but from September to December is lower.

Table 6.1 The details of houses for continuous data measurement.

District	Climate	No. of houses	Storey	Wall materials	U-value W/(m^2.K)	Door and window materials	U-value W/(m^2.K)	Floor materials	U-value W/(m^2.K)	Roof material	U-value W/(m^2.K)	Measured space	Survey date
Kalikot	Cold	3	3	Stone, mud	1.7	Wood	3.5	Wood, mud	1.1	Wood, mud	1.1	Bed and living room	Jan. 24th - 28th, 2018
Kathmandu	Temperate	3	3	Plaster, Brick	2	Particle board, glass	3.4	Plaster, concrete	3.4	Plaster, concrete	3.4	Bed room	Feb. 12th - 16th, 2018
Chitwan	Sub-tropical	3	3	Plaster, Brick	2	Particle board, glass	3.4	Plaster, concrete	3.4	Plaster, concrete	3.4	Bed and living room	Feb. 5th -9th, 2018

6.2 Thermal measurement

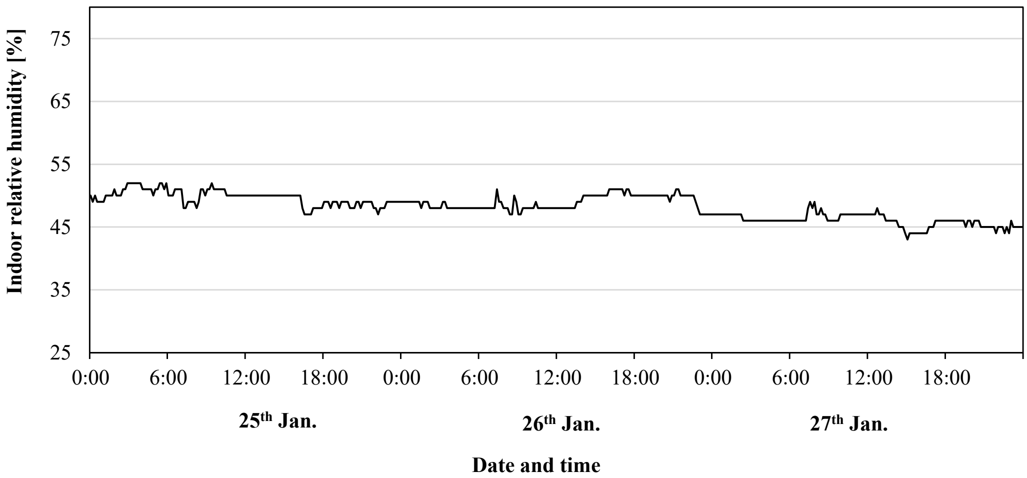
Three houses were selected for continuous thermal measurement from each region to other shown in Fig. 3.1. All selected houses were three storied. We have measured the indoor air temperature in bedrooms and living rooms for five days in ten minute intervals as shown in Table 6.1. The data loggers were placed in the middle or the corner of respective investigated houses; they were set 1 m above the floor level. The outdoor air temperature was measured just outside the houses in each region. Table 6.1 shows the instruments used.

6.3 Variation of indoor relative humidity

Relative humidity (RH) is an important environmental factor that could affect thermal comfort in a building. A high or low humidity environment is not only closely related to many health problems, but also has a significant impact on construction durability and energy use (Zhang and Yoshino 2010). It is very important to control humidity level, in order to achieve a healthy and comfortable indoor environment. However, various problems of the air humidity in inhabited dwellings are not yet taken into serious consideration in Nepal. Moreover, there is hardly any information available regarding the actual humidity environment in Nepalese residential houses. According to Vellei et al. (2016) a new designer-friendly relative humidity-inclusive adaptive model that significantly extends the range of acceptable indoor conditions for designing low-energy naturally-conditioned buildings all over the world. Therefore, it is necessary to discuss the relative humidity (RH) of cold, temperate and subtropical climates.

Table 6.2 The minimum, maximum, mean and standard deviation of CO_2 and relative humidity in cold, temperate and sub-tropical regions.

Study	Variables	N	Minimum	Maximum	Mean	S.D.
Cold	CO_2 [ppm]	432	353	816	494.1	117.0
	Relative humidity [%]	432	43	52	48.2	2.0
	Indoor air temperature [°C]	432	9.6	13.3	11.0	0.6
Temperate	CO_2 [ppm]	432	477	3366	1306.8	783.8
	Relative humidity [%]	432	31	69	50.1	8.1
	Indoor air temperature [°C]	432	16.7	20.8	18.1	0.8
Sub-tropical	CO_2 [ppm]	430	438	3780	1025.5	592.2
	Relative humidity [%]	432	59	78	69.4	3.7
	Indoor air temperature [°C]	432	15.7	21.9	19.7	1.4



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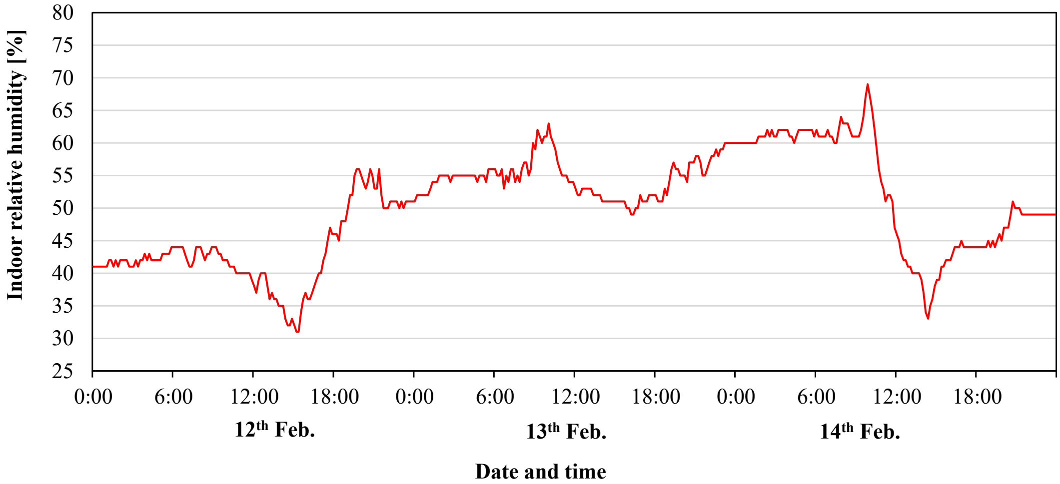

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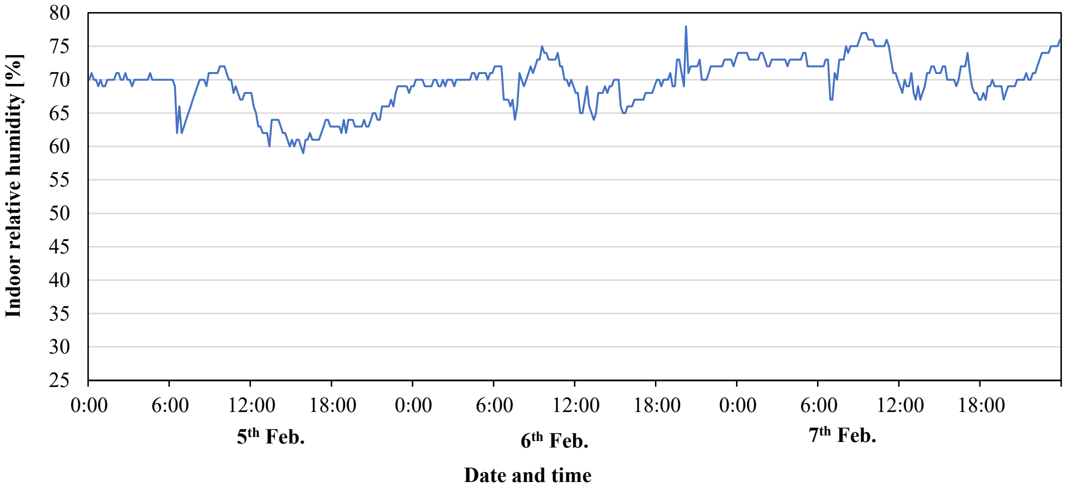


(c)

Fig. 6.3 Variation of indoor relativity humidity of three house: (a) Cold, (b) Temperate, (c) Sub-tropical regions

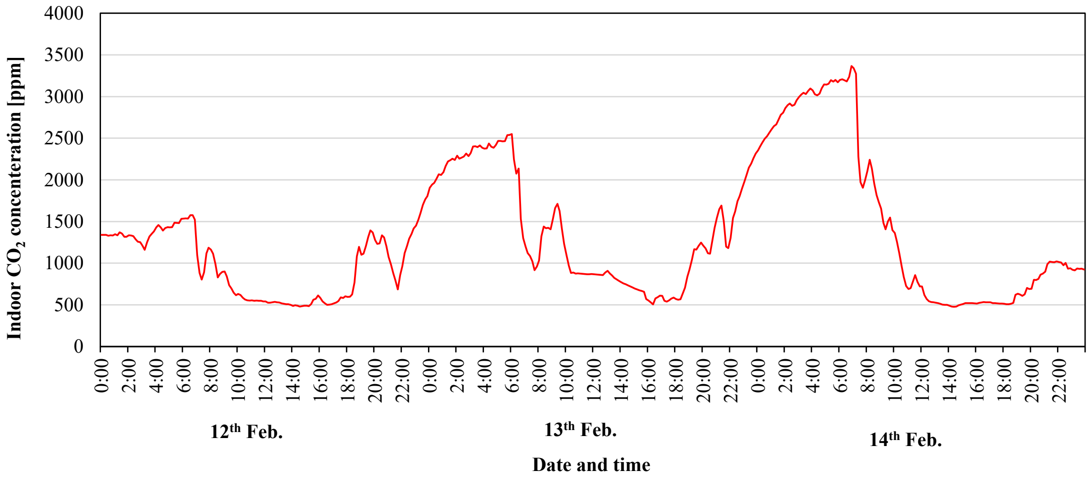
Fig. 6.3 (a-c) shows the indoor relative humidity (RH) for three days of cold, temperate and sub-tropical regions. The variation of relative humidity (RH) in cold region is not so large. As shown in Table. 6.2 the minimum relative humidity (RH) is 43%, maximum is 52%, and average is 48.2%. According to the ASHRAE guidelines recommend a relative humidity (RH) of 30 to 60 percent is recommended. Relative humidity (RH) fluctuations in temperate region is higher than in cold and subtropical regions. The minimum relative humidity (RH) is 31%, the maximum is 69%, and the average is 50.1%. The trend shows that relative humidity (RH) increases during the day and decreases in the evening. Relative humidity (RH) is small fluctuations in sub-tropical region but the higher relative humidity (RH) than in cold and temperate regions. The minimum relative humidity (RH) is 59%, the maximum is 78%, and the average is 69.4%. The minimum relative humidity (RH) in the subtropical region is higher than the maximum relative humidity (RH) in cold climates. The relative humidity (RH) is higher in sub-tropical region than the ASHRAE guidelines.

6.4 Variation of CO_2 in houses

Carbon dioxide is one of the major greenhouse gases that cause global warming, so it is often used while talking about global warming. However, CO_2 is a good indicator of indoor air quality in houses where residents and their other cooking and boiling activities are the main source of pollution, as it is emitted by all humans during breathing, rather than many other sources. However, CO_2 is rarely a health issue in itself. Nevertheless, it is a very good indicator of human presence and the rate of infiltration. According to (CEN 2019; Active house Alliance 2020 400 ppm air contain in outdoor is generated through breathes, so the indoor CO_2 concentration will always be at least 400 ppm and usually higher. An indoor CO_2 level of 1150 ppm provides adequate air quality, 1400 ppm will ensure good indoor air quality in most situations, and 1600 ppm indicates poor air quality. Humans are the primary source of indoor air pollution since we have to exhale carbon dioxide and moist air ceaselessly from our nose and mouth. It is very important to minimize the ordinary indoor air so that the resulting pollution does not cause any health related problems, that is so-called sick-building syndrome and also so that the required rate of fresh air to be taken in through mechanical heating and cooling systems can be minimized (Shukuya 2018).

Table 6.3 Description of measure houses

House	Room floor	Volume of room [m^3]	Door size [m^2]	Window size [m^2]	Number of window	Number of door	Use of firewood	Use of mechanical heating	Number of occupants	Air velocity [m/s]	Average indoor air temp. [ºC]	Relative humudity [%]
Cold	3	21.6	1.3	-	-	1	Used in 2nd floor in this room	No	1 adult	0.06	10	42
Temperate	3	25.1	2.4	2.1	1	2	No	No	2 adult and 2 child	0.02	20.2	55
Subtropical	1	27.5	2.7	2.1	1	1	No	No	2 adult and 2 child	0.07	20.2	65



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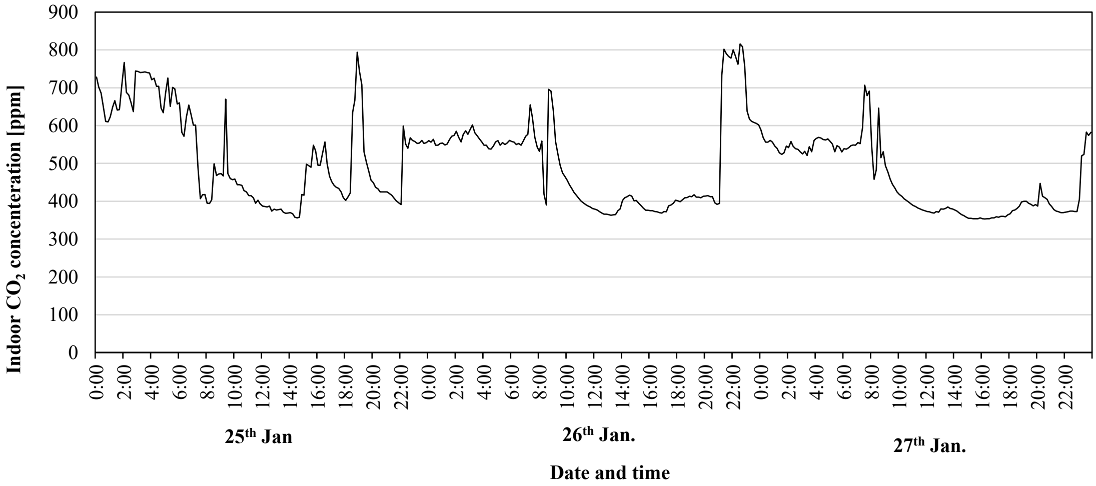

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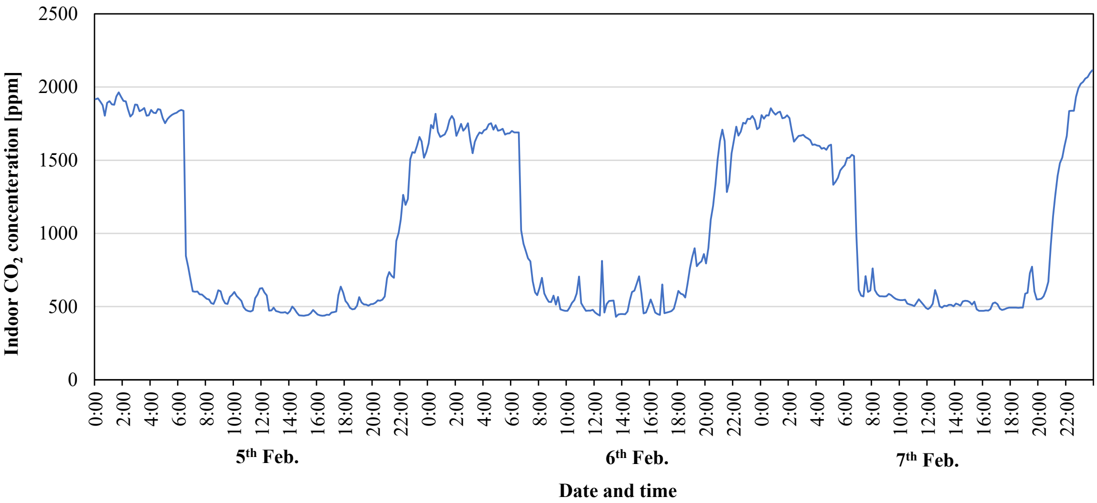


(c)

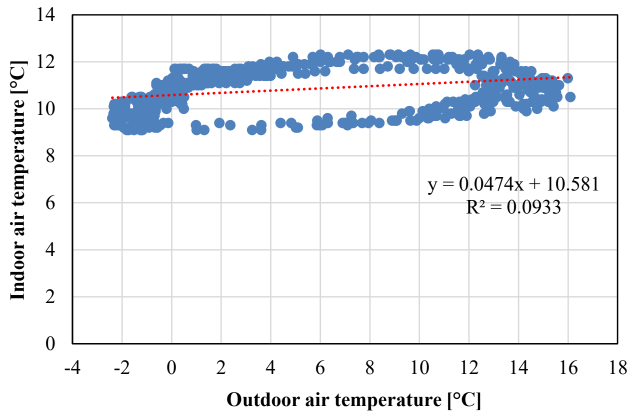
Fig. 6.4 Indoor CO_2 concentration of three houses: (a) Cold, (b) Temperate, (c) Sub-tropical regions

Fig. 6.4 (a-c) shows the rate of CO_2 concentrations in indoor for three days in cold, temperate and sub-tropical regions in Nepal. The CO_2 concentration in cold regions is a large variation during cooking time, and higher at nighttime. As shown in Table 6.2, in cold region, the minimum CO_2 concentration is 353 ppm, the maximum is 816 ppm, and the average is 494.1 ppm. The CO_2 was measured in living room which was on third floor. As shown in Table 6.3, there is only one person living in the room, there are no windows, and the second floor is cooked with firewood, so there is no direct effect on the living room. But some smoke might be emitted while cooking on the second floor. The CO_2 concentration in temperate region is higher than other regions. The variation of CO_2 concentration in temperate is sharply increased during night time. The minimum CO_2 concentration is 477 ppm, the maximum is 3366 ppm, and the average is 1306.8 ppm. The behavior of occupants is the primary role to increase indoor CO_2 concentration, particularly in cemented houses. It shows the occupants close and open door frequently in cold and temperate regions during daytime. Occupants close the doors and windows during nighttime, and four people lives in one room. The minimum CO_2 concentration is 438 ppm, the maximum is 3780 ppm, and the average is 1025.5 ppm. Respondents close the doors and windows during nighttime in winter season. The CO_2 concentration pattern in the subtropical region is similar to that in the temperate region. According to (Shukuya 2018) the concentration of CO_2 of exhaled air is very high, more than one-hundred times the outdoor concentration of CO_2. This confirms that ventilation is necessary to keep healthy and comfortable built environment. The indoor air is also contaminated with moisture discharged from occupants. Fresh air taken in should be decreased down to be required minimum rate in winter. Results shows the rate of CO_2 concentration is higher than CEN 2019 standard during night time. It indicates the poor air quality during night time in temperate region.

6.5 Relation between indoor air temperature and outdoor air temperature

The indoor air temperature was low in cold region and high in sub-tropical region as shown in Table 6.4. The structure and materials of the houses are different from one region to the others. In this section, we analyze how the relationship between indoor air temperature and the outdoor air temperature in cold, temperate and sub-tropical regions.

Fig. 6.5 shows the relation between indoor air temperature and outdoor air temperature in respective regions for three days in the 10 min time interval. Generally, the indoor air temperature is higher than outdoor air temperature. We have found the no relation between indoor and outdoor air temperature in cold region. In cold regions the very thick walls and the size of wall and window is very low. The using materials are mud, stone and wood. In cold regions, stone and mud are used for the wall material, the thickness is 500 mm, and the U-value of the wall is 1.7 W/(m^2.k). Wood is used for window and its U-value is 3.5 W/(m^2.k). Wood and mud are used in floor and roof, its U-value is 1.5 W/(m^2.k) (Table 6.1). Due to the very low heat transfer coefficient, heat loss from wall is very slowly, and remaining some heat on the walls. The indoor temperature hardly fluctuates as the outdoor temperature rises or falls. In temperate region, indoor air temperature is correlated by outdoor air temperature. The indoor temperature fluctuates as the outdoor temperature rises and falls. Similarly, in sub-tropical regions, indoor temperatures are related to the outdoors, but not appropriate. The indoor air temperature looks rather independent of outdoor air temperature in cold region. But, it is dependent on outdoor air temperature in temperate and sub-tropical regions.



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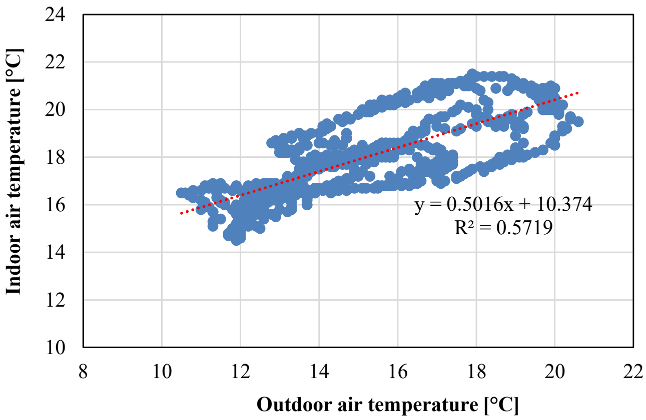

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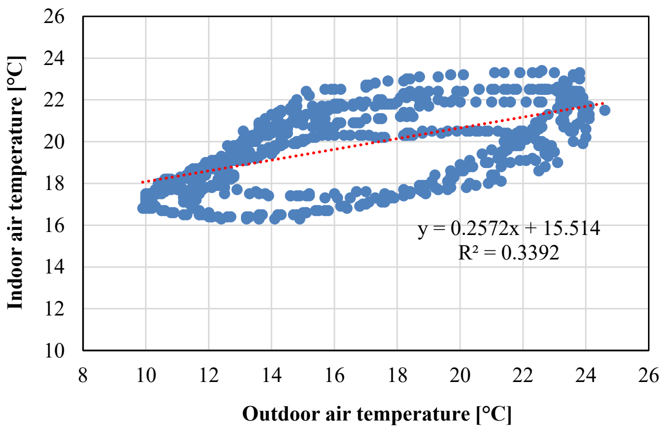


(c)

Fig. 6.5 Relation between indoor and outdoor air temperature of three house: (a) Cold, (b) Temperate, (c) Sub-tropical regions

6.6 Variation of indoor and outdoor air temperature

The outdoor air temperature in winter is low during night time, particularly in the cold region. The indoor air temperature usually depends on outdoor air temperature, and their difference varies from one region to another. In this section, we describe the results of analysis on the indoor air temperature in each region. Fig. 6.5 shows the indoor air temperature of three houses for five days. Three lines C1, C2 and C3 indicate the indoor air temperature of three different houses in cold regions. Similarly, T1, T2 and T3 are in temperate and S1, S2 and S3 are in sub-tropical regions. The average comfort temperature and the average indoor air temperature are also shown as respective horizontal solid and dashed lines. In cold region, the variation of indoor air temperature is small due to large thermal mass of walls. The size of doors and windows is small. They used firewood for cooking and heating. During the nighttime, the indoor air temperature is 11.5 ºC higher than outdoor air temperature, while during daytime it is 3.8 ºC lower than outdoor air temperature. In temperate region, the indoor air temperature variation of house T3 does not fluctuate so much; it is because the occupants in T3 were not indoors and the door and window were kept closed during the measurement period. The indoor air temperature during nighttime is 4 ºC higher than outdoor air temperature and; it was higher during daytime is 0.9 ºC. In sub-tropical region, the indoor air temperature is 6.4 ºC higher during nighttime than outdoor air temperature and it was 1.2 ºC lower during daytime in sub-tropical region. The variation of indoor air temperature in temperate and sub-tropical regions is large compared to the cold region due to small thermal mass, large size of doors and windows. Very few people used electric heaters for heating in temperate and sub-tropical regions.

We took one day data in Fig. 6.7 (a-c) for more clear expression. It shows the variation of indoor air temperature of three house for one day in cold, temperate, sub-tropical regions. As we explain in above the same variation found in this figure.

As seen in Table 6.5, the minimum outdoor temperature in cold region is -2.4 ºC and maximum temperature is 16.1 ºC and mean temperature is 4.3 ºC which is very small compared to temperate and sub-tropical regions. The average indoor air temperate is 10.9 ºC which is 6.6 ºC higher than outdoor air temperature. The mean outdoor air temperature in temperate region is 15.1 ºC and indoor temperature is 17.5 ºC which is 2.4 ºC higher. The mean outdoor air temperature in sub-tropical region is 16.4 and indoor air temperature is 18.9 ºC which is 2.5 ºC higher. If we compare to (Yu et al. 2017) in cold region the indoor air temperatures in residential buildings fluctuate greatly within the range 0 °C–26 °C during the daytime when the outdoor temperature is between −20 °C and 0 °C.

Table 6.4 Description of investigated houses in three regions.

Study area	Cooking fuel	Cooking stove	Heating fuel	Number of person living per house	Thickness of wall [mm]
Cold	Firewood	Traditional stove	Firewood	4	500
Temperate	LPG	Gas stove	None	2	230
Sub-tropical	LPG	Gas stove	None	4	230

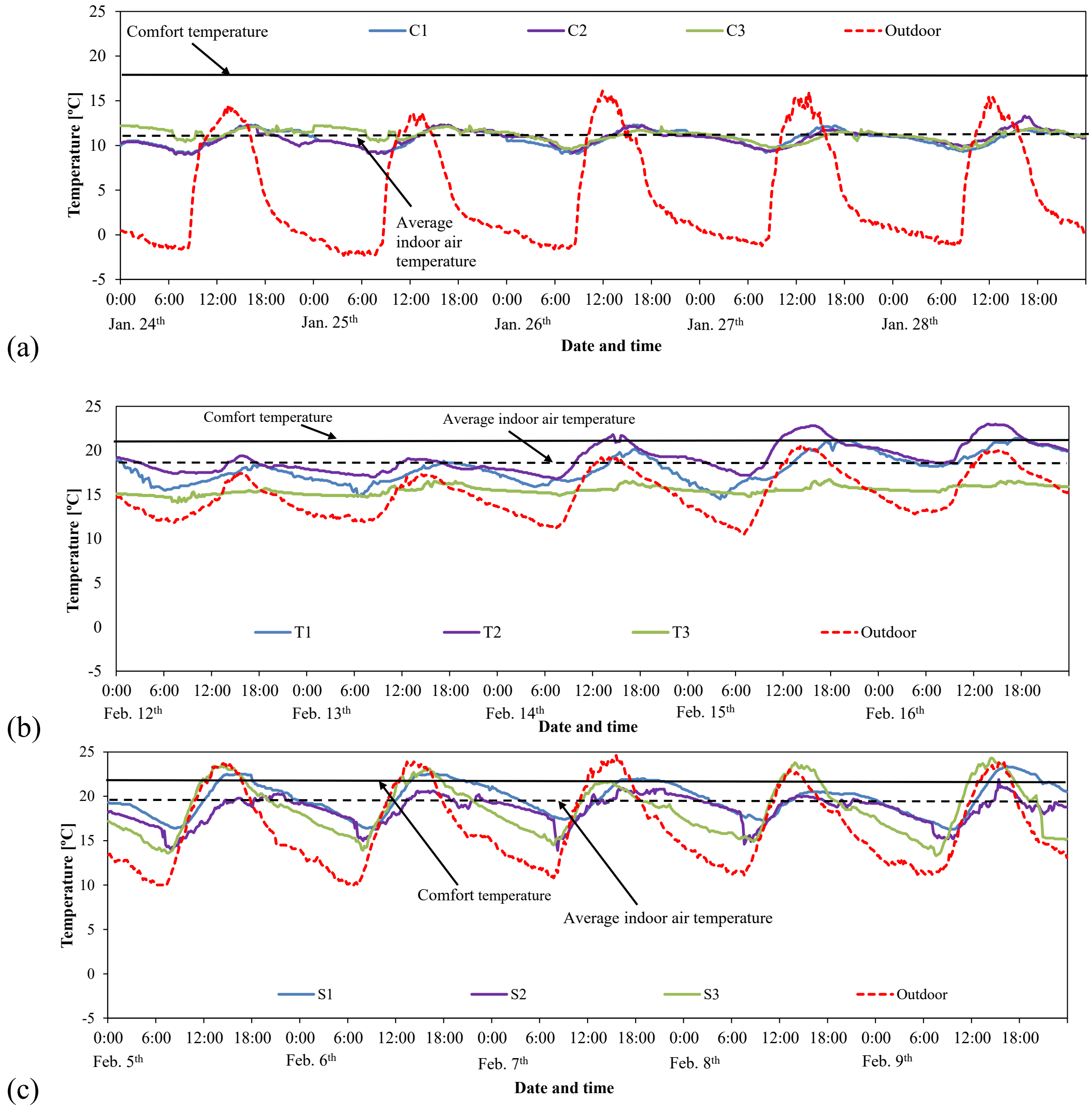
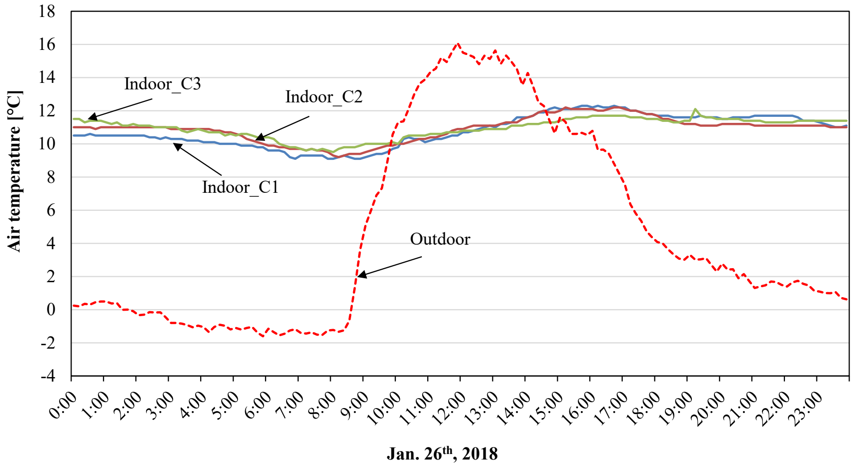
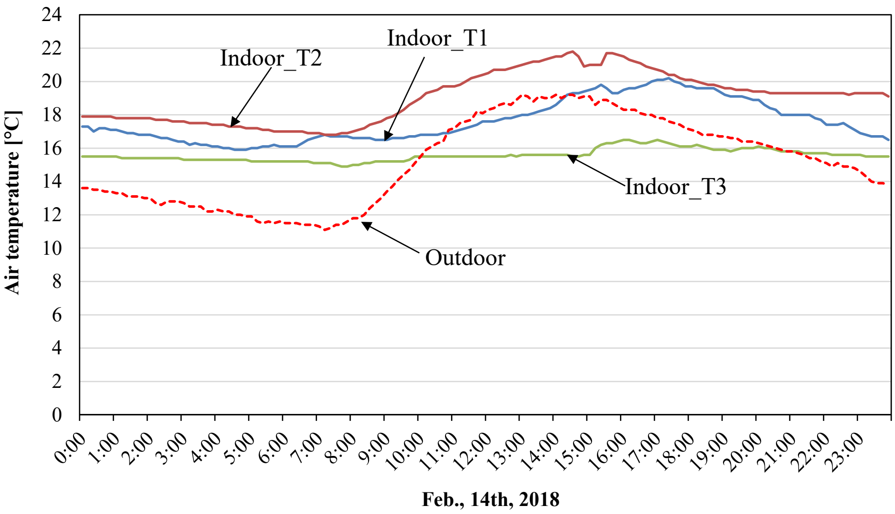


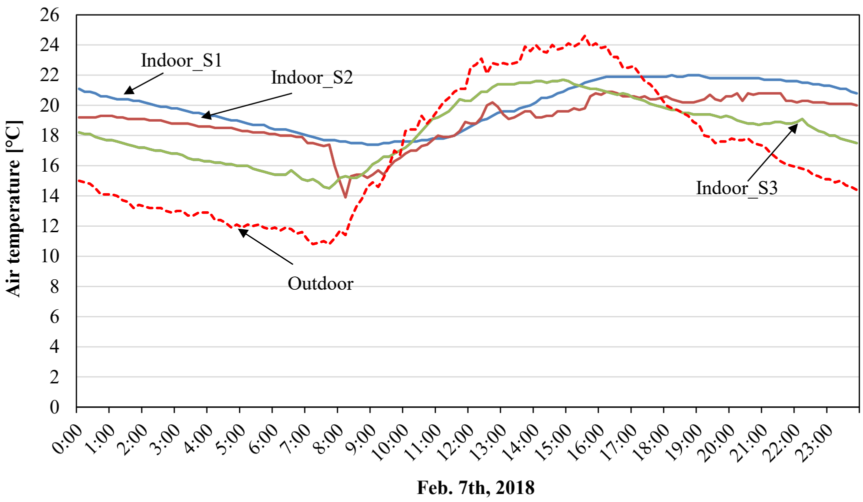
Fig. 6.6 Variation of indoor and outdoor air temperature of three houses: (a) Cold, (b) Temperate, (c) Sub-tropical regions



(a)



(b)



(c)

Fig. 6.7 Variation of indoor air temperature of three house for one day: (a) Cold, (b) Temperate, (c) Sub-tropical regions

The indoor air temperature looks rather independent of outdoor air temperature in cold region. But, it is dependent on outdoor air temperature in temperate and sub-tropical regions. The average indoor air temperature in cold, temperate and subtropical regions are 10.9 ºC, 18 ºC and 20 ºC and they are 6.3 ºC, 2.9 ºC and 2 ºC lower than that of comfort temperature. These results show that indoor air temperature need to be increased significantly in cold region.

Table 6.5 Indoor and outdoor air temperatures of three house of three regions.

Study area	Houses	N	Minimum [°C]	Maximum [°C]	Average [°C]	S.D. [°C]
Cold	Indoor air temperature_C1	720	9.1	12.3	10.8	0.88
	Indoor air temperature_C2	720	9	13.3	10.8	0.86
	Indoor air temperature_C3	720	9.5	12.2	11.2	0.66
	Outdoor air temperature T_o	720	-2.4	16.09	4.3	5.67
Temperate	Indoor air temperature_T1	720	14.5	21.5	17.9	1.66
	Indoor air temperature_T2	720	16.8	23	19.1	1.63
	Indoor air temperature_T3	720	14.1	16.7	15.5	0.48
	Outdoor air temperature T_o	720	10.5	20.6	15.1	2.51
Sub-tropical	Indoor air temperature_S1	720	16.3	23.4	19.7	1.87
	Indoor air temperature_S2	720	13.9	21.9	18.5	1.55
	Indoor air temperature_S3	720	13.3	24.3	18.5	2.84
	Outdoor air temperature T_o	720	9.9	24.6	16.4	4.23

6.7 Conclusions

We spend more than two-thirds of our time indoors, so it is important to understand the quality of the indoor thermal environment. The indoor environment is mainly affected by the generation of indoor pollutants, but it also depends on the outdoor environment. Indoor air quality has a significant impact on health and comfort. The indoor thermal environment affects human perception. A good indoor thermal environment can be defined as the absence of pollutants that cause irritation, discomfort, or health problems for the occupants. In this research, we measured the thermal environments indoor air temperature, outdoor air temperature, relative humidity and CO_2 constrictions in the Nepalese houses for winter season, and found the following results.

1. The variation of relative humidity (RH) in cold region is not so large. The average relative humidity (RH) in cold, temperate and sub-tropical regions are 48.2%, 50.1% and is 69.4% respectively. Relative humidity (RH) fluctuations in temperate region is higher than in cold and subtropical regions. Relative humidity (RH) is slightly fluctuates in sub-tropical region but the higher relative humidity (RH) than in cold and temperate regions. The minimum relative humidity (RH) in the subtropical region is higher than the maximum relative humidity (RH) in cold climates. In sub-tropical region the relative humidity (RH) is higher than the ASHRAE guidelines.

2. The average CO_2 concentrations in the cold, temperate and sub-tropical region are 494.1 ppm, 1306.8 ppm and 1025.5 ppm, respectively. The rate of CO_2 concentrations in temperate and sub-tropical regions is higher than the cold region.

3. The indoor air temperature looks rather independent of outdoor air temperature in cold region. But, it is dependent on outdoor air temperature in temperate and sub-tropical regions.

4. The minimum outdoor temperature in cold region is -2.4 ºC and maximum temperature is 16.1 ºC and mean temperature is 4.3 ºC which is very small compared to temperate and sub-tropical regions. The indoor air temperate is higher in all regions. The temperature differences between indoor and outdoor in cold, temperate and sub-tropical are 6.6 ºC, 2.4 ºC and 2.5 ºC, respectively.

5. The indoor air temperature measured in cold, temperate and sub-tropical regions were 10.9 ºC, 18 ºC and 20 ºC, respectively; they were 6.3 ºC, 2.9 ºC and 2 ºC lower than those of comfort temperature, respectively.

Chapter 7: Thermal improvement

7.1 Introduction

Building, energy and the environment are the key issues that the building professions and energy policy makers have to address, especially in the area of sustainable development (Liu et al. 2008). Nepalese people have less income and less access of energy (Shahi et al. 2020) compared to other developing countries. Building sector in developing countries accounts for one-third of total energy use and consumes more than half of the electricity use (Synnefa et al. 2007). As shown in Fig. 4.1 most of the developed countries use fossil fuel to meet the energy demand of various sectors. Developing country have two ways; one is the conventional path of development that a developing country follows to become a developed country with high energy use, or the other from rational way to energy use. This is considered to become possible by introducing, for example in building sector, the design of thermally well-insulated building envelopes and the associated construction methodology. As shown in Fig. 5.1, there are two way to be obtained by rationalizing the range of air temperature, radiant temperature and others by either passive or active systems. If we apply active systems function to maintain the thermal environment by the use of biomass, electricity from fossil fuels, hydro, photovoltaic cell and wind turbine through mechanical devices. Using fossil fuels and biomass mainly to maintain the indoor thermal environment leads to a variety of environmental problems locally and globally. And, the energy demand will be increased. If we apply passive systems are working as non-mechanical system through the improvement of building envelopes. In order to improve the overall thermal environment indoors, it is necessary to improve the thermal performance of windows, walls, roof and floor.

7.2 Selection of houses

Three houses were selected for the simulation of houses from each region shown in Fig. 3.1. Those selected houses were three storied. We have measured the indoor air temperature in bedrooms and living rooms for five days in ten minute intervals as shown in Table 6.1. The data loggers were placed in the middle or the corner of respective investigated houses; they were set 1 m above the floor level. The outdoor air temperature was measured just outside the houses in each region. We used the instruments for the measured indoor and outdoor air temperature as shown in Table 6.1.

As shown in Fig. 7.1 in cold regions, stone and mud are used for the wall material, the thickness is 500 mm, and the U-value of the wall is 1.7 W/(m^2.k). Wood is used for window and its U-value is 3.5 W/(m^2.k). Wood and mud are used in floor and roof, its U-value is 1.5 W/(m^2.k) (Table 6.1). In temperate and sub-tropical regions, plaster and brick are used for wall materials and its U-value is 2 W/(m^2.k). Particle board and glass are used for door and window and its U-value is 3.4 W/(m^2.k). Plaster and concrete are used for floor and roof and its U-value is 3.4 W/(m^2.k).

(a)

(b)

Fig. 7.1 Measuring the physical parameters of house in cold region; (a) length of house, and (b) thickness of celling wood

7.3 Estimation of indoor air temperature

The indoor air temperature was lower than comfort temperature during nighttime as shown in Fig. 6.1. We need to increase the indoor air temperature for improving thermal comfort. In order to clarify how much effective the enchainment of thermal insulations would be rather than merely installing mechanical heating systems. We first analyzed the actual indoor air temperature based on measured data and then we estimated the indoor air temperature based on theoretical base model. By improving the thermal insulation in building walls and reducing the infiltration, we should be able to increase the indoor air temperature and also internal surface temperature. For this purpose, we decided to make use of a simple model to calculate the indoor air temperature during nighttime (18:00 ~ 5:50). The energy balance equation for a room on focus is given as follows (Shukuya 2019).

[Thermal energy input] = [Thermal energy stored] + [Thermal energy output] (7.1)

Using the mathematical symbols, this equation can be expressed as follows.

$$H_i \Delta t = \overline{C\rho V_r}\left(T_{r,i} - T_{r,i-1}\right) + \sum_{i}^{6}\left\{\left(A_i U_i + C^* \rho^* n V_r^*\right)\left(T_{r,i} - T_{r,i-1}\right)\right\}\Delta t \qquad (7.2)$$

where H_i is the rate of human-body and other thermal energy generations [W], Δt is a short period of time t[s], $\overline{C\rho V_r}$ is the effective heat capacity of room [J/K], $T_{r,i}$ is the indoor air temperature at time i [°C], $T_{r,i-1}$ is indoor air temperature of $T_{r,i}$ at, time (i-1) [°C], A_i is the area of "i" th walls, floor or ceiling (i = 1, 2, . . 6) [m^2], U_i is the heat transmission coefficient of "i" th walls (i = 1, 2, . . 6) [W/(m^2·K)], C^* is specific heat capacity of air [J/(kg·K)], ρ^* is the density air [kg/m^3], n is the number of air change by infiltration [1/s], V_r^* is the volume of room air [m^3]. To obtain the U_i value, the following equation was applied.

$$U_i = \frac{1}{\dfrac{1}{h_{r,o} + h_{c,o}} + R_1 + R_2 + \dfrac{1}{h_{r,i} + h_{c,i}}} \qquad (7.3)$$

where $h_{r,o}$ and $h_{r,i}$ are radiative heat transfer coefficient at the external and internal surfaces [W/(m^2·K)], $h_{c,o}$ and $h_{c,i}$ are convective heat transfer coefficient along the external and internal surfaces [W/(m^2·K)], R_1 and R_2 are the resistance of two materials in "i" th wall [(m^2·K)/W]. In the calculation of U_i, we referred to the thermal conductivity data of the solid materials available from (Shukuya, 2013, JSME, 1987) and we assumed the values of radiative and convective heat transfer coefficient to be as follows: $h_{r,o}$ = $h_{r,i}$ = 5.2 W/(m^2·K), $h_{c,o}$ = 12 W/(m^2·K) and $h_{c,i}$ = 3 W/(m^2·K). The heat transmission coefficient was calculated from Eq. (7.4) and then, the total heat loss coefficient was obtained by summing all the heat transmission coefficient multiplied by respective surface areas.

Effective heat capacity, $\overline{C\rho V_r}$ is estimated by the following equation that is derived from Eq. (7.3).

$$\overline{C\rho V_r} = \frac{\left\{H_i - \sum_i^6\left(A_i U_i + C^* \rho^* n V_r^*\right)\left(T_{r,i} - T_{o,i}\right)\right\}\Delta t}{\left(T_{r,i} - T_{r,i-1}\right)} \qquad (7.4)$$

where $T_{o,i}$ is the outdoor air temperature [°C]. The values of $\overline{C\rho V_r}$ obtained for each time interval, Δt, are averaged to determine the single value of $\overline{C\rho V_r}$. The values of $\overline{C\rho V_r}$ and $C\rho V_r$ were compared to confirm the rationality of the estimation of effective heat capacity. The total heat capacity $C\rho V_r$ of room was also calculated by referring the data given in (JSME, 1987). We have determined two types of heat capacity: the effective heat capacity to be estimated from Eq. (7.4) using the indoor and outdoor air temperature and the total heat capacity calculated from using the normal values of materials referring to the data sources.

The indoor air temperature $T_{r,i}$ is calculated by the following equation that is also derived from Eq. (7.2)

$$T_{r,i} = \frac{H_i \Delta t + \overline{C\rho V_r} T_{r,i-1} + \{\sum_i^6 (A_i U_i) + C^* \rho^* n V_r^{\ *}\} T_{o,i} \Delta t}{\overline{C\rho V_r} + \{\sum_i^6 (A_i U_i) + C^* \rho^* n V_r^{\ *}\} \Delta t} \tag{7.5}$$

We took one house shown in Fig. 6.6 at each region for the present analysis. The indoor air temperature of C1, T1 and S1 were taken to be on focus. In the calculation of indoor air temperature, we assumed miscellaneous heat generation per floor area to be 40 W/m^2 as a portion of H_i in all three regions; the other portion of H_i was assumed to be human-body heat generation at the rate of 69.9 W/person. Air changes rate per hour was assumed to be 1.5 times in cold region and 2 times in temperate and sub-tropical regions. Table 7.1 shows the description of investigated houses and the heat loss coefficient, total heat and effective heat capacities in respectives regions. The effective heat capacity obtained was much smaller than the total heat capacity; the former is from 9.5 to 15.1 % of the latter. This is because the heat capacity of the walls affects only partially the indoor thermal energy stored with the indoor air temperature as its reference.

Table 7.1 Description of investigated houses in terms of heat loss coefficient and heat capacities.

Study area	Wall area [m^2]	Roof area [m^2]	Floor area [m^2]	Door area [m^2]	Window area [m^2]	Total surface area (wall + roof) [m^2]	Total heat loss coefficient [W/K]	Total heat loss coefficient per floor area [W/(m^2·K)]	Total heat loss coefficient per surface area [W/(m^2·K)]	Effective heat capacity [kJ/K]	Heat capacity of air only [kJ/K]	Total heat capacity (Air + walls + floor + roof) [kJ/K]	Effective heat capacity, per floor area [kJ/(m^2·K)]
Cold	25.1	10.8	10.8	1.3	-	37.2	69.5	6.4	1.9	2288.0	28.1	18572.1	211.9
Temperate	25.0	10.0	10.0	4.9	2.1	42.0	145.6	14.5	3.5	1515.5	32.6	15998.6	151.1
Sub-tropical	33.5	11.1	11.1	1.4	1.9	47.9	159.1	14.3	3.3	2683.7	39.8	17757.2	240.7

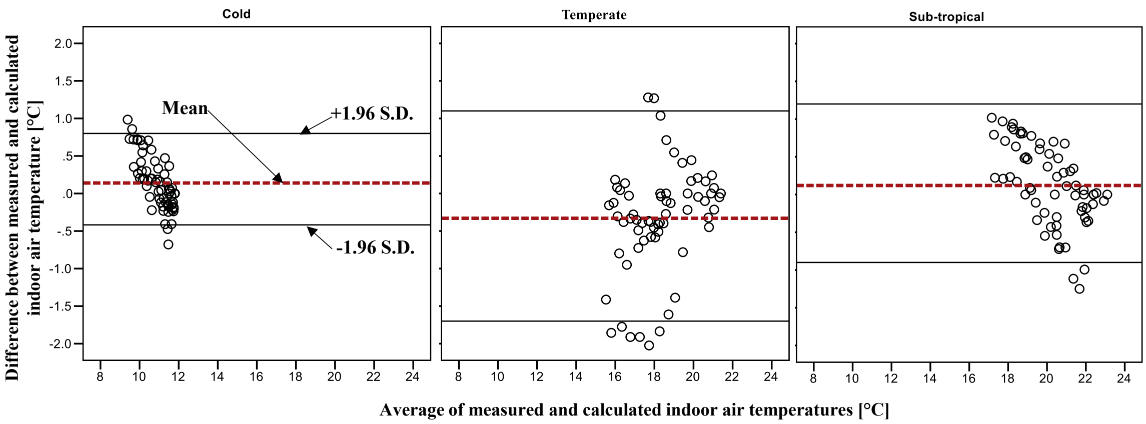


Fig. 7.2 Relationship between calculated and measured indoor air temperature of three regions.

Fig. 7.2 shows the comparison between indoor air temperature calculated from Eq. (7.5) and the measured indoor air temperature during nighttime for five days. The Bland-Altman (Du et al. 2019) method was applied to make a comparison between the difference between measured and calculated indoor air temperatures, and average of the two temperatures. The two horizontal lines above and below the dotted line indicating the 95% limits of data points for the mean difference (1.96 SD). Most of data plots lie between the 95% limits of the mean difference. The results indicate that the indoor air temperature can be calculated rationally with assumed values of heat loss coefficient, infiltration rate and effective heat capacity. Thus, we decided to use the simplified energy balance equation developed so far to investigate on the possible improvements.

7.4 Result and discussion

7.4.1 Improvement of indoor air temperature

The reduction of heat loss coefficient and infiltration rate is considered to play major roles for the improvement of indoor air temperature. Fig. 7.3 shows the base model and improved model of the wall, ceiling and floor of the houses in each region. In cold region, the thickness of stone wall was 500 mm and it's the heat transmission coefficient was 1.66 W/(m^2.K), mud and wooden ceiling and floor was 250 mm and these heat transmission coefficient was 1.08 W/(m^2.K). We assumed to add cellulose fiber boards 15 mm as insulation in four walls; the heat transmission coefficient is decreased to 1.02 W/(m^2.K) by 0.7 W/(m^2.K). We have also assumed to add 15 mm wood fiber insulating board in the ceiling and thereby the heat transmission coefficient is decreased to 0.77 W/(m^2.K) by 0.3 W/(m^2.K). We assumed no insulation added in the floor. In the temperate and sub-tropical region, the thickness of brick wall was assumed to be 230 mm and its heat transmission coefficient was 2.04 W/(m^2.K). We added cellulose fibre boards of 10 mm thick in four walls; the heat transmission coefficient is decreased to 1.35 W/(m^2.K) by 0.7 W/(m^2.K). The thickness of concrete ceiling and floor was 150 mm and the heat transmission coefficient was 3.35 W/(m^2.K). We have also added 10 mm wood fibre insulating board in ceiling and the heat transmission coefficient is decreased to 1.82 W/(m^2.K) by 1.6 W/(m^2.K). Addition of insulation layers in walls and ceiling is effective for the reduction of heat loss coefficient, but the floor area is slightly decreased. Although there is such a negative effect the relative size of indoor space will be increased by the emergence of warmer indoor environment by the enhancement of thermal insulation. Thus, the thermal insulation is of the first priority rather than installing merely high-efficient mechanical heating systems. Better indoor thermal environment can be realized without increasingly energy use (Symbiotic Housing 2011, Sginken-Shinbun 2014).

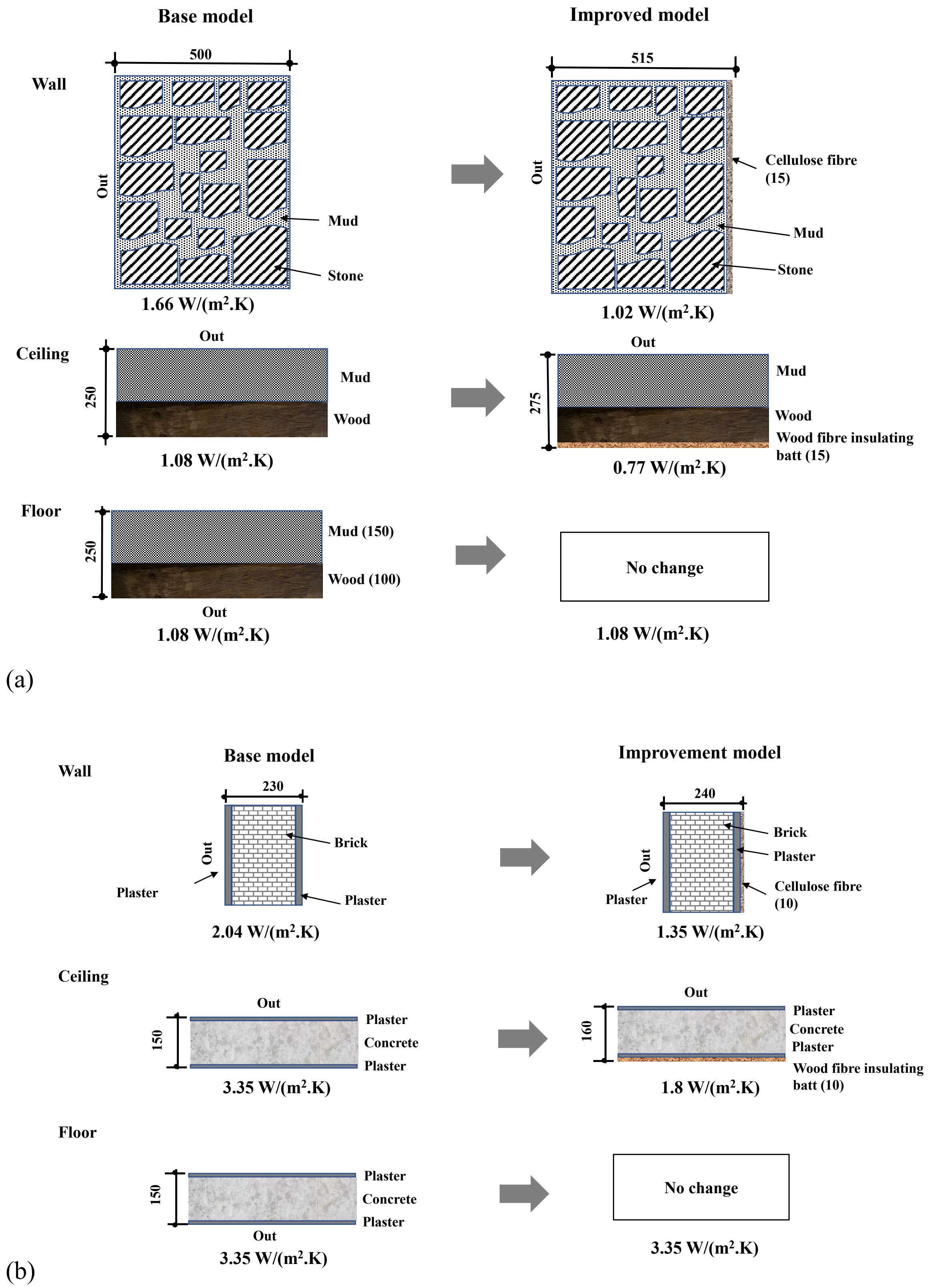


Fig. 7.3 Base and improved models of the wall, ceiling and floor constructions in: (a) Cold, and (b) Temperate and Sub-tropical regions (thickness unit: mm)

Fig. 7.4 shows that the cumulative frequency of calculated indoor air temperature in the cases of base model and improved model in respective regions. In cold region, all of the indoor air temperature in the base model lower than 12 ºC, but in the improved model 40% of indoor air temperature exceed 12 ºC. In temperate region, for the base model all of 100% indoor air temperature is lower than 21 ºC, but it was reduced by 74% for the improved model. In the sub-tropical region, for the base model all of 100% indoor air temperature was lower than 22 ºC, but it was reduced by 50% for the improved model. The thermal insulation is significantly effective in increasing the indoor air temperature during nighttime for all regions, but in particular in cold region.

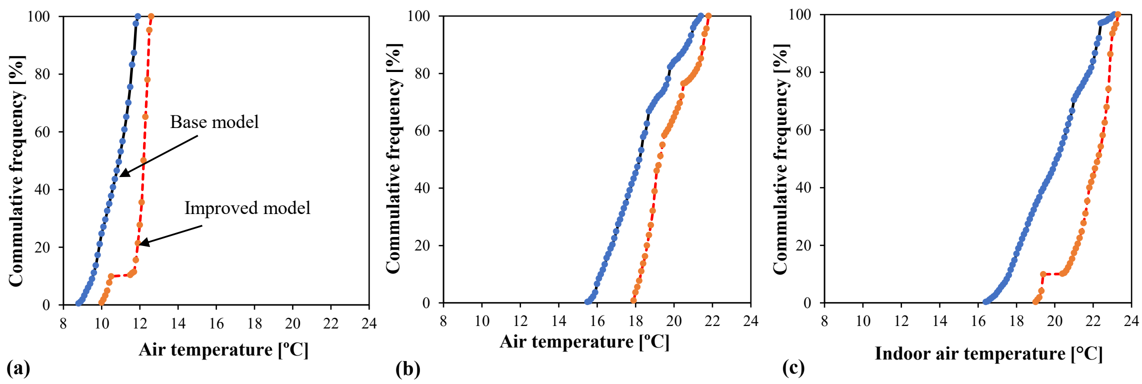


Fig. 7.4 Cumulative frequency of indoor air temperature in the case of base and improved models: (a) Cold, (b) Temperate, and (c) Sub-tropical regions

7.4.2 Relation of thermal comfort, thermal improvement and energy saving

In this section, we discuss the relationship between thermal comfort and the thermal improvement of thermal insulation and their associated energy saving potential what was described in based on previous sections.

We made estimation of the indoor air temperature assuming more insulation in the walls, ceiling together with the reduction of infiltration. The increased indoor air temperature were compared with the comfort temperature in each region. If the improvement is made, the average indoor air temperature were found to become 12.1 °C, 19.7 °C and 22 °C in cold, temperate and sub-tropical regions, respectively; they are 1.1 °C, 1.7 °C and 1.8 °C higher than the base model in respective regions. The results showed that the indoor air temperature obtained after the improvement in temperate and sub-tropical regions would be acceptable to the residents. However, it is still for lower than the comfort temperature in the cold region. The comfort temperature estimated was based on the votes mainly given during the daytime. Nevertheless, the increase of indoor air temperature was investigated during nighttime. As shown in Fig. 10, the votes of comfort temperature are different in the morning, day and evening time. We didn’t collect the clothing insulation of residents, but according to (Ghiabaklou 2003) the clothing insulation increases from 0.5 to 1.0 clo during sleeping hours, and thus the clothing insulation in sleeping hours in cold region could be much higher than daytime. Thus, the residents may perceive thermally acceptable with a slight increase of indoor air temperature.

Table 7.2 Reduction of energy use after the increased or decreased temperatures comparison with various studies.

References	Country	Building type	Strategies	Reduction of energy use (%)
Urge-Vorsatz [3]	Different part of the world	Dwelling and office	Improve thermal efficiency of the building	18 ~ 73
Nicol and Roaf [50]	Pakistan	Office	Raising set point temperature	20 ~ 23
Tong et al. [56]	China	Office	Natural ventilation	8 ~78
Xu et al. [57]	China	Dwelling	Set temperature of the air conditioning systems	26.87 ~ 36.51
Yun et al. [58]	South Korea	Office	Adaptive comfort models	22
Roussac et al. [59]	Australia	Office	Dynamic (adjust set point temperature in direct response to variations in ambient conditions)	6.3
González-Lezcano and Hormigos-Jiménez [60]	Spain	Dwelling	Natural ventilation	13
Sánchez-Guevara et al. [61]	Spain	Dwelling	Shifting from the conventional fixed thresholds to the adaptive energy demand	20 ~ 80
Kramer [62]	Netherlands	Museum	Set point algorithm	53 ~ 74
Barbadilla-Martín et al. [63]	Spain	Office	Adaptive control algorithm	11.4 ~ 27.5
Walker [64]	US	-	Natural ventilation	10 ~ 30

Table 7.2 shows the speculated reduction of energy use by changing indoor temperature referring to various strategies given in previous studies (Urge-Vorsatz 2015, Nichol and Roaf 1996, Tong et al. 2016, Xu et al. 2020, Yun et al. 2016, Roussac 2011, González-Lezcano1 and S. Hormigos-Jiménez1 2016, Sánchez 2017, Karmer 2017, Barbadilla-Martín 2018, Walker 2016). The heating energy use in winter could be saved by a decreasing 1 °C in the indoor air temperature (Nicol 2012). If the same could be applied to the present study, the increased indoor air temperature of 1.1 to 1.8 °C of the improved models could be equivalents to 10 ~ 20% saving the energy use.

7.5 Conclusions

Three houses were selected for the simulation of houses. We have measured the indoor air temperature and outdoor air temperature for five days in ten minute. We need to increase the indoor air temperature for improving thermal comfort. In order to clarify how much effective the enchainment of thermal insulations would be rather than merely installing mechanical heating systems. We first analyzed the actual indoor air temperature based on measured data and then we estimated the indoor air temperature based on theoretical base model. By improving the thermal insulation in building walls and reducing the infiltration, we should be able to increase the indoor air temperature and also internal surface temperature. For this purpose, we decided to make use of a simple model to calculate the indoor air temperature during nighttime (18:00 ~ 5:50). Then we added the thermal insulation. The major findings are as follows:

1. Measured indoor air temperature and estimated indoor air temperature are related each other. The indoor air temperature can be calculated rationally with assumed values of heat loss coefficient, infiltration rate and effective heat capacity.

2. The enhancement of thermal insulation and the reduction of infiltration was effective to increase the indoor air temperature during nighttime. In cold region, all of the indoor air temperature were lower than 12 ºC in the base model, but the improved model 40% of indoor air temperature has turned out to exceed 12 ºC. In temperate region, for the base model all of 100% indoor air temperature was lower than 21 ºC, but it was reduced by 74% for the improved model. In the sub-tropical region, for the base model all of 100% indoor air temperature was lower than 22 ºC, but it was reduced by 50% for the improved model.

3. As a whole, the enhancement of the thermal insulation and reduction of infiltration, the indoor air temperature was found to increase by 1.1 to 1.8 °C.

The enhancement of thermal insulation and the reduction of infiltration was effective to increase the indoor air temperature of 1.1 to 1.8 °C during nighttime. In winter season, the indoor temperature can be increased with the improvement of building envelope systems without increasing energy use for heating. The findings of this study should be useful for energy saving building design and thereby hopefully help promote better indoor thermal environment in Nepalese houses.

Chapter 8: Conclusions and Recommendations

8.1 Conclusions of chapter 2

We reviewed previous studies on energy use, thermal comfort, thermal environment, and thermal improvement. We found the followings results.

In the context of Nepal, the researchers have so far conducted on overall energy sectors such as firewood, fossil fuels, biomass, electricity, and solar PV system. But no studies have focused yet on household sector in particular. Adaptive thermal comfort model is effective method than the PMV-PPD model for implementation on Nepalese homes due to its variation of climate, unique culture, socio-economic factors and adoption behavior. There is less researches done in Nepal than other countries and more research is needed in Nepal. It is very important to develop thermal comfort standards to improve the good indoor thermal environment that helps to people and policy makers. Nepal is a developing country with very low income levels and poor access to electricity. When Nepalese people use mechanical heating and cooling appliances, the energy demand increases, so that the indoor thermal environment model can be effective model than other energy use model. Many researchers have focused, either, on current indoor thermal condition and or, on the improvement, but not on both. Therefore, this study need to focus on thermal comfort condition of residents in houses in winter, and thermal performance improvement of these houses.

8.2 Conclusions of chapter 4

In this chapter, we have investigated the structure of rural, semi-urban and urban household's energy use in Nepal by field survey combined and identified the current Nepalese situation of household energy use. We found the main energy source in rural and urban area is firewood, while on the other hand, that in semi-urban and urban areas is LPG and electricity. The use of electricity in rural area is smaller than that in semi-urban and urban areas. The average electricity use of all areas in Nepal was 2.06 GJ/household/year, which is lower than that in other developing countries. The use of firewood is 2.08 GJ/household/month in Nepalese rural areas, which is twice higher than other developing countries. The access to electricity and the household income were associated with the possession of electric appliances. Nepal is in the least state of electric appliance ownership among developing countries. A higher income level of household tends to bring about an increase of the home-appliance ownership. The rate of electricity use is correlated with the income levels. There is a strong linear relationship between GDP and per-capita electricity use in Nepal and also in other South-Asian countries. The use of electricity in households is affected by the household income in urban area. It is correlated with household income. The social class of households affects the total electricity use in urban areas, but it doesn't affect much in rural and semi-urban areas. In all of three areas, as the family size increases, the rate of electricity use also increases. But the per-capita electricity use decreases as the family size increases. There is a significant relationship between electricity use and income regarding to the education level of household responsible person. As their level of education and income of household increase, the electricity use tends to increase. The education level of household responsible person affects the use of LED lamps. It was correlated with the use of LED lamps, although its mechanism is not ascertained. The use of electricity from 5:00 to 11:00 and from 18:00-21:00 were more than other time. The household electricity demand is very high at these period of time. The electricity load patterns in second and third day were similar to that of first day. The GDP and CO_2 emission were highly correlated worldwide.

We found that rural households use more firewood and the rate of electricity use in Nepal is one of the least in the world. The access to electric appliances is very low. The findings identified in this study should be useful for the improvement of the life of people in Nepal. The GDP is increasing in Nepal and the energy use will definitely increase in the future. Thus, the government needs to plan for the sustainable energy use in Nepal.

8.3 Conclusions of chapter 5

We have collected 203, 407 and 229 votes from 114, 216 and 112 households in cold, temperate and sub-tropical regions, respectively. We took 839 votes from 442 households from the people whose age ranges from 15 to 65 years. Focusing on ordinary houses in three climatic regions in Nepal, we have conducted a thermal comfort survey together with indoor and outdoor thermal environment measurement in winter. Then, we analyzed the characteristics of indoor air temperature in cold, temperate and sub-tropical regions, respectively.

We found the thermal sensation votes for "2. cold" was the largest proportion in cold and temperate regions, and those for "4. Neutral" was in sub-tropical region. The proportion of cold side vote increases as the indoor globe temperature decreases. For the indoor globe temperature at 20 °C, 50% of the votes was in cold side. The mean comfort temperature was estimated to be 17.2 °C, 20.9 °C and 21.7 °C in cold, temperate and sub-tropical regions, respectively. The indoor globe temperature of the cold region was significantly lower than comfort temperature. In other two regions, the tendency was similar, but the difference in two temperatures was less significant. The comfort temperature has a large regional difference. The mean preferred temperature was estimated to be 17.9 °C, 21.4 °C and 21.8 °C in cold, temperate and sub-tropical regions, respectively. The preferred temperature is 0.7 °C higher in cold, 0.5 °C higher in temperate and 0.1 °C in sub-tropical regions This residents of the cold region in particular desire a much warmer indoor environment condition than comfort temperature.

In cold region, the estimated comfort temperature was significantly higher than the indoor globe temperature measured. In the other two regions, the estimated comfort temperature was higher than the measured indoor globe temperature, but their difference was less significant.

8.4 Conclusions of chapter 6

We spend more than two-thirds of our time indoors, so it is important to understand the quality of the indoor thermal environment. The indoor environment is mainly affected by the generation of indoor pollutants, but it also depends on the outdoor environment. Indoor air quality has a significant impact on health and comfort. The indoor thermal environment affects human perception. A good indoor thermal environment can be defined as the absence of pollutants that cause irritation, discomfort, or health problems for the occupants. In this research, we measured the thermal environments indoor air temperature, outdoor air temperature, relative humidity and CO_2 constrictions in the Nepalese houses for winter season, and found the following results.

The variation of relative humidity (RH) in cold region is not so large. The average relative humidity (RH) in cold, temperate and sub-tropical regions are 48.2%, 50.1% and is 69.4%. Relative humidity (RH) fluctuations in temperate region is higher than in cold and subtropical regions. Relative humidity (RH) is small fluctuations in sub-tropical region but the higher relative humidity (RH) than in cold and temperate regions. The minimum relative humidity (RH) in the subtropical region is higher than the maximum relative humidity (RH) in cold climates. In sub-tropical region the relative humidity (RH) is higher than the ASHRAE guidelines. The average CO_2 concentrations in the cold, temperate and sub-tropical region are 494.1 ppm, 1306.8 ppm and 1025.5 ppm, respectively. The rate of CO_2 concentrations in temperate and sub-tropical regions is higher than the cold region. The indoor air temperature looks rather independent of outdoor air temperature in cold region. But, it is dependent on outdoor air temperature in temperate and sub-tropical regions. The minimum outdoor temperature in cold region is -2.4 ºC and maximum temperature is 16.1 ºC and mean temperature is 4.3 ºC which is very small compared to temperate and sub-tropical regions. The indoor air temperate is higher in all regions. The temperature differences between indoor and outdoor in cold, temperate and sub-tropical are 6.6 ºC, 2.4 ºC and 2.5 ºC, respectively. The indoor air temperature measured in cold, temperate and sub-tropical regions were 10.9 ºC, 18 ºC and 20 ºC, respectively; they were 6.3 ºC, 2.9 ºC and 2 ºC lower than those of comfort temperature, respectively.

8.5 Conclusions of chapter 7

Three houses were selected for the simulation of houses. We have measured the indoor air temperature and outdoor air temperature for five days in ten minute. We need to increase the indoor air temperature for improving thermal comfort. In order to clarify how much effective the enchainment of thermal insulations would be rather than merely installing mechanical heating systems. We first analyzed the actual indoor air temperature based on measured data and then we estimated the indoor air temperature based on theoretical base model. By improving the thermal insulation in building walls and reducing the infiltration, we should be able to increase the indoor air temperature and also internal surface temperature. For this purpose, we decided to make use of a simple model to calculate the indoor air temperature during nighttime (18:00 ~ 5:50). Then we added the thermal insulation.

We confirmed that the measured indoor air temperature and estimated indoor air temperature are related each other. The indoor air temperature can be calculated rationally with assumed values of heat loss coefficient, infiltration rate and effective heat capacity. The enhancement of thermal insulation and the reduction of infiltration was effective to increase the indoor air temperature during nighttime. In cold region, all of the indoor air temperature were lower than 12 ºC in the base model, but the improved model 40% of indoor air temperature has turned out to exceed 12 ºC. In temperate region, for the base model all of 100% indoor air temperature was lower than 21 ºC, but it was reduced by 74% for the improved model. In the sub-tropical region, for the base model all of 100% indoor air temperature was lower than 22 ºC, but it was reduced by 50% for the improved model. As a whole, the enhancement of the thermal insulation and reduction of infiltration, the indoor air temperature was found to increase by 1.1 to 1.8 °C.

The enhancement of thermal insulation and the reduction of infiltration was effective to increase the indoor air temperature of 1.1 to 1.8 °C during nighttime. In winter season, the indoor temperature can be increased with the improvement of building envelope systems without increasing energy use for heating. The findings of this study should be useful for energy saving building design and thereby hopefully help promote better indoor thermal environment in Nepalese houses.

8.6 Recommendations

Some rate of energy-use is necessary for human being to realize a certain required living standard. It can be an indicator to know about the household living condition. Availability of energy source is one of the human basic requirements for a better quality of life and thereby the development of a whole nation. Energy use at a certain rate is necessary for the development of any society to upgrade the quality of life, to achieve socio-economic growth and thereby to realize rational modernization. This study found that rural households use more firewood and the rate of electricity use in Nepal is one of the least in the world. The access to electric appliances is very low. The findings identified in this study should be useful for the improvement of the life of people in Nepal. The GDP is increasing in Nepal and the energy use will definitely increase in the future. Thus, the government needs to plan for the sustainable energy use in Nepal.

In cold region, the Nepalese government needs to focus on improving the efficiency of cooking stoves. The use of the jungle as a sustainable perspective like Hokkaido, the so-called Shimokawa plan. In other way, the government needs to focus on the production of renewable energy such as small micro hydropower plants, solar cells and wind turbines, and difficult to access the national grid due to geographical burden. The housing style in cold region are made by traditional manner and in temperate and subtropical regions made by modern materials, but there is no fixed insulation materials available on the market. The Nepalese government needs to focus on the production of local insulation materials that is easily accessible to the locals.

This research will be fruitful in cold region to improve the indoor air temperature. In cold region, the estimated comfort temperature was significantly higher than the indoor globe temperature measured. In the other two regions, the estimated comfort temperature was higher than the measured indoor globe temperature, but their difference was less significant. The enhancement of thermal insulation and the reduction of infiltration was effective to increase the indoor air temperature of 1.1 to 1.8 °C during nighttime. If the same could be applied to the present study, the increased indoor air temperature of 1.1 to 1.8 °C of the improved models could be equivalents to 10 ~ 20% saving the energy use. In winter season, the indoor temperature can be increased with the improvement of building envelope systems without increasing energy use for heating. The findings of this study should be useful for energy saving building design and thereby hopefully help promote better indoor thermal environment in Nepalese houses.

8.7 Further work

Nepal is a developing country and the rate of urbanization is very high. New residential and commercial buildings are under construction. Nepalese people were satisfied in day time thermal condition of their traditional houses, and residents wore more clothing and used firewood for heating to adjust the thermal environment in night time (Rijal et al. 2010). But the use of traditional materials and manners are decreasing day by day. Modern building materials are used in newly buildings. The installation rate of air conditioner units and other electric appliances is also increasing. However, those people do not consider the indoor environments: Insulation, infiltration and solar radiation. Insulation is not very accessible. Nepal experienced 18 hours of power cut 5 years ago but now it is significantly improved. It happened to show that Nepalese grid electricity has been so far very fragile and the people do not have a good access to electricity. Nepal has diverse in geographical variation. The average maximum outdoor air temperate in summer is 37.4 °C and average minimum outdoor air temperature in winter is -5 °C (DHM 2020). But as mentioned above very few mechanical systems are being used for the improvement of indoor environment. The income level of many households is still quite low to purchase electric appliances and then pay electricity bills. However, if they have a good access to energy and high level of income, they may start using more fossil fuels for mechanical heating and cooling appliances to obtain better indoor thermal environment. Then the energy demand will increase in the future. A large electric-power plants could be required to fulfil the increasing energy demand. Such type of power plants are costly and they necessarily cause environmental problems to be avoided, although some rate of energy is definitely necessary to upgrade their lifestyle. The indoor thermal environment improvement by improving the building envelope system is very important, since it could be realized without energy use. Therefore, further tasks are categorized as follows.

1) In order to improve the indoor thermal environment, The model houses will be constructed for how much energy can be reduced by improving the thermal insulation, infiltration and solar radiation.

2) The local insulation materials will be recognized for thermal insulation.

3) The household energy use model will be developed, and which can help to reduce the energy use in Nepal.

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Appendix

Household energy use patterns survey of Nepal_2019

Date:

Time:

Name of data collector:

Vote no.:

Household energy use patterns of rural, semi-urban and urban areas of Nepal

1. Name of respondent:

2. Sex:

☐ Male ☐ Female

3. Contact number:

4. Address:

5. Marital status:

☐ Married ☐ Unmarried

6. Family details, education status, occupation and income

S. N.	Name	Sex: Male:1, Female:0	Education level: No schooling:0, Primary: 1, Secondary: 2, Intermediate:3, Bachelor: 4 Master or above: 5	Occupation: Farmer: 1, Salary man: 2, Business: 3	Income (NRs)
1.					
2.					
3.					
4.					
5.					
6.					

7. Electrical appliances

S.N.	Name	Yes:1, No:0	Number	Voltage	Ampere	Using hour per day	Other

1.	Electric lamps						
2.	Computer						
3.	Electric fan						
4.	Air conditioning unit						
5.	Electric heater						
6.	Micro wave						
7.	Vacuum cleaner						
8.	Refrigerator						
9.	Washing machine						
10.	Mobile						
11.	Electric iron						
12.	TV						
13.	Rice cooker						
14.	Water pump						
15.	Hot put						
16.	Mixer Grander						
17.	Others:						

8. Sources of electricity:

☐ No ☐ National grid ☐ Local plant

☐ Other renewable sources

9. Sources of firewood:

☐ No ☐ Own land ☐ Public jungle

☐ Buy from others

10. LPG gas:

☐ No ☐ Local market ☐ Imported from away

☐ Others

11. Amount of energy use

Month	Electricity		Firewood		LPG		Kerosene		Candle		Others:	
	kWh	Price	Bhari	Price	KG	Price	Litter	Price	KG	Price		
Jan.												
Feb.												
Mar.												
Apr.												
May												
Jun.												

Jul.												
Aug.												
Sep.												
Oct.												
Nov.												
Dec.												

12. Energy using for cooking:

☐ Firewood ☐ LPG ☐ Bio gas

☐ Kerosene ☐ Electricity

13. Energy using for lighting:

☐ Firewood ☐ LPG ☐ Bio gas

☐ Kerosene ☐ Electricity

14. Energy using for heating:

☐ Firewood ☐ LPG ☐ Bio gas

☐ Kerosene ☐ Electricity

15. Currently load shedding hour: ☐

16. Other energy sources:

☐ Solar panel ☐ Animal dung ☐ Bio gas

☐ Agri residue ☐ Others

17. Any subsidy gets from government of Nepal

☐ Yes ☐ No

18. Are you light off electricity when you sleep ?

☐ Yes ☐ No

19. Did you change the LED light bulb, recently ?

☐ Yes ☐ No

20. What energy sources do you use when no electricity ?

☐ Solar PV ☐ Battery ☐ Inverter

☐ Charging lights ☐ Others

21. House details

Room No	Room size (meter)			Room type: (Kitchen:1, Bed room: 2, Living room: 3, Baranda:4)	Materials used for house
	Length	Width	Hight		☐ Stone ☐ Mud ☐ Wood ☐ Zinc ☐ Iron ☐ Cement Block ☐ Others
1.					
2.					
3.					
4.					

Thank you very much !

Thermal comfort survey questionnaire_2018

Date:

Time:

Name of data collector:

Vote no.:

Name of respondent: Sex: ☐ Male ☐ Female,

Address:

Age:

1. How do you feel at this time (अहिले बायुको तापक्रम कस्तो अनुभव गर्नु भएको छ) ?

☐ 1. Cold (जाडो) ☐ 2. Cool (चिसो) ☐ 3. Slightly cool (अलिकति चिसो) ☐ 4. Neutral (ठिक्क)

☐ 5. Slightly warm (अलिकति तातो) ☐ 6. Warm (तातो) ☐ 7. Hot (गर्मि)

2. I would prefer to be (अहिले बायुको तापक्रम भन्दा चिसो, तातो कस्तो चाहनु हुन्छ) ?

☐ 1. Much warmer (धेरै न्यानो चाहिन्छ) ☐ 2. A bit warmer (अलिकति न्यानो चाहिन्छ) ☐ 4. No change (यत्तिकै ठिक छ)

☐ 5. A bit cooler (अलि शितलता चाहिन्छ) ☐ 6. Much cooler (धेरै शितल चाहिन्छ)

3. Activity (अहिले के गरि रहनु भएको छ) ?

☐ 1. Studying (पढिरहेको) ☐ 2. Cooking (खाना पकाईरहेको) ☐ 4. Relaxing (आनन्द लगिरहेको) ☐ 5. Communicating (बार्तालाप गरिरहेको)

4. How do you feel about the lighting level at this time (यस समयमा तपाईलाई प्रकाशको अवस्था कस्तो अनुभव गर्नु भएको छ) ?

☐ 1. Very bright (धैरै उज्यालो)
☐ 2. Bright (चम्किलो)
☐ 3. Slightly bright (अलिकति मात्र चम्किलो)
☐ 4. Neutral (ठिक्क)
☐ 5. Slightly deem (अलिकति अध्यारो)
☐ 6. Deem (अध्यारो)
☐ 7. Very dark (धैरै अध्यारो)

5. I would like to prefer lighting level than this time (अहिलेको भन्दा तपाइँ कस्तो प्रकाश रुचाउनु हुन्छ) ?

☐ 1. Much dimmer (अझै अध्याँरो)
☐ 2. A bit dimmer (अलिकती मात्र अध्यारो)
☐ 4. No change (एत्तिकै ठिक छ)
☐ 5. A bit brighter (अलिकति चम्किलो)
☐ 6. Much brighter (धैरै चम्किलो)

Thank you very much !

Survey record sheets:

Vote no.	Instrument no.	Date	Time	Height	Weight	Air temp. feeling (°C)	Air temp. prefer (°C)	Hou do you feel temp. (°C)	How do you prefer temp. (°C)	Activity	How do you feel light	Light prefer	Indoor humidity	Indoor CO_2	Indoor air temp. (°C)	Indoor light (LX)	Indoor globe temp. (°C)	Indoor wind velocity	Outdoor air temp. (°C)

					Close: 0, Open: 1		Close: 0, Open: 1					Surface temperature (°C)							
Vote no.	Weather (घमाइलो: 1, कहिले वर्षा कहिले बादल: 2, बादल: 3, वर्षा: 4, हिउँ: 5)	Room type (Kitchen:1, Bed Room: 2, Living Room:3, Varanda:4)	Floor	Inner door	Window	Curtain	Cooling use	Fan use	Heating use	Firewood use	Celling light	Floor	East	West	South	North			

Publication list

Journal papers (with review)

1. D.K. Shahi, H.B. Rijal and M. Shukuya, A study on household energy-use patterns in rural, semi-urban and urban areas of Nepal based on field survey, Energy and Buildings 223 (2020), 110095.
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Personal History

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Research interest		Energy, thermal comfort and built environment
Ph.D. research title	**:**	Thermal improvement of Nepalese houses based on the evaluation of energy use and adaptive comfort (エネルギー使用と適応的快適性の評価に基づくネパールの住宅の温熱環境の改善)

Educational career:

Level	Passed year	Institution name and address	Major study field
Secondary	2003	Shree Badimalika Higher Secondary School, Raskot, Kalikot, Nepal	-
Intermediate	2005	Shree Jana Higher Secondary School, Birendranagar, Surkhet, Nepal	Mathematics

Bachelor	2009	Baneshwor Campus (Tribhuvan University), New Baneshwor, Kathmandu, Nepal	Mathematics
Master	2011	University Campus, Central Department of Education (Tribhuvan University), Kirtipur, Kathmandu, Nepal	Mathematics
Research student	2018	Yokohama Campus (Tokyo City University), Yokohama, Japan	Energy use
Doctorial	2021	Yokohama Campus (Tokyo City University), Yokohama, Japan	Energy use, Thermal comfort, Thermal improvement

Working experience:

Institution name and address	**Worked period**	**Designation**	**Major role**
Mt. Royal Co. Ltd, Tokyo Japan	2016- Current	CEO	Management
Royal Management Service Co. Ltd. Tokyo, Japan	2020- Current	CEO	Management
Amphy Co. Ltd. Osaka, Japan	2020- Current	CEO	Management
Mt. Royal Education Pvt. Ltd. Kathmandu, Nepal	2016-Current	CEO	Management

Royal Japanese Language & Culture Center Pvt. Ltd.	2017-Current	CEO	Management
Anisa Co. Ltd. Tokyo, Japan	2015-2016	International affairs chief	Translation and interpretation
Ushakiran National Monthly Magazine	2010-2014	Publisher/Editor	Editing and management
Kantipur Temple House	2005-2009	Front officer	Official work

Additional skills and award

Language	English	:	Business level
	Hindi	:	Conversation level
	Japanese	:	Business level (N1)
Award		:	Best presentation, SHASE (The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan), 2017.
		:	High impact factor journal published in international journal. Encouragement award (Tokyo City University, 2021)