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Energy use, thermal environment and indoor air pollution in different ecological regions in Nepal

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Abstract

Energy is the important ingredients for generating human well-beings of the society, as it enables a variety of improvements for the better quality of life. It is widely acknowledged that buildings account for more than 30% of total energy consumption in the world, among which 30–60% are for improving indoor thermal environment. Buildings are the place where we spent our significant time and it requires inputs of energy to create favorable thermal environment. However due to high cost and limited supply of clean commercial fuels, millions of people particularly living in the rural area of developing countries consume less per- capita energy and consequently they have to face harsh thermal environment. Each year, harsh thermal environment creates serious health problems ranging from discomfort to illness and even to death. Household energy availability is one of the important ingredients required to provide the occupants with adequate indoor thermal environments, with which they can minimize thermal dissatisfaction. The indoor burning of traditional fuels in improperly ventilated buildings deteriorates the indoor environment and the people who lives there are exposed to harmful levels of indoor air pollution. According to the world health organization, indoor air pollution is the world's most serious air pollution problem, especially for poor people. Since the improvement of residential buildings can have a vital impact on energy use, thermal environment as well as indoor air pollution, and it is necessary to conduct research aiming to get a better quantitative knowledge on the current situation of the indoor thermal environmental of the residential buildings and its relation to the household energy use and associated indoor air pollution.

In order to get quantitative information on this issue, a series of survey on household energy-use patterns and the indoor thermal environmental characteristics in three different climatic regions in Nepal was carried out in winter season of 2018. The survey results showed that most of the indoor air temperatures of investigated houses in three climatic regions were lower than the adaptive comfort standard. Average measured indoor air temperature was 8.0 °C, 13.9 °C and 12.8 °C, respectively, and per-capita daily energy

use was 37, 30 and 20 MJ/(person.day) in cold, temperate and sub-tropical regions, respectively. Firewood, electricity and liquefied petroleum gas (LPG) were found as the major energy carriers used in the studied households. The present finding suggests that a substantial improvement of the indoor thermal environment by improving thermal insulation of building envelopes together with rationally small energy use must be required for the well-being of the people in all three regions. This survey results are hopefully useful to understand the current energy-use situation and thermal environment of existing residential buildings in Nepal and thereby to assist the policy formulation for better indoor thermal environment of existing buildings with low energy use.

Nepal has low per-capita energy use, and a majority of its rural residents use firewood as their primary energy source. Excessive use of firewood in improperly ventilated buildings degrades the indoor environment and health condition of the inhabitants. This study assesses the influence of hourly firewood consumption patterns on CO_2 emissions and resulting concentrations in rural households in Nepal. The results suggest that most of the households tend to use more firewood during the morning and evening hours. Family size and number of animals reared by the households were positively correlated with firewood consumption, whereas family size was negatively correlated with per-capita firewood consumption. Per-capita firewood consumption was found to be 1.8 kg/ (capita · day). Household firewood consumption and CO_2 emissions were 12 kg/ (family · day) and 14.26 kg CO_2 e/ (household · day), respectively. The larger households spent more time for cooking, while their consumption rate was similar (1.3 kg/hour) to that of smaller households. High indoor CO_2 emissions in the morning and evening hours due to high firewood consumption may pose severe health risks to the inhabitants. Therefore, intensive awareness programs and pollution.

論 文 要 旨（和文）

エネルギーは、生活の質を高めるためのさまざまな改善を可能にするため、社会の人間の幸福を生み出すための重要な要素です。建物は世界の総エネルギー消費量の 30%以上を占めており、そのうち 30〜60%が建物の室内熱環境の改善に使用されていることは広く認識されています。建物は好ましい熱環境を作り出すためにエネルギーの投入を必要としますが、コストが高く、商業用燃料の供給が限られているため、ネパールの農村部の人々の 80%は、調理や暖房に薪、農業残渣、動物の糞などの伝統的な燃料に依然依存しています。不適切に換気された建物での従来の燃料の屋内燃焼は、人々を有害なレベルの室内空気汚染にさらします。世界保健機関によると、室内空気汚染は、特に貧しい人々にとって、世界で最も深刻な大気汚染問題です。住宅の改善は、エネルギー使用、熱環境、室内空気汚染に重大な影響を与える可能性があるため、エネルギー使用の現状とその関係について、より定量的な知識を得るための研究を行う必要があります。ネパールのさまざまな気候地域の世帯の室内熱環境。この研究の目的は、ネパールのさまざまな気候地域の住宅が、利用可能なエネルギー資源を使用して屋内の熱環境を実現するためにどのように運用されているかを特定することです。この研究はまた、ネパールの 3 つの気候地域におけるさまざまな燃料使用世帯の不均一なエネルギー使用パターンを知ることを目的としてい

ます。さらに、この研究は、家庭のエネルギー消費に起因する直接的な CO_2 排出パターンを調査し、従来の混合燃料および商用燃料ユーザーの家庭におけるLPG および電気による調理用燃料代替の CO_2 排出削減の可能性を推定することも目的としています。2018 年の冬季に 3 つの気候地域の 516 世帯からエネルギー使用調査を実施しました。継続的な室内熱環境測定のために、各地域から 3 つの住宅を選択しました。データロガーを使して、室内の気温、相対湿度、CO_2 濃度を 10 分間隔で測定しました。測定された室内空気温度は、寒冷、温帯、亜熱帯地域で、それぞれ 8.0°C、13.9°C、12.8°C でした。調査結果は、調査対象の住宅の室内空気温度のほとんどが ASHRAE の快適基準を下回っていることを示しています。 3 つの気候地域で調査されたすべての世帯の室内空気温度は、外気温に大きく依存しています。測定された平均室内空気温度は、寒冷、温帯、亜熱帯地域で、それぞれ 8.0°C、13.9°C、12.8°C でした。3 つの地域に住む人々は、主に調理と暖房を薪に依存しています。一人当たりの総エネルギー使用量は、寒冷、温帯、亜熱帯地域でそれぞれ 37、30、20 MJ /（1 人日）のオーダーでした。 25%の世帯は、他のクリーンな調理用燃料を使用せずに従来の調理用燃料に依存しています。67%の世帯は、エネルギーシステムにクリーンな調理用燃料を追加しています。8%の世帯だけが、毎日の調理用燃料の要件を満たすために商用燃料に依存しています。非常に非効率的な調理技術を使用してい

るため、家庭用の従来型および混合燃料は、家庭用の商用燃料よりも多くのエネルギーを使用し、より多くの CO_2 を排出する必要があります。従来の混合燃料を使用する家庭も、商用燃料を使用する家庭よりも調理にかなり長い時間を費やしていました。時間ごとの屋内 CO_2 の分析では、薪の消費量が多いため、朝と夕方に高い排出量と濃度が示されました。従来の混合燃料ユーザー世帯は、エネルギー消費率が高く、使用される調理技術の効率が低いため、商用燃料ユーザー世帯よりも多くの CO_2 を排出します。 CO_2 排出の還元電位は、温帯地域の中部亜熱帯地域で高く、寒冷地域で低いことがわかった。この研究は、屋外の気候条件が屋内の熱環境に影響を及ぼし、それが家庭のエネルギー使用パターンに関連していることを示しました。 3 つの気候地域の家庭にある既存の建物の外皮を改善することは、家庭のエネルギー使用を最適化しながら、人々により良い室内熱環境を提供するための理想的なオプションです。家庭の CO_2 濃度は、家庭のエネルギー消費に起因する CO 2 排出量と正の相関があったため、クリーンな調理用燃料と効率的な調理技術は、家庭のエネルギー使用とその結果生じる CO_2 排出量を最小限に抑えるのに役立ちます。

Abbreviations and Nomenclature

AEPC	Alternative Energy Promotion Center
BAU	Business as Usual
CBS	Central Bureau of Statistics
CO_2	Carbon Dioxide
GDP	Gross Domestic Production
GoN	Government of Nepal
ICS	Improved Cook Stove
IEA	International Energy Agency
IPP	Independent Power Producer
km	Kilometer
kW	Kilowatt
kWh	Kilowatt hour
LES	Lowest Emission Scenario
LPG	Liquefied Petroleum Gas
MES	Moderate Emission Scenario
NEA	Nepal Electricity Authority
UN	United Nation
WB	World Bank
WESC	Water and Energy Secretariat
WHO	World Health Organization

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Chapter 1: Introduction

1.1 Background

Based on topography and distinct climatic features, Nepal is broadly classified into three ecological regions: mountain, hill and terai regions, all of which extend from east to west with some irregular widths from north to south (Malla S.; 2013). Different regions with distinct climatic features can be seen within short distance due to geographical location with a distinctive variation of altitude in particular. In the North, summer is cool and winter is severe, while in the South, summer is tropical and winter is mild. According to previous study, living-space temperature was found to be very low in cold climate in winter and very high in subtropical climate in summer (Rijal et al., 2002). People have to face extreme hot and extreme cold due to the lack of appropriate heating and cooling systems in residential buildings. The harsh thermal environment without proper heating and cooling systems creates many serious problems ranging from discomfort to illness and even to death (Rijal et al.; 2010). In developing countries like Nepal, rural areas in particular, the mechanical heating and cooling systems have not yet been widely used for indoor thermal environmental control and therefore most of the people take passive measures such as clothing adjustment, window opening and closing, and hot or cold drinks, all of which do not require the input of commercial fuels (Rijal; 2018). In the developed countries, the use of heating and cooling devices plays a major role for thermal environmental control, but this is realized with a large rate of energy use, i.e. 30 ~ 60% of total energy use in developed countries have been for heating and cooling purposes in buildings (Li et al.; 2018). Suitable design of buildings under local climate into consideration, the use of renewable energy and the use of locally available materials for the construction of residential buildings to achieve better indoor thermal environment with low energy use and hence low CO_2 emission has become our focus for current research. Therefore, this study brings three interrelated issues; energy use, thermal environment and indoor air pollution that are pertinent to research, but which have rarely been considered together in previous research.

How the energy use patterns are affected by thermal environmental condition in the domestic sphere is important not just for improving indoor thermal environment but also for indoor air quality of the residential buildings. The need to understand how buildings are operated with energy availability is also important while improving indoor environmental quality for the wellbeing of the occupants as well as for building designers and policy makers to minimize the residential energy use since it has a vital impact both on indoor thermal environment and on the whole of energy use. Therefore, it is necessary to conduct research aiming to get a better quantitative knowledge on the current situation of energy use and its relation to the indoor environment (thermal and air quality) under a variety of outdoor environmental conditions in Nepal.

1.1.1 Thermal environment and energy use in buildings

Buildings are the place where people spend up to 87% of their time indoors whether it in be a residential or commercial building and being continuously exposed to the indoor environment (Kiepeis et al., 2001). Providing a comfortable and healthy indoor environment is one of the important functions of building systems. Therefore, it is crucial to fully understand the factors influencing indoor environmental quality (IEQ) and their interdependent, complex and dynamic nature for improving human comfort and health concern of the occupant. It is widely acknowledged that buildings account for more than 30% of total final energy consumption in the world and are responsible for consuming 35–40% in the developed countries among which 30–60% are for improving indoor thermal environment in buildings (Li et al., 2018). Heating Ventilation Air Conditioning (HVAC) systems alone account for approximately half of the total energy consumption of buildings (Perez-Lombard et al., 2008). In 2018, the primary energy consumption of the building sector was 1123 million tons coal equivalent (Mtce), which includes 1032 Mtce of commercial and 91 Mtce of non-commercial biomass accounting for approximately 20% of all commercial energy consumption; the total carbon emissions related to building energy use were approximately 2.2 billion tCO_2 (Guo et al., 2021). Since 2001, building energy consumption has almost doubled and commercial primary energy use per capita has increased 1.5 folds, from 291 kgce/cap to 739 kgce/cap (Guo et al., 2021).

As long as there is a plenty of space for improvement in living standards through the improvements of indoor thermal environments particularly in the developing countries like Nepal, where wintery indoor air temperature and per-capita daily energy consumption was at a low-level during (Pokharel et al., 2020). It has also suggested that the probability of building energy consumption in developing countries will rapidly grow in the coming years. Xue et al., (2016) reported that that Indoor air quality exerts a significant effect on occupant's satisfaction, health and productivity. Especially, indoor thermal environment has been proved to affect the cognitive level for other environmental parameters (Geng et al., 2017) and production efficiency (Mujan et al., 2019). For developed countries, large amount of energy is being consumed to realize a thermal comfort and healthy indoor environment (Pokharel et al., 2020). Many researchers around the world have carried out investigations on indoor thermal environment in residential buildings. For instance, Bea et al., (2009) carried out research on seasonal indoor thermal environment and occupant control behavior of cooling and heating systems in Korea and concluded that the development of an HVAC system has created an expectation of comfort for residents and has shifted their thermal comfort zone warmer in winter and cooler in summer. Rijal et al. (2010) carried out field measurement on indoor thermal environment and found significant difference in the relationship between room air temperature and estimated neutral temperature of the occupants for a couple of regions in Nepal. Fuller et al. (2009) conducted a field measurement in a traditional house in Simikot and found that indoor air temperature was far below the lowest value of internationally recognized acceptable temperature. Susanne et al. (2014) analyzed a variety of vernacular houses located in different climatic regions to identified that houses were made based on the passive solar design strategies in all regions in Nepal. Chu et al. (2017) introduced Ondol, a traditional Korean heating system with firewood use in a southern village of

Nepal and investigated the possibility for the improvements of indoor thermal environment. Field studies on vernacular architecture, thermal performance of typical vernacular buildings and thermal comfort in existing residential buildings in India have been undertaken by Singh et al., (2009, 2010, 2016). Some other investigations on indoor thermal environment and thermal performance of residential buildings in diverse climatic regions provides detailed literature review together with thermal environments of other countries (Li et al., 2019; Song et al., 2019; Li et al., 2018; Porcaro et al., 2019; Yu et al., 2017; Kuchen and Fuch, 2009).

Table 1.1 summarizes the literature available on the thermal environmental studies.

Reference	Year	Country	Study on
Bea et al.	2009	Korea	Living thermal environment and control behavior
Kuchen and Fuch	2009	Germany	Indoor thermal environment of centrally heated buildings
Mavrogianni et al.	2013	UK	Historical variation of indoor temperature
Rijal et al.	2018	Nepal	Seasonal and regional variation of thermal environment
Thapa et al.	2019		Thermal environment of temporary shelter
Gautam et al.	2020		Thermal environment of buildings in three climatic regions

Low per-capita energy consumption with traditional energy resources and low indoor air temperature of the residential buildings in Nepal has been responsible for unhealthy and unproductive indoor environment. This leads to many serious health and environmental problems ranging from discomfort to illness and even to death (Rijal et al., 2010). In order to minimize the health burden associated with indoor environmental condition and to estimate the future trend of residential energy consumption, it is necessary to know the energy situation and the indoor thermal environment of the residential buildings.

1.1.2 Energy situation in Nepal

Nepal is a small country situated in the Himalayan mountain range between India and China. It has difficult mountain topography which makes difficult to develop modern energy infrastructure in all parts of the country. Unavailability and unaffordability of clean commercial fuel has long been a serious problem in rural households in Nepal. Access to clean cooking fuels is essential for generating human well-beings of the society, as it enables a variety of improvements for the better quality of life (Kurniawan et al.; 2018). Enormous potential of renewable energy resources of the country such as; hydropower, solar power and wind power can be utilized for the betterment of the living condition of the people through clean energy development, however, due to economic and other social constrains most of these resources have remained underutilized and thus, large number of households have to rely on traditional fuels (Islar et al.; 2017 and Ghimire et al.; 2018). According to the survey conducted by CBS-Nepal, about 70% of the total households including urban and rural areas and 90% of the rural households in Nepal depend primarily on the traditional cooking fuels for daily cooking activities (CBS-Nepal, 2011).

Firewood is the major source of cooking and heating energy and it provides 78% of the total energy demand of the country (Poudayl et all. 2019, IEA, 2016). Without giving up firewood, many households add alternative fuels such as; LPG, electricity, kerosene and biogas to fulfill their everyday cooking energy demand. However, the share of other fuels is marginal due to the limited supply and comparatively high price. LPG is the second widely used cooking fuel in Nepal and consumed 1.4 million tons every year (Poudyal et al.2019). Electricity is still unreliable with many times of load shedding and used mostly for lighting and other electric appliances. According to the World bank report, about 90% of the households have access to electricity either from grid supply or from off grid supply, with per-capita electricity consumption of 146.5 kWh/year which is approximately twenty times lower than the world average of 3104 kWh/year (World bank, 2019). Total electricity used in Nepal was 6394.38 GWh, an increased by 14% over the corresponding figure of last year (NEA report 2018/19). Despite large potential and a long history of hydropower generation, the total hydropower generation of Nepal stands at only 1233.1 Mega Watts as of February 2020 (Acharya and Adhikari, 2021).

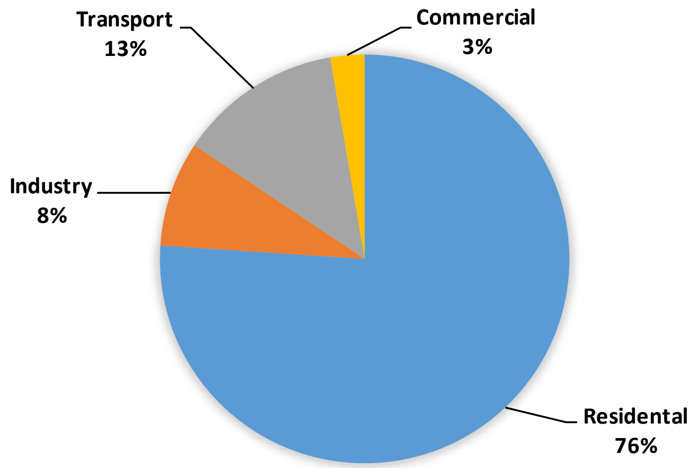


Figure 1.1 Sector wise energy consumption in 2018

Energy is an important element for social development as it enables the living condition of people. Economic and social development of Nepal is being hampered by its inadequate energy supply. The country does not have its own reserves of gas, coal or oil. However, it is richly endowed with renewable energy resources such as hydroelectricity, solar, wind, biogas, and various forms of biomass energy. Although the most significant energy resource of Nepal is hydropower, around 12% of the population, as of 2013 had access to electricity through other renewable energy sources. Around 23 MW of electricity was coming from micro hydro schemes, 12 MW was from solar photovoltaic (PV) systems, and about 20 kilowatts (kW) was from wind energy. Biomass, oil products, coal, hydro, and electricity are the main energy resources in Nepal. Among these, biomass, in the form of firewood, agricultural waste, and animal dung, has consistently dominated supply because of the lack of other alternative energy sources and the poor state of the economy, particularly in the rural areas. The largest share of energy consumption goes to the residential sector. The share of industry and transport is now small, but these sectors are growing fast. From 1990 to 2014, total final energy consumption rose from 106 kilotons of oil equivalent (ktoe) to 665 ktoe for the industry sector, and from 111 ktoe to 858 ktoe for the transport sector. **Figure 1.1** shows the sector wise energy consumption of Nepal in 2018.

Firewood is an important source of household energy for the rural population of many developing countries. Approximately 2.6 billion people from developing countries fulfil a majority of their basic energy demand for cooking and space heating from fuelwood, a practice that is inefficient, unhealthy, and unsustainable (Petersen et al.; 2014). This trend is expected to continue in the future, especially in rural areas of developing countries (Petersen et al.; 2014). Nepal is one of the least developed countries that has one of the lowest per-capita energy consumption globally (Pokharel S.; 2007). The energy use and energy access levels in Nepal are significantly below the level of basic human needs, and firewood is expected to remain the dominant cooking fuel for the foreseeable future (Malla S.; 2013). As of 2010, over 30% households lacked access to electricity, and 78% households relied on traditional biomass for cooking and space heating (CBS; 2011). According to the household survey 2015/16 of Nepal, firewood is a major source of cooking fuel for more than half of the households in the country and is used by 76.5% rural households and 38.0% urban households to meet their everyday cooking energy demands (CBS;2015/16). Lack of financial and technical capabilities has compelled the rural population to use inefficient and hazardous sources of solid biomass energy (Gurung et al.; 2013). **Figure 1.2** shows the scarcity of LPG gas during the crisis in 2015 due to economic blockade in Nepal.

In developing countries like Nepal, particularly in rural areas, direct firewood consumption in inefficient traditional cook stoves without chimneys in improperly ventilated buildings is considered the major cause of indoor air pollution. Exposure to pollutants resulting from the burning of solid fuels has been responsible for the death of at least 4.3 million people per annum worldwide (WHO; 2016).

Figure 1.2 People waiting to exchange LPG cylinder during the crisis of LPG fuel in 2015 due to Indian economic blockade in Nepal

Improvements in the indoor air quality of residential buildings is important for minimizing the health burden on rural population. CO_2 emissions and concentrations resulting from firewood consumption inside buildings are the simplest indicators of indoor air quality of residential buildings in rural areas and this information can be used to monitor the indoor air quality of residential buildings.

1.1.3 Thermal environment and residential buildings

In a broad sense, the term thermal environment refers to the things that can affect the heat transfer at the point. Indoor thermal environment is the system in which continuous heat exchange taking place between indoors and the surrounding environments through conduction, convection and radiation. The indoor thermal environment of the residential building is affected by air temperature, surface temperatures, humidity and heat flow rate of the building materials. Good indoor environment is characterized by the right room temperature, proper humidity, cleanliness and freshness suitable for the human beings. The most important function of the building is to provide shelter with appropriate thermal environment to achieve thermal comfort for its occupants. Inappropriate thermal environment of the building either creates uncomfortable indoor environment or require input of extra energy to improve the indoor thermal environment. Appropriate indoor thermal environment of the residential buildings is important for the thermal comfort of the occupants. Thermal comfort refers to a condition where a person is satisfied with the ambient temperature. In the modern societies, occupant tend to achieve thermal comfort by creating favorable indoor thermal environment in the residential buildings which requires the input of energy resources. In residential buildings of developed countries, energy consumption for mechanical space heating and cooling is a large in the total residential energy consumption. It is widely acknowledged that buildings account for more than 30% of total final energy consumption in the world and are responsible for consuming 35–40% in the developed countries, among which 30–60% are for improving indoor thermal environment of the buildings (Li et al.; 2018). In China, the building energy consumption has increased by 45% in two decades and the proportion of building energy consumption was about 27.5% in 2001 and it was up to 36% in 2014 (Li et al.; 2018). In order to estimate the future trend of energy consumption considering the energy required to maintain indoor thermal environment in Nepal, it is necessary to understand the energy situation and thermal environment of the residential buildings. The purpose of this study is to investigate the actual conditions of indoor thermal environment of the existing buildings in three climatic regions and energy use patterns of the households in that regions.

1.1.4 Indoor air pollution and associated health problems

The World Health Organization (WHO) estimates that about 2.8 billion people in developing countries depend on solid fuels and traditional cook stoves for cooking and heating (WHO; 2016). Burning of solid fuel in inefficient traditional stoves is responsible for the emission of various indoor air pollutants, which have direct and indirect impacts on the health of the inhabitants. Small and improperly ventilated buildings reduce the dilution of indoor pollutants and increase the concentration of harmful gases, which creates unfavorable indoor environments. In developing countries like Nepal, particularly in rural areas, direct firewood consumption in inefficient traditional cook stoves without chimneys in improperly ventilated buildings is considered the major cause of indoor air pollution. Exposure to indoor air pollution is one of the important risk factor of infant and child mortality. Exposure to pollutants resulting from the burning of solid fuels has been responsible for the death of at least 4.3 million people per annum worldwide (WHO; 2016). Improvements in the indoor air quality of residential buildings is important for minimizing the health burden on rural population. CO_2 emissions and the concentrations resulting from firewood consumption inside buildings are the simplest indicators of indoor air quality of residential buildings in rural areas and this information can be used to monitor the indoor air quality of residential buildings.

1.2 Significance of the study

Despite the various efforts of governmental and non-governmental organizations to improve the household energy situation, still 70% of the total households in Nepal are relying on firewood for cooking and space heating with traditional cook stoves in improperly ventilated buildings. Excessive use of firewood for cooking and for optimizing indoor thermal environment of the buildings in improperly ventilated space deteriorate the indoor air quality and degrade the health condition of the people. This study brings three interrelated issues; household energy use, thermal environment and indoor air pollution that are pertinent to research, but which have rarely been considered together. How the thermal environmental condition affects the energy use practices in the domestic sphere is important not just for improving indoor thermal environment but also for indoor air quality of the houses. Since the energy use patterns in the building can have a vital impact both on indoor thermal environment and on the indoor air quality. Therefore, it is necessary to conduct research aiming to get a better quantitative knowledge on the current situation of energy use and its relation to the indoor thermal environment and indoor air pollution.

1.3 Aim and objectives

The objectives of this research are as follows.

To identify how the residential buildings in different climatic regions in Nepal have been operated to achieve indoor thermal environment under the use of available energy resources.

To know the heterogeneous energy use patterns of the different fuel user households in three climatic regions of Nepal.

To explores the hourly CO_2 emission patterns of rural households, CO_2 emission patterns and CO_2 emission reduction potential of clean cooking fuel substitution by LPG and Electricity in traditional mix and commercial fuel user households.

1.4 Conceptual contribution of this thesis

Household energy availability is one of the important ingredients required to provide the occupants with adequate indoor thermal environments, with which they can minimize thermal dissatisfaction. The health impact and energy efficiency of the residential buildings are important concerns of the contemporary global societies. However, very little is known about thermal environment and associated energy use patterns of the residential buildings in Nepal. Lack of empirical evidence of thermal environmental characteristics on energy consumption and on resulting indoor air quality impacts the wellbeing of the occupants. This thesis contributes evidences regarding thermal environment, energy consumption and resulting indoor air pollution in three ecological regions in Nepal. It also contributes to the literature by addressing heterogeneous energy use patterns of traditional, mix and commercial fuel using households cold, temperate and sub-tropical regions in Nepal.

1.5 Structure of the thesis

This thesis is mainly divided into five chapters including this introductory chapters which gives the general information of the building characteristics, energy situation and the existing problems of indoor air pollution in three climatic regions in Nepal. This chapter highlights the importance of research on energy use, thermal environment and indoor air pollution in Nepal. Available literature on energy use, thermal environment and indoor air pollution of the residential buildings were presented.

Chapter 2 presents the finding of thermal environmental condition of the households in cold, temperate and sub-tropical regions. The main objective of this chapter was to demonstrate the housing patterns in three climatic regions with thermal environmental parameters. Variation in daily temperature, humidity and water vapor concentration are analyzed and presented here.

Chapter 3 is divided into three subsections. The first present a regional variation of energy use patterns, the second presents the variation of energy use patterns among three fuel user households and third subsection presents the hourly firewood consumption patterns. The main objective of this chapter was to identify regional heterogeneity of the energy consumption patterns of the households. Hourly variation of firewood consumption, high amount of energy used by the traditional and mix fuel user households than commercial fuel user households are the novel findings in this chapter.

Chapter 4 is divided into two subsections. The first presents the variation of direct CO_2 emission and concentration of the households and the second presents the emission reduction potential of cooking fuel substitution by LPG and electricity.

Chapter 5 summaries the conclusions of this research.

Chapter 2: Indoor Thermal Environment

2.1 Introduction

The indoor thermal environment of the residential building is vital for human health and well-being of the society because people spent their significant time indoors whether it in be a residential or commercial building (Kiepeis et al., 2001). Building efficiency, health impact and energy efficiency of the buildings are greatest concern of the contemporary society however very little was known in the context of Nepal. Nepal is broadly classified into three ecological regions: mountain, hill and terai regions, with distinctive variation of climatic condition due to high altitude variation. It has a variety of altitudes from 60 to 8,848 meter from the sea level within 200 km distance. In the North, summer is cool and winter is severe, while in the South, summer is tropical and winter is mild. According to previous study (Rijal and Yoshida; 2002). living-space temperature was found to be very low in cold climate in winter and very high in subtropical climate in summer. People living in cold and temperate region have to face extreme cold during winter while people living in sub-tropical region have to face extreme hot due to the lack of appropriate heating and cooling systems in residential buildings. Each year, the harsh thermal environment without proper heating and cooling systems creates many serious problems ranging from discomfort to illness and even to death (Rijal et al.; 2010). In developing countries like Nepal, rural areas in particular, the mechanical heating and cooling systems have not yet been widely used for indoor thermal environmental control and therefore most of the people take passive measures such as clothing adjustment, window opening and closing, and hot or cold drinks, all of which do not require the input of commercial fuels (Rijal; 2018). In the developed countries, the use of heating and cooling devices plays a major role for thermal environmental control, but this is realized with a large rate of energy use, i.e. 30 ~ 60% of total energy use in developed countries have been for heating and cooling purposes in buildings (Li et al.; 2018). Suitable design of buildings under local climate into consideration, the use of renewable energy and the use of locally available materials for the construction of residential buildings to achieve better indoor thermal environment with low energy use and hence low CO_2 emission has become on focus in recent years (Walker and Pavia; 2018, Fuller et al.; 2009, Susanne et al.; 2014).

2.1.1 Literature review

With respect to Nepal, only a few pieces of literature are available on indoor thermal environment and domestic energy use. Rijal et al. (Rijal et al.; 2010) carried out field measurement on indoor thermal environment and found significant difference in the relationship between room air temperature and estimated neutral temperature for a couple of regions in Nepal. Fuller et al. (2009) also conducted a field measurement in a traditional house in Simikot, the northwest of Nepal and found that indoor temperature was far below the lowest value of internationally recognized acceptable temperature. Susanne et al. (Susanne et al.; 2014) analyzed a variety of vernacular houses located in different climatic regions to identify the applied climate responsive design strategies and concluded that they have widely been used passive solar design strategies in all regions in Nepal. Chu et al. (Chu et al.; 2017) introduced Ondol, a traditional Korean heating system with firewood use, in a southern village of Nepal and investigated the possibility for the improvements of indoor thermal environment. Field studies on vernacular architecture, thermal performance of typical vernacular buildings and thermal comfort in existing residential buildings in India have been undertaken by Singh et al. (Singh et al.; 2009, Singh et al.; 2010, Singh et al.; 2016). Some other investigations on indoor thermal environment and thermal performance of residential buildings in diverse climatic regions provides detailed literature review together with thermal environments of other countries (Li et al.; 2019, Song et al.; 2019, Li et al.; 2018, Porcaro et al.; 2019, Yu et al.; 2017, Bhatt and Sachan; 2004). Malla, 2013 carried out a household energy-use research in Nepal and found energy use is heterogeneous across the regions and biomass dominates the countries' energy use. An intensive investigation in different climatic regions in mountain village of India has identified the altitudinal difference in firewood use (Bhatta and Sachan; 2004).

The need to understand how buildings are operated with energy availability is important while improving indoor thermal environmental quality, not just for occupants but also for building designers and policy makers to minimize the residential energy use, since the improvement of residential buildings can have a vital impact both on indoor thermal environment and on the whole of energy use. Therefore, it is necessary to conduct research aiming to get a better quantitative knowledge on the current situation of energy use and its relation to the indoor thermal environment under a variety of outdoor environmental conditions in Nepal.

2.1.2 Objectives

The main objective of this research is to identify how the residential buildings in different climatic regions in Nepal have been operated to achieve indoor thermal environment under the use of available energy resources. This paper identifies the current energy use patterns and indoor thermal environment of residential buildings in three climatic regions of Nepal.

2.2 Materials and methods

2.2.1 Study area and climates

Nepal lies in between 26°22’ to 30°27’ latitude and 80°04’ to 88°12’longitude. The country is approximately 885 km long from east to west and its width in north-south direction varies from 130 to 260 km. It is broadly classified into three ecological regions: mountain, hill and terai regions, all of which extend from east to west with some irregular widths from north to south. Within this range the altitude varies from approximately 60 m above the sea level in the southern terai region to the highest peak 8848m, the Mount Everest in the north mountain region. Steep variation in altitude creates a wide range of climatic conditions; that is, within the span of 200 km, there are almost all types of climates, from sub-tropical to alpine. To represent such different climatic regions, we have selected three districts: Solukhumbu for mountain, Panchthar for hill, and Jhapa for terai region. We have further selected three municipalities from these three districts; Solududkunda, Phidim and Gauradaha for indoor thermal measurement and energy use survey. **Figure 2.1** shows the location of three study districts.

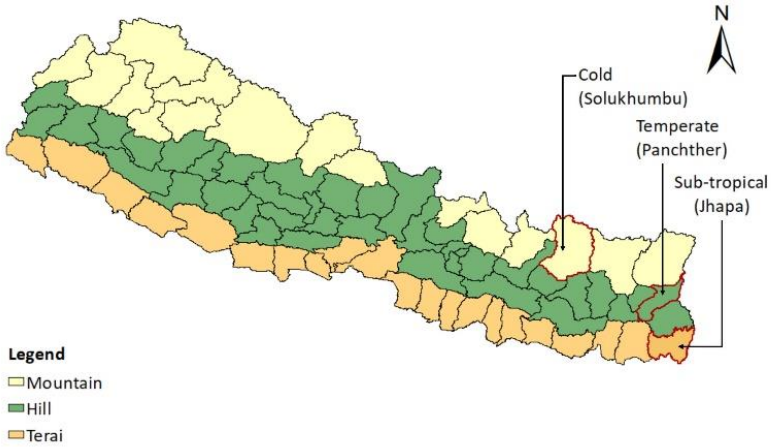


Figure 2.1 Investigated areas, climates and three districts for the present study

Figure 2.2 shows the monthly mean outdoor air temperature of these districts. The monthly mean outdoor air temperature is the lowest during winter (December-January) and it rather sharply increases in March due to the increase in solar insolation. The arrival of monsoon rain tends to mitigate the increase in outdoor air temperature during monsoon period, which is from June to September. May and June represent the hottest season in Nepal.

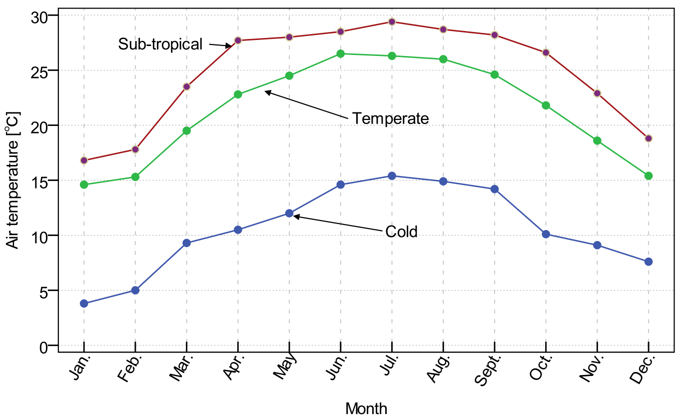


Figure 2.2 Monthly mean outdoor air temperature of study area obtained from the climatological and agro-meteorological records of 2016 of Nepal.

2.2.2 Selection of the houses to be studied

To ascertain the household energy –use pattern in three regions, Household energy-use survey was carried out from 516 households comprising 76 households in cold, 262 in temperate and 178 households in sub-tropical region. Out of these houses, to calculate firewood use more precisely, five houses from each region were selected for firewood use measurements and from these five houses from each region, three houses were selected for thermal environmental measurement. Due to the similarity of the existing buildings in three regions and availability of limited number of instruments, we have chosen only three houses from each region for measurements. All these houses had constructed by local skillful craftsmen with locally available materials with the construction methods inherited from previous generations. **Table 2.1** shows the survey period and the numbers of house for the investigation of energy use and indoor thermal environment. and **Figure 2.2** shows the schematic illustration of present study.

Table 2.1 Survey periods and the numbers of investigated houses for energy use, firewood use and indoor thermal environment.

Region	Survey period	Number of houses surveyed		
		Energy use	Firewood use	Indoor thermal environment
Cold	9 - 13 Jan. 2018	76	5	3
Temperate	30 Dec. 2017 - 3 Jan. 2018	262	5	3
Sub-tropical	9 - 13 Jan. 2018	178	5	3
Total		516	15	9

2.2.3 Description of the houses selected for indoor thermal environmental survey

All of nine houses, three houses chosen from each region, selected for continuous indoor thermal environmental measurement rely on firewood for cooking and space heating. **Table 2.2.2** shows the characteristics of three investigated houses. Floor area and ratio of window area to floor area were calculated from living and kitchen room of all investigated houses. **Figure 2.3** shows the ground floor plan view and the exterior look of three investigated houses from respective regions.

Table 2.2 Details of the investigated houses in three regions.

Region	House code	Family size (person)	Floor area (m^2)	Floor type	Wall thickness (m)	Materials for walls	Window area (m^2)	Ratio of window area to floor area	Celling
Cold	C1	7	22	Cemented	0.523	Stone and mud with cement plaster	0.81	0.128	Wood
	C2	6	22.5	Stone and mud	0.507	Stone and mud with cement plaster	0.81	0.108	Wood
	C3	6	26	Earth floor	0.507	Stone and mud with mud plaster	0.54	0.062	Wood
Temperate	T1	5	17.9	Earth floor	0.456	Stone and mud with mud plaster	0.13	0.014	Timber and mud
	T2	5	18.5	Earth floor	0.456	Stone and mud with mud plaster	None	–	Timber and mud
	T3	2	18	Earth floor	0.456	Stone and mud with mud plaster	None	–	Timber and mud
Sub-tropical	S1	4	16	Earth floor	0.25	Timber	0.54	0.135	Bamboo
	S2	3	15	Earth floor	0.75	Timber and bamboo	0.54	0.123	Bamboo
	S3	3	17.5	Earth floor	0.13	Brick and cement plaster	1.25	0.16	wood and bamboo

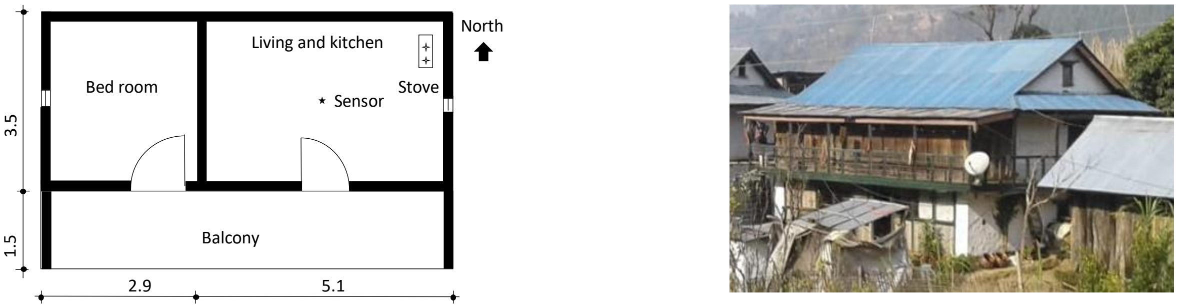
All investigated houses in cold and temperate regions were two story, while those in sub-tropical region were one story. The ratio of window area to floor area is larger in sub-tropical region than in other two regions. In all three regions, ground floor accommodates main living space and kitchen space in all studied houses. All houses in three regions have pitched roof made of zinc sheets.

The walls of the houses in cold regions are made of stone and mud. The walls of C1 house is plastered both side by cement and painted white. That house had six windows, each of which has the area of 0.81 m^2. The inner side of C2 house is finished with wooden sheets of 20mm thick, which may perform as a kind of thermal insulation barrier. The interior side of walls of C3 house is plastered by mud. The doors and windows were not air-tight.

The walls of the houses in temperate region are also made by stone and mud with mud plasters. Two small sized windows of 0.13 m^2 in the shorter facade are in T1 house. T2 house has one small opening of 0.25 m diameter for smoke outlet just above the cook stove and doors are not air tight. T3 house has no opening except one door. In T3 house, two elderly people lived and kept fire in the stove for boiling water.

The walls of S1 house is made of wood panels having small vertical gaps in between. S2 house is made of loosely woven bamboo strips with thin cement plaster on both sides. The wall of S3 house was made of bricks with cement plaster. S1 and S2 houses have 0.54 m^2 and S3 house has 1.25 m^2 sized window.

(a)



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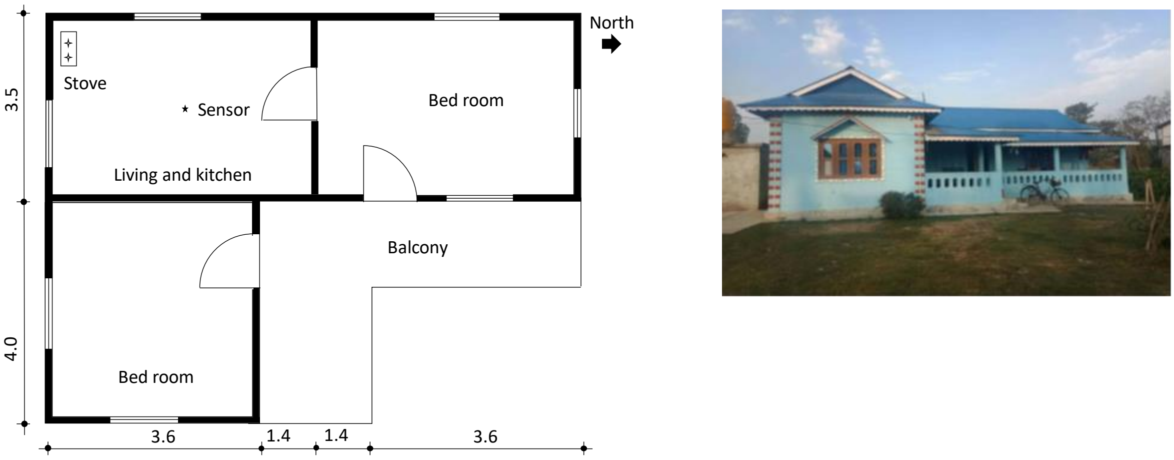


(c)

Figure 2.3 Ground floor plan view and the exterior look of investigated three houses in three climatic regions: (a) cold, (b) temperate and (c) sub-tropical (Dimensions are in meter)

2.2.4 Plan and sectional view

Figure 2.3 shows the plan and sectional view of the investigated households in three climatic regions. Households in cold and temperate regions were constructed to minimize the cold effect of outdoor environmental conditions while houses in sub-tropical regions were constructed to minimize the effect of sever hot.

2.2.5 Thermal environmental survey

Indoor air temperature and relative humidity were measured at 10-minute intervals with the respective sensors with electronic data loggers. The sensors used have the accuracy of temperature at ±0.5 °C and relative humidity at ±5%. The devices for measuring indoor air temperature and relative humidity were placed 1.1 m above the floor surface in the center of main living and kitchen room of all investigated houses as indicated in **Fig. 2.3** Outdoor air temperature and relative humidity were measured with the same instruments as ones for indoors at the same height in the balcony area of C1, T1 and S1 house. These values were considered to represent the outdoor values for other houses in each region. At first, we installed the instruments in sub-tropical region and performed thermal environmental survey. Then we did similar survey in temperate region by using another set of instruments and finally, we went to the cold region for the survey with same instruments which was used in temperate region. Hence, in this study, as mentioned in **Table 2.1** data corresponding to cold and sub-tropical region were analyzed for same period but quite earlier for temperate region. This measurement was carried out for five days in all regions.

Fig 2.4 Instruments used to measure thermal environmental parameters in study area

Indoor and outdoor water vapour concentration was calculated by the following formula (Shukuya M.; 2019):

$$Cwv = 1000 \text{ X } \left(\frac{\text{Mw}}{R}\right) \frac{\text{Pv}}{T} \qquad (2.1)$$

Where *Cwv* is the water vapour concentration [g/m^3], *Mw* is molar mass of water which is 18.015 X 10^{-3} kg/mol], *R* is gas constant which is 8.314J/ (mol. K)], *Pv* is water-vapour pressure [pa] calculated from the relative humidity [%] and saturated water vapour pressure [pa] and *T* is temperature [K]. As the water vapour concentration [g/m^3] and humidity ratio or specific humidity [g/kg (DA)] are proportional and thus we used water vapour concentration because it is easy to compare in buildings having different volume.

Figure 2.5 shows the heating devices and improved cooking stoves used in cold region, which was found during the field survey. Mechanical heating and cooling devices were not found in all investigated houses during our field study. The main source of heat for space heating was firewood burning during cooking activities inside the houses in all regions. However, two households: one from cold region and the other from temperate region, in which elderly people live, burn firewood for the whole days in the survey period.

(a) (b) (c)

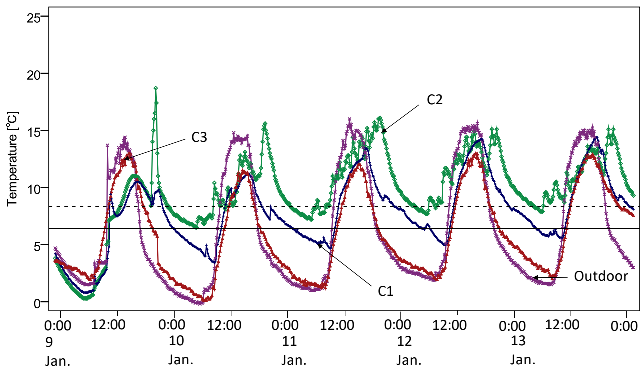
Figure 2.5 Heating device and cooking stoves: (a) firewood-burning room heater used in cold region, (b) improved cooking stove found in cold region and (c) traditional cooking stove used in temperate region.

2.3 Variation of indoor and outdoor air temperature

Figure 2.6 shows the indoor and outdoor air temperature variations of respective investigated houses for five days. In each graph, horizontally drawn solid line represents the daily mean outdoor air temperature, and dashed line represent the daily mean indoor air temperature. The variation of indoor air temperature relative to the corresponding outdoor air temperature is sharper in cold and temperate regions than in sub-tropical region. During the period of this series of measurement, outdoor air temperature in cold region ranged from -0.2 to 16.0 °C with the average of 6.4 °C. While those of temperate region ranged from 4.1 to 22.1 °C with the average of 10.5 °C and in sub-tropical ranged from 5.5 to 21.5 °C with the average of 11.7 °C, respectively. The average measured indoor air temperature was 8.0 °C, 13.9 °C, 12.8 °C and the lowest value of indoor air temperature was 0.1 °C,6.5 °C, 5.9 °C respectively, in cold, temperate and sub-tropical regions.

Among three houses in cold region, C2 had high, C1 had medium and C3 had low indoor air temperature on average. Building envelope characteristics, the rate of energy use and the number of occupants must have affected the difference in indoor air temperature. In the case of C3, one of the major causes of low indoor temperature was considered due to the lack of proper sealing for the frame of door, window and ceilings to reduce infiltration. On the other hand, C2 was observed to have better insulation by moderately air-tight doors and windows. This is probably why C2 had higher temperature than other two houses in cold region.

Among three houses in temperate region, T3 shows the highest, T1 medium and T2 the lowest indoor air temperature. As shown in **Table 2.2**, T2 has larger floor area than other two houses and the frames of windows and doors are not air-tight; therefore, this could result in the lowest indoor air temperature in T2. T3 had narrow and small space without windows and other openings except some gaps in the ceiling; this house probably causes the highest indoor air temperature. The major cause of high indoor air temperature in T3 especially during night time must be the use of firewood for all day long as mentioned in the previous section.



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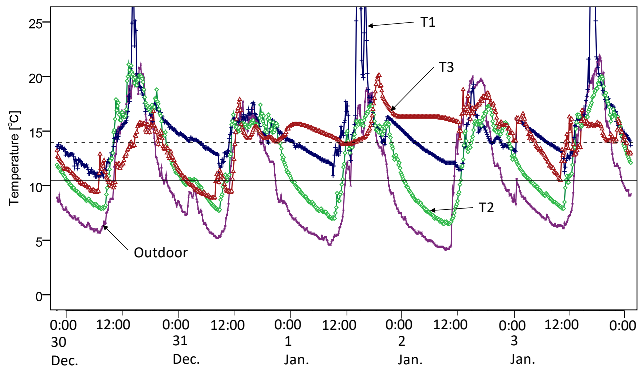

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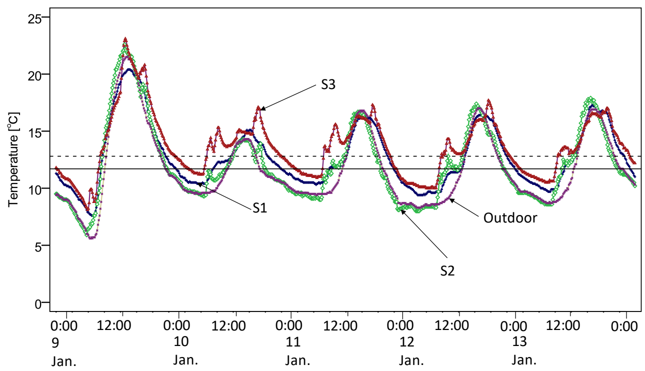


(c)

Figure 2.6 Indoor and outdoor temperature variation during field survey; (a) cold region, (b) temperate region, and (c) sub-tropical region.

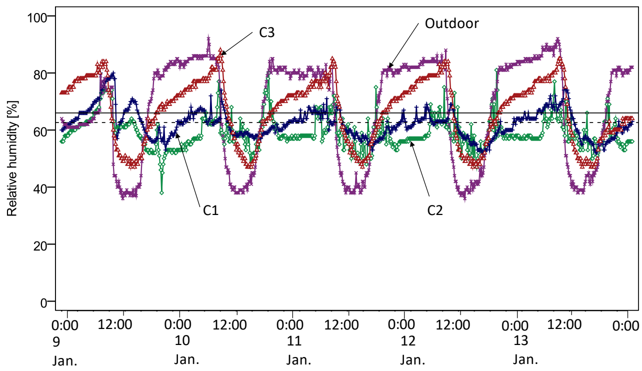
In T3 two elderly persons were living and we observed that they frequently had hot tea so that it is reasonable to speculate that they keep fire in the stove for all day long.

Previous researchers also found that older people are less sensitive to low humidity and normally prefer 2 °C warmer environment in winter compared to young age people (Boerstra et al.; 2015, Vecchi et al.; 2015, Joshi and Bohara; 2017). T1 had medium sized floor area and had only one small sized opening for smoke outlet. People living in T1 were observed keeping the door closed; for this reason, the indoor air temperature must have not dropped down to the values of outdoor air temperature.

In the investigated houses in sub-tropical region, indoor air temperature variations are quite similar to that of outdoor air temperature. This is probably due to the ventilation effect. As shown in **Table 2.2**, in sub-tropical region comparatively larger sized windows were observed than other two regions. S3 showed the highest indoor air temperature than other two, S1 and S2. S3 has brick walls with cement plaster. These thermally heavy material, may have caused the higher level of indoor air temperature than S1 and S2.

2.4 Variation of relative humidity and water vapor concentration

Figure 2.7 shows the variation of relative humidity and water vapour concentration during the five-day measurement in three climatic regions. Here also, horizontally drawn solid line in each graph represents daily mean outdoor value of relative humidity and water vapour concentration, and dashed line represent the daily mean indoor value of relative humidity and water vapour concentration. Indoor and outdoor water vapour concentration was calculated from air temperature and relative humidity (Shukuya M.; 2019). Outdoor relative humidity in sub-tropical region is high and that in cold region is low. The average value of outdoor relativity humidity was 66, 76 and 88% in cold, temperate and sub-tropical regions, respectively. The fluctuation of indoor and outdoor relative humidity in cold and temperate region is larger than that in sub-tropical region. This is considered due to the air temperature variation. Addition of moisture inside the room for cooking and occupants’ breathing must have influenced on the variation of relative humidity. As shown in **Fig. 2.7**, the small difference in air temperature between outdoors and indoors was considered due to much of infiltration and ventilation in the sub-tropical houses. Similar trend was observed in terms of relative humidity. In residential buildings, the acceptable relative humidity is known to be above 30% in winter and lower than 70% in summer (Yu et al.; 2017). The measured relative humidity in the houses measured was all higher than 40%. Yu et al. (2017) reported that the low indoor relative humidity has negative impact on thermal comfort of the occupant. In this respect, those measured houses satisfy the requirement.



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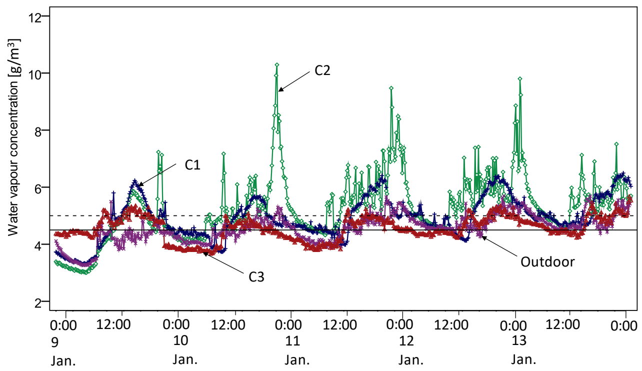

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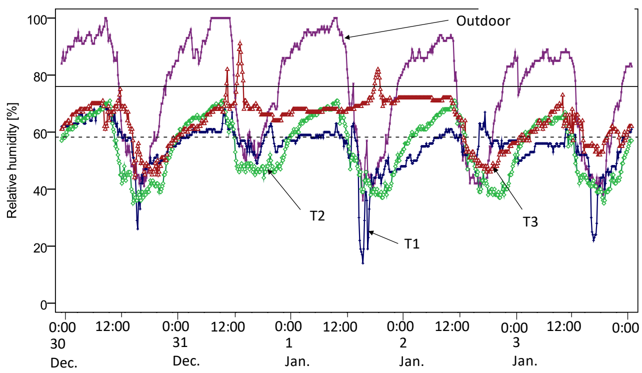

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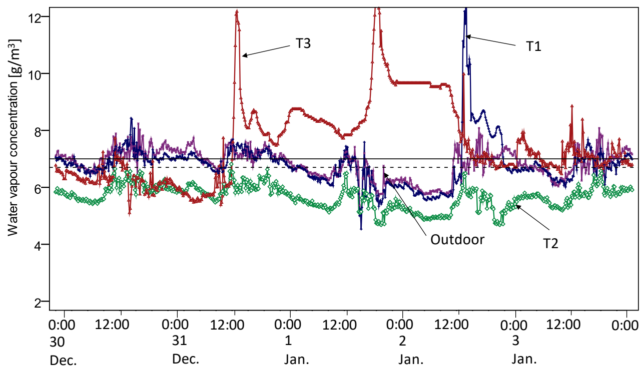

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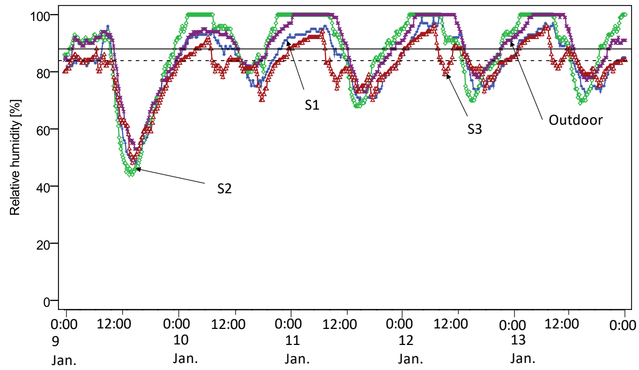

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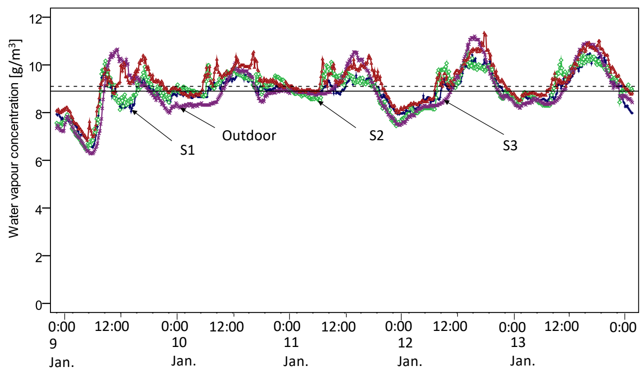


(f)

Figure 2.7 Variation of relative humidity and water vapour concentration in three regions: (a, b) in cold, (c, d) in temperate and (e, f) in sub-tropical

Mean outdoor water vapour concentration was found as 4.6, 7.0 and 8.9 g/m3 in cold, temperate and sub-tropical region, respectively. Cold region is much drier than sub-tropical region. The variation of water vapour concentration in the measured three houses look quite different.

Among three houses in cold region, C2 shows a sharp variation in water vapour concentration. Its major cause is considered due to the addition of moisture during tea making. In C2 people gathered and used to drink hot tea during daytime and due to that water boiling process, water vapour concentration was kept at high level.

In temperate region, T3 shows a sharp variation of water vapour concentration than other two houses. No window and water boiling activity must be the main cause of high indoor water vapour concentration in T3. T2 shows the lowest water vapour concentration than other houses and even lower than outdoor water vapour concentration. Indoor water vapour concentration can be lower than outdoor water vapour concentration only by a kind of dehumidification process but in that house, there was no mechanical system for dehumidification. Therefore, only a possible reason is moisture absorption by building walls but so far, we cannot confirm whether it is likely or not because of the limitation of information to be available for a further discussion.

The variation of indoor water vapour concentration is very similar to that of outdoor water vapour concentration in sub-tropical houses. This suggests that there may be a significant ventilation effect, but no similarity can be seen with respect to temperature shown in **Fig. 2.7** In sub-tropical houses, the exchange of water vapour between indoors and outdoors is easily made due to comparatively large windows. Therefore, the variation of indoor water vapour concentration in all house shows similar trends of outdoor water vapour concentration.

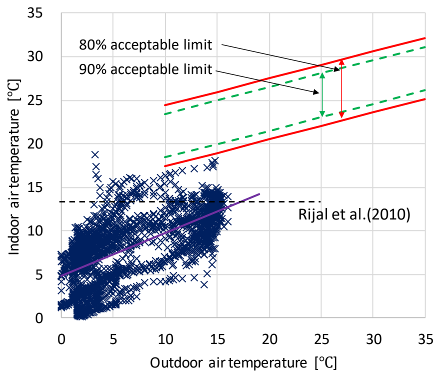
2.5 Comparison of measured temperature with comfort temperature standards

In **Figure2.8**, all measured temperatures were plotted with the comfort band of ASHRAE standard. The solid parallel lines represent the 80% acceptability range and dashed parallel lines represent the 90% acceptability range. The horizontal dotted line represents the comfort temperature of respective region and solid line represents the regression line of respective three regions (Rijal et al.; 2010).

Here we examined indoor air temperature of investigated buildings with corresponding outdoor air temperature so as to be compared with one of the comfort-temperature standards (ASHRAE-55), which presents comfort temperature as a function of the prevailing outdoor temperature for naturally ventilated room space (Rijal, 2012, Jin et al.; 2020).

Many previous studies found that the comfort temperatures are highly correlated with indoor operative temperature measured during voting time. (Rijal et al.; 2010, Humphreys et al. 2013, Humphreys et al. 2019, Indraganti et al.; 2015, Gautam et al.; 2019). According to adaptive comfort principal, people tend to adjust their clothing, posture etc. and environment to become comfortable at the temperature they typically encounter and this process tend to make their comfort temperature close to the mean temperature they experience (Humphreys et al. 2013). Thus, measured indoor air temperature must be one of the indicators to evaluate the thermal comfort in buildings. In this study, we did not conduct the thermal comfort survey and therefore we have compared measured indoor air temperature of investigated buildings with ASHRAE-55 comfort band, and comfort temperature of respective three regions which was found by Rijal et al. (2010), to evaluate whether the indoor temperatures of investigated buildings are within the comfortable range or not. According to this study comfort temperature in winter season was 13.4, 18 and 16.2°C in cold, temperate and sub-tropical region respectively.

In cold region, the indoor temperatures span from 0 °C to nearly 17 °C and they are below the comfort band of ASHRAE standard and about 5% plots are above the neutral temperature of cold region. In temperate region, the majority of indoor temperatures span from 6 to 20 °C. and about 2%plots are inside or above the comfort band. Here also about 5% data are above the neutral temperature of that region. Similar to the temperate region, in the sub-tropical region, indoor temperatures span from around 6 °C to nearly 22 °C and only about 2% of the data are distributed within the comfort band and 5% data are above the neutral temperature of that region. It shows that, in all of the investigated houses, the indoor air temperature maintained far below the lower limit of acceptable comfort temperature range of ASHRAE-55 standard and about 95% of plots are below the neutral temperature of respective regions.



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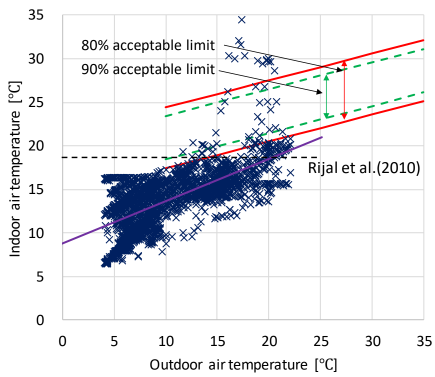

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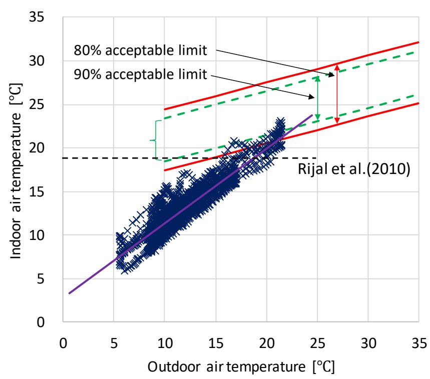


(c)

Figure 2.8 Comparison of indoor air temperature measured with ASHRAE adaptive-comfort standards and neutral temperatures in respective regions: (a), cold, (b) temperate and (c) sub-tropical regions.

Heraceleous and Michael (2020) have used operative temperatures for thermal comfort assessment of school buildings of East-Mediterranean region and concluded all classrooms are below thermal comfort limit. Tuck et al.; 2019 have also compared operative temperatures of different ventilation approaches with related international comfort standards. The method applied for the comfort assessment of investigated buildings in this study are similar with above mentioned studies (Heracleous and Michael; 2020, Tuck et al.; 2019).

To know the influence of outdoor air temperature to the indoor air temperature in three regions, we have carried out a regression analysis on indoor and outdoor air temperatures and we obtained the following equations for cold, temperate and sub-tropical regions, respectively.

Cold: T_i=0.49T_o+4.8 (n=2160, R^2=0.43, S.E.= 0.012, P< 0.001) (2.2)

Temperate: T_i=0.45T_o+9.1(n=2160, R^2=0.41, S.E.=0.012, P<0.001) (2.3)

Sub-tropical: T_i=0.86T_o+2.8(n=2160, R^2=0.86, S.E.=0.012, P<0.001) (2.4)

where T_i and T_o are indoor and outdoor air temperature, R^2 is coefficient of determination, S.E. is the standard error for the regression coefficient and p is the level of significance for the regression coefficient for respective three regions. Regression lines of respective regions are also presented in Figure **2.7** The slope obtained for cold region is quite similar to that obtained for temperate region. This is probably due to the similarity of thermal mass of the houses in cold and temperate region. The slope of sub-tropical region is sharper than other two regions and the difference in air temperature between indoors and outdoors is the least among three regions. This is due to small thermal mass of the houses and much of the ventilation effect in sub-tropical houses. Among the investigated houses in three regions, a rather strong relationship (r=0.93) can be seen in sub-tropical region. It shows that indoor thermal environments are much sensitive and indoor and outdoor air temperature are closely equal to each other in sub-tropical houses.

2.6 Relationship between indoor and outdoor air temperature

Fig. 2.9 shows the relationship between indoor air temperature and outdoor air temperature of three investigated households for all 5 days in winter. The indoor air temperatures for all households are highly dependent on outdoor air temperature. The reasons for this, these investigated households were not properly made to protect the outdoor thermal influences through infiltration of the outdoor air.

Cold $T_i = 0.50T_o+4.83$ (N= 2160, $R^2= 0.888$, S.E.= 0.003, $p<0.001$) (2.5)

Temperate $T_i = 1.00T_o-2.19$ (N= 2160, $R^2= 0.692$, S.E.= 0.007, $p<0.001$) (2.6)

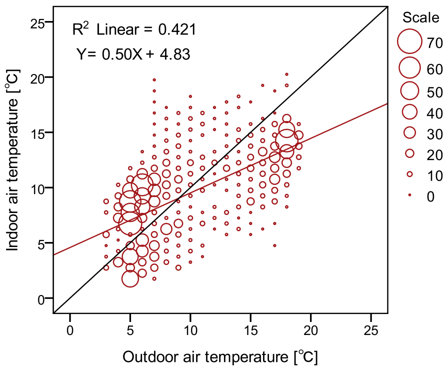
Sub-tropical $T_i = 0.91T_o-2.16$ (N= 2160, $R^2= 0.783$, S.E.= 0.010, $p<0.001$) (2.7)

N: number of samples, R^2: coefficient of determination, S.E.: standard error of the regression coefficient, p: significance level of the regression coefficient.

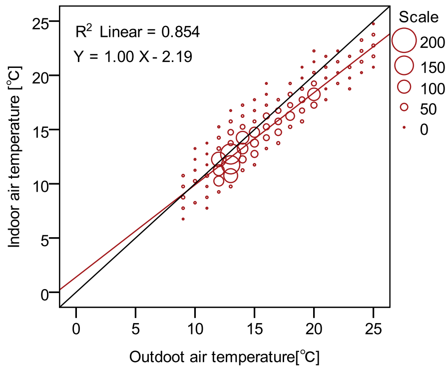
2.7 Relationship between outdoor air temperature and firewood use

This study examined the relationship between outdoor air temperature and firewood used in three climatic regions. **Figure 2.10** demonstrates the relationship between firewood use per floor area and outdoor air temperature at 6:00; the plots are from the measured 15 houses for five days (n= 75). For this analysis we took outdoor air temperature as independent variable and firewood use per floor area as a dependent variable.

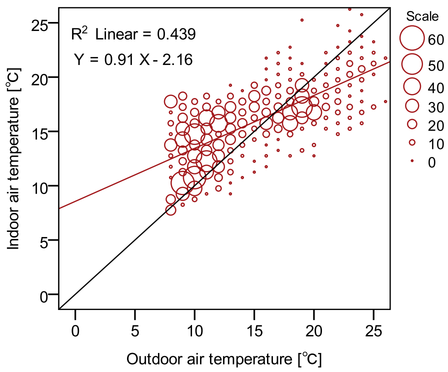
The cold region shows the highest firewood use per floor area due to lowest outdoor air temperature. The temperate region also shows higher value than sub-tropical region due to the comparatively low outdoor air temperature than sub-tropical region. Lower firewood use per floor area was investigated in the case of high outdoor air temperature, while the use of firewood tends to increase for space heating as the outdoor air temperature decreases. There are, of course, consistent with what was described with respect to Fig. 10. As assumed in the discussion with Fig. 10, if firewood use for space heating is negligibly small, we come to know that no heating is made in the case of outdoor air temperature early in the morning (at 6:30) being 12 to 14°C. The correlation coefficient was found -0.68; this indicates that there is a negatively linear relationship between firewood use per floor area and outdoor air temperature. Hu et al. (2018) also found that the temperature difference in residential buildings are associated with energy use. sub-tropical region.



(a)



(b)



(c)

Figure 2.9 Relationship between indoor and outdoor air temperature: (a), cold, (b) temperate and (c) sub-tropical regions.

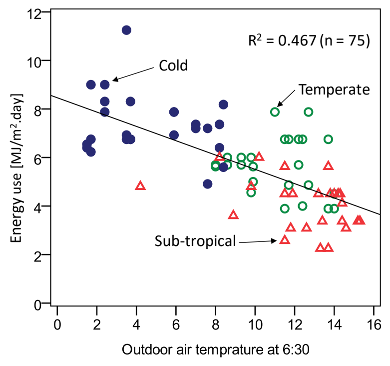


Figure 2.10 Relationship between outdoor air temperature and firewood use per floor area in three regions

2.8 Conclusions

How the household energy use is related to the indoor thermal environment of residential buildings in developing countries has not yet been known very well so that it is important to clarify this relationship in order to draw the future consideration about energy saving policy in developing countries such as Nepal. As the results of our survey and the follow-up analyses made on the current situation in Nepal, the followings were found:

1. Indoor air temperature of all studied households in three regions were below ASHRAE comfort standard.
2. The daily average regional household energy-use patterns in winter season are influenced by regional outdoor climatic conditions: high per-floor firewood energy use in cold region, medium in temperate region and low in sub-tropical region was found as household energy use.
3. Outdoor climatic condition has a strong influence on indoor thermal environment and it is associated with household energy use patterns. Intensive improvements of existing building envelopes should be performed for providing people with better indoor thermal environment while optimizing the household energy use.

Chapter 3: Household Energy Use

3.1 Variation of household energy use in three climatic regions

3.1.1 Introduction

Nepal is one of the low per-capita energies using country among contemporary global societies and it has no known deposits of oil, gas, or coal except for some lignite deposits. Biomass, oil products, coal, hydro, and electricity are its main sources of primary energy. Among these, biomass, in the form of firewood, agricultural waste, and animal dung, has consistently dominated supply because of the lack of other alternative energy sources and the poor state of the economy, particularly in the rural areas. The largest share of energy consumption goes to the residential sector. The share of industry and transport is now small, but these sectors are growing fast. From 1990 to 2014, total final energy consumption rose from 106 kilotons of oil equivalent (ktoe) to 665 ktoe for the industry sector, and from 111 ktoe to 858 ktoe for the transport sector. Nepal is richly endowed with renewable energy resources, comprising hydropower, solar, wind, biogas, and various forms of biomass energy. As of 2013, around 12% of the population had access to electricity through renewable energy sources. Around 23 MW of electricity generation came from micro hydro schemes, 12 MW from solar photovoltaic (PV) systems, and less than 20 kilowatts (kW) from wind energy.

Nepal should transform its energy supply system into a more sustainable system using clean and renewable energy resources. Energy statistics are the foundation for developing sound national energy policies as they reveal where interventions and improvements are required and what opportunities are available. However, in the context of Nepal, there are not sufficient research on energy balance and energy use pattern due to the lack of appropriate data. Therefore, the result of different research does not match each other which make difficult to conclude best decision for good energy policy in national level as well as regional level. Access to clean cooking fuels is essential for generating human well-beings of the society, as it enables a variety of improvements for the better quality of life (Kurniawan et al.; 2018). Enormous potential of renewable energy resources of the country such as; hydropower, solar power and wind power could be utilized for the betterment of the living condition of the people through clean energy development, however, due to economic and other social constrains most of these resources have remained underutilized and thus, large number of households have to rely on traditional fuels (Islar et al.; 2017 and Ghimire et al.; 2018). About 70% of the total households including urban and rural areas and 90% of the rural households in Nepal depend primarily on the traditional cooking fuels for daily cooking activities (CBS-Nepal, 2011). Due to high cost and limited supply of commercial fuels, 80% of rural people in Nepal still rely on traditional fuels like firewood, agricultural residue and animal dungs for cooking and space heating (Webb and Dhakal; 2011, Pokharel et al.; 2019, Rijal et al.; 2010). Suitable design of buildings under local climate into consideration, the use of renewable energy and the use of locally available materials for the construction of residential buildings to achieve better indoor thermal environment with low energy use and hence low CO_2 emission has become on focus in recent years (Walker and Pavia; 2018, Fuller et al.; 2009, Susanne et al.; 2014)

3.1.1.1 Literature review

With respect to Nepal, only a few pieces of literature are available on indoor thermal environment and domestic energy use. Rijal et al. (2010) carried out field measurement on indoor thermal environment and found significant difference in the relationship between room air temperature and estimated neutral temperature for a couple of regions in Nepal. Fuller et al. (2009) also conducted a field measurement in a traditional house in Simikot, the northwest of Nepal and found that indoor temperature was far below the lowest value of internationally recognized acceptable temperature. Susanne et al. (2014) analyzed a variety of vernacular houses located in different climatic regions to identify the applied climate responsive design strategies and concluded that they have widely been used passive solar design strategies in all regions in Nepal. Chu et al. (2017) introduced

Ondol, a traditional Korean heating system with firewood use, in a southern village of Nepal and investigated the possibility for the improvements of indoor thermal environment. Field studies on vernacular architecture, thermal performance of typical vernacular buildings and thermal comfort in existing residential buildings in India have been undertaken by Singh et al. (2009, 2010, 2016). Some other investigations on indoor thermal environment and thermal performance of residential buildings in diverse climatic regions provides detailed literature review together with thermal environments of other countries (Li et al.; 2019, Song et al.; 2019, Li et al.; 2018, Porcaro et al., 2019, Yu et al.; 2017). Malla (2013) carried out a household energy-use research in Nepal and found energy use is heterogeneous across the regions and biomass dominates the countries' energy use. An intensive investigation in different climatic regions in mountain village of India has identified the altitudinal difference in firewood use (Bhatta and Sachan; 2004).

The need to understand how buildings are operated with energy availability is important while improving indoor thermal environmental quality, not just for occupants but also for building designers and policy makers to minimize the residential energy use, since the improvement of residential buildings can have a vital impact both on indoor thermal environment and on the whole of energy use. Therefore, it is necessary to conduct research aiming to get a better quantitative knowledge on the current situation of energy use and its relation to the indoor thermal environment under a variety of outdoor environmental conditions in Nepal.

3.1.1.2 Objectives

The main objective of this research is to identify how the households in different climatic regions in Nepal have been operated to achieve indoor thermal environment under the use of available energy resources. This paper identifies the current energy use patterns and factors affecting household energy consumption in three climatic regions.

3.1.2 Materials and methods

3.1.2.1 Study area and climate

Nepal is a small, landlocked, and developing country situated between 26º and 30º north latitude, and between 80º and 88º east longitude. It covers an area of about 147 km^2. The altitude ranges from less than 100 meters above sea level to 8,848 meters at the highest point on earth—Mt. Everest, where the climate varies from subtropical to arctic. The population, 28.5 million in 2015, about 50% of the total is in the low-lying Terai region in the south, about 43% in the mid-hill region running east to west in the central part of the country, and the remaining 7% in the high-altitude Himalayan region.

Field studies for household energy use survey represents cold, temperate and sub-tropical regions in Nepal. To capture a variation in geographical condition, population demographics, socioeconomics and local cultures, we have selected three non-adjoining districts viz. Solukhumbu (cold), Panchthar (temperate) and Jhapa (sub-tropical). Within these districts the altitude ranges from approximately 60m above the sea level in the southern terai region to the highest peak 8848 m, the Mount Everest in the north region. **Table 3.1** presents the physical and demographic characteristics of the study area.

Table 3.1 Demographic and physical characteristics of the study area

Study area (district)	Area (Km^2)	Climate	Population (individual)	Population density (individual/Km^2)	Access to grid electricity	Access to black topped road
Solukhumbu	3312	Cold	105,885	39	no	yes
Panchthar	1241	Temperate	191,817	150	yes	yes
Jhapa	1606	Sub-tropical	812,650	510	yes	yes

Solukhumbu is the northern mountainous district, with Salleri as its headquarters lies with an altitude of 2413m from the sea level. It covers an area of 3312 km^2 and most of the area represents cold climatic features. Population density of this district was lowest among three study area and total population was 105,886 according to the national census 2011. Sherpa and Rai are the indigenous ethnic cast living in that area. Panchthar district lies in the hill region in between northern mountain and southern terai region. Phidim is headquarter lies with an altitude of 1276m from the sea level. It covers an area of 1241 km^2 and it is dominated by temperate climate. The population density of this district was $150/m^2$ and the total population was 191,817 in 2011. Limbu, Gurung and Rai are the indigenous ethnic cast living in that area. Jhapa is the southern terai region having plain and fertile land. It covers 1606 km^2 area and dominated by sub-tropical climate. The population and population density of this district was highest among three districts. From these three districts, we have further selected three municipalities; Solududkunda, Phidim and Gauradaha for household energy use survey.

3.1.2.2 Selection of households to be studied

To ascertain the household energy use pattern in three regions, Household energy-use survey was carried out from 516 households comprising 76 households in cold, 262 in temperate and 178 households in sub-tropical region. Out of these houses, to calculate firewood use more precisely, five houses from each region were selected for firewood use measurements and from these five houses from each region, three houses were selected for thermal environmental measurement. Due to the similarity of the existing buildings in three regions and availability of limited number of instruments, we have chosen only three houses from each region for measurements. All these houses had constructed by local skillful craftsmen with locally available materials with the construction methods inherited from previous generations. **Table 3.1** shows the survey period and the numbers of house for energy use survey.

3.1.2.3 Energy use survey

To estimate the firewood used in households we used two methods. One is questionnaire that was to ask people to answer the firewood use from each of 516 households. We assumed that all stated amount of firewood was used for cooking, space heating and other miscellaneous use. The other method taken is actual firewood use measurement. From five households in each district we measured the weight of firewood for five days.

Estimation of household energy use

To estimate the firewood used in the households we used two methods. One is questionnaire that was to ask people to answer the firewood use from each of 516 households. All bioenergy used in these households were considered as firewood. People used firewood, agricultural residues such as branches and twigs to fulfill their energy need. We assumed that all stated amount of firewood was used for cooking, space heating and other miscellaneous use. The other method taken is actual firewood use measurement. From five households in each district we measured the weight of firewood for five days. This process was carried out as follows (Bhatta et al.; 1994, Fox, 1984). First, we measure the weight of air-dried firewood bundle ready for use with spring balance and left them in the kitchen of each household and instruct the household members to burn firewood only from these weighted bundles. On the next day the remaining bundles of firewood were weighted and the difference in the weights between the previous day and the present day was taken to be the weight of burnt firewood.

To estimate household electricity use, we used monthly electricity utility bills provided by the local electricity authority in kWh/ (household. month). Then we have converted them into the unit of MJ/ (household. day). For the LPG use, we asked the duration of one LPG cylinder lasting for their family during the questionnaire survey. In Nepal, metallic cylinder containing 13.4 kg of LPG fuel are available in grocery stores. From this specific weight and the duration of one cylinder lasting for one family, we calculated the LPG use assuming that thermal energy to be released is 48MJ/kg (Fox, 1984).

3.1.3 Accessibility of energy sources

Energy access is one of the basic issues of rural areas and is a key to socioeconomic progress for developing nations (Das et al., 2018). In rural area, it is not always possible to provide continuous supply of clean commercial energy and bioenergy can serve as the primary source of energy which are locally available independent and decentralized energy source for the rural people. Firewood and agricultural residue are the essential household energy source for cooking, for water and space heating, for cooking feed for livestock and for rice beer preparation in rural areas in Nepal. **Figure 3.1** presents four energy sources for households in three climatic regions. The vertical axis shows the number of households investigated in respective regions and the horizontal axis shows the percentage of those households using respective kinds of fuel: firewood, LPG, grid electricity and other electricity.

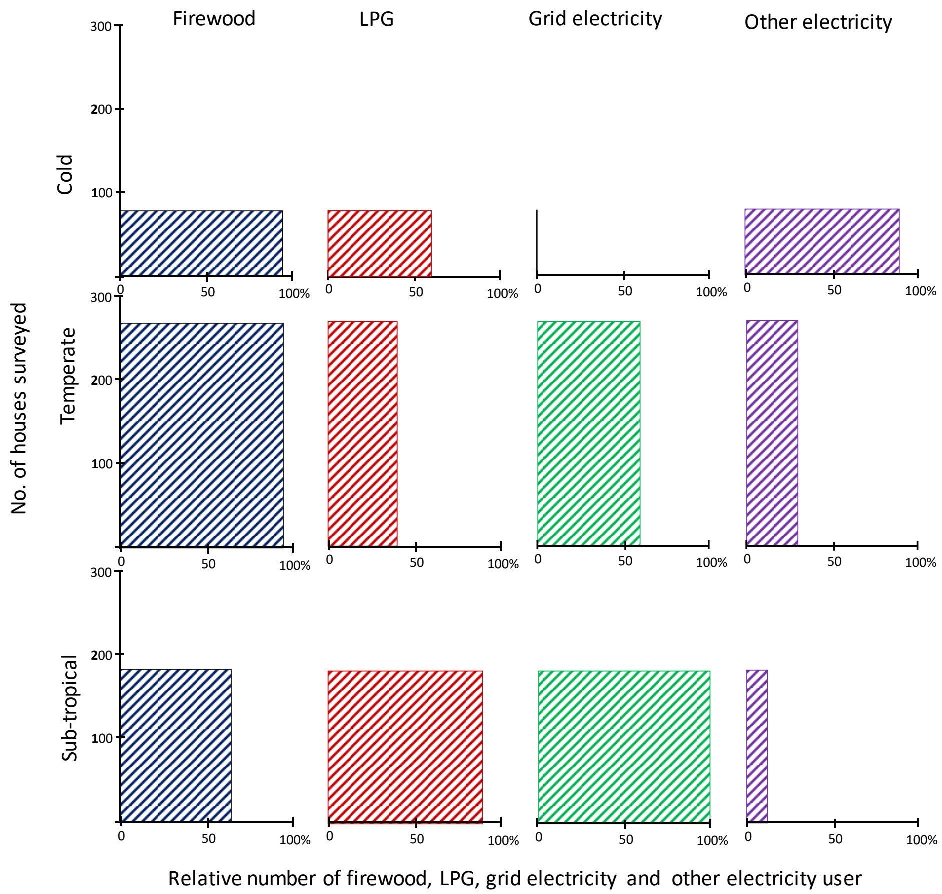


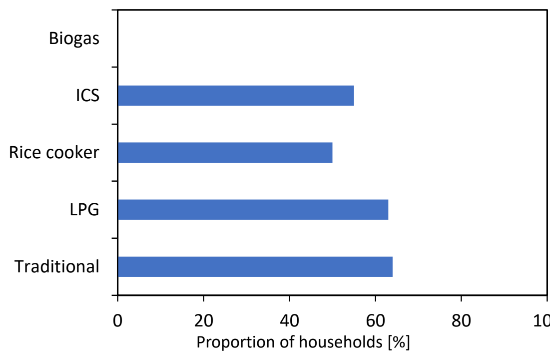
Figure 3.1 Share of Firewood, LPG, grid electricity and non-grid electricity used as household energy sources in three regions.

All houses use more than one kind of fuels. Firewood is the first common energy source in all regions. The LPG is the second most energy sources; 60, 40 and 90% of total surveyed households in cold, temperate and sub-tropical regions use LPG. It is mainly for cooking purpose. The source of electricity is either from grid electricity or from other sources. In this study, other source includes stand-alone photovoltaic panels and micro hydro-electric power plants. The houses of 90% surveyed in cold regions are connected to the electricity generated from micro hydro-electric power plants or photovoltaic panels. No households in cold region are connected to the grid electricity. In temperate region, it was 60% and in sub-tropical region it was 100%. Comparing the three regions with respect to electricity source, the more use of grid electricity, the less use of other electricity.

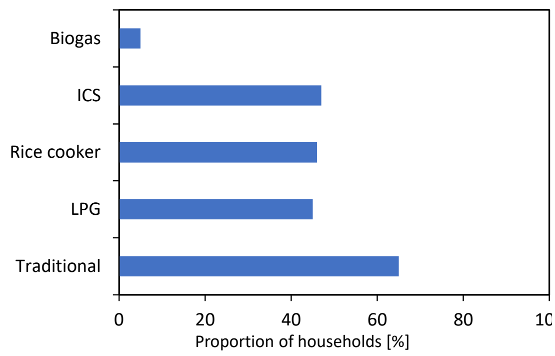
Firewood was mainly used for cooking and space heating. During cooking process with firewood, the flame of firewood, heated stove and oven emit thermal radiation to the surrounding indoor environmental space; this helps to improve the indoor thermal environment. Generally, before and after cooking meal, firewood is used for boiling water and improve indoor thermal environment in cold and temperate regions. LPG is also used for cooking purpose. Economically affordable households use LPG as their regular cooking fuel, while other households use it occasionally to perform cooking activities. The use of LPG lets the length of cooking time shorter. Electricity is mainly used for lighting and for electrical appliances such as cell phone, radio and TV sets.

3.1.4 Kitchen characteristics and types of cook stoves used

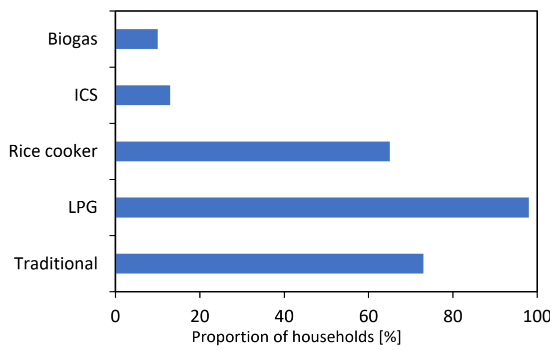
Kitchen characteristics and the type of cook stove used are important factors to determine the indoor air quality (Ravindra et al. 2019). In this study 45% households had kitchen separated from the main living house, while the remaining 55% had the kitchen inside their living house, located at the corner of the big common room in the ground floor. Inhabitants in the study area used wide range of cook stoves for cooking. For example, in some houses they used outdoor three stone stoves for making animal feed, indoor traditional cook stoves for regular cooking purpose, LPG stoves for occasional cooking and rice cooker for making rice when electricity is available. Various improved cook stoves have been developed and distributed by national and international agencies to minimize the health burden of the people. Most of these improved cook stoves, particularly in cold and temperate region had been constructed with a short and attached chimney for the shake of the extraction of the smoke from indoor environment while households having only traditional cook stove had not been installed the chimney.



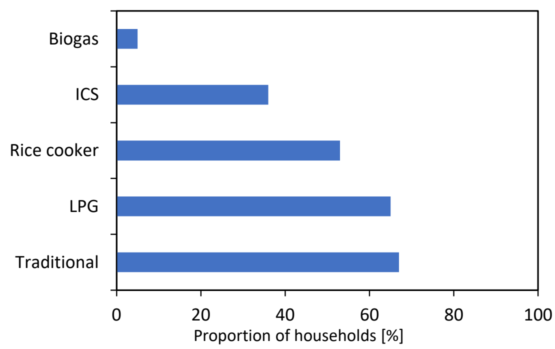
(a) Cold region



(b) Temperate region



(c) sub-tropical region



(d) Average

Figure 3.2 Availability of cooking stoves in study area; (a) Cold region, (b) Temperate region, (c) sub-tropical region and (d) Average

Figure 3.2 shows the proportion of different types of cook stoves used in the study area. It shows that the most popular cook stove available in all region was traditional cook stove followed by LPG stove. The biogas cook stove had a small share and it was not observed in cold region. This result also shows that proportion of ICS using households are highest in cold region and lowest in sub-tropical region. The result seems reasonable because in the cold region due to lack of reliable clean cooking fuels and grid electricity, many governmental agencies and non-governmental organizations were promoting ICS as a clean cooking technology. However, easy access to grid electricity and easy availability of LPG near to the house in sub-tropical region, people are less interested to install ICS. But they prefer to use LPG and electricity as clean cooking fuel therefore the proportion of the households that have LPG was found nearly about 100% in sub-tropical region.

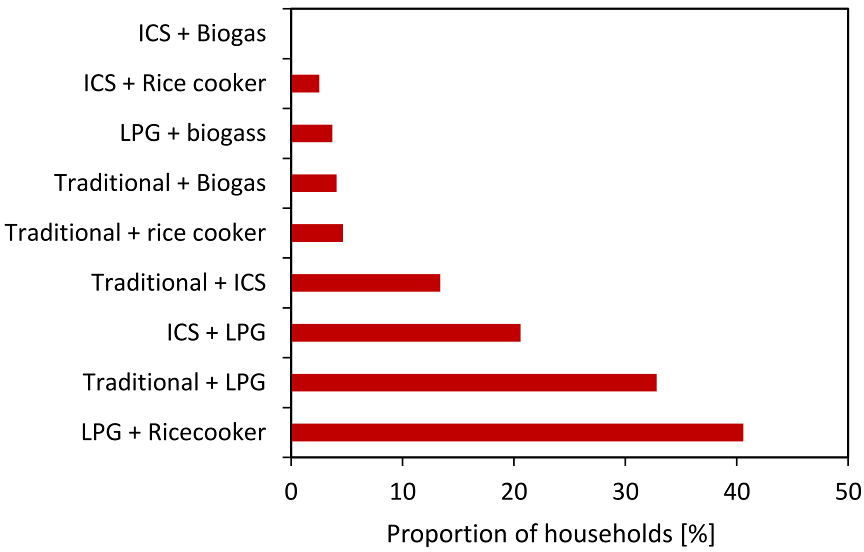


Figure 3.3 Combinations of different cooking stoves used in study area

People living in all regions used multiple fuels and respective type of cook stove to fulfill their energy demand. **Figure 3.3** shows the number of households having different combinations of cook stoves in investigated area. The most popular combination was LPG stoves and electric rice cooker in 44% of households, followed by traditional and LPG in 33% households. Nearly 25% households used only traditional cook stoves and 8% households used cook stoves for commercial fuels like LPG and electric rice cooker while other remaining households in the study area used different combination of cook stoves. The highest proportion of the combination of clean cook stoves like LPG and rice cooker revels that more people are preferring clean cooking fuels in the study area.

3.1.5 Firewood use and family size

Figure 3.4 indicates daily average firewood use per household. The vertical axis represents the daily firewood use in the unit of kg per family and the horizontal axis the number of household members. The dashed straight lines represent the relationship between the number of household members and the daily household firewood use in respective regions. The slopes of these lines correspond to per-capita firewood use. The number of household members ranges from two to seven. The greater the family size, the larger the household firewood use, but the quantity of household firewood use differs from one region to another. The slope value decreases from cold via temperate to sub-tropical region.

Figure 3.5 shows the per-capita firewood use calculated for each house investigated. Closed circles represent average value of each household with 95% confident interval (average ± 2 S.E.). As already stated with **Figure 3.4**, the per-capita firewood use is high in cold region, medium in temperate region and low in sub-tropical region. The average per-capita firewood uses are 1.7, 1.2, 1.0 kg, respectively.

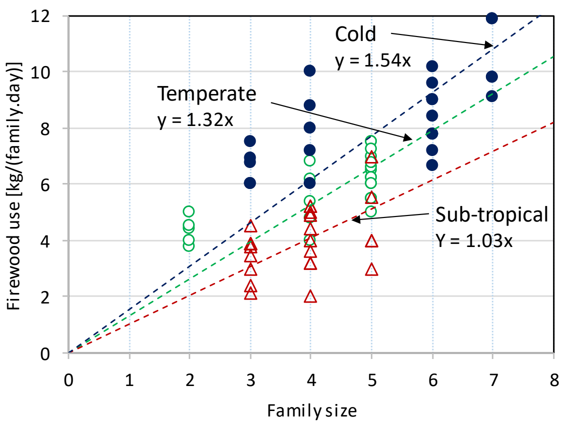


Figure 3.4 Household firewood use obtained from physical measurement

People living in cold region use more firewood than people living in temperate and sub-tropical regions. The cause of more firewood use in cold region is the need of firewood to boil water for cooking and also to keep indoor thermal environment as much as possible in winter season, but as shown in **Figure 2.6**, the realized indoor air temperature in cold reason remains very low. The low firewood use in the sub-tropical region compared to other two regions must be due to the favorable indoor temperature realized due to the average outdoor air temperature higher than other two regions.

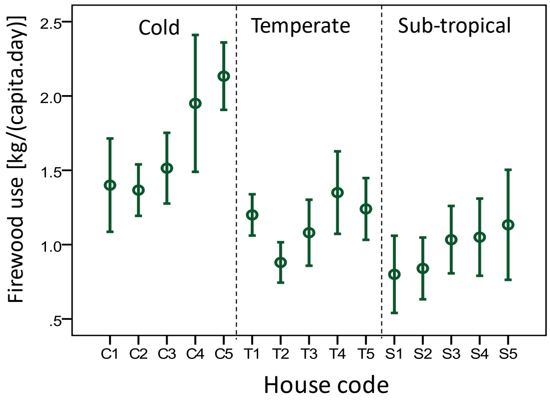


Figure 3.5 Per-capita firewood use obtained from physical measurement

Previous studies Illustrated that the amount of firewood use depends on various factors such as the economic level of people, the availability of firewood and commercial fuels, the level of urbanization, and other demographic and climatic factors. **Figure 3.6** shows the variation of average per-capita firewood use of the households having different family size.

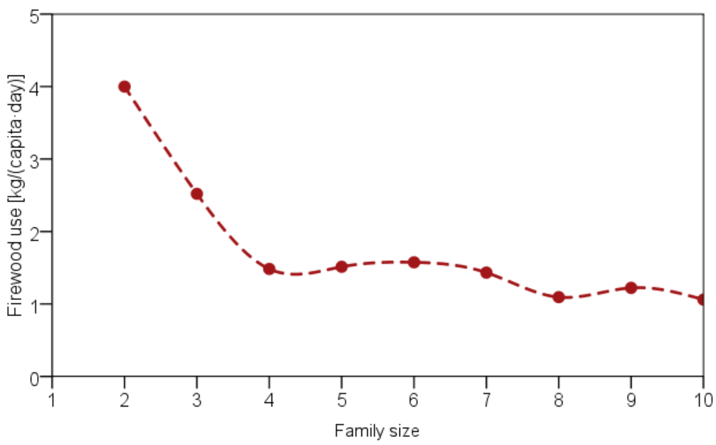


Figure 3.6 Variation of per-capita firewood use according to the family size

Bhatta and Sachan (2004) found that the firewood use was 2.6 times higher at high altitude (above 2000m) compared to firewood used at low (up to 500m) altitude. Yu et al. (2017) also reported that the higher value of firewood consumption in high altitude because more consumption is needed for space heating. Our results are more or less consistent with the findings of these previous studies. Table 3.2 shows the number of investigated households and their average rate of per-capita firewood consumption.

Table 3.1.5 Average rate of per-capita firewood consumption according to the family size

Family size	Number of households	Firewood use [kg/(capita·day)]	Std. Deviation
2	5	4.0	3.4
3	34	2.5	1.5
4	115	1.5	1.4
5	148	1.5	1.2
6	80	1.6	1.0
7	69	1.4	0.8
8	38	1.1	0.8
9	11	1.2	0.9
10	10	1.1	0.6
Total	**510**	**1.5**	**1.3**

3.1.6 Energy use for space heating

Figure 3.7 shows the relationship between the indoor and outdoor air temperature difference and the amount of energy use per floor area in the surveyed nine houses in three regions. The main heating fuel used in all houses surveyed was firewood. It is hard to extract the actual amount of firewood used for the purpose of space heating alone, because there are no particular heating unit and people always performed heating together with cooking activities by stoves. But it may be worth trying to perform a rough estimate of the energy use for space heating. What follows describes this trial.

In order to estimate the energy-use for space heating, we first made regression analysis with the plots of daily energy use per floor area and the indoor and outdoor air temperature difference of investigated houses for respective three regions. The regression equations obtained are given below.

E_c =0.402 (T_i-T_o) + 6.3 (3.1)

E_t = 0.231 (T_i-T_o) + 4.7 (3.2)

E_s = 0.070 (T_i-T_o) + 4.4 (3.3)

where E_c, Et and Es are daily average energy use per floor area in cold, temperate and sub-tropical regions, respectively. (T_i-T_o) is the difference in air temperature between indoors and outdoors [°C].

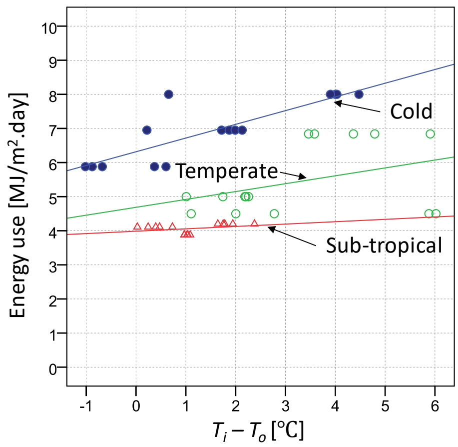


Figure 3.7 Energy use per-floor area as the function of indoor and outdoor air temperature difference in three regions

In cold and temperate region, it looks that energy use is linearly correlated with the indoor and outdoor temperature difference. Plots obtained from the survey data in cold and temperate region are not placed linearly, but if the slopes of cold and temperate regions are compared, we come to know that the former is slightly larger than the later. This looks reasonable, since the same temperature difference may require more energy use for space heating because of the cold storage within the walls caused by the long lasting indoor and outdoor air temperature difference and some other miscellaneous effects such as the level of water temperature. Here, let us regard that space heating is done similarly in cold and temperate region but it is slightly less dependent on the indoor and outdoor temperature difference in temperate region. There may be some amount of thermal energy used for space-heating purpose in sub-tropical region, but it would be much smaller than other two regions.

For the case of indoor-outdoor air temperature difference being zero, the difference in energy use between temperate and sub-tropical region is very small. The slope of eq. (3.3) is significantly smaller than other two slopes; in other words, eq. (3.3) is almost flat. Therefore, let us assume here no use of thermal energy for space heating in sub-tropical region. If we further assume that the energy use for cooking is, although it is only for rough estimate, not different much from cold to sub-tropical region, then approximately 4.0 MJ/ (m^2. day) may be regarded for cooking in all regions; this is equivalent to the intercepts of the regression lines for sub-tropical regions, eq. (3.3).

From eq. (3.1), (3.2) and (3.3) we can express energy use for space heating in cold and temperate regions as

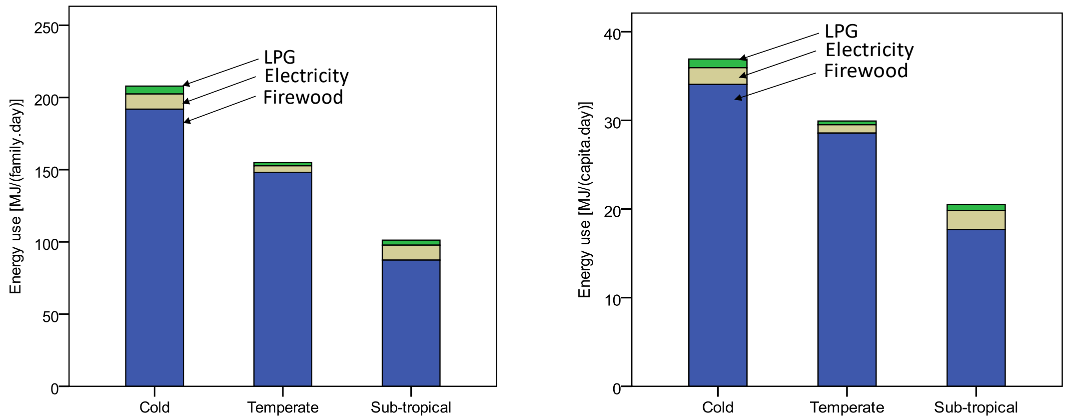
$$E_{CH} = 0.402\ (T_i - T_o) + 2.3 \tag{3.4}$$

$$E_{TH} = 0.231\ (T_i - T_o) + 0.7 \tag{3.5}$$

where E_{CH} and E_{TH} are energy use for space heating in cold and temperate region respectively. The intercept of eq. (3.4), that is 2.3 MJ/(m^2.day), may be regarded as the thermal energy use to meet the heating demand due to the cold storage effect within the thick walls in the houses in cold regions. In temperate region, we may regard that most of the thermal energy use is to increase the temperature inside the walls due to less cold storage effect caused by comparatively high outdoor and indoor air temperature than in cold region.

3.1.7 Total household energy use

Figure 3.8 (a) presents the daily average rate of household energy use and (b) daily average rate of per-capita energy use in three regions. It is observed that the firewood is the major source and LPG and electricity are minor sources in all regions. The total average household energy use was 207, 154 and 101 MJ/family/day and per-capita energy use were 37, 30, 20 MJ/(capita·day) in cold, temperate and subtropical regions, respectively.



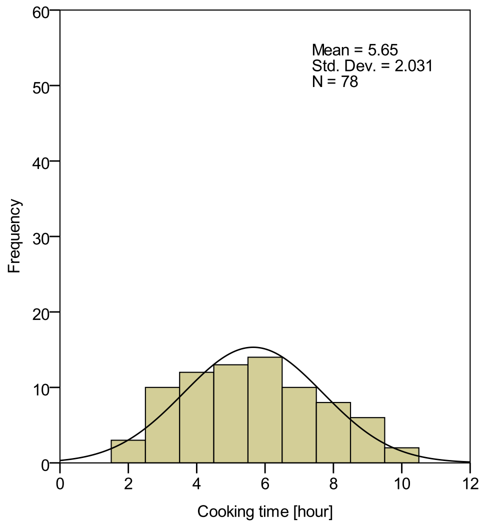
(a) (b)

Figure 3.8 Daily total energy-use in three regions: (a) Per-family and (b) per-capita energy uses.

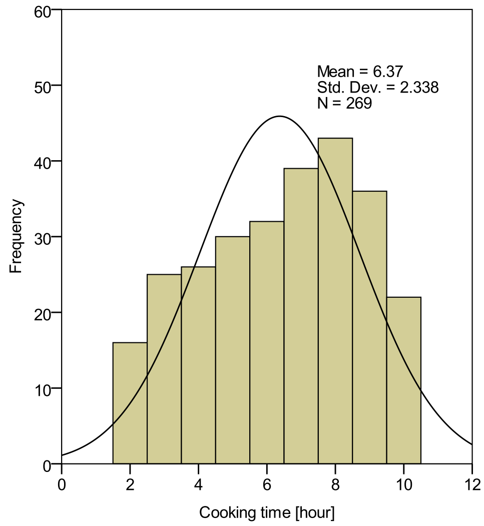
This is because firewood is comparatively cheaper than other fuels and available nearby their houses as a by-product of agricultural activities and still very common in rural areas of developing countries including Nepal (Jin et al.; 2020, Hoof et al.; 2006, Sunwoo et al.; 2006). The major dependency of the household energy sources on firewood for cooking and space heating in all regions suggests the importance of firewood-use reduction and it should be emphasized in residential energy policy of Nepal.

3.1.8 Time expenditure for fuel collection

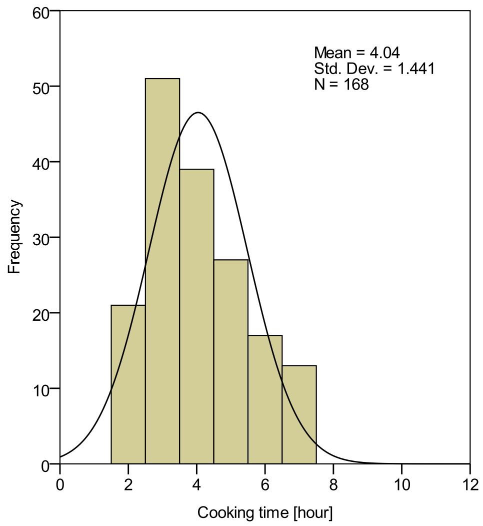
Firewood is the most vital source household fuel in rural societies, providing 9% of the global primary energy supply (CIFOR, 2012; Arabatzis et al., 2013). It is an essential source of cooking, for space and water heating, for cooking animal feed and for rice beer preparation in the rural societies (Bhatta and Sachan, 2004). However, there is several disadvantages of the firewood use. First, the growing use of firewood is the serious cause of deforestation particularly in the developing countries. Furthermore, households relying on firewood as their primary energy lost their precious time in firewood collection, which thereby reducing time for other productive work which might help to improve their economic condition. Agra et al. (2010) estimated that about 20% of the time per day is spent for the collection of firewood. Most of the households in our survey depend primarily on firewood for cooking fuel. There was no fuelwood market in cold and in temperate region but some of the sawmill selling firewood was found in sub-tropical region. **Figure 3.9** shows the distance required to firewood collection in three regions.



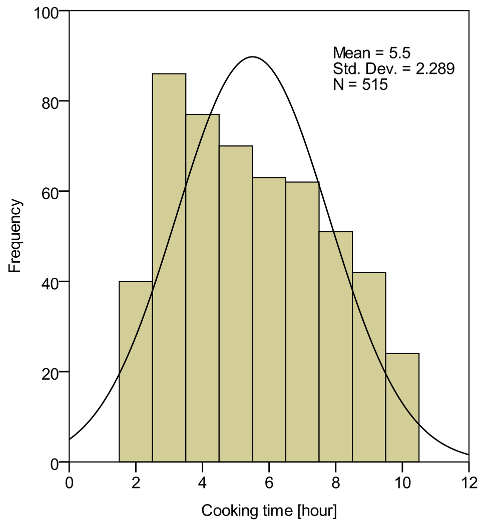
(a) Cold



(b) Temperate



(c) Sub-tropical



(d) All

Figure 3.10 Variation of cooking time among the households in three climatic regions; (a) Cold, (b) Temperate, (c) Sub-tropical and (d) All

3.1.9 Exposure on cooking activities

A cooking time was calculated based on the time a responsible person for cooking spends in different cooking activities including preparation of meal, boiling water, making tea, preparation of animal feed and so on. During this time a responsible person simultaneously performed other miscellaneous household activities such as feeding cattle, cleaning the floor and utensils. **Figure 3.10** shows the variation of cooking time among the households in three climatic regions. In this study, daily cooking time ranging from 4 to 10 hours per day. Some of the households in cold and temperate region spent upto 10 hours per day for cooking activities which includes making meal for household members, prepearing animal feed etc. The average cooking time was 5.6, 6.37 and 4.04 hours per day in cold, temperate and sub-tropical regions respectively.

3.1.11 Conclusions

How the household energy use is related to the indoor thermal environment of residential buildings in developing countries has not yet been known very well so that it is important to clarify this relationship in order to draw the future consideration about energy saving policy in developing countries such as Nepal. As the results of our survey and the follow-up analyses made on the current situation in Nepal, the followings were found:

1. The daily average regional household energy-use patterns in winter season was found 207 MJ/ (family. day) in cold region, 154 MJ/ (family. day) in temperate region and 101 MJ/ (family. day) in sub-tropical region.
2. People living in three regions are primarily dependent on firewood for cooking and space heating; per-capita total energy use was found in the order of 37, 30 and 20 MJ/ (capita. day) in cold, temperate and sub-tropical regions, respectively.
3. Outdoor climatic condition has a strong influence on indoor thermal environment and it is associated with household energy use patterns. Intensive improvements of existing building envelopes should be performed for providing people with better indoor thermal environment while optimizing the household energy use.

3.2 Variation of household energy use among different fuel user households

3.2.1 Introduction

Access to clean energy is key to socio-economic development and one of the basic issues of developing countries. Nepal is a small country situated in the Himalayan mountain range between India and China. It has high geographical diversity, which makes it difficult to develop modern energy infrastructure in all parts of the country. The unavailability and unaffordability of clean commercial fuel has long been a serious problem in rural households. Access to clean cooking fuels is essential for promoting human well-being as it improves the quality of life (Kurniawan et al., 2018). The enormous potential of renewable energy resources of the country, such as hydropower, solar power, and wind power, can be utilized for improving the living conditions of people through clean energy development. However, due to economic and other social constraints, most of these resources have remained underutilized, and thus, a large number of households have to rely on traditional fuels (Gurung et al., 2011; Islar et al., 2017; Ghimire et al., 2018). Approximately 70% of the total households, including urban and rural areas, and 90% of rural households in Nepal depend primarily on traditional fuels for daily cooking (CBS-Nepal, 2011).

Firewood is the major source of cooking and heat energy and provides 78% of the total energy demand of the country (IEA, 2016; Poudyal et al., 2019). In addition to using firewood, many households add different types of fuels, such as liquified petroleum gas (LPG), electricity, kerosene, and biogas, to fulfil their everyday cooking energy demand. LPG is the second most widely used cooking fuel, with a total annual consumption of 1.4 million tons (Poudyal et al., 2019). Electricity is still unreliable with a high frequency of load shedding and is mostly used for lighting and other electric appliances. Approximately 90% households have access to electricity either from grid or off-grid supply, with per-capita electricity consumption of 146.5 kWh/year, which is approximately 20 times lower than the global average of 3104 kWh/year (World Bank, 2019; Acharya and Adhikari, 2021). In 2018, the total electricity used was 6394.38 GWh, an increase of 14% over the previous year (NEA report 2018/19).

Energy use varies between rural and urban households, between low- and high-income groups within a country, and among countries (Pachauri et al., 2004). Major factors contributing to these differences are the level of urbanization, economic development, and living standards. Other factors are country- or region-specific, such as climate, culture, and season (Reddy and Balachandra, 2006). Energy use patterns among regions and different fuels used in households in Nepal show heterogeneous pattern. However, differences among households on meeting their energy requirements has not received considerable attention in research ((Naumann and Rudolph, 2020).

Nepal's energy sector is governed by the Ministry of Energy, which is responsible for the development of the country's energy policy. To improve the health, economic, and environmental burden of the people, the government has set a target of 100% electrification by 2030 (75% and 25% from grid and off-grid supplies, respectively) (Poudyal et al., 2019; Pradhan et al., 2019). However, even with 100% electrification and clean cooking fuels availability, all households cannot afford and adopt electricity and other clean cooking fuels as their regular cooking fuels, and several households might have to rely on traditional cooking fuels due to various socio-economic circumstances.

The substitution of traditional cooking fuels by LPG and electricity may offer great potential to reduce indoor CO_2 emissions as well as other associated emissions. Thus, several countries have implemented nationwide cooking fuel substitution programs. For example, the Indonesian government initiated the world's largest exercise to substitute kerosene with LPG in 2007, where 58 million LPG packages were distributed to reduce dependency on kerosene (Kurniawan et al., 2018). Since the 1970s, the government of Ecuador has heavily subsidised LPG and fixed household LPG prices at 1.60 USD per 15 kg cylinder. As of 2014, more than 90% Ecuadorian households were primarily cooking with LPG (Gould et al., 2020). The government of India has also initiated several policies to promote LPG accesses and has provided huge subsidies for low-income Indian households (Gould and Urpelanien, 2018; Sharma and Jain, 2019).

The use of clean cooking fuels has substantial health, climatic, and environmental benefits of reducing indoor air pollution. Moreover, it increases the energy consumption efficiency of the household sector, which plays a significant role in reducing indoor CO_2 emissions (Kurniawan et al., 2018). To determine the effectiveness of various policies directed towards the development of clean cooking fuels in the household sector and draw necessary improvements for future consideration, it is necessary to understand the complex energy use and associated emission patterns of different fuels used in households.

3.2.1.1 Literature review

Several studies have investigated energy use patterns in Nepal (Islar et al., 2017; Poudyal et al.; 2019; Rijal et al., 2018; Shrestha et al., 2020; Acharya and Adhikari, 2021;). For instance, Malla (2013) studied household energy consumption patterns and their environmental implications in Nepal. Joshi and Bohora (2017) assessed the impact of various socio-economic factors on household cooking fuel preference and the motive for making a transition towards cleaner fuels. Rupakheti et al. (2019) monitored indoor levels of black carbon and particulate matter and found that the commonly used improved cook stove might help in reducing particulate matter emissions but may not reduce black carbon emissions. Das et al. (2019) estimated the time required and human energy expenditure for the production of cooking fuel for four alternative cooking energy systems and found that human energy expenditure and time had a significant influence on the selection of cooking fuel. Bartington et al. (2017) assessed the patterns of domestic air pollution and found that air quality levels associated with biomass fuel consumption exceeded WHO indoor air quality standards and fell in the hazardous range for human health. Pradhan et al. (2019) analysed the biogas and electricity-based cooking practices and found that the use of cleaner cooking fuels can reduce the firewood consumption by 12–24% in the residential sector (Pradhan and Limmeechokchai, 2017, Pradhan et al., 2019). Other comprehensive studies on energy use have been conducted in several countries, including

India (Gould and Urpelainen, 2018; Ravindra et al., 2019), Bangladesh (Baul et al., 2018), Myanmar (Win et al., 2018), and Indonesia (Kurniawan et al., 2018). While assessing the potential of CO_2 emission reduction using clean cooking fuels, it is necessary to conduct comprehensive studies that focus on the heterogeneous energy use patterns of different fuels used in households across regions.

3.2.1.2 Objectives

The main objective of this study was to provide the existing heterogeneity of the household energy use patterns of traditional, mix and commercial fuel user households in three climatic regions. This study also aims to identify the proportion of households that are relying on the different fuel resources for their everyday energy requirements. Furthermore, this study also explores energy stacking or fuel stacking behavior and cooking time of the households in three climatic regions.

3.2.2 Materials and methods

3.2.2.1 Study area and climate

Field studies for household energy use survey represents cold, temperate and sub-tropical regions in Nepal. To capture a variation in geographical condition, population demographics, socioeconomics and local cultures, we have selected three non-adjoining districts viz. Solukhumbu (cold), Panchthar (temperate) and Jhapa (sub-tropical). Within these districts the altitude ranges from approximately 60 m above the sea level in the southern terai region to the highest peak 8848 m, the Mount Everest in the north region. Solukhumbu is the northern mountainous district, with Salleri as its headquarters lies with an altitude of 2413m from the sea level. It covers an area of 3312 km^2 and most of the area represents cold climatic features. Population density of this district was lowest among three study area and total population was 105,886 according to the national census 2011. Sherpa and Rai are the indigenous ethnic cast living in that area. **Table 3.3** presents the physical and demographic characteristics of the study area.

Table 3.3 Demographic and physical characteristics of the study area.

Study area (district)	Area (Km^2)	Climate	Population (individual)	Population density (individual/Km^2)	Access to grid electricity	Access to black topped road
Solukhumbu	3312	Cold	105,885	39	no	yes
Panchthar	1241	Temperate	191,817	150	yes	yes
Jhapa	1606	Sub-tropical	812,650	510	yes	yes

Panchthar district lies in the hill region in between northern mountain and southern terai region. Phidim is headquarter lies with an altitude of 1276m from the sea level. It covers an area of 1241 km^2 and it is dominated by temperate climate. The population density of this district was 150/m^2 and the total population was 191,817 in 2011. Limbu, Gurung and Rai are the indigenous ethnic cast living in that area. Jhapa is the southern terai region having plain and fertile land. It covers 1606 km2 area and dominated by sub-tropical climate. The population and population density of this district was highest among three districts. From these three districts, we have further selected three municipalities; Solududkunda, Phidim and Gauradaha for household energy use survey.

3.2.2.2 Household survey

A household questionnaire survey was conducted in the winter season of 2018. Altogether 515 households: 76 in cold, 261 in temperate and 178 in sub-tropical regions were interviewed to collect necessary information by the help of questionnaire. The information on family size, occupation, type and amount of fuel, characteristics of the kitchen types (separated or attached to main house), time required for cooking, distance travel to collect firewood (two-way from the house to the place of firewood source), types and location of cook stoves and source of firewood were included in the questionnaire.

3.2.2.3 Estimation of household energy use

To estimate household electricity use, we used monthly electricity bills provided by the local electric power company in kWh/(household·month). Then we have converted them into the unit of MJ/ (household · day). For the LPG use, we asked the duration of one

LPG cylinder lasting for their family. In Nepal, LPG cylinder containing 14.2kg of LPG fuel are available in grocery stores. From this specific duration obtained from the answer of respondent and the weight of one cylinder lasting for one family, we calculated the amount of household LPG used. To estimate the total firewood used in households, we have asked people to answer the total amount of firewood used in the unit of kg. We assumed that the stated amount of firewood covers energy source for cooking, heating and for making animal feed. Finally, by using conversion factor of all respective fuel, all the energy data obtained were converted into an energy unit of MJ. Energy conversion units used were assumed as LPG 48MJ/kg, electricity 3.6MJ/kWh, firewood 16MJ/kg as referring Nansaior et al. (2011).

3.2.2.4 Estimation of energy used for cooking

It is not easy to estimate the energy used only for cooking purpose in the investigated households because people always perform cooking, heating and making animal feed together. In this study we considered per-capita firewood used for cooking is similar in all regions. Since firewood is the primary source of cooking energy in all regions and sub-tropical households did not use any fuels for space heating during survey period, we have selected five households in sub-tropical region for experimental measurements to estimate per-capita firewood use for cooking (Pokharel et al. 2020). For this measurement, we have excluded the firewood used for other purposes like space heating and animal feed preparation. This firewood measurement was carried out as described by the weight survey method (Bhatt et al. 1994, Fox 1984). At first, we measured the weight of air-dried firewood bundle ready for use with spring balance and left them in the kitchen of each household and instruct the household members to use firewood only from these weighted bundles. On the next day the remaining bundles of firewood were weighted and the difference in the weights between the previous day and the present day was taken to be the weight of firewood used for cooking. Per-capita LPG used for cooking was also estimated using the data of five LPG user households in sub-tropical region. Although no any households were fully depended on electricity for cooking purpose, we considered amount of per-capita LPG energy used as a cooking fuel is equal to the amount of electric energy used for cooking.

3.2.2.5 Fuel switching

Several studies indicated that traditional energy systems will slowly be replaced by modern fuels as households become wealthier, following the theory of 'energy ladder'. This theory suggests that when the income of households increases, they ascend the ladder linearly from low quality fuels to more efficient, convenient and cleaner fuels (Van Der et al., 2013, Lohri et al., 2016, Das et al., 2018). In the first stage, households depend mainly upon solid biomass, deriving energy from the combustion of agricultural residues, waste and firewood. In the intermediate stage, these households shift to more efficient fuels, but still result in significant emissions, such as charcoal and kerosene. Finally, households move to the most convenient and cleanest commercial fuels, such as LPG and electricity. In recent years the 'fuel-stacking' model has gained significant attention and this model suggests that households integrate modern fuels slowly into existing energy use patterns, resulting in the use of multiple cooking fuels simultaneously (Masera et al., 2000). This phenomenon of integrating different fuels in household energy system is known as fuel switching or fuel stacking. It is one of the important characteristics of energy use behavior of the households in developing countries. Based on the energy ladder and energy stacking hypothesis this study developed TMC (traditional, mix and commercial) model. Energy models are an important aspect to consider when designing and implementing effective energy policies to increase the use of improved traditional energy systems.

3.2.2.6 Characterization of TMC model

Earlier studies have applied "Energy ladder" and "Energy stack" model to describe fuel choice or process of energy transition in the household sector. Energy ladder model suggested that as families gain socio-economic status, they abandon technologies that are inefficient, less costly and most polluting, i.e., ones lower in the energy ladder (Lohri et al., 2016, Van Der et al., 2013, Das et al., 2018). But recently, some other researcher has purposed energy stack model which suggests that households do not fully abandoned cooking fuels in favor of efficient ones, but rather they integrate fuels gradually into their energy system (Masera et al.; 2000, Ogwumike et al., 2014, Schlag et al., 2008, Cheng et al., 2014). Energy models are used to explore and understand the possible future changes in the energy system however there are very limited energy models available in developing countries (Ruijven et al, 2008). Global energy models developed in industrialized country mainly focused on issues which are important for industrialized energy system but these models ignored the essential element of the rural energy systems and cannot have generalized the energy use patterns of rural area of developing countries (Ruijven et al.; 2008). As the determinants of energy systems are likely to be region specific, study across different regions using a variety of methods are necessary to provide a more comprehensive picture that can guide energy policy.

Taken these considerations to account and to analyze heterogeneous energy use patterns, this study developed a simple three step TMC model on the basis of available cook stoves. This model assumed that traditional (T) fuel user households gradually add clean cooking fuels in their energy system and become mix (M) fuel user households, after that mix fuel user households intensify the clean fuels and leave traditional fuels and becomes commercial (C) fuel user households. In each three steps of TMC model household can rely on multiple cooking devices and fuels, however energy ladder model suggests that households completely switch the fuels they used with income, and energy stacking model rejected that and suggested an alternative behavior of using multiple fuels at the same time. On the basis of TMC model energy situation of any society may be explained in three levels. The first level is the abundance of traditional cooking mode, the second is the abundance of mix cooking mode and the third is the abundance of commercial cooking mode. **Figure 3.11** shows the process of energy transition as purposed by energy ladder, energy stack and TMC model. The details of TMC model are described as follow.

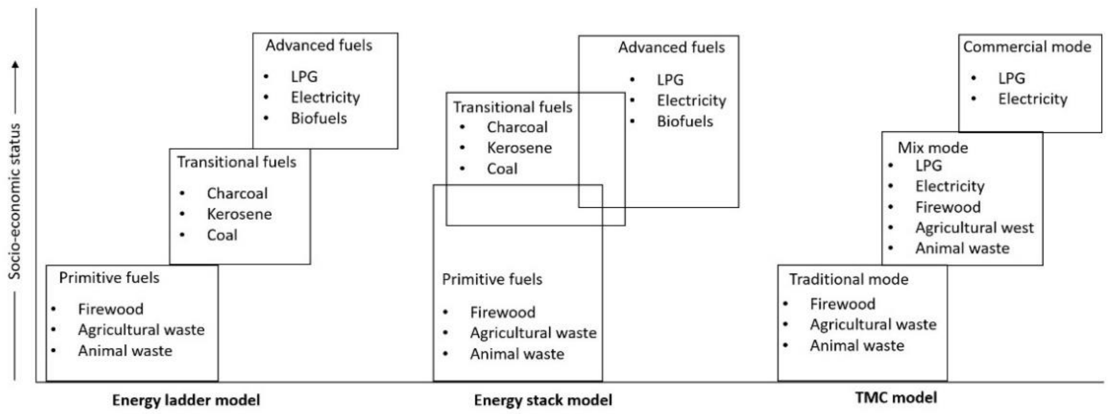


Figure 3.11 The process of energy transition in energy ladder, energy stack and TMC model. Figure of energy ladder and energy stack models are employed and modified from Kroon et al. (2013).

Primary cooking fuel are broadly classified into two categories: traditional and commercial. Traditional fuel includes firewood, agricultural residue and animal dungs. Commercial fuel includes LPG and electricity. Biogas and kerosene are considered as transitional fuels and neither placed as commercial nor as traditional fuels. In this study we excluded biogas and kerosene because biogas cannot be used in all region of the country due to unfavorable climatic conditions for biogas production and kerosene was not reported as cooking fuels in this study.

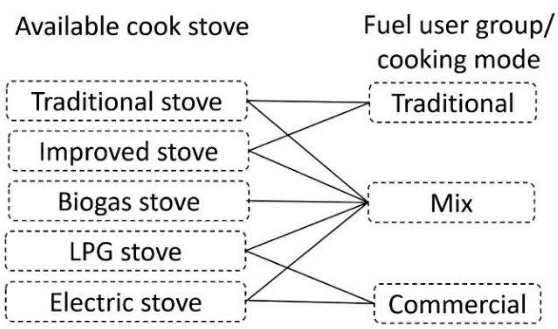


Figure 3.12 The categorization of fuel user households and their cooking modes

All investigated households were categorized into one of the three categories as: traditional, mix, and commercial fuel user households. Households having cook stoves only for traditional fuels are classified as a traditional fuel user household, households with cook stoves both for traditional as well as commercial fuels are classified as mix fuel user households and households having cook stoves only for commercial fuels are classified as commercial fuels user households. The cooking mode of traditional mix and commercial fuel user households were considered as traditional, mix and commercial mode respectively. **Figure 3.12** shows the categorization of fuel user households and cooking modes on the basis of cook stoves.

We assumed that households will switch from traditional mode through mix mode to commercial mode with changes in income and accessibility of the modern commercial energy services. However, in rural society of developing countries adoption and rejection of clean cooking fuels is continuous process which depends on various socioeconomic circumstances and cultural behaviors of the people and that determine the position of households in TMC model. We expect this model to be helpful in showing the state of existing energy situation and to predict possible further changes in the household energy system of the society in developing countries like Nepal. **Figure 3.13** shows the cooking stove used in three climatic regions in Nepal.

(a) (b) (c)

Figure 3.13 Improved cook stove found in study area; (a) Cold region, (b) Temperate region and (c) Sub-tropical region.

3.2.3 Proportion of households in traditional, mix and commercial cooking mode

In this section, we estimated the proportion of households that belongings to either in traditional, mix or in commercial mode on the basis of TMC model. As shown in **Figure 3.14** similar tendency was found across all regions, that is all regions are dominated by mix mode followed by traditional mode. The percentage of households that belongs to traditional mode were high in temperate, medium in cold and low in sub-tropical region. The high percentage of traditional mode in temperate region might be due to the low income and limited accessibility of commercial cooking fuels where most of the residents were relying on sustenance agriculture.

The percentage of households belonging to mix mode was high in sub-tropical, medium in cold and low in temperate region. Commercial fuel user households were marginally small in all regions, however the percentage of households that belongs to commercial mode was also high in sub-tropical region. High percentage of mix and commercial mode in sub-tropical region may be attributed to the increased accessibility and affordability for commercial fuel.

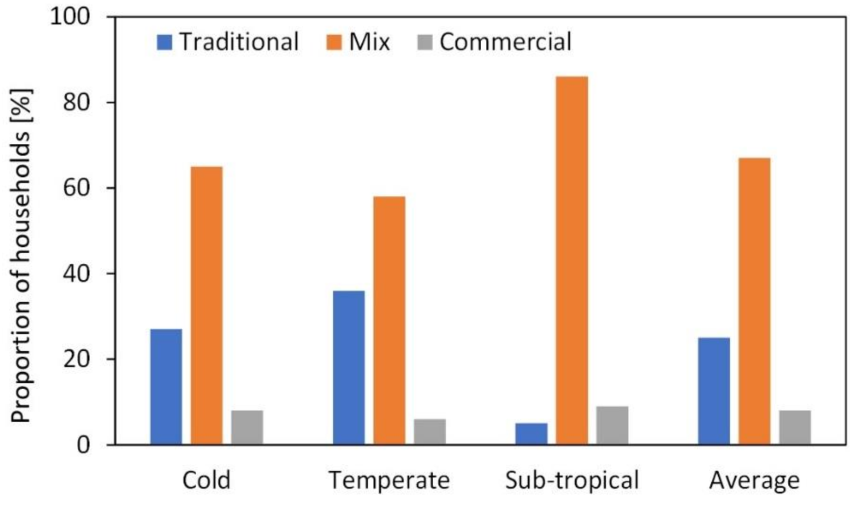


Figure 3.14 Proportion of traditional, mix and commercial fuel user households

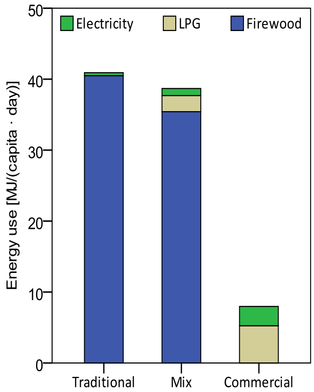
Figure 3.14 also indicates that in total 25% of households were in traditional mode, 67% households were in mix mode and 8% households were in commercial mode. This result revels that 25% of the households are totally relying on traditional cooking fuels without using any other commercial cooking fuels, 67% of households are relying on both traditional as well as commercial fuels for their cooking activities and only 8% households are using clean cooking fuels as a regular source of household cooking fuel. From this result we can speculate that 25% households either they do not have accessible source of clean cooking fuels or they do not have purchasing ability to buy clean cooking fuels and they are totally relying on traditional cooking fuels. This result also identify that 76% households add clean cooking fuels like LPG and electricity to some extent in their cooking system without giving up traditional fuels, however the frequency and quantity of clean cooking fuel consumption varies depending up on socio-economic circumstances and cultural behaviors. Mix fuel user households had reported that only 16% households used clean cooking fuel once a day, 46% households used once a week and remaining 38% households used occasionally. Ravindra et al. (2019) reported that in India about 13% households depend primarily on clean cooking fuels. Our result showed that the clean cooking fuel remains relatively rare in Nepal, though there are several clean cooking fuel initiatives like subsidies on LPG price, comparatively low pricing of electricity for domestic user.

It was reported that the households having sufficient income and without agricultural activities prefer to use clean cooking fuels regularly whereas medium and low-income households involved in subsistence agricultural prefer to use LPG and electric rice cooker together with firewood. The most common reason for non-adoption of LPG as regular cooking fuel in all region was reported as high installation cost, irregular supply and high regular expenditure as cooking fuel than firewood. The unavailability of regular electricity supply, high installation cost and high regular cost of cooking and lack of knowledge about electric cooking technology was reported as the barriers for the adoption of electricity as a regular cooking fuel. It was also noticed that firewood was easily available either from nearby community forest or their plantations in agricultural fields, and hence most of the households were preferred to use firewood as their primary cooking fuel. The findings of this study are concordance with the findings from earlier studies conducted in India (Ravindra et al.; 2019).

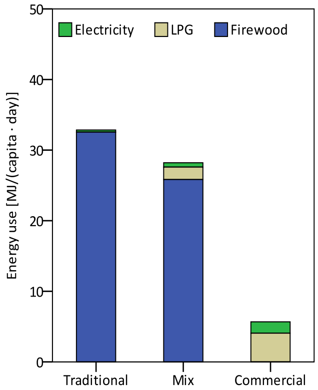
3.2.4 Total household energy use in traditional, mix and commercial mode

Most of the households used more than one variety of fuels simultaneously to fulfill their everyday household energy needs. Firewood and LPG were the most common sources used for cooking. Electricity was the primary lighting fuel of all households. No any households in the study area used kerosene and animal dung as cooking fuel. Access to grid electricity was uneven in the three regions however all households fulfill their lighting energy either by grid electricity, micro hydro power plant or standalone photovoltaic solar system. **Figure 3.15** (a), (b) and (c) shows the per-capita total energy used in cold, temperate and sub-tropical region and (d) shows the average of that in all three regions by traditional, mix and commercial fuel user households. As shown in **Figure 3.15**, in traditional and mix fuel user households most of the energy was provided by firewood and only small fraction was from electricity and LPG. Electricity was used for lighting and for mobile charging purpose while LPG was used for occasional cooking. Similarly, in commercial fuel user household all energy was provided either by LPG or electricity.

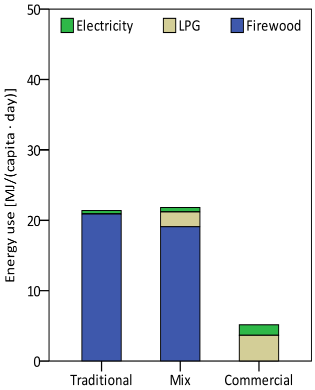
In cold region, total household energy used in traditional, mix and commercial fuel user households were 40, 35 and 8 MJ/ (capita· day), in temperate region, it was 37, 28 and 5 MJ/ (capita· day) and in sub-tropical region it was 21, 18 and 5 MJ/ (capita· day), respectively. This result shows that traditional fuel user households in all region used high, mix fuel user households used medium and commercial fuel user households used low amount of energy. Significantly high energy used in traditional and mix fuel user households must be due to the use traditional cooking fuels in very inefficient cook stoves and another region might be the rearing of livestock which require extra energy for the preparation of animal feed. Due to the occasional use of LPG and electricity as their cooking fuels, mix fuel user households showed slightly low amount of energy use than traditional fuel user households. The smaller number of livestock reared in the mix fuel user households might also be another reason of low firewood used in mixed fuel user households.



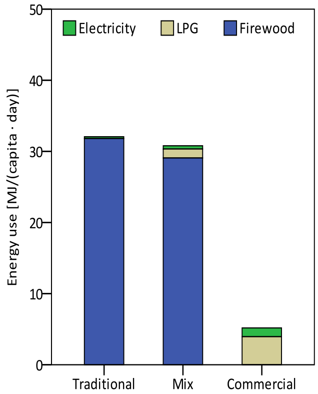
(a) cold



(b) temperate



(c) Sub-tropical



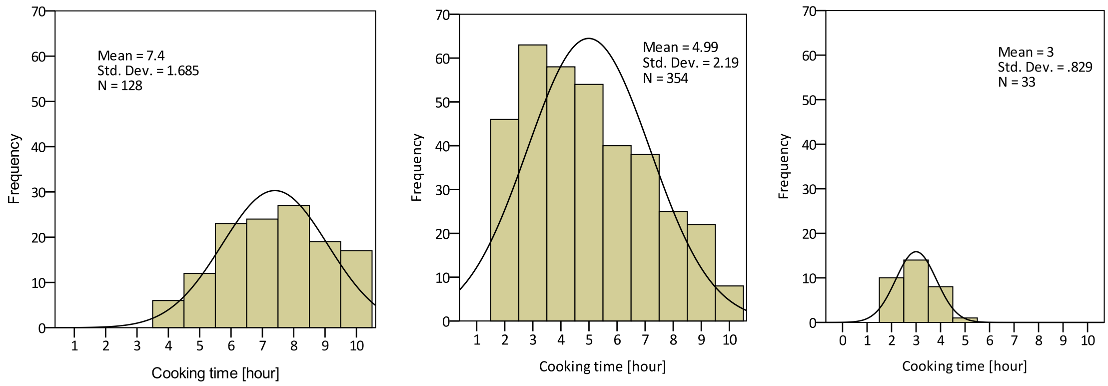
(d) Average

Figure 3.15 Total household energy used among three fuel user households; (a) cold, (b) temperate, (c) sub-tropical and (d) Average

In commercial fuel user households, almost all household cooking energy was provided either by LPG, electricity or by the use of both fuels. Generally, commercial fuel user households LPG used for regular cooking purpose and electricity used for making rice, for lighting and for other electrical appliances. It indicates that the commercial fuel user household can afford the regular cost of commercial fuels like LPG and electricity. Among three regions, households in cold region used high, households in temperate region used medium and households in sub-tropical region used low amount of household energy. Those households which are connected to the grid electricity prefer to use rice cooker together with LPG stoves, due to that reason these households used highest amount of LPG and electricity than other two fuel user households. The total energy used in commercial fuel user households was calculated as 8, 5 and 5MJ per capita/day in cold, temperate and sub-tropical regions, respectively. Significantly low amount of per capita energy used in commercial fuel user households might be due to the use of efficient cooking technology and low frequency of energy used.

3.2.5 Variation of cooking time among three fuel user households

Figure 3.16 shows the variation of cooking of three fuel user households. In this study, daily exposure on cooking activities ranging from 4 to 10 hours in traditional fuel user, 2 to 10 h in mixed fuel user and 2 to 5 hours in commercial fuel user households. The average exposure on cooking was 7.4, 5.0 and 3 hours per day for traditional, mixed and commercial fuel user households. It is interesting to find that commercial fuel user households are most time efficient fuel users and they spent only 3 hours per day on cooking while traditional and mix fuel user households spent 7.4 and 5.0 hours per day on cooking. It is very noteworthy result, as it indicated that clean cooking fuel substitution has a greater potentiality to reduce the exposure on cooking time. Ultimately, it has positive impact on the health condition of the people. It is interesting to find that commercial mode is most time efficient and people spent only 3 hours per day on cooking while in traditional and mix mode they spent 7.4 and 5.0 hours per day on cooking. It is very noteworthy result, as it indicated that households in traditional and mix mode can save significant time just by switching traditional cooking fuels into commercial cooking fuels which has a greater potentiality to reduce the exposure on cooking activities. providing people with better indoor thermal environment while optimizing the household energy use.



(a) Traditional (b) Mix (c) Commercial

Figure 3.16 Variation of cooking time among three fuel user households; (a) Traditional, (b) Mix and (c) Commercial

3.2.6 Conclusions

This study accessed energy use patterns of the households in traditional, mix and commercial modes in three climatic regions of Nepal and made following conclusions;

1. Results of this study suggests that 25% households are heavily relying on traditional cooking fuels without using any other clean cooking fuels, 67% households add clean cooking fuels to their energy systems and only 8% households are relying in commercial fuels to fulfil their daily cooking fuel requirements.
2. Inhabitants of the study area used variety of cook stove however traditional cook stoves are the most abundant in all regions. Combination of LPG and electric rice cooker was the most common cook stoves combination found in the investigated households.
3. Due to the use of inefficient cooking technology, traditional and mix fuel user household have to use more household energy than commercial fuel user households and these households emits more CO_2 than commercial fuel user households. Moreover, traditional and mix fuel user households spent significantly longer time exposure on cooking than commercial fuel user households.

3.3 Hourly firewood consumption patterns and CO_2 emission

3.3.1 Introduction

Firewood is an important source of household energy for the rural population of many developing countries. Approximately 2.6 billion people from developing countries fulfil a majority of their basic energy demand for cooking and space heating from fuelwood, a practice that is inefficient, unhealthy, and unsustainable (Petersen et al., 2014). This trend is expected to continue in the future, especially in rural areas of developing countries (Petersen et al., 2014). Nepal is one of the least developed countries that has one of the lowest per-capita energy consumption globally (Pokharel, 2007). The energy use and energy access levels in Nepal are significantly below the level of basic human needs, and firewood is expected to remain the dominant cooking fuel for the foreseeable future (Malla, 2013). As of 2010, over 30% households lacked access to electricity, and 78% households relied on traditional biomass for cooking and space heating (CBS; 2011). According to the household survey 2015/16 of Nepal, firewood is a major source of cooking fuel for more than half of the households in the country and is used by 76.5% rural households and 38.0% urban households to meet their everyday cooking energy demands (CBS; 2015/16). Lack of financial and technical capabilities has compelled the rural population to use inefficient and hazardous sources of solid biomass energy (Gurung et al.; 2013).

The World Health Organization (WHO) estimates that about 2.8 billion people in developing countries depend on solid fuels and traditional cook stoves for cooking and heating (WHO; 2016). Burning of solid fuel in inefficient traditional stoves is responsible for the emission of various indoor air pollutants, which have direct and indirect impacts on the health of the inhabitants. Small and improperly ventilated buildings reduce the dilution of indoor pollutants and increase the concentration of harmful gases, which creates unfavorable indoor environments.

In developing countries like Nepal, particularly in rural areas, direct firewood consumption in inefficient traditional cook stoves without chimneys in improperly ventilated buildings is considered the major cause of indoor air pollution. Exposure to pollutants resulting from the burning of solid fuels has been responsible for the death of at least 4.3 million people per annum worldwide (WHO; 2016). Improvements in the indoor air quality of residential buildings is important for minimizing the health burden on rural population. CO_2 emissions and concentrations resulting from firewood consumption inside buildings are the simplest indicators of indoor air quality of residential buildings in rural areas and this information can be used to monitor the indoor air quality of residential buildings.

3.3.1.1 Literature review

Previous studies have showed that firewood consumption varies due to socio-economic factors, cultural factors, and availability and accessibility of fuels (Fox, 1984; Rijal, 2018; Bhatta and Sachan, 2004; Shrestha, 2005; Griffin et al., 1987; Bewket W., 2005). Fox (1984) conducted a study on firewood consumption in a Nepali village and found a mean firewood consumption of 0.95 m^3/ (person · year). This study also found that the rate of firewood consumption was influenced by family size, caste, and season. Bhatta and Sachan (2004) found that higher firewood consumption was mainly caused by a lack of conventional energy sources. They also concluded that firewood consumption differs according to family size: smaller families have more per capita firewood consumption than medium and large families. Bhatta and Sachan (2004) also found that firewood consumption increased with altitude.

Some studies have highlighted related health concerns, focusing on the use of traditional cooking fuels and indoor environmental conditions of houses in Nepal. Pandey et al. (1989) conducted research on domestic smoke pollution and acute respiratory infections in Nepal and found that episodes of moderate and severe acute respiratory infections increased with an increase in the level of exposure to domestic smoke pollution. Fuller et al. (2009) used measured firewood and temperature data to validate a simple and cost-effective model of rural houses. Some studies in other countries have highlighted the firewood use patterns associated with socio-economic factors and CO_2 emissions (Baul et al.; 2018, Pokharel et al.; 2020). However, there has been a lack of focus on hourly variation of firewood consumption patterns and associated CO_2 emissions and concentrations in rural households of Nepal. Hourly firewood consumption patterns and associated CO_2 emission patterns offer important information for assessing indoor environmental conditions, and this information can be used to simulate the thermal environmental conditions and indoor air quality of such houses.

The above literature review indicates that there is a need to focus on hourly firewood consumption patterns and associated CO_2 emission patterns of rural households to understand and minimize the associated health impacts. Thus, the present study aims to assess the effects of firewood consumption patterns on CO_2 emissions and concentrations of residential buildings in rural areas of Nepal. The findings of this study can be used to understand the energy use patterns of rural households in Nepal. Furthermore, this information is important for developing effective energy policies for rural households.

3.3.1.2 Objectives

The main objective of this study was to identify the hourly firewood consumption patterns and associated CO_2 emission patterns from firewood consumption in rural houses. Furthermore, this study also intended to identify the effect of different factors, such as family size and number of animals reared, on firewood consumption patterns. The goal of this study was to provide information on hourly variations in firewood consumption and associated CO_2 emissions to policymakers, researchers, and concerned stockholders to enable the development of better policies with respect to cleaner indoor environments and diffusion of clean and affordable energy resources for the rural population.

3.3.2 Materials and Methods

3.3.2.1 Study area and climate

The research was conducted in Nilakantha municipality in Dhading district, situated at an altitude of approximately 1500 m. This municipality is situated 90 km west of Kathmandu. It ranges from the Himalaya in the North to the Mahabharat range in the south. Of the 199.85 km^2 of the total area under the municipality, forest occupies 99.31 km^2, which is nearly 50% of the total area [18]. The land form is sloped and terraced. We chose this area for the study as the terrain, living conditions, energy use patterns, and housing conditions are representative of rural communities of the hill regions in Nepal. According to the Annual Household Survey 2015/2016, the total population of this municipality was 71,131. The major economic resources of this municipality are agriculture, trade, and tourism. However, most people in the municipality depend on subsistence and traditional agriculture (nilakanthamun.gov.np; 2020). **Figure 3.17** shows the location of the study area.

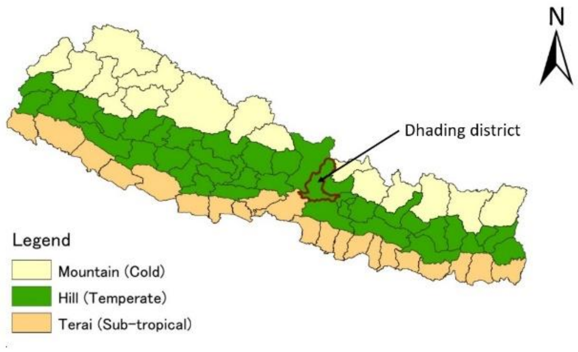


Figure 3.17 Map of Nepal and the study area.

Figure 3.18 shows the monthly mean, minimum, and maximum outdoor air temperatures obtained from the Dhading meteorological station of Dhading district. The climate of this region is temperate, and the annual average, minimum, and maximum outdoor air temperature were 22.8, 17.3, and 28.4 °C, respectively, in 2016. The annual average rainfall is 2329 mm, of which 80% occurs in the three months of the monsoon season.

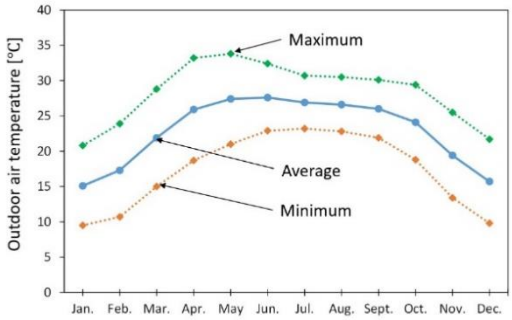


Figure 3.18 Monthly outdoor air temperatures of the study area in 2016, obtained from the climatological and agro-meteorological records of Nepal.

3.3.2.2 Selection of houses

For this study, we selected 16 such households from the Nilakantha municipality in Dhading district, where all inhabitants depended on subsistence agriculture for their living and used firewood in a traditional cookstove. These houses were constructed by local skillful craftsmen with locally available materials, using construction methods and designs inherited from previous generations. These houses ranged from being two to three-story ones. All houses had attached kitchens in the first floor of the main living house, and they burnt firewood inside the house to keep it warm during the winter. Most of the houses were south-facing, whereas only a few of them were east-facing. **Figure 3.19** shows the ground floor plan and sectional views, and **Figure 3.20** shows the exterior view of the investigated houses.

3.3.2.3 Data collection

In all houses, we measured the weight of firewood used every hour over one day. All biomass used, such as firewood, twigs, and agricultural residue, was considered firewood. The measurement was conducted using a weight survey method (Fox, 1984, Bhatta and Sachan; 2004). We measured the weight of the air-dried firewood bundles ready for use with a spring balance and left them in the kitchen. We instructed the household members to burn firewood only from the weighted bundles.

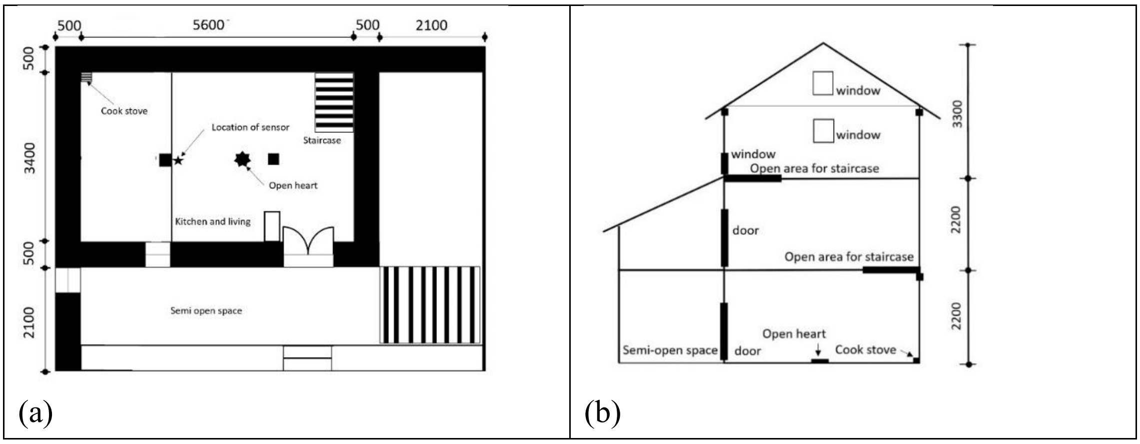


Figure 3.19 Design of a typical house in investigated area: (a) Plan view and (b) Sectional view (unit: mm).

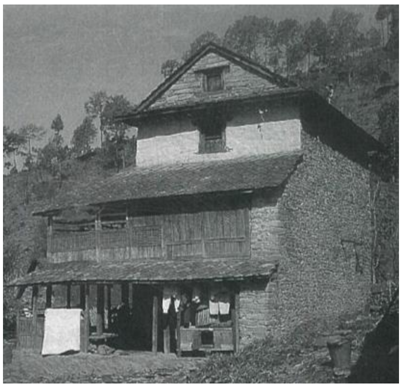


Figure 3.20 External view of an investigated house.

For each hour, the remaining firewood was measured and the difference in the weight between the previous hour and present hour was taken as the amount of hourly firewood consumption. A questionnaire survey was also performed simultaneously in all houses to collect necessary socio-economic and demographic information. Indoor CO_2 concentrations were measured at one-minute intervals in one of the investigated houses for two days using a digital device equipped with a sensor with an electronic data logger (Q Track, 2352, Kanomax). The sensor had an accuracy of ±3%. The device for measuring indoor CO_2 concentrations was placed 1.1 m above the floor surface in the kitchen room. To avoid the effect of indoor CO_2 emissions, we measured outdoor CO_2 concentrations in an open area 500 m away from the houses with the instrument same as the one used for indoor measurements; the device was placed 1.5 m above the ground surface.

3.3.2.4 Calculation for analysis

In this study, per-capita firewood use, household firewood use, and CO_2 emissions were calculated using the following formula:

Household firewood use [kg/ (capita·day)] = (Total firewood used by all households in one day)/ (Number of total households) (3.6)

Per-capita firewood use [kg/ (capita·day)] = (Total firewood used by all households in one day)/ (Total population of all households) (3.7)

CO_2 emissions [kg CO_2 e] = Amount of firewood used [kg] × 1.163 kg CO2 e /kg firewood (3.8)

CO_2 emissions from firewood consumption were calculated by multiplying the amount of firewood consumed with the emission factor used in previous section.

3.3.2.5 Household characteristics

The family size of the investigated households ranged from 2 to 12 members. The average family size was 6.5, which is slightly higher than the recent average family size of 4.9 persons published in the Annual Household Survey 2014/15 of Nepal. Males and females had equal proportions in the investigated population. All households used firewood to cook meals and make tea and animal feed. No household used other fuels such as kerosene, LPG, and electricity for cooking. All investigated households had similar types of traditional cooking stoves, made using stones and mud, in the ground floor of their main house. There were no improved cook stoves in the investigated houses. Approximately 80% of the households cooked meals thrice per day, while 20% of the households cooked meals twice per day. Nearby community forests and private plantations were the main sources of firewood. Firewood chopping was mainly done by men, and firewood collection was done by all family members. Only physical energy was used for firewood collection.

3.3.3 Firewood consumption rate

Firewood is a major source of cooking fuel, and nearly 60% of households in Nepal use firewood as their primary cooking fuel. In this study, all households used firewood to cook meals, boil water, and make animal feed, but the quantity of firewood used varied among the investigated households depending on household size and other factors. Daily household and per-capita firewood consumption were 12 kg/ (capita · day) and 1.8 kg/ (capita · day), respectively. **Table 3.4** shows the variation in firewood consumption in the morning, day, and evening in households with different family sizes. Firewood consumption in the morning and evening was significantly higher than that during the day.

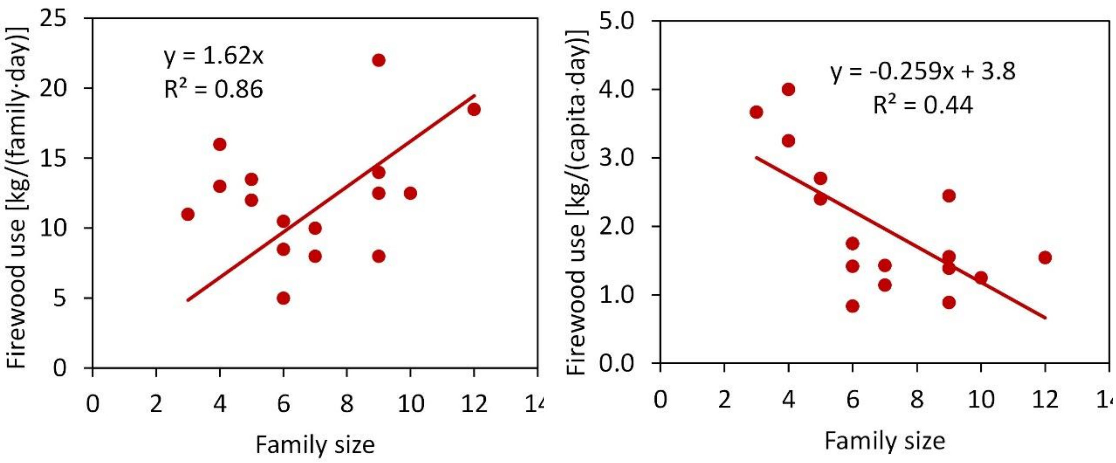
Table 3.4 Firewood consumption for different time of day by family size.

Family size	Firewood consumption [kg/(family · day)]		
	Morning (5:00 - 10:00)	Day (10:00 - 15:00)	Evening (15:00 - 22:00)
3	6	0	5
4	6	2	7
5	6	1	6
6	5	1	3
7	5	1	3
8	0	0	0
9	6	4	4
10	7	1	4
11	0	0	0
12	7	2	11
Average	6	1	5

0: Data unavailable

3.3.4 Relationship between family size and firewood consumption

Firewood consumption is correlated with family size. In order to understand this relationship, we performed a regression analysis between family size and firewood consumption. **Figure 3.21** (a) shows the relationship between household firewood consumption and family size of the investigated households. The number of household members ranged from two to twelve, and household firewood consumption ranged from 5 to 22 kg/day. This result shows that the greater the family size, the larger the household firewood consumption ($r = 0.90$, $P < 0.001$). Besides family size, factors such as number of animals reared, volume of kitchen, and indoor thermal environmental conditions of the houses might have affected household firewood consumption. As the larger households rear more livestock as a part of their income source, they require more firewood to cook animal feed (Pokharel et al.; 2020).



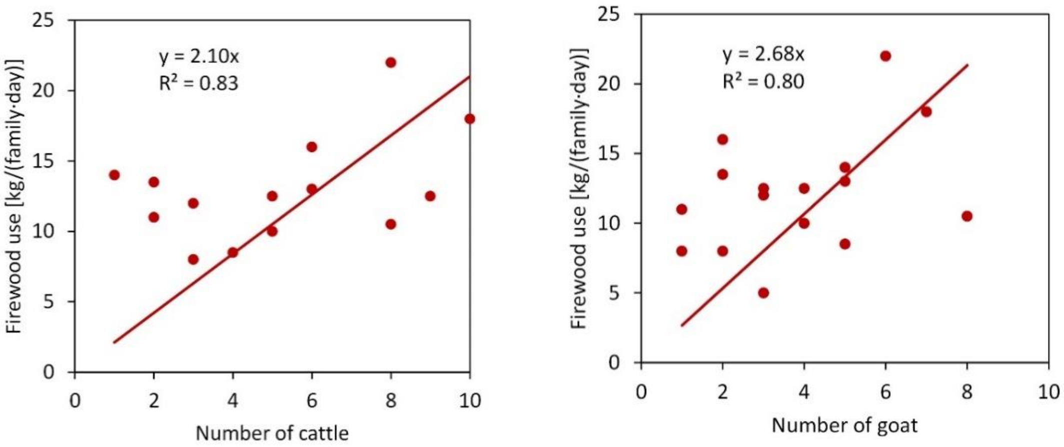
(a) **(b)**

Figure 3.21 Relationship between firewood consumption and family size: (a) Daily household firewood consumption and family size and (b) Daily per-capita firewood consumption and family size.

Figure 3.21 (b) shows the relationship between per-capita firewood consumption and family size. Per-capita firewood consumption ranged from 0.5 to 4 kg/day and significantly decreased as family size increased ($r = -0.66$, $P < 0.001$). The low per-capita firewood consumption in larger households might be due to sharing of firewood used to cook animal feed and maintain the thermal environmental conditions of the houses. This shows that larger households are more efficient firewood users than smaller households, and a smaller family requires more per-capita firewood to fulfil their daily energy needs. This difference in per-capita firewood consumption between smaller and larger households is probably due to the sharing of firewood used to heat firewood burning cook stoves, cooking pots, and other indoor surroundings, which are common in all households.

3.3.5 Relationship between livestock rearing and firewood consumption

Rural population that relies on subsistence agriculture rear animals for different purposes. In the study area, people reared cow and buffalo for milk, ox for energy, particularly for ploughing cultivated land, and goat for meat. The number of animals reared influences the energy use patterns of rural households. **Figure 3.22** presents the relationship between livestock rearing and firewood consumption.



(a) (b)

Figure 3.22 Relationship between firewood consumption and livestock rearing: (a) Cow rearing and (b) Goat rearing.

All investigated households reared cattle (here we consider cattle as cows and buffalos) and goats, but the number varied between houses. The number of cattle ranged from one to ten, and the number of goats ranged from one to eight. It can be seen from **Figure 3.22** that there was a positive correlation between firewood use and livestock rearing, indicating that households with more livestock units use more firewood than those with fewer livestock units. This result seems reasonable because, as the number of livestock increases, the requirement of firewood for cooking animal feed also increases. Further, the correlation coefficient of cattle rearing ($r = 0.91$, $P < 0.001$) was found to be slightly higher than that of goat rearing ($r = 0.89$, $P < 0.001$). This might be due to the requirement of more feed for larger animals than that for smaller animals. In general, in the investigated area, people provided more feed for bigger animals, increasing firewood consumption. Households having milk-producing animals reported that they provided more animal feed to milk-producing animals for better milk production.

3.3.6 Hourly firewood consumption patterns

Hourly firewood consumption patterns varied among houses depending on the work plan and cooking behavior of the residents. The normal routine of the investigated family included awakening between 5:00 to 6:00 hours and sleeping after 21:00 hours. The main meal was cooked twice a day, and only a few households cooked snacks during the day. **Figure 3.23** shows the average hourly household firewood consumption patterns of the investigated households. Generally, firewood burning started at approximately 5:00–6:00 hours.

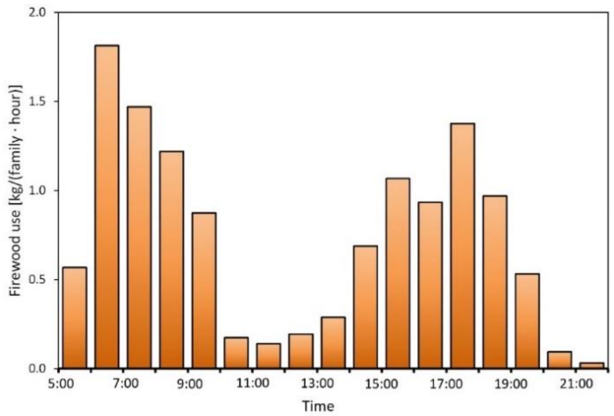


Figure 3.23 Average hourly firewood consumption pattern of investigated 16 households.

When the residents wake up, they started a fire to make tea, followed by cooking the morning meal and animal feed between 7:00 and 9:00 hours. Evening meal preparation started around 17:00 hours, which took 2–3 hours depending on the family size and food traditions. Only two households reported that they prepared animal feed in the evening. Out of the 16 households, 11 households used firewood twice a day, 4 households used firewood thrice a day, and 1 household with elderly residents used firewood for the whole day. As the elderly residents do not go for outdoor work and always stay at home, they prefer to keep the fire burning for the whole day to make tea and to keep their house warm. As shown in **Figure 3.23** highest average hourly firewood consumption was 1.9 kg from 6:00 to 7:00 hours, followed by 1.4kg from 17:00 to 18:00 hours. Higher firewood consumption in the morning is due to the common tradition of cooking meals and animal feed early in the morning.

3.3.7 Relationship between cooking time and rate of firewood consumption

Indoor air pollution depends on the amount and type of fuel used in a household (Thakur et al.; 2017). The indoor air quality of a rural households is affected by firewood consumption inside the houses, and exposure to pollution from firewood consumption has been linked to a variety of health issues (Fuller et al.; 2009). Cooking time and firewood consumption rate are considered simple indicators to determine the exposure and intensity of indoor air pollution. Therefore, we compared cooking time and firewood consumption rate with respect to the household size. We classified all households into small and big households depending on the number of family members. Family members ranging from two to six were considered small households and family members ranging from seven to twelve were considered big households. The average family size was 5 and 9 persons/family for small and big households, respectively.

Figure 3.24 shows the relationship between firewood consumption and cooking time for small and big households. In this figure, the slope of the regression lines corresponds to the hourly rate of firewood consumption in kg/h. The cooking time of small households ranged from 6 to 12 h, and that of the big households ranged from 8 to 15 h per day. The average cooking time was 8.7 and 9.9 h/day for small and big households, respectively. As shown in **Figure 3.24**, there was a strong relationship between firewood use and cooking time in both small ($r = 0.87$, $p < 0.001$) and big ($r = 0.91$, $p < 0.001$) households. However, there was no significant difference in the rate of firewood use between small and big households. The average rate of firewood consumption was similar between small and big households (1.3 kg/h), possibly due to the use of similar types of cook stoves. This implies that both small and big households use firewood at a similar rate. However, big households have to use firewood for longer durations to fulfil their cooking energy requirements.

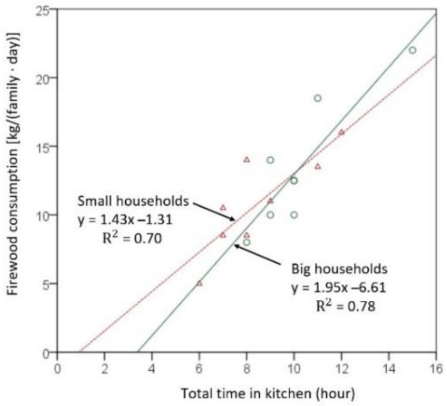


Figure 3.24 Relationship between firewood consumption and cooking time.

3.3.8 Discussion

A large number of households in Nepal still rely on firewood for cooking fuels. There have been several studies on firewood consumption patterns in Nepal, and these studies reported that the annual per capita firewood use varies widely among different parts of the country (Bhatta and Sachan; 2004, Shrestha S.; 2005, Griffin et al.; 1987, Thakur et al.; 2017, Adhikari et al.; 2004, Metz J.; 1994, Shahi et al.; 2020). Table 2 shows the results of similar studies conducted in temperate regions of Nepal and India. The firewood consumption in the present study was 663 kg/capita · year, which falls in the middle of values from previous studies. Several factors could have affected the rate of firewood consumption as there was significant variation in firewood consumption patterns within similar climatic zones (Metz J.; 1994, Shahi et al.; 2020, Webb and Dhakal; 2011, Kandel et al.; 2016). Another cause might be the difference in the research method applied. For example, some researchers measured firewood use only for a few days, but some researchers measured firewood consumption for longer periods, which can influence the firewood consumption rate in similar climatic regions.

Table 3.5 Results of previous studies carried out in temperate climatic regions.

References	Periods	Country	Study area	Climate/ altitude	Firewood use (kg/capita · year)
This study	2002	Nepal	Dhading	Temperate	663
Fox, (1984)	1981	Nepal	Gorkha	Temperate	570
Shrestha (2003)	2003	Nepal	Gorkha and Dhading	Temperate	464
Bhatta and Sachan (2001)	2000-2001	India	Uttranchal	1500-2000m	720
Webb and Dhakal (2003)	2002-2003	Nepal	Dhading	Temperate	683
Kandel et al. ()	none	Nepal	Dolakha	Temperate	612

The per-capita firewood consumption rate in our study was 1.8 kg/ (capita · day), which is similar to the results of Fox (1984), and higher than that of Rijal et al. (2018). The difference might be associated with differences in the socio-economic conditions of the people, availability of fuels in the locality, and family size. Other methodological differences may also have influenced these results. In this study, firewood data were collected on hourly basis for one day in each house during winter, but in the study conducted by Rijal et al. (2018), firewood data were collected on daily basis for the whole year. Therefore, seasonal factors must have affected the results. As our study was conducted in winter, we found a marginally higher value of firewood consumption rate than the previous study (Rijal, 2018). The present study shows that firewood consumption differs according to family size; i.e. per-capita firewood consumption is negatively correlated with family size and household firewood consumption is positively correlated with family size. Bhatta and Sachan (2004) also found similar results and reported that smaller families have more per capita firewood consumption than those of medium and large families. Our present study is consistent with previous studies indicating that smaller households have higher per capita firewood consumption than bigger households, and bigger households are typically efficient firewood users (Rijal, 2018; Bhatta and Sachan, 2004).

The household firewood consumption in this study was 12 kg/family · day, which is higher than the results obtained in other studies (Fox, 1984, Pokharel et al.; 2020). The cause of higher household firewood consumption in our study might be associated with family size, the number of animals reared, and other socioeconomic factors. We found that household firewood consumption is positively correlated with household size. This result aligns with many other studies that have also found that household firewood consumption was positively correlated with family size (Fox J.; 1984, Bhatta and Sachan; 2004, Pokharel et al.; 2018, Kandel et al.; 2016). Thus, we confirmed that household size was indeed an important factor of firewood consumption.

Nepal is an agriculturally dominant economy where 74% of the households rely on the subsistence-based agricultural (Kandel et al.: 2016, Joshi et al.; 2017). People living in rural areas rear many animals for energy, meat, and other economic purposes that may affect the household firewood consumption patterns. The results of this study showed a positive relationship between firewood consumption and the number of livestock reared. This is similar to many other studies that have found that households with more livestock units consume more firewood (Mahapatra and Mitchell; 1999, Cook P.; 2009, Baland et al.; 2012). Our result is however opposite to the result obtained by Bewket (2005) in Ethiopia, where household firewood consumption was negatively correlated with the number of livestock units. The reason for lower firewood consumption by households with more livestock units was the use of animal dung as a substitute for firewood in Ethiopia (Bewket W.; 2005). In our study, people used animal dung only as organic fertilizer, and hence firewood consumption did not decrease with an increase in the number of livestock units. On the contrary, the amount of firewood consumption increased with the increase in the number of livestock units due to the requirement of additional firewood for preparing animal feed.

Indoor air pollution produced by the domestic combustion of solid fuels is a significant cause of morbidity and mortality across the world especially in developing countries (WHO; 2006). We have found that all investigated households used more firewood in the morning and evening hours. It indicates that high CO_2 emissions and high indoor CO_2 concentrations in the morning and evening hours may pose a serious health risk to the rural people. The health problem due to indoor air pollution in rural households becomes more severe during winter when cooking occurs in non-ventilated conditions, and people enjoy staying near the cooking place for a longer time to keep themselves warm (Rupakheti et al.; 2019, Rijal et al.; 2005, Regmi et al.; 2016, 2017). We can speculate that the installation and use of mechanical ventilation system in the rural households would result in some health gain, particularly in the morning and evening hours. Rijal et al. (Rijal et al.; 2005) showed that installation of an improved cookstove can minimize indoor air pollution in rural areas of Nepal. Therefore, improved cooking technology and introduction of mechanical ventilation in the rural houses with necessary preventive measures would be the ideal way of dealing with indoor air pollution. To create favorable indoor environment in the rural houses, knowledge on hourly firewood consumption helps assess the influence of firewood consumption on indoor air pollution.

Average exposure on firewood consumption was found to be 8.7 and 9.9 hours/day for small and big households, respectively, which is higher than the exposure time of 3–7 hours/day reported by Ranavat et al. (Ranabhat et al.; 2015). Longer cooking time has a significant negative effect on the health condition of people who are exposed directly to firewood burning (WHO;2016, Pandey et al.; 1989, Arnold et al.; 2006, Win et al.; 2018).

Household CO_2 emission was found 14.26 kg CO_2 e/ (household · day) which is more than the value of 6.4 kg CO_2 e/ (household · day) obtained in Bangladesh (Baul et al.; 2018). This difference might be due to the difference in the type of fuel, rate of fuel used and efficiency of cooking devices used between the two countries. The use of clean cooking fuel and efficient technologies can play an important role in the reduction of household CO_2 emissions. Therefore, an intensive awareness program is required to improve the indoor air quality and health condition of the rural population.

3.3.9 Conclusions

Based on the present study conducted to assess the hourly firewood consumption patterns and associated CO_2 emission patterns of rural households in Nepal, we summaries our findings below:

1. People living in rural areas fulfil their daily energy need by using firewood, and the rate of per-capita and household firewood consumption was found to be 1.8 kg/ (capita · day) and 12 kg/ (family · day), respectively.
2. Household firewood consumption was positively correlated with family size and the number of livestock reared. The per-capita firewood consumption was negatively correlated with family size.
3. The average cooking time was found to be 8.7 and 9.9 h/day for small and big households, respectively. Regardless of household size, people consumed firewood at the same rate (1.3 kg/hour). However, bigger households spent more time cooking to fulfil their daily energy needs.
4. High emissions of indoor CO_2 in the morning and evening hours due to high firewood consumption may pose a serious health risk to the rural population. Therefore, intensive awareness programs and installation and use of mechanical ventilation devices in the morning and evening would improve the air quality and health conditions of the rural population.
5. Household CO_2 concentration was positively correlated with CO_2 emissions due to firewood burning, and daily CO_2 emissions were 14.26 kg CO_2 e/ (household · day). Clean cooking fuels and efficient cooking technologies would help minimize household CO_2 emissions.

3.4 Energy transition toward cleaner energy sources

3.4.1 Introduction

Energy is one of the most important inputs for modern economics, as it improves the socioeconomic development and well-being of society. Worldwide, the demand for energy has rapidly risen owing to an increase in the population and industrial sectors, leading to increased use of non-renewable energy resources, such as petroleum and coal (Hussain et al.; 2019). Ensuring universal access to affordable energy services has been identified as one of the targets of the Sustainable Development Goals (SDGs) set for 2030 (Shahi et al.; 2020). The expansion of the energy infrastructure and efficient technology upgrades, facilitating clean energy services, remain challenging for most developing countries. With rising concerns over environmental sustainability, the focus of energy policies has generally shifted from inefficient technology and traditional energy resources toward improved technologies and clean energy resources, especially in the context of developing countries.

Nepal, situated in the Himalayan mountain range between India and China, is one of the least developed countries in the world and has a low per-capita energy. The mountainous topography of Nepal yields a challenge to the development of modern energy infrastructure in all regions of the country. The unavailability and unaffordability of clean commercial fuels, such as electricity and liquified petroleum gas (LPG), has long been a serious problem in Nepal. Owing to the lack of access to clean commercial fuels in rural areas, most people rely on traditional fuel resources to fulfil their daily household energy needs. A heavy reliance on traditional fuels and low per-capita electricity consumption has resulted in adverse environmental and public health impacts, especially for women who work as the gatherers, processors, carriers, and end-users of household energy (Sovacool et al.; 2011). Nepal has no major assessable reserves of coal, natural gas, or oil, and is largely dominated by traditional energy sources, such as firewood, agricultural residue, and animal dung for domestic energy requirements (Gurung et al.; 2011, Parikh, 2011). Owing to the steep gradient and mountainous topography, Nepal is characterised by a substantial potential for hydroelectricity and other renewable energy resources; however, this potential remains untapped due to various economic and other constraints (Parajuli et al.; 2014). Electricity generated from hydropower is regarded as a clean and sustainable source of energy because it does not require the input of fossil fuels and does not directly emit greenhouse gases to the surrounding environment. Geographical remoteness, a scattered consumer, higher costs associated with the energy supply and maintenance, low consumption, and low level of household income are only a few of the factors that make linking rural mountainous areas to the national electricity grid difficult or even impossible (Parikh, 2011).

The Nepalese government is committed to taking actions to support the initiatives of SDGs by improving access to efficient and environmentally friendly energy sources, particularly electricity, across the country. However, due to the lack of access to clean energy and low incomes, rural residents rely heavily on locally available traditional fuels. The Nepalese government encourages rural inhabitants to use better cooking technologies through subsidy schemes, especially biogas and updated cook stoves, to improve their living standards. Solar panels are also encouraged and widespread in households where grid electricity is not available. The establishment of subsidy schemes and a package of incentives for private sector hydropower generation projects was established to ensure a reliable electricity supply at a reasonable price (Parikh, 2011). Similar to other developing countries, with improved accessibility to clean energy and higher income levels, rural residents gradually switch from traditional energy to clean energy resources. This energy transition pattern leads to a structural change in the energy demand and consumption and has important policy implications for the sustainable management of energy resources. Thus, this study allows us to compare the prevalence of energy transition patterns based on a literature review and a field survey study on household energy in three climatic regions in Nepal.

3.4.1.1 Background

Previous studies have recently widely examined the residential energy use in Nepal. Malla (2013), examined the energy use patterns, reporting that energy use is heterogeneous across regions, with biomass dominating the energy mix in Nepal. Fox (1984), conducted a field survey in Nepal, finding that firewood consumption ranges from 0.96–1.75 kg/capita/day in rural households. Family size, cast, and season all have an influence on this consumption rate. Rijal (2002), also investigated the firewood consumption rate in traditional households in Nepal, finding that the firewood consumption rate was 235–1,130 kg/capita/year. Shahi et al. (2020), found that electricity use in Nepal is lower than that in other developed and developing countries. They found that electricity use is a function of the household income level, occupation, family size, and educational level of the responsible person. In Bhutan, Rahut et al. (2014) analysed the determinants of household energy use, finding that wealthier households tend to use cleaner energy for lighting, cooking, and heating. Pradhan and Limmeechokchai (2017) conducted research on electric and biogas stoves as options for cooking, reporting that the consumption of imported fossil fuels would decrease with the use of electricity and biogas for cooking in Nepal. Hydropower is the only source of electricity in Nepal; some studies have highlighted the opportunities and challenges associated with this energy source. For example, Sovacool et al. (2011), examined the socioeconomic barriers to hydropower development in Nepal, providing evidence of the technical, social, economic, and institutional barriers to electricity development in Nepal. Gurung et al. (2011) found that micro-hydropower plants could be the milestone in providing clean, affordable, and sustainable energy in rural areas of Nepal. Alam et al. (2017) reported that Nepal, with the development of hydropower, can meet its domestic electricity demand, create a surplus for exports, and generate employment for citizens. Many other studies have reported that previous severe electricity crises led to blackouts for up to 16 h per day and a dependency on traditional fuels due to the lack of accessible and affordable sources of other clean fuels in different parts of the country (Sovacool et al.; 2011, Nakarmi et al.; 2016, Shahi et al.; 2020, Achary and Adhikari; 2021,). Access to clean energy resources is important to not only to promote better health and environmental conditions but also to enhance the socioeconomic development of the region. However, to date, no studies have focused on the energy transition patterns in Nepal. Thus, this study highlights the current energy transition patterns in Nepal. The findings of this study can aid in the formulation of effective energy policies and development strategies that allow us to explore how to overcome the existing challenges to providing clean and affordable energy to the citizens of Nepal, as well as to people worldwide.

3.4.1.2 Objectives

Nepal has recently made notable progress in rural electrification and the distribution of clean commercial fuels across the country (Shahi et al.; 2020). Despite the ambitious rural electrification projects and rise in per-capita income, a significant proportion of Nepalese households still use traditional fuels for cooking and space heating. Therefore, considering the recent developments in energy accessibility, use of clean energy resources, and improved cooking technology are crucial. Therefore, the main objective of this study is to review the current energy transition patterns in Nepal while specifically focusing on clean energy development and improved cooking technologies in Nepal. To understand the current energy development trends, this study provides an updated view of current electricity consumption trends, hydropower development trends, and the dispersion of other clean and alternative energy services throughout the country. Furthermore, based on a field survey, this study analysed the cooking fuel situation in three climatic regions in Nepal.

3.4.2 Material and methods

This study used two methods. The first method was used to conduct an analysis of the national clean energy development situation based on secondary data. These data were collected from various national and international sources, such as the International Energy Agency (IEA), Government of Nepal/Water Energy Commission Secretariat (GoN/WECS), Alternative Energy Promotion Center (AEPC), Nepal Electricity

Authority (NEA), and other relevant published research articles and reports. The second method was a case study on the household energy use of 516 households in three climatic regions in Nepal. **Table 3.6** shows the information on the study area and surveyed houses.

Table 3.6. General information on the study area and surveyed houses.

Description.	Cold (Solukhumbu)	Temperate (Panchthar)	Sub-tropical (Jhapa)
Total population [# of persons]	105 885	191 817	812 650
Population density [person/km^2]	39	150	510
Area [km^2]	3,312	1,241	1,606
Altitude [m]	2,413	1,376	300
No. of houses	76	262	176
Survey period (2018)	8–14 Jan. 2018	29 Dec. 2017 to 6 Jan. 2018	16–24 Dec. 2017
Availability of grid electricity	No	Yes	Yes
Access to black-topped roads	Yes	Yes	Yes

3.4.3 Per-capita electricity consumption

Electricity is a modern energy resource used for various purposes with modern technology. In Nepal, almost all the electricity is generated via clean hydroelectric resources. Access to electricity is a determining factor for improving the quality of life. There has been a recent substantial increase in the electrification rate, reaching up to 82% of the population in 2016 (Zahnd and Kimber; 2009). In the rural areas of developing countries, people use electricity for lighting and charging mobiles. In contrast, in urban areas, people also use electricity for cooking, as well as for mechanical heating and cooling purposes (Shahi et al.; 2020).

Figure 3.25 shows the annual rate of per-capita electricity consumption and per-capita gross domestic production (GDP) from 2000 to 2018 in Nepal. Both values appear to have grown steadily during that period. The per-capita electricity consumption increased from 63 kWh/yr in 2000 to 238 kWh/yr in 2018; however, this per-capita electricity consumption still remains the lowest among contemporary global societies. **Table 3.7** shows the per-capita energy consumption of some neighboring countries and the global average.

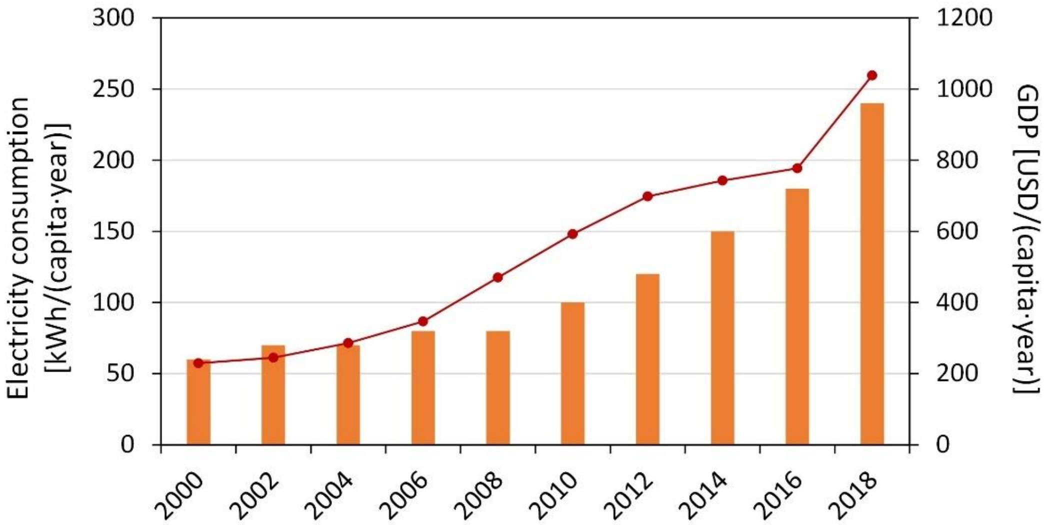


Figure 3.25. Per-capita electricity consumption trend from 2000 to 2018 (World bank, 2020).

This shows that Nepal consumes marginally less per-capita electricity than other developed and developing countries. Several reasons are associated with the low per-capita electricity consumption in Nepal. First, Nepal relies heavily on locally available traditional energy sources, such as firewood and agricultural residues, which represent 78% of the total energy consumption in Nepal (WESC, 2014). Second, low-income levels and high electricity prices also impact poor people who, upon gaining access to electricity, are unable to fully use electricity for cooking and space heating. According to Poudyal et al. (WESC, 2010), the cost of electricity was $0.90 USD/kWh for end-users in 2018, which is among the highest in the world. Such a high price for electricity and the low-income levels may also minimise the per-capita electricity consumption. Shahi et al. (2020) reported that household income has a positive correlation with electricity consumption, where low-income residents use less per-capita electricity. Third, the electricity crisis in Nepal disrupts the daily lives of individuals and businesses through frequent power outages. As a result, residents must face 12–14 h of load shedding every day, especially during the winter months (WESC, 2010).

In Nepal, the residential sector is the major electricity-consuming sector, accounting for nearly 87% of the total electricity consumption (Nakarmi et al.; 2016, WESC, 2014). Owing to the high price, unreliable electricity supply, and the availability of firewood adjacent to their houses, most of the households that participated in our case study reported that they did not prefer to use any mechanical heating and cooling system in their houses. This revealed that an affordable price, reliable supply, and use of electricity for cooking and heating in the domestic sector may increase the per-capita electricity consumption, which can play a vital role in socioeconomic development and well-being of the residents. Low per-capita electricity-consuming countries, including Nepal, must promote the use of clean sources of electricity to the greatest extent possible, instead of traditional biomass and imported fossil fuels.

Table 3.7 Per-capita electricity consumption in neighboring countries.

Year	Per-capita electricity consumption [kWh/ (capita·year)]				
	World average	India	Bangladesh	China	Japan
2000	2300	400	100	1000	8100
2010	2900	600	300	3000	8100
2018	3300	1000	500	4900	7600

3.4.4 Trends of hydroelectricity development in Nepal

Hydropower has been considered one of the sources of clean electricity because it does not emit polluting materials into the air or onto land. Nepal is characterised by significant hydropower resources, where more than 6,000 perennial rivers and rivulet flow with an average annual water runoff of 225 billion m3, thereby providing a substantial energy potential (Zand and Kimber; 2009). Previous studies have estimated that the feasible potential of Nepal for hydropower generation is approximately 83 GW, of which approximately 43 GW are considered technically and economically viable (WESC, 2010). Hydropower development in Nepal began on 22 May 1911 with the installation of 500 kW of electricity at Pharping. However, Nepal has only harnessed 2% of its commercially feasible hydropower potential (Gunatilake et al.; 2020).

Figure 3.26 shows the hydroelectricity generation trends in Nepal from 1991 to 2018. This shows that the growth in the installation capacity of hydroelectricity began to occur in a visible manner from 1997 to 2002, and is characterised by a continuously increasing trend. The first hydropower development policy was announced in 1992 to attract the private sector for hydropower development. The private sector started to develop hydropower projects shortly thereafter (Ministry of energy, 1992). During 2000 and 2001, the private sector successfully completed large projects, such as Khimti Khola 60 MW and Upper Votekoshi 45 MW (Table 3); these projects contributed to an increase in the hydroelectricity installation capacity. In 2002, the NEA also completed the 144 MW Kaligandaki hydropower project, which plays a significant role in partially fulfilling the electricity demand.

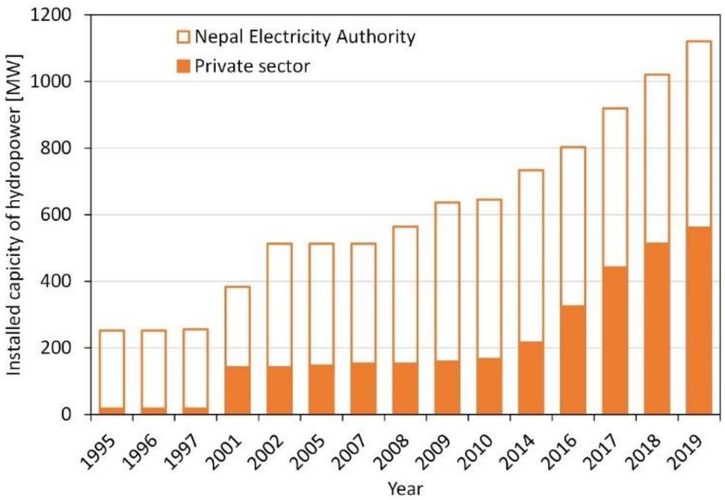


Figure 3.26. Hydropower development trend in Nepal (1995-2019) [Shrestha; 2017, NEA 2020]

During the political unrest period, investors were not willing to take risks for hydropower development; from 2001 to 2010, the private sector was unable to develop hydropower projects (Singh et al.; 2020). After 10 years of civil war, a peace agreement was signed in 2006, and the political environment became stable, allowing hydroelectricity development. Subsequently, hydroelectricity development began to accelerate. As a result, the number of hydroelectricity projects has gradually increased since 2010. As of 2019, the installed electricity capacity in Nepal reached approximately 1,120 MW, including both the private and public sectors (Shrestha; 2017, NEA; 2018). Some other new hydropower projects are currently under development for electricity generation, which will add another 1,300 MW to the national grid, creating a surplus for the export of clean hydroelectricity during the fiscal year 2020/21 (Alam et al.; 2017, Acharya and Adhikari; 2021).

Tables 3.8 and 3.9 list the hydropower plants developed by the NEA and private sector with their locations and capacities. Hydropower development in Nepal began on 22 May 1911 with the installation of 500 kW of electricity at Pharping. In recent years, the rapidly increasing trend of hydroelectricity production in Nepal shows that the energy situation has changed to an optimistic attitude toward clean resources; however, the replacement of traditional fuels for cooking and heating is a challenging task. Energy transition toward modern clean energy sources can improve the future of Nepalese citizens in various ways. For example, the use of electricity for cooking and heating, instead of traditional fuels, can benefit millions of people with respect to respiratory health risks caused by indoor air pollution. Moreover, fuel collection is a time-consuming task in rural societies, and its replacement by electricity can conserve a considerable amount of time. There must be improvements to the current state of low per-capita electricity consumption and the high dependency on traditional fuels for cooking and space heating. The Nepalese government must implement policies to enhance electricity use in all households for cooking and heating by providing subsidies to adopt new and clean technologies. They must also simultaneously promote clean and renewable energy development in all parts of the country.

Table 3.8 Hydropower plants developed by NEA and country of origin (NEA; 2020, Shrestha 2017).

Name	Installed capacity (MW)	Year established	Location (district)
Upper Trisuli 3A	60.0	2019	Rasuwa and Nuwakot
Chameliya	30.0	2018	Darchula
Middle Marsyangdi	70.0	2008	Lamjung
Kaligandaki A	144.0	2002	Syangja
Modi Khola	14.8	2000	Parbat
Puwa Khola	6.2	1999	Ilam
Chatara	3.2	1995	Sunsari
Marsyangdi	69.0	1989	Tanahu
Kulekhani-II	32.0	1986	Makawanpur
Seti	1.5	1985	Kanski
Devighat	15.0	1984	Nuwakot
Kulekhani-I	60.0	1982	Makawanpur
Gandak	15.0	1981	Nawalparasi
Sunkoshi	10.1	1972	Sindhupalchwk
Fewa	1.0	1969	Kanski
Trisuli	24.0	1967	Nuwakot
Panauti	2.4	1965	Kavrepalnchok
Sundarijal	0.6	1934	Kathmandu
Pharping	0.5	1911	Kathmandu
Total	**559.3**		

As the installed capacity of hydroelectricity growth begins slowly and then accelerate rapidly, this study carried out exponential regression analysis on installed capacity of hydroelectricity and time. **Figure 4** shows the installed capacity of hydroelectricity from NEA and private sector in corresponding year. All values plotted in this Figure were obtained from **Tables 3.4** and **Table 3.5**. However, we did not plot the small projects less than 5 MW which is shown in **Table 3.5**. The regression line shows the continuous increasing trend of hydroelectricity capacity in Nepal. However, it is still below the current electricity demand of the country and this is being fulfilled by importing electricity from India.

Table 3.9 Hydropower plants developed by IPP and country of origin (NEA; 2020, Shrestha 2017).

Name	Installed capacity (MW)	Year established	Location (district)
Rudi Khola A	8.8	2019	Lamjung and Kaski
Bagmati Khola small	22.0	2019	Makwanpur and Lalipur
Pikhuwa Khola	5.0	2019	Bhojpur
Molung Khola	7.0	2018	Okhaldhunga
Madkyu Khola	13.0	2018	Kaski
Super Mai	7.8	2018	Ilam
Mai Sana Cascade	8.0	2018	Ilam
Mai Cascade	7.0	2016	Ilam
Upper Mai Khola	10.0	2016	Ilam
Daraudi Khola A	6.0	2016	Gorkha
Andhi Khola	9.4	2015	Syangza
Naughad gad Khol	8.5	2015	Darchula
Mailung Khola	5.0	2014	Rasuwa
Mai Khola	22.0	2014	Ilam
Upper Hugdi Khola	5.0	2014	Gulmi
Lower MadiI	10.0	2013	Parbat
Sipring Khola	9.7	2013	Dolakha
Tadi Khola (Thaprek)	5.0	2013	Nuwakot
Ankhu Khola-I	8.4	2013	Dhading
Jogmai	7.6	2012	Ilam
Upper Mai C	5.1	2012	Ilam
Upper Marsyangdi A	50.0	2011	Lamjung
Hewa Khola A	14.9	2011	Panghthar
Thapa Khola	13.6	2011	Mygdi
Upper Madi	25.0	2009	Kaski
Chilime	22.1	2003	Rasuwa
Indrawati-III	7.5	2002	Sindhupalchok
Upper Bhotekoshi	45.0	2001	Sindhupalchowk
Khimti Khola	60.0	2000	Dolakha
Jhimruk Khola	12.0	1994	Pyuthan
Small projects less than 5 MW	120.4		
Total	**560.8**		

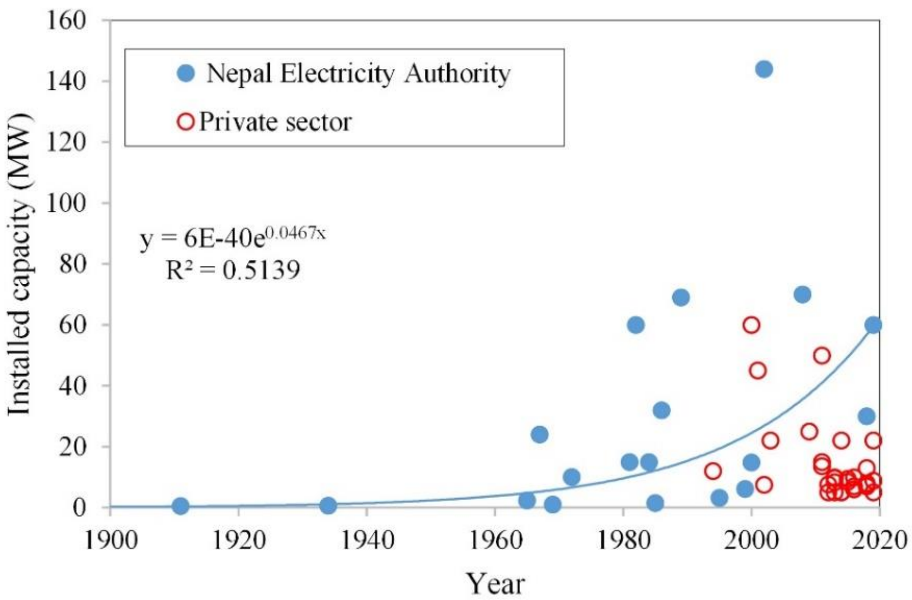


Figure 3.27. Hydropower development trend in Nepal (1995-2019)

3.4.5 Installed capacity of hydroelectricity and GDP

Several national policy makers and international organizations consider the availability of hydroelectricity as an engine for socioeconomic development, which can provide access to electricity, as well as stimulate economic activity and the economic growth of the country (Singh et al.; 2020). The installed hydroelectricity capacity may play an important role in increasing the GDP by providing energy impetus for industrial development. **Figure 3.28** shows the relationship between the GDP and installed hydroelectricity capacity in Nepal. The vertical axis denotes the per-capita GDP and the horizontal axis denotes the installed hydroelectricity capacity of Nepal from 1991–2018. We obtained the GDP per capita data from the World Bank data book (2020) and the installed hydroelectricity capacity from the NEA annual reports. The GDP appears to have a good linear correlation with the installed hydroelectricity capacity in Nepal.

As the installed capacity increases, the GDP per capita also increases significantly ($r = 0.95$, $p < 0.001$), indicating that with the rise in the installed hydroelectricity capacity, the GDP per capita must increase to a higher level. The energy sector of Nepal faces two serious problems. The first is an excessive dependence on the use of traditional energy sources, such as firewood and agricultural residues, which is one of the main causes of economic, environmental, and health threats. The second is the highly uneven access to modern energy services and low rate of clean energy (electricity and LPG) consumption (World bank; 2020) both of which are highly dependent on the level of socioeconomic development and societal well-being. This result indicates that increasing the installed hydroelectricity capacity in Nepal is necessary to achieve socioeconomic growth and subsequent rational modernization.

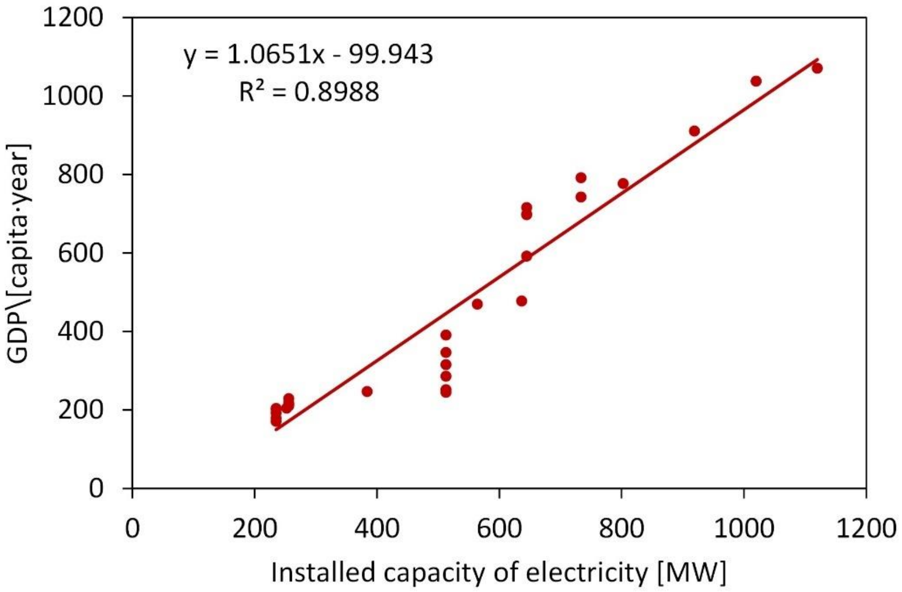


Figure 3.28 Relationship between the GDP per capita per year and installed hydroelectricity capacity in Nepal from 1991 to 2019.

3.4.6 Installed capacity of hydroelectricity and GDP

Achieving affordable and clean energy access for all people has been a priority of the Nepalese government for societal well-being. The AEPC is a central organization that aims to promote alternative energy and clean cooking technology (Islar et al.; 2017). **Figure 3.29** shows the cumulative number of households that installed biogas, solar home systems, and improved cooking stoves from 2007 to 2017 with the help of the AEPC. Figure 5 shows a continuously increasing trend. According to the AEPC, by 2019,794 276 solar home systems, 400,432 domestic biogas plants, and 1,343,224 improved cook stoves were installed in households to provide clean energy services. Progress in the access to solar home systems and clean cooking technology has helped people reduce household indoor air pollution and lower associated health problems. Providing clean energy to the rural population remains a key priority to further reduce air pollution and emissions, which ensures the sustainable socioeconomic development of the nation. By 2014, more than 1,000 micro-hydro power plants, with a total capacity of 25 MW, were installed to provide affordable and reliable electricity to rural households unable to access national grid electricity.

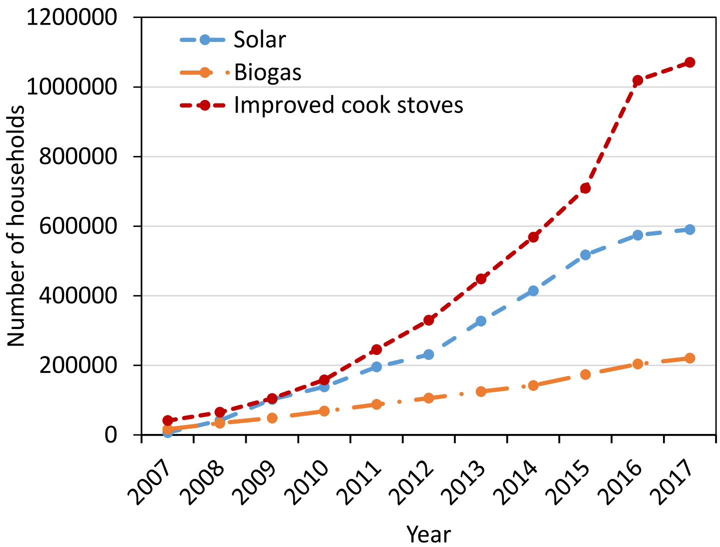


Figure 3.29. Cumulative distribution of biogas, solar home system and improved cooking stoves in Nepal (2007-2017) (AEPC,2019)

3.4.7 Current household cooking fuel access in three regions

Based on the case study carried out in the three climatic regions in Nepal, the accessibility to cooking fuel was analysed. In each region, all households were categorised into traditional, mixed, and commercial fuel-using households based on the cook stoves present in each household. **Figure 3.30** shows the percentage of traditional, mixed, and commercial fuel-using households in the three regions. In general, most of the households used mixed fuels, where the maximum number of households in all regions used both traditional and commercial fuels for everyday cooking purposes. However, the frequency of the use of clean cooking fuels varied depending on the socioeconomic conditions of each household. Only 20% of mixed fuel-using households used electricity and LPG at least once per day for cooking while the remaining households only occasionally used clean cooking fuels. The percentage of mixed fuel-using households was quite high in sub-tropical regions (86%), followed by cold regions (65%), but significantly lower in temperate regions (58%). The percentage of traditional fuel-using households declined gradually from temperate (36%) and cold (27%) regions to sub-tropical (5%) regions.

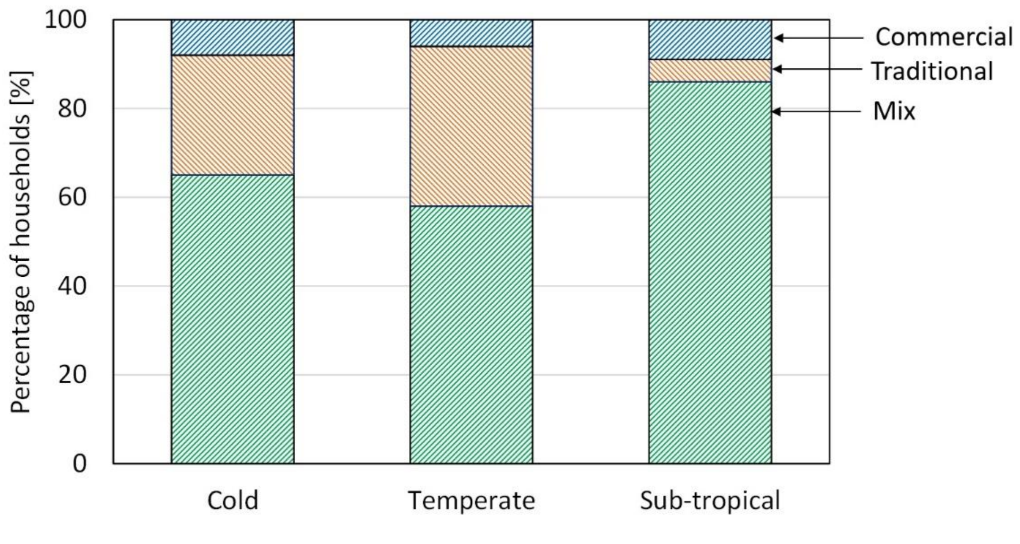


Figure 3.30 Proportion of traditional, mixed and commercial fuel user households in the three regions.

The high percentage of mixed fuel-using households, low percentage of traditional fuel-using households, and high percentage of commercial fuel-using households in sub-tropical regions indicates that comparatively more households are shifting toward clean energy resources than the other two fuel types. Several factors may affect the energy transition patterns, such as the high accessibility of commercial fuels and the low availability of traditional fuel resources in sub-tropical regions. This may be the main cause in the more rapid shift toward clean fuels than in the two other regions. This result appears to be reasonable because the sub-tropical region is more urbanised and highly populated than the other regions (see Table 1). All the investigated households in the sub-tropical region were connected to grid electricity, with easy access to other commercial fuels. The percentage of households in commercial mode was 8%, 6%, and 9% in the cold, temperate, and sub-tropical regions, respectively.

On average, 25% of the households relied on traditional cooking fuels, such as firewood and agricultural residues, while only 8% of the households relied on clean cooking fuels, such as LPG and electricity. The remaining 67% of the household relied on both traditional and commercial fuels for cooking activities. The high percentage of mixed fuel user households in all regions reveals that most of these households prefer to use a combination of clean cooking fuels and traditional sources. Ravindra et al. (2018) reported that only 13% of the households in India primarily depend on clean cooking fuels, which is slightly higher than the results obtained in this study. This shows that clean cooking fuel remains relatively rare in the case study area. The most common reason for the non-adoption of clean cooking fuels was the unavailability of reliable clean fuels near the households, high installation costs, and comparatively high monthly expenditures on fuels. These factors in addition to a lack of knowledge regarding electric cooking technology have been reported as barriers to the adoption of electricity as a regular cooking fuel.

3.4.8 Energy mix shift towards clean resources

Energy is conceptualised as the share of various primary energy resources used to meet the energy requirement for a given reason, which can vary significantly from one country to another. The energy resources of Nepal are generally categorised into three groups: traditional energy resources, including firewood, agricultural residue, and animal dung; commercial energy resources include modern energy resources, such as electricity, LPG, and petroleum products; and renewable energy resources include other alternative natural resources, such as solar power, wind power, and electricity from isolated micro- and mini-hydropower plants. Commercial and renewable energy resources are considered cleaner sources of energy as compared to traditional resources.

Figure 3.31 shows how the energy mix changed from 2014/15 to 2019/20 in Nepal. **Figure 3.31** indicates that the energy mix has slowly and continuously changed toward commercial energy resources. The share of traditional energy resources has decreased from 78% to 68%, while that of commercial energy resources increased from 20% to 28% during that period. Renewable energy resources contribute to a very low share in the primary energy supply of Nepal, which has increased from 2.5% to 3.2%.

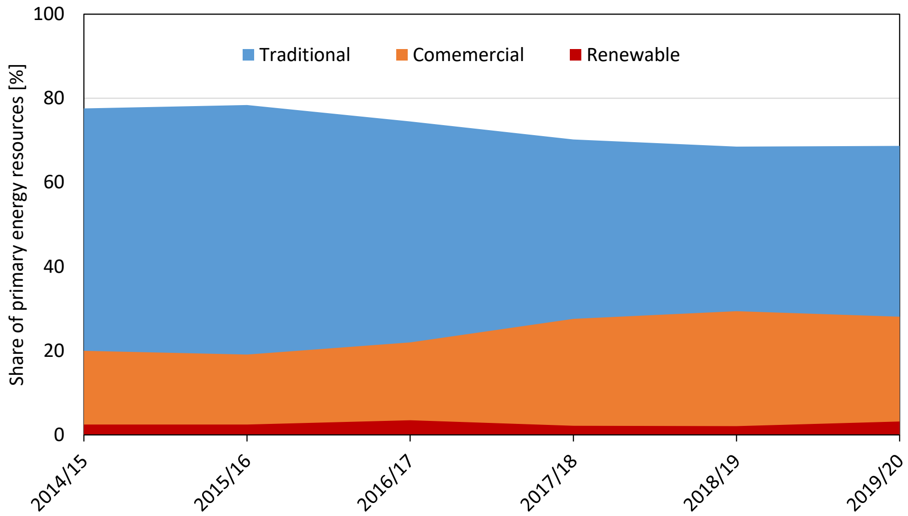


Figure 3.31. Energy mix in different years from 2014/15 to 2019/20 (Parajuli et al.; 2014, Gurung et al.; 2013, AEPC; 2019)

This statistic also indicates that more than half of the energy used in Nepal is fulfilled by traditional resources. Traditional energy resources are mostly used in the household sector, particularly in cooking and heating, which suggests that the Nepalese household energy sector still relies heavily on traditional fuel resources. The slower rate of energy transition toward cleaner energy resources can be attributed to the lack of reserves of coal, natural gas, or oil and insufficient electricity production to fulfil the energy demands of the country (Islar et al.; 2017). Hussain et al. (2019) reported that Nepal has to increase its installed electrical capacity and production not only to meet the current demand, but also to meet the growing future demand for electricity. Nepal must emphasise the production and utilisation of renewable energy to enhance its energy transition toward cleaner resources.

3.4.9 Conclusions

How the energy transition taking place is important to draw future consideration to enhance the socioeconomic development and to promote health and environmental condition of the people particularly living in developing countries but so far, it has not yet been known very well. This study analyzed the current energy transition patterns in Nepal through a field survey and literature review. The findings are summarized as follows.

1. The rate of per-capita electricity consumption was 238 kWh/capita/year, which is lower than that of other contemporary global societies. In Nepal, due to the lack of reliable electricity, rural households heavily rely on firewood; therefore, the per-capita electricity use is the lowest in the world. An effective energy policy is required to increase the per-capita electricity consumption.
2. Hydropower development is an emerging sector that provides clean energy resources in Nepal. The current installed hydroelectricity capacity has reached 1,120 MW. The increasing trend in hydroelectricity development in Nepal is expected to meet the country's demand for cleaner energy to improve the quality of life for its citizens.

3. A significant relationship exists between the GDP and installed hydroelectricity capacity. As the installed hydroelectricity capacity increases, the GDP per capita tends to increase.
4. Cleaner technologies, such as solar home systems, domestic biogas plants, and improved cook stoves, have played a vital role in minimizing health and environmental problems, particularly in rural areas of Nepal where national grid electricity is not accessible.
5. The field survey showed that 25% of the households relied entirely on traditional cooking fuels while 67% and 8% of the households relied on mixed and commercial cooking fuels, respectively.
6. The share of traditional energy resources has decreased from 78% to 68%, while the share of commercial energy resources increased from 20% to 28% from 2014/15 to 2019/20. This indicates that the Nepalese government must eliminate its heavy reliance on traditional energy resources by providing clean and sustainable energy resources to all citizens.

Chapter 4: Indoor Air Pollution

4.1 CO_2 emissions and concentrations

4.1.1 Introduction

In Nepal most of the households in rural and peri urban area still burn solid fuels in inefficient cook stoves inside the improperly ventilated kitchens, which results in very high levels of indoor air pollutions. Indoor air pollution is the world's most serious air pollution problem, especially for poor people living in the developing countries. In developing Asia, low-grade solid fuel such as wood, agricultural waste, cattle dung, and low-quality coal are still commonly used in rural and peri-urban areas. Three-stone stoves or simple clay cook stoves with low efficiency are prevalent in rural areas, hence more fuel is required and higher amount of indoor pollutants are produced per unit of energy (Rupakheti et al., 2019).

Figure 4.1 Children exposed to indoor air pollution while sitting near to fire

According to World Health Organization 3.5 million people prematurely die every year through diseases caused by HAP due to the lack of proper and efficient cooking stoves (WHO, 2018). These deaths are classified into five major categories in which mostly people die from pneumonia (27%) and ischemic heart disease (27%), while 18% dies from stroke, 20% from chronic obstructive pulmonary disease and 8% from lung cancer

(WHO, 2018). In Nepal, firewood is the major source of cooking and heating energy and it provides 78% of the total energy demand of the country (Poudayl et al.; 2019, IEA; 2016). Many households start to use different fuels such as; LPG, electricity, kerosene and biogas to fulfill their everyday cooking energy demand, however the fraction and the frequency of using clean fuels is very low due to the lack of affordability and accessibility. Therefore, indoor air pollution due to the indoor firewood burning is a major health risks in Nepal. It was reported that household air pollution from cooking with solid fuels was the third largest contributor to the burden of disease in Nepal and was responsible for around 1500preamature death in 2013 (Rupakheti et al., 2019). CO_2 concentration is the simplest indicator of combustion-related air pollution evaluation in the households therefore in this study we have investigated the CO_2 concentrations of the households in Cold temperate and sub-tropical households.

Figure 4.2 shows the firewood burning to cook food inside poorly vented house in Solukhumbu district and children are exposing themselves in health hazardous indoor air pollution.

4.1.1.1 Literature review

Rupakheti et al. (2019) monitored indoor level of black carbon and particulate matters emission using biomass fuel comparing with traditional and improved cook stoves in two types ok kitchens (separated and attached to the main house) and found that commonly used Improved Cook Stove (ICS) might help in particulate matter emission reductions but not necessarily black carbon emission reduction. Das et al. (2019) estimated the time required and human energy expenditure for the production of cooking fuel for four alternative cooking energy system and reported that a significant influence in the selection of cooking fuel due to human energy expenditure and time dependent. Bartington et al. (2017) assessed the patterns of domestic air pollution and found that air quality level associated with biomass fuel consumption exceeds WHO indoor air quality standards and are in the hazardous range of human health. Pradhan et al. (2019) analyzed the biogas and electricity-based cooking on energy use and greenhouse gas emission and found that the use of cleaner cooking fuel can reduce the firewood consumption by 12-24% in the residential sector. Some other comprehensive studies of energy situation exist in other countries including India (Ravindra et al.; 2019, Gould and Urpelainen; 2018), Bangladesh (Baul et al.; 2018), Myanmar (Win et al.; 2018), Indonesia (Kurniawan et al.; 2018) and so on. Dealing with the possibility of reduction potential of CO2 emission by the use of clean cooking fuels, it is necessary to conduct comprehensive studies that focuses on the heterogeneous energy use patterns of different fuel user households in different regions.

4.1.1.2 Objectives

This study aims to explore the CO_2 emission patterns and CO_2 emission reduction potential of cooking fuel substitution by; LPG and electricity. For that purpose, the study developed a TMC (traditional, mix and commercial) model on the basis of available cook stoves. On the basis of that model this study categorized all households into one of the three modes of cooking; traditional mode, mix mode and commercial mode and analyzed direct CO_2 emission patterns of the households in traditional, mix and commercial cooking mode. Furthermore, this study analyzes the emission reduction potential of cooking fuel substitution of these households by considering BAU scenario and other two hypothetical alternative scenarios; MES and LES. Hopefully this research finding are useful for policy maker and concerned organization to identify the proportion and type of the households that how they use and add clean cooking fuels in their energy system without giving up traditional fuels.

4.1.2 Household CO_2 emission

Household CO_2 emission depends upon the type and amount of fuel used. We analyzed direct CO_2 emission by using emission coefficient by fuel type. **Figure 4.3** shows the household CO_2 emission of the households in traditional, mix and commercial mode in three climatic regions.

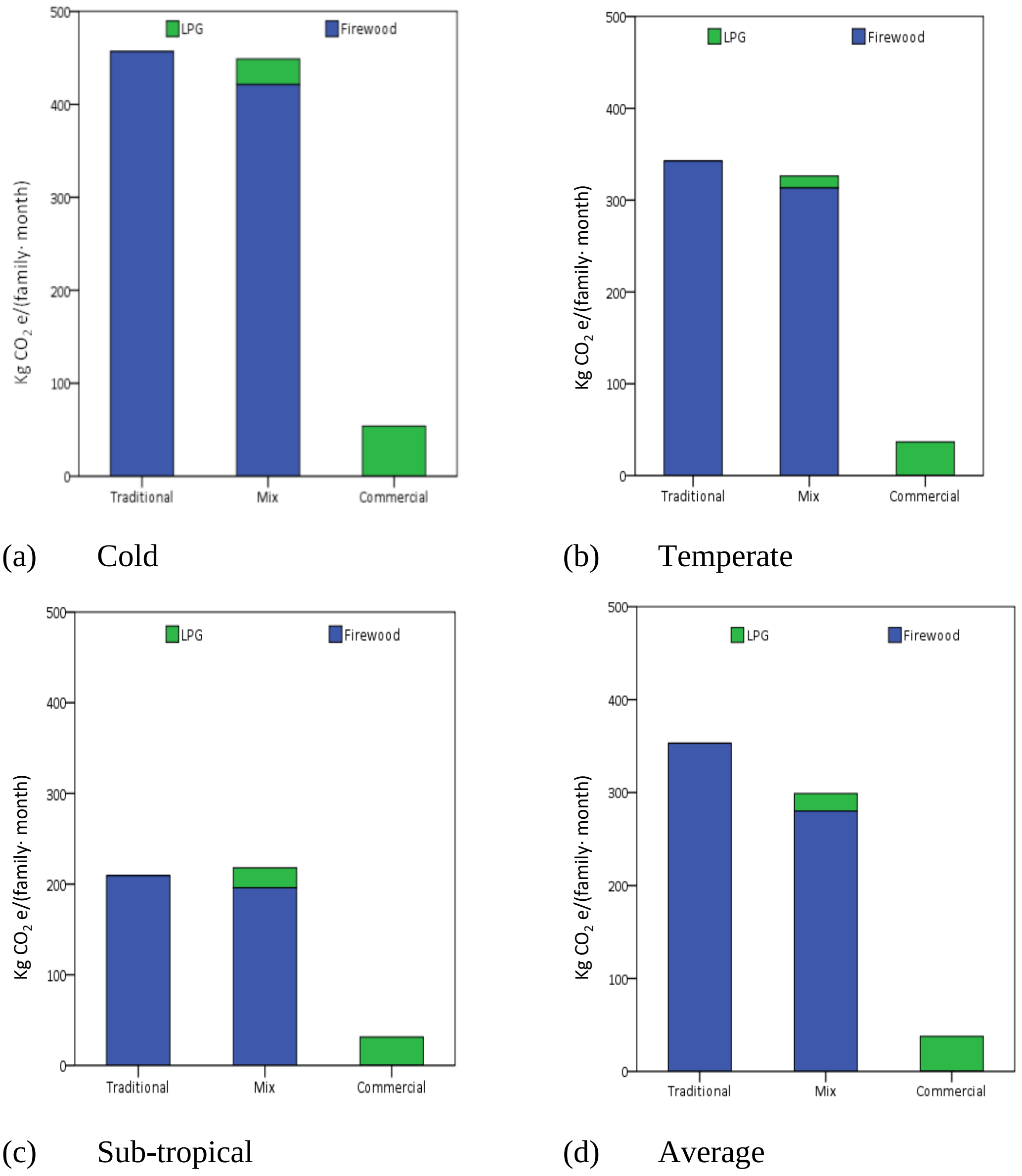


Figure 4.3 Household CO_2 emission among traditional, mix and commercial modes; (a) cold, (b) Temperate, (c) Sub-tropical and (d) Average

In cold region, the household CO_2 emission in traditional, mix and commercial mode were 460, 440 and 50 kg CO_2 e/month, respectively and the value of CO_2 emission obtained in traditional and mix mode are more or less similar but significantly higher than that of commercial mode. There are two main reasons for the higher CO_2 emission in traditional and mix modes. On the one hand, households in traditional and mix mode heavily rely on traditional cooking fuels with very inefficient cook stoves and on the other hand, these households were doing subsistence agriculture in which they rear animals which require extra fuels to make animal feed and emits extra CO_2 than households in commercial mode. Slightly lower emission in mix mode than traditional mode might be associated with occasional use of commercial cooking fuels and lower number of animals reared in mix fuel user households. Similar tendency can be seen in temperate and sub-tropical regions. In temperate region, the household CO_2 emission in traditional, mix and commercial modes were 400, 340 and 40 kg CO_2 e/month and in sub-tropical region, the household CO_2 emission in traditional, mix and commercial mode were 360, 340 and 30 kg CO_2 e/month, respectively.

Comparing the regional variation with respect to three cooking modes, the household CO_2 emission in cold region was higher, temperate region was medium and sub-tropical region was lower. This is probably due to the variation in the amount of fuel used in three regions. Previous studies have reported high household energy requirement in cold region due to the indoor thermal environmental condition of the households. Therefore, the higher energy requirement in the cold and temperate region must be the cause of higher CO_2 emission than sub-tropical region.

4.1.3 Hourly variation of CO_2 emission and concentrations

Household firewood consumption generates indoor air pollution. The amount of firewood used, type of cook stove, and ventilation capacity of the building are the determining factors for variation in indoor CO_2 emissions and concentrations. **Figure 4.4** shows the average variation in CO_2 emissions, and **Figure 4.5** shows the variation in CO_2 concentrations measured in the investigated house during the survey period.

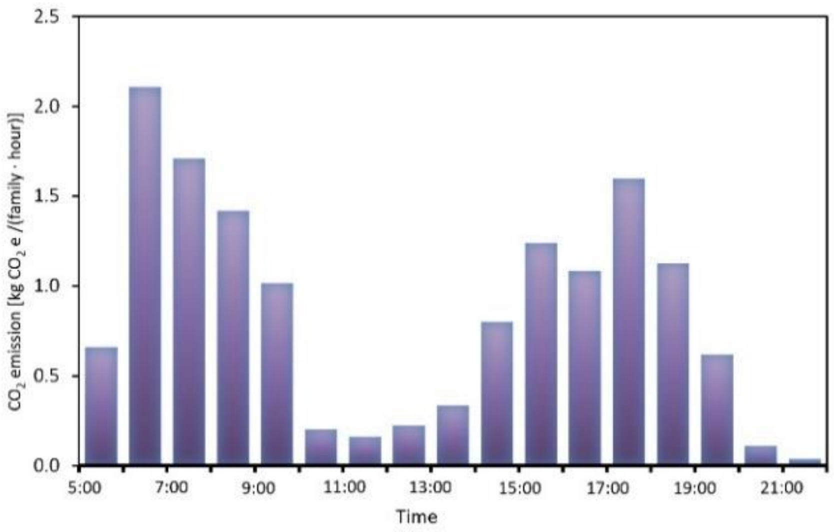


Figure 4.4 Diurnal variation of CO_2 emission

Household CO_2 emissions ranged from 0.04 to 2.11 kg CO_2e/(household·hour), and household CO_2 emissions from firewood consumption were 14.26 kg CO_2e/(household·day). A similar hourly pattern of CO_2 emissions and concentrations can be seen in **Figure 4.5**.

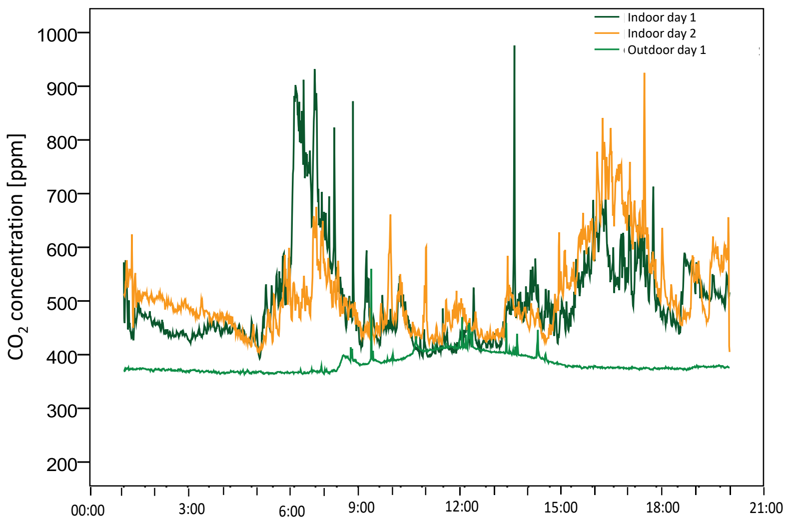


Figure 4.5 CO_2 concentrations of the investigated households.

This figure also shows high emissions in the morning and evening hours, which reflects the firewood consumption patterns shown in **Figure 3.23** Generally, people living in rural area cook meal and animal feed before and after their outdoor agricultural work.

Therefore, high CO_2 emissions were found in the morning and evening hours due to high firewood consumption. Lower emissions during the day were associated with a lower amount of firewood use.

CO_2 concentrations were higher on the ground floor, 2F and 3F than in the rooms with semi-open spaces. The maximum CO_2 concentrations was 2147 ppm. It is interesting that the concentrations were found to be different on each floor according to the position of the staircase. When the staircase is located indoors the CO_2 concentrations are lowest on the 1F, medium on the 2F and highest on the 3F. When the staircase is located in a semi-open space, the results are the opposite. Even when attempting to eliminate indoor air pollution by relocating the staircase to a semi-open space, the concentrations on the 2F and 3F were still high. This is related to the open type of house, which has no window panes and an excessive gap between the top of the wall and the roof.

4.1.4 Relationship between CO_2 emission and concentration

As explained in the previous section, firewood burning is the main source of indoor CO_2 emissions, which influence the indoor CO_2 concentrations. To determine the relationship between CO_2 emissions and concentrations, we conducted a regression analysis between hourly CO_2 concentrations calculated from measured data and hourly CO_2 emissions calculated from hourly firewood consumption of the investigated house.

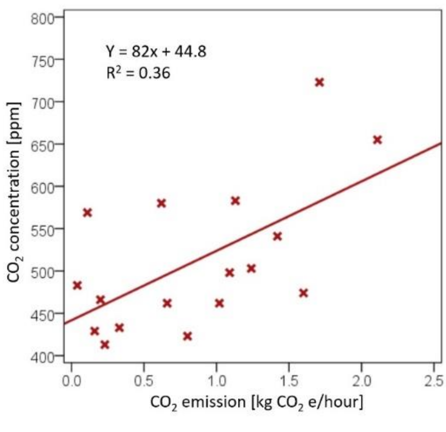


Figure 4.6 Relationship between CO_2 emission and concentrations.

As shown in **Figure 4.6**, a positive linear relationship ($r = 0.60$, $p < 0.001$) between CO_2 emissions concentrations was obtained. This result seems reasonable as firewood consumption inside the house increases the level of indoor CO_2 concentration. Number of occupancies is also influential factor on indoor CO_2 concentration but, in this study, only a female household member responsible for cooking was exposed frequently during day time and nobody were exposed during sleeping time. Location of staircase inside the kitchen room and open type of house structure helps to move indoor air pollution outwards and upwards therefore the indoor concentration of CO2 was found below 1000ppm during firewood burning. According to Rijal et al.; (2005) when the staircase is located indoors the CO2 concentrations are lowest on the 1F, medium on the 2F and highest on the 3F. Other building characteristics, such as infiltration and ventilation rate, play an important role in the variation of indoor CO_2 concentration. However, due to the limited research data collected, this study cannot further discuss the quantities of CO_2 that leaves the house through chimneys and diffuse into the surrounding environment. might cause outlet of pollution.

4.1.4 Conclusions

High emissions of indoor CO_2 in the morning and evening hours due to high firewood consumption may pose a serious health risk to the rural population. Therefore, intensive awareness programs and installation and use of mechanical ventilation devices in the morning and evening would improve the air quality and health conditions of the rural population. Household CO_2 concentration was positively correlated with CO_2 emissions due to firewood burning, and daily CO_2 emissions were 14.26 kg CO_2 e/(household·day). Clean cooking fuels and efficient cooking technologies would help minimize household CO_2 emissions.

4.2 CO_2 emission reduction potential of clean cooking fuel substitution

4.2.1 Introduction

The substitution of traditional cooking fuels by LPG and electricity may offer great potential to reduce indoor CO_2 emissions as well as other associated emissions. Thus, several countries have implemented nationwide cooking fuel substitution programs. For example, the Indonesian government initiated the world's largest exercise to substitute kerosene with LPG in 2007, where 58 million LPG packages were distributed to reduce dependency on kerosene (Kurniawan et al., 2018). Since the 1970s, the government of Ecuador has heavily subsidized LPG and fixed household LPG prices at 1.60 USD per 15 kg cylinder. As of 2014, more than 90% Ecuadorian households were primarily cooking with LPG (Gould et al., 2020). The government of India has also initiated several policies to promote LPG accesses and has provided huge subsidies for low-income Indian households (Gould and Urpelanien, 2018; Sharma and Jain, 2019).

The use of clean cooking fuels has substantial health, climatic, and environmental benefits of reducing indoor air pollution. Moreover, it increases the energy consumption efficiency of the household sector, which plays a significant role in reducing indoor CO_2 emissions (Kurniawan et al., 2018). To determine the effectiveness of various policies directed towards the development of clean cooking fuels in the household sector and draw necessary improvements for future consideration, it is necessary to understand the complex energy use and associated emission patterns of different fuels used in households.

4.2.2 Estimation of household direct CO_2 emission reduction potential

In order to estimate the reduction potential of indoor CO_2 emission by cooking fuel substitution, we consider three scenarios: Business as usual (BAU) scenario and two other hypothetical scenarios; moderate emission scenario (MES) and low emission scenario (LES). The two alternative scenarios analyze the implication of diffusion of LPG and electricity as a clean cooking fuel respectively. These three scenarios represent three different levels of indoor CO_2 emissions: high, medium and low. Total household CO_2 emissions from all these fuels were calculated by applying equation (1). Detail of these scenarios are described as follows:

1) Business as usual scenarios (BAU)

This scenario represents the existing fuel use patterns of all investigated households. In this scenario households in traditional mode use only traditional cooking fuels, households in mix mode use either traditional or commercial fuels and households in commercial mode use only commercial fuels like LPG or electricity to fulfill their everyday cooking energy requirements.

2) Moderate Emission Scenario (MES)

It is an alternative hypothetical scenario with comparatively low emission than BAU scenarios. In this scenario, per-capita firewood used for cooking in all households was replaced by per-capita LPG used for cooking. In Nepal, most of the people living in the rural and semi urban area relying on substance agricultural in which people use firewood for various purposes like space heating, animal feed preparation, domestic alcohol preparation and so on. Therefore, substitution of all firewood particularly in cold and temperate region is very expensive and it is sometime not practical and impossible therefore, this study replaced only the amount of firewood used for cooking. The total CO2 emission in this scenario includes emission from LPG as a regular cooking fuel in all households and emissions from firewood used for other purposes besides cooking.

3) Low Emission Scenario (LES)

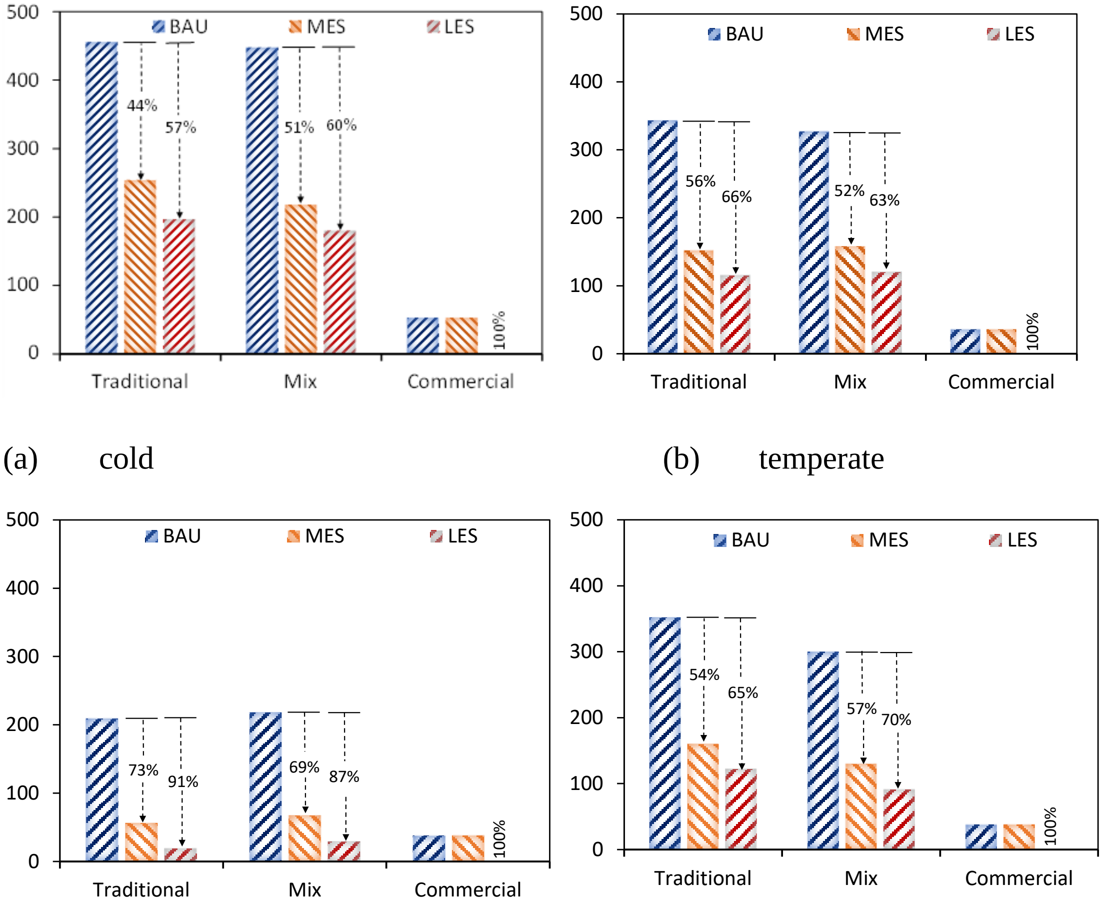
It is also an alternative hypothetical scenario with lowest emission among three scenarios. In this scenario, per-capita firewood and LPG used for cooking was replaced by electricity as a clean cooking fuel. Since the hydroelectricity used in Nepal does not emit any CO_2, we considered that this scenario is a lowest emission scenario. Total CO_2 emissions in this scenario includes emission from firewood and LPG used in all households for other purposes besides cooking.

4.2.3 Reduction potential of CO_2 emission by cooking fuel substitution

Figure 4.7 shows the reduction potential of household CO_2 emission in cold, temperate and sub-tropical region among the households in traditional, mix and commercial cooking mode. This figure shows that the emission of CO_2 from cooking fuel substitution in two alternative scenarios will decrease significantly in traditional and mix mode while it is not decreased in commercial mode under MES but it is decreased by 100% in LES.

In cold region, the CO_2 emission in MES will decrease by 0-44% and in LES, it will decrease by 57%-100%. In temperate region, the CO_2 emission in MES will decrease by 0- 56% and in LES it will decrease by 66-100%. Similarly, in sub-tropical region, the CO_2 emission in MES will decrease by 0-73% and in LES it will decrease by 91-100%. On average, the CO_2 emission in MES will decrease by 0-54% and in LES, the CO_2 emission will decrease by 65-100%.

On comparison with three regions, high CO_2 reduction potential was found in sub-tropical region followed by temperate region and low CO_2 reduction potential was found in cold region. The result seems reasonable because sub-tropical households did not require any heating energy due favorable thermal environmental condition and cooking fuel substitution significantly reduces the CO_2 emission. On the other hand, households in cold region used some extra energy particularly, firewood to maintain their indoor thermal environmental condition of the buildings and this part of energy emits extra CO_2 and hence, the reduction potentiality of cooking fuel substitution in cold region seems lower than other two regions.



(a) cold (b) temperate

(c) sub-tropical (d) average

Figure 4.7 Reduction potential of clean cooking fuels among traditional, mix and commercial modes; (a) cold, (b) Temperate, (c) Sub-tropical and (d) Average

4.2.4 Conclusions

By employing TMC model we have accessed energy use patterns and CO_2 emission patterns of the households in traditional, mix and commercial modes in three climatic regions of Nepal. Furthermore, we considered BAU and other two hypothetical scenarios; MES and LES to analyzed CO_2 reduction potential of cooking fuel substitution by clean cooking fuels; LPG and electricity and made following conclusions;

1. Due to the use of very inefficient cooking technology, traditional and mix fuel user household have to use more household energy than commercial fuel user households

and these households emits more CO_2 than commercial fuel user households. Moreover, traditional and mix fuel user households spent significantly longer time exposure on cooking than commercial fuel user households.

2. Reduction potential of CO_2 emission was found high in sub-tropical region medium in temperate region and low in cold region. The emission of the CO_2 would be decreased in MES by 54%, 57% and 0% and in LES by 65%, 70% and 100% in traditional, mix and commercial fuel user households respectively as compared to the BAU.

Chapter 5: Conclusions and Recommendations

5.1 Conclusions of Chapter 2

Household energy use is important to maintain the indoor thermal environment of residential buildings in developing countries such as Nepal but it has not yet been known very well in the developing societies so that it is important to clarify this relationship in order to draw the future consideration about energy saving policy. As the results of our survey and the follow-up analyses made on the current situation in Nepal, the followings were found: Indoor air temperature of all studied households in three regions were below ASHRAE comfort standard. People living in three regions are primarily dependent on firewood for space heating; per-capita total energy use was found in the order of 37, 30 and 20 MJ/ (capita. day) in cold, temperate and sub-tropical regions, respectively. Outdoor climatic condition has a strong influence on indoor thermal environment and it is associated with household energy use patterns. Intensive improvements of existing building envelopes should be performed for providing people with better indoor thermal environment while optimizing the household energy use.

5.2 Conclusions of Chapter 3

How the household energy use is related to the indoor thermal environment of residential buildings in developing countries has not yet been known very well so that it is important to clarify this relationship in order to draw the future consideration about energy saving policy in developing countries such as Nepal. The daily average regional household energy-use patterns in winter season are influenced by regional outdoor climatic conditions: 207 MJ/ (family. day) in cold region, 154 MJ/ (family. day) in temperate region and 101 MJ/ (family. day) in sub-tropical region was found as the daily rate of household energy use. People living in three regions are primarily dependent on firewood for cooking and space heating; per-capita total energy use was found in the order of 37, 30 and 20 MJ/ (capita. day) in cold, temperate and sub-tropical regions, respectively. Outdoor climatic condition has a strong influence on indoor thermal environment and it is associated with household energy use patterns. Intensive improvements of existing building envelopes should be performed for providing people with better indoor thermal environment while optimizing the household energy use. Nepal is currently undergoing a significant transition of governance into a federal system with newly elected 7 federal and 773 local governments (Poudyal et al., 2019). This creates opportunities to restructure energy systems and to improve energy access to all people living in different geography and with different energy access situation. In this study, we found low cost and relatively abundant firewood remained a common and primary cooking fuels, LPG fuel was widely used as secondary cooking fuel in all regions. Most of the households used more than one variety of fuels simultaneously for their everyday household energy needs. Firewood and LPG were the most common sources used for cooking. Electricity was the primary lighting fuel of all households. The government of Nepal has given priority to improve energy situation in Nepal mainly through hydropower development and other alternative clean energy development program. Despite the economic and geographic barriers, about 70% households are connected to electricity facility. 75% of total surveyed household has access to clean cooking fuels but due to the low household income only 6% households use clean cooking fuels as a regular cooking fuel. 25% household has no access to clean fuels and totally depends on traditional fuels for cooking. The assess of clean energy services and share of clean energy in national energy mix is in increasing trend. An intensive clean cooking fuel improvement program is necessary to improve the clean household cooking fuels in all regions in Nepal.

5.3 Conclusions of Chapter 4

By employing TMC model we have accessed energy use patterns and CO_2 emission patterns of the households in traditional, mix and commercial modes in three climatic region of Nepal. Furthermore, we considered BAU and other two hypothetical scenarios; MES and LES to analyzed CO_2 reduction potential of cooking fuel substitution by clean cooking fuels; LPG and electricity. Results of this study suggests that 25% households are heavily relying on traditional cooking fuels without using any other clean cooking fuels, 67% households add clean cooking fuels to their energy systems and only 8% households are relying in commercial fuels to fulfil their daily cooking fuel requirements. Inhabitants of the study area used variety of cook stove however traditional cook stoves are the most abundant in all regions. Combination of LPG and electric rice cooker was the most abundant cook stoves combination found in the investigated households. Due to the use of very inefficient cooking technology, traditional and mix fuel user household have to use more household energy than commercial fuel user households and these households emits more CO_2 than commercial fuel user households. Moreover, traditional and mix fuel user households spent significantly longer time exposure on cooking than commercial fuel user households. Reduction potential of CO_2 emission was found high in sub-tropical region medium in temperate region and low in cold region. The emission of the CO_2 would be decreased in MES by 54%, 57% and 0% and in LES by 65%, 70% and 100% in traditional, mix and commercial fuel user households respectively as compared to the BAU.

5.4 Recommendations

Since solid cooking fuel use and indoor air pollution exposure affects the health condition of the people particularly, living in the rural area of the developing countries, there are significant demands for alternative solutions. However, given the variability of households, socio economic and geographical condition securing clean and equal energy access for all is often constrained by various factors. There are number of clean cooking fuels such as; LPG, natural gas, biogas, electricity and ethanol that burns with very few emissions present alternatives to solid cooking fuel (Gould et al.; 2018). It seems unlikely that that there will be single solution in all regions. In the context of Nepal, in particular, electricity is promising; it can be generated from the renewable hydro resources and can easily be used to substitute other cooking fuels. This study shows electricity has high potentiality to reduce indoor CO2 emission. On the other hand, the dependence on solid biomass is a part of the rural system which is a complex, closely interlinked mutually supportive (Ravindra et al.; 2019). Generally, solid fuels are often used for cooking, for space heating and for making animal feed. Therefore, complete switching to clean cooking fuel seems unpractical in rural households since it is closely associated with the complex socio-cultural behaviors of the rural people.

Regular cooking fuel substitution would be the ideal option and it has many benefits for people health and to the environment. The information of the ground reality of the energy use patterns of different fuel user households in different regions are essential to formulate effective energy policy. Previous researches provide evidences of regional variation of energy use patterns of the households; however, they are lacking to identify the heterogeneity of the energy use behavior of the different fuel user households in the same regions. This study identified that households with easy access of clean cooking fuel were also found dependent on solid biomass fuel to fulfill their daily cooking energy demand which indicates that complete transition to clean cooking fuel is not only associated with fuel accessibility but also associated with many other socio-economic and cultural behavior of the people. Result of this study shows that 25% households totally rely on traditional cooking fuels, 67% households add clean cooking fuel in their energy system and only 8% households use clean cooking fuels as a regular cooking fuel. Therefore, the study stresses the need of the policy makers and concerned stockholders to well synchronize the information of heterogeneous energy use patterns among different regions and among different fuel user households for formulating effective interventions and energy policies.

This study has also found that use of cleaner cooking fuels like LPG and electricity can significantly reduce the CO_2 emission in the household sector in all region and among all fuel user households when compared to BAU scenario. The emission of other associated pollutants from solid biomass fuel would also decrease proportionally by clean cooking fuel substitution. It is also found that electricity used as a clean cooking fuel can reduce more CO_2 emission than LPG used as a clean cooking fuel. Previous research found that the use of electricity for the cleaner cooking in the urban and rural households will reduce the dependency on imported fuels as well as enhance hydropower development, which can further promote employment opportunities and economic development (Pradhan et al.; 2019). Therefor to minimize the health and environmental burden of the people, it is essential to start effective energy policy and interventions to meet and fulfill the peoples need considering the socio-economic and cultural dimensions incorporated with their cooking behaviors and thoughts. This result also showed that the substitution of clean cooking fuel can significantly minimize the cooking hours of the households which has multiple benefits to the household members. Currently, Nepal is undergoing a significant transition of governance into a federal system with newly elected 7 federal and 773 local governments (Poudyal et al., 2019). This creates opportunities to restructure energy systems, incorporating necessary valuable findings to improve clean energy access to all people living in different geography with heterogeneous energy access situation. We hope this information will help to formulate new strategies to achieve rapid transition from traditional cooking fuel to clean cooking fuels in the household sector of Nepal and countries alike.

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