KATHMANDU UNIVERSITY

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DEPARTMENT OF MECHANICAL ENGINEERING

DISSERTATION

MODELING AND OPTIMIZATION OF ENERGY SYSTEMS FOR NEPAL – A CASE STUDY OF GORKHA DISTRICT

In Partial Fulfillment of the Requirements for the Doctor of Philosophy Degree in

Mechanical Engineering

by

Nawaraj Sanjel

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Worldwide, nearly more than half a billion people will still not have a reliable and affordable electricity till 2040 and nearly 1.8 billion may compel to rely on traditional fuel sources for day to day activities. Specially the case is even more critical in remote areas of developing countries. Remote areas of undeveloped and developing countries suffer from limited or no access to electricity. In Nepalese context, varieties of renewable energy sources are available for energy access; limited to lighting and cooking. In line with sustainable development goal no. 7, “Ensure access to affordable, reliable, sustainable and modern energy for all”, Nepal has also set its own targets and indicators”. Thus, this study aims to assess the level of energy access in rural context and further analyze the viability of replacement by reliable and sustainable energy sources. Providing electricity access in remote areas is one of the foremost challenges of any developing country. Alternative Energy Promotion Center (AEPC), a government institution under the Ministry of Energy, Water Resources and Irrigation (MoEWRI), is promoting renewable energy technologies in Nepal since 1996. AEPC looks after all the available renewable energy (RE) technology widely being implemented in Nepalese context like, solar energy technology, wind energy technology, biomass energy technology, biogas technology, biofuel technology, and mini/micro hydro technology. Availability of the mentioned technologies varies with different topography of Nepal. To full-fill the energy demand, which is the basis of development of Nepal, optimization and hybridization of such energy technologies is must.

To address these energy problems, research on modeling and optimization of rural energy system is proposed for the overall development of developing countries like Nepal. Thus, the study aims to model and optimize the existing energy systems; solar energy and mini/micro hydro technologies backed up with battery and diesel generator (DG). The study has assessed the energy potential and existing energy supply for the community through the mentioned renewable energy technologies. The study has also analyzed the potentiality of replacement of the less reliable energy systems by the most reliable electricity source i.e., hydropower (grid extension).

The purpose of this study is to develop and propose a reliable and low-cost model for electrification. Thus, the research has modeled and assessed the feasibility of replacement of short-term energy sources/systems by long term sustainable energy sources and the overall impact of policy injections. The study is focused on energy trend of Nepal, energy planning methodologies, analysis of prevailing energy modeling and optimization techniques in context of developing and under developed countries.

The research gap is traced for the energy planning through the literature review of published papers and government reports. The research is conducted analyzing both primary and secondary data. Field level data collection of 17 village development committees (VDCs) of Gorkha district (research site) is carried out via questionnaire survey. Primary data is collected through various in-person meetings, focus group discussions, survey questionnaire and checklists. The electrification data is collected from Nepal Electricity Authority (NEA), District Development Committee (DDC), World Bank (WB) and community rural electrification entities (CREEs). Further, secondary data is collected from Alternative Energy Promotion Center (AEPC), Renewable Energy for Rural Livelihood (RERL), Central Bureau of Statistics (CBS) etc. Based on the available primary and secondary data the analysis is conducted in three methods; analytical method, techno-economic optimization by HOMER 2.68, and regression analysis. More than fifteen thousand (15,775) households, 24 educational institutions, 24 offices or health posts, and 24 industries exist in the research area with an average of electrical load growth of 10 % in first year and 5 % in the subsequent five years. Electricity load demand for the next five years calculated for 17 VDCs is 965 kW and is considered 1MW for the further analysis and calculation purposes. For the detail analysis, valid analytical method and Homer Pro 2.68 software is considered. The research has further analyzed the impact of Gross Domestic Product (GDP) on Electricity per Capita (EPC) through a regression analysis of an econometric model. Impact of policy injections is qualitatively assessed by analyzing the electricity generation, import, peak demand and the trend.

Opting for an analytical method for modeling and analysis of electrification options based on life cycle cost (LCC) and economic distance limit (EDL), each energy system for varied load conditions is compared for a better option. The study presents an optimized choice between decentralized renewable energy systems and grid expansion.

A framework for energy system selection based on available resources is proposed. It compares the grid expansion option with potential isolated renewable energy systems to ensure energy access to the area under consideration. Additionally, off-grid configurations that rely on renewable energy sources are also considered for the necessity of backup supply to ensure continuous power to the research area. Techno-economic assessment of different off-grid and hybrid configurations proposed in this study and their feasibility checks are carefully examined. Commercial efficacy of the proposed hybrid energy systems by comparing the life cycle and energy cost and by performing different additional sensitivity is conducted.

The major results show that grid expansion is feasible only for high load requirements. Off-grid technologies in hybrid mode are more feasible for low load requirements; depending on the availability of energy resources as well. The study shows that the energy cost for low load conditions is high and is low for high load conditions. This way the best alternative electrification option can be adopted. The study shows that; the reduced generation cost will support increasing the electrification penetration. The results from analytical study show that, EDL increases linearly with the increase in load and supply hours. Increased backup hours from battery or DG will ultimately increase the EDL which shows the dependency on DG is very expensive for electrification compared with other technologies. Further, EDL regularly increases on increasing the load and needed supply hours.

LCC for grid expansion for 5 kW of the load was NRs 50.84 / kWh, whereas LCC for PV + DG for the same condition was NRs 11.41 / kWh. LCC for low load conditions is high, which is quite higher for grid expansion. The result shows that LCC decreases with the increased load to a certain level and stabilizes thereafter. LCC for electrification options appeared to increase in the order of PV+ DG, Grid expansion, MHP, PV (inc battery), MHP+DG, and DG.

Further fluctuation of PV system cost shows that LCC varies between 12.6 to 16.2 Rs/kWh. The analysis of cost of generation, capital cost, discount rate and the losses in grid extension is found less sensitive compared with other energy systems. The analysis shows that, annual discount rate generated has positive impact on LCC and reduced the cost 14.1 to 13.0 Rs/kWh.

The techno-economic optimization result shows the highest penetration of hydropower is the most economic. The regression analysis shows a positive and significant relationship between GDP per capita and electricity per capita. This reveals that one-dollar increase in GDP increases 0.27 kWh consumption of electricity. The modeling indicates that higher the GDP per capita, higher would be the consumption of electricity.

The study concludes that reduced generation cost supports increasing electrification penetration. Life cycle cost for grid expansion is the most economical in high load conditions whereas for the isolated and sparsely settled populations with low load conditions, photovoltaic (PV) backed up with diesel generator (DG) is the most economic among the energy systems under this study. Energy planning models (EPMs), approaches and optimization techniques play an important role in energy sectoral policy formulation.

Above all, the research has traced a bi-linear polynomial equation with available data points of EDL, supply hours, and the demand load. The equation can further be utilized to identify the necessary EDL based on required supply hours and the load demand. Similarly, additional four bi-linear polynomial equation is fitted for the energy systems considered under the research. Thus proposed methodology for the development of such equations can be further replicated for other energy systems for research.

The proposed bi-linear polynomial equations and the developed methodology to generate the equation can be utilized for long term energy planning. The long term energy planning through energy modeling and optimization techniques of energy technologies have a better impact to mitigate the issues of energy access. Energy demand forecasting and the subsequent planning is one of the most important aspect when dealing with long-term energy planning.

For the technical researchers who want to continue similar research and energy planning, I would like to recommend extending the research scope to all the potential energy systems; not limiting to the energy systems and resources available in the research area. Further, the research site extended to the district level or national level will give more prominent, comparable and replicable results. Further, the policy makers, who plays a vital role in planning and policy making, I would recommend that the policies should be formulated in such a way that it promotes the electricity generation to the optimum level. During energy planning, it is recommended that, even energy planning at local level, both analytical comparison of each energy technology in line with LCC and EDL should be mandatory. Further, adoption of the techno-economic optimization via various simulations of the potential energy systems for energy planning is essential.

Dedication

To

My Father, Mr. Uddhab Prasad Sanjel and Mother Mrs. Shyam Sanjel

I would like to dedicate my Ph.D. research work to my loving and caring Father and Mother. Your dream to edify me, affection and encouragement, prays of days and nights have made me able to accomplish this work.

LIST OF ABBREVIATIONS

ABD	Asian Development Bank
AEPC	Alternative Energy Promotion Centre
CBS	Central Bureau of Statistics
DDC	District Development Committee
DG	Diesel Generator
EDL	Economic Distance Limit
EPC	Electricity Per Capita
EPM	Energy Planning Models
FGD	Focus Group Discussion
FY	Fiscal Year
GDP	Gross Domestic Product
GHG	Green House Gases
GoN	Government of Nepal
HOMER Software	Hybrid Renewable and Distributed Generation System Design
IPPs	Independent Power Producers
LCC	Life Cycle Cost
MHP	Micro-hydro Power
NEA	Nepal Electricity Authority
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
RE	Renewable Energy
RERL	Renewable Energy for Rural Livelihoods
RETs	Renewable Energy Technologies
ToE	Tons of oil equivalent
VDC	Village Development Committee
WB	World Bank

LIST OF SYMBOLS

C_B	Capital cost of battery [NRs]
C_R	Replacement cost of diesel generator [NRs]
C_{FUEL}	Cost of fuel annually [NRs]
C_{GEN}	Capital cost of diesel generator [NRs]
C_{grid}	Grid line cost [NRs]
C_{MHP}	Capital cost of MHP system [NRs]
C_{MHPR}	Capital cost of replacement after economic life [NRs]
C_{PV}	Capital cost of PV system (excluding battery) [NRs]
C_R	Replacement cost of battery [NRs]
C_t	Cost of transformer [NRs]
d	Discount rate [%]
h	Annual operating hours [hours]
L	System capacity [kW]
LCC_{GE}	Life cycle cost of grid expansion [NRs]
LCC_{gen}	Life cycle cost of electricity generation [NRs]
LCC_{grid}	Life cycle cost of grid line [NRs]
$LCC_{transfer}$	Life cycle cost of transformers [NRs]
n	Life of complete system [years]
n_1	Life of replacement of components
P(d,n)	Present net worth factor of annual O&M
$P(d,n_1)$	Present net worth factor of component
t_{gen}	Electricity generation cost [NRs]
X	Distance from load centre to grid point [km]
β	Capital cost fraction for annual O&M
$\delta_{t\&d}$	Transmission & distribution losses

1 INTRODUCTION

1.1 Background

Nepal has enormous potential of energy resources to its area and population (83,000MW hydro, 2100MW Solar, 3000 MW wind). About 87% of the total energy requirement (401 million GJ) is met from traditional fuels i.e. fuel wood 77%, agri-residue and the animal waste 9% [1]. The annual peak power demand of the integrated Nepal power system in 2020 was 1408 MW and is anticipated to be 1482 MW in 2021 [2]. Total electricity available at national level (combined electricity generation from NEA and IPPs) in 2020 is 6012 GWh. In the Fiscal Year (FY) 2019/20, Nepal has been able to export 107 GWh (an increase of 18.6 % than earlier year) of electricity to India. However, a total of 1,729 GWh of electricity was imported in FY 2019/20 [2].

The state-owned Nepal Electricity Authority (NEA) is responsible for the electricity supply through the national grid. The access to electricity is limited to only 85% of the country's total households have access to electricity. Especially in the rural areas there is no access to electricity, hampering both economic development and access to information and education [3].

Nepal's electricity production is heavily dependent on hydropower, as nearly 93% of the total electricity is generated by either NEA-owned or private hydropower plants. In order to meet the growing hunger for electricity (nearly 9 % annual), imports have become more important during the last decade, except in the year 2020 [2]. Mismatch between available resources and year-round necessity to generate hydroelectricity creates a complicated engineering challenge, leading severe load shedding particularly in winter, of regularly 11.5 hours up to 13 to 14 hours/day in winters [4]–[7]. According to estimations of the NEA, energy demand will grow yearly with an average annual rate of 9 %. Because of increasing household consumption, the evening peak demand has risen dramatically. Due to the continuously rising demand and stagnation in creating additional power generation capacities, a noticeable shortage of power supply since 2007 is noticed.

The NEA as the major electricity utility, faces an immense increase in electricity demand, whereas at the same time production and transmission capacities are limited. Though, ambitious development targets are announced, the development of generation plants and transmission lines cannot keep up with economic development and the resulting increase in demand. The yearly demand is expected to exceed 17,400 GWh by 2027. Along with the growing demand it is projected that system peak load will increase with similar annual growth rates, reaching 3679 MW in 2027. Climate changes are resulting in increasing drought intensity and frequency in winter months in northern side of Nepal [8]. AEPC is promoting renewable energy technologies in Nepal since 1996. AEPC looks after all the available RE technology widely being implemented in Nepalese context like, solar energy technology, wind energy technology, biomass energy technology, biogas technology, biofuel technology, and mini/micro hydro technology. Availability of the mentioned technologies varies with different topography of Nepal. To full-fill the energy demand, which is the basis of development of Nepal, optimization and hybridization of such energy technologies is must.

To address these energy problems, research on modeling and optimization of rural energy system is proposed for the overall development of Nepal. Thus, the study aims to model and optimize the existing energy systems; solar energy and mini/micro hydro technologies backed up with battery and diesel generator (DG). The study has assessed the energy potential and existing energy supply for the community through the mentioned renewable energy technologies. The study has also analyzed the potentiality of replacement of the less reliable energy systems by the most reliable electricity source i.e., hydropower. The assessment is conducted in first phase by calculating economic distance limit (EDL), which is further analyzed based on life cycle cost (LCC) as well. The study has covered the energy policy analysis and its impact on electricity generation. In overall, the research has modeled and assessed the feasibility of replacement of short-term energy sources/systems by long term sustainable energy sources and the overall impact of policy injections.

1.2 Literature Review

Various studies are conducted for energy planning in developing and developed countries. Rohini et. al., 2014 has conducted a study on optimization of resources by integrated planning of power system in Nepal. The study is focused on possible layout for integrating generating substation and power evacuation substation with distribution system with a case study of Kabeli corridor of Nepal. Researchers have conducted a review on optimization of hybrid renewable energy power systems [9]. The study has focused on optimal sizing of energy systems components of hybrid power systems. Study on optimization of hybrid renewable energy power systems for remote installations under case study of Nepal and South Korea has also been conducted [10]. Globally, modeling and optimization of integrated renewable energy systems has been conducted [11]. The research was conducted on cost optimization for electricity demand using HOMER software developed by National Renewable Energy Laboratory and need-resource modeling of the system is performed by MATLAB.

Modeling, analysis and optimization of integrated energy systems for multigeneration purposes has been conducted [12]. The study has conducted research on both renewable and non-renewable based multigeneration system. Modeling and optimization of renewable energy systems has also been conducted [13]. The research has presented two proactive models based on forecasted imbalances between supply and demand, the models aim at reducing intra-hour balancing cost by optimally adjusting the production level before real-time operation by utilizing manual reserves. Modeling of electric systems to some extent has been done by some researchers [14]. The brief literature survey indicates that mostly the integration of the energy systems to grid is analyzed but the comparison of energy systems (via modeling and optimization) within itself and grid integration is less focused. Thus, this research has focused in followings:

- Modeling and optimization of the energy systems and analyzed in line with grid expansion
- Analyze the policy environment for electricity generation

Further, for the research purpose an extension literature review on energy systems and the prevailing policies are conducted in the Chapter 2 Literature Review.

1.3 Problem Statement

In Nepal, modeling and optimization of energy systems is traced but modeling and optimization of energy systems and its analysis in line with prevailing energy policies is very limited. In Nepal, about 70 % of people live in rural areas, whereas access of electricity is nearly 85% of total, which is very low in case of rural areas. NEA electrifies rural Nepal through community model of electrification (90 % of cost by GoN and 10 % by community itself). Due to lack of enough transmission line to evacuate the generated energy, GoN has been promoting isolated micro hydro and mini hydro power plants in previous decades. But, to enhance system efficacy of such electric system, research on modeling and optimization of those rural energy system, which are back bone of electricity access of Nepal is very rare.

In Nepalese context, varieties of renewable energy sources are available for energy access; limited to lighting and cooking. This unreliable source of energy has been documented as energy access. In line with sustainable development goals no. 7, “Ensure access to affordable, reliable, sustainable and modern energy for all”, Nepal has also set its own targets and indicators”. Thus, this study aims to assess the level of energy access in rural context and further analyze the viability of replacement by reliable and sustainable energy sources. Hence, the research has investigated the modeling and optimization of renewable energy systems and policy impact for electricity generation.

The research has collected primary and secondary data, analyzed them and optimized to enhance efficacy of the energy system, which may further be replicated in broader aspects in similar ground.

1.4 Objectives

General objective of the research is to comprehensively model, analyze and optimize the energy systems and policies of Nepal. Specific objectives of the research are:

1. To perform analytical modeling of the energy systems for rural context of Nepal.
2. To optimize the energy mix for rural context of Nepal.
3. To analyze the renewable energy policies of Nepal.

To fulfill the above objectives, a detailed literature survey of the context in Nepal and the developing countries is carried out extensively.

1.5 Scope of Research

The research is confined to the study of limited renewable energy technologies based on available and applicability and have impact on overall development of Nepal. Solar energy and mini/micro hydro energy technologies are considered the primary energy technologies for the study purpose. To contextualize the research, battery backup and DG has also been incorporated in the research work. Further, for the integrated energy planning the stated energy systems have also been analyzed in hybrid mode (integrating each technology with the another). In overall, the following combinations are studied:

1. MHP
2. MHP + DG back up
3. PV + Battery back up
4. PV + DG back up
5. DG

Technoeconomic optimization for cost optimization of the renewable energy systems for identification of the technically and economically better energy technology mix has been conducted.

The study has assessed the energy potential and existing energy supply for study site (Gorkha district) for all the mentioned renewable energy sources and the technologies. The study has also assessed the potentiality of replacement of the less reliable energy systems by the most reliable electricity source; grid extension. The assessment is conducted by analyzing through analytical modeling and simulation & optimization through HOMER Pro 2.68. The result from the different analysis techniques is further compared for validation of the work and recommendation. The study has covered the economic viability for the replacement of the energy systems via LCC calculations. Finally, a bi-linear polynomial equation to calculate EDL with input of required supply hours and the load demand is identified.

The research has further analyzed the governing energy policies of Nepal as a foundation and factor for overall electricity generation leading for total energy access.

In overall, the research has assessed the role of policy injections for conducive environment for electricity generation. Analysis and optimization of the energy technology, energy mix and economic analysis is done from analytical method and techno-economic optimization using HOMER Pro 2.68.

1.6 Research Methodology

Overall approach and methodology of this research is analyzing the national energy data by analytical modeling. Further, the techno-economic optimization is done using HOMER Pro 2.68. The research is conducted analyzing both primary and secondary data. Primary data is collected from the research site and secondary data is collected from the reports published by GoN bodies and bilateral-multi lateral organizations. Primary data is collected through various in-person meetings, focus group discussion and survey questionnaire and checklists. The collected data is analyzed using qualitatively and quantitatively. For the detail analysis, valid analytical method and Homer Pro 2.68 software is considered. The analysis has finally developed a model for EDL calculation.

The research has further analyzed the impact of Gross Domestic Product (GDP) on Electricity per Capita (EPC) through a regression analysis of an econometric model. Detail description of the methods and methodology is presented under the Chapter 3 Methodology.

1.7 Research Questions

Research questions has been thematically categorized in three objective areas as listed below.

1. Model and optimize demand and supply side of renewable energy technologies for rural context of Nepal.
    a. What is the energy demand of the research area?
    b. What is the energy supply status for the research area?
    c. What is the growth rate of energy demand?
    d. What are the parameters to optimize the energy systems?
2. Optimize the renewable energy mix for rural context of Nepal.
    a. What are the energy sources and the prevailing energy systems in the research area?
    b. What will be the optimized energy system mix out of the available energy sources to meet the present and future demand of the community?
    c. What it the viability of the replacement of less reliable energy sources by sustainable energy supply; hydropower.
3. Analyze the renewable energy policies of Nepal
    a. What are the renewable energy policies of Nepal?
    b. What is the effectiveness of the policy interventions on electricity generation and energy access?
    c. Are the energy policies of Nepal to the optimal?

1.8 Limitations

The research conducted is one of its own kind. Due to the uniqueness in nature, the modeling and optimization analysis is conducted in two ways, analytical method and techno-economic optimization. The output of each technique is not the same. Thus, it is difficult to conclude the efficacy of analytical modeling technique with the simulation result from Homer Pro in each parameter. In addition to this, the research has following limitations.

1. Literature on modeling and optimization of renewable energy systems is very limited for developing countries like Nepal.
2. Case study-based analysis may have reliability in understanding the trends but might be limited for precise prediction for other diverse communities.
3. Due to limited scope of the research, only the selective parameters for optimization of renewable energy systems is analyzed.

1.9 Organization of Dissertation

The dissertation is divided into five chapters and are presented as follows:

Chapter 1 Introduction

Chapter 2 Literature review

Chapter 3 Methodology

Chapter 4 Results and discussion

Chapter 5 Conclusion and the recommendation

2 LITERATURE REVIEW

Nepal has long history of electricity generation from hydropower, started from Pharping Hydropower Station back in 1911 AD, with installed capacity of 500 kW. Per capita energy consumption of Nepal only 14.8 GJ, which is one of the lowest in the world; despite the huge potential of energy resources. Majority of the total energy requirement is fulfilled from traditional fuels; fuel wood, agri-residue and the animal waste[15][1]. Nepal's residential consumption is 83% and non-residential use is 17%.

Despite the abundant energy potential, Nepal still have no enough electricity generated. The state-owned Nepal Electricity Authority (NEA) is responsible for the electricity supply through the national grid. During fiscal year (FY) 2017 and 2018 the annual peak power demand of Nepal 1444 and 1508 MW respectively but the system remains unable to meet about 400 MW needed during the winter peak. To meet the gap, Nepal imported nearly 400 MW (1,777 GWh in 2016, 2,175 GWh in 2017 and 2581 GWh of electricity [16]. Out of 1444 MW of peak demand as of 2017/18, 2,305 GWh has been generated by NEA itself, 2,175 GWh and 1,777 GWh is purchased from India and IPPs respectively [16]. Import of electricity from India is high during the FY 2019, which was 2813 GWh despite the lowered peak demand of 1320 MW of electricity. Whereas in the FY 2020, due to the increased national electricity generation, significant reduction in import of electricity from India is seen, i.e. 1729 GWh. But, for the fiscal year of 2021 due to increased peak demand to 1482 MW (increase of 74 MW than last year) and not much increased national electricity generation (national electricity generation increased by only 40 GWh) import from India is increased massively; i.e. 2826 GWh (which was only 1729 GWh in earlier year).

Unavailability of enough electricity remains the major driving force to limit the electricity per capacity consumption, which is 171 kilowatt-hours (kWh) per year and is one of the lowest in the world. Nepal's access to electricity and per capita consumption is lower than the 2010 average global access rate of 83% and average global consumption per capita of 685 kWh. Especially in the rural access, there is no access to electricity, hampering both economic development and access to information and education [3].

According to estimations of the NEA, energy demand grows yearly with an average annual rate of 9 %. Because of increasing household consumption, the evening peak demand has risen dramatically. Due to the continuously rising demand and stagnation in creating additional power generation capacities, a noticeable shortage of power supply since 2007 has been the consequence. The yearly demand is expected to exceed 17,400 GWh by 2027. Along with the growing demand, it is projected that system peak load will increase with similar annual growth rates, reaching 3679 MW in 2027 or even more. To address these electricity problems, comprehensive energy master planning is essential, and this research is an attempt for the same.

2.1 National energy scenario

Renewable energy

Nepal's energy sources are characterized as (i) traditional, (ii) commercial and (iii) alternative energy sources. Alternative energy is identical with renewable energy sources. This categorization is based on the use of resources in extracting the energy contents from the sources. The traditional source of energy includes biomass fuels particularly fuelwood, agricultural residues, and animal dung. These sources of energy are used in direct combustion traditionally. Whereas, traditional energy sources are further transformed into modern types. Fossil fuels and electricity falls under commercial sources of energy. Solar power, wind power, micro-hydro, bioenergy resources fall under category of alternative energy sources. Despite Nepal’s huge potential for hydropower production, its exploitation very below than optimal. This is the main reason behind maximum exploitation of traditional energy resources such as biomass. This massive exploitation has accelerated the depletion of natural resources and finally acting as a major cause for the degradation of environment. Biomass dominates the overall energy supply and consumption in the country. **Figure 2.1** shows the total supply and their share of energy consumption by fuel types in Fiscal Year 2014/15 [1].

As shown in **Figure 2.1**, total energy consumption in FY 2014/15 was 500 million Giga Joule (GJ); among which, fuel - wood is the largest energy resources and occupies about 70.47% of the total energy demand. Other sources of bio-masses were agricultural residues and animal dung which contributed about 3.48% and 3.68%, respectively. Share of petroleum fuels in the total energy system is about 12.53%. Other sources of commercial energy are coal and electricity contributed about 3.97% and 3.39%, respectively in the total energy supply. In aggregate, the share of traditional fuel is 77.63%, commercial (coal, petroleum, and electricity) is 19.88 % and renewable (Solar, Biogas, Micro-hydro, Wind) is 2.49% [1].

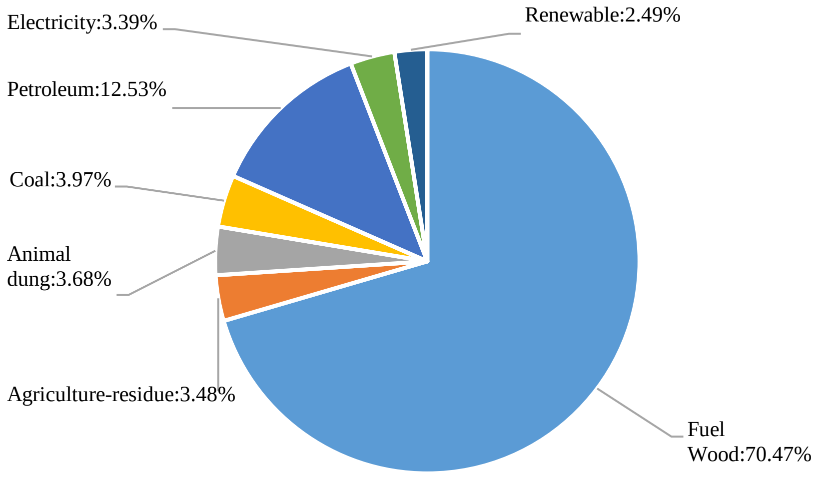


Figure 2.1 Nepal's energy consumption scenario by fuel types in 2014/15[1]

Further a literature review is conducted on total energy consumption and the trend during last one and half decade and is presented in **Figure 2.2**. The figure indicates that, the consumption of renewable energy is almost stagnant. Whereas, as per **Figure 2.2** the traditional fuel consumption pattern and commercial fuel consumption pattern in moving towards unsustainability. The 15 years' data depicts that traditional fuel consumption is decreased from nearly 90 % to less than 70 % (i.e. 20 % decrease in 15 years). But total energy consumption of the same period which was 8,616,000 tons of oil equivalent (ToE) has increased to 14,464,000. This increase in energy consumption is slightly covered from renewable sources and the majority is covered from commercial energy sources. Further, the data as in **Figure 2.2** indicates that, consumption of commercial fuels has increased from nearly 10 % to 30 %. However, in Nepal no commercial fuel (neither coal nor other petroleum products) is available and need to import from India. Thus, the fuel consumption pattern in Nepal is pushing towards unsustainability.

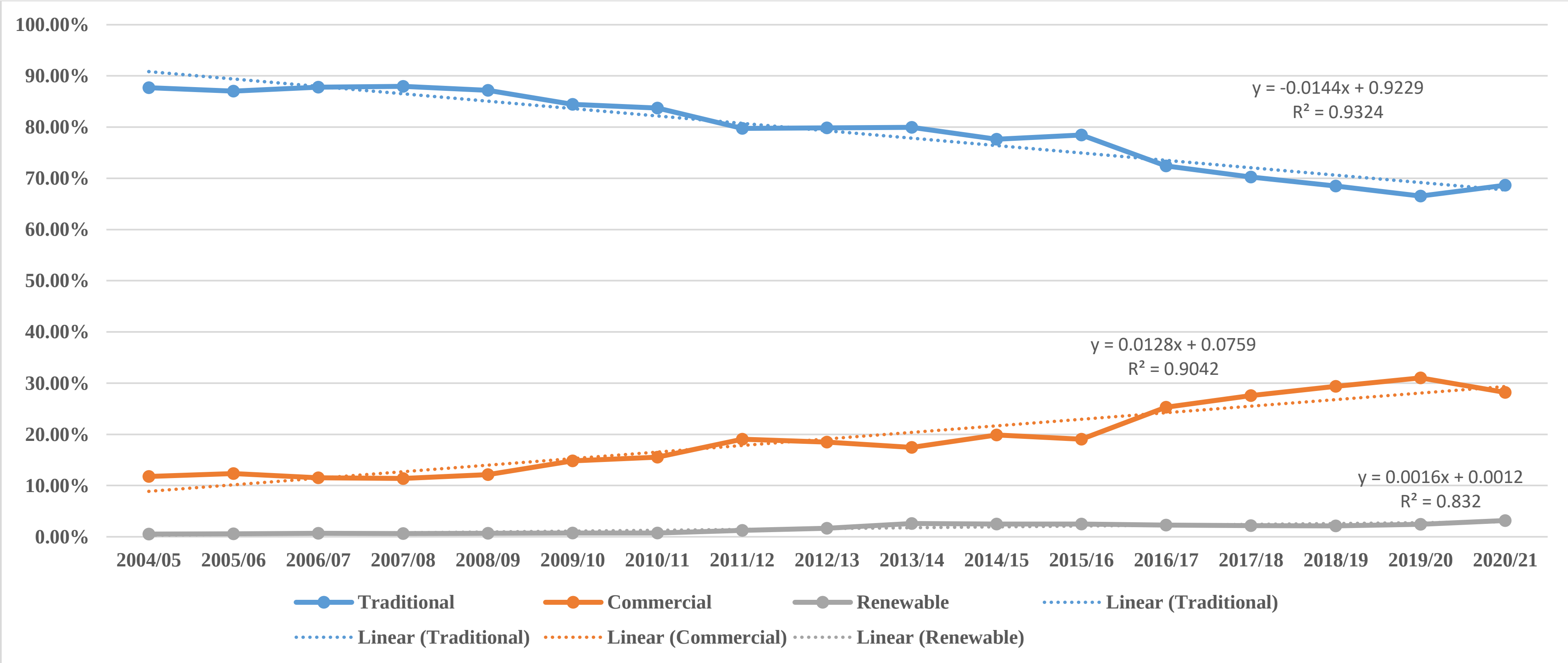


Figure 2.2 Fuel consumption pattern

Hydro-electricity

Nepal has tremendous hydropower potential [17]. Though long disputed, various literature has backed up the most entrusted theoretical and economical hydropower potential to be 83 GW and 42 GW respectively as shown in **Table 2.1**.

Table 2.1 Basin wise hydropower potential in Nepal [18][19]

River basin	Annual flow (billions of m^3)	Catchment area (km^2)	Theoretical value (GW)	Economically feasible (GW)
Karnali and Mahakali	49	47300	36.18	25.1
Sapta Koshi	33	28140	22.35	10.86
Sapta Gandaki	50	31600	20.65	5.27
Southern Rivers	42	5410	4.11	0.88
Total	**174**	**112450**	**83.29**	**42.11**

Out of 42 GW of economically feasible hydropower potential in Nepal, as of now only 1182 MW is installed, but much more to come in near future [2]. Tremendous hydro potential is due to more than 6000 perennial rivers and rivulets with an average annual flow of 174 billion m^3 as shown in **Table 2.1**.

Electricity generation and the peak demand

Electricity generation for the period of 2009 to 2020 with provisional figure for 2021 is tabulated in **Table 2.2**.

As shown in **Table 2.2**, peak electricity demand in 2021 has remained to be 1441.35 MW. Whereas, out of 8878 GWh of total energy available (NEA hydro generation and NEA thermal generation), NEA has generated 2811 GWh, 3241 GWh has been purchased from independent power producers (IPPs) and 2826 GWh has been imported from India[2][16]. Literature shows that the combined generation and the installed capacity of IPPs and NEA is in increasing trend, however, the steep gradient of the electricity demand, as presented during 2009 – 2021, shows that the generation is not to the optimal. Detail analysis, with regression, is conducted in results and discussion section and conclusion is presented accordingly. The generation being not optimal is further related with existing energy policies of Nepal and the policy review is conducted accordingly to trace the gap between energy generation and the policy injections.

Table 2.2 Nepalese energy generation and the peak demand for the period of 2009-2021 [2][16]

Particulars	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021***
Peak Demand (MW)	812.5	885.28	946.1	1026.65	1094.62	1200.98	1291.1	1385.3	1444.1	1508.16	1320	1408	1482
NEA Generation (GWh)	1849	2122	2125	2359	2292	2298	2368	2133	2305	2308	2548	3021	2811
Power Purchase from India	356.46	638.68	694.05	746.07	790.14	1318.75	1369.89	1777.68	2175.04	2581.8	2813	1729	2826
Power Purchase from IPPs	925.74	591.43	1038.84	1073.57	1175.98	1070.47	1268.93	1166.24	1777.24	2167.76	2190	2991	3241
National Generation (GWh)	2774.74	2713.43	3163.84	3432.57	3467.98	3368.47	3636.93	3299.24	4082.24	4475.76	4738	6012	6052
Power Purchase Total (GWh)	**1282.2**	**1230.11**	**1732.89**	**1819.64**	**1966.12**	**2389.22**	**2638.82**	**2943.92**	**3952.28**	**4749.56**	**5003**	**4720**	**6067**
Available Energy (GWh)	**3131.2**	**3352.11**	**3857.89**	**4178.64**	**4258.12**	**4687.22**	**5006.82**	**5076.92**	**6257.28**	**7057.56**	**7551**	**7741**	**8878**

2.2 Energy policies

In the energy context of Nepal, existing Nepalese energy policies and provisions which remain appropriate in promotion of overall energy sector in Nepal are summarized in brief with specific policy concentration and is presented in **Table 2.3**.

Table 2.3. Nepalese existing policies and provisions [20][21][22][23][24][25][26][27].

SN	Policy Provisions	Policy Concentration
1	Nepal Electricity Authority Act, 1984	NEA Act 1984 created scope to manage activities related to electricity generation and distribution in the country.
2	Water Resources Act, 1992	Water Resources Act, 1992 expedite the scope for the balanced utilization and conservation, of water resources in the country.
3	Hydropower Development Policy 1992 and 2001	Hydropower Development Policy 1992 and 2001 encourages the private sector investment through various fiscal and other incentives for the development of hydropower in the country.
4	Electricity Act 1992 and 2001	Electricity Act 1992 and 2001 provides legal arrangements to endorse Hydropower Development Policy 1992 and 2001.
5	Local Self-Governance Act, 1998	Local Self-Governance Act, 1998 provided local authority for the formulation, implementation, distribution and maintenance of mini and micro hydropower projects.
6	NEA Community Electricity Distribution Bye-Laws, 2003	NEA Community Electricity Distribution Bye-Laws, 2003 provided opportunity for community electrification through country and community participation.
7	National Water Plan 2005	National Water Plan 2005 is the only document with a time-bound target for rural electrification.
8	Rural Energy Policy 2006	Rural Energy Policy 2006 has provisioned for rural energy and electrification activities in rural areas through Renewable Energy Technologies (RETs).

9	Renewable Energy Subsidy Policy 2000-2016	Renewable Energy Subsidy Policy 2000-2016 has provisioned for a direct financial subsidy to off-grid electrification in rural areas.
10	RE Subsidy Delivery Mechanism for Special Program 2018	RE Subsidy Delivery Mechanism for Special Program 2018 has provisioned in subsidy for special renewable energy programs.
11	National Energy Efficiency Strategy 2018	National Energy Efficiency Strategy 2018 has a national target of energy efficiency in Nepal which is to double by the year 2030 A.D.

The study has analyzed the existing pertinent energy policies as listed in **Table 2.3**. The study has further tried to relate the role of energy-related policies and trace its impact and the implications on electricity generation. The study shows that in Nepalese context, institutional coordination and synergies of energy policies with the institutional coordination is vital for its better implementation[28]. The research has shown that policy intervention has significant roles in removing market barriers[29]. Meaning, proper policy interventions in the energy sector could also mitigate the existing barriers and move towards higher electricity generation. The research has also analyzed renewable energy policies and suggested some definite models to reduce various burden and barriers for adoption of the same[30]. Such implementation has forecasted to increase the use of renewable energy as well. Research over-evaluation of renewable energy policy has revealed that better policy interventions increase the total amount of electricity generation[31]. Research has also concluded that the regular performance of different energy policies instrument the dissemination of new energy technologies[32]. In US, evaluation of energy policies has shown that polices ultimately reduces the financial burden for the energy technologies and make them adaptable. In the meantime, improper policies being implemented has also harmed the sustainable economy of the country, thus renewable energy policies should focus on energy efficiency, improving energy structure and reshaping energy industry[33]. Other researches have also shown a positive implication over the adoption of various renewable energy technologies[34][35].

In nutshell, the analysis of various renewable energy policies show that better policies always have a positive impact on the adoption of existing energy technologies as well as reflect positive impact over electricity generation. In Nepalese context, there might be numerous reasons behind the gap in the generation and the demand, but policies show a significant impact on it. Based on this evidence and current electricity scenario of Nepal, it is claimed that Nepalese energy policies are not up to the optimal, else the gap would not have been visible.

2.3 Energy planning

Network Planner has been used to estimate investment costs and financing requirements to support electrification programs and identify opportunities for cost-effective grid expansion in Kenya [36]. The model can be used to rapidly estimate connection costs and compare different regions and communities. Inputs that are modeled include electricity demand, costs, and geographic characteristics. The penetration rate, an exogenous factor chosen by electricity planners, is found to have a large effect on household connection costs, often outweighing socio-economic and spatial factors such as inter-household distance, per household demand, and proximity to the national grid [36]. A study to identify potential areas in India where the provision of electricity through renewable energy-based decentralized generation options can be financially more attractive as compared to extending the grid [36]. The cost of generation of electricity from coal, hydro and nuclear power plants with cost of transmission and distribution of electricity in the country are estimated. The study indicates that renewable energy-based decentralized electricity supply options could be financially attractive as compared to grid extension for providing access to electricity in small remote villages with low load conditions. Whereas, in high load conditions, grid expansion is more feasible.

The cost of grid electricity to the end-user compared with the cost of electricity from decentralized energy systems to obtain the specific distances from the grid, the level of demand and the load factor conditions under which using decentralized energy systems for rural India makes economic sense is analyzed [37]. The finding of the research is that, for small and isolated villages with low load factors, decentralized energy technologies make economic sense. A similar study is conducted by USAID for Zambia rural electrification [38]. An analytical model for choosing between conventional grid extension and off-grid solar photovoltaic, biomass gasifier-based power generation for remote village electrification is conducted [39]. The model provides a relation between renewable energy systems and the economical distance limit (EDL) from the existing grid point, based on life cycle cost (LCC) analysis, where the LCC of energy for renewable energy systems and grid extension will match. The research was found to be most relevant for the purpose, and analytical method followed in this study in identifying the optimal choice among the electrification options based on renewable energy sources and the grid is based on this literature [40][39]. Thus, this research studies the EDL based on LCC for renewable energy systems compare it with grid-extension for Gorkha district.

Modeling and optimization techniques

The study has conducted review and analysis of energy planning methodologies proposed by numerous researchers and reviews [41]–[44]. After analyzing those methodologies, the research has proposed its own simple methodology or steps as stated below.

Step 1: Identification of load (demand analysis)

In this step, depending upon the scope of energy planning, demand load is identified for residential, commercial and industrial level. The data is collected from each user entity level. In case of sampling data collection, it is extrapolated to forecast the total current and future load demand.

Step 2: Assessment of meteorological conditions (resource analysis)

Before planning to actual energy supply to meet the load demand, resource analysis is conducted. During the resource analysis, various meteorological conditions of hydropower, solar irradiation, wind velocity and biomass potential are assessed. Hydropower potential, current grid situation, solar irradiation, wind velocity, biomass potential etc. are assessed in detail.

Step 3: Energy supply model (model analysis)

Based on the resources available in the area, energy modeling is conducted. The modeling may be conducted in any of the appropriate tool, software or methodology. During the process of model identification, various models are tried and tested. The objective of the energy supply modeling is to identify the best method/tool to electricity the area at least cost.

Step 4: Model development (optimized model)

Once the model analysis is done, a best fit model is selected for energy planning. During the model development, various parameters under planning are optimized and tested for its efficacy.

Step 4: Sizing using simulation and optimization (system configuration)

Once the optimized model is finalized, exact energy planning is only possible based on forecasted load demand and the necessary system configuration of energy resources. Optimization also takes cares of the available technologies and resources for energy planning.

Step 5: Model implementation (contextualized system configuration)

After ensuring system optimization parameters, technology selection with configuration for the appropriate model, the model is implemented for the specific location.

One way or the other the above-mentioned steps are found relevant and being implemented by energy planners and proposed herewith. In summary the optimization techniques are finalized and presented in the following **Figure 2.3**. The modeling and the optimization techniques are not unidirectional process. Depending upon the demand load, resources available, optimization models it has feedback loop in each step. Moreover, it is more a site specific for exact implementation. Thus, the following process as depicted in **Figure 2.3** is proposed by the study for better energy planning and optimization process

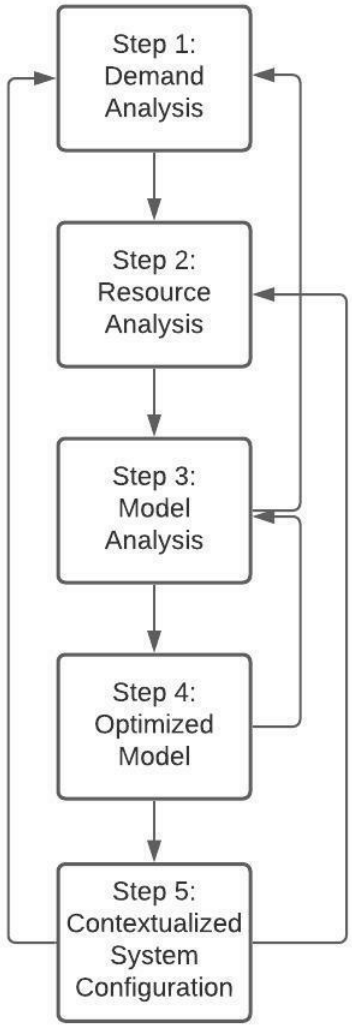


Figure 2.3 Energy planning: modeling and optimization techniques

Further, apart from optimization techniques in energy planning, there are numerous energy planning approaches. The research has reviewed the various approaches and presented as follows as a part of literature of the study.

1. Energy planning approaches

Based on various published articles and literature, the study here presents four best approaches for energy planning.

i. Bottom up approach for energy planning

In this energy planning approach, energy demand of each household at specific time of day is recorded at primary level. The demand data for every household, commercial entity and industry is collected for better demand forecast. Further, the daily data is extrapolated (or recorded manually) to year-round data. In case, data collection of every entity is not possible, sampling may be conducted in a scientific way. The approach is very time consuming, but accuracy of the planning is very high.

ii. Top down approach for energy planning

In top down approach for energy planning, energy demand of each entity at user level is not collected. Basically, the energy demand data is considered from secondary source and extrapolated for demand forecast. Energy planning is done based on earlier data adding a factor for increase in energy demand; demand forecasting. The approach is very useful when a planning is to be carried out in short span of time and having no primary data at hand. But, the accuracy of the planning is relatively low than the bottom up approach.

iii. As usual approach for energy planning

The approach is not about top-down or bottom-up, but this is about giving continuity to the current energy planning method. Future load demand is forecasting by extrapolating the available demand data. This approach of energy planning is the least efficient approach for energy planning thus not recommended for execution.

iv. Hybrid approach for energy planning

Hybrid approach for energy planning is the mix of bottom-up and top-down approach. In this approach depending upon necessity, primary data is collected, and secondary data is utilized. So, it is the mix of top-down and bottom-up approach. Accuracy of the approach is high and is most widely used for efficient energy planning.

2. Optimization models

During energy planning models, the planner needs to optimize various technical and financial parameters and forecast the future scenario accordingly. Thus, these energy planning and forecasting models fall under the umbrella of optimization models or techniques. Depending upon requirements of energy planners and field situation, various energy optimization models are presented in **Table 2.4**.

Table 2.4 Comparison of energy optimization models

Optimization models	**Scope of the models**	**Pros**	**Cons**	**References**

Analytical	Follows both top-down and bottom-up approach Least cost calculation Economic distance limit comparison	[45][39]
Hybrid Optimization of Multiple Energy Resources (HOMER Energy)	Follows bottom up approach Techno-economic optimization Parametric optimization Sensitivity analysis	[46]–[51]
Long-range Energy Alternatives Planning (LEAP)	Follows bottom up approach Energy system analysis Energy policy analysis and climate change mitigation Scenario-based modeling tool Covers both conventional and renewable energy sources	[52]–[57]
Model for Analysis of Energy Demand (MAED)	Follows bottom up approach Energy demand forecasting model Systematic framework for mapping trends and anticipating change in energy needs, Covers both conventional and renewable sources	[58][59], [60]
MARKAL	Follows bottom up approach Numerical model used to carry out economic analysis of different energy systems Optimal technology mix	[58], [61]
MESSAGE	Framework for medium to long-term energy system planning, energy policy analysis, and scenario development	[59]

	Identification of socioeconomic and technological response Description of future uncertainties Development of robust technology strategies and related investment portfolios to meet a range of user-specified policy objectives	
Econometric	Statistical model Specifies statistical relationship between various economic quantities pertaining to a particular economic phenomenon	[62]–[65]
Wien Automatic System Planning Package (WASP)	Framework for power system planning Determines the optimal long-term expansion plan for a power generating system Optimal expansion is determined by minimizing discounted total costs	[66]–[68]

Based on the above presented optimization models, the study found the HOMER to be more appropriate for the research purpose. Further, the appropriateness is checked after evaluating the appropriateness with close to similar type of optimization tools as indicated in **Table 2.5**.

Table 2.5 Appropriateness of tools

Tools	GHG analysis	Design optimization	Sensitivity analysis	Load profile	User friendly
HOMER	Yes	Yes	Yes	Yes	High
Ret screen	Yes	Yes	No	No	Low
Energy Pro	No	No	No	Yes	Low
DER-CAM	No	Yes	No	No	Medium

TRANSYS	No	Yes	No	No	Low
iHOGA	No	Yes	No	Yes	Medium

Based on the appropriateness check among the similar tools, HOMER tool is considered the research and analysis.

2.4 Techno-economic optimization

For the techno-economic optimization of hybrid energy systems, HOMER 2.68 software is adopted in this research. The HOMER Pro is a microgrid software by HOMER Energy in the global standard for optimizing microgrid design in off-grid and grid-connection. HOMER is originally developed at the National Renewable Energy Laboratory (NREL) and enhanced and distributed by HOMER Energy (Hybrid Optimization Model for Multiple Energy Resources) has three tools, viz, simulation, optimization and sensitivity analysis. Simulation model development is the major on HOMER. HOMER simulates a viable system for all possible combinations of the equipment for grid and off-grid energy technologies. HOMER simulates the operation of a hybrid microgrid for an entire year, in time steps from one minute to one hour. HOMER examines all possible combinations of system types in a single run, and then sorts the systems according to the optimization variable of choice. HOMER simplifies the design process for identifying least-cost options for microgrids or other distributed generation electrical power systems. HOMER optimizer is a proprietary “derivative free” optimization algorithm that was designed specifically to work in HOMER. For sensitivity analysis, HOMER has provision of asking many “What if?” questions, because we cannot control all aspects of a system, and we cannot know the importance of a variable or option without running hundreds or thousands of simulations and comparing the results. HOMER makes it easy to compare thousands of possibilities in a single run. This allows to see the impact of variables that are beyond the control, such as wind speed, fuel costs, etc, and understand how the optimal system changes with these variations.

This section presents literature on various techno-economic optimization done using HOMER software. Cost comparison, analysis and optimization using HOMER for isolated energy technologies and the hybrid system for India is calculated by researchers [69]. Similar research for techno-economic optimization is done by various researchers for countries line Pakistan, Bangladesh, Ethiopia, Cameroon etc. Like our research, various research on hybrid of PV-DG system, biomass, hydro-DG etc are done [70][71]. Similarly, study on techno-economic parameters of DG/PV/Battery/Wind for south of Iran is conducted. HOMER was used to model the operation of the system and to identify the appropriate configuration based on comparative technical, economical, and environmental analysis [72]. Study on possible standalone diesel generators, hybrid PV/diesel/battery, and 100% PV/battery scenarios are analyzed. The operational behaviors of the different systems and impact of PV penetration levels were also analyzed. The results show the trends towards use of renewable energy sources in energy generation and less dependence on stand systems [73]

Such a numerous studies and research for real field applications in energy planning through simulation, optimization and sensitivity analysis using HOMER Pro if found relevant and useful.

3 METHODOLOGY

3.1 Introduction

The energy planning and optimization is conducted through various tools and methodologies. Various energy planning approaches and tools are explained in detail in the literature section. Out of the mentioned tools and techniques for planning and optimization, this research is conducted through analytical modeling for energy planning. Further, energy optimization is done using a Homer Pro tool (HOMER 2.68 Beta). Moreover, the policy analysis is conducted through regression of GDP vs EPC, qualitative analysis, expert consultations and FGDs and the conclusions are drawn accordingly.

3.2 Methods

Detail procedure of each method and the methodology is explained in the following sub-sections:

Desk Study

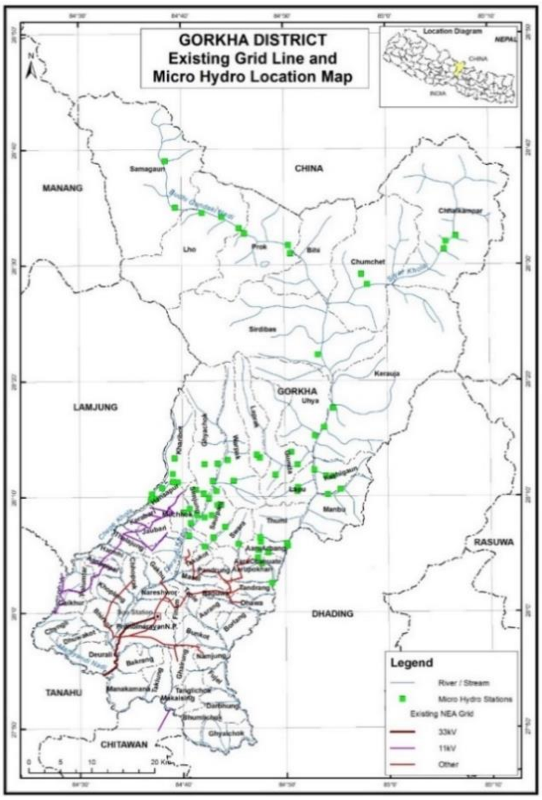
Under the desk study, literature review of national, regional and international level reports and publications is reviewed to trace progress on research topic done so far. Under desk study phase, all the necessary check lists, list of questionnaires and data collection forms and formats was finalized. Desk study conducted the detail analysis of analytical modeling. Detail literature review is conducted on analytical modeling approaches. Analytical modeling is done to trace the Economic Distance Limit (EDL), Life Cycle Cost (LCC) and the refurbishment cost for the various energy systems. The analytical modeling is widely accepted model and thus selected for this research [39].

Further, the HOMER 2.68 Beta is compared against other similar optimization tools and selected upon its better features for design optimization, emission analysis, load profile as time series data, user friendly and others. HOMER is used to optimize the hybrid solar (PV), micro-hydro (MHP), battery, diesel generator (DG) and feasibility study and to model and refine energy networks in decentralized and interconnected modes using sustainable and traditional sources. In addition, the HOMER 2.68 is trustable for techno-economic research for off-grid and grid-connected power systems for the various dimensions and preparation of hybrid renewable energy systems.

Site Selection

An ideal site for this type of study should have grid access, micro-hydropower system potential, solar energy, and areas with limited or no electricity access. Gorkha district lying in Gandaki province of Nepal is considered the most suitable site to study as the location with all the required characteristics to be chosen as an ideal case. The district has two geographical regions: mountain/hill on the South from 228 m to 2500 m altitude; and the high Himalayas from 2500 m to 8163 m. The population density of the district decreases massively from south to the north. **Figure 3.1** represents the electrification status of the research site: the existing NEA grid line along with the existing micro hydro stations plotted through Geographic Information System (GIS) tool.

After site selection, data collection is done through various secondary sources like Alternative Energy Promotion Center (AEPC), Renewable Energy for Rural Livelihood (RERL), Central Bureau of Statistics (CBS), Village Development Committee (VDC), District Development Committee (DDC), World Bank (WB) etc. More than fifteen thousand (15,775) households, 24 educational institutions, 24 offices or health posts, and 24 industries exist in the research area with an average of electrical load growth of 10 % in first year and 5 % in the subsequent five years [74]. Electricity load demand for the next five years is calculated for 17 VDCs which is 965 kW and considered 1MW for the further analysis and calculation purposes.

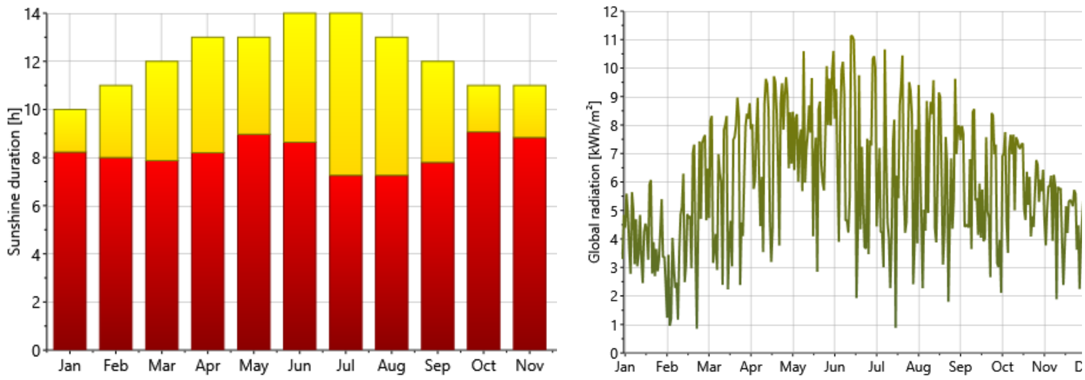


Source: www.dos.gov.np

Figure 3.1 Map of Gorkha district indicating energy systems availability

Based on the plotted map as shown in **Figure 3.1**, the research site is selected in an appropriate geographical location having abundant solar energy. In this study, we employ Meteonorm software, which uses an empirical method for calculating solar radiation on horizontal and arbitrarily oriented surfaces that are situated in any location. The method consists of composing databases and interpolation algorithms in a predetermined scheme. The average monthly data for the weather stations are stored in the Meteonorm database, while the hourly data are generated when needed. The average monthly values for the cities and other locations are obtained by interpolation, and the hourly values are generated based on them [www.meteotest.ch]. Similar publications that have adopted such Meteonorm data further validate the use of such data [75][76].

The meteorological data provided by Meteonorm v8.0.3.15190 for the Gorkha district are presented in **Figure 3.2** (sunshine hours and global radiation), whereas the uncertainty parameters are embedded in the software itself thus not considered in our study to avoid duplication.



a. Sunshine hours b. Global radiation

Source: www.meteonorm.com/en/

Figure 3.2 Sunshine hours and global radiation of Gorkha district

Parameters selection and data collection

Under data collection, the required data on energy potential, energy generation and demand were collected for analytical modeling and techno economic optimization.

Data collection was focused to meet the following requirements.

1. Optimization parameters for demand and supply side management of renewable energy technologies – Modeling from Analytical
    a. Energy potential
    b. Demand and supply forecast
    c. Loss minimization
    d. Economic distance limit
    e. Least cost planning among available renewable energy systems and hydropower
    f. Forecast of future demand
    g. Policy analysis
2. Optimization of renewable energy supply mix – Optimization from HOMER 2.68 Beta
    a. Optimized model
    b. Analysis of green-house gas (GHG) emissions
    c. Existing renewable energy source data collection
    d. Future demand projection

In particular, the study has considered the following data and parameters:

Data collection:

- No. of households, educational institutes, offices and industries of each village (further grouped to VDC level)
- Distance between villages in km
- Load growth
- Cost of equipment
- Consumption of fuel by types

Parameters calculated and analyzed:

- Total connected load of households, educational institutes, offices and industries
- Calculation of Economic Distance limit (EDL)
- Calculation of Life Cycle Cost (LCC)
- Impact of battery in the project cost
- Distribution of energy consumption by fuel types
- Future of energy consumption trend
- Impact of Gross Domestic Product (GDP) on Electricity Per Capita (EPC)

Data analysis and modeling

The collected data is analyzed, cleaned and verified for reliability. The final verified data is analyzed and modeled from analytical method, and HOMER 2.68 Beta for optimization of demand and supply side management and optimization of renewable energy supply mix, LCC and EDL. Finally, the result of the modeling is analyzed, and conclusion is drawn accordingly.

Analytical modeling and analysis

Analytical modeling is a mathematical modeling technique used for simulation, analysis and making predictions about the techniques involved in complex processes. Thus, the analytical modeling is a trusted method for complex analysis. In case of analytical modeling of energy systems it is widely accepted and trusted tool for energy planning in developing countries for its simplicity [45][77][78][79]. Thus, analytical modeling is adopted for the study. In this study, various mathematical assumptions and processes are defined for necessary calculations. For analytical modeling, firstly LCC of the system is calculated after which EDL is calculated. Both primary data, collected from NEA & AEPC, and secondary data collected from census [74] are analyzed. After the analysis, the best cost-effective technology is selected. EDL is used to check better electrification technology depending upon distance for electrification. This techno-economic optimization is deployed by various researchers for the optimization of renewable energy systems [80][78]. Given the methods' accepted applicability, analytical modeling coupled with LCC and EDL analysis is considered in this research. This analytical modeling is best suited for developing and underdeveloped countries like Nepal for efficient electrification planning.

HOMER 2.68 Beta, technoeconomic optimization and analysis

HOMER is used to optimize the hybrid solar (PV), micro-hydro (MHP), battery, diesel generator (DG) and feasibility study and to model and refine energy networks in decentralized and interconnected modes using sustainable and traditional sources. HOMER simplifies the task of designing distributed generation (DG) systems—both on- and off-grid. The software simulates the energy systems specifications by providing the electrical and thermal load per hour. It allows and optimally limited grid size to be calculated according to the decreased power by placing various energy systems, generations and the storage configurations. HOMER's optimization and sensitivity analysis algorithms allow to evaluate the economic and technical feasibility of many technology options and to account for variations in technology costs and energy resource availability [47][81][78]. Thus, optimization of the energy systems adopted in the study is validated by the result analysis from the Homer Pro tool. The Homer Pro tool by default provides the sensitivity cases and the optimization results through simulation. The sensitivity cases show a list of the most feasible systems under study. The optimization results present all the feasible simulations for any selected sensitivity case.

Energy policy, regression, survey and analysis

Energy related policies are analyzed qualitatively as a desk study. Impact of Nepalese energy policy injection is validated by tracing the effect in electricity generation further leading to impact in GDP and EPC. Impact of GDP on EPC is calculated by regression analysis. Further analysis is carried out by in-person expert consultations and focus group discussions (FGD). The outcome of the regression is validated by qualitative survey with 30 academic professionals, 30 independent experts through qualitative questionnaire survey and 4 Focus Group Discussions (FGDs) with academicians, experts, community level and policy makers.

After conducting research from analytical method, HOMER 2.68 and policy analysis, the conclusions are drawn and validated with published results. Since the policy research study is more qualitative type, it has less possibilities for experimental verifications.

The research methods adopted for the research methodology is presented in the following flow chart.

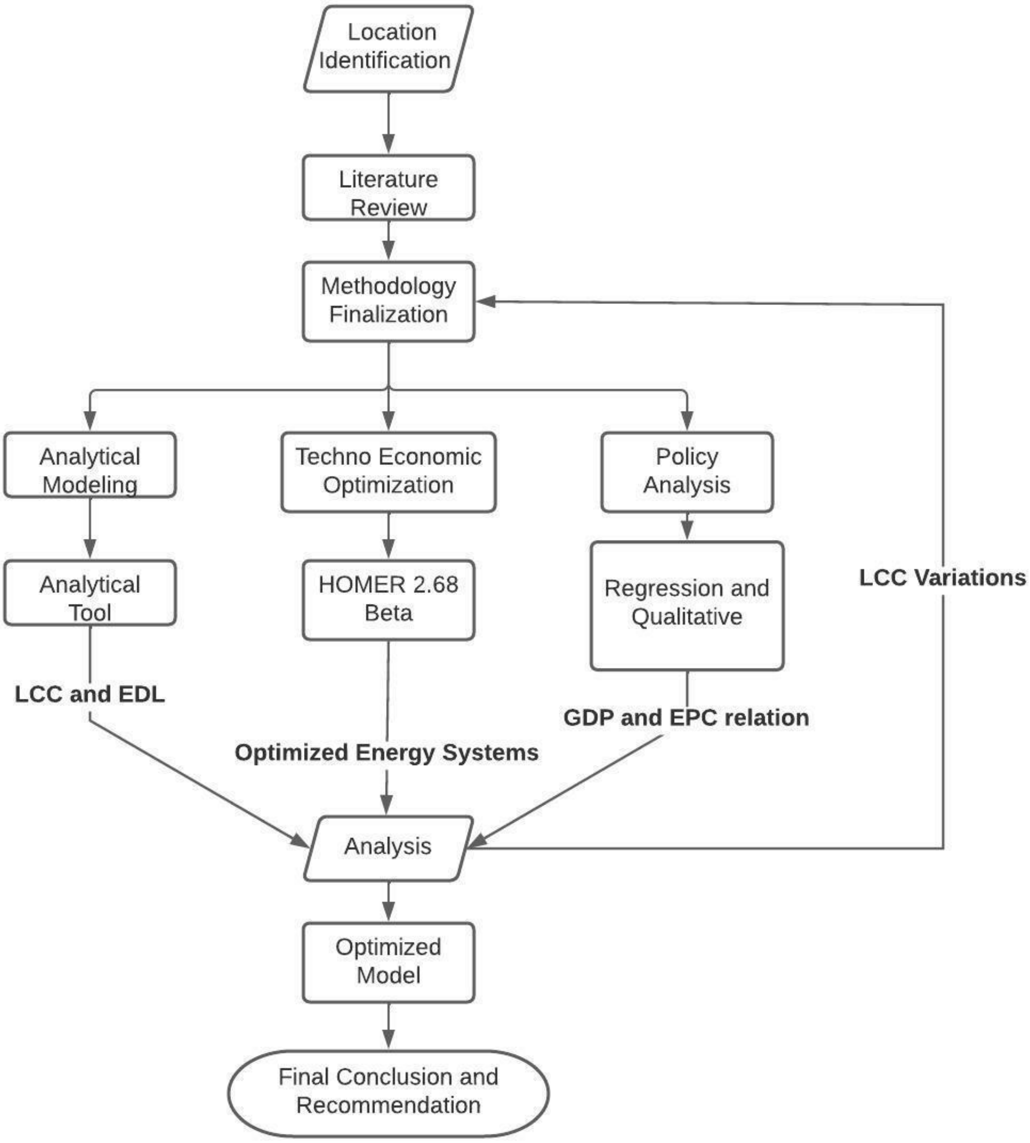


Figure 3.3 Research methodology

Validation

The research is conducted through analytical modeling for energy planning of Gorkha district. Further, the techno-economic study is conducted by HOMER 2.68 Beta. Experimental verification of energy planning of a district is less feasible, neither the techno-economic optimization of all the energy systems is possible through experimental validation. Thus, research outcomes of analytical modeling, techno-economic optimization and policy analysis is validated with national and international published results, consultations and verification with academicians, independent experts, policy makers, and the past trends.

3.3 Theory, Mathematical models and the Assumptions

Life cycle cost (LCC)

For the analysis and comparison of energy technologies, the study calculated the LCC of each energy technology considered in this research. The operating constraints like geographic terrain, climatic conditions, available technology for each technological option have varied impacts over energy production and are considered an error and limitations for the research provision.

LCC for different energy systems, photovoltaic system (PV), micro-hydropower system (MHP), and diesel generator system (DG) for varied capacities, are calculated by the Eqs. (3.1), (3.2)and, (3.3) respectively [40].

$$LCC_{PV} = \frac{C_{PV} + C_B + (C_{PV} + C_B).\beta.P(d,n) + C_R.P(d,n_1)}{L.h.n} \quad (3.1)$$

$$LCC_{MHP} = \frac{C_{MHP} + C_{MHP}.\beta.P(d,n) + C_{MHPR}}{L.h.n} \quad (3.2)$$

$$LCC_{DG} = \frac{C_{DG} + (C_{DG}).\beta.P(d,n) + C_R.P(d,n_1) + C_{FUEL}.n}{L.h.n} \quad (3.3)$$

LCC calculation for a PV system backed up by DG is the combination of the two Eqs. (3.1) and (3.3).

LCC calculation for the MHP system backed up by DG is the combination of the two Eqs. (3.2) and (3.3).

LCC calculation for grid expansion is given in Eq. (3.4).

$$LCC_{GE} = \frac{LCC_{gen} + LCC_{transf} + LCC_{grid}.X}{L.h.n} \quad (3.4)$$

Where,

$$LCC_{gen} = t_{gen}.L.h.\left(\frac{1}{1-\delta_{t\&d}}\right).P(d_1,n)$$

$$LCC_{grid} = C_{grid} + (C_{grid}).\beta.P(d_{2,}n)$$

$$P(d,n) = \frac{(1+d)^n - 1}{d.(1+d)^n}$$

This approximates 1+ d + d_2 +d_3+d_4+………d_n for n to infinity.

The lifecycle cost of electricity generation and lifecycle cost of grid expansion is calculated considering the energy systems' capacity, generation cost, system refurbishment cost, and maintenance cost.

Economic distance limit (EDL)

EDL is a break-even analysis of grid expansion and an alternate energy system and is calculated as in Eq. (3.5).

$$\frac{LCC_{grid}.EDL + LCCtransf + LCC_{gen}}{L.h.n} - LCC_{MHP/PV/DG} = 0 \quad (3.5)$$

From the above-given equations (3.1) to (3.5), EDL is calculated for MHP, MHP+DG, PV (inc battery), PV+DG, DG, and grid expansion. Considering the Nepalese past and current energy scenario, EDL for each energy system is calculated for 6,8,10,12 and 14 operating hours. Further, energy systems for load capacities of 5,10,15,40,75, and 150 kW are considered for comparison to meet the total load demand of 1 MW. The selection of this method is grounded on the fact that a similar methodology has been adopted and verified in previous research [82].

Assumptions

Load factor, diversity factor, and the connected load for various types of institutions are considered as presented in following **Table 3.1**.

Table 3.1 Assumptions for load forecast. [83][16].

Factors	**Domestic**	**Education**	**Offices**	**Industries**
Load factor	0.2	0.2	0.5	0.5
Demand factor	0.9	0.2	0.4	0.3

Connected load(W)	200	500	400	2000
Load growth				
Year 1	10%	10%	10%	10%
Year 2 to 5	5%	5%	5%	5%

3.4 Ethical considerations

Ethical issues in this research activity is given highest priority with the following considerations to the extent possible.

1. Research participants is not subjected to harm in any ways whatsoever.
2. Respect for the dignity of research participants is highly prioritized.
3. Full consent is obtained from the participants prior to the study.
4. The protection of the privacy of research participants is ensured.
5. Anonymity of individuals and organizations participating in the research is ensured.
6. Any deception or exaggeration about the aims and objectives of the research is avoided.
7. Affiliations in any forms and publications, sources of funding, as well as any possible conflicts of interests is declared.
8. All the communications related to the research is done with honesty and transparency.
9. Any type of misleading information, as well as representation of primary data findings in a biased way is avoided.

3.5 Uncertainties

The study has considered various parameters for the energy planning process such as demand load, demand fluctuation, irradiation, load factor, diversity factor, life cycle cost, etc. The possible changes of the parameters correspond to the possibilities of uncertainties of the coefficients [84]. To minimize the uncertainty, the study is conducted with varieties of the values of a single parameter or coefficient. For example, the study has considered varying load of 5, 10, 25, 40, 75, and 150 kW to meet total demand of 1 MW. Considering Nepalese past and present energy scenario, power available hours per day are considered varying hours of 6, 8, 10, 12, and 14 hours per day. Life cycle cost is calculated with prevailing costs with inclusion of possible discount rates for solar PV and batteries etc. Further, the study utilizes the Meteonorm data for sunshine hours and global radiation and limits the study over their uncertainties. Certain prevailing assumptions, as indicated above, in the study are considered in the research and the incorporated errors are taken as uncertainties and errors.

4 RESULTS AND DISCUSSION

This section presents the results from the research in thematical manner and the discussion is presented subsequently. The results are presented in three main thematic sections:

1. Analytical modeling, optimization of the energy systems and the sensitivity analysis
2. Techno-economic optimization of the energy systems
3. Policy analysis

4.1 Analytical modeling, optimization of the energy systems and the sensitivity analysis

This section presents the results of EDL against various indicators used in the research, namely electrification model, generation cost, load, and electricity supply. Further, it presents the impact of battery back-up in solar PV energy systems and LCC comparison against varied load conditions. The result of each analysis is analyzed and discussed immediately afterwards. The major results show that grid expansion is feasible only for high load requirements. Off-grid technologies in hybrid mode are more feasible for low load requirements; depending on the availability of energy resources as well. The study shows that the energy cost for low load conditions is high and is low for high load conditions. This way the best alternative electrification option can be adopted. The study shows that; the reduced generation cost will support increasing the electrification penetration. Among the options studied, PV backed up with DG is found better electrification alternative to grid expansion.

Load estimations

Study has considered 17 VDCs and the load for all VDC are calculated and further summarized to total for the analysis. The total load for next five years accounted to be 965.3 kW as presented in the following **Table 4.1**. The load forecast is done for next 15 years as presented in **Table 4.1**but for the research planning for next five years is considered.

Table 4.1 Load demand calculation

VDC	Village name	Demand for different Years in kW														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
AaruArbang	Arbik	48.7	53.7	56.3	59.2	62.1	70	71.4	72.8	74.3	75.7	76.5	77.3	78	78.8	79.6
AaruChanuate	Dandagaun	61.6	68	71.4	74.9	78.7	88.6	90.4	92.2	94	95.9	96.9	97.8	98.8	99.8	100.8
Ghyakchok	Torkekharka	19.9	22	23.1	24.2	25.4	28.6	29.2	29.8	30.4	31	31.3	31.6	32	32.3	32.6
Gumda	Singla	18.9	20.9	21.9	23	24.1	27.2	27.7	28.3	28.9	29.4	29.7	30	30.3	30.6	30.9
Hansapur	Lapsibot	55	60.6	63.7	66.9	70.2	79.1	80.7	82.3	83.9	85.6	86.5	87.3	88.2	89.1	90
Kashigaun	Yamkang	15.8	17.4	18.3	19.2	20.2	22.7	23.2	23.6	24.1	24.6	24.8	25.1	25.3	25.6	25.8
Kharibot	Gumda	24.1	26.6	28	29.4	30.8	34.7	35.4	36.1	36.8	37.6	38	38.3	38.7	39.1	39.5
Laprak	Kirunje	17.7	19.5	20.5	21.5	22.6	25.5	26	26.5	27	27.6	27.9	28.1	28.4	28.7	29
Lapu	Nambaikharka	21.1	23.2	24.4	25.6	26.9	30.3	30.9	31.5	32.2	32.8	33.1	33.5	33.8	34.1	34.5
Manbu	Kaigung	70.5	77.7	81.6	85.7	89.9	101.3	103.3	105.4	107.5	109.6	110.7	111.9	113	114.1	115.2
Saurpani	Danje	139.1	153.4	161.1	169.1	177.6	200	204	208.1	212.3	216.5	218.7	220.9	223.1	225.3	227.6
Simjung	Lapsibot	42.9	47.3	49.6	52.1	54.7	61.6	62.9	64.1	65.4	66.7	67.4	68.1	68.7	69.4	70.1
Swara	Dihigaun	44.5	49.1	51.5	54.1	56.8	64	65.3	66.6	67.9	69.2	69.9	70.6	71.3	72.1	72.8
Takukot	Lamidanda	42.1	46.4	48.7	51.2	53.7	60.5	61.7	63	64.2	65.5	66.2	66.8	67.5	68.2	68.9
Thumi	Khoriya Chaurgaun	61.4	67.7	71.1	74.7	78.4	88.3	90.1	91.9	93.7	95.6	96.6	97.5	98.5	99.5	100.5
Uhya	Kolkate	0.6	0.6	0.7	0.7	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1
Barpak	Tallahgare	72.4	79.9	83.9	88	92.5	81.6	83.2	84.9	86.6	88.3	80.8	81.6	82.4	83.3	84.1
Total load demand in kW		756.3	834	875.8	919.5	965.3	1064.8	1086.3	1108	1130.1	1152.5	1155.9	1167.3	1178.9	1191	1202.9

Electrification models and EDL

EDL for all electrification options is calculated. The results for various electrification models are tabulated in **Table 4.2**. For the swift comparison of EDL, the table presents EDL in increasing order.

Table 4.2 Electrification models and EDL.

SN	Electrification models	Economic distance limit (km)
1	PV + DG	14.24
2	MHP	14.70
3	PV + battery	22.84
4	MHP + DG	28.10
5	DG	38.58

The result as presented in **Table 4.2** shows that the area within 14.24 km length from existing grid end-points is economical to electrify through grid expansion. For the areas beyond 14.24 km, energy access from decentralized options is seen as economical. Specifically, electrification up to 14.24 km, PV + DG appears economically beneficial. Further, grid expansion up to 14.70 km is more economical than MHP, grid expansion up to 22.84 km is more economical than PV + battery. Grid expansion up to 28.10 km is more economical than MHP+DG, and grid expansion up to 38.58 km is more economical than DG. Other hybrid options like PV + DG, MHP, PV+ battery, MHP + DG or, DG would be better than grid expansion if the distance is beyond calculated EDL. Apparently, PV+DG is the best economical option for off-grid electrification after grid-expansion. This result perfectly matches the results obtained from Homer Pro modeling by other similar researchers [85][77]. Importantly, similar hybrid systems for electrification have been validated to be a more reliable and efficient source of energy access [86][87].

Generation cost and EDL

Figure 4.1 presents different EDL for varied energy generation costs. EDL is analyzed with a change in the range of -60 to +60 % of NEA generation cost, which is 7 Rs/kWh. The change (either increasing or decreasing) in generation cost showed a direct and linear relationship with EDL.

Figure 4.1 shows reduced generation cost increased the distance limit for grid expansion. That is, if generation cost is minimized, distance for grid expansion will increase. If generation cost increases, distance for grid expansion will decrease. This concludes that reduced generation cost will support to increase the electrification penetration, which is in line with the earlier study [88]. **Figure 4.1** also shows the EDL trend in the following pattern:

DG > MHP+DG > PV (inc battery) > MHP > PV + DG

The pattern shows that DG has the highest EDL, whereas PV+DG has the lowest EDL. This means, among the analyzed energy systems PV+DG is a better electrification option than others if the location is beyond the grid expansion limit.

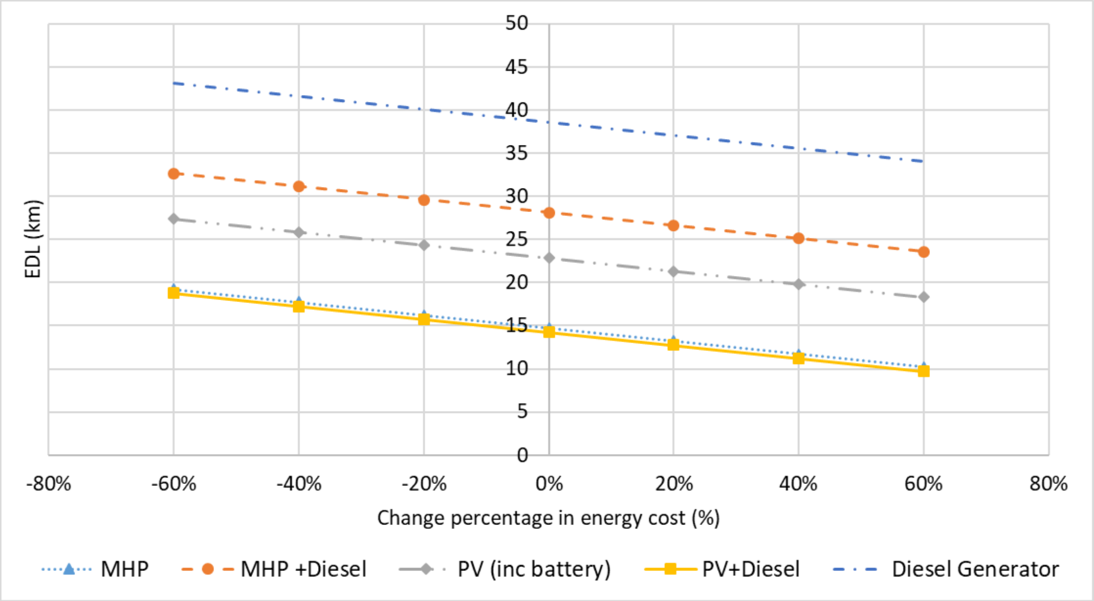


Figure 4.1 EDL with changing generation cost, 0% = 7 Rs/kWh.

Load and electricity supply, and EDL

EDL for various loads and electricity supply is calculated as shown in **Figure 4.2 (a-e)**. EDL is calculated for 6, 8, 10, 12, and 14 hrs/day of electricity supply. From the analysis, two scenarios are observed as mentioned below:

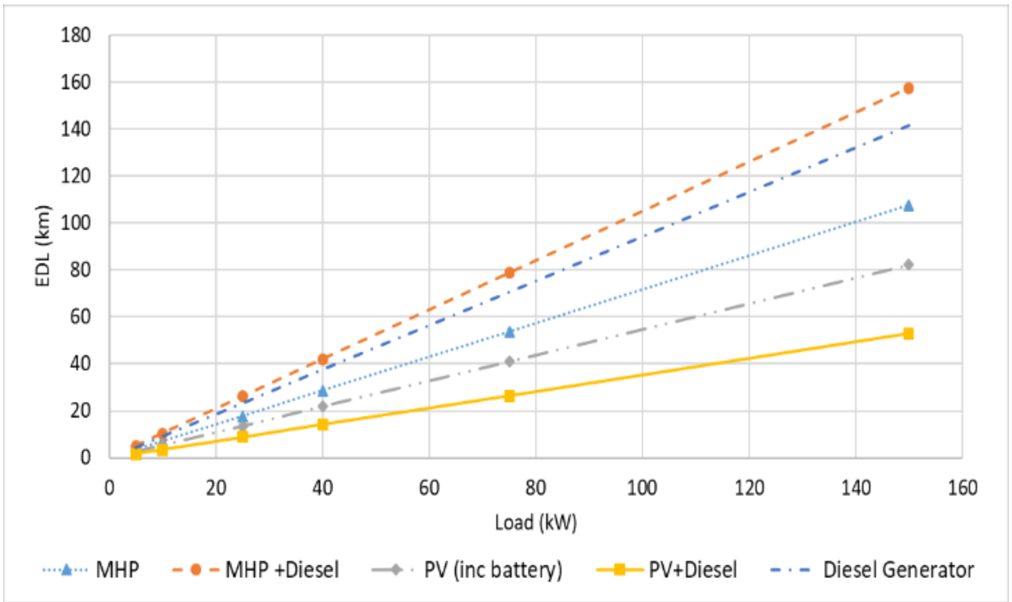
1. In the case of 6, 8, and 10 hours of electricity supply required, EDL of PV + DG is low. EDL slightly increased when the electricity supply hours increased. This is due to the increase in battery backup cost and the increase in fuel cost for DG. Similar results were obtained in previous research [51][89].
2. With a further increase in electricity supply, EDL for MHP was found more promising as no backup cost was incurred. The result may be valid only for limited hours of supply because increasing the no. of supply hours would require a backup system.

Furthermore, the following additional specific outcomes are presented as below:

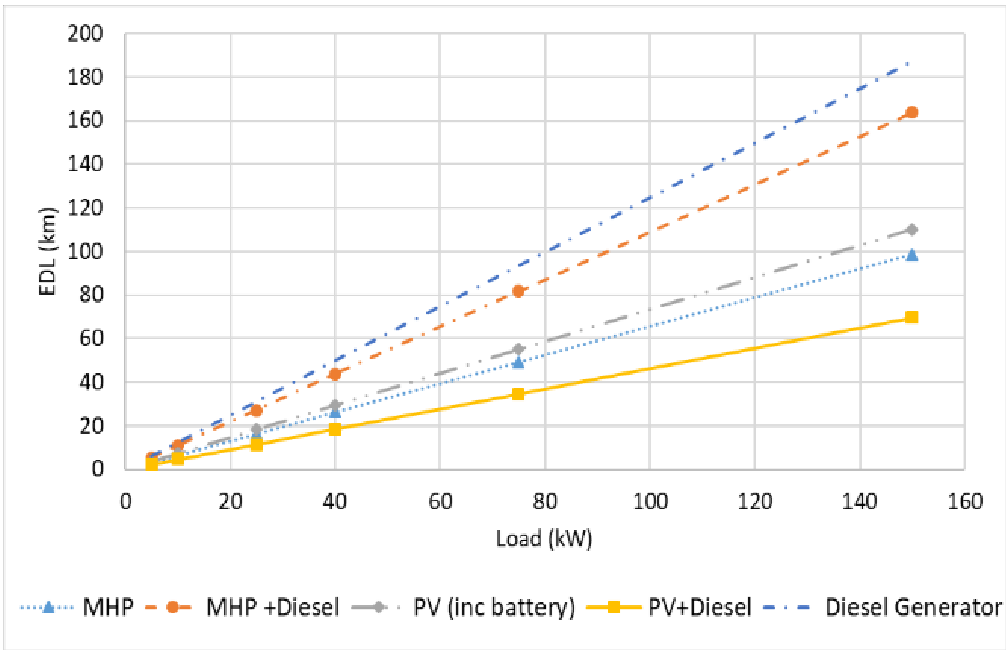
1. For 6 hrs/day of supply required, MHP + DG was found to have the highest EDL. This means MHP + DG is the last option for electrification for lower hours of supply required. When the supply hours required are high, DG should be the last option.
2. For 10 hours of supply required, MHP + DG or PV backed up with battery was an almost similar viable option for electrification.

Apart from the specific findings, the study has further discussed the trends of the EDL and are presented as follows:

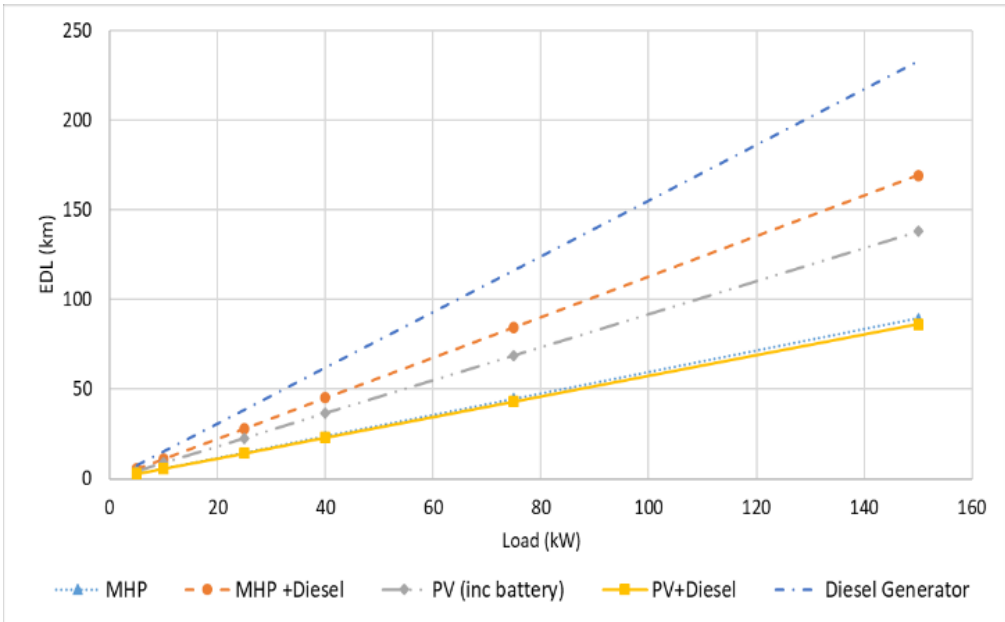
1. EDL increased linearly with the increase in load; this result resembles the findings of an earlier study [82].
2. EDL increased for increased backup hours from battery or DG. This shows that the dependency on DG is very expensive for electrification compared with other technologies. This finding matches with various other research findings [85][90][91].
3. In **Figure 4.2** (a-e), the line indicating PV with battery backup system was observed continuously moving in the upward direction. This concludes that EDL regularly increases on increasing the load and the needed supply hours.



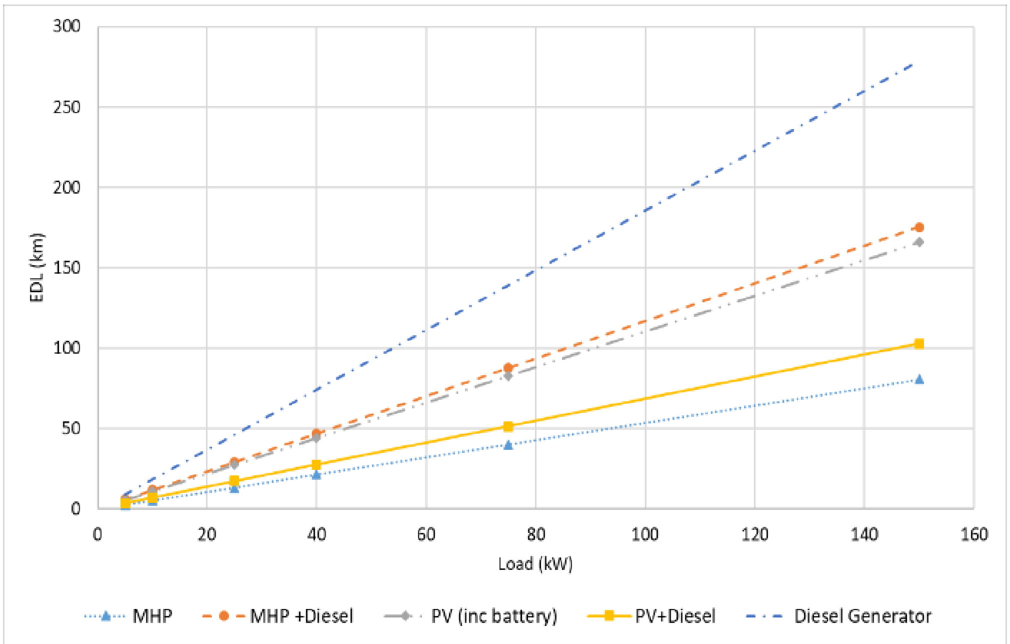
a. Power availability = 6 hrs/day



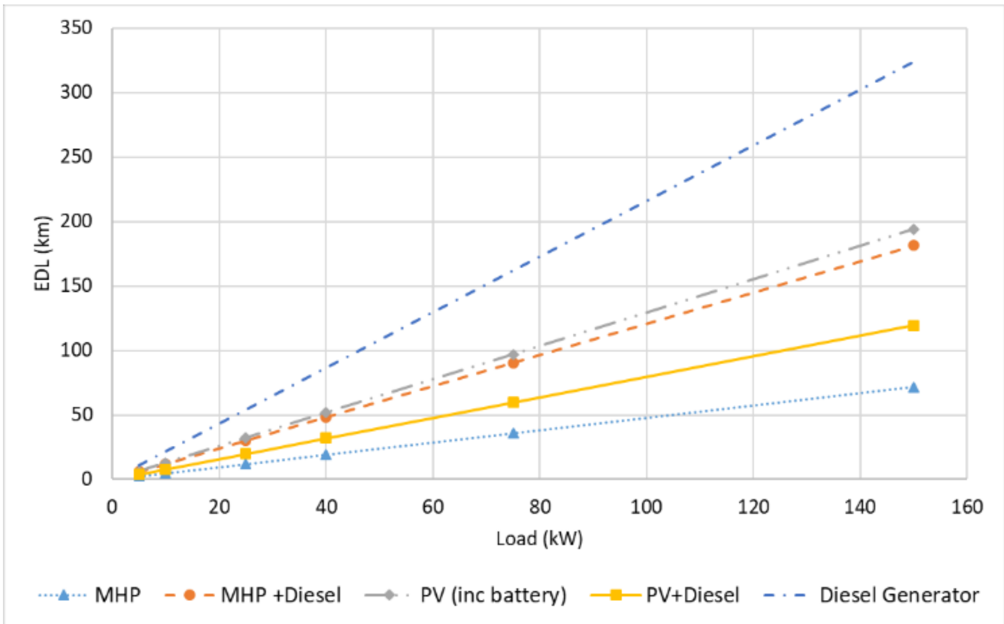
b. Power availability =8 hrs/day



c. Power availability = 10 hrs/day



d. Power availability = 12 hrs/day



e. Power availability = 14 hrs/day

Figure 4.2 EDL against system capacity and different hours of power availability per day

Impact of battery back-up

Figure 4.3 shows the impact of battery backup cost on total system cost. The analysis was done for 25 kW of the PV system, for daily 10 hours of supply for 20 years of system life with the backup system for 2.5 autonomous days which should be replaced every 5 years. The battery size of 12 V and 150 Ah is considered for the analysis.

The result shows that the cost of the battery is 63.4 % of the total system cost. No fluctuation (0%) in battery cost resembles the current situation. Further, increasing the battery cost increases total system cost, and decreasing the battery cost decreases total system cost. A maximum decrease in battery cost (up to 80%) has a minimum impact (not linear) on total energy system cost. This effect was traced due to the upfront cost of other energy systems remaining the same.

This impact of battery back-up has also been justified with increased EDL as shown in **Figure 4.2** (a-e). An almost linear trend is observed in energy cost for varied (decreasing and increasing) battery costs as presented in **Figure 4.3**. This shows that increase or decrease in the battery cost will have direct impact in the energy generation cost.

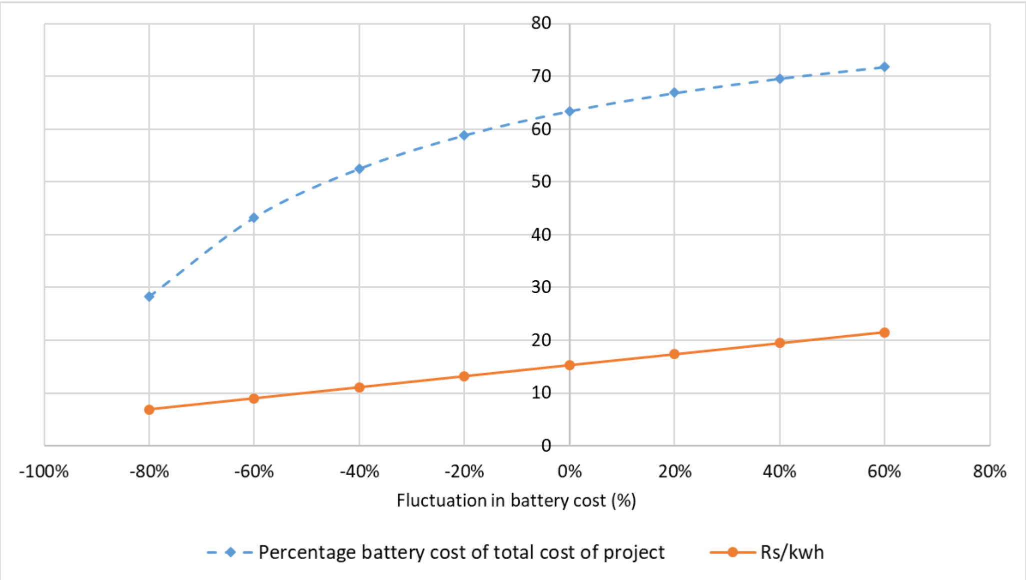
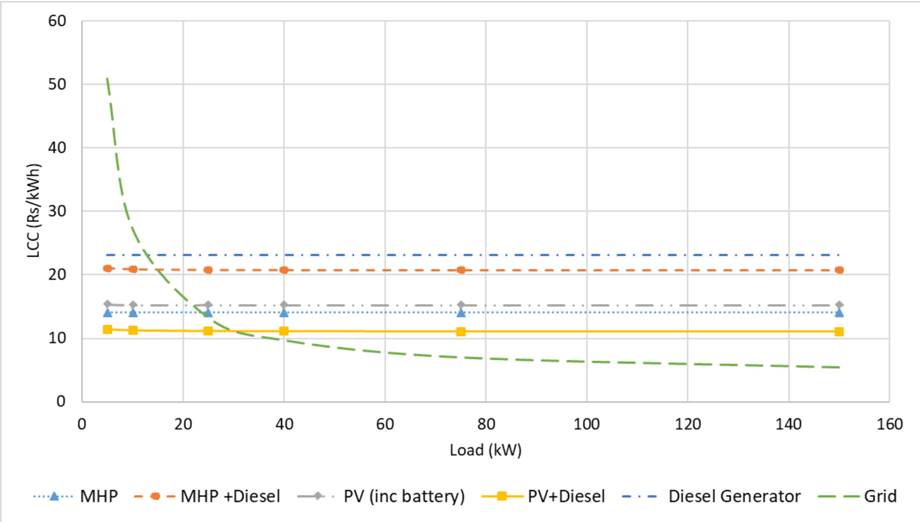
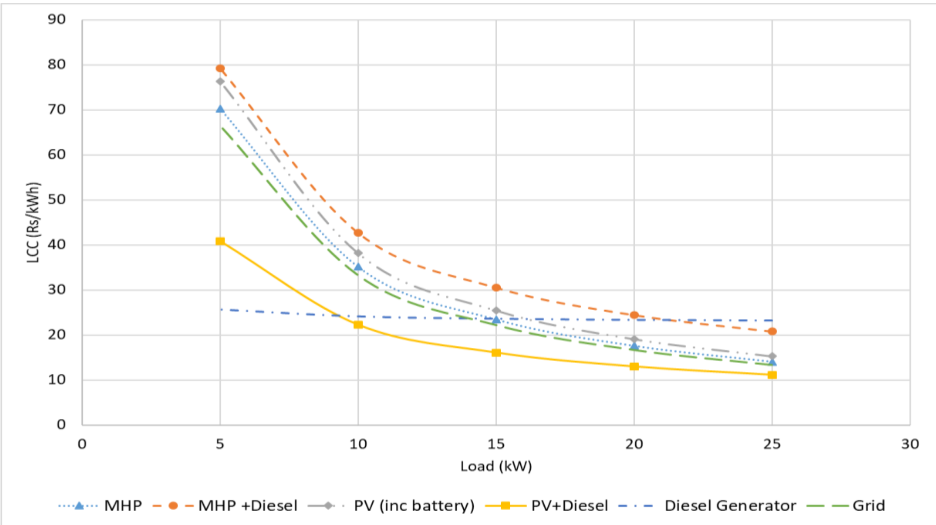


Figure 4.3 Battery capacity and the cost.

LCC comparison against load



a. Increasing load



b. Actual load

Figure 4.4 LCC comparison for (a) increasing load and (b) actual load

Considering the distribution line length, distribution transformer capacity, and the demand at the local level, a transformer each of 25 kVA is found suitable. This minimizes the distribution loss to each transformer. Thus, in the study, 25 kW is considered as the actual load, to each of the transformers, and the other loads like 5, 10, 25, 40, 75, and 150 are considered for the study purpose to analyze the pattern in increasing load. **Figure 4.4** (a) gives LCC for varied loads of 5, 10, 25, 40, 75, and 150 kW. LCC for grid expansion for 5 kW of the load was NRs 50.84 / kWh, whereas LCC for PV + DG for the same condition was NRs 11.41 / kWh.

From **Figure 4.4** (a), two conclusions are drawn.

1. Energy cost (LCC) for low load conditions is high, which is quite higher for grid expansion. LCC for grid expansion is the lowest at higher load starting from 40 kW.
2. Energy cost (LCC) decreases with the increased load to a certain level and stabilizes thereafter.

Figure 4.4 (b) depicts that energy cost for low load conditions is high, and it is low for higher loads. In general, LCC for grid expansion is the most economic, but as observed in this study, PV + DG is the most economical only up to 25 kW. Further, as shown in figure, increasing the load beyond 25 kW, grid expansion is the most economic.

Considering the limit of load up to 25 kW, increasing LCC for electrification options appeared to increase in the order of:

PV+ DG, Grid expansion, MHP, PV (inc battery), MHP+DG, and DG.

But, considering the load beyond 25 kW, the trend is the same expect the LCC for the grid expansion is the lowest and thus the order is seen as:

Grid expansion, PV+ DG, MHP, PV (inc battery), MHP+DG, and DG

This clearly indicates that LCC for grid expansion for low load conditions is high, whereas, LCC for grid expansion for higher load conditions is low.

Actual values of LCC for 25 kW of actual load are expressed in **Table 4.3**.

Table 4.3 LCC for 25 kW of actual load condition for various electrification options.

SN	Electrification option	LCC (NRs/kWh)
1	PV + DG	11.13
2	Grid expansion	13.30
3	MHP	14.05
4	PV (inc battery)	15.26
5	MHP+DG	20.78
6	DG	23.16

4.2 Model Development

Analysis for varying load and the EDL for a specific energy system is conducted. Each of the electrification option, PV + DG, MHP, PV (inc battery), MHP + DG and DG is compared to trace the EDL trend for the different supply hours and load demand.

With the available data of EDL and load; curve fit on a bi-linear polynomial equation is conducted, and a model is developed for each of the energy system discussed. Each of the model can further be utilized to predict EDL for a specific supply hour and the required load. This section further explains the EDL trend of energy system and finally develops a bi-linear polynomial equation for each energy system under the research.

1. PV + DG

The **Figure 4.5** depicts the trend of PV + DG for varying supply hours and load. The trend shows that the variation in EDL for low load conditions is low and is high in higher load conditions. The EDL indicates that the EDL increases with increase in load and the supply hours.

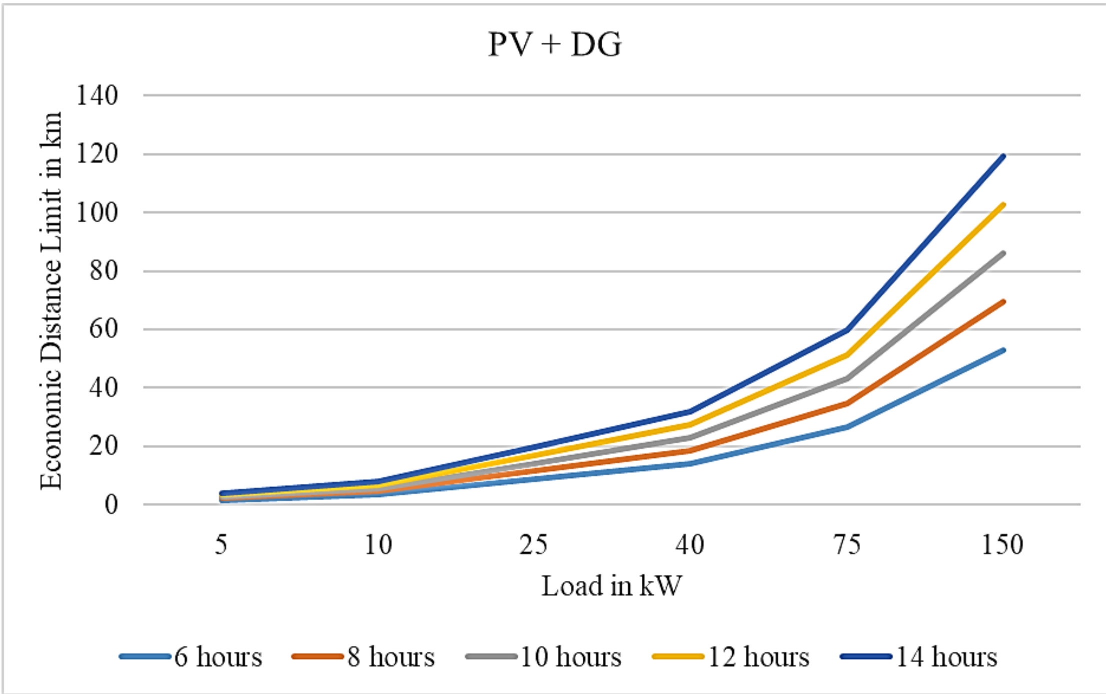


Figure 4.5 EDL of PV + DG for varying load and supply hours

Further, the study calculated the coefficient of variance for each of the supply hours, 6, 8, 10, 12, and 14 and is presented in **Table 4.4**.

The coefficient of variance as indicated in **Table 4.4** is low and found hovering in between 0.272 to 0.279, which shows the EDL data is accurate.

Table 4.4 Coefficient of variance for PV+DG of different supply hours for varying load

Supply load (kW)	Coefficient of variance (for 6,8,10,12,14 supply hours)
5	0.279
10	0.274
25	0.274
40	0.272
75	0.273
150	0.273

2. MHP

The **Figure 4.6** depicts the trend of MHP for varying supply hours and load. The trend shows that the variation in EDL for low load conditions is low and is high in higher load conditions. In contrary with the trend of PV + DG, EDL for DG shows the opposite pattern, i.e., the EDL increases with increase in load but decreases with the increase in supply hours.

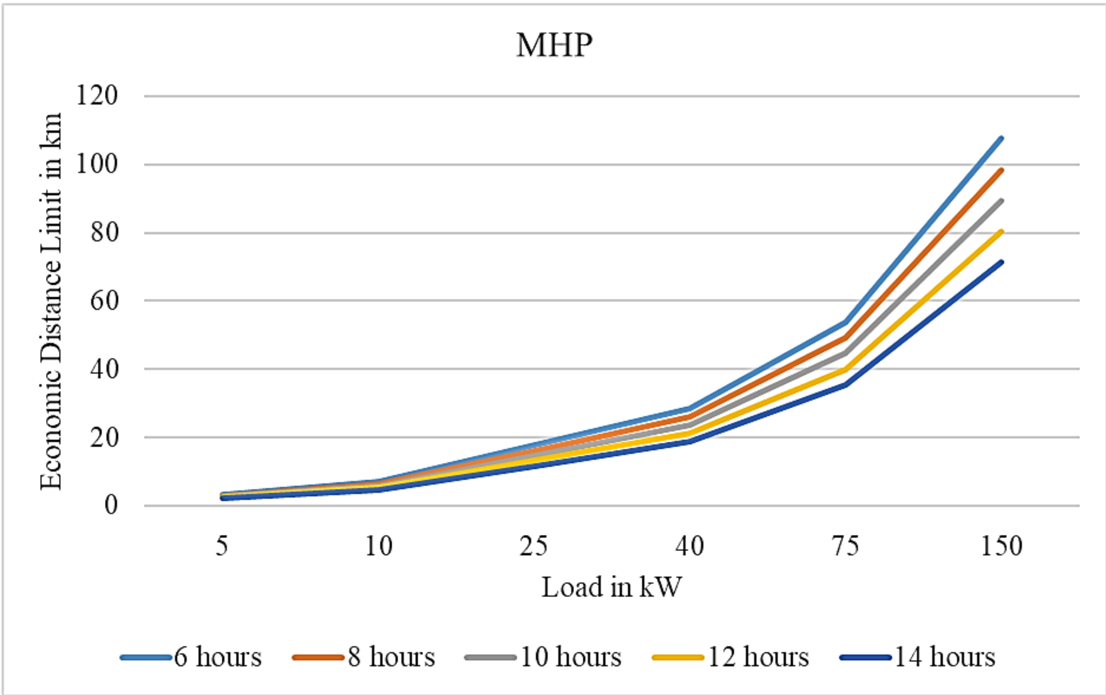


Figure 4.6 EDL of MHP for varying load and supply hours

The coefficient of variance as indicated in **Table 4.5** is low and found hovering in between 0.143 to 0.153, which shows the EDL data is accurate.

Table 4.5 Coefficient of variance for MHP of different supply hours for varying load

Supply load (kW)	**Coefficient of variance (for 6,8,10,12,14 supply hours)**
5	0.279
10	0.274
25	0.274
40	0.272
75	0.273
150	0.273

This graphical model can be further utilized to trace the trend of EDL based on required load and supply hours.

3. PV (inc battery)

The **Figure 4.7** depicts the trend of PV (inc battery) for varying supply hours and load. The trend shows that the variation in EDL for low load conditions is low and is high in higher load conditions.

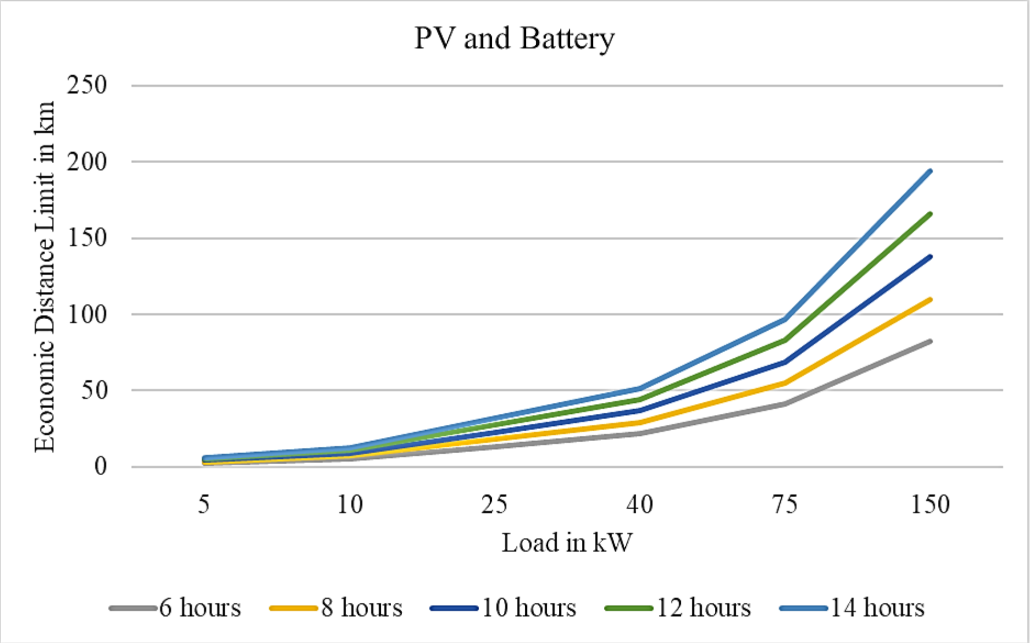


Figure 4.7 EDL of PV (inc battery) for varying load and supply hours

The coefficient of variance of PV (inc battery) as indicated in **Table 4.6** is low and found hovering in between 0.143 to 0.153, which shows the EDL data is accurate.

Table 4.6 Coefficient of variance for PV (inc battery) of different supply hours for varying load

Supply load (kW)	Coefficient of variance (for 6,8,10,12,14 supply hours)
5	0.296
10	0.290
25	0.288
40	0.287
75	0.287
150	0.286

4. **MHP + DG**

The **Figure 4.8** depicts the trend of MHP + DG for varying supply hours and load. The trend shows that the variation in EDL for low load conditions is low and is high in higher load conditions.

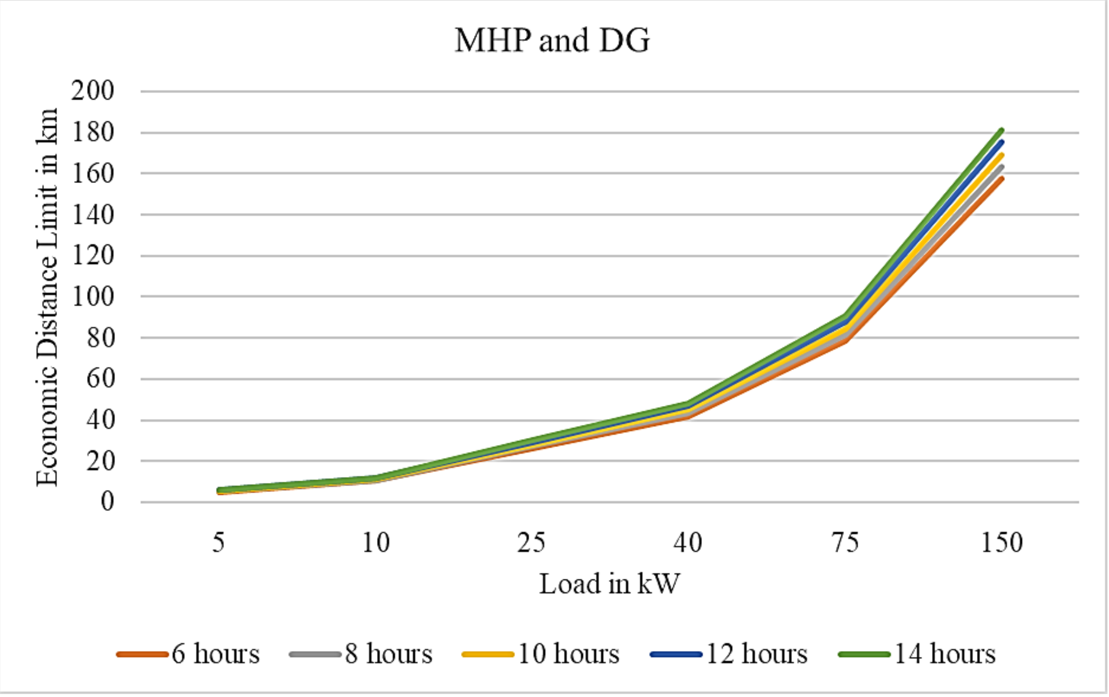


Figure 4.8 EDL of MHP and DG for varying load and supply hours

The coefficient of variance of MHP and DG as indicated in **Table 4.7** is low and found hovering in between 0.050 to 0.051, which shows the EDL data is accurate.

Table 4.7 Coefficient of variance for MHP and DG of different supply hours for varying load

Supply load (kW)	**Coefficient of variance (for 6,8,10,12,14 supply hours)**
5	0.051
10	0.050
25	0.050
40	0.050

75	0.050
150	0.050

5. DG

The **Figure 4.9** depicts the trend of DG for varying supply hours and load. The trend shows that the variation in EDL for low load conditions is low and is high in higher load conditions.

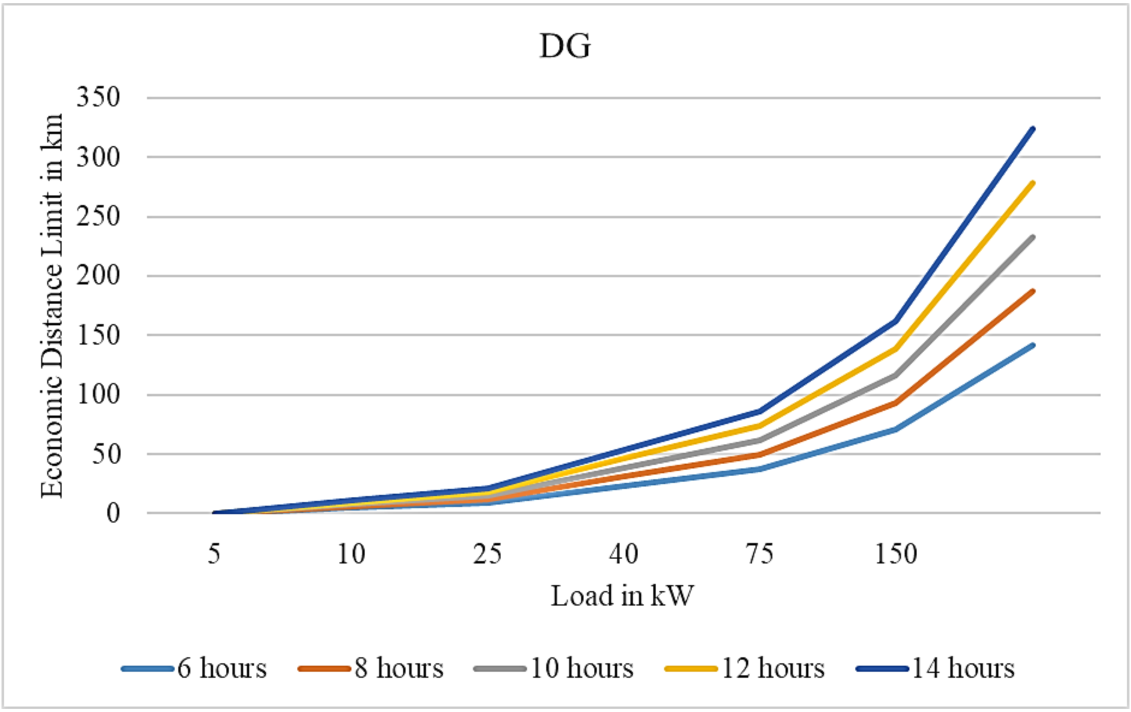


Figure 4.9 EDL of DG for varying load and supply hours

The coefficient of variance as indicated in **Table 4.8** is low and found hovering in between 0.278 to 0.285, which shows the EDL data is accurate.

Table 4.8 Coefficient of variance for DG of different supply hours for varying load

Supply load (kW)	**Coefficient of variance (for 6,8,10,12,14 supply hours)**
5	0.285
10	0.280
25	0.279
40	0.278

75	0.278
150	0.278

All these five graphical models can be further utilized to trace the trend of EDL based on required load and supply hours through interpolation and extrapolation method.

Curve fitting

The study has done a curve fitting of bi-linear polynomial equation with available data points of EDL, supply hours and the demand load. This section further explains the detail process of curve fitting of bi-linear polynomial equation.

Let us conduct a curve fitting of bi-linear polynomial equation for the case of Solar PV + DG.

Using bilinear regression through least squares method;

EDL can be written as a function of load demand and supply hours as:

$Z = a_0 + a_1x + a_2y + a_3xy$ …….(4.1)

Where,

x is the load demand (kW)

y is the supply hours (hours) and

Z is the EDL (km)

Where the coefficients a_0, a_1, a_2, a_3 are calculated using the matrix multiplication through elimination method.

Wherein the values of Z are taken from the calculated EDL for various load demand and supply hours.

For example,

For load demand of 5 kW with supply hours of 6 hours; EDL can be written as;

$$Z = a_0 + a_1 5 + a_2 6 + a_3 5 \times 6$$

$$1.71 = a_0 + a_1 5 + a_2 6 + a_3 5 \times 6 \text{ …….(4.2)}$$

Similarly, for load demand of 5kW with supply hours 10 hours, EDL can be written as;

$$Z = a_0 + a_1 5 + a_2 10 + a_3 5 \times 10$$

$$2.82 = a_0 + a_1 5 + a_2 10 + a_3 5 \times 10 \text{ …….(4.3)}$$

In similar way, EDL can be written in the form of supply hours and load demand for all 30 measured data points where in the equation can be written in matrix form as:

AX = B;

Where the values for the matrix A, X and B are presented as follows:

$$A = \begin{bmatrix} 1 & 5 & 6 & 30 \\ 1 & 10 & 6 & 60 \\ 1 & 25 & 6 & 150 \\ 1 & 40 & 6 & 240 \\ 1 & 75 & 6 & 450 \\ 1 & 150 & 6 & 900 \\ 1 & 5 & 8 & 40 \\ 1 & 10 & 8 & 80 \\ 1 & 25 & 8 & 200 \\ 1 & 40 & 8 & 320 \\ 1 & 75 & 8 & 600 \\ 1 & 150 & 8 & 1200 \\ 1 & 5 & 10 & 50 \\ 1 & 10 & 10 & 100 \\ 1 & 25 & 10 & 250 \\ 1 & 40 & 10 & 400 \\ 1 & 75 & 10 & 750 \\ 1 & 150 & 10 & 1500 \\ 1 & 5 & 12 & 60 \\ 1 & 10 & 12 & 120 \\ 1 & 25 & 12 & 300 \\ 1 & 40 & 12 & 480 \\ 1 & 75 & 12 & 900 \\ 1 & 150 & 12 & 1800 \\ 1 & 5 & 14 & 70 \\ 1 & 10 & 14 & 140 \\ 1 & 25 & 14 & 350 \\ 1 & 40 & 14 & 560 \\ 1 & 75 & 14 & 1050 \\ 1 & 150 & 14 & 2100 \end{bmatrix} \quad X = \begin{bmatrix} a_0 & a_1 & a_2 & a_3 \\ a_0 & a_1 & a_2 & a_3 \end{bmatrix} \quad B = \begin{bmatrix} 1.71 \\ 3.51 \\ 8.75 \\ 14.19 \\ 26.42 \\ 52.93 \\ 2.24 \\ 4.61 \\ 11.5 \\ 18.63 \\ 34.72 \\ 69.52 \\ 2.82 \\ 5.72 \\ 14.24 \\ 23.02 \\ 43.01 \\ 86.12 \\ 3.35 \\ 6.83 \\ 17.04 \\ 27.45 \\ 51.31 \\ 102.76 \\ 3.93 \\ 7.94 \\ 19.79 \\ 31.89 \\ 59.61 \\ 119.35 \end{bmatrix}$$

The coefficients a_0, a_1, a_2, a_3 are calculated using the matrix multiplication through elimination method.

Such that, $X = A^{-1}B$ but since A is not a square matrix, inverse of A is not possible thus, we solve the above equation as by multiplying both sides by transpose of matrix A, which is written mathematically as follow:

$$A^T \times A \times X = A^T \times B$$

$$A2 \times X = A3$$

Where, A2 = $A^T \times A$

And, A3 = $A^T \times B$

Now,

X = $A2^{-1} \times A3$

Solving above equation the values for a_0, a_1, a_2, a_3 are obtained as follows:

a_0 = -0.0264
a_1 = 0.0209
a_2= -0.0014
a_3 = 0.0554

Based on the coefficient values, the equation 1 can be re-written as the generalized equation for EDL as a function of load demand and supply hours as follows:

Z = f(x,y)

$$Z = -0.0264 + 0.0209x - 0.0014y + 0.0554xy$$

Where, Z, x and y have their usual meaning.

Similarly, generalized equations for other energy systems were obtained as follows:

For MHP: $Z = -0.0264 + 0.0209x - 0.0014y + 0.0554xy$

For PV (inc battery): $Z = -0.1441 - 0.0104x - 0.0002y + 0.0932xy$

For MHP + DG: $Z = -0.0657 + 0.9306x + 0.0003y + 0.0199xy$

For DG: $Z = -0.1724 + 0.0288x - 0.0000y + 0.1524xy$

Sensitivity Analysis

Numerous sensitivity analysis is conducted in the research to ensure and project the understanding of variations over specific parameters. For the sensitivity analysis, four different cases are considered in line with the scope of research. Each of the sensitivity analysis is carried out within the fluctuation limit of -40% to + 40 % for the study purpose. Further the research can be extended to higher fluctuation per cent or even lower as per the parameters' sensitivity.

The details of each sensitivity analysis are explained on case basis in different figures and are presented as follows:

Case 1:

Parameters like battery price, discount rate on battery price, PV system cost, time that the system can consecutively run on batteries are compared in **Figure 4.10**.

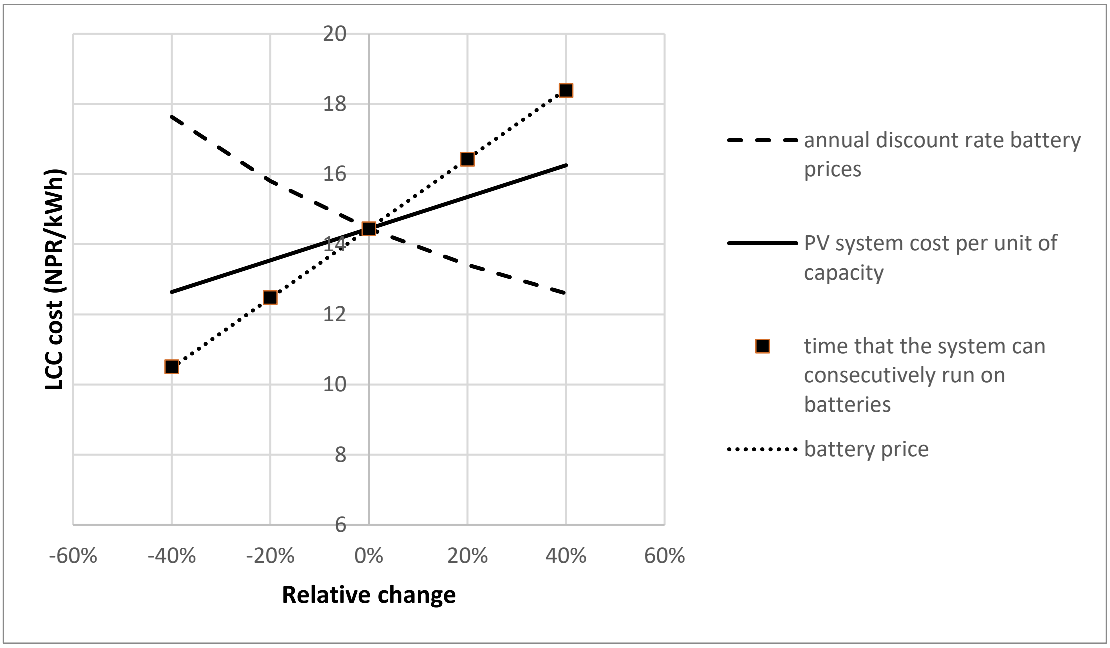


Figure 4.10 Sensitivity analysis - Case 1

As indicated in **Figure 4.10**, as the discount on battery price increases from -40 % to 40 %, LCC of the system gradually decreases and fluctuates between little more than 12.6 to 17.6 Rs/kWh. The fluctuation of 5 Rs/kWh indicates the discount on battery price is significant in energy cost. In the same line, increased cost of battery has significant impact on LCC, 10.5 to 18.4 Rs/kWh. That is, increase in 40 % of battery cost has almost doubled the LCC.

Further fluctuation of PV system cost shows that LCC varies between 12.6 to 16.2 Rs/kWh. This fluctuation of 40 % has impact of only 28.6% to the LCC cost. It shows that price fluctuation on PV systems per unit of capacity has relatively less impact on LCC in comparison to fluctuation on battery cost.

Case 2:

Parameters like fraction of annual O&M, annual discount on O&M, hardware cost fluctuations of MHP are compared in **Figure 4.11**.

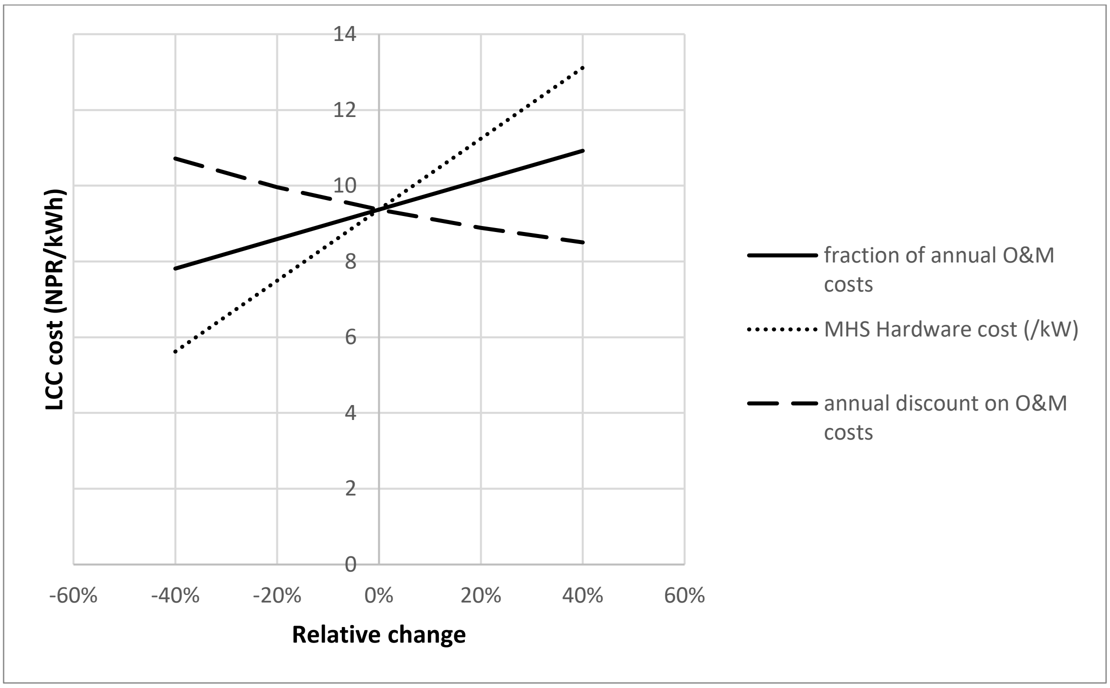


Figure 4.11 Sensitivity analysis - Case 2

Major O&M cost is not incurred in fixed type of PV systems; thus, the analysis is focused on the more moving/rotating energy systems like MHP. In overall, the O&M cost on the MHP system is calculated. The analysis shows that, the impact on LCC is seen to be 7.8 to 10.9 Rs/kW.

MHP hardware cost per unit kW is seen varying between 5.6 to 13.11 Rs/kWh. This significant, almost tripled, change in LCC is due to high O&M cost in MHP. The analysis further indicates that if the O&M cost is fluctuated between – 40% to + 40%, the LCC of the system varies between 10.7 to 8.5 Rs/kWh.

Case 3:

Parameters like unit cost of fuel and the generation cost are analyzed in **Figure 4.12**.

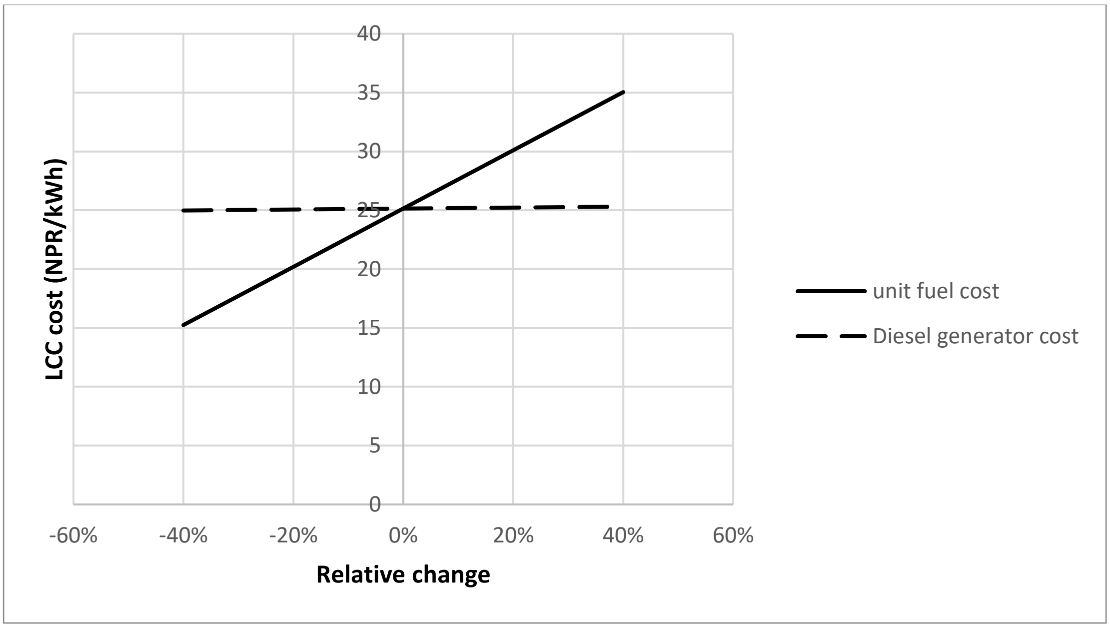


Figure 4.12 Sensitivity analysis - Case 3

In general, fixed unit rate of fuel (diesel) is considered for the purpose of research calculations, which is not practical in real world. Thus, sensitivity analysis of the fuel cost and the generation cost of the same is analyzed over certain limit of variations. The result is found obvious. Diesel generation cost is considered constant and the analysis of fuel price fluctuation between – 40 % to +40 % shows the LCC fluctuation between 15. 2 to 35.04 Rs/kWh, more than double the price. Discount on fossil fuel is less expected and thus not considered for the research.

Case 4:

Parameters like cost of electricity generation, capital cost to distance of grid extension, annual discount rates and the losses are very important parameters and thus analyzed and compared as in **Figure 4.13**.

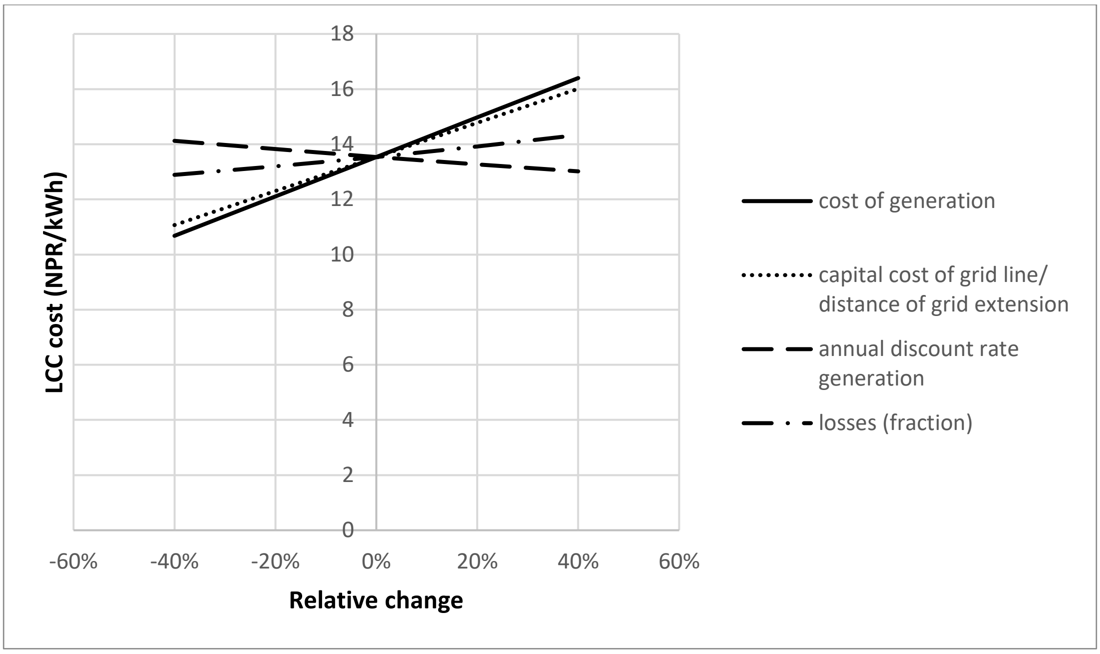


Figure 4.13 Sensitivity analysis - Case 4

The analysis of cost of generation, capital cost, discount rate and the losses in grid extension is found less sensitive compared with other energy systems. Base rate of cost of generation is considered 7 Rs/kWh and the sensitivity analysis is considered imposing -40 % to +40 % fluctuations. The analysis shows that, annual discount rate generated has positive impact on LCC and has very minimal impact which hovers between the cost 14.1 to 13.0 Rs/kWh as shown in **Figure 4.13**.

4.3 Techno-economic optimization of the energy systems

In this research techno-economic optimization using HOMER 2.68 is conducted. The section onward presents the details of techno-economic optimization.

Load of study area

The total load demand of the study is presented in **Table 4.1**. Further, the hourly load for the study area is as below.

Table 4.9 Hourly load demand of the study area

Hours of a day (Hrs)	Load (kW)
00:00 - 01:00	3.5
01:00 - 02:00	3.5
02:00 - 03:00	3.5
03:00 - 04:00	3.5
04:00 - 05:00	280
05:00 - 06:00	227.5
06:00 - 07:00	133
07:00 - 08:00	577.5
08:00 - 09:00	577.5
09:00 - 10:00	175
10:00 - 11:00	245
11:00 - 12:00	70
12:00 - 13:00	105
13:00 - 14:00	105
14:00 - 15:00	245
15:00 - 16:00	262.5
16:00 - 17:00	210
17:00 - 18:00	630
18:00 - 19:00	787.5
19:00 - 20:00	787.5
20:00-21:00	280
21:00- 22:00	3.5
22:00-23:00	3.5
23:00 - 00:00	3.5

The **Table 4.1** presents hourly demand of the study site. Assumptions of various parameters (like load factor, diversity factor, load growth etc.) for the load demand calculations are further presented in **Table 3.1.**

Schematic model of study

For the techno-economic optimization from HOMER, a model comprising of Hydro (MHP), Generator (DG), Photovoltaic (PV), Battery and Converter is considered as presented in **Figure 4.14**.

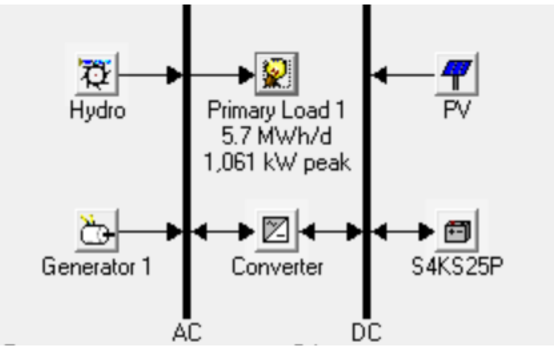


Figure 4.14 Schematic model of study

From the given schematic 6 optimized models are generated by the systems (out of many simulation models) as presented in **Figure 4.15**.

Double click on a system below for simulation results. Categorized

PV (kW)	Hydro (kW)	Label (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)	Batt. Lf. (yr)
	535	50	600	550	$ 2,418,500	55,905	$ 3,133,155	0.117	1.00	3,063	333	12.0
	535		720	600	$ 2,443,000	57,209	$ 3,174,327	0.119	1.00			12.0
50	535	50	600	550	$ 2,468,500	55,836	$ 3,182,271	0.119	1.00	3,012	327	12.0
50	535		600	700	$ 2,471,500	55,624	$ 3,182,558	0.119	1.00			12.0
2000		400	2640	1150	$ 3,108,750	184,980	$ 5,473,413	0.205	0.91	62,179	543	12.0
		900	720	250	$ 589,750	1,109,289	$ 14,770,184	0.553	0.00	846,057	3,666	12.0

Figure 4.15 Optimized models

Out of the six optimized models third model (as highlighted) in the **Figure 4.15** is considered for the further discussion and analysis, because of its cost competitiveness and the first model with inclusion of all PV, MHP and DG.

Resources input for the study

Solar resources

Nepal lying in solar belt has abundant solar resources with 300 days of sunshine hours. The **Figure 4.16** gives the monthly solar radiation and the cleanliness index of the study site.

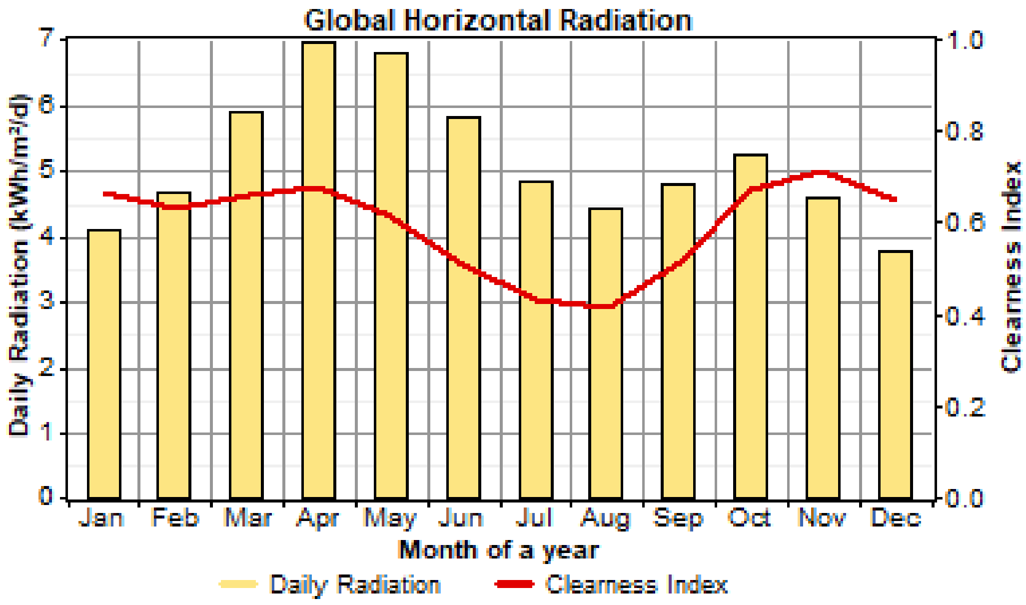


Figure 4.16 Monthly global horizontal irradiance of the research site

Scaled annual average global horizontal irradiance of the research site is 5.15 kWh/m2/d. The irradiance shows the abundance of the solar energy in the research site.

Hydro resources

In the HOMER software, we need to input the cumulative hydro resources available in the research area. The research area has numerous micro hydro powers and for the cumulative hydro resources, data input is done accordingly, and the following hydro resources is generated for the analysis.

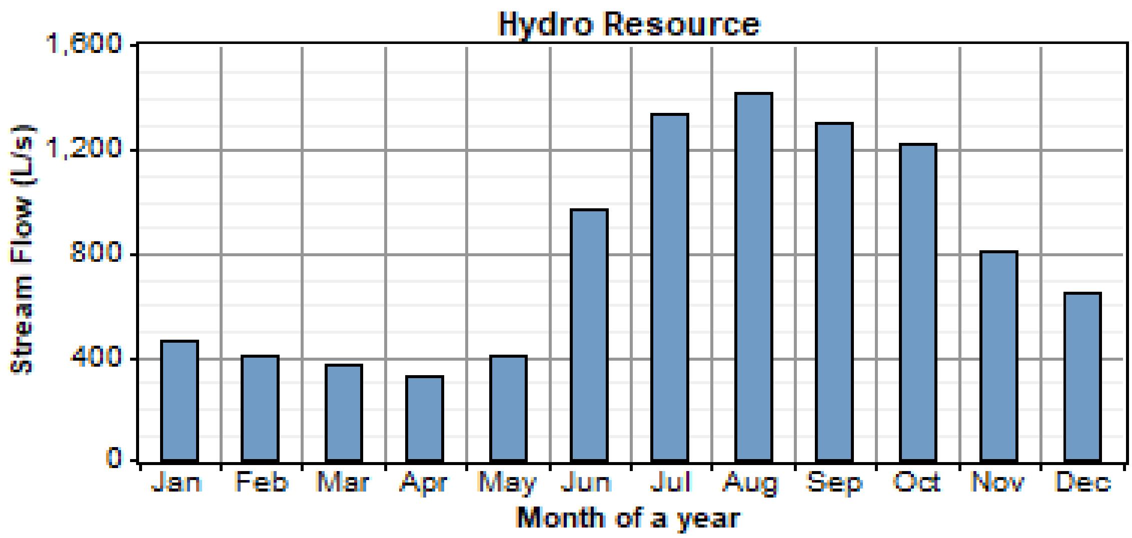


Figure 4.17 Hydro resources scenario of the study area

Optimization of the hybrid energy systems

System architecture

Out of the six optimized models, the research has considered a best model with PV array, MHP, DG, Battery and Inverter. The system architecture of the energy systems is as depicted in **Table 4.10**.

Table 4.10 System architecture of the optimized model

PV Array	50 kW
Hydro	535 kW
Generator	50kW
Battery	600 Surrette 4KS25P
Inverter	550 kW
Rectifier	550 kW
Dispatch strategy	Cycle Charging

Electrical output

The following **Table 4.11** indicates the electrical output from each energy technology, viz, PV, MHP and DG. Since the total energy demand is of 1 MW, the system cost (initial capital cost) of MHP being the most prominent the software designs to provide electrical output from hydro nearly 98 %. Solar PV array is considered for 2 % of total energy production for an entire year. DG is considered only as back-up system and thus, provides less than 1 % of electrical output.

Table 4.11 Electrical output from each energy system

Component	Production (kWh/yr)	Fraction (%)
PV array	85,053	2
Hydro turbine	5,349,970	98
Generator	6,817	0
Total	5,441,840	100

Electric production

Monthly electric production by each energy technology as considered for the research is presented in **Figure 4.18**. The **Figure 4.18** shows that majority of electric energy is generate from MHP with little back up from PV and DG as required.

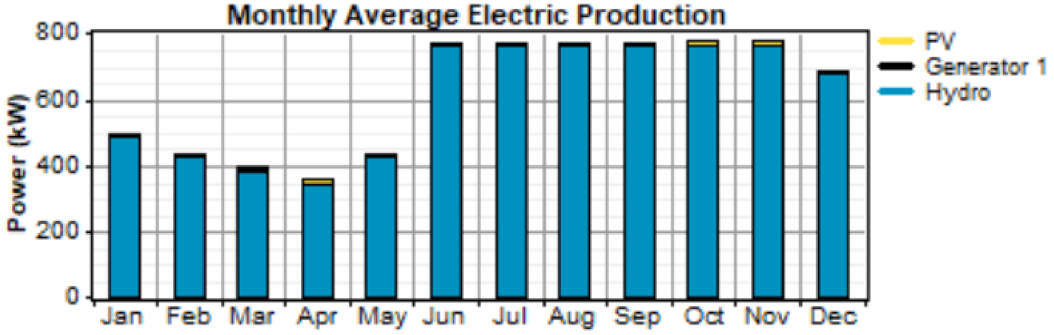


Figure 4.18 Monthly average electric production

Photovoltaic

The following **Table 4.12** gives the details of the PV system used for analysis and the outputs of the PV system. Rated capacity of the PV considered is 50 kW, capacity factor is 19.4 %. Maximum PV system penetration is of 4.07 %. PV system is remained active for 4,368 hours per year.

Table 4.12 PV system and the output details

Quantity	Value	Units
Rated capacity	50.0	kW
Mean output	9.71	kW
Mean output	233	kWh/day
Capacity factor	19.4	%
Total production	85,053	kWh/yr
Minimum output	0.00	kW
Maximum output	49.6	kW
PV penetration	4.07	%
Hours of operation	4,382	Hr/yr
Levelized cost	0.0460	$/kWh

Further for graphical visibility, the PV system output is presented in the color diagram in **Figure 4.19**

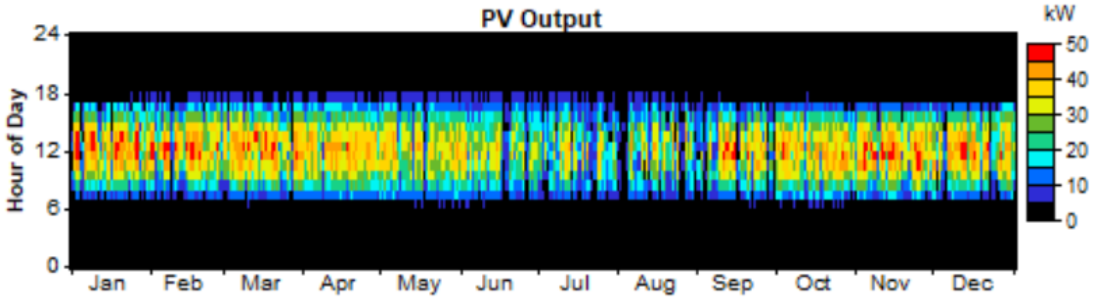


Figure 4.19 PV system output

Micro hydropower

The following **Table 4.13** depicts the details of the MHP system used for analysis and the output of the same. Nominal capacity of the MHP system considered is 535 kW whose mean output is 611 kW with the capacity factor is 114 %. Annual total energy production from MHP is 5,349,970 kWh with total hours of operation of 8,760 per year.

Table 4.13 MHP system and the output details

Quantity	**Value**	**Units**
Nominal capacity	535	kW
Mean output	611	kW
Capacity factor	114	%
Total production	5,349,970	kWh/yr
Minimum output	340	kW
Maximum output	763	kW
Hydro penetration	256	%
Hours of operation	8,760	Hr/yr
Levelized cost	0.0350	$/kWh

For generic understanding of the MHP output throughout the year, a color diagram is presented as **Figure 4.20**.

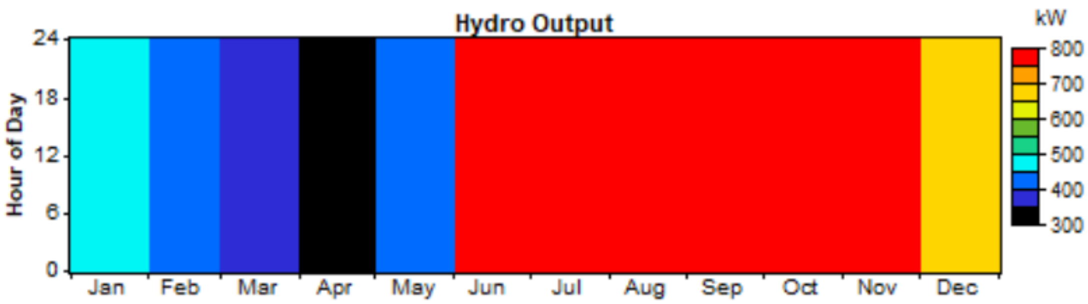


Figure 4.20 Color diagram of hydro output

Generator

The following table with details of the DG with its output are presented in **Table 4.14**. DG is used for 327 hours per year with 45 starts. The operational life of the DG is 45.9 years. The capacity factor of the DG is 1.56 %. Energy production from the DG system is 6,817 kWh/year with total fuel consumption of 3,012 L/yr. The DG has specific fuel consumption value of 0.442 L/kWh and the mean electrical efficiency of the DG is 23.0%.

Table 4.14 Generator system and the output details

Quantity	Value	Units
Hours of operation	327	Hr / yr
Number of starts	45	Starts / yr
Operational life	45.9	yr
Capacity factor	1.56	%
Fixed generation cost	7.75	$/hr
Marginal generation cost	0.250	$/kWhyr
Electrical production	6,817	kWh/yr
Mean electrical output	20.8	kW
Min. electrical output	15.0	kW
Max. electrical output	50.0	kW
Fuel consumption	3,012	L/yr
Specific fuel consumption	0.442	L/kWh
Fuel energy input	29,640	kWh/yr
Mean electrical efficiency	23.0	%

For generic picture of the generator output throughout the year, a color diagram is presented in **Figure 4.21**.

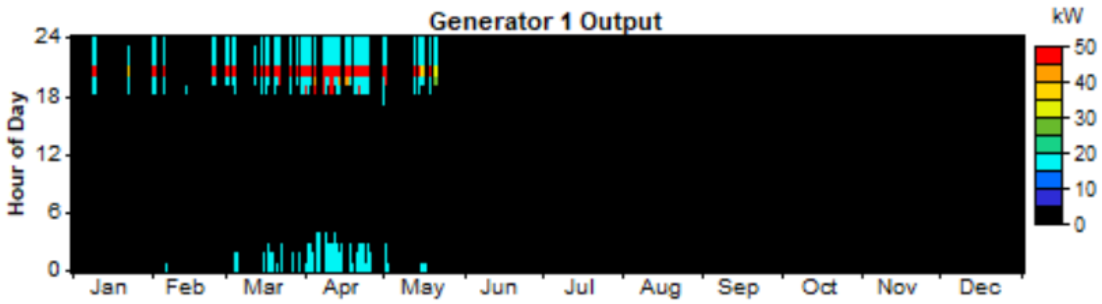


Figure 4.21 Color diagram of the DG outut

Battery

The following **Table 4.15** with the details of battery size, no. of batteries, nominal capacity and the output details are presented. In the battery system, batteries with 4 V, with each string size of 6 are considered to maintain the 24 V system. To meet the total supply, 100 strings in parallel are considered with total nominal capacity of 4,560 kWh. The battery size is designed for 11.5 hrs of autonomy.

Table 4.15 Battery system, configuration and the output details

Quantity	**Value**	**Units**
String size	6	No.
Strings in parallel	100	No.
Batteries	600	No.
Nominal capacity	4,560	kWh
Usable nominal capacity	2,736	kWh
Autonomy	11.5	hr
Lifetime throughout	6,341,160	kWh
Battery wear cost	0.032	$/kWh
Average energy cost	0.001	$/kWh
Energy in	297,264	kWh/yr
Energy out	237,905	kWh/yr
Storage depletion	137	kWh/yr
Losses	59,222	kWh/yr
Annual throughout	265,986	kWh/yr
Expected life	12.0	yr

Further frequency histogram of the battery bank with state of charge (%) is presented in **Figure 4.22**.

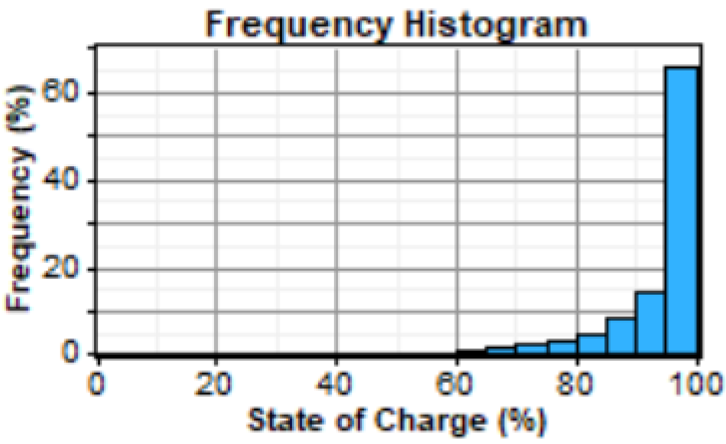


Figure 4.22 Frequency histogram of battery bank

Further, the monthly statistics of State of Charge (SOC in %) with maximum, mean and minimum values are presented in the following **Figure 4.23**.

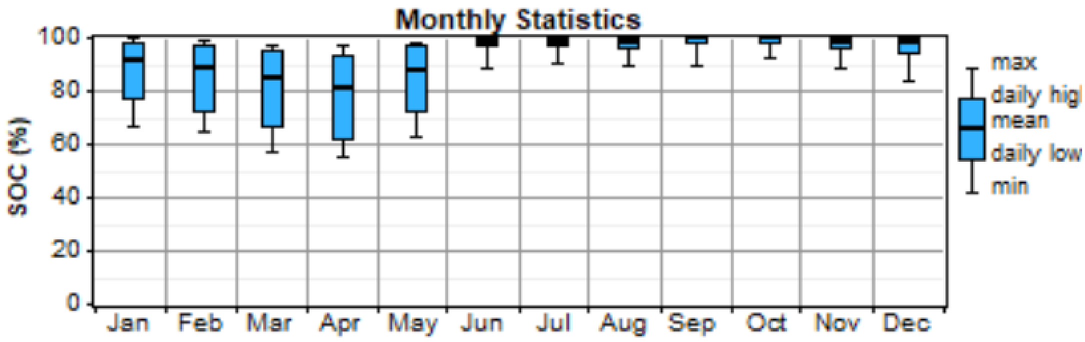


Figure 4.23 Monthly statistics of SOC of battery bank

Further, for the generic view of the monthly SoC (%) during 24 hrs of a day is presented in the following **Figure 4.24**.

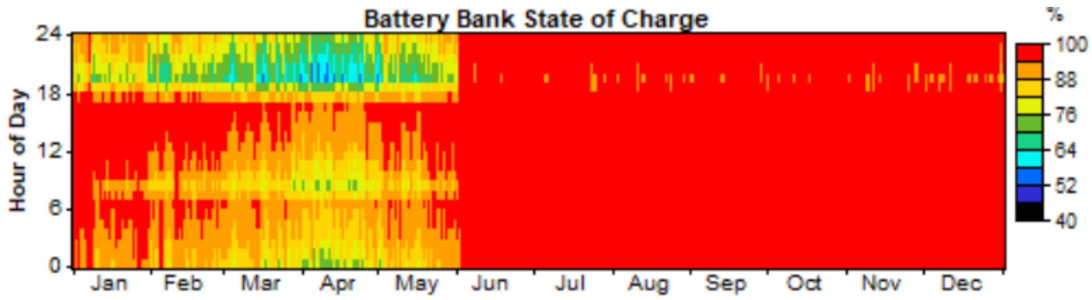


Figure 4.24 Color diagram of the monthly SOC throughout the day

Converter

The following **Table 4.16** presents the details of converter and the outputs with other system parameters. Capacity of the inverter and the rectifier is 550 kW with mean output of 25 kW from inverter and 30 kW from rectifier with maximum output of 550 and 181 kW respectively. Capacity factor of inverter is 4.5 and that of rectifier is 5.5. Total hours of operation per year of inverter and rectifier are 1,046 and 5,038 pe year respectively. The total annual losses of inverter and rectifier are 24,293 kWhr and 46,441kWhr.

Table 4.16 Converter system configuration and the output details

Quantity	Inverter	Rectifier	Units
Capacity	550	550	kW
Mean output	25	30	kW
Minimum output	0	0	kW
Maximum output	550	181	kW
Capacity factor	4.5	5.5	%
Hours of operation	1,046	5,038	Hrs/yr
Energy in	242,932	309,617	kWh/yr
Energy out	218,639	263,176	kWh/yr
Losses	24,293	46,441	kWh/yr

Further, for the generic view of inverter output power during each month of a year throughout 24 hrs a day is presented in a color graph as depicted in **Figure 4.25**.

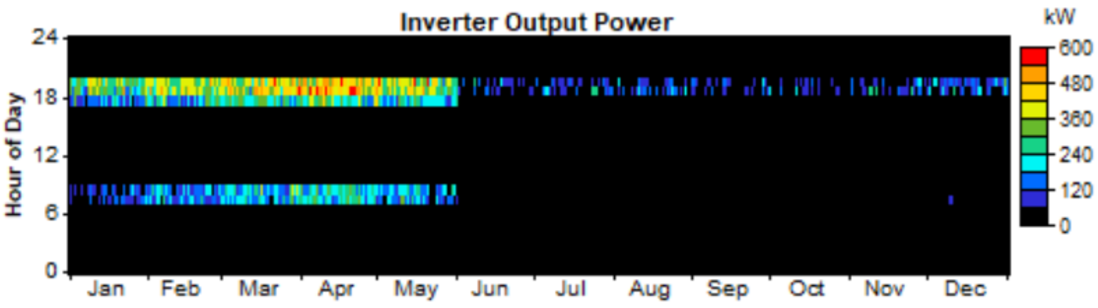


Figure 4.25 Color diagram of inverter output

Similarly, for the generic view of rectifier output power during each month of a year throughout 24 hrs a day is presented in a color graph as depicted in **Figure 4.26**.

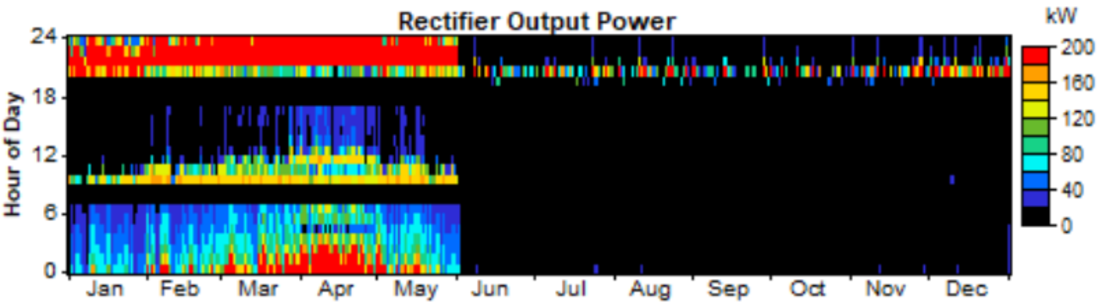


Figure 4.26 Color diagram of rectifier output

Final summarized result of the optimized system is presented in the following **Figure 4.27**.

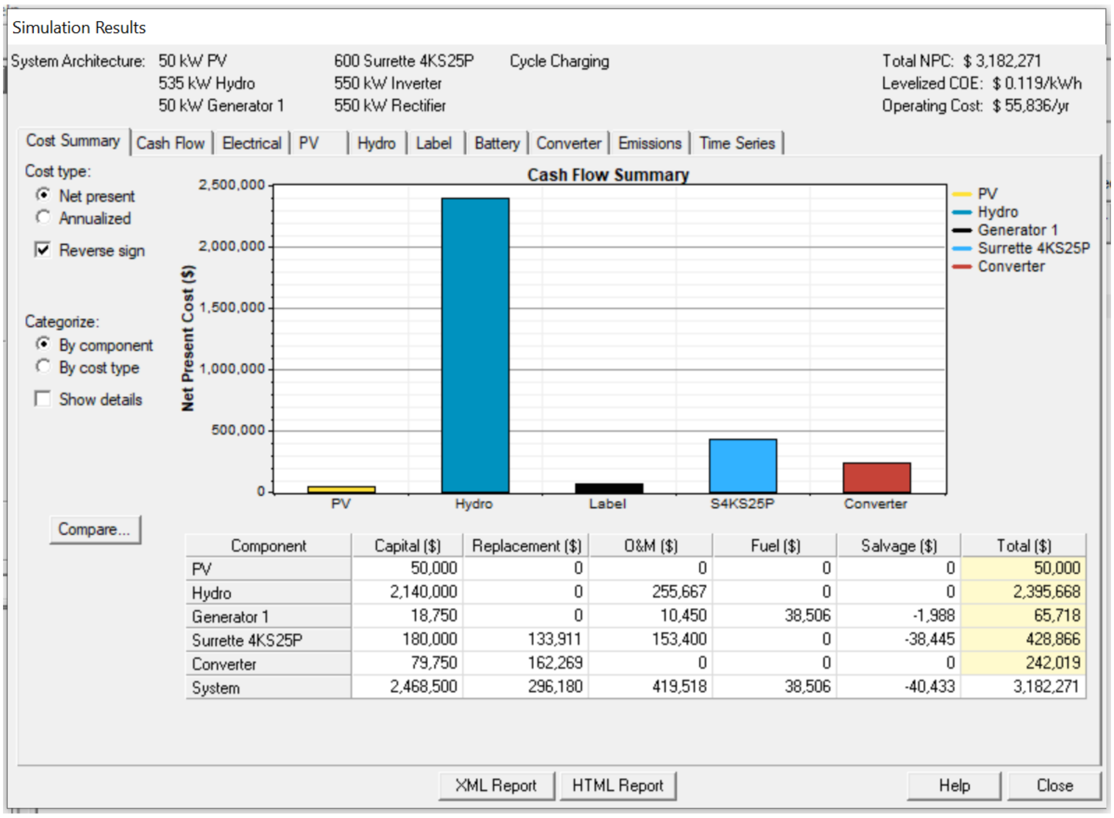


Figure 4.27 Simulation results of the optimized systems

The result shows the highest penetration of hydropower is the most economic. The simulation result presents the total NPC, levelized COE, operating cost of the system, with all the system architecture. The optimized simulation result also presents the capital cost, replacement cost, O&M cost, fuel cost, salvage cost and the total cost of each system, i.e. pv, hydro, generator, battery, and converter.

Emissions

Further, considering the optimized model with DG and the associated fossil fuel, it is expected to generate the GHGs viz, CO2, CO, unburned hydrocarbons, particulate matters, SOX, NOX as presented in the following **Table 4.17**.

Table 4.17 Emissions detail from the optimized model

Pollutants	Emissions (kg/yr)
Carbon dioxide	7,932

Carbon monoxide	19.6
Unburned hydrocarbons	2.17
Particulate matter	1.48
Sulfur dioxide	15.0
Nitrogen oxides	175

4.4 Policy analysis

In this section, the study is focused in the results and the detail policy analysis is presented under the literature review section. Energy policies have (should have) direct impact on electricity generation, because if the policy environment is conducive then the generation is automatically flourished. Once the enough electricity is generated, it will have direct impact on electricity consumption, i.e. electricity per capita (EPC). That is, higher electricity generation will have first higher EPC. In parallel, EPC is also affected by GDP. The research hypothesis is higher GDP will result to higher EPC. Due to this interrelated scenario; energy policies, trend of electricity generation, EPC and GDP; are co-related. Thus, this section has put an effort to analyze and co-relate the energy policies with electricity trend analysis. Also, impact of GDP on EPC is analyzed via regression analysis. Further, barrier analysis for energy sector and policies in Nepal are analyzed qualitatively.

Electricity Trend Analysis

The policies are directly related with the electricity generation, further leading to import in case of deficit and export in case of abundance. Thus, the result of the policy injection is compared with the electricity generation and accordingly electricity trend analysis is conducted as follows. **Figure 4.28** presents the electricity trend of Nepal during the period of 2009 to 2021. The figure shows the huge gap between energy generation and the demand.

As per latest report published by NEA in 2021, out of total electricity generated, hydro plays the dominant role with very minimal from thermal power plants [2]. But low energy access and increasing energy demand has not been full filled by NEA electricity generation. The trend and the gap can be observed from the **Figure 4.28**. The total number of Individual Power Producers (IPPs) owned 108 projects in operation has combined installed capacity of 814.65 MW. A total of 138 projects to be developed by IPPs, with a combined installed capacity of 3506.8 MW are under construction after financial closure. Similarly, 99 IPPs-owned projects with a combined installed capacity of 1851.3 MW are at various stages of development. Currently there are 20 generating hydropower stations and 2 thermal power plants having total installed capacity of 626.7 MW [2]. **Figure 4.28**, peak demand of electricity is ever increasing (except that of in FY 2019) and has been recorded to be as high as 1508 MW in 2018 which is further traced 1482 MW in the year of 2021. In the history of more than 100 years of hydropower establishment starting from Pharping Hydro Power Project in 1911 AD, only little more than 1400 MW of hydropower is being generated in the country[2] [16][74][92][93].

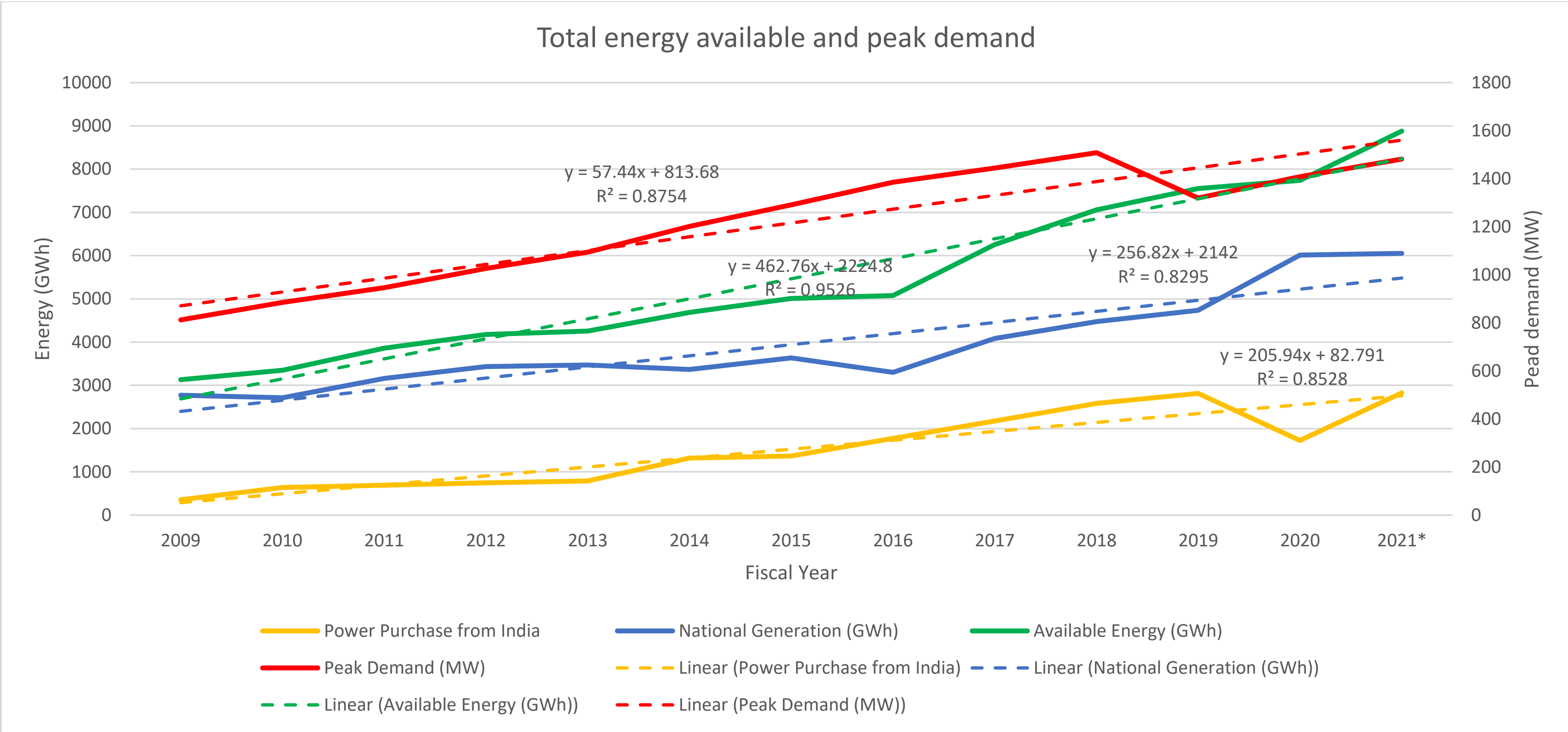


Figure 4.28 The total energy available and peak demand [2]

Figure 4.28 represents the overall electricity trend in Nepal for the last 12 years. More specifically, **Figure 4.28** shows annual electricity generated from NEA, purchased from IPPs, imported from India and the annual peak demand for the period of 2009 to 2021. The **Figure 4.28** shows almost linear electricity generation of NEA (including IPPs) against the steep gradient of peak power demand has ultimately increased the power purchase from India. Until now, NEA has been importing electricity from India to meet the gap. To meet the gap, power purchase is ever increasing, as reflected in **Figure 4.28**.

Slope of peak power demand of Nepal is calculated to be 57.44 and the slope of energy import from India to meet the demand is 205.94. This increasing slope shows that import from India is leading towards unsustainability. Slope of peak demand and import from India during 2009 to 2016 (as indicated in **Figure 4.28)** is steeper and later (during 2016 – 2021) is normalized due to diminished due to drop in peak demand in the year of 2019. The overall available energy since 2009 follows the increasing trend. The electricity demand may be full-filled by grid extension in case of densely populated areas and by stand-alone systems for sparsely populated areas [32]. Literature has also traced that increased import of commercial fuel has decreased consumption of traditional fuel despite its abundant availability. Increased used of traditional fuel and renewable energy contributes to reducing greenhouse gas emissions providing institutional arrangements to energize clean development mechanisms [94]. But in contrary, Nepal seems to be moving in the opposite direction by increasing import of commercial fuel and decreasing use of traditional fuel.

Regression analysis

The regression analysis of electricity per capita (EPC) over GDP per capita (GDP) is conducted to trace the impact on EPC for increment on GDP. GDP gives a country's economic output, which accounts for the total population. In other words, it gives the prosperity of the people of that country whereas EPC is the unit (kWh/year) of electricity consumed by one person of that country averaging the whole population of the country. Electricity per capita usage is often considered as a key indicator of development. Nepal as one of the least developed countries, its EPC which is 244 kWh/year is far less than the global average energy per capita [95]. Low EPC has found a direct impact on the country's economy and development [96]. Thus, this article has further analyzed the impact of GDP on EPC through a regression analysis where EPC is a dependent variable and GDP is an independent variable. The model for the regression analysis is developed as follows:

$$EPC= \alpha + \beta\ GDP + e \qquad (4.4)$$

The regression analysis gives the following output:

Table 4.18 Regression analysis of GDP on EPC.

Variables	**Constant (α)**	**Coefficient. (β)**	**SEE**	**F-value**	**Adj-R^2**
GDP	-28.18 (-1.43)	0.27*** (10.21)	0.03	104.31***	0.92

***** significant at 1% level of significance*

(...) Parenthesis values are t-stat

Table 4.18 shows a positive and significant relationship between GDP per capita and electricity per capita. This reveals that one-dollar increase in GDP increases 0.27 kWh consumption of electricity. The Adj-R2 shows the goodness of fit of the developed model; this indicates that the GDP explains 92% of the variation in consumption of electricity. The modeling indicates that higher the GDP per capita, higher would be the consumption of electricity.

Barriers of the energy sector in Nepal

The policy analyzed and compared with electricity injection shows that the polices are not up to the optimal and thus, the study is further focused to trace the barriers for the development of energy sector and the relevant policies in Nepal. Based on the literature, formal and informal consultation with experts, focus group discussions and interviews, various relevant barriers for promotion of energy sector in Nepal are traced. Relevant literatures are analyzed in contextual to underdeveloped and developing countries like Nepal [97][98]. Based on such primary and secondary data collection and subsequently followed analysis, the position of the power sector remains unsatisfactory due to various issues and barriers like high tariffs, high system losses, high generation costs, high overheads, overstaffing, lower domestic demand, less political interest, social and cultural diversities etc. and many others. Based on all the collected information, issues and barriers are thematically categorized in three major barriers as technical, economic, and geographical.

These are the three major thematic barriers identified for promotion of energy sector in Nepal is concluded to be the most prominent ones. The thematic barriers are further elaborated as follows.

Technical Barriers

In the case of remote areas in underdeveloped and developing countries like Nepal, grid connection often is technically prohibitive. Due to this technical issue, an alternative model has been evolved with the maturation of contextual stand-alone energy systems [98]. Such stand-alone systems generate energy locally facilitating the supply of local energy demand. By the passage of time, communities are switching energy sources from traditional to modern/commercial. Depending upon available renewable energy sources communities are using improved cookstoves (efficient use of traditional fuels), micro or pico-hydro, small wind energy systems, solar photovoltaic, etc. These modern renewable energy systems are environment-friendly and technically matured alternatives for grid expansion, even at an economical rate [97]. But grid integration of electricity generated from such off-grid technology has been successful just in pilot-scale and full fledge implementation of grid integration has remained as a major technical challenge for maturation in Nepal. Other technical barriers include high technical and non-technical losses, lack of enough transmission line, weak distribution system etc.

Economic Barriers

Renewable energy (e.g. solar, wind, water resources, etc.) is abundantly available and applicable in the stand-alone system, which is the reason for it to be a better option for energy access where grid extension is not feasible. Solar home system (SHS) has contributed to more than 3 million households for energy access [98]. Clean electricity is the core of attraction for utilization of SHS for lighting. Depending upon the size of SHS, its use can be further expanded towards utilization for other modern technologies like telecommunications. The high upfront cost of stand-alone systems like solar PV and wind turbine along with battery backup has always remained as a common issue throughout the world. However, the high upfront cost is a barrier for grid electrification/extension as well. In countries like Nepal with difficult geographic terrain and low population density, stand-alone systems for energy access could be a better alternative. Stand-alone systems could ensure energy access not only for such sparsely settled population but also for various community entities like health posts, schools, community centres, and micro-business enterprises [99]. Despite these possibilities for energy access for rural communities through stand-alone systems, it is difficult for the rural dwellers to manage the high upfront cost for energy access. Additionally, these small stand-alone systems could mitigate lighting issues at the micro-level. But macro-level energy access and planning, which could possibly support rural enterprises and access a higher level of energy access (Tier wise) always come with economic barriers for underdeveloped countries.

Additionally, high generation cost leading to higher tariff, higher overheads and overstaffing at each level from generation, transmission and distribution is leading toward economic barriers for increased generation of electricity.

Thus, an economic barrier as a thematic one has remained as another pertinent barrier to the development of macro-scale renewable energy technologies in Nepal.

Geographical Barriers

Nepal is a country with most of the land in the hilly and mountainous region followed by a sparsely settled population. To ensure energy access to all those regions has always remained a major issue for the Nepalese government. Thus, geographical barriers for development to maturity of the energy sector in Nepal is one of the most challenging barriers for the long run. Due to difficult geographic terrain of mountainous countries like Nepal, generation cost of hydropower projects is always high. Additionally, harsh geographic landscapes have caused difficult in access and always increases the transportation cost to the project sites.

Energy generation specially from hydropower projects in Nepal is being done from remote and mountainous areas. In contrary, rural communities are the one who are deprived from electricity access. Geographical barriers are seen hand in hand with social and political issues.

The literature and the discussion above witness the existence of various issues and barriers for rural electrification and the promotion of renewable energy systems. Thus, the study concludes economic, technical and geographical as the thematically major underlying issues and barriers for renewable energy system promotion in Nepal.

5 CONCLUSION AND RECOMMENDATION

Conclusion and recommendation of the research is categorized as per the research objectives and are presented below.

Analytical modeling

Nepal as a topographically diverse country comprises many remote and rural areas which are yet to be electrified. The issue of energy access can be addressed by harnessing energy from off-grid energy technologies that are distance and cost-effective. Currently, numerous tools and technologies are available for energy modeling and optimization. In the context of underdeveloped and developing countries, easily available and user-friendly tools and technologies may be the best alternative. This study conducted energy planning and optimization from analytical modeling, one of the most suitable methods for developing and underdeveloped countries. The study has analyzed prevalent electrification options like MHP, MHP + DG, PV (inc battery), PV + DG, DG and grid expansion. The result shows that EDL linearly increases with the increase in load and supply hours from battery or DG. Dependency on DG is very expensive for electrification compared with other technologies. It is concluded that electrification distance can be increased by reducing the generation cost. Further, as the battery cost is found to take up to 63.4 % of the total project cost, this research encourages minimizing the use of battery back-up.

Particularly, the modeling has found that energy cost (LCC) for low load conditions is high, which is substantially higher for grid expansion. In general, LCC for grid expansion is the most economic for higher load conditions (i.e., more than 40 kW) whereas, for the researched geographical conditions, PV + DG is the most economical. Thus, in case of low load conditions, PV + DG or MHP, is recommended. The analysis for the various electrification option shows the LCC in the increasing order of:

PV+ DG, Grid expansion, MHP, PV (inc battery), MHP+DG, and DG.

The analytical modeling of the electrification options could be helpful for government and energy planners to work in remote areas for better alternate. This generic study of the Gorkha district can be further implemented as a generalized low-cost energy model for low-cost electrification.

Techno-economic optimization

Techno-economic optimization study is conducted by incorporating the energy systems as, PV, hydro, diesel generator, battery and converter. For the study site, the optimized system (incorporating all the mentioned energy systems) is considered. The system is optimized based on the following criteria

- System with all the energy technologies under research
- Relatively financially low initial capital cost
- Relatively low operating cost per year
- Competent net present cost (NPC)
- Competent cost of energy (COE)

Based on the set priority parameters, an optimized system from the simulation result is considered.

The total NPC for the system is found to be $ 3,182,271, levelized cost COE is $ 0.119/kWh and the operating cost for the system per year is $ 55,836. Despite the study conducted for renewable energy, diesel generator is considered as backup system and the pollutant emission is traced as mentioned in **Table 4.17** Emissions detail from the optimized model. The emission of pollutants (kg/year) is subject to change based on level of use of the generator. Thus, the limited use of the generator is recommended.

The simulation result is very useful for techno-economic optimization. Techno-economic optimization is must during feasibility study of any such off-grid projects, which gives the exact outcomes of the systems with cost summary, cash flow, electrical scenario, each system detail with emission and time series graphs.

Policy Analysis

Plenty of opportunities for the development of renewable energy technologies in Nepal exists through renewable energy policy and provisions. The Nepalese government has given high priority for the upliftment of the overall energy sector through White Paper 2018 and Energy Efficiency Strategy 2019 as the latest policy provisions. Barriers to the development of the energy sector based on literature review and formal and informal interactions is presented. The study has ultimately traced technical, financial and geographical as the most important thematic barriers to be addressed to meet the ambitious target of 15000 MW in the next 10 years as put forward in White Paper 2018.

Several advantages and positive features are highlighted against each policy provisions along with the limitations. Existing energy sector policy provisions seem challenging to meet the government target on time. The study has concluded the existing polices being not optimal has led to almost linear electricity generation of NEA (including electricity generation from IPPs) against the steep gradient of peak power demand. The trend analysis of energy scenario of Nepal shows that the Government of Nepal (GoN) should emphasize on electricity production as the electricity demand is continuously increasing. Further, the regression analysis reveals a positive and significant relationship between GDP and EPC, thus it is recommended that higher the GDP per capita, higher would be the consumption of electricity, thus, GoN should prioritize to increase its per capita income.

The results show that, electricity trend of Nepal is moving towards unsustainability which is witnessed from increasing slope of electricity purchase and import from India relative to electricity generation. Analysis of the optimization tools and techniques show that currently energy models seem to be based towards status of the energy systems and economic indicators of the developed countries. However, it is different for the developing countries. Therefore, energy modeling should be done in isolation than a common approach for all. At the current situation, it is very difficult, to find a universal model that fulfills all requirements that may adequately address the energy systems and economies of any developing countries. This is due to technical restrictions, data inconsistencies, limited purposes of the models and the complexity of the system. Thus, the research concludes that, it is not possible to recommend a specific optimization tool as a universal-approach. An optimization tool may fit in one situation but may not fit into another. This concludes that an optimization technique can only be opted after determining the specific models for energy planning. The study has discussed pros and cons of the four pertinent energy planning approaches and concludes on recommending the bottom up approach as the better alternative among others. The research has proposed a five-step energy planning methodology starting from demand analysis, resource analysis, model analysis, model optimization and execution of the model. The proposed methodology is expected to be very helpful to energy planners and policy makers in developing and under developed countries.

Above all, the research has traced a bi-linear polynomial equation with available data points of EDL, supply hours, and the demand load. The equation can further be utilized to identify the necessary EDL based on required supply hours and the load demand. Similarly, additional four bi-linear polynomial equation is fitted for the energy systems considered under the research. Thus, proposed methodology for the development of such equations can be further replicated for other energy systems for research.

Recommendations

In addition to the recommendations made under each intervention, the study recommendation is further elaborated and categorized for technical researchers and policy makers. For the technical researchers who want to continue similar research and energy planning, I would like to recommend the followings:

- extend the research scope to all the potential energy systems; not limiting to the energy systems and resources available in the research area. This will lead the researchers to develop a more generic model for energy planning than specific model that fits-in to only the limited renewable energy systems.
- extend the research site to national level. This will lead the researchers to compare their outcomes with the national level energy planning.

For the policy makers, who play a vital role in planning and policy making, I would recommend the followings:

- for better energy access, electricity generation is mandatory. For the optimum electricity generation, conducive policy formulation is must. Thus, the policy makers should develop and/or amend the existing policies in such a way that it will lead to optimum generation of energy/electricity.
- even energy planning at local level both analytical comparison of each energy technology in line with LCC and EDL is the must. This will help to adopt the suitable energy technology in the context at the optimum cost.
- adopt the techno-economic optimization via simulations of the potential energy systems for energy planning. The simulations and the sensitivity analysis may be carried out by a trusted tool like HOMER or others. The techno-economic

optimization is very essential to ensure the best output against the optimum capital investment, ensuring various sensitivity options.

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6 ANNEXES

Annex 1: Table A.1: Energy consumption pattern of Nepal

Annex 2: Table A.2: Distribution of energy consumption by fuel types in FY 2014/15

Annex 3: Table A.3: Research site data

Annex 4: Table A.4: VDC wise annual load in kWh

Annex 5: Table A.5: VDC wise annual load in kW

Annex 6: Published articles

1. Nawaraj Sanjel and Bivek Baral, "Modelling and analysis of decentralized energy systems with photovoltaic, micro-hydro, battery and diesel technology for remote areas of Nepal", on Clean Energy, 2021, 690-703; https://doi.org/10.1093/ce/zkab042
2. Nawaraj Sanjel and Bivek Baral, "Technical investigation of Nepalese electricity market – A review", on IOP Conf. Series: Journal of Physics: Conf. Series 1608 (2020) 012005; doi:10.1088/1742-6596/1608/1/012005
3. Nawaraj Sanjel and Bivek Baral, "A review of renewable energy sector of Nepal", on International (SAARC) Youth Scientific Conference (IYSC) 2019, 115-120
4. Nawaraj Sanjel, Bivek Baral, Mahesh Acharya and Satish Gautam, "Analytical Modelling for Optimized Selection between renewable energy systems and the conventional grid expansion", on IOP Conf. Series: Journal of Physics: Conf. Series 1266 (2019) 012014; doi:10.1088/1742-6596/1266/1/012014

Table A.1 Energy consumption pattern of Nepal

			Traditional				Commerical				
Fiscal Year	Unit	Traditional Total	Firewood	Agriculture Residue	Cowdung cake	Commerical Total	Coal	Petrolium Products	Electricity	Renewable	Grand Total
2004/05	000 ToE	**7556**	6732	327	497	**1014**	152	705	157	**46**	8616
2005/06	000 ToE	**7698**	6862	329	507	**1093**	243	686	164	53	8844
2006/07	000 ToE	**7854**	6999	337	518	**1031**	144	709	178	59	8944
2007/08	000 ToE	**8015**	7149	337	529	**1038**	193	655	190	59	9112
2008/09	000 ToE	**8185**	7301	344	540	**1139**	182	775	182	64	9388
2009/10	000 ToE	**8342**	7467	324	551	**1464**	286	965	213	70	9876
2010/11	000 ToE	**8500**	7606	331	563	**1580**	293	1058	229	75	10155
2011/12	000 ToE	**7032**	6274	310	448	**1679**	348	1083	248	109	8820
2012/13	000 ToE	**8017**	7153	353	511	**1854**	415	1182	257	166	10037
2013/14	000 ToE	**8983**	8154	403	426	**1959**	320	1264	375	291	11233
2014/15	000 ToE	**9104**	8264	408	432	**2331**	465	1469	397	292	11727
2015/16	000 ToE	**9228**	8376	414	438	**2238**	536	1275	427	292	11758
2016/17	000 ToE	**9319**	8459	418	442	**3253**	664	2088	501	294	12866
2017/18	000 ToE	**9473**	8604	425	444	**3715**	762	2388	565	296	13484
2018/19	000 ToE	**9601**	8720	431	450	**4115**	970	2633	512	299	14015
2019/20	000 ToE	**9625**	8762	436	427	**4488**	1046	2895	547	352	14465
2020/21 *	000 ToE	**6586**	5986	295	305	**2704**	636	1707	361	305	9595

* Upto mid march

TableA.2: Distribution of energy consumption by fuel types in FY 2014/15

SN	Fuel Types	Amount (000 GJ)	Perecnetage Share
1	Fuel Wood	352,229.10	70.47%
2	Agriculture-residue	17,408.43	3.48%
3	Animal dung	18,401.96	3.68%
4	Coal	19,819.09	3.97%
5	Petroleum	62,618.27	12.53%
6	Electricity	16,932.75	3.39%
7	Renewable	12,430.26	2.49%
	Total	499,839.86	100.00%

Table A.3: Research site data

VDC	No. of Households	No of Educational Institutions	No. of Offices/Health posts	No of Industries	Load growth		
Load factor	0.2	0.2	0.5	0.5			
Diversity factor	0.9	0.2	0.4	0.3			
Connected load (W)	200	500	400	2000	1-5 years	6-10 years	11-15 years
AaruArbang	1015	3	3	3	5%	2%	1%
AaruChanuate	1285	3	3	3	5%	2%	1%
Ghyakchok	416.00				5%	2%	1%
Gumda	395	1	1	1	5%	2%	1%
Hansapur	1147	2	2	2	5%	2%	1%
Kashigaun	330	1	1	1	5%	2%	1%
Kharibot	504				5%	2%	1%
Laprak	370	1	1	1	5%	2%	1%
Lapu	440	1	1	1	5%	2%	1%
Manbu	1469	2	2	2	5%	2%	1%
Saurpani	2900	1	1	1	5%	2%	1%
Simjung	894	2	2	2	5%	2%	1%
Swara	928				5%	2%	1%
Takukot	878	2	2	2	5%	2%	1%
Thumi	1281	2	2	2	5%	2%	1%
Uhya	13	1	1	1	3	5%	2%
Barpak	1510	2	2	2	5%	2%	1%

	Domestic	Education	Offices	Industries
Load factor	0.2	0.2	0.5	0.5
Diversity factor	0.9	0.2	0.4	0.3
Connected load (W)	200	500	400	2000
Load growth:				
1-5 years	5%	5%	5%	5%
6-10 years	2%	2%	2%	2%
11-15 years	1%	1%	1%	1%

Table A.4: VDC wise annual load demand in kWh

Load Forecast	Initial year connection rate	40%

VDC	Village name	Demand in Year (KWh)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
AaruArbang	Arbik	128036	141159	148217	155628	163409	184020	187700	191454	195283	199189	201180	203192	205224	207276	209349
AaruChanuate	Dandagaun	162095	178709	187645	197027	206878	232973	237632	242385	247233	252178	254699	257246	259819	262417	265041
Ghyakchok	Torkekharka	52475	57853	60746	63783	66972	75416	76924	78463	80032	81633	82449	83273	84106	84947	85797
Gumda	Singla	49827	54934	57680	60565	63593	71611	73043	74504	75994	77514	78289	79072	79862	80661	81467
Hansapur	Lapsibot	144687	159517	167493	175867	184661	207953	212112	216354	220681	225095	227345	229619	231915	234234	236577
Kashigaun	Khanibesi	41627	45893	48188	50597	53127	59824	61021	62241	63486	64756	65403	66057	66718	67385	68059
Kharibot	Ram Bhanjyang	63576	70092	73597	77277	81140	91371	93199	95063	96964	98904	99893	100891	101900	102919	103949
Laprak	Laprak	46673	51456	54029	56731	59567	67077	68418	69787	71183	72606	73332	74065	74806	75554	76309
Lapu	Khanigaun	55503	61192	64251	67464	70837	79768	81364	82991	84651	86344	87207	88079	88960	89849	90748
Manbu	Patalekharka	185305	204298	214513	225239	236501	266333	271660	277093	282635	288288	291170	294082	297023	299993	302993
Saurpani	Gairigaun	365817	403313	423478	444652	466885	525783	536299	547025	557965	569125	574816	580564	586370	592233	598156
Simjung	Mahabhir	112773	124332	130548	137076	143930	162083	165325	168631	172004	175444	177198	178970	180760	182567	184393
Swara	Tallo Thotneri	117061	129059	135512	142288	149402	168245	171610	175043	178544	182115	183936	185775	187633	189509	191404
Takukot	Bhaledhunga	110754	122106	128211	134622	141353	159181	162365	165612	168924	172303	174026	175766	177523	179299	181092
Thumi	Soranggaun	161590	178152	187060	196413	206234	232247	236893	241631	246463	251393	253906	256445	259010	261600	264216
Uhya	Khorla	1640	1808	1898	1993	2093	2352	2399	2447	2496	2546	2571	2597	2623	2649	2675
Barpak	Atali	190477	210000	220500	231525	243102	214508	218798	223174	227637	232190	212509	214634	216780	218948	221137

Table A.5: VDC wise annual load demand in kW

VDC	Village name	Demand for different Years in kW														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
AaruArbang	Arbik	48.7	53.7	56.3	59.2	62.1	70	71.4	72.8	74.3	75.7	76.5	77.3	78	78.8	79.6
AaruChanuate	Dandagaun	61.6	68	71.4	74.9	78.7	88.6	90.4	92.2	94	95.9	96.9	97.8	98.8	99.8	100.8
Ghyakchok	Torkekharka	19.9	22	23.1	24.2	25.4	28.6	29.2	29.8	30.4	31	31.3	31.6	32	32.3	32.6
Gumda	Singla	18.9	20.9	21.9	23	24.1	27.2	27.7	28.3	28.9	29.4	29.7	30	30.3	30.6	30.9
Hansapur	Lapsibot	55	60.6	63.7	66.9	70.2	79.1	80.7	82.3	83.9	85.6	86.5	87.3	88.2	89.1	90
Kashigaun	Yamkang	15.8	17.4	18.3	19.2	20.2	22.7	23.2	23.6	24.1	24.6	24.8	25.1	25.3	25.6	25.8
Kharibot	Gumda	24.1	26.6	28	29.4	30.8	34.7	35.4	36.1	36.8	37.6	38	38.3	38.7	39.1	39.5
Laprak	Kirunje	17.7	19.5	20.5	21.5	22.6	25.5	26	26.5	27	27.6	27.9	28.1	28.4	28.7	29
Lapu	Nambaikharka	21.1	23.2	24.4	25.6	26.9	30.3	30.9	31.5	32.2	32.8	33.1	33.5	33.8	34.1	34.5
Manbu	Kaigung	70.5	77.7	81.6	85.7	89.9	101.3	103.3	105.4	107.5	109.6	110.7	111.9	113	114.1	115.2
Saurpani	Danje	139.1	153.4	161.1	169.1	177.6	200	204	208.1	212.3	216.5	218.7	220.9	223.1	225.3	227.6
Simjung	Lapsibot	42.9	47.3	49.6	52.1	54.7	61.6	62.9	64.1	65.4	66.7	67.4	68.1	68.7	69.4	70.1
Swara	Dihigaun	44.5	49.1	51.5	54.1	56.8	64	65.3	66.6	67.9	69.2	69.9	70.6	71.3	72.1	72.8
Takukot	Lamidanda	42.1	46.4	48.7	51.2	53.7	60.5	61.7	63	64.2	65.5	66.2	66.8	67.5	68.2	68.9
Thumi	Khoriya Chaurgaun	61.4	67.7	71.1	74.7	78.4	88.3	90.1	91.9	93.7	95.6	96.6	97.5	98.5	99.5	100.5
Uhya	Kolkate	0.6	0.6	0.7	0.7	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1
Barpak	Tallahgare	72.4	79.9	83.9	88	92.5	81.6	83.2	84.9	86.6	88.3	80.8	81.6	82.4	83.3	84.1
Total VDC load in kW		756.3	834	875.8	919.5	965.3	1064.8	1086.3	1108	1130.1	1152.5	1155.9	1167.3	1178.9	1191	1202.9

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RESEARCH ARTICLE

Modelling and analysis of decentralized energy systems with photovoltaic, micro-hydro, battery and diesel technology for remote areas of Nepal

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Abstract

Remote areas of Nepal suffer from limited or no access to electricity. Providing electricity access in remote areas is one of the foremost challenges of any developing country. The purpose of this study is to develop and propose a reliable and low-cost model for electrification. The study presents an optimized choice between decentralized renewable-energy systems and grid expansion. Opting for an analytical method for the modelling and analysis of electrification options based on life-cycle cost (LCC) and economic distance limit, each energy system for varied load conditions is compared for a better option. A framework for energy-system selection based on available resources is proposed. It compares the grid-expansion option with potential isolated renewable-energy systems to ensure energy access to the area under consideration. Additionally, off-grid configurations that rely on renewable energy sources are also considered for the necessity of backup supply to ensure continuous power to the research area. Techno-economic assessment is carried out for different off-grid and hybrid configurations proposed in this study and their feasibility checks are carefully examined. Commercial efficacy of the proposed hybrid energy systems is assessed by comparing the life cycle and energy cost and by performing different additional sensitivity analyses. The study concludes that reduced generation cost supports the increasing penetration of electrification. The LCC for grid expansion is the most economical under high-load conditions, whereas for the isolated and sparsely settled populations with low-load conditions, photovoltaic power backed up with a diesel generator is the most economical.

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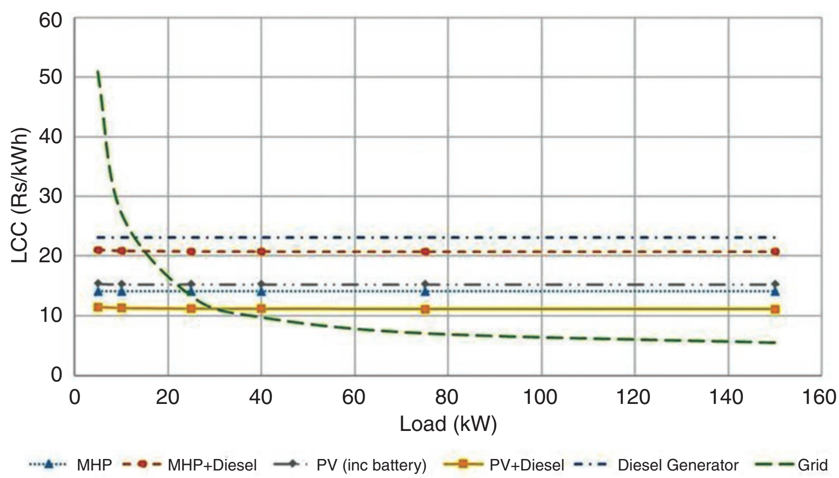
Graphical Abstract



Keywords: decentralized energy system; energy planning; rural electrification; economic distance limit; life-cycle cost

Introduction

Around 10% of the world's population as per the recent statistics do not have electricity access (17.5% rural and 2.7% urban) [1]. To increase electricity access, not only new electricity policies need to be formulated, but also significant sectoral policy and institutional reforms are required [2, 3]. Energy access may be increased to wider communities through many optimization techniques, the study of which is carried out in different parts of the world. Grid expansion in Kenya was studied by Parshall *et al.* using the Network Planner tool [4]. The study focused on identifying better electrification options among conventional grid expansion and decentralized energy systems. The study found that, in general, national grid expansion is a better option among other decentralized energy options. Paudel *et al.* conducted a case study on the resource optimization of the Kabeli corridor of Nepal focusing on a possible layout for the integration of a generating and power-evacuation substation (which is a facility that allows generated power to be immediately transmitted from a generating plant to the grid for further transmission or distribution to load centres) with a distribution system [5]. The study conducted by Sihem *et al.* researched the optimization and sizing of available off-grid power systems and their hybrid options [6]. In the study, Sihem *et al.* examined the techno-economic sizing of hybrid renewable-energy systems to minimize the cost of energy. Globally, similar studies have been performed focusing on the modelling of decentralized renewable-energy systems and their integration and optimization [7–9].

Hybrid and decentralized renewable-energy systems typically consist of renewable energy as the primary source coupled with backup from batteries and/or diesel generators (DGs). This hybridization of decentralized renewable-energy systems is applied to maintain the stability of the energy supply. Such systems are attractive due to their reliability and cost-effectiveness to ensure electricity access for remote communities. Numerous studies have been carried out to address the techno-economic optimization for the adequate utilization of renewable energy resources [10]. Although several studies have focused on applications of hybrid technologies for renewable energy sources and their optimization, appropriate energy technologies for the most suitable location and size for off-grid photovoltaic (PV) systems integrated with storage units and DGs are lacking the most. Most of the existing studies have focused on minimizing the total cost of the hybrid system only. Such analyses neglect the relationship between the specific energy technology of optimal size and the location of a hybrid system, which can significantly alter installation and operational decisions. Hence, for the cases of rural areas of developing countries, where grid expansion is not possible in the next 10–15 years, specific energy technologies coupled with backup from batteries and/or DGs are a suitable option to increase energy access [11]. A similar study on the techno-economic analysis of off-grid technologies was conducted in Sweden. The study concluded that the larger investment in grid expansion has led to the use of off-grid technologies and their mini-grids [12]. Research has been carried out on cost optimization for electricity demand using HOMER Pro (hybrid optimization model for multiple energy resources) and need-resource modelling using MATLAB (matrix laboratory) [13]. Optimization of energy systems helps to ensure reliable and financially beneficial supply. An unreliable supply of electricity causes a loss in revenue generation [14]. This speaks to the fact that the optimization of energy systems is important.

The United States Agency for International Development (USAID) study report provided an approach for using rapid resource assessment for rural electrification planning in Zambia [15, 16]. This methodology has been already implemented and presented by Mahapatra and Dasappa [17].

They implemented the model to identify better energy options between grid expansion and the other decentralized renewable-energy systems for rural areas. The analytical model examines economic distance limit (EDL) from the current grid access point and compares the life-cycle cost (LCC) of various available energy systems. The EDL helps to compare the economic distance of decentralized energy systems with grid expansion and the LCC helps to select a cost-effective electrification option among the available technologies. Sinha and Kandpal quantified and compared the LCC of off-grid energy technologies with the LCC of grid expansion [18–20].

In general, grid expansion is found to be cost-effective under normal geographical conditions; however, in remote places, grid expansion is found to be less feasible due to difficult geographical terrain. Nouni *et al.* conducted research comparing the cost of energy between energy access from grid expansion and the cost of energy from available off-grid technologies [21]. The research showed that there are many places where energy access from off-grid technologies is more cost-effective financially than grid expansion, depending upon geographical access and difficulties. In the context of energy access and reliability of off-grid energy technologies, the Government of Nepal (GoN) has prioritized off-grid energy technologies in its development plans. The GoN has not only promoted energy access, but also focused on its effective utilization to improve rural livelihood. The Alternative Energy Promotion Centre (AEPC) has been supporting the rural communities to install >1000 micro/pico hydropower plants of <100-kW capacities resulting in a cumulative installation of >20 MW that ensures energy access to >200 000 households [22]. Nepal Electricity Authority (NEA), the state-owned electricity monopoly, is carrying out large-scale rural electrification activities through grid expansion. NEA generated a total of 2308.37 GWh of electricity in fiscal year (FY) 2017–18. Given the high energy demand, the NEA generation could not address the energy demand for this period, and thus electricity was imported from India that accounted for a total of 2581.80 GWh. In addition, NEA also purchased electricity from Independent Power Producers (IPPs) within Nepal, which accounted for 2167.76 GWh. In the next FY, the total energy available in NEA's system increased by 12.79%. Out of the total available energy, imports from India and IPPs accounted for 30.71% [23–25]. Other sources of energy contributed to a larger portion of the supply—biomass constituents 80%, electricity 1%, oil 12%—whereas hydro made up 3% of the primary energy supply [26]. Thus, the need for optimized choice for rural electrification has been envisioned for increased energy access with enhanced reliability.

Lack of consolidated planning is the pertinent problem in the energy systems causing low energy access. According to the recent report of the World Bank (WB), 9.3% of the total population of Nepal has no access to electricity at all [27]. Grid connection, which is the most prominent mode of energy access, has less reliable electricity because >60% of people in Nepal are living in hilly areas that are sparsely populated and thus it is difficult to ensure energy access through the national grid [28]. In this context, energy access through isolated renewable-energy systems may be the best solution. But there are numerous issues in isolated renewable-energy systems such as the periodic nature of renewable energy sources, high installation and operating costs, poor reliability, low load factor, maintenance and monitoring activities [29]. To solve these issues, techno-economic optimization with the proper design of an energy system will be instrumental [30–32]. An isolated hybrid energy system may be a better option to provide a reliable energy system by minimizing issues associated with energy systems [33].

Rural electrification can be done using the central grid, isolated decentralized energy systems and hybrid technologies. Given these possibilities, the present study focuses on all three options for reliable energy access. The preference for a specific technology depends on the locally available resources and economic feasibility. This study compares the grid-expansion option with potential isolated and hybrid energy systems. Techno-economic assessment of different off-grid configurations is proposed and their feasibility checks are carefully examined. Commercial efficacy of the proposed systems is evaluated through comparison with the life-cycle and energy costs. This critical examination is anticipated to be helpful for better energy planning.

In developing countries like Nepal, there are two options for electrification. Understandably, national grid expansion is the first and foremost option, but it may not be a viable option due to the high upfront cost [34]. In such cases, decentralized energy systems could be the most suitable alternatives, even for long-term options. The options should be technically and financially compared for the selection of better choices between off-grid electrification and grid expansion. In developing countries, micro-hydropower (MHP), solar PV, DG and backups (battery and DG) are the major and viable off-grid technologies used for energy access [35]. In Nepal as well, these technologies are widespread. In Nepal, ~3000 MHP projects contributing ~35 MW of electricity have been installed. More than 600 000 household-level solar PV systems with battery-backup systems and 1500 units of the institutional solar PV plant are already installed [36]. Additionally, as a backup supply system for electricity access, batteries and DGs are prominently utilized. PV, battery and DG technologies in rural areas of Nepal are utilized as a source of electricity access, whereas in urban and peri-urban areas of Nepal, they are considered as backup supplies. Thus, based on the current usage, availability and viability of these technologies, these energy systems along with their hybrid options, as mentioned below, are considered for the study purpose:

(i) MHP
(ii) MHP + DG backup
(iii) PV + battery backup
(iv) PV + DG backup
(v) DG

Each of these options is compared to identify a better alternative based on EDL. Further, these hybrid energy systems are compared with the LCC of grid expansion. This comparison will be helpful for long-term and short-term energy-systems planners. Thus, the focus of this research is to optimize the decentralized energy systems and compare them with grid expansion through analytical modelling, calculating LCC and EDL.

1 Methodology

1.1 Site selection and data collection

An ideal site for this type of study should have grid access, micro-hydropower-system potential, solar energy and any site with no electricity access. Gorkha district lying in the Gandaki province of Nepal is considered the most suitable site to study, as the location has all the required characteristics. The district has two geographical regions: mountain/hill on the south from 228 to 2500 m in altitude and the high Himalayas from 2500 to 8163 m. The population density of the district decreases massively going from south to north. Fig. 1 represents the electrification status of the research site: the existing NEA grid line along with the existing micro-hydro stations plotted using a geographic information system tool.

After site selection, data collection was done through various secondary sources like AEPC, Renewable Energy for Rural Livelihood, Centre Bureau of Statistics (CBS), Village Development Committee (VDC), District Development Committee and the WB; 15 775 households, 24 educational institutions, 24 offices or health posts and 24 industries exist in the research area with an average of 5% electrical-load growth [28]. Electricity-load demand for the next 5 years has been calculated as 17 VDCs, which is 1000 kW.

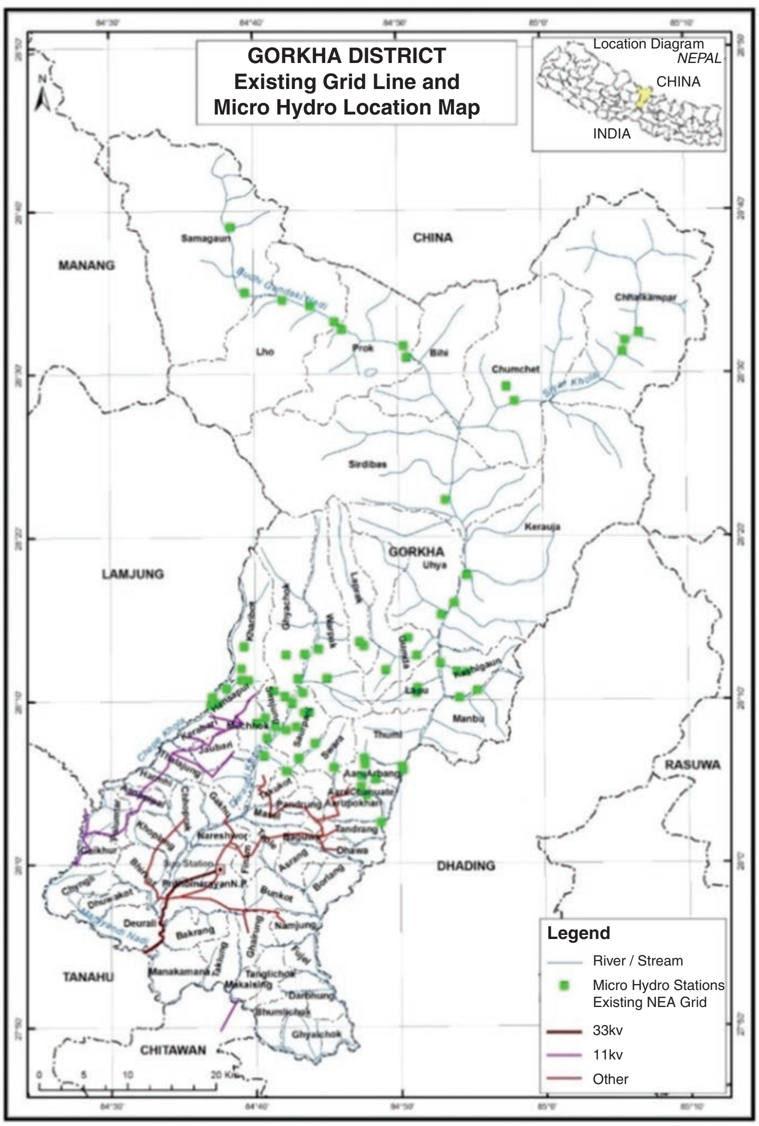


Fig. 1: Map of Gorkha district indicating energy-systems availability

Source: www.dos.gov.np..

Based on the plotted map as shown in Fig. 1, the research site is selected in an appropriate geographical location having abundant solar energy. In this study, we employ Meteonorm software, which uses an empirical method for calculating solar radiation on horizontal and arbitrarily oriented surfaces that are situated in any location. The method utilizes databases and interpolation algorithms in a predetermined scheme. The average monthly data for the weather stations are stored in the Meteonorm database, while the hourly data are generated when needed. The average monthly values for the cities and other locations are obtained by interpolation and the hourly values are generated based on them (www.meteotest.ch). Similar publications that have adopted such Meteonorm data further validate the use of such data [37, 38].

The meteorological data (sunshine hours and global radiation) provided by Meteonorm v8.0.3.15190 for the Gorkha district are presented in Fig. 2, whereas the uncertainty parameters are embedded in the software itself and are thus not considered in our study to avoid duplication.

1.2 Sources of energy

The study area is rural and lies in the northern belt of Nepal; thus, the major energy consumption in the area is for cooking and lighting. Considering the dominant utilization of the dominant energy sources, the study has focused on the energy sources used for cooking and lighting, which are presented in Figs 3 and 4.

Fig. 3 shows that most households (nearly 84%) use fuelwood as the energy source for cooking, and liquefied petroleum gas and biogas are the other major energy sources used for cooking by most households. Fig. 4 shows that most of the households (76%) use electricity for lighting. The source of electricity for lighting is solar PV and microhydropower in some cases.

The available energy-resource assessment is presented in Fig. 3; it shows the abundant availability of biomass in the study area. Electricity generation from biomass, however, is challenging due to the lack of prominent biomass-based electricity-generation technologies at the local level, difficulties in the road accessibility of the research site, etc. At the global level as well, there are several studies which agree that biomass is a complicated technology for electricity extraction and is considered less efficient for electricity generation [39–41]. Thus, the study does not consider electricity generation from biomass resources.

Further, to be commercially viable, the wind-power density must be 300 W/m^2, whereas the wind-power density in Gorkha is 96 W/m^2 (Solar and Wind Energy Resource Assessment in Nepal, SWERA), as indicated in Fig. 5. Thus, wind-energy technology is also not considered for the study purpose.

1.3 Electricity-demand profile

The study covers the 17 VDCs with 214 villages of the Gorkha district. Each of the households, educational institutions, health posts, offices and industries are considered to develop a demand profile. The load factor, diversity factor and the connected load for various types of institutions are considered as presented in Table 1.

The load factor is a measure of the utilization rate or efficiency of the electrical-energy usage; a high load factor indicates that the load is using the electric system more efficiently, whereas consumers that underutilize the electric distribution will have a low load factor. The load factor is the ratio of the load that the equipment draws to the full load (that it could draw). Thus, the load factor of the power system is always <1. Thus, as indicated in Table 1, in rural areas of Nepal, households have a very low load factor, i.e. they use electricity almost exclusively for lighting purposes, whereas offices and industries in rural areas in Nepal have relatively better load factors.

The diversity factor is a fraction of the total load contributed to the peak demand. It is usually >1 because the

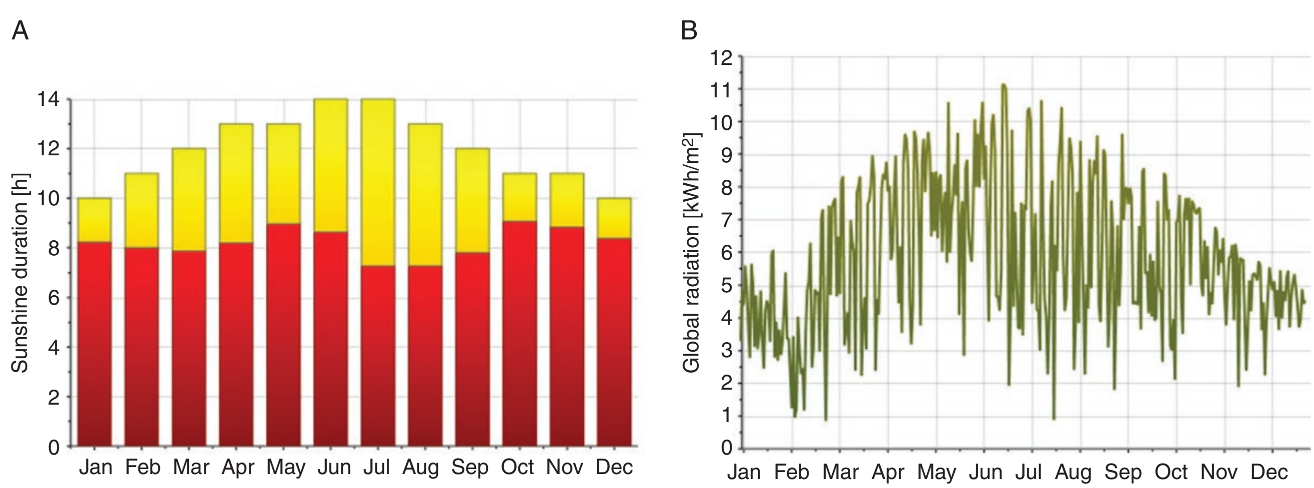


Fig. 2: Sunshine hours and global radiation of Gorkha district

Source: www.meteonorm.com/en/..

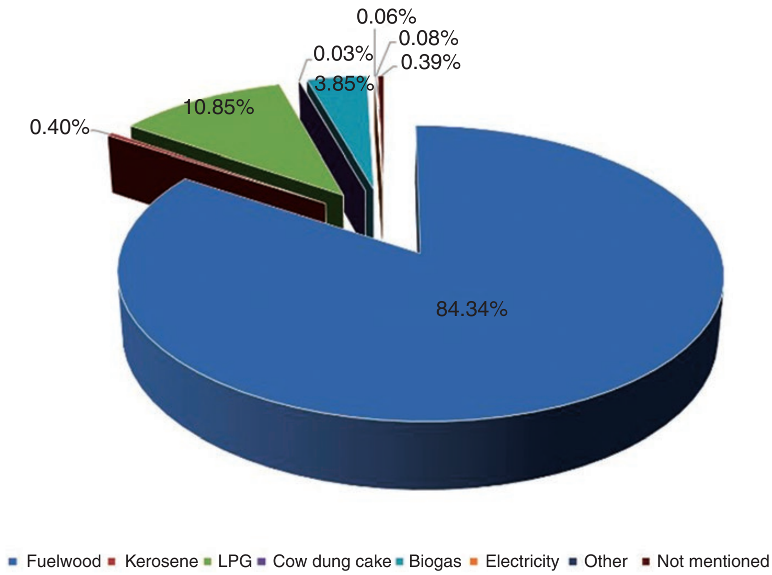


Fig. 3: Households using various energy sources for cooking [28]

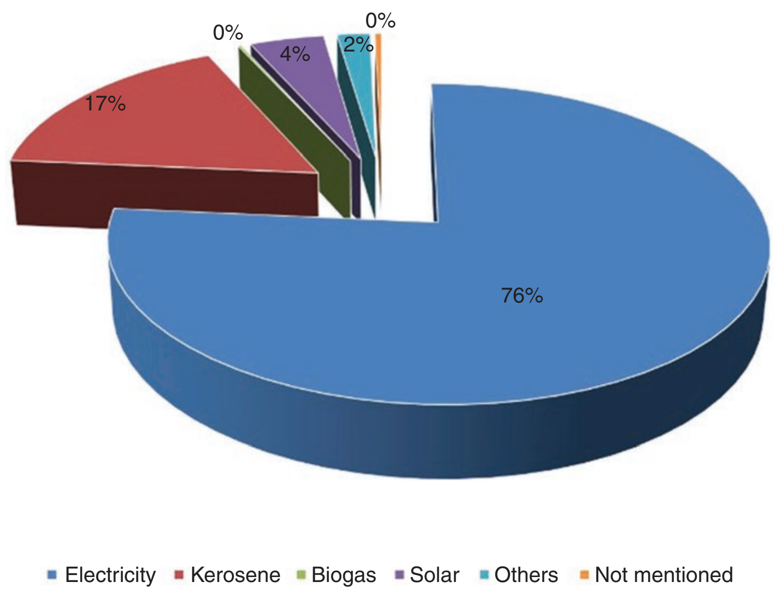


Fig. 4: Households using various energy sources for lighting [28]

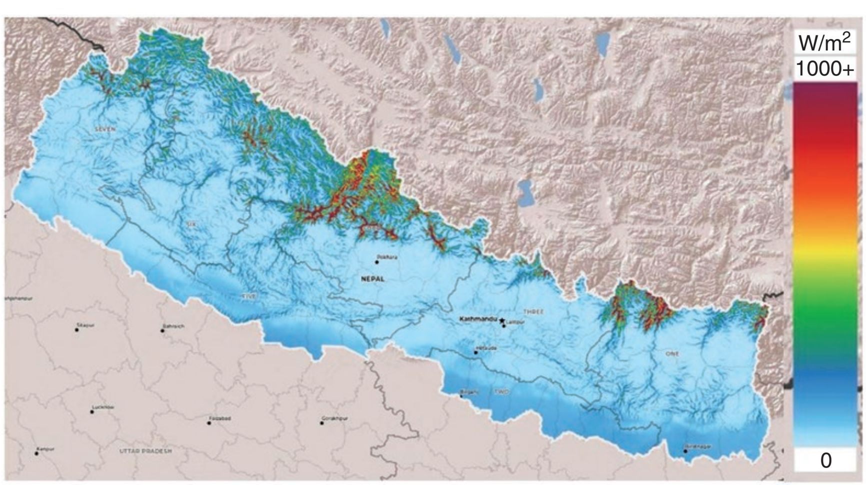


Fig. 5: Wind-energy potential in Nepal [42]

sum of the individual maximum demands is greater than the maximum demand. The diversity factor is equal to the ratio of the maximum demand on the power station and the sum of the individual maximum demands. For example, a diversity factor of 0.9 (90% diversity) means that the device operates at its nominal or maximum load level 90% of the time for which it is connected and turned on. Thus, as indicated in Table 1, households in rural areas are the major contributor to the peak load as compared to offices and industries.

The load demand of the research site for 5 consecutive years is listed in Table 2.

The cumulative load demand of the study area is 959.1 kW, as indicated in Table 2. Thus, the study has considered 1000 kW as the forecasted load of the study area.

Accordingly, the electricity demand in MWh for each village considering the presented load and diversity factor for 5 consecutive years was prepared and is presented in Fig. 6.

Table 1: Assumptions for load forecast [23, 24]

	Domestic	Education	Offices	Industries
Load factor	0.2	0.2	0.5	0.5
Diversity factor	0.9	0.2	0.4	0.3
Connected load (W)	200	500	400	2000
Load growth				
Year 1	10%	10%	10%	10%
Years 2–5	5%	5%	5%	5%

Table 2: Load demand for 5 consecutive years

Year	Year 1	Year 2	Year 3	Year 4	Year 5
Load demand (kW)	756.3	831.9	873.5	917.2	963.0

According to the electricity-demand indication in Fig. 6, the energy demand for Saurpani is the highest and that for Uhya is the lowest.

1.4 Analytical modelling

Mathematical assumptions and processes are defined for the necessary calculations. For analytical modelling, first the LCC of the system is calculated, after which the EDL is calculated. Both the primary data, collected from the NEA and AEPC, and secondary data collected from the census [28] are analysed. After the analysis, the best cost-effective technology is selected. The EDL is used to check better electrification technology depending upon the distance for electrification. This techno-economic optimization has been deployed by various researchers for the optimization of renewable-energy systems [43, 44]. Given the accepted applicability of the methods, analytical modelling coupled with LCC and EDL analysis has been considered in this research. This analytical modelling is best suited for developing and underdeveloped countries like Nepal for efficient electrification planning.

1.5 Assumptions and data analysis

To select better energy technology for contextual energy planning and electrification, a detailed calculation of the EDL and LCC is required. For these calculations, various assumptions such as the load forecast and connected load and diversity factors are made as presented in Table 1.

Further, for the calculation of the LCC and EDL, various parameters have been assumed and adopted as per the standard values adopted by NEA and AEPC reports. The details of the assumed values against each parameter are depicted in Table 3.

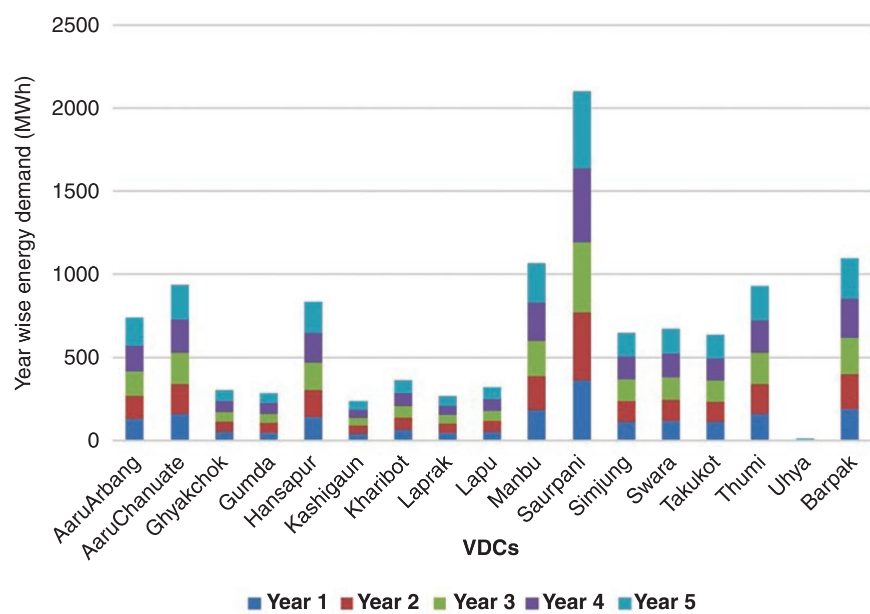


Fig. 6: Energy demand (in MWh) of 17 VDCs of Gorkha district for 5 years

Table 3: Assumed parameters for the calculation [24, 25]

Symbol	Description	Unit	Quantity
$\delta_{t\&d}$	Transformer and distribution losses	%	20%
β	Fraction of capital cost for O&M of grid	%	1.5%
L	Load demand	kW	25
h	Annual operation hours	H	2920
n	Life of project	Years	25
d	Discount rate	%	10%
P	Present worth factor		0.0907

[a]O&M, operation & maintenance.

The reliability of the grid supply and other technologies is assumed to be the same for calculation purposes.

1.6 Uncertainties

The study has considered various parameters for the energy-planning process such as the demand load, demand fluctuation, irradiation, load factor, diversity factor, LCC, etc. The possible changes in the parameters correspond to the possibilities of uncertainties of the coefficients [45]. To minimize the uncertainty, the study was conducted with verities of the values of a single parameter or coefficient. For example, the study has considered varying loads of 5, 10, 25, 40, 75 and 150 kW. The power available for hours per day are considered with varying hours of 6, 8, 10, 12 and 14 hrs per day. The LCC is calculated using prevailing costs with the inclusion of possible discount rates for solar PV and batteries, etc. Further, the study utilizes the Meteonorm data for sunshine hours and global radiation, and limits the study over their uncertainties.

2 Theory

2.1 LCC

For the analysis and comparison of energy technologies, the study calculated the LCC of each energy technology considered in this research. The operating constraints such as geographic terrain, climatic conditions and available technology for each technological option have varied impacts on energy production and are considered an error for the research provision.

The LCC for different energy systems, namely PV, MHP and DG, for varied capacities are calculated using Equations (1), (2) and (3), respectively [21]:

$$LCC_{PV} = \frac{C_{PV} + C_B + (C_{PV} + C_B)\,.\beta.P\,(d,n) + C_R.P(d,n_1)}{L.h.n} \tag{1}$$

$$LCC_{MHP} = \frac{C_{MHP} + C_{MHP}.\beta.P\,(d,n) + C_{MHPR}}{L.h.n} \tag{2}$$

$$LCC_{DG} = \frac{C_{DG} + (C_{DG})\,.\beta.P\,(d,n) + C_R.P\,(d,n_1) + C_{FUEL}.n}{L.h.n} \tag{3}$$

where LCC_{PV} represents the LCC of PV generation (in Nepalese rupees or Rs), C_{PV} represents the capital cost of a PV system (excluding battery) (Rs), C_B represents the capital cost of a battery, β represents the capital-cost fraction for annual O&M, $P(d,n)$ is the present net worth factor of annual O&M, n represents the life of the complete system (years), d represents the discount rate (%), C_R represents the replacement cost of a battery (Rs), $P(d,n_1)$ represents the present net worth factor of components, n_1 represents the life of replacement of components, L represents the system capacity (kW), h represents the annual operating hours, LCC_{MHP} represents the LCC of MHP generation (Rs), C_{MHP} represents the capital cost of an MHP system (Rs), C_{MHPR} represents the capital cost of replacement after economic life (Rs), LCC_{DG} represents the LCC of DG generation (Rs), C_{DG} represents the replacement cost of a diesel generator (Rs) and C_{FUEL} represents the cost of fuel annually (Rs). The LCC calculation for a PV system backed up by a DG is the combination of Equations (1) and (3).

The LCC calculation for the MHP system backed up by a DG is the combination of Equations (2) and (3).

The LCC calculation for grid expansion is given in Equation (4):

$$LCC_{GE} = \frac{LCC_{gen} + LCC_{transf} + LCC_{grid}.\ X}{L.h.n} \tag{4}$$

where

$$LCC_{gen} = t_{gen}.L.h.\left(\frac{1}{1-\delta_{t\,\&\,d}}\right).\,P(d_1,n)$$

$$LCC_{grid} = C_{grid} + (C_{grid}).\beta.P(d_2,n)$$

$$P\,(d,n) = \frac{(1+d)^n - 1}{d.(1+d)^n}$$

where LCC_{GE} represents the LCC of grid expansion (Rs), LCC_{gen} represents the LCC of electricity generation (Rs), LCC_{transf} represents the LCC of transformers (Rs), LCC_{grid} represents the LCC of grid lines (Rs), X is the distance from the load centre to the grid point (km), t_{gen} represents the electricity-generation cost (Rs), $\delta_{t\&d}$ represents the transmission and distribution losses and C_{grid} represents the grid-line cost (Rs). This approximates to $1 + d + d_2 + d_3 + d_4 + \ldots\ldots\ d_n$ for n to infinity.

2.2 EDL

The EDL is a break-even analysis of grid expansion and an alternate energy system, and is calculated as in Equation (5):

$$\frac{LCC_{grid}.\ EDL + LCCtransf + LCC_{gen}}{L.h.n} - LCC_{MHP/PV/DG} = 0 \tag{5}$$

From Equations (1)–(5), the EDL is calculated for MHP, MHP+DG, PV+battery, PV+DG, DG and grid expansion. The EDL for each energy system is calculated for operating hours of 6, 8, 10, 12 and 14. Further, energy systems for load capacities of 5, 10, 15, 40, 75 and 150 kW are considered for comparison. The selection of this method is grounded in the fact that a similar methodology has been adopted and verified in previous research as well [46].

3 Results and discussion

This section presents the results about EDL against various indicators used in this study, namely electrification model, generation cost, load and electricity supply. Further, it presents the impact of battery backup in solar PV energy systems and LCC comparison against varied load conditions. The result of each analysis is presented and discussed immediately afterwards. The major results show that grid expansion is feasible only for high-load requirements. Off-grid technologies in hybrid mode are more feasible for low-load requirements; it depends on the availability of energy resources as well. The study shows that the energy cost for low-load conditions is high and is low for high-load conditions. In this way, the best alternative electrification option can be adopted. The study shows that the reduced generation cost will support increasing the electrification penetration. Among the options studied, PV backed up with a DG is found to be a better electrification alternative to grid expansion.

3.1 LCC

The LCC of electricity generation and LCC of grid expansion are calculated considering the capacity of the energy system, the cost of system refurbishments and maintenance costs. It is found that the LCC of electricity-generation costs from MHP is 23.82 Rs/kWh, the LCC of electricity-generation costs from MHP (including refurbishment after 15 years) is 35.12 Rs/kWh, the LCC of electricity generation from PV backed up with a battery is 274.18 Rs/kWh, whereas the LCC of electricity generation from PV (without battery backup) is 14.22 Rs/kWh [34].

3.2 Electrification models and EDL

The EDL for all electrification options was calculated. The results for various electrification models are tabulated in Table 4. For the swift comparison of EDL values, the table presents EDLs in increasing order.

The result as presented in Table 4 shows that the area within 14.24 km length from existing grid end points is economical to electrify through grid expansion. For the areas beyond 14.24 km, energy access from decentralized options is seen as economical. Specifically, for electrification of ≤14.24 km, PV+DG appears economically beneficial. Further, grid expansion of ≤14.70 km is more economical than MHP, grid expansion of ≤22.84 km is more economical than PV+battery, grid expansion of ≤28.10 km is more economical than MHP+DG and grid expansion of ≤38.58 km is more economical than DG. Other hybrid options such as PV+DG, MHP, PV+battery, MHP+DG or DG would be better than grid expansion if the distance is beyond the calculated EDL. Apparently, PV+DG is the best economical option for off-grid electrification after grid expansion. This result reiterates the result obtained from HOMER Pro modelling by other researchers [11, 30]. Importantly, similar hybrid

Table 4: Electrification models and EDL

SN	Electrification models	EDL (km)
1	PV+DG	14.24
2	MHP	14.70
3	PV+battery	22.84
4	MHP+DG	28.10
5	DG	38.58

systems for electrification have been validated to be a more reliable and efficient source of energy access [47, 48].

3.3 Generation cost and EDL

Fig. 7 presents different EDLs for varied energy generation costs. The EDL was analysed with a change in the range of –60 to +60% of the NEA generation cost, which is 7 Rs/kWh. The change (either increasing or decreasing) in generation cost showed a direct and linear relationship with the EDL.

Fig. 7 shows that a reduced generation cost increases the distance limit for grid expansion. That is, if the generation cost is minimized, the distance for grid expansion will increase. If the generation cost increases, the distance for grid expansion will decrease. This concludes that a reduced generation cost will support increasing the electrification penetration, which is in line with the earlier study [22]. Fig. 7 also shows the EDL trend in the following pattern:

DG > MHP+DG > PV+battery > MHP > PV+DG

The pattern shows that DG has the highest EDL, whereas PV+DG has the lowest EDL. This means that, among the analysed energy systems, PV+DG is a better electrification option than others if the location is beyond the grid-expansion limit.

3.4 Load and electricity supply, and EDL

The EDL for various loads and electricity supply was calculated as shown in Fig. 8a–e. The EDL was calculated for 6, 8, 10, 12 and 14 hrs/day of electricity supply. From the analysis, two scenarios (numbers 1 and 2) were observed; numbers 3 and 4 present specific outcomes:

(1) In the case of 6, 8 and 10 hrs of electricity supply required, the EDL of PV+DG was low. The EDL slightly increased when the electricity-supply hours increased. This was due to the increase in battery-backup cost and the increase in fuel cost for the DG. Similar results were obtained in previous research [30, 49].
(2) With a further increase in the electricity supply, the EDL for MHP was found to be more promising as no backup cost was incurred. The result may be valid only for limited hours of supply because increasing the numbers of supply hours would require a backup system.
(3) For 6 hrs/day of supply required, MHP+DG was found to have the highest EDL. This means that MHP+DG was the last option for electrification for lower hours of supply required. When the supply hours required are high, a DG should be the last option.

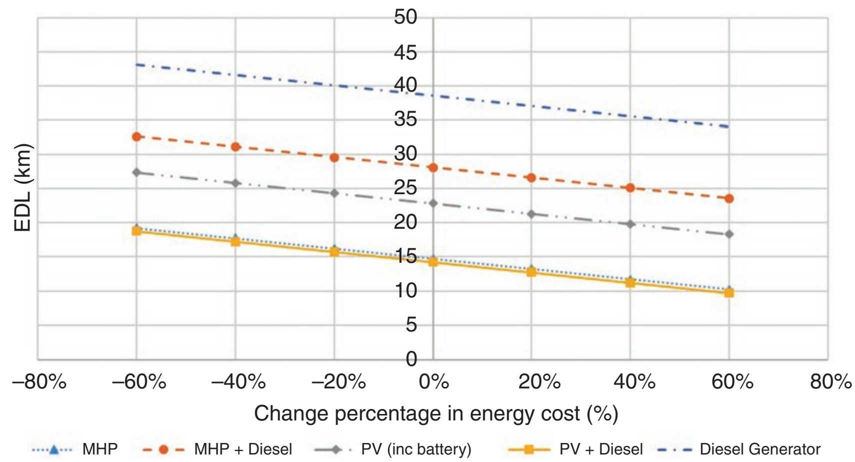


Fig. 7: EDL with changing generation cost, 0% = 7 Rs/kWh.

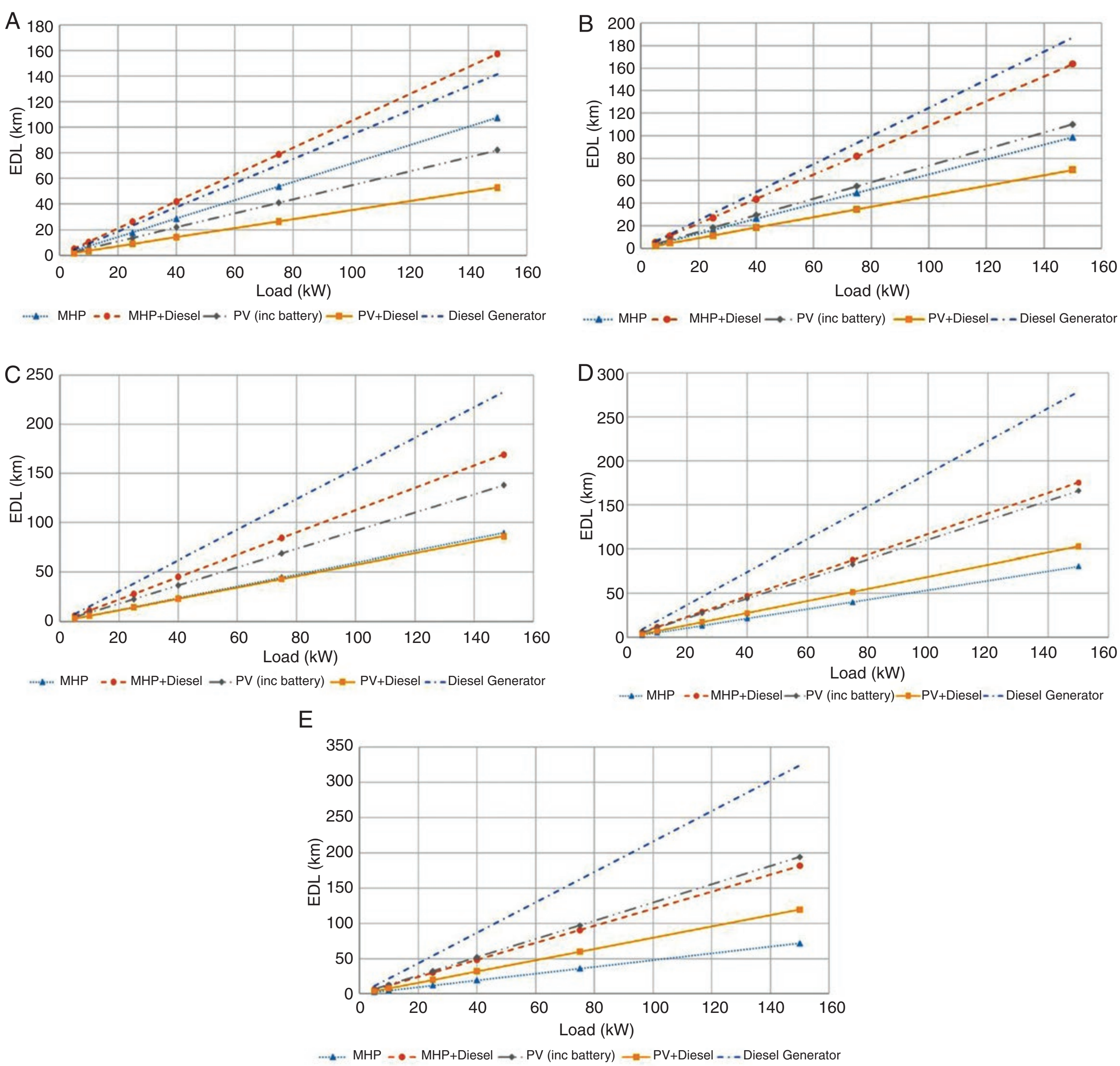


Fig. 8: EDL against system capacity and different hours of power availability per day. (a) 6 hrs/day electricity supply; (b) 8 hrs/day electricity supply; (c) 10 hrs/day electricity supply; (d) 12 hrs/day electricity supply; (e) 14 hrs/day electricity supply.

(4) For 10 hrs of supply required, MHP+DG or PV+battery was an almost similar viable option for electrification.

Further, two trends were observed, as follows:

(i) The EDL increased linearly with the increase in load; this result resembles the findings of an earlier study [46].
(ii) The EDL increased for increased backup hours from a battery or DG. This shows that the dependency on a DG is very expensive for electrification compared with other technologies. This finding matches various other research findings [50–52].

In Fig. 8a–e, the line indicating the PV+battery system was observed continuously moving in the upward direction from which it can be concluded that the EDL regularly increases with increasing load and supply hours needed.

3.5 Impact of battery backup

Fig. 9 shows the impact of battery-backup costs on total system costs. The analysis was done for 25 kW of the PV system for 10 hrs of supply daily for 20 years of system life with the backup system for 2.5 autonomous days, which should be replaced every 5 years. The battery size of 12 V and 150 Ah was considered for the analysis.

The result shows that the cost of the battery was 63.4% of the total system cost. No fluctuation in battery cost resembles the current situation. Further, increasing the battery cost increases the total system cost and decreasing the battery cost decreases the total system cost. A maximum decrease in the battery cost (≤80%) has a minimum impact (not linear) on the total energy-system cost. This effect was attributed to the upfront cost of other energy systems remaining the same.

This impact of battery backup has also been justified by an increased EDL as shown in Fig. 8a–e. An almost linear trend was observed in the energy cost for varied (decreasing and increasing) battery costs as presented in Fig. 9.

3.6 LCC comparison against load

Considering the distribution line length, the distribution transformer capacity and the demand at the local level, a transformer of 25 kVA was found to be suitable. This

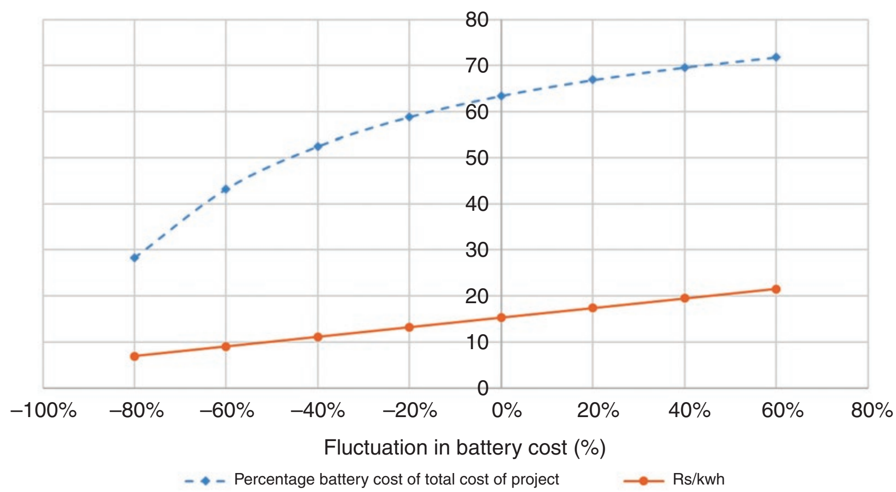


Fig. 9: Battery capacity and the cost.

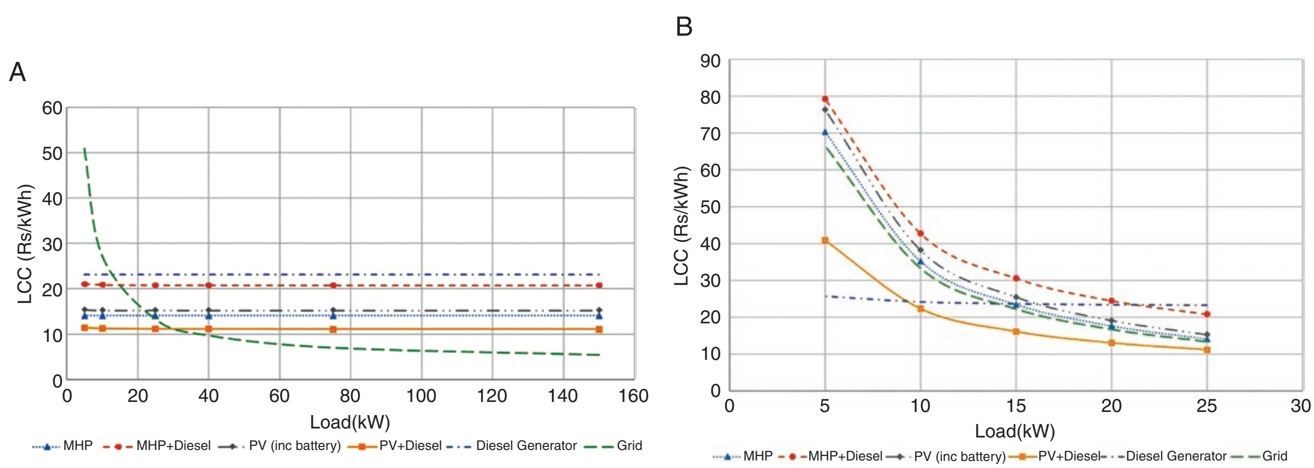


Fig. 10: LCC comparison for (a) increasing load and (b) actual load.

Table 5: LCC for 25 kW of actual load conditions for various electrification options

SN	Electrification option	LCC (Rs/kWh)
1	PV+DG	11.13
2	Grid expansion	13.30
3	MHP	14.05
4	PV+battery	15.26
5	MHP+DG	20.78
6	DG	23.16

minimizes the distribution loss to each transformer. Thus, in the study, 25 kW is considered as the actual load to each of the transformers, and other loads such as 5, 10, 25, 40, 75 and 150 kW are considered for the study purpose to analyse the effect of increasing the load. Fig. 10a gives the LCC for varied loads of 5, 10, 25, 40, 75 and 150 kW. The LCC for grid expansion for 5 kW of load was 50.84 Rs/kWh, whereas the LCC for PV+DG for the same condition was 11.41 Rs/kWh.

From Fig. 10a, two conclusions can be drawn:

(i) The energy cost (LCC) for low-load conditions is high—much higher for grid expansion. The LCC for grid expansion is the lowest at a higher load starting from 40 kW.
(ii) The energy cost (LCC) decreases with the increased load to a certain level and stabilizes thereafter.

Fig. 10b depicts that the energy cost for low-load conditions is high and it is low for higher loads. In general, the LCC for grid expansion is the most economical but, as observed in this study, PV+DG is the most economical.

Further, increasing the LCC for electrification options appeared to increase in the order of PV+ DG, grid expansion, MHP, PV+battery, MHP+DG and DG. The actual values of the LCC for 25 kW of actual load are expressed in Table 5.

4 Conclusion

Nepal as a topographically diverse country comprises many remote and rural areas that have yet to be electrified. The issue of energy access can be addressed by harnessing energy from off-grid energy technologies that are distance-effective and cost-effective. Currently, numerous tools and technologies are available for energy modelling and optimization. In the context of underdeveloped countries, easily available and user-friendly tools and technologies may be the best alternative. This article conducted energy planning from analytical modelling, which is one of the most suitable methods for underdeveloped countries. We analysed prevalent electrification options such as MHP, MHP+DG, PV+battery, PV+DG, DG and grid expansion. The result shows that the EDL linearly increases with the increase in load and supply hours from a battery or DG. Dependency on a DG is very expensive for electrification compared with other technologies. It is concluded that the electrification distance can be increased by reducing the generation cost. Further, as the battery cost is found to make ≤63.4% of the total project cost, this research encourages minimizing battery usage.

Particularly, the modelling has found that the energy cost (LCC) for low-load conditions is high, and substantially higher for grid expansion. In general, the LCC for grid expansion is the most economical for higher-load conditions (i.e. >40 kW) whereas, for the researched geographical conditions, PV+DG is the most economical. Thus, in the case of low-load conditions, PV+DG or MHP is recommended. The electrification option increases the LCC in the order of PV+DG, grid expansion, MHP, PV+battery, MHP+DG and DG.

The modelling of the electrification options could be helpful for government and energy planners to work in remote areas for better alternatives. This generic study of the Gorkha district can be further implemented as a generalized low-cost energy model for low-cost electrification.

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Conflict of interest statement

None declared.

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Technical investigation of Nepalese electricity market – A review

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Technical investigation of Nepalese electricity market – A review

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Abstract. The article reviews the options of renewable energy technologies with the background of long-lasting power shortages that Nepal has been facing and examines the energy-related policies of Nepal and provisions to promote renewable energy technologies in Nepal and its regulatory framework. It analyses the pertinent energy policies related to energy generation and distribution. The research focuses on the context of the renewable energy sector of Nepal and its future. The research has found a positive role in renewable energy policies for adoption of renewable energy technologies and poses a positive impact on electricity generation. The article has also reviewed and analyzed the trend of electricity generation, peak demand and the resulted import to meet the gap. The almost linear electricity generation of Nepal Electricity Authority (including generation of Individual Power Producers against the steep gradient of peak power demand has ultimately increased the power purchase from India pushing towards unsustainability. It shows that energy policies are not up to the optimal. The research has further analyzed the impact of per capita GDP on electricity per capita by regression analysis. The analysis has found, higher the GDP per capita would increase the consumption of electricity per capita. The paper discusses issues and barriers for promotion of rural electrification and suggested economical, technical and geographical to be the three most pertinent barriers in developing countries.

Keywords: Energy Policy, Electricity per capita, GDP per capita, Regression Analysis.

1. Introduction

Electricity demand in Nepal has been rising rapidly with an exponential increase in electrical appliances. However, the electricity generation capacity of Nepal does not meet the demand and would need to be increased substantially. Energy security has been an emerging issue throughout the world. The issue has been found driven by geopolitical developments and supply shortages. In some cases, the issue has been raised due to institutional and regulatory failures as well. Energy demand has been ever-increasing, but the source of energy is limited, which may lead to potential threats to supply security [1]. Nepal has a huge potential of energy resources (83,000 MW hydro, 2100 MW Solar, 3000 MW wind), whereas per capita energy consumption is only 14.8 GJ. The total energy requirement of Nepal has remained in the periphery of 500 million GJ, about 87% of which is met from traditional fuels. The source of traditional fuels has further been sub-categorized into fuelwood (77%), agricultural residue and animal waste (9%) [2,3]. Further, 12.1% of energy demand has been met by commercial energy sources like electricity and fossil fuels. Annual peak demand in fiscal year 2017/18 was 1444.10 MW and the projected peak demand for fiscal year 2018/19 is 1508.16 MW. Out of total annual peak demand of 1444.10 MW of 2017/18, 2,305.45 GWh was generated by NEA itself, 2,175 GWh and 1,777.24 GWh was purchased from India and IPPs, respectively [4]. In Nepal, more than 83% of people live in rural areas [5]. Due to various difficulties like sparsely settled population, geographical variations, illusive electricity development strategy, poor transportability, lack of enough capital and fragmented settlements, it has been a to meet the energy demand of Nepal [6].

To solve this electricity deficiency problem in Nepal, mostly in the rural context, the Government of Nepal (GoN) has introduced the production and distribution of contextual renewable energy technologies. In Nepal, to date, there is no dedicated policy for rural electrification. Rural Energy Policy 2006 and other sector policies and acts make several provisions for access to modern energy sources and electrification of rural areas in the form of an open statement with no fixed time-bound targets and action plans. Outcomes of these provisions are not monitored and analyzed to find their effectiveness for further improvement [7].

The study outlines basically two aspects of the energy sector in Nepal. Firstly, it analyzes the gap between national generation and the peak load, which is being balanced by external and internal power purchases. Further, analysis of the impact of increment of per capita GDP (GDP) on electricity per capita (EPC) has not been researched. Thus, the article has analyzed the same through econometric modelling. Secondly, the research analyses the pertinent policies supporting electricity generation in Nepal and the major barriers affecting the promotion of renewable energy technologies. Numerous factors based on a review of available resources have been pertinent in identifying the current scenario of the energy policy & provisions. EPC and GDP have been considered as dependent and independent variables and analysis of the review have been carried out through regression analysis. The analysis is done over time series data of 10 years to trace the level of impact of GDP on EPC. The objective of the research is focused on tracing the policy barriers that have led to the current pullback of renewable energy promotion in Nepal despite the government's declarations of firm interest in it. The method was to trace interlink of energy development and the policy provisions for clear know-how of the influential policy barriers impacting the development of renewable energy in Nepal. Semi-structured interviews, formal and informal meetings, focus group discussions, secondary data collection from literature reviews and the current energy policies remained the source of data for further analysis. Necessary energy data has been collected from different government agencies such as Centre of Bureau of Statistics (CBS), NEA, Ministry of Energy, Water Resources and Irrigation (MoEWRI), Alternative Energy Promotion Centre (AEPC). Further relevant peer-reviewed journal articles, reports and websites of various national and international agencies were selected to represent central government, renewable energy technology manufacturers, individual power producers, I/NGOs, academicians, and other experts. Qualitative research and analysis have been done referring to the relevant energy policies ensuring no single interaction was considered in isolation. The analysis of energy scenario backed up with prominent energy policies followed by the analysis of the impact of GDP on EPC through regression analysis inhabits the thrust of the article.

2. Energy sector in Nepal

2.1. Renewable energy scenario.

Nepal's energy sources have been characterized as (i) traditional, (ii) commercial and (iii) alternative energy sources. Alternative energy is identical to renewable energy sources. This categorization is based on the use of resources in extracting the energy contents from the sources. The traditional source of energy includes biomass fuels, particularly fuelwood, agricultural residues, and animal dung. These sources of energy are used in direct combustion traditionally. Whereas traditional energy sources are further transformed into modern types. Fossil fuel and hydropower fall under commercial sources of energy. Solar power, wind power, micro-hydro, bioenergy resources fall under the category of alternative energy sources. Despite Nepal's huge potential for hydropower production, its exploitation is very below than optimal. This is the main reason behind the maximum exploitation of traditional energy resources such as biomass. This massive exploitation has augmented the depletion of natural resources and finally acting as a major cause for the degradation of the environment. Biomass dominates the overall energy supply and consumption in Nepal. Figure 1 shows the total energy supply and their share of energy consumption by fuel types in Fiscal Year 2014/15 [2].

Figure 1 shows the breakdown of Nepal's energy consumption scenario by fuel types for the fiscal year when the total energy consumption remained around 500 million Giga Joule (GJ). Out of total energy consumption, fuelwood is the largest energy resources and occupies about 70.47% of total energy demand. Other sources of bio-masses were agricultural residues and animal dung, which contributed about 3.48% and 3.68%, respectively. Petroleum fuels in the total energy system occupy about 12.53%. Other sources of commercial energy are coal and electricity from hydropower, which contributed about 3.97% and 3.39% respectively in the total energy supply. In aggregate, the share of traditional fuel is 77.63%, commercial fuel (coal, petroleum, and electricity) is 19.88 % and renewable (Solar, Biogas, Micro-hydro, Wind) is 2.49% [2].

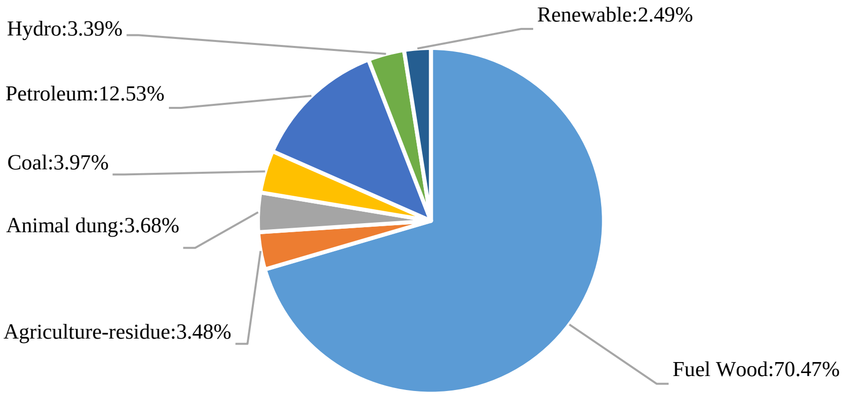

Figure 1. Nepal's energy consumption scenario by fuel types in 2014/15 [2]

This shows that, in the Nepalese context, traditional fuel is dominant with huge potential of hydro yet to be harnessed to meet national energy demand. Alongside, there is a threat of increased import of commercial fuels.

2.2. Electricity trend analysis.

In the history of nearly 108 years of hydropower establishment starting from Pharping Hydro Power Project in 1911 AD, only little more than 1000 MW of hydropower is being generated in the country [4-7].

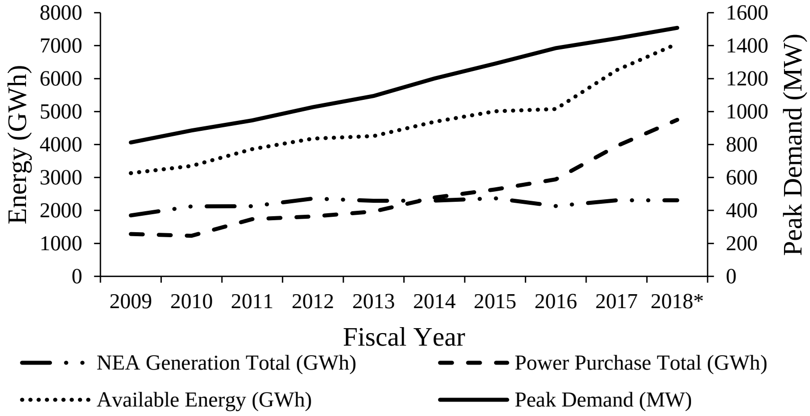

Figure 2. The total energy available and peak demand [4]

In this article, the electricity trend in Nepal for the last 10 years has been reviewed as presented in Figure 2. More specifically, Figure 2 shows annual electricity generated from NEA, purchased from IPPs, imported from India and the annual peak demand for the period of 2009 to 2018. The figure 2 shows almost linear electricity generation of NEA (including IPPs) against the steep gradient of peak power demand has ultimately increased the power purchase from India. Until now, NEA has been importing electricity from India to meet the gap. To meet the gap, power purchase is ever increasing, as reflected in Figure 2. The overall available energy since 2009 follows the increasing trend. The electricity demand may be full-filled by grid extension in case of densely populated areas and by stand-alone systems for sparsely populated areas [8]. Literature has also traced that increased import of commercial fuel has decreased consumption of traditional fuel despite its abundant availability [9]. Increased used of traditional fuel and renewable energy contributes to reducing greenhouse gas emissions providing institutional arrangements to energize clean development mechanisms [10]. But in contrary, Nepal seems to be moving in the opposite direction by increasing import of commercial fuel and decreasing use of traditional fuel.

2.3. Regression analysis.

The regression analysis of electricity per capita (EPC) over GDP per capita (GDP) has been conducted to trace the impact on EPC for increment on GDP. GDP gives a country's economic output, which accounts for the total population. In other words, it gives the prosperity of the people of that country whereas EPC is the unit (kWh/year) of electricity consumed by one person of that country averaging the whole population of the country. Electricity per capita usage is often considered as a key indicator of development. Nepal, as one of the least developed countries its EPC, which is 244 kWh/year is far less than the global average energy per capita [11]. Low EPC has found a direct impact on the country's economy and development [12]. Thus, this article has further analysed the impact of GDP on EPC through a regression analysis where EPC is a dependent variable and GDP is an independent variable. The econometric model for the regression analysis is developed as follows:

$$EPC = \alpha + \beta\ GDP + e \quad (1)$$

The regression analysis gives the following output:

Table 1. Regression analysis of GDP on EPC.

Variables	Constant (**α**)	Coefficient. (**β**)	SEE	F-value	Adj-R^2
GDP	-28.18 (-1.43)	0.27*** (10.21)	0.03	104.31***	0.92

***** significant at 1% level of significance*
(...) Parenthesis values are t-stat

Table 1 shows a positive and significant relationship between GDP per capita and electricity per capita. This reveals that one-dollar increase in GDP increases 0.27 kWh consumption of electricity. The Adj-R2 shows the goodness of fit of the developed model; this indicates that the GDP explains 92% of the variation in consumption of electricity. The modeling indicates that higher the GDP per capita, higher would be the consumption of electricity.

2.4. Energy policies in Nepal.

To regulate energy projects and industries in Nepal, the government has formulated numerous policies, acts and regulations. Currently, the Nepalese government and the policymakers are exploring the hybrid models and promoting off-grid renewable energy and mini-grid models [13]. Considering that the current Nepalese energy plans and policies will be implemented effectively, it is likely that current and future electricity demand of Nepal is fully met. In the given energy context of Nepal, existing Nepalese energy policies and provisions which remain appropriate in promotion of the overall energy sector have been summarized with specific policy concentration is given below in Table 2.

Table 2. Nepalese existing policies and provisions [14-21].

SN	Policy Provisions	Policy Concentration
1	Nepal Electricity Authority Act, 1984	NEA Act 1984 created scope to manage activities related to electricity generation and distribution in the country.
2	Water Resources Act, 1992	Water Resources Act, 1992 expedite the scope for the balanced utilization and conservation, of water resources in the country.
3	Hydropower Development Policy 1992 and 2001	Hydropower Development Policy 1992 and 2001 encourages the private sector investment through various fiscal and other incentives for the development of hydropower in the country.
4	Electricity Act 1992 and 2001	Electricity Act 1992 and 2001 provides legal arrangements to endorse Hydropower Development Policy 1992 and 2001.
5	Local Self-Governance Act, 1998	Local Self-Governance Act, 1998 provided local authority for the formulation, implementation, distribution and maintenance of mini and micro hydropower projects.
6	NEA Community Electricity Distribution Bye-Laws, 2003	NEA Community Electricity Distribution Bye-Laws, 2003 provided opportunity for community electrification through country and community participation.
7	National Water Plan 2005	National Water Plan 2005 is the only document with a time-bound target for rural electrification.
8	Rural Energy Policy 2006	Rural Energy Policy 2006 has provisioned for rural energy and electrification activities in rural areas through Renewable Energy Technologies (RETs).
9	Renewable Energy Subsidy Policy 2000-2016	Renewable Energy Subsidy Policy 2000-2016 has provisioned for a direct financial subsidy to off-grid electrification in rural areas.
10	RE Subsidy Delivery Mechanism for Special Program 2018	RE Subsidy Delivery Mechanism for Special Program 2018 has provisioned in subsidy for special renewable energy programs.
11	National Energy Efficiency Strategy 2018	National Energy Efficiency Strategy 2018 has a national target of energy efficiency in Nepal, which is to double by the year 2030 A.D.

The study has analyzed the existing pertinent energy policies as listed in table 2. The study has further tried to relate the role of energy-related policies and trace its impact and the implications on electricity generation. The study shows that in Nepalese context, institutional coordination and synergies of energy policies with the institutional coordination is vital for its better implementation [22]. The research has shown that policy intervention has significant roles in removing market barriers [23]. Meaning, proper policy interventions in the energy sector could also mitigate the existing barriers and move towards higher electricity generation. The research has also analyzed renewable energy policies and has suggested some definite models reduce various burden and barriers for adoption of the same [24]. Such implementation has forecasted to increase the use of renewable energy as well. Research over-evaluation of renewable energy policy has revealed that better policy interventions increase the total amount of electricity generation [25]. Research has also concluded that the regular performance of different energy policies instruments the dissemination of new energy technologies [26]. In US evaluation of energy policies has shown that polices ultimately reduces the financial burden for the energy technologies and make them adaptable. In the meantime, improper policies being implemented has also harmed the sustainable economy of the country. Thus renewable energy policies should focus on energy efficiency, improving energy structure and reshaping energy industry [27]. Other researches have also shown a positive implication over the adoption of various renewable energy technologies [28,29].

In a nutshell, the analysis of various renewable energy policies shows that better policies always have a positive impact on the adoption of existing energy technologies as well as reflect positive impact over electricity generation. In the Nepalese context, there might be numerous reasons behind the gap in the generation and the demand, but policies show a significant impact on it. Based on this evidence and current electricity scenario of Nepal, it is claimed that Nepalese energy policies are not up to the optimal, else the gap would not have been visible.

3. Barriers of the energy sector in Nepal

Based on the literature, formal and informal consultation with experts, focus group discussions and interviews, various relevant barriers for promotion of energy sector in Nepal has been traced [30]. Relevant literature has been analyzed [9,31,32]. Based on such primary and secondary data collection and subsequently followed analysis, the position of the power sector remains unsatisfactory because of high tariffs, high system losses, high generation costs, high overheads, overstaffing, and lower domestic demand. Based on the status of the energy sector of Nepal, following three major thematic barriers are identified for promotion of energy sector in Nepal has been concluded to be the most prominent ones.

3.1. Technical Barriers.

In the case of remote areas in underdeveloped and developing countries like Nepal, grid connection often is technically prohibitive. Due to this technical issue, an alternative model has been evolved with the maturation of contextual stand-alone energy systems [32]. Such stand-alone systems generate energy locally facilitating the supply of local energy demand. By the passage of time, communities are switching energy sources from traditional to modern/commercial. Depending upon available renewable energy sources communities are using improved cookstoves (efficient use of traditional fuels), micro or pico-hydro, small wind energy systems, solar photovoltaic, etc. These modern renewable energy systems are environment-friendly and technically matured alternatives for grid expansion, even at an economical rate [31]. But grid integration of electricity generated from such off-grid technology has been successful just in pilot-scale and full fledge implementation of grid integration has remained as a major technical challenge for maturation in Nepal.

3.2. Economical Barriers.

Renewable energy (e.g. sun, wind, water, etc.) is abundantly available and applicable in the stand-alone system, which is the reason for it to be a better option for energy access where grid extension is not feasible. Solar home system (SHS) has contributed to more than 3 million households for energy access [32]. Clean electricity is the core of attraction for utilization of SHS for lighting. Depending upon the size of SHS, its use can be further expanded towards utilization for other modern technologies like telecommunications. The high upfront cost of stand-alone systems like solar PV and wind turbine along with battery backup has always remained as a common issue throughout the world. However, the high upfront cost is a barrier for grid electrification/extension as well. In countries like Nepal with difficult geographic terrain and low population density, stand-alone systems for energy access could be a better alternative. Stand-alone systems could ensure energy access not only for such sparsely settled population but also for various community entities like health posts, schools, community centres, and micro-business enterprises [33]. Despite these possibilities for energy access for rural communities through stand-alone systems, it is difficult for the rural dwellers to manage the high upfront cost for energy access. Additionally, these small stand-alone systems could mitigate lighting issues at the micro-level. But macro-level energy access and planning, which could possibly support rural enterprises and access a higher level of energy access (Tier wise) always come with economic barriers for underdeveloped countries. Thus, an economic barrier has remained as another pertinent barrier to the development of macro-scale renewable energy technologies in Nepal.

3.3. Geographical Barriers.

Nepal is a country with most of the land in the hilly and mountainous region followed by a sparsely settled population. To ensure energy access to all those regions has always remained a major issue for the Nepalese government. Thus, geographical barriers for development to maturity of the energy sector in Nepal is one of the most challenging barriers for the long run.

The literature and the discussion above witness the existence of various issues and barriers for rural electrification and the promotion of renewable energy systems. Economical, technical and geographical are the major issues and barriers for renewable energy system promotion in Nepal.

4. Conclusion

Plenty of opportunities for the development of energy technologies in Nepal exists through numerous policy and provisions. The Nepalese government has given high priority for the upliftment of the overall energy sector through White Paper 2018 an Energy Efficiency Strategy, 2019 as the latest policy provisions. Barriers to the development of the energy sector based on literature review and formal and informal interactions have been presented in the article. The article has ultimately traced technical, financial and geographical as the most important barriers to be addressed to meet the ambitious target of 15000 MW in the next 10 years as put forward in White Paper 2018. Several advantages and positive features have been highlighted against each policy provisions along with the limitations. Existing energy sector policy provisions seem challenging to meet the government target on time. The study has concluded the existing polices being not optimal has led to almost linear electricity generation of NEA (including IPPs) against the steep gradient of peak power demand. The trend analysis of energy scenario of Nepal shows that the Government of Nepal (GoN) should emphasize on electricity production as the electricity demand is continuously increasing. Further, the regression analysis reveals a positive and significant relationship between GDP and EPC. Thus, it is recommended that higher the GDP per capita, higher would be the consumption of electricity, highlighting the fact that GoN should prioritize to increase its per capita income.

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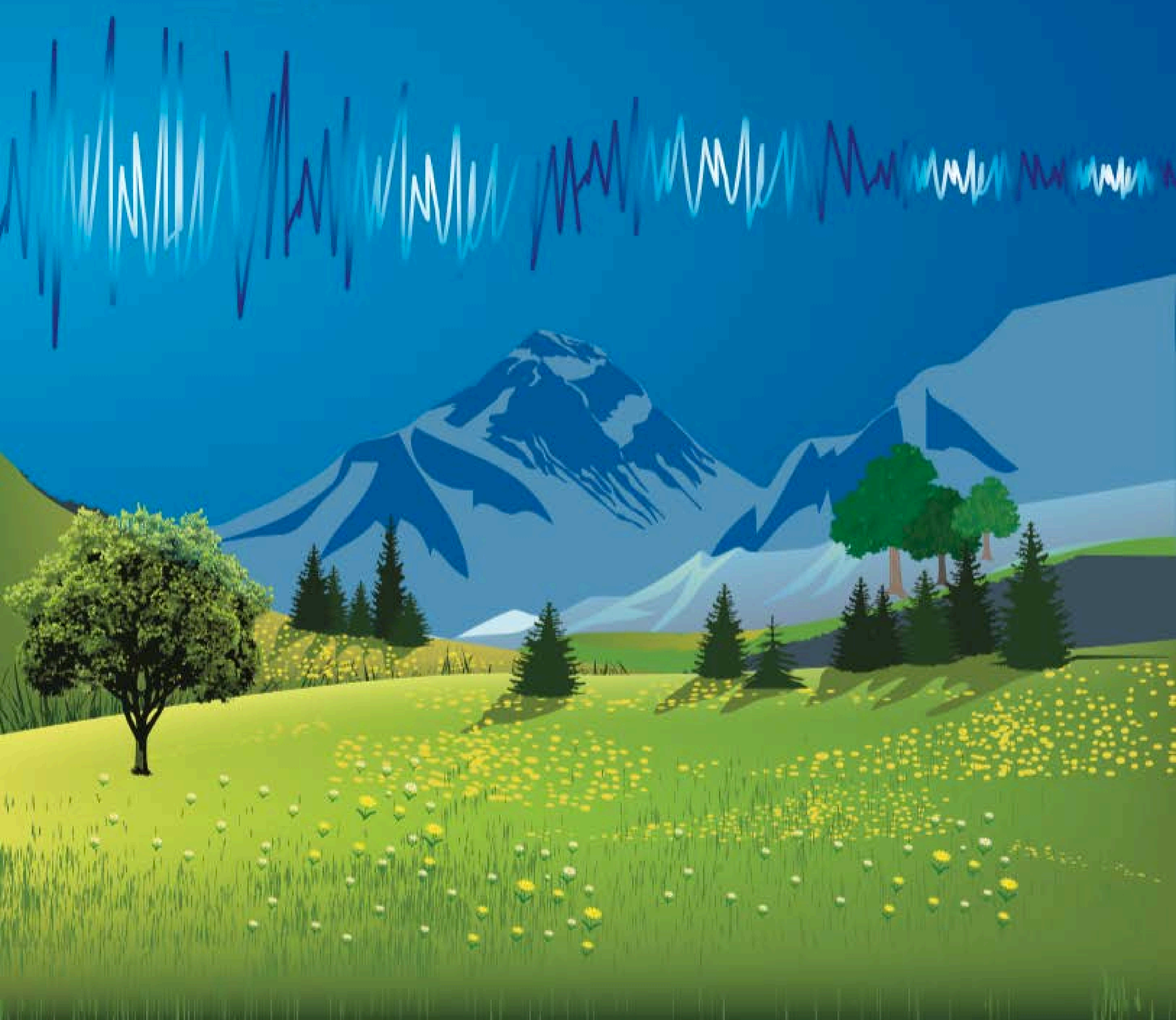

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A review of renewable energy sector of Nepal

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Abstract

The article presents the brief overview of current energy scenario including electricity potential, generation and the peak demand in Nepal. Nepal being a developing country, electricity demand is increasing in high rate. Slope of peak demand is 80 whereas slope of national electricity generation is 33. The given gap in slope is increasing the electricity import from India. The electricity demand has been triggered by increasing GDP in recent years. Out of total energy consumption, traditional fuel types have remained dominant but is slightly (by 5.6 percent) being transferred to commercial, whereas commercial energy consumption has been increased by 5.9 percent. Various national level hydropower projects are being planned and implemented under ownership of government as national pride projects to meet the rapid increase in electricity demand. To cope up with the barriers and challenges of the energy sector, Government of Nepal (GoN) has made various policy and provisions like, White Paper 2018, Renewable Energy (RE) Subsidy Policy, Biomass Energy Strategy 2017, Energy Efficiency Strategy 2018 and segregation of hydro power projects as national pride projects under Ministry of Energy, Water Resources and Irrigation (MoEWRI) which are expected to play a crucial role to enhance energy access and sustainable development of Nepal.

Keywords: renewable energy, electricity generation, policy provisions

1. Introduction

Nepal poses a significant gap between electricity generation and the demand. As per recent report published by Nepal Electricity Authority (NEA) in 2018, peak power demand of Nepal in 2017 is 1444 MW, more specifically, it has been recorded up to 1508 MW (*Annual Report NEA*, 2018) . In general, Nepal has electricity shortage of nearly 400 MW and to full-fill this demand, electricity has been imported from India since long back. The electricity import from India has been gradually increased from 2009 (356 GWh) to 2017 (2175 GWh) (*Annual Report NEA*, 2018). Gross Domestic Product (GDP) of Nepal of Fiscal Year (F/Y) 2017/18 has remained 6.66 percent and has been forecasted to be 7.05 percent in F/Y 2018/19 (CBS, 2013)(Ministry of Finance, 2018). Increasing urbanization of Nepal fueled up by the economic growth has created a huge demand of energy. The trend is very similar with other developing countries like Bangladesh, Pakistan and Vietnam (Islam & Khan, 2017)(Minh Do & Sharma, 2011)(Duc Luong, 2015)(Rauf, Wang, Yuan, & Tan, 2015).

Nepal is an under developed country with nearly 80 % of total population residing in rural areas (CBS, 2012)("Nepal Rural Population Percent Of Total Population," n.d.). Nepal's energy sources have been categorized as traditional, commercial and alternative (*Government of Nepal Water and Energy Commission Secretariat Electricity Demand Forecast Report*, 2017)(Pokharel, 2007). An alternative energy is synonymous with new, renewable and non-conventional forms of energy. Traditional source of energy includes biomass fuels particularly fuel wood, agricultural residues and animal dung used in the traditional way through direct combustion. Commercial sources of energy are fossil fuels and electricity. Alternative sources of energy include micro hydro, solar, wind power, biogas and briquettes etc. Biomass, hydropower and solar are the three major indigenous energy resource bases in the country (*Government of Nepal Water and Energy Commission Secretariat Electricity Demand Forecast Report*, 2017)(Pokharel, 2007).

Nearly 10% of Nepal's population have no energy access ("Access to electricity (% of population) | Data," n.d.). Out of total energy access, reliability has always remained an issue especially among those who have energy access through off-grid renewable energy technologies (RETs). Furthermore, energy demand has been increasing with nearly 7-9 % (*Nepal energy sector asssessment, strategy, and road map*, 2017) against almost stagnant electricity generation (*Annual Report NEA*, 2018). Thus, to improve the situation, government of Nepal (GoN) needs regularly revision of its energy policies and programs. In the subsequent sections, the article thus explains about electricity generation, peak demand and renewable energy scenario and recent policy interventions of GoN.

2. Hydro-electricity potential, generation and peak demand

As shown in figure 1, hydro-electricity generation in Nepal has been almost stagnant with slope of 33 and peak demand has been steep with gradient of 80. The gap is ever increasing in an unsustainable way and the gap is being somehow managed with import from India and the necessary power cuts in last few years.

2.1 Hydro-electricity potential in Nepal

Nepal has tremendous hydropower potential("Nepal | International Hydropower Association," n.d.). Though long disputed, various literature has backed up the most entrusted theoretical and economical hydropower potential to be 83 GW and 42 GW respectively as shown in Table 1.

Table 1. Basin wise hydropower potential in Nepal (Pokharel, 2001)(Sharma & Awal, 2013)

River basin	Annual flow (billions of m^3)	Catchment area (km^2)	Theoretical value (GW)	Economically feasible (GW)
Karnali and Mahakali	49	47300	36.18	25.1
Sapta Koshi	33	28140	22.35	10.86
Sapta Gandaki	50	31600	20.65	5.27
Southern Rivers	42	5410	4.11	0.88
Total	**174**	**112450**	**83.29**	**42.11**

Out of 42 GW of economically feasible hydropower potential in Nepal, as of now only 981.7 MW has been installed, but much more to come in near future(*Annual Report NEA*, 2018).

2.2 Electricity generation and the peak demand

Electricity generation for the period of 2009 to 2017 with provisional figure for 2018 has been tabulated in Table 2.

Table 2. Nepalese energy generation and the peak demand for the period of 2009-2018 (*Annual Report NEA*, 2018)

Particulars	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018*
Peak Demand (MW)	**812**	**885**	**946**	**1027**	**1095**	**1201**	**1291**	**1385**	**1444**	**1508**
NEA Hydro Generation (GWh)	1839	2109	2122	2357	2273	2288	2367	2133	2305	2308
NEA Thermal Generation (GWh)	9.0	13.0	3.4	1.5	18.9	9.6	1.2	0.08	0.28	0.1
NEA Generation Total (GWh)	**1849**	**2122**	**2125**	**2359**	**2292**	**2298**	**2368**	**2133**	**2305**	**2308**

As shown in Table 2, peak electricity demand in 2017 has remained to be 1444 MW. Whereas, out of 6258 GWh of total energy available (NEA hydro generation and NEA thermal generation), NEA has generated 2305 GWh, 1777 GWh has been purchased from independent power producers (IPPs) and 2175 GWh has been imported from India(*Annual Report NEA*, 2018). Nevertheless, Nepal has tremendous hydro potential with more than 6000 perennial rivers and rivulets with an average annual flow of 174 billion m^3 as shown in Table 1(Pokharel, 2001). Furthermore, to observe the trend of energy generation and the peak demand of Nepal, electricity generation in Nepal during the period of 2009 to 2018 has been plotted in Figure 1 (*Annual Report NEA*, 2018). The figure shows the huge gap between energy generation and the peak demand. As per latest report published by NEA in 2018, out of total electricity generated, hydro plays the dominant role with very minimal from thermal power plants (*Annual Report NEA*, 2018). But low energy access and increasing energy demand has not been full filled by NEA electricity generation. The trend and the gap can be observed from the figure 1. The total number of Individual Power Producers (IPPs) owned 75 projects in operation has combined installed capacity of 512.7 MW, whereas combined installed capacity of NEA projects is only 469 MW (*Annual Report NEA*, 2018). Additionally stated owned multifuel plant of installed capacity 39 MW and diesel plant of installed capacity 14.4 MW combines to total installed state owned installed capacity of 522.7 MW (*Annual Report NEA*, 2018). As per latest NEA report, peak demand of electricity is ever increasing and has been recorded to be as high as 1508 MW in 2018 with increasing slope of more than 80%.

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3 Off-grid renewable energy scenario in Nepal

Of the total energy consumption of 8,257 Tons of Oil Equivalent (ToE) in the first eight months of the FY 2016/17, the proportion of traditional, commercial and renewable energy consumption in the total energy consumption was 74.5 percent, 22.0 percent and 3.5 percent respectively, whereas in the corresponding period of the FY 2017/18, this proportion is 68.9 percent, 27.9 percent and 3.2 percent respectively, and commercial energy consumption has increased by 5.9 percent as depicted in Table 3 (Ministry of Finance, 2018)("Ministry of Energy, Water Resources and Irrigation :: Government of Nepal," n.d.).

Table 3. Fuel consumption percent of Nepal by its types (Ministry of Finance, 2018)("Ministry of Energy, Water Resources and Irrigation :: Government of Nepal," n.d.)

Fuel Type	**Consumption percent**	
	FY 2016/17	**FY 2017/18**
Traditional	74.5	68.9
Commercial	22	27.9
Renewable Energy	3.5	3.2

Two years data from table 3 shows, out of total energy consumption, traditional fuel types have remined dominant but is slightly (by 5.6 percent) being transferred to commercial. Such energy consumption practice is increasing Nepalese dependency over commercial fuel type or import. Characteristics of Nepal's energy consumption is small, inefficient and is largely dominated by traditional fuel (Ministry of Finance, 2018).

Nepal has very good potential for solar and hydro energy as an alternate source of energy. These renewable energy technologies like solar and micro hydro can play a crucial role to increase energy access in a country like Nepal with unique geography of sparsely settled and low population density (CBS, 2012).

3.1 Solar PV

Nepal lies in solar belt and has an average of 3.9 – 5.1 kWh/day/m^2 of solar insolation with nearly 300 days of sunshine per year ("Alternative Energy Promotion Centre," n.d.). Various studies have strongly recommended to resolve the environmental, economic, ansd energy issues by utilizing solar energy, though less explored (Adhikari, Gurung, & Bhattarai, 2014). Research on feasibility of grid connected solar PV and research on roof top solar PV has also assessed a similar energy potential in Nepal (Nawaraj, Malesh, Alex, & Muniraj, 2009)(Chianese et al., n.d.). As of now, nearly 12 MW of solar PV has been installed as solar home systems in Nepal (Ranabhat & Khadka, 2018)("Alternative Energy Promotion Centre," n.d.). The largest planned solar energy project is of 120 MW in Dhalkebar in Mahottari district. Solar project of 25 MW capacity is under construction since 2018 in Nuwakot district. Department of Electricity Development (DoED) has approved survey license for 21 locations to install 56 solar plants which could have a combined solar capacity of 317 MW. Thus, increasing trend of solar energy power plant installations in Nepal will play a crucial role to enhance energy access in both rural and urban areas.

3.2 Micro hydro power

Micro hydropower was initiated during the decade of 1960s in Nepal and still pose a very good source for electricity supply in a hilly country like Nepal with sparsely settled population. To date there are nearly 3300 micro hydro power plants installed in Nepal("Nepal Micro Hydropower Development Association," n.d.). Those micro-hydro has cumulative installed capacity of 30 MW ("Nepal Micro Hydropower Development Association," n.d.). Nepal has the potential of developing more than 50 MW of electricity from MHP schemes (Gurung, Gurung, & Oh, 2011). Micro hydropower plant has been very successful model in earlier phase, whereas they are facing various issues and challenges recently ("Renewable Energy for Rural Livelihood | UNDP in Nepal," n.d.). Like solar PV, micro hydro power plants have remained to be very effective solutions for rural and sparsely settled communities of Nepal.

4 Recent renewable energy policy provisions

Recently, GoN has made some specific policy and some provisions to uplift the energy sector, enhance energy access through clean and reliable source of energy.

4.1 Renewable energy (RE) policy 2006 (Government of Nepal, 2006)

The RE policy was been introduced in 2006 to promote off-grid RETs, specially focused for rural areas of Nepal. The efforts of RE policy has made possible to provide energy access to about 40

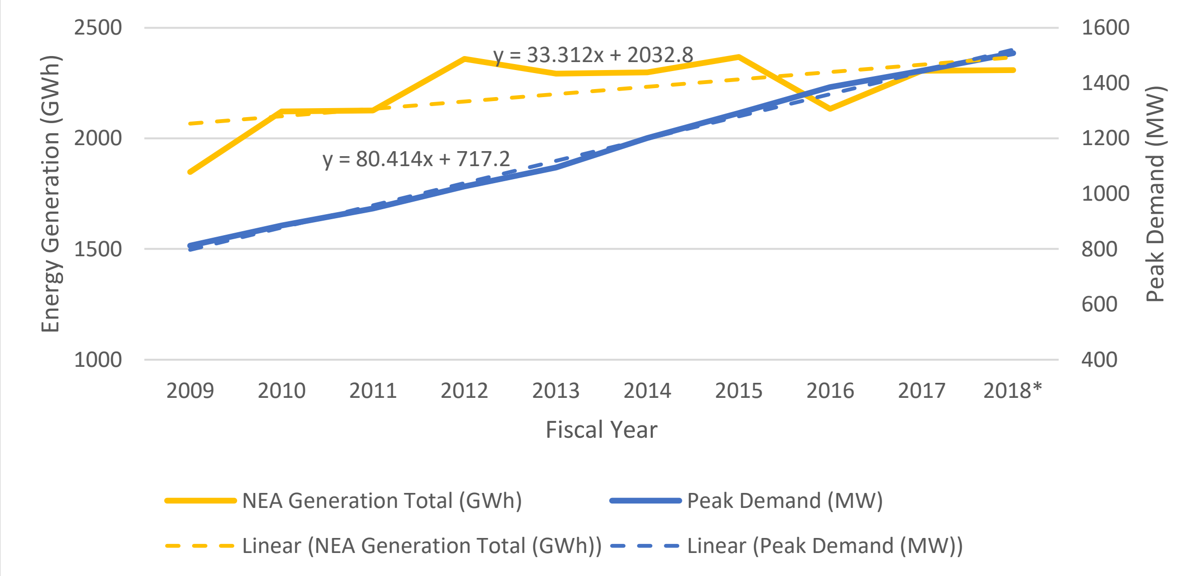

Figure 1. Trend of total energy generation and peak demand of Nepal

percent of the population in the country. Rural population in Nepal was reported to be 81% in 2016("Nepal Rural Population Percent Of Total Population," n.d.). In those rural areas, nearly 15% of the population has access to electricity("Nepal Rural Population Percent Of Total Population," n.d.) and the RE policy has target to ensure energy access for those rural population.

4.2 Status and future course of energy, hydropower and irrigation sector *(Government of Nepal, Energy, Water Resources and Irrigation, White paper 2018)*

The Ministry of Energy, Water Resources and Irrigation published a White paper in 2018 giving an overview of the current performance and future regarding the Energy, Water Resources and Irrigation sector. The paper has given high priority for under construction hydro power projects. The White paper focuses on 'Decade of energy and hydropower, 2018-2028'. The concept of 'energy decade' has been taken ahead to expedite energy production in a short-term, medium-term and long-term strategic manner. Under this provision, GoN has set target of 5000 MW in next 5 years and 10000 MW in next 10 years. Such strong commitment of GoN shows clear priority in energy sector and its needs.

4.3 Biomass Energy Strategy, 2017 (*Government of Nepal Ministry of Population and Environment Biomass Energy Strategy 2017*, 2017)

To promote sustainable supply of biomass energy available from animal waste, human excreta, fuelwood, agricultural residue, trees, forest residues including any biodegradable matters and to improve the efficient use of such biomass energy, the government of Nepal has developed and adopted the Biomass Energy Strategy 2073.

4.4 National energy efficiency strategy, 2018 (*National energy efficiency strategy, 2075*, n.d.)

This strategy has been prepared for the promotion of energy efficiency and demand side management of energy, energy conservation for the sustainable development of primarily modern and improved energy sources including hydropower, solar energy, wind energy, coal, natural gas, LPG and other petroleum products except biomass energy (which is also called traditional energy).

5 Discussion

The article has reviewed the energy scenario of Nepal. The article has traced the recent energy choice being transferred from traditional energy type to commercial energy type. This switch in energy choice has burdened energy sector with increasing import which is ultimately increasing national dependency over import. The ever increasing (during 2009-2018) import from India is a result of almost stagnant national electricity generation. Considering other factors constant, national hydro power and energy policy has been concluded to be a pertinent reason for almost constant electricity generation. However, recent energy policies and GoN's commitments as discussed should have positive impact in electricity generation with increasing slope.

6 Conclusion

The article reviews and discusses current scenario of RETs and the policy provisions in Nepal. Traditional fuel has always remained dominant in fuel consumption as of now and the recent trend shows that fuel consumption type is slightly being deflected towards commercial. Such deflection is increasing fuel dependency and the import, which has significant impact in GDP as well. The article also discusses the potential of hydropower and other off-grid technologies. To minimize the dependency, GoN has prioritized renewable energy sector (hydropower and off-grid technologies) through various policy provisions like, White Paper 2018, RE Subsidy Policy, Biomass Energy strategy 2017, Energy Efficiency Strategy 2018 and segregation of hydro power projects as national pride projects under MoEWRI. Despite earlier policy, share of renewable energy has remained only 3.5 percent. Thus, contextualized policy provisions are expected to increase generation and use of renewable energy and ultimately dependency of commercial fuel will be decreased. Off-grid renewable energy technologies will have an important role in providing reliable electricity supply in country like Nepal with low population density.

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Analytical modelling for optimized selection between renewable energy systems and the conventional grid expansion

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Analytical modelling for optimized selection between renewable energy systems and the conventional grid expansion

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Abstract -The study aims to present the analysis of Economic Distance Limit (EDL) of conventional grid extension and some renewable energy systems for Gorkha District based on Life Cycle Cost (LCC) analysis. The study is an attempt to prepare a framework for the evaluation of a least cost electricity master plan which may be applied to other districts in future. An analytical tool has been followed to carry out the least cost electrification planning. The least cost planning has been done for the load forecast for the 5th year, which is 965 kW in aggregate. Accordingly, to meet this demand, it has been assumed that there will be 40 numbers of 25 kVA transformers feeding the settlements in the study Village Development Committee (VDCs), and an alternative option of electrifying these villages will consist of 40 Micro-Hydro Power plants (MHPs) of 25 kW capacities each. The result shows that extension from the existing grid points up to additional 22.41 km (economic distance limit, or EDL) is more economical than supplying through the installation of MHPs. A similar comparison was attempted with grid vs commercial scale solar photovoltaic (PV) for a theoretical load of 25 kW; the EDL for grid-extension has been worked out to be 47.96 km with battery storage. Furthermore, the costs of low voltage lines have not been included in comparison assuming they are common costs to both options. Reliability from the grid supply, MHPs and commercial solar PV has been assumed to be similar.

Keywords: Rural electrification master plan, Life cycle cost, Economic distance limit

1. *Introduction*

1.1 Background
Nepal has enormous potential of energy resources to its area and population (83,000MW hydro, 2100MW Solar, 3000 MW wind), whereas per capita energy consumption is one of the lowest in the world only 14.8 GJ. About 87% of the total energy requirement (401 million GJ) is met from traditional fuels i.e. fuel wood 77%, agri-residue and the animal waste 9% [1][2]. Despite of the abundant energy potential, Nepal is experiencing an electricity crisis. The annual peak power demand

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of Nepal in 2017 was 1444 MW and is anticipated to be 1508 MW in 2018 [3][4] but the system is unable to meet about 400 MW needed during the winter peak. To meet the gap, Nepal is importing nearly 400 MW (1,777 GWh in 2016, 2,175 GWh in 2017 and 2581 GWh has been anticipated to import in 2018] [5][3].. Out of 1444 MW of peak demand as of 2017/18, 2,305 GWh has been generated by NEA itself, 2,175 GWh and 1,777 GWh has been purchased from India and IPPs respectively [4].

The state-owned Nepal Electricity Authority (NEA) is responsible for the electricity supply through the national grid. The access to electricity is low with only 65% of the country's households having access to electricity (56% through the national grid and 9% through off-grid solutions). Per capita electricity consumption is 102 kilowatt-hours (kWh) per year, one of the lowest in the world. Nepal's residential consumption is 83% and non-residential use is 17%. Nepal's access to electricity and per capita consumption is lower than the 2010 average global access rate of 83% and average global consumption per capita of 685 kWh. Especially in the rural access, there is no access to electricity, hampering both economic development and access to information and education [6]. According to estimations of the NEA, energy demand grows yearly with an average annual rate of 9 %. Because of increasing household consumption, the evening peak demand has risen dramatically. Due to the continuously rising demand and stagnation in creating additional power generation capacities, a noticeable shortage of power supply since 2007 has been the consequence. The yearly demand is expected to exceed 17,400 GWh by 2027. Along with the growing demand, it is projected that system peak load will increase with similar annual growth rates, reaching 3679 MW in 2027. To address these electricity problems, comprehensive energy master planning is essential, and this research is an attempt for the same.

1.2 Literature review

Network Planner has been used to estimate investment costs and financing requirements to support electrification programs and identify opportunities for cost-effective grid expansion in Kenya [7]. The model can be used to rapidly estimate connection costs and compare different regions and communities. Inputs that are modeled include electricity demand, costs, and geographic characteristics. The penetration rate, an exogenous factor chosen by electricity planners, is found to have a large effect on household connection costs, often outweighing socio-economic and spatial factors such as inter-household distance, per household demand, and proximity to the national grid [7]. A study to identify potential areas in India where the provision of electricity through renewable energy-based decentralized generation options can be financially more attractive as compared to extending the grid [8]. The cost of generation of electricity from coal, hydro and nuclear power plants are also cost of transmission and distribution of electricity in the country have been estimating. The study indicates that renewable energy-based decentralized electricity supply options could be financially attractive as compared to grid extension for providing access to electricity in small remote villages.

The cost of grid electricity to the end-user compared with the cost of electricity from decentralized energy systems to obtain the specific distances from the grid, the level of demand and the load factor conditions under which using decentralized energy systems for rural India makes economic sense has been analysed [9]. The paper finding is that for small and isolated villages with low load factors, decentralized energy technologies make economic sense. A similar study has been conducted by USAID for Zambia rural electrification [10]. An analytical model for choosing between conventional grid extension and off-grid solar photovoltaic, biomass gasifier-based power generation for remote village electrification has been conducted [11]. The model provides a relation between renewable energy systems and the economical distance limit (EDL) from the existing grid point, based on life cycle cost (LCC) analysis, where the LCC of energy for renewable energy systems and grid extension will match. The research was found to be most relevant for the purpose, and analytical method followed in this study in identifying the optimal choice among the electrification options based on renewable energy sources and the grid is based on this literature [8] [11]. This article studies the EDL

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based on LCC for renewable energy systems compare it with grid-extension for Gorkha district. Further, the model can be implemented in other similar districts and the communities.

1.3 Gorkha district

The energy planning research has been conducted for Gorkha district as a case study based on secondary data available. Out of 67 VDCs in the Gorkha district 41 VDC's[1] have been electrified through grid completely or partially. Load forecast is carried out for 17 VDCs north of the currently grid-electrified VDCs. The 9 VDCs further north have not been considered, as they are sparsely populated precluding economic justification for grid electrification.

2. Analytical model

2.1 Modelling using analytical method

Modelling using spatial planning tool such as Network Planner is now widely practiced in rural electrification planning, it is rather involved in terms of data collection and preparation of GIS maps. But this research is based on analytical method for the optimal choice among the electrification option based on renewable energy systems and the grid extension [11]. This method enables us to work out the Economical Distance Limit (EDL), a break-even distance between the life cycle cost of the grid and the life cycle cost of alternatives (micro hydro power and commercial solar PV considered for this analysis). The outcome of this calculation is the distance up to which a grid expansion is economically feasible compared to MHP and commercial solar PV which is beneficial to energy planners and developers for efficient energy planning and management.

The competitiveness of micro hydro power and commercial solar based generation for rural electrification is assessed and compared with the conventional option of extending a grid. In this study, micro hydro power and commercial solar PV has been considered as alternate source of electricity to grid extension for the analysis. However, the same analytical methodology can be used for all other available renewable energy technologies and the energy systems. The costs of MHP grid-based systems and commercial solar PV are determined for different capacities. The cost incurred to extend the grid from the available grid point to the village is also determined. The life cycle cost (LCC) of energy generated at the end (Rs/kWh) is used to compare these options. An exact and fair comparison between renewable energy systems and the conventional power grid is rendered difficult by the different operating situations. As the type and character of input energy is different, cost and availability of input energy differ with time and geographic region, technological maturity and operating constraints. All these have a significant impact on the result of the economic analysis. The salvage value of generation options is not considered for simplicity in calculations. All these calculations are made using a discount factor of 10%. The cost of LV distribution lines within villages has been excluded since it is the same in all the cases.

2.2 Life cycle cost of energy from solar PV system

LCC of energy for each option is calculated by dividing the total LCC of the system by the total energy output in the system's life [12] [11]. The LCC values for different capacities of photovoltaic systems are calculated by using the following relation:

$$LCC_{PV} = \frac{C_{PV} + C_B + (C_{PV} + C_B).\beta.P(d,n) + C_R.P(d,n_1)}{L.h.n} \quad (1)$$

Where,

[1] Currently the VDCs have been converted into rural or municipalities

$C_{PV} = \text{ Capital cost of PV system (excluding battery)}$ (Rs)
$C_B = \text{ Capital cost of battery}$ (Rs)
$\beta = \text{ Fraction of capital costs for annual O\&M of the system}$
$C_R = \text{ Replacement cost of battery}$ (Rs)
$h = \text{ Annual operating hour}$ (hours)
$n = \text{ Life of complete system}$ (years)
$n_1 = \text{ Life of replacement components (Batteries)}$ (years)
$d = \text{ Discount rate (\%)}$

$P(d,n) = \text{ Present net worth factor}$
$L = \text{ System capacity}$ (kW)

2.3 Life cycle cost of energy from micro-hydro
The LCC values for different capacities of micro-hydro plants are calculated by using the following relation:

$$LCC_{MH} = \frac{C_{MH} + C_{MH}.\beta.P(d,n) + C_{HMR}}{L.h.n} \quad (2)$$

Where,
$C_{MH} = \text{ Capital cost of micro hydro system}$ (Rs)
$C_{HMR} = \text{ Cost of relacemment of parts after the } 15 - \text{year economic life of plant}$ (Rs)
$\beta = \text{ Fraction of capital costs for annual O\&M of the system}$
$h = \text{ Annual operating hours}$ (hours)
$n = \text{ Life of complete system}$ (years)
$d = \text{ Discount rate}$ (%)

$P(d,n) = \text{ Present net worth factor}$

$$P(d,n) = \frac{(1+d)^n - 1}{d.(1+d)^n} \quad (3)$$

$L = \text{ System capacity } (kw)$

2.4 Life cycle cost of grid extension
The grid extension cost depends on the distance of the village/load center from the existing grid, cost of distribution transformer and operation and maintenance cost of the grid line along with the transformer. The cost of delivered electricity at the village or load center depends on the cost of unit power generation (electricity cost at existing grid point), transmission and distribution losses, load demand and grid availability. So, the life cycle cost of grid extension depends on life cycle cost of electricity generation at the village load center, capital cost for grid line depending on the distance of the village load center from the existing grid point, cost of distribution transformer and operation and maintenance cost. The expression for calculation of LCC of energy (Rs/kWh) for grid extension can be written as:

$$LCC_{GE} = \frac{LCC_{gen} + LCC_{grid}.X}{L.h.n} \quad (4)$$

Where,
$$LCC_{gen} = t_{gen}.L.h.\left(\frac{1}{1-\delta_{t\&d}}\right).P(d.n) \quad (5)$$
$$LCC_{grid} = C_{grid} + C_t + \left(C_{grid} + C_t\right).\beta.P(d,n) \quad (6)$$

IOP Conf. Series: Journal of Physics: Conf. Series **1266** (2019) 012014 doi:10.1088/1742-6596/1266/1/012014

$LCC_{GE} = Life\ cycle\ cost\ of\ grid\ extention$ (Rs)
$LCC_{gen} = Life\ cycle\ cost\ of\ electricity\ generation$ (Rs)
$LCC_{grid} = Life\ cycle\ cost\ of\ grid\ line\ (line\ plus\ transformers)$ (Rs)
$X = Distance\ from\ the\ village\ load\ center\ to\ the\ existing\ grid\ point$ (km)
$L = Load\ demand$ (kW)
$t_{gen} = Cost\ of\ generation\ of\ electrcity$ (Rs/kWh)
$\delta_{t\&d} = Transmission\ and\ distribution\ losses$ (%)

$C_{grid} = Cost\ of\ grid\ line$ (Rs)
$C_t = Cost\ of\ transformer$ (Rs)
$\beta = Fraction\ of\ capital\ costs\ for\ annual\ O\&M\ of\ the\ grid$
$h = Annual\ operating\ hour$ (hours)
$n = Life\ of\ complete\ system$ (years)
$d = Discount\ rate$ (%)

$P(d,n) = Present\ net\ worth\ factor$

2.5 Economic distance limit (EDL)
The economical distance limit (EDL) is calculated by considering the life cycle cost of the renewable energy system and the distance at which this cost and the life cycle cost of grid extension match; this is like break even analysis. The following expression is used for the calculation:

$$\frac{LCC_{grid}.EDL+LCC_{gen}}{L.h.n} - LCC_{MH/PV} = 0 \quad (7)$$

2.6 *Load forecast*
Load forecast is one of the key elements of energy planning. To size the capacity of the alternative supply options (e.g., grid vs micro-hydro/commercial solar PV), the demand in the area has been forecasted. For this, the number of households forecast for the 2015 has been used to determine the energy demand and then with suitable load factor, diversity factor and connected loads, and the future growth rate of energy use, the load forecast has been prepared [13]. We have been conservative in assigning the growth figures because over the 2001-2011 census period there has been net decrease in the population in the district by about 0.6%, and most of the VDCs under study have shown marked slowdown in population growth over that period[14]. The assumed factors are as follows:

Table 1. Assumptions for load forecast [3][4]

Factors	Domestic	Education	Offices	Industries
Load factor	0.2	0.2	0.5	0.5
Diversity factor	0.9	0.2	0.4	0.3
Connected load (W)	200	500	400	2000
Load growth:				
1-5 years	5%	5%	5%	5%
6-10 years	2%	2%	2%	2%
11-15 years	1%	1%	1%	1%

Based on the assumptions made the yearly load forecast in kW has been calculated as follows:

Table 2. Load forecast for 15 years

Yearly load forecast (kW)														
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
756	834	876	920	965	1065	1086	1108	1130	1152	1156	1167	1179	1191	1203

3. Results and discussion

Calculations to draw the conclusion are based on the given formula 1 to 7, the assumptions made in Table 1, and the load for the 5th year. Load for the 5th year has been forecasted to be 965 kW and the calculations have been done for the 1000 kW; remaining in higher factor of safety. Results of EDL for MHP and commercial solar PV has been compared with grid extension as calculate in the following two tables Table 3 and 4 respectively.

3.1 EDL and LCC calculation for grid vs mhp

Table 3. Economic distance for grid extension vs micro-hydro (MHP)

Symbols	Description	Unit	Quantity	Assumptions
	Life cycle cost of grid extension			
	Capacity of each distribution transformer	kVA	25	
	Number of units	No.	40	
	Total capacity of the transformer	kVA	1000	
	Cost of one unit of 25 kVA transformer	Rs	200,000	
$\mathbf{C_t}$	Cost of distribution transformer (25 kVA)	Rs	8,000,000	
$\mathbf{t_{gen}}$	Electricity generation cost	Rs/kWh	7	
	Cost of 11 kV transmission line	Rs/km	800,000	
	Length of line	km	60	
$\mathbf{C_{grid}}$	Cost of transmission line	Rs	48,000,000	
$\boldsymbol{\delta_{t\&d}}$	T&D losses		20%	
$\boldsymbol{\beta}$	Fraction of capital cost for O&M of grid		1.5%	
L	Load demand	kW	900	
h	Annual operation hours	h	2920	8 h per day for 365 days
n	Life of project	yr	25	
d	Discount rate		10%	
P	Present worth factor		9	
$\mathbf{LCC_{gen}}$	Lifecycle cost of electricity generation	Rs	208,726,535	
$\mathbf{LCC_{grid}}$	Lifecycle cost of grid extension	Rs	63,624,713	
	Lifecycle cost of micro hydro (MHP)			
	Capacity of MHP	kW	25	
	Number of plants	No.	40	
	Total capacity of MHP	kW	1000	
$\mathbf{C_{MH}}$	Capacity cost of MHP	Rs	400,000,000	

Symbols	Description	Unit	Quantity	Assumptions
β	Fraction of capital cost for O&M of MHP		10%	
L	Load demand	kW	900	
h	Annual operation hours	h	2190	6 h per day for 365 days
n	Life of project	yr	15	
d	Discount rate		10%	
P	Present worth factor		7.61	
PV	Present worth factor at 15th year		4	
LCC_{MH}	Lifecycle cost of electricity generation	Rs/kWh	23.82	
C_{HMR}	Cost of refurbishment after 15 years	Rs	80,000,000	20% of original cost
LCC_{MHR}	Lifecycle cost of electricity generation after refurbishment	Rs	35	
EDL	Economical distance limit without refurbishment	km	21.32	
EDL	Economical distance limit with refurbishment	km	33	

Considering the normal size of micro hydro power plants in Gorkha and in Nepal, 25 kW capacity has been considered for the calculations. Further, to meet the load demand of nearly 1000 kW, the given size of the power plant ha been multiplied by 40 no. of units. Further same size of transformer (25 kVA) has been considered as shown in the given Table 3.

3.2 EDL and LCC calculation for grid vs commercial solar PV

Table 4. Economic distance for grid extension vs commercial solar PV

Symbols	Description	Unit	Quantity	Assumptions
	Life cycle cost of grid extension			
	Capacity of each distribution transformer	kVA	25	
	Number of units	No.	1	
	Total capacity of the transformer	kVA	25	
	Cost of one unit of 25 kVA transformer	Rs	200,000	
C_t	Cost of distribution transformer (25 kVA)	Rs	200,000	
t_{gen}	Electricity generation cost	Rs/kWh	7	
	Cost of 11 kV transmission line	Rs/km	800,000	
	Length of line	km	10	
C_{grid}	Cost of transmission line	Rs	8,000,000	
$\delta_{t\&d}$	T&D losses		20%	

Symbols	Description	Unit	Quantity	Assumptions
β	Fraction of capital cost for O&M of grid		1.5%	
L	Load demand	kW	22.5	
h	Annual operation hours	h	2920	
n	Life of project	yr	25	
d	Discount rate		10%	
P	Present worth factor		9	
LCC_{gen}	Lifecycle cost of electricity generation	Rs	3,478,775	
LCC_{GE}	Lifecycle cost of grid extension	Rs	9,316,476	
	Lifecycle cost of commercial solar PV			
	Capacity of a solar PV	kWp	25	
	Number of plants	No.	1	
	Total capacity of PV	kWp	25	
	Cost of solar PV	Rs	5,000,000	
	Battery	Rs	9,000,000	
	Balance of system and installation	Rs	2,800,000	
C_{PV}	Capacity cost of PV system	Rs	16,800,000	
β	Fraction of capital cost for O&M of MH		9%	
n	Life of project	yr	25	
	Capacity factor		14%	
U	Annual energy generation	kWh	30660	
d	Discount rate		10%	
P	Present worth factor (1-25 years)		9	Years
P_5	Present worth factor (5th year)		1	5
P_{10}	Present worth factor (10th year)		2	10
P_{15}	Present worth factor (15th year)		3	15
P_{20}	Present worth factor (20th year)		5	20
P_{25}	Present worth factor (25th year)		8	25
LCC_{PV}	Lifecycle cost of electricity generation	Rs/kWh	274	
C_{BATR}	Cost of battery replacement on 6th year	Rs	9,000,000	
EDL	Economical distance limit without refurbishment	km	48	

As we have considered size of micro hydro power plant to be 25 kW for the calculation purpose, we have considered the same size for commercial solar PV plant as well. Since, we do not compare solar PV and micro hydropower plant in this research. We have limited the load of 25 kW for commercial solar PV for the calculation purpose; since we do not compare MHP and the commercial solar PV. Further, depending upon the load demand (eg. if 1 MW) the system can be multiplied by the necessary factor as well. Further same size of transformer (25 kVA) has been considered as shown in the given Table 4.

A summary of calculation for the EDL based on LCC has been presented in Table 3 and 4. In case of MHP, the least cost planning has been done for the load forecast for the 5th year, which is 965 kW in aggregate for the study VDCs. Accordingly, to meet this demand, it has been assumed that there will be 40 numbers of 25 kVA transformers feeding several settlements and that an alternative option of electrifying these villages will be by 40 MHPs each of 25 kW. Reference values for calculation have been considered as average reference from AEPC and NEA practice. In case of commercial solar PV, the load forecast for 25 kW has been considered for the calculation purpose. The result shows that grid extension up to 22 km and 48 km from the existing grid point is more economical than installing MHPs and commercial solar PV respectively without refurbishment. EDL may be increased if we consider the case of refurbishment as shown in Table 3.

We have assumed that the reliability of the grid supply, solar PV and MHPs is same; without which calculation would have no basis for comparison. Further, the costs of LV lines have not been included in the comparison, assuming they are common costs to both options. The villages in all the 17 VDCs falling within 22 km for the case of MHP and 48 km length for the case of solar PV of 11 kV lines from the existing endpoints are economical to electrify by extending the grid than the assessed alternative approach.

4. Conclusions

The analytical model for comparing EDL based on LCC of any renewable energy technology is a well-established method for energy planning. The analysis has been conducted on various parameters which are subject to change for different technologies and climatic conditions. The research has been conducted for Gorkha District of Nepal as a case study. The analysis has been conducted based on available secondary data collected from DDC, census, NEA, GIS etc. The result shows that grid extension up to 22 km and 48 km from the existing grid point is more economical than installing MHPs and commercial solar PV respectively without refurbishment. EDL may be increased if we consider the case of refurbishment. The study indicates that renewable energy-based decentralized electricity supply options could be financially attractive as compared to grid extension for providing access to electricity in small remote and the sparsely settled villages, which can be witnessed in terms of EDL. The calculated EDL based on LCC for renewable energy systems compares it with grid-extension for Gorkha district. Further, the model can be implemented in other similar districts and the communities. The tool is very beneficial for energy planners, energy developers and policy makers to prepare an energy master plan for other similar district and the communities. The model can be fit with exact and specific site data exact energy planning for the site.

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