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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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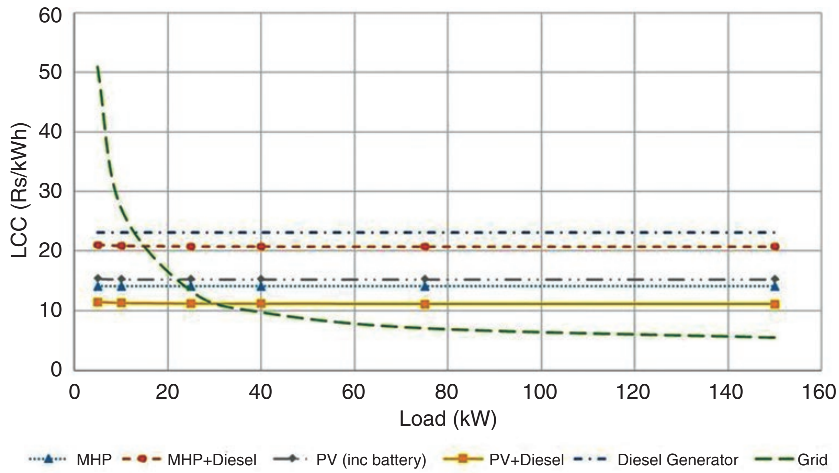
Graphical Abstract



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, microhydropower (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.

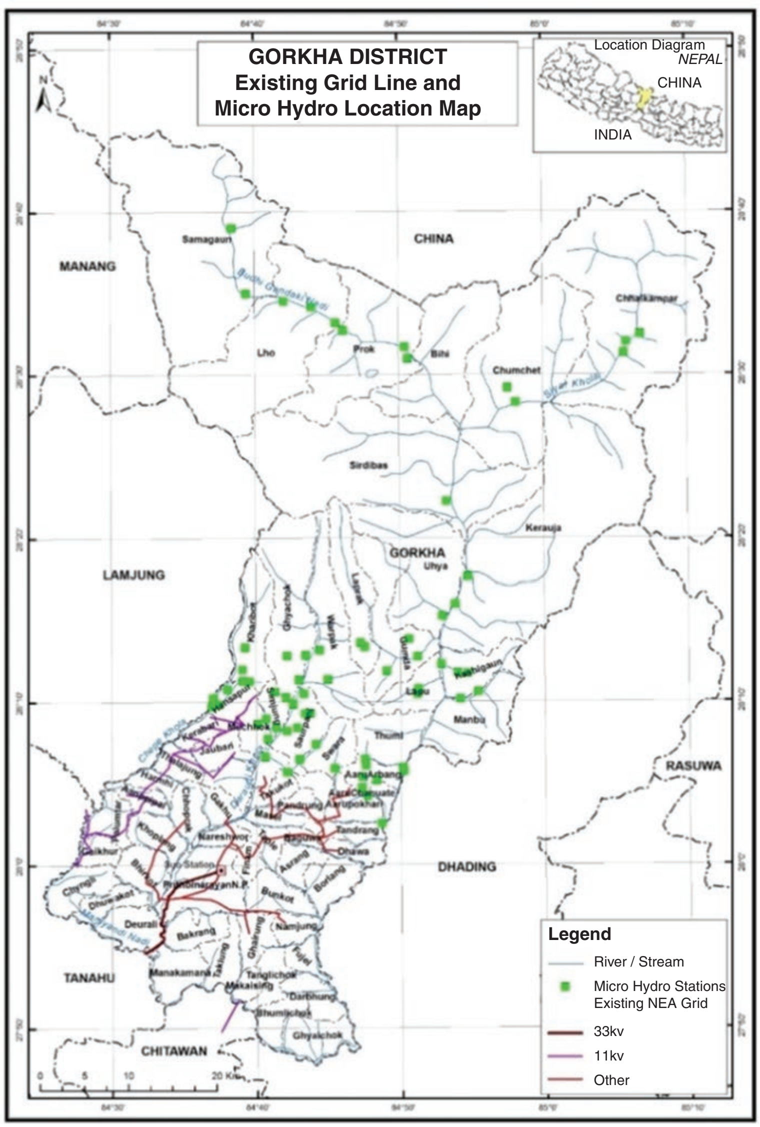


Fig. 1: Map of Gorkha district indicating energy-systems availability

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

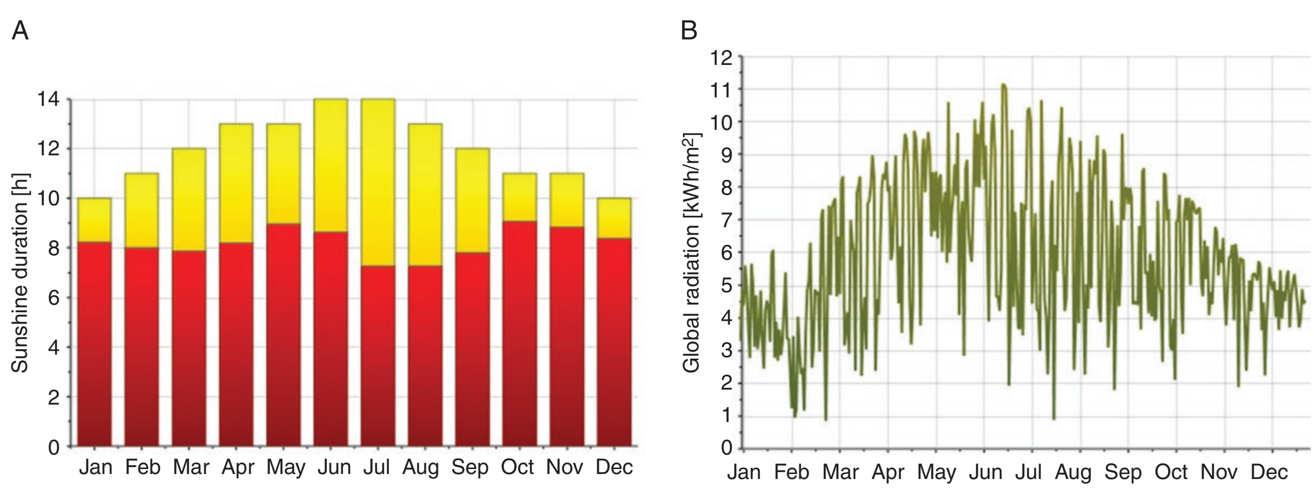


Fig. 2: Sunshine hours and global radiation of Gorkha district

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

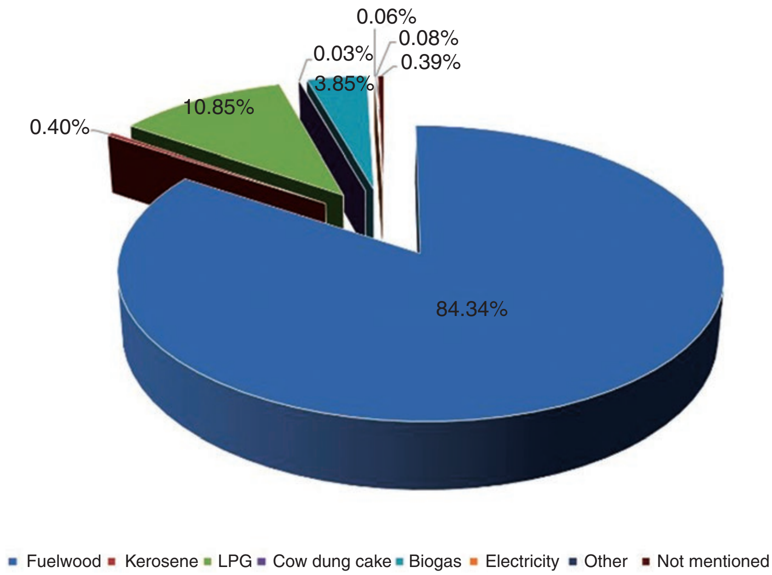


Fig. 3: Households using various energy sources for cooking [28]

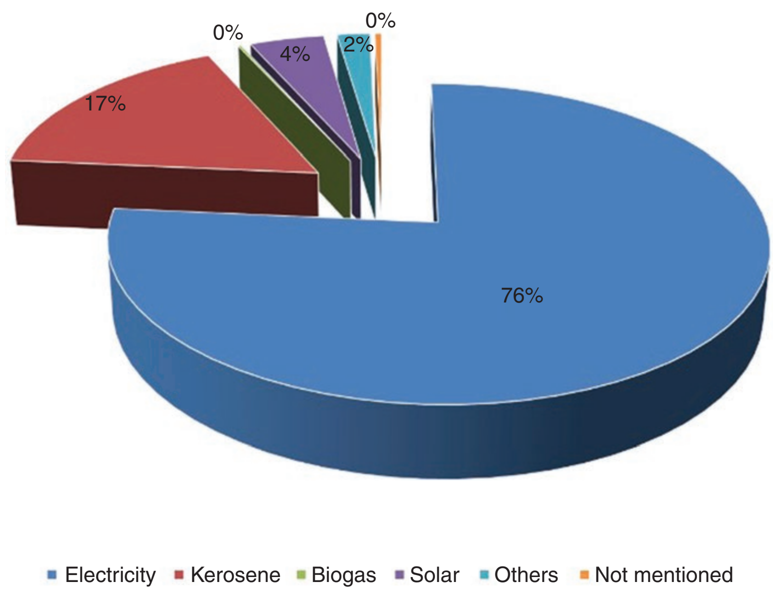


Fig. 4: Households using various energy sources for lighting [28]

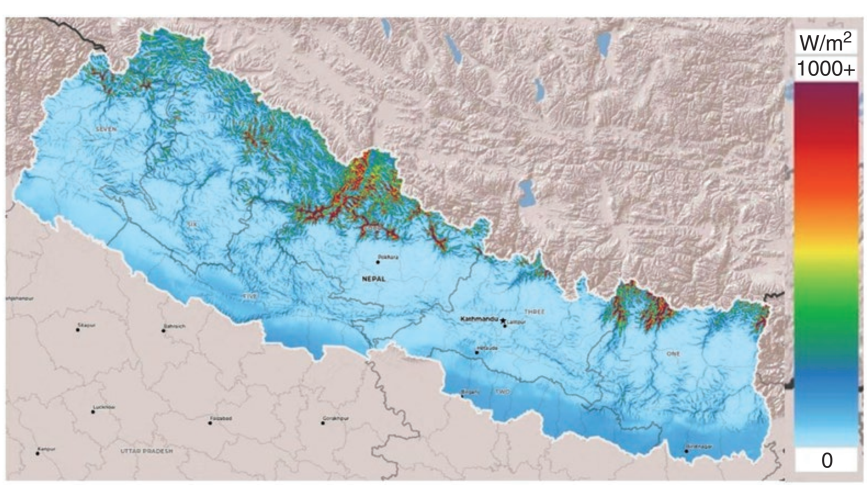


Fig. 5: Wind-energy potential in Nepal [42]

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.

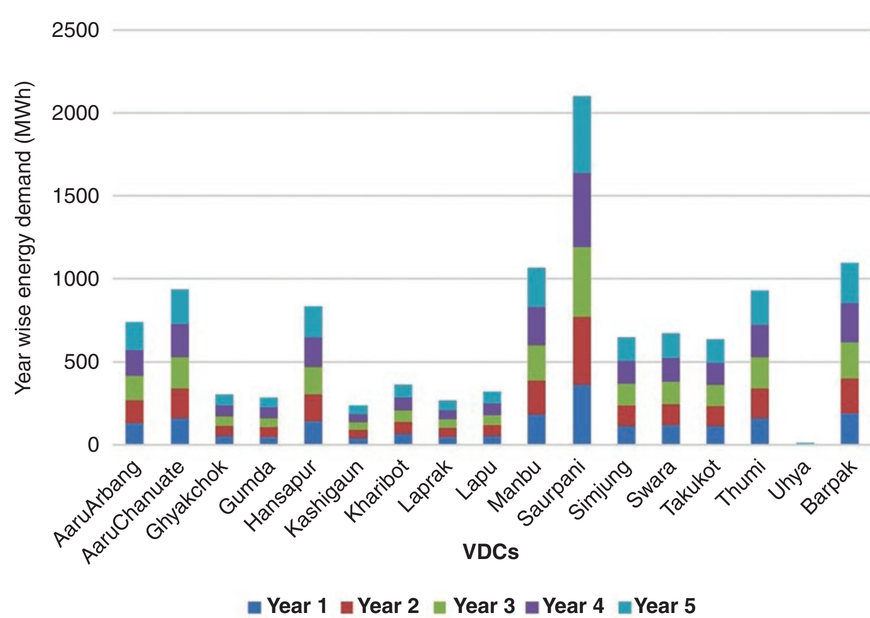


Fig. 6: Energy demand (in MWh) of 17 VDCs of Gorkha district for 5 years

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]:

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

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

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

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):

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

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 $1 + d + d_2 + d_3 + d_4 + \ldots\ldots\ldots d_n$ 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):

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

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

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

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.

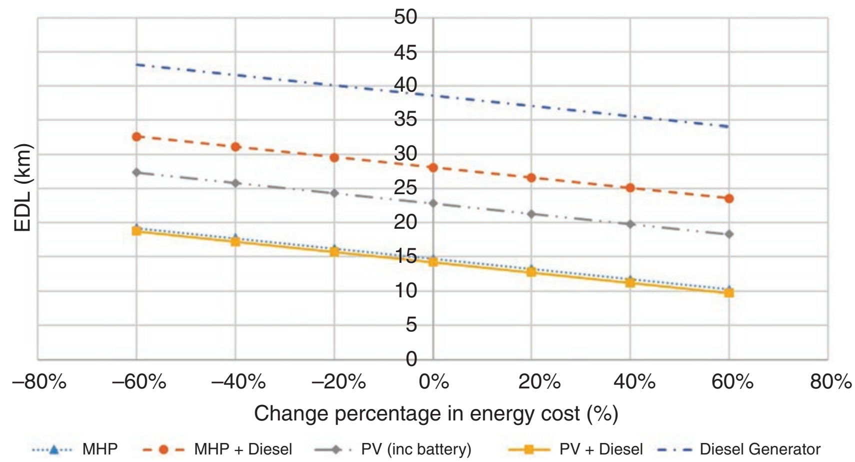


Fig. 7: EDL with changing generation cost, 0% = 7 Rs/kWh.

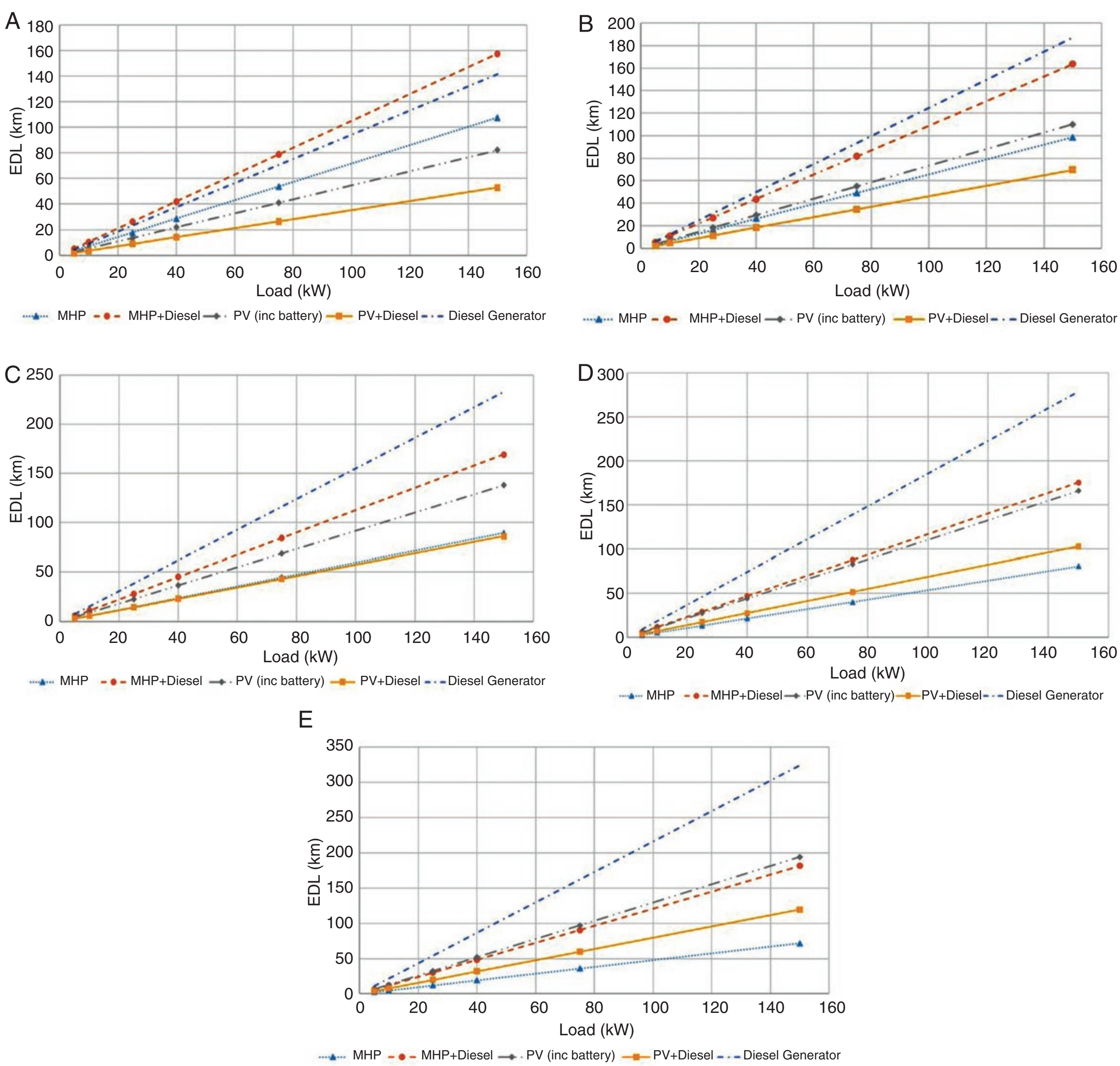


Fig. 8: EDL against system capacity and different hours of power availability per day. (a) 6 hrs/day electricity supply; (b) 8 hrs/day electricity supply; (c) 10 hrs/day electricity supply; (d) 12 hrs/day electricity supply; (e) 14 hrs/day electricity supply.

(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

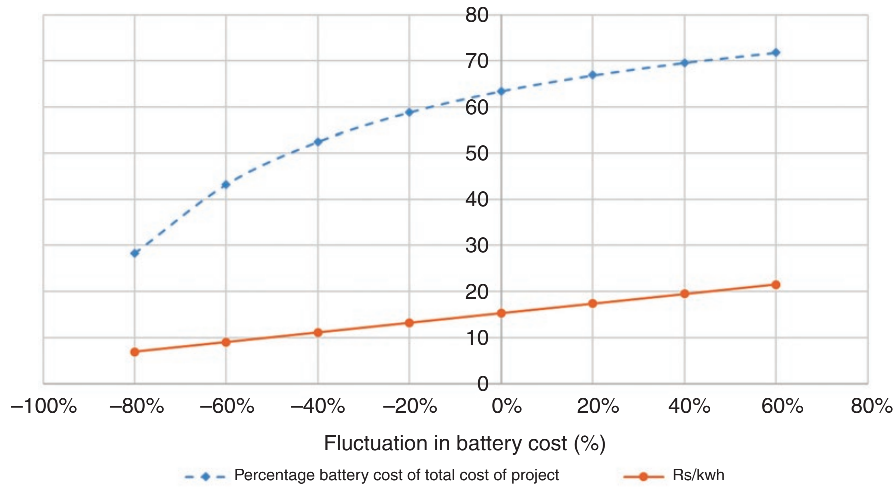


Fig. 9: Battery capacity and the cost.

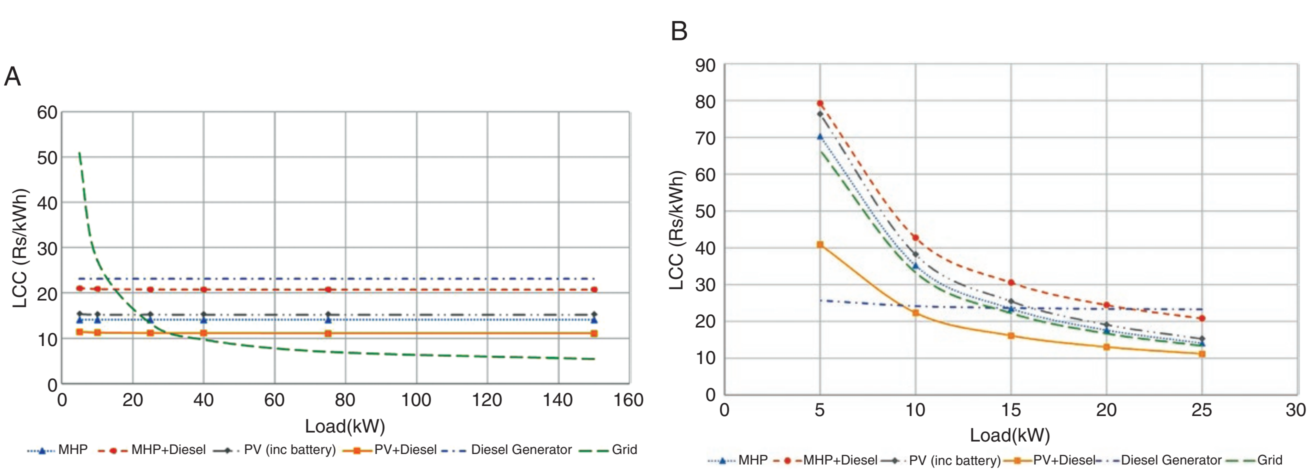


Fig. 10: LCC comparison for (a) increasing load and (b) actual load.

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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