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

Nawaraj Sanjel1*, Bivek Baral1, Mahesh Acharya2, Satish Gautam3
1 School of Engineering, Kathmandu University, Nepal
2 Renewable Energy for Rural Livelihood (RERL), Nepal
3 Millennium Challenge Corporation (MCC), Nepal
*Corresponding Author (sanjelnawaraj@ku.edu.np)

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...
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
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 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:

$$LCC_{PV} = \frac{C_{PV} + C_{B} + (C_{PV} + C_{B}) \cdot \beta \cdot P(d, n) + C_{R} \cdot P(d, n)}{L \cdot h \cdot n}$$

Where,  

1 Currently the VDCs have been converted into rural or municipalities.
\[ C_{PV} = \text{Capital cost of PV system (excluding battery)} \ (\text{Rs}) \]
\[ C_B = \text{Capital cost of battery} \ (\text{Rs}) \]
\[ \beta = \text{Fraction of capital costs for annual O&M of the system} \]
\[ C_R = \text{Replacement cost of battery} \ (\text{Rs}) \]
\[ h = \text{Annual operating hour (hours)} \]
\[ n = \text{Life of complete system (years)} \]
\[ n_1 = \text{Life of replacement components (Batteries) (years)} \]
\[ d = \text{Discount rate} \ (%) \]

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

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:
\[
LCC_{MH} = \frac{C_{MH} + C_{MH} \cdot \beta \cdot P(d, n) + C_{HMR}}{L \cdot h \cdot n} \quad (2)
\]

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

\[ P(d, n) = \text{Present net worth factor} \]
\[
P(d, n) = \frac{(1+d)^n-1}{d(1+d)^n} \quad (3)
\]
\[ L = \text{System capacity (kw)} \]

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:
\[
LCC_{GE} = \frac{LCC_{gen} + LCC_{grid} \cdot X}{L \cdot h \cdot n} \quad (4)
\]

Where,
\[ LCC_{gen} = t_{gen} \cdot L \cdot h \cdot \left( \frac{1}{1-\beta_{td}} \right) \cdot P(d, n) \quad (5)
\]
\[ LCC_{grid} = C_{grid} + C_t + \left( C_{grid} + C_t \right) \cdot \beta \cdot P(d, n) \quad (6)
\]
\[ LCC_{GE} = \text{Life cycle cost of grid extension (Rs)} \]
\[ LCC_{gen} = \text{Life cycle cost of electricity generation (Rs)} \]
\[ LCC_{grid} = \text{Life cycle cost of grid line (line plus transformers) (Rs)} \]
\[ X = \text{Distance from the village load center to the existing grid point (km)} \]
\[ L = \text{Load demand (kW)} \]
\[ t_{gen} = \text{Cost of generation of electricity (Rs/kWh)} \]
\[ \delta_{t&d} = \text{Transmission and distribution losses (%)} \]

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

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

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:

\[ \frac{LCC_{grid}^{EDL} + LCC_{gen}}{L.h.n} - LCC_{MH/PV} = 0 \]  \hspace{1cm} (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                      |
|---------|--------------------------------------------------|-------|----------|----------------------------------|
| $C_t$   | Cost of distribution transformer (25 kVA)        | Rs    | 8,000,000|                                  |
| $t_{gen}$| Electricity generation cost                      | Rs/kWh| 7        |                                  |
| $C_{grid}$| Cost of transmission line                       | Rs    | 48,000,000|                                  |
| $\delta_{t&d}$ | T&D losses                                   |       | 20%     |                                  |
| $\beta$ | 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       |                                  |

| $\text{LCC}_{\text{gen}}$ | Lifecycle cost of electricity generation | Rs     | 208,726,535 |
| $\text{LCC}_{\text{grid}}$ | 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 |
| $C_{\text{MH}}$                     | Capacity cost of MHP                  | Rs     | 400,000,000 |

Symbols | Description | Unit | Quantity | Assumptions  
--- | --- | --- | --- | ---  
\( \beta \) | 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 |  
\( C_{\text{HBR}} \) | Cost of refurbishment after 15 years | Rs | 80,000,000 | 20\% of original cost  
\( LCC_{MHBR} \) | 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 has 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  
--- | --- | --- | --- | ---  
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 |  
Cost of distribution transformer (25 kVA) | Rs | 200,000 |  
\( t_{\text{gen}} \) | Electricity generation cost | Rs/kWh | 7 |  
Cost of 11 kV transmission line | Rs/km | 800,000 |  
Length of line | km | 10 |  
\( C_{\text{grid}} \) | Cost of transmission line | Rs | 8,000,000 |  
\( \delta_{\text{T&D}} \) | 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 |             |

**Symbols**

- $LCC_{gen}$: Lifecycle cost of electricity generation
- $LCC_{GE}$: Lifecycle cost of grid extension

**Symbols**

- $C_{PV}$: Capacity cost of PV system
- $\beta$: Fraction of capital cost for O&M of MH
- n: Life of project
- U: Annual energy generation
- d: Discount rate
- P: Present worth factor
- $P_5$: Present worth factor (5th year)
- $P_{10}$: Present worth factor (10th year)
- $P_{15}$: Present worth factor (15th year)
- $P_{20}$: Present worth factor (20th year)
- $P_{25}$: Present worth factor (25th year)
- $LCC_{PV}$: Lifecycle cost of electricity generation
- $C_{BTR}$: Cost of battery replacement on 6th year
- EDL: Economical distance limit without refurbishment

**Symbols**

- Capacity of a solar PV: kWp
- Number of plants: No.
- Total capacity of PV: kWp
- Cost of solar PV: Rs
- Battery: Rs
- Balance of system and installation: Rs
- Capacity factor: 14%
- Annual energy generation: kWh
- Present worth factor (1-25 years): 9
- Present worth factor (5th year): 1
- Present worth factor (10th year): 2
- Present worth factor (15th year): 3
- Present worth factor (20th year): 5
- Present worth factor (25th year): 8
- Lifecycle cost of electricity generation: Rs/kWh
- Cost of battery replacement on 6th year: Rs
- Economical distance limit without refurbishment: km
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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