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Options for off-grid electrification in the Kingdom of Bhutan

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Abstract

Bhutan sells electricity across the border to India. However large sections of its population do not have access to electricity. The harsh mountainous terrain coupled with sparse and dispersed settlements in Bhutan makes grid extension difficult, costly and economically unviable. Therefore, it is worth looking at renewable energy options to meet electricity demand in remote locations. This study aims to identify the least-cost technologies that could be used in the rural areas of Bhutan. The study analyses the energy needs of rural households, the resources available, and current policies and programs on rural electrification. The Hybrid Optimization Model HOMER for designing distributed generation (DG) systems both on and off-grid was used to find the least-cost technologies for different potential resources and to compare the cost of deploying these technologies with conventional electrification through grid extension. This paper identifies possible rural electrification options for Bhutan and compares them with extending the grid to the remote areas.
Introduction

Bhutan is a small landlocked country situated in Southern Asia between China and India. The latitude and longitude are 27.30°N and 90.30°E respectively. The total area of Bhutan is 38,394 sq km and its climate varies within the country from tropical to alpine [1].

Bhutan’s economy depends on agriculture, forestry, tourism and the sale of hydroelectric power to India. The main occupations are agriculture and more than 80 percent of the population depends on it. There is also a handicrafts industry, particularly weaving and the manufacture of religious art for home altars. The landscape of Bhutan varies from hilly to ruggedly mountainous which makes it difficult and expensive to build roads and other infrastructure.

Bhutan is amongst a few countries where hydropower is the main source of electricity. Although Bhutan exports about 75% of its total generation capacity of 1488 MW, less than 60% of its rural households have access to electricity [2]. The Royal Government of Bhutan (RGOB) has set a target to achieve 100% electrification by the end of the year 2020. About 3900 households have been identified for off-grid electrification, where grid connection is technically, and economically infeasible [2].

In an isolated place, where grid extension is not possible, electrification using Solar Home Systems (SHS) and micro-hydro plants has been carried out since the 1980s, mainly through outside donor assistance to Bhutan [3]. Like many developing countries, SHS have had limited success in Bhutan, mainly because the project implementers did not consider the
long-term sustainability aspects of the technology. User training was limited, systems were poorly designed, and there was no provision for repairs, maintenance support, and spare parts, thus many programs failed [3]. In addition, most of the micro-hydro plants are owned and operated by Bhutan Power Corporation (BPC) in the off-grid areas. These are not financially viable as the revenue is not able to meet the costs of operation and maintenance.

These experiences from the past seem to have had a profound impact on the general perception of the policy makers on the reliability and cost effectiveness of renewable energy technologies. Bhutan’s Rural Electrification Master Plan (REMP) recommends renewable energy technologies (only solar and micro-hydro have been considered) to be used only in places where grid extension is practically impossible [4].

Presently, Bhutan Power Corporation, the government owned utility, which is responsible for transmission and distribution of electricity, undertakes all grid connection projects and also acts as a network operator and retailer. Most of these projects are financed through concessional loans from multilateral financial institutions like the Asian Development Bank (ADB) and the Japanese Bank for International Cooperation (JBIC). With more than 40% of rural households still to be electrified, it puts a huge pressure on the government’s limited financial resources. The average cost of electrifying a household in a remote village in the previous rural electrification projects was around US$1800 to US$2000. It is estimated that about US$71 million would be required to provide electricity by grid extension to the remaining un-electrified households [4].
Renewable energy technologies have become commercially viable for electrification projects in remote areas due to technological improvements and cost reductions due to economies of scale. Recent studies on solar and wind resources in Bhutan by the National Renewable Energy Laboratory (NREL), have enabled mapping of solar and wind resources for Bhutan, making it much easier for project planners to access location specific data for design and technology choice [5].

This paper provides a techno-economic analysis of different renewable energy technology options for rural electrification in Bhutan using recent cost and resource data. The cost of implementing these technologies for rural electrification was also compared with the cost of grid extension.

**The energy situation in Bhutan**

Due to its geography and fast flowing rivers, Bhutan has a huge hydropower potential estimated to be around 30,000 MW. At present about 1488 MW of this resource is tapped, from which about 75% of the electricity generated is exported to India [2]. However, Bhutan imports all of its petroleum-based fuel for use mainly in the transport sector. Fig. 1 and Fig. 2 show Bhutan’s energy supply mix and energy consumption by sector in 2005.

The central government agency responsible for the energy sector is the Department of Energy (DOE). After the power sector reform in 2001, the Department of Power (DOP) was split into three agencies:
1) Department of Energy as the central government agency,

2) Bhutan Electricity authority (BEA) as the regulator, and

3) Bhutan Power Corporation as the utility responsible for transmission and distribution.

**Rural electrification in Bhutan**

The cost of electrifying one rural household is about US$1800–US$2000 [7]. The capital cost is fully borne by the government, mainly financed through soft loans from the Asian Development Bank (ADB), while other agencies like the Austrian Coordination Office, Stichting Nederlandse Virijwilligers (SNV), UNDP/GEF, Government of India (GoI), Japan Bank for International Cooperation (JBIC) have also financed rural electrification through a mix of grants and concessional loans. The electricity tariff is subsidized and set at Nu. 0.75/kWh (US$0.0159/kWh) for rural households while the estimated cost for electricity supply is in the range of Nu. 4.50/kWh (US$0.095/kWh) [4].

A master plan for rural electrification was formulated in 2005 with the support of the Japanese International Cooperation Agency (JICA) which aims to electrify 100% of households in Bhutan by 2020 [8]. Fig. 3 shows the cumulative achievement in rural electrification and the achievement in each developmental plan period. It also shows the targeted households to be electrified in the years up to 2020.
Electrification using renewable energy

Solar electrification in Bhutan started in the 1980s, to supply electricity for institutions, health clinics, monasteries and some of the rural households. Mini- and micro-hydroelectric systems were constructed in Bhutan in the 1980’s and 1990s with grant assistance, mostly from the Japanese Government. There are currently about 22 plants in operation [6]. These plants are mainly located in areas close to roads and, in the past, provided the only source of electricity to some district centers and satellite towns. However, most of these plants are now expected to be connected to the grid with the arrival of grid electricity in most of these places.

Problems encountered by these programs

General problems in regard to the solar electrification programs were:

- Lack of maintenance support and spare parts backup as a result of which the systems were abandoned by the users. No local people were trained for maintenance.

- Users were not educated about what the system can and cannot do. For example, while most of the systems were only meant for lighting purposes, users manipulated them for other uses, like entertainment, which contributed to premature failure of components.

- The systems were inappropriately sized due to lack of radiation data.

- Lack of government planning has resulted in electrification of some villages which were going to be connected to the grid in the near future [9].
Some of the problems that have plagued the micro-hydro sector in Bhutan are [3] and [9]:

- High capital cost requirement. Therefore, it is not the preferred mode of electrification by the Government.
- Operation and maintenance costs were generally higher than the income from the sale of electricity in the domestic market. Thus, the government owned utility is reluctant to take up ownership of newly constructed plants.
- Inability to meet peak demand during the day, due to excessive load growth. However, energy is wasted during the night.
- Transportation of machinery and construction materials to remote places without road access is difficult and adds significantly to the overall costs.

**Resource assessment**

**Solar and wind resource potential**

Past solar electrification programs in Bhutan utilized raw estimates of solar irradiation at a fixed mean value of 4 kWh/m² per day for all months and for all locations. This resulted in improper system sizing, which partly explained why most Solar Home Systems failed to deliver the intended services in the past [10].

In 2008, as part of the South Asia Regional Initiative for Energy (SARIE), the National Renewable Energy Laboratory (NREL) developed high resolution solar and wind resource maps for Bhutan. These maps were developed using weather satellite data as well as a numerical modeling approach and empirical validation methodology. The wind resource
maps have a resolution of 1 km\(^2\) and solar maps have a resolution of 10 km\(^2\)[11]. Solar resource maps for direct radiation, global horizontal radiation as well as tilted-surface radiation are available for all months of the year. Fig. 4 and Fig. 5 show the annual solar radiation and wind speed maps.

From Fig. 4 we can see that parts of northern and western regions of Bhutan receive higher levels of solar radiation, compared with other parts of the country. Global horizontal radiation varies from 4.5 to 6.5 kWh/m\(^2\)-day in summer to 3.5–4.5 kWh/m\(^2\)-day in winter. Therefore, the potential for developing concentrating solar power (CSP) is not very promising.

The above map (Fig. 5) shows that the wind resource is not significant for most areas of Bhutan. However, the wind power density is generally good along valleys of Bhutan’s major rivers. Incidentally, most of these areas are connected by road and existing electricity grid infrastructure. Therefore, these areas could provide potential sites for the future development of utility scale wind generation.

**Micro-hydro resources**

Being a mountainous country, Bhutan has numerous fast flowing streams and rivers which provide a lot of potential for hydropower generation. Mega hydropower projects are a major source of Bhutan’s revenue. The estimated capacity of large hydropower is around 30,000 MW with plans in the pipeline to develop 10,000 MW by 2020 [7].
Due to the widely dispersed nature of small rivers and streams, it might be difficult to ascertain the resource capacity of mini/micro-hydro power. The Department of Energy in the past has done some measurements of dry season discharge in various Dzongkhags (districts) by taking measurements annually at 72 gauging stations across the country. Eastern parts of Bhutan are expected to have higher potential for micro-hydro power due to much higher dry season discharge rates [4]. According to a study conducted in 1999, as many as 31 potential sites for small scale hydro facilities were identified [9]. So, there are many opportunities for small hydro projects in Bhutan.

**Demand for energy services in off-grid areas**

Demand for energy services depends on various factors, such as

- Distance from the local grid and accessibility,
- Demography of the remote areas,
- Socio-cultural status of the population,
- Economic status of the people living in that area [12].

Most of the areas which are not reached by the national grid in Bhutan are remote villages and isolated settlements where the cost of grid extension is economically unviable or technically infeasible and often practically impossible due to physical factors like the harsh terrain. These places are far away from accessible roads. Some of the areas are inaccessible during parts of the year due to heavy snow or swollen rivers. As transportation is an important criterion for planning energy services [3] and [4] these areas remain un-electrified.
The demography of a place also influences the choice of energy supply system. Mini-grids for example, may not be suitable in scattered settlements. In northern Bhutan, where nomadic yak herders migrate between seasons, temporary pastoral settlements are common. Out of a total of 367 villages allocated for off-grid electrification, 105 of them have more than 10 households [13]. There are also a number of villages having just one or two households.

The income level of the people living in these areas is expected to be less than the national average due to lack of access to market, information and technology. The number of public and commercial facilities like health clinics, schools, shops, etc. are also very small [4].

**Energy consumption scenario and forecast**

A survey of 627 non-electrified households was carried out by JICA in 2005 [4] to understand the energy needs of rural households. The results of the survey are presented in Table 1.

Firewood is one of the main sources of energy for domestic cooking, cooking fodder for animals and heating. On average, a household spends over 29 man days of every 4–5 months collecting firewood [4]. Long-term energy policy should therefore not only address the lighting needs but also cooking and heating requirements to reduce dependence on firewood.

In order to estimate the potential energy demand and load profiles in an un-electrified village, it is helpful to examine electricity consumption patterns in the electrified villages in rural
areas. Significant changes in the usage of alternative energy sources are observed in these areas. 76.8% of the electrified villages used electricity as their main source for cooking and lighting. These villages consumed 25% less fuel wood, mainly due to the use of electric cooking appliances and electric rice cookers [6], [14] and [15].

**Options for rural electrification in remote areas of Bhutan**

The selection of an appropriate technology is very important and depends on a whole range of social, political, cultural, technical, economic and environmental factors. The aim of this analysis is to address the technical and economic viability of a number of possible technologies that could be practically implemented in remote villages in Bhutan. The result of this analysis may be useful in presenting an idea of the cost of deploying different technologies in different places with different resource potential and for varied end uses. Based on the availability of the resources mentioned in Section 3, the following technologies were selected for this analysis:

- Solar PV systems
- Wind systems
- Hybrid systems
- Micro/Pico hydro systems

The economics of a particular generation source not only depends on the cost of the technology, but also on the resource potential and the nature of the end use application. In this study the analysis was carried out in four different places, Gasa, Lunana, Yangtse and Getena and for lighting and essential communication services. Gasa, Lunana and Getena are
off-grid and do not have access to national grid electricity. So, the cost comparison to electrify these villages with off-grid renewable energy solutions is relevant. Also, these places have better solar energy resources compared to many other places in Bhutan. Yangtse has one of the highest wind energy potentials in Bhutan. Therefore, these places, like many other regions in Bhutan, have the potential to be considered for off-grid electrification through distributed generation.

In order to carry out the analysis, the software modeling package HOMER [16] was used to undertake optimization and economic analysis of different distributed generation systems as it is able to simulate the energy production and consumption for every hour of the year. The authors summed up HOMER’s modeling capability by stating, “HOMER can model grid-connected and off-rid electrification systems serving electric and thermal loads, and comprising any combination of photovoltaic (PV) modules, wind turbines, small hydro, biomass power, reciprocating engine generators, microturbines, fuel cells, batteries, and hydrogen storage” [17]. HOMER’s calibrated PV modeling process seems reliable, but uncertainty remains for HOMER’s wind power modeling process. This can be attributed to the hourly simulation scheme that lends itself well to the complexity of optimizing the systems, but not to the dynamic performance of wind turbines. Another drawback of HOMER is that, it could not categorize the essential and non-essential load. It optimizes the system based on Net Present Cost which may result in choosing the wrong system because the cheapest option may not always be a suitable system.

HOMER provides a much better understanding of the technical performance of the system together with the economic analysis. The simulation was run for the following systems
a) Solar-wind-diesel-battery hybrid system

b) Solar-wind battery hybrid

c) Solar-battery hybrid

d) Wind-battery hybrid

e) Solar home system (AC)

In this study only solar and wind are considered as primary resources. A diesel generator is used as backup for the hybrid system.

**Input data for HOMER**

*Load:* It is assumed that electricity will be used for providing basic services like lighting and communications. The average load is expected to be 12.12 kWh per day for the village with each household consuming on average 0.6 units of electricity per day.

*Resource:* Solar and wind resource data, together with other location specific details like altitude, latitude and longitude, are obtained from the Geospatial Toolkit developed by NREL.
Cost: Market cost information on solar PV components was obtained from DOE, Bhutan. Since only SHS have been implemented in Bhutan so far, other important cost details like installation costs, operation and maintenance costs and balance of system cost were not available. Therefore this cost information was obtained from the literature on centralized system community projects undertaken by the Government of India in many states in the years 2003–2004. The cost of PV projects in the Sagar Islands of West Bengal, India ranged from Rs. 280 (US$5.95) to Rs. 373 (US$7.90) per peak watt [18]. On average, PV panels made up 53% of the cost, batteries 11%, power conditioning systems 20% and the balance of the system 16% of the total cost. Therefore, Rs. 350 (US$7.44) per peak watt is assumed as the current average capital cost of a PV project in Bhutan. The cost of PV panels, power conditioning system and BOS are deduced based on the above data. However, the market price of Trojan T-105 batteries was used. Operation and maintenance cost is assumed to be 1% of the total capital cost for a PV system. The simulation was carried out for the lowest cost of US$5.95 and average cost of US$7.44 per peak watt for the system.

Nouni et al. (2007) carried out a techno-economic analysis of Small Wind Electric Generators (SWEG) in the range of 0.4–50 kW installed in rural areas of India. The capital cost ranged from US$4272/kW to US$5309/kW. The simulation was carried out for the lowest cost of US$4272/kW and the average cost of US$4772/kW. The capital and operating costs of the diesel generators used in this study are based on cost figures from a study by the World Bank [19]. The cost of diesel fuel is assumed to be double the current market price in Bhutan to reflect the high cost of transporting it to remote areas. Table 2 shows a summary of the parameters used in HOMER.
Results and discussion

The results from the analysis are summarized in Table 3, Table 4 and Table 5 below. Table 3 shows the initial capital cost (ICC), Table 4 shows the Net Present Cost (NPC) and Table 5 shows the Levelised Unit Cost of Energy (LUCE) for different hybrid and individual systems in the four identified locations.

The initial capital cost is lower for the wind-battery hybrid system in Yangtse than for any other technology or site, but this technology is more expensive in other locations. This is because of the excellent wind resources in Yangtse. For all other locations the diesel-PV-battery hybrid is the lowest cost option, although it is similar in cost to the SHS in several locations.

Fig. 6 shows that the initial cost does not vary as much for diesel-PV-battery, diesel-PV-wind-battery, PV-wind-battery, and PV system as it does for the wind-battery hybrid system. In regard to the NPV, the wind-battery hybrid is still the cheapest option at one location (see Table 4).

From these results (Table 4) we can see that, apart from the SHS, PV-battery is the most cost effective technology for Gasa and Lunana while the diesel-PV-battery Hybrid system is the cheapest in Getena. The wind-battery system is the most viable in Yangtse due to higher wind speed there. The diesel-PV-battery hybrid system is slightly more expensive than these other options because of high operating costs of diesel based systems due to the high cost of diesel
fuel in remote areas. In all cases the simple SHS was competitive with the best hybrid system and cheaper than grid extension as shown in Fig. 5.

The Levelised Unit Cost of Electricity was also calculated to obtain the cheapest options. LUCE can be thought as the sale price at which energy must be sold to break even over the lifetime of the technology. This cost represents the generation cost, using different sources, including the costs over its lifetime, initial investment, operation and maintenance and running fuel cost for the system.

Table 5 shows the LUCE of different systems in different locations. Here again the wind-battery hybrid system is the best option for Yangtse followed by the diesel-PV-wind-battery hybrid and PV-wind-battery hybrid. The Diesel PV-battery hybrid is the cheapest option for Getena while the PV-battery hybrid has the lowest LUCE for Lunana and Gasa. The SHS option is marginally cheaper than the hybrid village power systems for Lunana and Gasa.

HOMER also calculates the break even grid extension distance (BEGD) for a standalone system compared with extending the grid line. The average cost of constructing 1 km of 11 kV line in Bhutan has been approximately US$14,327 (JICA 2005). The export price of electricity from Bhutan is Nu 2/kWh (US$0.0425/kWh). Therefore, the opportunity cost to the government of supplying electricity in the domestic market is the export price. Using the above data, the break-even grid extension distances for the lowest cost option are identified for the four places considered in this study are shown in Fig. 7.
This shows the most economic option for standalone electricity generation will be in Yangtse (wind-battery system) in terms of the break even grid distance. The BEGD varies from 1.2 km for a Wind-Battery system in Yangtse to 1.6 km for SHS in Lunana followed by 1.9 km for a Diesel-PV-Battery system in Getena. This analysis shows that renewable energy sources could provide a more cost effective means for rural electrification than grid extension in the four places considered for this study.

Sensitivity analysis

The results above are sensitive to diesel price and the cost of PV modules. A sensitivity analysis was carried out involving diesel price and PV cost to see how much the COE and NPC varies. The variation of the COE with respect to diesel price and PV cost are shown in Table 6 and Table 7 respectively. It can be observed if diesel price increases 100% from the base case, NPC increases by 6%, 2%, 5% and 1% in Gasa, Getena, Lunana and Yangstse (Table 6). Changing PV cost has more effect than changing diesel price. By decreasing PV cost only 20%, the NPC decreases in Gasa, Geneta, Lunana and Yangstse by 8.8%, 9.1%, 8.2% and 4.9% respectively (Table 7). Adding a diesel generator is an expensive option but it increases system reliability.

Conclusions

This study evaluated different options of renewable energy technologies to meet the electricity demand of some off-grid areas in rural Bhutan. Four different configurations were used: PV-diesel Hybrid, PV-wind-diesel, PV-battery and Wind-diesel in four different locations. Of these options, the wind-battery hybrid system of Yangtse is found to be the best
option, followed by the diesel-PV-wind-battery hybrid and PV-wind-battery hybrid. The diesel-PV-battery hybrid is the cheapest option for Getena while the PV-battery hybrid has the lowest LUCE for Lunana and Gasa.

From this study we can see that renewable energy technologies, such as PV-battery and wind-battery hybrids could be considered as alternatives even in the areas identified for grid connection under the Rural Electrification Master Plan in Bhutan. The COE varies, based on the type of system, diesel cost and cost of PV. Technologies like solar and wind-battery hybrids should be considered as a means of providing lighting and power for information and communication technologies like television and telecommunications in rural areas because these technologies will become viable with increases in fossil fuel costs. It was also found that the most economical option varies from one location to another, depending on the local renewable energy resources. Therefore, in choosing systems for village electrification, it is important to carefully model the proposed systems and to compare a range of options using load and resource data specific to the village.

References


Fig. 1. Bhutan's energy supply mix.

Source: Department of Energy [6].
Fig. 2. Bhutan's sectoral energy consumption.

Source: Department of Energy [6].
Fig. 3. Rural electrification achievements and projections.

Source [4].
Fig. 4. Annual global horizontal solar radiation for Bhutan.

Source: [11].
Fig. 5. Wind resource map of Bhutan.

Source: [12].
Fig. 6. Initial capital cost of the systems in different locations.
Fig. 7. Break even generation distance for the most economic energy supply options.
Table 1. Mode of energy sources used by the non-electrified households of Bhutan.

<table>
<thead>
<tr>
<th>Type of use</th>
<th>Energy sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>Kerosene 97% (They also use dry cell batteries and candles)</td>
</tr>
<tr>
<td></td>
<td>Candle 7.2%</td>
</tr>
<tr>
<td></td>
<td>Dry cell batteries 7.2%</td>
</tr>
<tr>
<td>Cooking</td>
<td>Firewood (94.7%), LPG (5.3%)</td>
</tr>
<tr>
<td>Heating</td>
<td>Firewood (100%)</td>
</tr>
<tr>
<td>Entertainment (Radio)</td>
<td>Dry cell 70.2%</td>
</tr>
</tbody>
</table>
Table 2. Summary of the input parameters for the HOMER simulation.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual maintenance cost as a fraction of capital cost for PV, batteries and inverters</td>
<td>N/A</td>
<td>0.01</td>
</tr>
<tr>
<td>Annual maintenance cost as a fraction of capital cost for SWEG</td>
<td>N/A</td>
<td>0.02</td>
</tr>
<tr>
<td>Analysis period</td>
<td>Years</td>
<td>20</td>
</tr>
<tr>
<td>Useful life of PV array</td>
<td>Years</td>
<td>20</td>
</tr>
<tr>
<td>Useful life of SWEG</td>
<td>Years</td>
<td>20</td>
</tr>
<tr>
<td>Useful life of power conditioning unit</td>
<td>Years</td>
<td>10</td>
</tr>
<tr>
<td>Inverter efficiency</td>
<td>%</td>
<td>90</td>
</tr>
<tr>
<td>Battery efficiency</td>
<td>%</td>
<td>85</td>
</tr>
<tr>
<td>Module de-rating factor</td>
<td>%</td>
<td>90</td>
</tr>
<tr>
<td>Discount rate</td>
<td>%</td>
<td>8</td>
</tr>
<tr>
<td>Diesel cost</td>
<td>US$/Litre</td>
<td>2</td>
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</tbody>
</table>
Table 3. Initial capital cost of the system (US$).

<table>
<thead>
<tr>
<th>Location</th>
<th>Diesel-PV-battery hybrid (US$)</th>
<th>Diesel-PV-wind-battery hybrid (US$)</th>
<th>PV-wind-battery hybrid (US$)</th>
<th>PV-battery hybrid (US$)</th>
<th>Wind-battery hybrid (US$)</th>
<th>Cost of individual SHS in US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasa</td>
<td>27,494</td>
<td>31,753</td>
<td>32,186</td>
<td>28,742</td>
<td>141,348</td>
<td>27,760</td>
</tr>
<tr>
<td>Lunana</td>
<td>24,539</td>
<td>28,284</td>
<td>29,745</td>
<td>25,701</td>
<td>147,620</td>
<td>26,020</td>
</tr>
<tr>
<td>Getena</td>
<td>29,431</td>
<td>33,599</td>
<td>34,629</td>
<td>31,396</td>
<td>112,144</td>
<td>30,860</td>
</tr>
<tr>
<td>Yangtse</td>
<td>27,708</td>
<td>20,352</td>
<td>21,053</td>
<td>30,369</td>
<td>16,620</td>
<td>30,120</td>
</tr>
</tbody>
</table>
Table 4. Net present value for different systems in different areas.

<table>
<thead>
<tr>
<th>Location</th>
<th>Diesel-PV-battery hybrid</th>
<th>Diesel-PV-wind-battery hybrid</th>
<th>PV-wind-battery hybrid</th>
<th>PV-battery hybrid</th>
<th>Wind-battery hybrid</th>
<th>Cost of individual SHS in US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasa</td>
<td>38,853</td>
<td>43,442</td>
<td>41,702</td>
<td>37,383</td>
<td>174,761</td>
<td>36,700</td>
</tr>
<tr>
<td>Lunana</td>
<td>35,335</td>
<td>40,042</td>
<td>39,296</td>
<td>34,448</td>
<td>182,816</td>
<td>35,040</td>
</tr>
<tr>
<td>Getena</td>
<td>43,798</td>
<td>44,069</td>
<td>40,086</td>
<td>141,409</td>
<td>34,320</td>
<td>40,020</td>
</tr>
<tr>
<td>Yangtse</td>
<td>38,737</td>
<td>29,156</td>
<td>29,350</td>
<td>38,941</td>
<td>24,489</td>
<td>39,380</td>
</tr>
</tbody>
</table>
Table 5. Levelised unit cost of electricity.

<table>
<thead>
<tr>
<th>Location</th>
<th>Diesel-PV-battery hybrid (US$)</th>
<th>Diesel-PV-wind-battery hybrid (US$)</th>
<th>PV-wind-battery hybrid (US$)</th>
<th>PV-battery hybrid (US$)</th>
<th>Wind-battery hybrid (US$)</th>
<th>Cost of individual SHS in US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasa</td>
<td>0.922</td>
<td>1.023</td>
<td>1.006</td>
<td>0.901</td>
<td>4.22</td>
<td>0.878</td>
</tr>
<tr>
<td>Lunana</td>
<td>0.841</td>
<td>0.953</td>
<td>0.943</td>
<td>0.831</td>
<td>4.412</td>
<td>0.824</td>
</tr>
<tr>
<td>Getena</td>
<td>0.953</td>
<td>1.054</td>
<td>1.063</td>
<td>0.966</td>
<td>3.415</td>
<td>0.963</td>
</tr>
<tr>
<td>Yangtse</td>
<td>0.929</td>
<td>0.699</td>
<td>0.701</td>
<td>0.94</td>
<td>0.582</td>
<td>0.944</td>
</tr>
</tbody>
</table>
Table 6. NPC and cost of electricity with variation of diesel price.

<table>
<thead>
<tr>
<th>Diesel ($/L)</th>
<th>NPC</th>
<th>COE ($/KWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gasa</td>
<td>Getena</td>
</tr>
<tr>
<td>2</td>
<td>41,935</td>
<td>39,223</td>
</tr>
<tr>
<td>2.5</td>
<td>42,581</td>
<td>39,706</td>
</tr>
<tr>
<td>3</td>
<td>43,152</td>
<td>39,856</td>
</tr>
<tr>
<td>3.5</td>
<td>43,720</td>
<td>39,856</td>
</tr>
<tr>
<td>4</td>
<td>44,289</td>
<td>39,856</td>
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</table>
Table 7. NPC and cost of electricity with variation of PV cost.

<table>
<thead>
<tr>
<th>Decrease PV cost (%)</th>
<th>NPC</th>
<th></th>
<th></th>
<th></th>
<th>COE ($/KWh)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gasa</td>
<td>Getena</td>
<td>Lunana</td>
<td>Yangtse</td>
<td>Gasa</td>
<td>Getena</td>
<td>Lunana</td>
<td>Yangtse</td>
</tr>
<tr>
<td>1</td>
<td>41,935</td>
<td>39,223</td>
<td>35,060</td>
<td>28,949</td>
<td>1.004</td>
<td>0.941</td>
<td>0.836</td>
<td>0.694</td>
</tr>
<tr>
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<td>41,011</td>
<td>38,349</td>
<td>34,341</td>
<td>28,615</td>
<td>0.982</td>
<td>0.921</td>
<td>0.819</td>
<td>0.686</td>
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<tr>
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<td>33,622</td>
<td>28,262</td>
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<td>0.9</td>
<td>0.802</td>
<td>0.679</td>
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<tr>
<td>0.85</td>
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<td>36,551</td>
<td>32,902</td>
<td>27,302</td>
<td>0.937</td>
<td>0.878</td>
<td>0.785</td>
<td>0.67</td>
</tr>
<tr>
<td>0.8</td>
<td>38,237</td>
<td>35,651</td>
<td>32,183</td>
<td>27,543</td>
<td>0.915</td>
<td>0.857</td>
<td>0.768</td>
<td>0.661</td>
</tr>
</tbody>
</table>