Techno-economic study of off-grid renewable energy system in Darma valley, Uttarakhand, India

Saakshi Chauhan[1,2,*], Rajnish Pande[2] and Subrat Sharma[1]

[1]G.B. Pant National Institute of Himalayan Environment, Almora 263 643, India
[2]Department of Economics, DSB Campus, Kumaun University, Nainital 263 001, India

Rural and remote regions of developing economies face a serious scarcity of reliable energy supply. Focus on providing electricity through renewable and off grid energy resources is becoming increasingly popular. Off the grid or decentralized renewable energy typically considers either solar or small hydro power to fill the supply deficit and increase in demand with time is generally ignored. This paper proposes a hybrid technology mix of various renewable energy options for two remote villages located in Darma valley of Uttarakhand state in the Indian Himalayan Region. Since the villages are at an average height of 3500 m amsl, they are inaccessible during winters due to heavy snowfall. Therefore, decentralized energy could be the most cost effective solution to provide electricity. This paper estimates the energy demand of these villages and identifies the most optimum off the grid solutions, and compares it with grid connected electricity supply using hybrid optimization model for electric renewables. Micro hydro energy generation was found to be the most cost effective and techno-economically viable solution. This paper also evaluates the barriers faced by remote Himalayan villages so as to achieve reliable application of the results of this study.

Keywords: Darna valley, HOMER, hybrid energy system, Indian Himalayan region, renewable energy.

THERE are about 840 million people in the world without electricity[1], and a supply of reliable, efficient and economical electricity is a challenge. Despite a significant progress in recent years, there is a shortage in supply of electricity. Goal seven of the Sustainable Development Goals set by the United Nations also focuses on the development of clean and efficient energy. Almost a fifth of global energy consumption in 2016 came from renewable energy sources, and despite significant progress made in the last decade, the gap between energy demand and energy supply in the developing economies is still persistent[1].

India has once again missed the target of becoming an energy surplus nation with a power deficit of about 0.8% for the year 2018–19 (ref. 2). A major issue in achieving electrification targets in India is the electrification of rural and remote areas. Grid extension remains the most popular measure to provide electricity, however, certain areas with hilly terrain, heavy rainfall and snowfall, etc. make it challenging for the electricity board authorities to do so in a cost effective and sustainable manner. In such cases, off grid renewable energy technologies like solar photo voltaic, micro hydro power plants, biogas systems and wind energy systems are becoming reliable. Nonetheless, such renewable energy technologies are usually focused on a single resource or technology. For example, solar rooftop systems and micro hydels are being widely used, but they are unable to fulfil the energy demands due to environmental factors like cloudy days or low rate of flow in rivers and streams during winter season. Also, relying on a single technology based system requires a high initial capital cost and hence is not very cost effective. A combination of solar, wind and hydro power has the potential to provide a reliable and economical source of energy. However, a significant research gap exists in determining the environmental and economical feasibility of hybrid energy systems, and hardly any research has been conducted in remote, rural and difficult to access villages, particularly of the Himalayan region.

Therefore, this study aimed to find the highly reliable and cost effective combination of renewable energy technology (RET) from the resources available in the vicinity of the selected study area that will meet the energy demands. We also analysed multiple hybrid systems to determine the most economically and environmentally sustainable mechanism suitable for a particular area. To achieve the said objective, we selected a village located in a remote valley of the Indian Himalayan Region (IHR); estimated the potential demand of the village; identified all the natural resources available in the vicinity of the village, and modelled different hybrid systems by combining various RETs and employing hybrid optimization model for electric renewables (HOMER) to arrive at the optimum combination of the energy resources. We finally selected a system with least net present cost (NPC), and then compared it with the cost of electricity supply through grid extension in the area. Many of the previous

*For correspondence. (e-mail: chauhansaakshi@gmail.com)

studies have focussed upon diesel generators, solar and wind energy; our study includes consumption of hydro electricity as well, in the form of micro hydro power being supplied to the village from a nearby stream. We have also included electricity demand from not just the residential sector but also the small commercial sector of the valley.

Review of literature

The purpose of this section is to determine the knowledge gaps in the existing studies and also the limitations of those studies that specifically used HOMER as an analytical tool.

HOMER is developed by National Renewable Energy Laboratory (NREL), USA, is a widely used tool for analysis of hybrid renewable energy systems. It provides the option of including multiple technologies and AC/DC loads. The software then combines the technologies and available resources and performs simulations to arrive at the most optimum solutions. In simple terms, HOMER is a modelling tool that will design an economically and environmentally feasible system for the locally available energy resources.

The software examines all the possible combinations of RET and then identifies the best combination. HOMER is frequently used for energy optimization problems and has been globally used to evaluate off the grid energy generation systems. However, there is a clear distinction between the energy resources usually incorporated in the developed and developing economies. The developed economies use advanced technologies like consumption of hydrogen fuel. Some of the examples include – study conducted by Khan and Iqbal[3] involved feasibility of combining various energy systems with hydrogen and its applicability in Newfoundland, Canada; Karakoulidis *et al.*[4] examined the replacement of conventional technologies with hydrogen technology; Giatrakos *et al.*[5] presented a hybrid renewable energy based system for Karpathos island in Greece by incorporating diesel generators with wind farms, solar photo-voltaic (SPV) and hydrogen production systems. These authors created a supply and demand model using historic data and evaluated a twenty per cent share of renewable energy in the total energy mix; Fantidis *et al.*[6] conducted a similar study in Greece using meteorological parameters and determined the profitability from utilizing SPV technology; another study in Lesvos island of Greece by Giannoulis and Haralambopoulos[7] evaluated the economic and technical aspects of using renewable energy technologies by simulating the electricity generation for a period of one year; Mestre *et al.*[8] presented a set of homogenization procedures integrated in the software package HOMER in Wien, Austria and surrounding areas; Mohammed *et al.*[9] conducted a study for Brest, France by combining photo-voltaic and fuel cell (without battery storage); and Barsoum and Vacent[10] investigated the cost of a hydrogen hybrid system and its application in remote locations by optimizing the size of the components and overall cost efficiency. Ways to increase efficiency through a high performance ratio for photo-voltaic was discussed by them and the power loss due to storage in hydrogen based systems was also depicted.

A large number of studies have been conducted for developing countries of which those that are highly relevant to this study have been evaluated. Karaghouli and Karzmerski[11] conducted a study in southern Iraq, and the demand for electricity was evaluated on the basis of the needs of the local health clinics. These authors demonstrated the role of SPV technology towards development of the region by determining the feasibility of the proposed solution and calculating the life cycle cost of the system through HOMER. Impact on cost of electricity from the changing diesel prices and rate of interest was also evaluated. The cost of electricity generated from solar photo-voltaic system was found to be only twenty five percent of that of electricity generated from a diesel system. This study, however, was conducted at a very micro-economic scale and therefore its real time application costs differed from the predicted costs.

Role of backup generators along with solar components was conducted by Givler and Lilienthal[12] in Sri Lanka. Reduction in overall system costs was explored by running simulations in HOMER of different system designs and combinations. Demand of a single home was hypothesized as a base value for calculating the overall load profile, that is, the model did not incorporate real time data. An interesting and unique part of the above study was the comparison of load threshold on the basis of variable solar radiation across the planet. HOMER simulation results presented a combination of photo-voltaic and batteries as the most optimal and cost efficient system with loads lying in the range of 3–13 kWh/day. The relation of a hybrid system with SPV showed higher cost efficiencies from a photo-voltaic system evaluated on the basis of variable solar irradiance in a particular region.

Hafez and Bhattacharya[13] compared the feasibility of oil based that is diesel generator system along with a combination of diesel and renewable energy system. The authors also compared the break-even distance of an off grid system with grid connected network of electricity supply. This is similar to our study where we have calculated the break-even distance for the two villages of Darma valley as they were highly isolated, and grid connectivity would be prone to multiple hazards such as landslides, snowfall, etc. The road to the villages is also not fully metalled and breaks down during heavy rainfall and snowfall leading to the villages being completely cut-off. This may lead to a delay in repairing the grid in case of a fault which suggests unreliability and a need to evaluate its feasibility.

Table 1. Selected examples of techno-economic analysis using hybrid optimization model for electric renewables

Reference	Technology used	Country	Demand focus
Lau *et al.*[15]	SPV–diesel hybrid	Malaysia	Not applicable in other areas due to a high demand profile
Givler and Lilienthal[12]	SPV–battery and diesel	Sri Lanka	Day to day needs
Himri *et al.*[18]	Hybrid of wind energy and diesel	Algeria	Technology options were restricted. Wind energy was added to diesel generator
Nfah *et al.*[19]	SPV, micro hydel, LPG generator, battery	Cameroon	Combination of SPV, diesel generator, micro hydel and grid connection on the basis of overall load profile for household electrification in Uganda
Ajao *et al.*[20]	SPV and wind turbine	Nigeria	Three decades of payback or return on investment duration

Shahzad *et al.*[14] conducted a study to design a least cost system in a small village in Pakistan. The study proposed a combination of photo-voltaic and biomass energy generating mechanisms, particularly for the purpose of daily needs of a community, and also for farming. The study considered demand from several farming equipments and household electric items like bulbs and fans and applied HOMER to arrive at the most optimum results. The study incorporated demand from every sector except the commercial demand, for example, demand of retail shops in the area. The study also did not include the widely available hydro energy resources in the area.

Lau *et al.*[15] compared the cost efficiency of using a diesel generator and a SPV system in a remote location of Malaysia. The authors used HOMER to perform the technical and economic assessment on the basis of energy demand from forty households. They also took into account the relatively higher prices of diesel in rural regions. The components incorporated in the model included photovoltaic system, diesel generator, batteries and inverter. The results suggested the most optimal combination would be a SPV system along with batteries. Most of the studies incorporated diesel and solar technology, however, other resources that could be optimally utilized in remote locations were frequently missed such as wind and small hydro.

Chaichan *et al.*[16] included wind energy along with solar technology to optimize a system for lighting the streets of Oman. The study compared several energy design systems: solar, wind, diesel and a hybrid wind and solar system. The results depicted that a hybrid system of solar energy, wind energy and batteries would be most economically and environmentally optimal. This study, however, only considered energy for lighting, and the high NPC even from an optimal RET based hybrid system could not be used in extreme rural context.

Elhassan *et al.*[17] designed a cost efficient integrated SPV system with a collection time of seven hours for Khartoum, Sudan. The study was conducted at a small scale and mainly for housing requirements. The demand also included power ratings of electrical appliances. The authors compared usability of hybrid renewable energy systems for a solitary or a single home with multiple houses in one building and found that designing a system for the latter would be more efficient. Wind energy was also included in the components and assessed with the help of HOMER, however, this component was not found to be significantly efficient.

Similar case studies have been conducted and Table 1 summarizes the choice of technology, country of application and demand focus of the respective studies.

It was observed that most of the studies took into account either one or two technologies and the focus was on supplying electricity to either a particular area like a health centre or a street or domestic requirements, but did not take into account the commercial, residential, community and agricultural requirements. We have integrated these factors into our study.

Methodology

The present study used the HOMER software, created by the National Renewable Energy Laboratory, United States. It evaluates the technical and economic viability of different combinations of hybrid renewable energy based power systems by taking into account the resource availability of the selected region, and the cost of power generating components. These components could include renewable energy mechanisms like solar, wind and hydro and also conventional means like a diesel generator. The application also provides an option to integrate batteries into the system. The framework of the present study is depicted in Figure 1. The sub-sections mentioned in Figure 1 like load profiles and the locally available resources that were used to fulfil the demand of the villages are indicated in Figure 2. We obtained the data on solar irradiance, wind speed, water discharge of a closely located stream, and the availability of biomass through primary and secondary means (details mentioned in respective figures), and the cost of components that utilized these resources to produce energy. We used HOMER to simulate different combinations of these energy producing mechanisms to arrive at the most cost effective solution. We also conducted sensitivity analysis that accounted for the fluctuating wind speed, solar irradiance or water discharge. The economic evaluation was based on the life cycle cost (LCC) or life cycle assessment which included both fixed and variable costs such as capital cost, installation cost and operation and maintenance cost. The software performed simulations based on the data that had been fed; it primarily acted upon the estimated demand of the village and the quantity of resources. The aim was to fulfil the demand of the village by using the available resources, and based on the cost efficiency of several combinations, we designed a system most suitable for our study area.

We considered small/micro hydro power (MHP), solar energy, wind energy, biodiesel generator and biomass to design an optimal system. The biodiesel generator and hydro power were connected to the AC side and batteries were connected to the DC side. SPV and wind turbine were also connected to the DC side. A diesel generator had been added only as a back up in times of less resource availability (Figure 2).

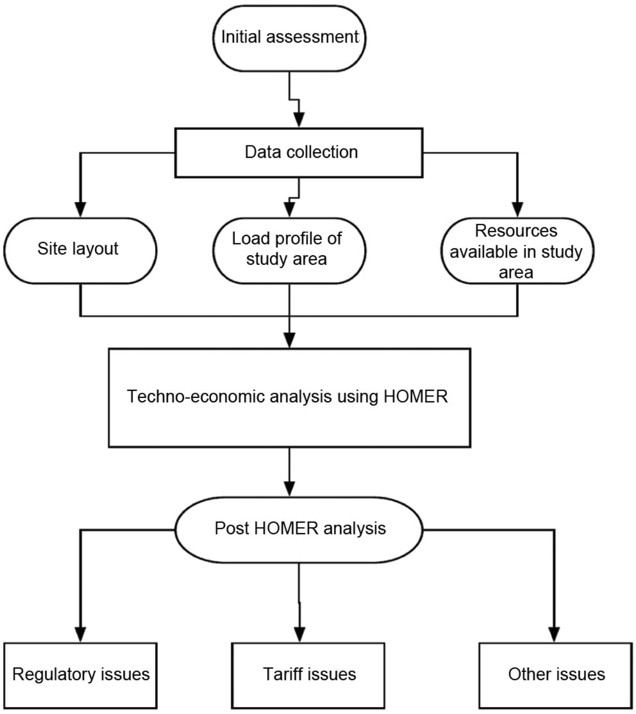

Figure 1. Framework of the analysis in the present study.

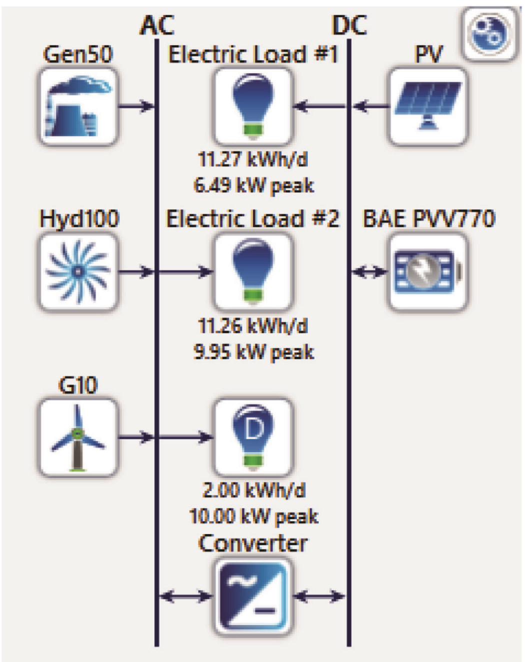

Figure 2. Selected energy technologies for the hybrid design.

Study area

The villages Dugtu and Dantu were selected as the study sites. The villages are located in the Darma valley, which is a highly remote and rural location in Dharchula tehsil of district Pithoragarh in the Indian state of Uttarakhand. Dugtu and Dantu are two set of villages which are adjacent to one another, and are only separated by a stream coming directly from the Panchachuli glaciers. Panchachuli glaciers emerge from the five Panchachuli peaks which stand at a height of 6300–6900 m amsl. The geographic profile and other details of the study sites are listed in Table 2. The nearest town is Dharchula which is at a distance of 70 km from the villages. Dugtu and Dantu are located at an elevation of 3300 m and 3400 m amsl respectively. The area is surrounded by mountains, meadows and forests of Rhododendron. The weather is cold even during the summers with an average temperature of 10°C. During the winters the place will be freezing with temperatures well below 0°C at all times. Although Uttarakhand Renewable Energy Development Agency (UREDA) has constructed a micro hydro project near the villages, yet, even after 3 years of installation, the place is not receiving electricity making it ideal for a RET hybrid system. Since the villages are too distant from a town, grid connection may not be a viable solution as the entire valley is prone to landslides. Heavy snowfall during the winter

Table 2. Details of the study area

Particulars	Dugtu	Dantu
Tehsil	Dharchula	Dharchula
District	Pithoragarh	Pithoragarh
State	Uttarakhand	Uttarakhand
Country	India	India
Latitude	30°14′51″N	30°15′11″N
Longitude	80°32′44″E	80°32′32″E
Elevation (m)	3300	3465
Rivers/streams	1	1
Fresh water resource	1	1
Grid electricity connection	0	0
Total households	78	42
Education facilities	0	0
Medical facilities	0	0
Post office	1	0

season makes the villages absolutely inaccessible. The road to the villages was only constructed recently and is not metalled yet which makes it inaccessible during summer as well as at times when heavy rains wash out parts of the road or bring down debris from the hills. The villagers also move to a lower altitude (preferably to Jauljibi or Dharchula) during harsh winters and therefore we have only considered the load for the duration when the area is inhabited by either tourists or the native population.

Figure 3 show satellite view of the selected study area. Figure 4 shows a satellite view of both the villages in one frame and it can be observed that the two villages are located close to each other and are only separated by a stream flowing between them. This stream will be used as the hydro power resource in the hybrid system.

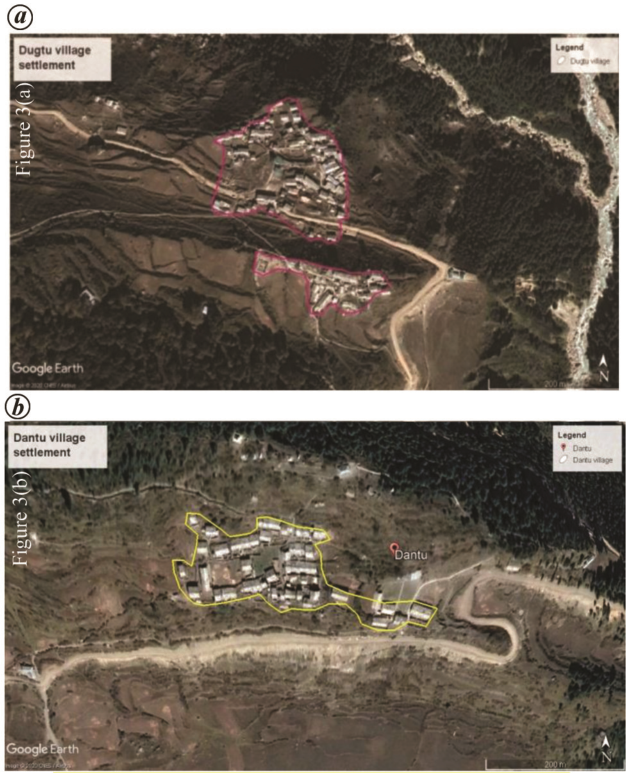

Figure 3. Aerial view of (***a***) Dugtu village and (***b***) Dantu village.

Figure 4. Aerial view of the study sites and Neola stream.

Load assessment

The electricity demand of small or remote villages and hamlets is generally not high. Villages located at high altitudes do not need fans, coolers or refrigerators due to the already low temperatures in the area. Dugtu and Dantu being located at extremely high altitude above sea level has a cold climate throughout the year and electricity is only required for lighting and heating purpose. Rural, commercial and small scale agrarian businesses may also require a certain amount of electricity, but in the selected study areas the main occupation, besides small scale agriculture was harvesting *Ophiocordyceps sinensis*, a parasitic fungus in the body of a caterpillar. Other occupation in the agrarian sector included growing potatoes, millets and rearing sheep.

In the study area, energy load requirement was estimated based on primary data collected. The demand was estimated only for the months of April to October as the habitants generally leave the valley and move to lower areas like Dharchula to escape harsh winters. In the month of November, a few residents remain to cater to the tourist inflow. However, tourist inflow will be extremely low at that time due to harsh weather and the energy demand is assumed to be negligible. The demand estimation also considered the number of electrical devices used in each household and their duration. Since the villages were not already connected with grid electricity, an increase in demand in terms of heating equipment like water heaters and room heaters had been assumed on the basis of direct interview conducted with the residents. The current demand of the village as well as the estimated demand is shown in Table 3.

Figures 5 and 6 depict the seasonal, yearly and hourly load profile of village Dugtu and Dantu respectively. Since the habitants vacated the village during the winter months, the overall load during that time was considered zero and is shown in Figures 5 *a* and 6 *a* and 5 *b* and 6 *b*. Figures 5 *c* and 6 *c* depict the maximum load observed during morning and evening hours as water heaters were generally used in the morning and room heaters in the evening. The load demand in Dugtu village was 91 kWh/day and 52.85 kW peak. It had a load factor of 0.07. The load demand in Dantu village was 42 kWh/day and 36.85 kW peak. It had a load factor of 0.05.

Figure 7 shows the deferrable load in the area. It was estimated by taking into account the religious festivities and high tourist influx for specific months.

Resource assessment

Micro hydro, wind, solar and diesel generator have been considered for the hybrid design. The data for solar energy and wind energy resources were collected from NASA's surface meteorology and solar energy report. The average

Table 3. Load profile for Dugtu and Dantu

Load	Numbers/units	Power (W)	Average (h/day)	Watt-hours day
Dugtu				
Domestic load				
Electric bulbs/CFL	64	10	4	2560
Electric bulbs/CFL	12	20	5	1200
Loud speaker	1	60	0.17	10.2
Commercial load				
Electric bulb/CFL	2	10	4	80
Estimated increase in load after electrification				
Room heater	12	2000	1	24,000
Room heater	17	1000	1	17,000
Water heater	19	2000	0.5	19,000
Water heater	23	1000	0.5	11,500
Overall load				75,350
Dantu				
Domestic load				
Electric bulbs/CFL	28	10	4	1120
Electric bulbs/CFL	8	20	5	800
Commercial load commercial load				
Electric bulb/CFL	2	10	5	100
Estimated increase in load after electrification				
Room heater	5	2000	1	10,000
Room heater	7	1000	1.5	10,500
Water heater	13	2000	1	26,000
Water heater	17	1000	1.5	25,500
Overall load				63,520

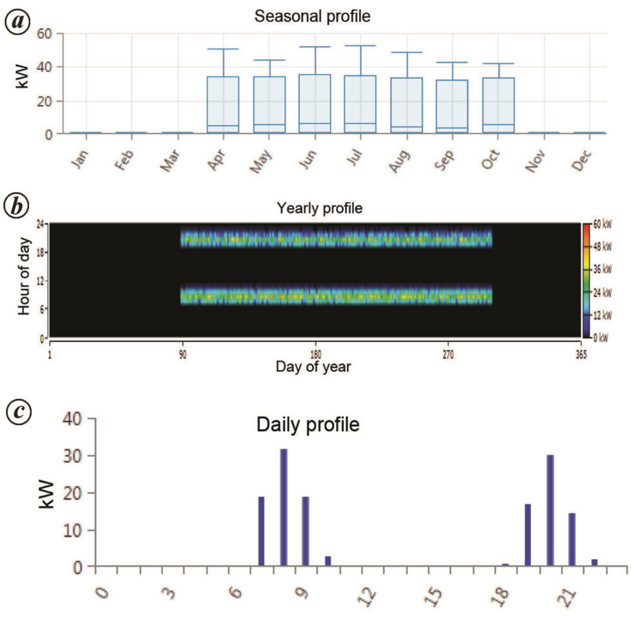

Figure 5. Seasonal (***a***), yearly and hourly (***b***) and everyday hourly (***c***) profile of Dugtu village.

solar radiation was 4.81 kWh/m^2/day. Month-wise daily radiation and clearness index is provided in Figure 8. Likewise, the annual average wind speed at anemometer height of 50 m was observed to be 5.55 m/s. The average monthly wind speed is given in Figure 9.

The data for hydro energy resource was collected by calculating the discharge of Neola stream (the stream originating from the snout of Panchachuli glaciers) that flows between Dugtu and Dantu. The discharge was recorded using the standard methodology developed by Bansal[21] using the following formula

$$Q = A * V, \quad (1)$$

where Q is the discharge, A the depth of cross section and V is the velocity of water in the cross section. Figure 10 shows the average monthly rate of flow or discharge of Neola river in Darma valley.

Details of components

We used solar energy, micro hydro power plant, wind energy and diesel generator as a back up to create the design of the hybrid system. Batteries and converter were also attached to store and convert the electricity.

The SPV panels were wired together in a sequence. The state of Uttarakhand provides large subsidies on solar panels, and therefore, the overall capital cost is relatively less in this area. The capital cost was taken as US$1400 and the replacement cost as US$1200 for 1 kW system. These values were based on the current market value of the solar panels in the state. Also, solar panels require little maintenance and therefore the cost of operation and maintenance (O and M) was taken as US$10 per year. The cost per kW included installation, logistics and other miscellaneous expenses. To account for the temperature in the area and dust/snow on the panels, the de-rating factor was set to 90%. The SPV was linked to a DC system with a 25 year life span and had been fixed with no tracking system, facing south and tilted at an angle of 45°.

A generic 10 kW turbine was proposed for wind energy. Since Dugtu and Dantu are located at significantly high elevations, the wind speed and availability is usually high. The G10 wind turbine gives a DC output of 10 kW. The turbine was at a hub height of 24 m with a life span of 20 years. The cost per unit was taken as US$28,000 and replacement cost US$20,000. The maintenance cost was taken as US$200. The cost of capital included the cost of installation and logistics. These costs have been considered on the basis of previous studies and literature[22–25].

A generic small genset generator was considered for providing electricity back up in times of low resource availability. The initial capital cost and replacement cost was estimated on the basis of current market price of diesel generator in the state. The capital cost per kW was found to be US$344 with the same replacement cost and a maintenance cost of US$0.030 per operating hour. The number of hours the generator was estimated to operate in a year formed the basis for determining the operational cost. The generator was connected to an AC output with a 150,000 h of operating life span.

Since the study areas were richly endowed with water resource, an output of 100 kW was designed for the small hydro power plant. The net head was considered to be 10 m and the design flow of the turbine was set at 1500 litres/sec which was considered on the basis of average minimum flow available in the area. However, a system with lower head and higher design flow may also be used. The efficiency of the turbine was 80% with a pipe head loss of 15%. The cost was estimated on the basis of methodology developed by Mishra *et al.*[26]. The following formula was used

$$C = 6.882H^{-0.0782}P^{0.6369}, \quad (2)$$

where C is the cost/kW in Indian rupees (lakhs), H the head (m) and P is the capacity (kW).

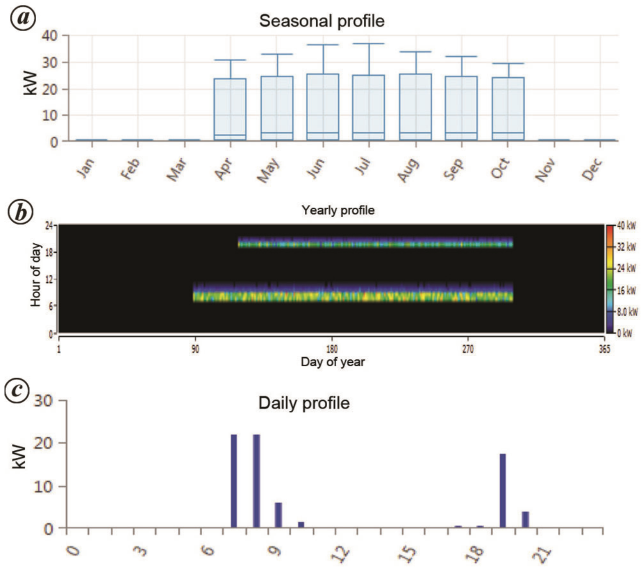

Figure 6. Seasonal (***a***), yearly and hourly (***b***) and everyday hourly (***c***) profile of Dantu village.

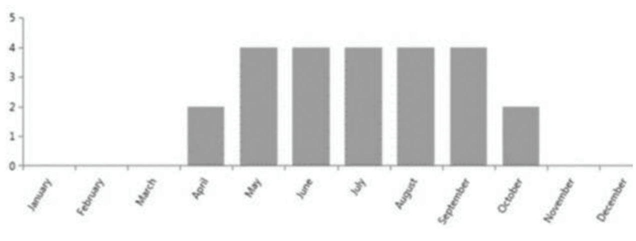

Figure 7. Deferrable load of Dugtu and Dantu.

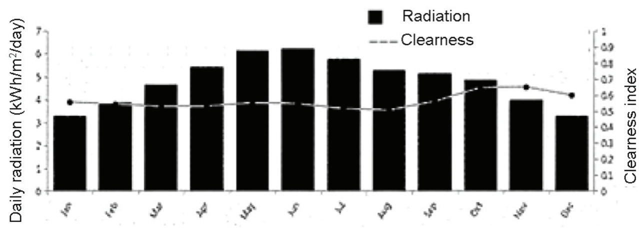

Figure 8. Month-wise daily radiation data and clearness index of study sites. (Source: NASA surface meteorology and Solar Energy Database.)

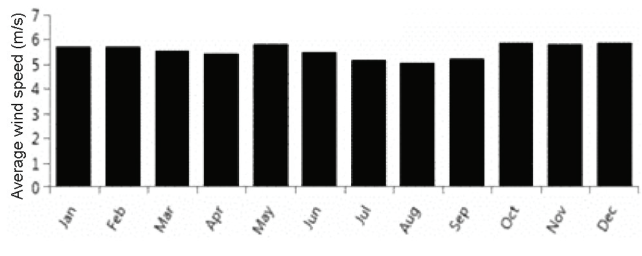

Figure 9. Average monthly wind speed of study sites. (Source: NASA surface meteorology and Solar Energy Database.)

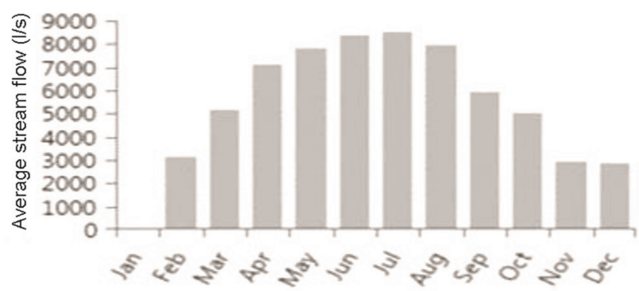

Figure 10. Water discharge in Neola stream.

Based on eq. (2), the cost was estimated to be US$149,555 (ref. 26), with a replacement cost of US$110,800 (ref. 27). The cost of O and M was estimated to be US$12,000/year (ref. 27). An AC output with a life span of 25 years was set for the small hydro power plant.

To maintain a constant voltage as well as to account for low energy production at certain times, batteries were being used as back up. The capital cost of the batteries was set at US$600 with a replacement cost of US$500. The O and M cost was set at US$50. The battery system selected was BAE PVV 770 which was a two volt battery. The nominal capacity of this component was 1.58 kWh.

The 1 kW converter selected for this system had a life span of 15 years. The inverter efficiency and the rectifier efficiency was set at 90% and 85% respectively[28]. The capital cost of the converter was US$700 (ref. 28). The O and M cost was set at US$100 per annum with a replacement cost of US$600 (ref. 28).

Sensitivity of components

Since several key variables of the energy resources like wind speed, average discharge and fuel prices are quite uncertain, sensitivity factors for these uncertainties have been considered in the RET design. The sensitivities entered for diesel prices were US$1 and US$0.85. The sensitivities entered for wind speed were 5.8 m/s and 4.5 m/s. The sensitivities entered for discharge of Neola stream were 4000 l/s and 1000 l/s.

Economic modelling

The currency for evaluation of this system including all economic calculations are in terms of US dollars.

HOMER minimizes the total NPC to select the most optimal system design for the hybrid RET system. The annual discount rate for the present project was set at 10% with a lifespan of 25 years. The fixed cost or the capital cost of the system was set at US$10,000 with the operational/maintenance cost set at US$500 per annum. Civil constructions, wages and salaries, logistic materials, licenses, approvals (administrative and governmental) as well as the miscellaneous costs are the fixed capital costs. In this study, HOMER compared the total NPC of the hybrid energy system with the cost of grid extension in order to determine which one was viable. Capital cost of grid extension was set at US$8000 and the O and M cost was US$1500 per annum (ref. 29). The grid power price based on state data was assumed to be US$0.44/kWh (ref. 29).

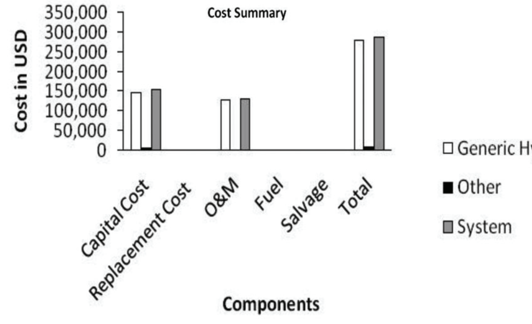

Figure 11. Cost summary of renewable energy technology components.

Results and discussion

This section presents the results of optimization and sensitivity analysis followed by economic and environmental aspects of the system.

Optimization results

The most optimum source of energy found from the analysis was a stand-alone micro hydro system with a capacity of 100 kW working at a nominal capacity of 97.1 kW. None of the other components were selected as part of the optimized result, as hydro power in the area was highly cost efficient and reliable. The total NPC and capital cost from this system were US$289,633 and 156,555 respectively. Figure 11 shows cost summary of the components of the RET system in US dollars.

Table 4 depicts the technical and economic details of the three best hybrid RET designs simulated by HOMER followed by the least cost design that employed all the components, initially assumed to be a part of the system. Table 4 indicates that the best and second best hybrid systems are almost alike in terms of cost and efficiency. The second best hybrid suggested including 40 W of solar power. Dugtu and Dantu have approximately 320 W

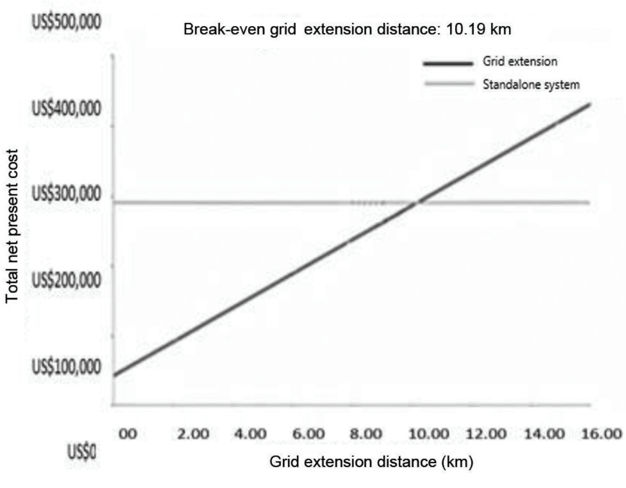

Figure 12. Break-even grid extension distance.

Table 4. Techno-economic details of selected hybrid renewable energy technology designs

Configurations	Unit	Best hybrid	Second best hybrid	Third best hybrid	Least cost hybrid design utilizing all components
SPV	kW	0	0.0417	0	0.521
Wind energy	kW	0	0	0	10
Diesel generator	kW	0	0	0	50
Battery	Quantity	0	0	1	1
Hydro energy	kW	97.1	97.1	97.1	97.1
Converter	kW	0	0.0740	0.201	0.625
NPC	US$	289,633	289,798	291,657	339,996
COE	US$	2.99	2.99	3.01	3.51
Operating cost	US$/year	12,300	12,305	12,419	12,614
Initial capital	US$	156,555	156,665	157,296	203,522
Fraction of renewable energy	%	100	100	100	100
Total fuel	L/year	0	0	0	0
Mean output	kW	68.4	68.4	68.4	68.4
Production	kW h	598,995	599,060	598,995	603,944
AC primary load	kWh/year	8,222	8,222	8,222	8,222
DC primary load	kWh/year	0	0	0	0
Deferrable load	kWh/year	734	734	734	734
Excess electricity	kWh/year	590,039	590,104	590,039	594,988

Table 5. Techno-economic aspects of the optimized micro hydro plant

Quantity	Value
Nominal capacity (kW)	97.1
Mean output (kW)	68.4
Capacity factor (%)	70.4
Total production (kWh/year)	598,995
Minimum output (kW)	0
Maximum output (kW)	118
Hydro penetration (%)	7,258
Hours of operation (kWh/year)	6,552
Levelized cost (US$/kWh)	0.0431

capacity of solar panels already installed by an NGO. This implies that the second best hybrid RET system can also be installed with an initial capital cost less than that is indicated in the model. Figure 12 shows the break-even grid extension distance as simulated by HOMER.

It can observed from Figure 12 that the break-even distance for grid extension is 10.19 km which means that grid extension will only be cost efficient for a distance of or less than 10.19 km. However, For a distance greater than this, the stand-alone system comprising of micro hydro power plant will be more cost efficient. Since hydro power is the only source of energy that has proven to be efficient and reliable in the designed RET, some of the techno-economic aspects of the micro hydro power plant are depicted in Table 5. Thus, it is evident that a stand-alone micro hydro plant is more efficient as the levelized cost of electricity was only US$0.0431 kWh/year (Table 5) against the grid extension cost of US$0.44 kWh/year.

Sensitivity analysis and emissions

Sensitivity analysis takes into account all the uncertain parameters of a variable, for example, changes in wind speed or clearness index or daily solar radiation. HOMER also takes into account increasing or decreasing load as per the demand data that has been fed into the software. Since the best RET system as per the simulations consisted only of a micro hydro power plant, we considered only the changes in flow rate or discharge of the stream.

Since the only component of the RET system was micro hydro, we did not include any other component in the sensitivity analysis. The sensitivity parameters set for discharge or flow rate of Neola stream were 1000 l/s and 4000 l/s. Even though a discharge of 1000 l/s is highly unlikely as the area is richly endowed with hydro resources, yet for special cases like less snowfall or rainfall during a particular year or climatic factors like global warming, a discharge of the said value was considered. It was observed that even with that low rate of flow, the amount of energy generated remained the same and the demand would be completely fulfilled. Therefore, sensitivity factors play no role as far as micro hydro in selected study sites is concerned.

As, only a micro hydro power plant was considered as the best RET system design, which was 100% renewable, the emissions were completely non-existent for this particular model. But, some amount of emissions would be existing as shown in the fourth design in Table 5. However, this design is completely cost inefficient and hence will not be considered for actual installation.

Conclusion

The optimal RET supply system utilized a 100 kW hydro power mechanism and none of the other resources available in the study area. However, it was observed that even a 100 kW power plant was too large for the area's current needs. This may significantly increase after the introduction of steady supply of electricity, but for the time being, most of the electricity generated through the plant will not be used. The solution to this lies in either making use of fewer turbines so as to generate just the required amount of electricity or to generate the nominal capacity (97.1 kW), and distribute it in the entire valley. The valley has 12 unelectrified villages nearby and the extra amount of energy generated could be used to fulfil the demands of these villages.

The projects in such remote locations may face multiple developmental barriers such as hostile natural environment, geo-political conflicts and outmigration of locals to settle in cities. Any or all of the above mentioned reasons could play a role in invalidating the predicted increase in demand, which may be one of the reasons why investors are not keen on setting up infrastructure or making big investments in extremely remote regions.

Tariff will also play a crucial role as investors will be keen on recovering the cost of the project. However, this will be a risk in remote and rural regions, since people of such villages would never have paid an electricity bill before, and therefore introducing an extra expenditure would rather be a difficult process.

There will always be limitations to any kind of new project that is introduced. The pursuit of a technologically realizable and economically feasible solution for a decentralized or off the grid electrification in remote and inaccessible villages has led to a least cost solution, which is a 100 kW hydro power plant. This mechanism will meet the demands of the consumers at a relatively low cost of electricity (as compared to grid electricity). It was also observed that a much smaller plant, for example, even a 20–30 kW hydro power system could easily bridge the gap between demand and supply. However, availability of such ample resource also showed a possibility of electrifying nearby villages in the near future, which is why we decided to keep the capacity as 100 kW. The main challenges associated with integrating such renewable energy technologies in remote areas are mainly political (to obtain permits and clearances to set up such a system) and financial (lower tariffs in remote areas discourage investors). Technical challenges will exist but mainly from a construction perspective as the high altitude Himalayan locations are prone to natural hazards. Finally, it is important to note that such projects can only work from government support and community participation. Further work is required in terms of spreading the access to electricity to the entire valley. Similarly, a systematic approach towards building a hybrid design in other high altitude and remote locations can prove to be efficient and reliable not only for economic development but also for environmental conservation.

1. The Energy Progress Report, Tracking SDG7, IRENA, 2019; https://trackingsdg7.esmap.org/
2. Annual Report, Central Electricity Authority, Ministry of Power, Government of India, 2019.
3. Khan, M. J. and Iqbal, M. T., Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland. *Renew. Energ.*, 2005, **30**, 835–854.
4. Karakoulidis, K., Mavridis, K., Bandekas, D. V., Adoniadis, P., Potolias, C. and Vordos, N., Techno-economic analysis of a stand-alone hybrid photovoltaic-diesel–battery-fuel cell power system. *Renew. Energ.*, 2011, **36**(8), 2238–2244.
5. Giatrakos, G., Tsoutsos, T. D., Mouchtaropoulos, P. G., Naxakis, G. D. and Stavrakakis, G., Sustainable energy planning based on a stand-alone hybrid renewable energy/hydrogen power system: application in Karpathos Island, Greece. *Renew. Energ.*, 2009, **34**(12), 2562–2570.
6. Fantidis, J. G., Bandekas, D. V., Potolias, C. and Vordos, N., Cost of PV electricity – case study of Greece. *Solar Energ.*, 2013, **91**, 120–130.
7. Giannoulis, E. D. and Haralambapoulos, D. A., Distributed generation in an isolated grid: methodology of case study for Lesvos–Greece. *Appl. Energ.*, 2011, **88**(7), 2530–2540.
8. Mestre, O. *et al.*, HOMER: a homogenization software-methods and applications. *Quart. J. Hung. Meteorol. Ser.*, 2013, **117**(1), 47–67.
9. Mohammed, O. H., Amirat, Y., Benbouzid, M. and Elbaset, A. A., Optimal design of a PV/fuel cell hybrid power system for the city of Brest in France. *First Int. Conf. Green Energy ICGE*, Sfax, Tunisia, 2014, pp. 119–123.
10. Barsoum, N. N. and Vacent, P., Balancing cost, operation and performance in integrated hydrogen hybrid energy system. First Asia International Conference Modelling and Simulation, AMS'07, Phuket, Thailand, 2007, pp. 14–18.
11. Al-Karaghouli, A. and Kazmerski, L. L., Optimization and life-cycle cost of health clinic PV system for a rural area in southern Iraq using HOMER software. *Solar Energ.*, 2010, **84**(4), 710–714.
12. Givler, T. and Lilienthal, P., Using HOMER software, NREL's micropower optimization model, to explore the role of gen-sets in small solar power systems, Case Study: Sri Lanka. NREL Technical Report NREL/TP-710-36774, 2005.
13. Hafez, O. and Bhattacharya, K., Optimal planning and design of a renewable energy based supply system for microgrids. *Renew. Energy*, 2012, **45(C)**, 7–15.
14. Shahzad, M. K., Zahid, A., Rashid, T., Rehan, M. A., Ali, M. and Ahmad, M., Techno-economic feasibility analysis of a solar-biomass off grid system for the electrification of remote rural areas in Pakistan using HOMER software. *Renew. Energ.*, 2017, **106**, 264–273.
15. Lau, K. Y., Yousof, M. F. M., Arshad, S. N. M., Anwari, M. and Yatim, A. H. M., Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions. *Energy*, 2010, **35**(8), 3245–3255.
16. Chaichan, M., Kazem, H. A., Mahdy, A. M. J. and Waeely, A. A. A., Optimal sizing of a hybrid system of renewable energy for lighting street in Salalah-Oman using Homer software. *Int. J. Sci. Eng. Appl. Sci.*, 2016, **2**(5), 157–164.
17. Elhassan, Z. A. M., Zain, M. F. M., Sopian, K. and Abass, A. A., Design and performance of photovoltaic power system as a renewable energy source for residential in Khartoum. *Int. J. Phys. Sci.*, 2012, **7**, 4036–4042.
18. Himri, Y., Stambouli, A. B., Draoui, B. and Himri, S., Techno-economical study of hybrid power system for a remote village in Algeria. *Energy*, 2008, **33**(7), 1128–1136.
19. Nfah, E. M., Ngundam, J. M., Vandenbergh, M. and Schmid, J., Simulation of off-grid generation options for remote villages in Cameroon. *Renew. Energ.*, 2008, **33**(5), 1064–1072.
20. Ajao, K. R., Oladosu, O. A. and Popoola, O. T., Using HOMER power optimization software for cost benefit analysis of hybrid-solar

power generation relative to utility cost in Nigeria. *Int. J. Recent Res. Appl. Stud.*, 2011, **7**, 96–102.
21. Bansal, R. K., *A Textbook of Fluid Mechanics and Hydraulic Machines*, Laxmi Publications, New Delhi, 2017, 9th edn.
22. https://www.conserve-energy-future.com/windenergycost.php
23. Kumar, J. C. R., Kumar, V. D. and Majid, M., Wind energy programme in India: emerging energy alternatives for sustainable growth. *Energy Environ.*, 2019, **30**(7), 1135–1189.
24. Sen, R., Small wind power perspective, 2014; https://mnre.gov.in/file-manager/UserFiles/Presentations-NWM-09012014/Rajshree-Sen.pdf
25. Birkhimer, N., Mbongo, W., Stockton, B. and Tice, J., *Wind Energy*; https://www.purdue.edu/discoverypark/energy/assets/pdfs/energy-camp-presentations/Students%20project%20presentation_Wind%20-Energy_Bohr%20group.pdf
26. Mishra, S., Singal, S. K. and Khatod, D. K., Costing of small hydropower projects. *Int. J. Eng. Technol*., 2012, **4**, 239–242.
27. Sen, R. and Bhattacharyya, S. C., Off-grid electricity generation with renewable energy technologies in India: an application of HOMER. *Renew. Energ.*, 2014, **62**, 388–398.
28. Deshmukh, M. K. and Deshmukh, S. S., Modelling of hybrid renewable energy systems. *Renew. Sustain. Energ. Rev.*, 2008, **12**, 235–249.
29. Nouni, M. R., Mullick, S. C. and Kandpal, T. C., Providing electricity access to remote areas in India: an approach towards identifying potential areas for decentralized electricity supply. *Renew. Sustain. Energ. Rev.*, 2008, **12**(5), 1187–1220.

ACKNOWLEDGEMENTS. The authors thank the National Mission on Himalayan Studies (NMHS; Fellowship Programme) and the Ministry of Environment, Forest and Climate Change; research scholars of GB Pant National Institute of Himalayan Environment and Sustainable Development and Ajay Bhoj, Nidhi Kunwar, Kuldeep Singh Rautela and Dilip Kumar of NMHS for their support.

Received 19 August 2020; revised accepted 19 August 2021

doi: 10.18520/cs/v121/i9/1216-1226