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Off-grid Electricity Generation with Renewable Energy Technologies in India: An Application of HOMER

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Abstract

Renewable energy-based off-grid or decentralised electricity supply has traditionally considered a single technology-based limited level of supply to meet the basic needs, without considering reliable energy provision to rural consumers. The purpose of this paper is to propose the best hybrid technology combination for electricity generation from a mix of renewable energy resources to satisfy the electrical needs in a reliable manner of an off-grid remote village, Palari in the state of Chhattisgarh, India. Four renewable resources, namely, small-scale hydropower, solar photovoltaic systems, wind turbines and bio-diesel generators are considered. The paper estimates the residential, institutional, commercial, agricultural and small-scale industrial demand in the pre-HOMER analysis. Using HOMER, the paper identifies the optimal off-grid option and compares this with conventional grid extension. The solution obtained shows that a hybrid combination of renewable energy generators at an off-grid location can be a cost-effective alternative to grid extension and it is sustainable, techno-economically viable and environmentally sound. The paper also presents a post-HOMER analysis and discusses issues that are likely to affect/ influence the realisation of the optimal solution.

Keywords: hybrid systems, off-grid electrification, HOMER, India.

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Abbreviations

COE: Cost of Energy

Km: Kilometre

EDL: Economical Distance Limit

RET: Renewable Energy Technology

RES: Renewable Energy Sources

GHG: Green House Gases

LCC: Life Cycle Cost

LUCE: Levelized Unit Cost of Electricity

NPC: Net Present Cost

O&M: Operation and Maintenance

BET: Bio Energy Technology

T&D: Transmission and Distribution

SPV: Solar Photovoltaic’s

BDG: Bio-Diesel Generator

SHP: Small Hydro Power

B100: 100% Pure Biodiesel

DG: Diesel Generator

MNRE: Ministry of New & Renewable Energy, India.

1. Introduction

With about 1.3 billion people in the world (or about 1 in 5) without access to electricity in 2010 [1], the challenge of providing reliable and cost-effective services remains one of the major global challenges facing the world in this century. Although grid extension still remains the preferred mode of rural electrification [2], extension of the central electricity grid to geographically remote and sparsely populated rural areas can either be financially unviable or practically infeasible. Off-grid options can be helpful in such cases.

Moreover, the efforts in using renewable energies have often focussed on single technologies. For example, Solar Home Systems (SHS), solar photovoltaic systems and micro-hydro power have been widely used, but such options are often unable to cater to consumers' needs adequately and reliably due to limited resource availability arising from variability of resources. Reliance on a single technology generally results in an over-sizing of the system, thereby increasing the initial costs. A hybrid system design can overcome the intermittent nature of renewable energy sources (RES), the over-sizing issue and enhance reliability of supply. Yet, hybrid systems have received limited attention due to their increased complexity and hardly any work has considered the issue of reliable supply of electricity in a rural context[1].

The purpose of this study is to find the best combination of RET from the available resources in a given village location that can meet the electricity demand in a reliable and sustainable manner and to analyse whether such a hybrid option is a cost effective solution or not. To achieve this objective, we use an example of an Indian village, estimate the potential demand, identify the available resources, model electricity generation based on multiple combinations of RETs with the application of HOMER software, select the best option based on the cost of electricity generation and then compare these performance indicators to grid extension related costs. Our choice of the tool is influenced by its popularity, ease of use and flexibility. Despite our reliance on HOMER, our contribution arises from four novel features: 1) most of the studies in the past have considered wind turbines, solar power and diesel technologies whereas we have considered four renewable

[1] By reliable supply we imply round-the-clock supply or supply on demand. In most studies, a limited period of supply is considered for rural areas. This is not the case in this study.

technologies namely micro-hydro, solar PV, wind turbines and bio-diesel thereby pushing the hybrid technology combinations; 2) the reliability of supply, which has not received adequate attention in the literature, is considered as a main supply objective; 3) we have included productive use of electricity in commercial and agricultural activities in addition to domestic energy needs, thereby enlarging the scope of the study; and 4) we have gone beyond a typical HOMER application by considering pre and post HOMER analysis (discussed in sections 3.1 and 5 in more detail).

The organisation of the paper is as follows: section 2 presents a review of related studies; section 3 briefly presents HOMER, section 4 presents the case study and results obtained from the study. Section 5 then presents the post-HOMER analysis, while concluding remarks are presented in section 6.

2. Literature Review

The purpose of the literature review presented here is twofold: first, this provides evidence of knowledge gap that justifies the need for this work; and second, it also provides support for the methodology used in the study and is a source of information for comparison, triangulation and referencing. Given the above purpose, we use the literature to show the limitations of existing studies by focusing mainly on studies that relied on HOMER as the analytical tool.

HOMER (Hybrid Optimisation Model for Electric Renewables), developed by NREL (National Renewable Energy Laboratory, USA) appears repeatedly in the literature as a preferred tool. It can handle a large set of technologies (including PV, wind, hydro, fuel cells, and boilers), loads (AC/DC, thermal and hydrogen), and can perform hourly simulations. HOMER is an optimization tool that is used to decide the system configuration for decentralized systems. It has been used both to analyse the off-grid electrification issues in the developed as well as developing countries. In the case of developed countries, often advanced fuel systems such as hydrogen are considered. Examples of such studies include the following Khan and Iqbal [3] who investigated the feasibility of a hybrid system with hydrogen as energy carrier in Newfoundland, Canada; Barsoum and Vacent [4]; Karakoulidis et al. [5], Giatrakos et al. [6] and Türkay and Telli [7].

For developing countries, a large number of studies exist and a detailed review of this literature is beyond the scope of this paper. Instead we focus on a selected set for our purpose. Givler and Lilienthal [8] conducted a case study of Sri Lanka where they identified when a PV/ diesel hybrid becomes cost effective compared to a stand-alone small solar home systems (50 W PV with battery). This study considers an individual household base load of 5W with a peak of 40 W, leading to a daily load average of 305 watt-hours. Through a large number of simulations, the study found that the PV-diesel hybrid becomes cost effective as the demand increases. However, this study focuses on the basic needs as such and does not include productive use of energy.

Munuswamy et al. [9] compared the cost of electricity from fuel cell-based electricity generation against the cost of supply from the grid for a rural health centre in India, applying HOMER simulations. The results showed beyond a distance of 44km from the grid, the cost of supply from an off-grid source is cheaper. This work just considered the demand of a rural health centre and was not part of any traditional rural electrification programme.

Hafez and Bhattacharya [10] analysed the optimal design and planning of renewable energy-based micro-grid system for a hypothetical rural community where the base load is 600 kW and the peak load is 1183 kW, with a daily energy requirement of 5000 kWh/day. The study considers solar, wind, hydro and diesel resources for electricity generation. Although the study considers electricity demand over 24 hours, the purely hypothetical nature of the assumptions make the work unrealistic for many off-grid areas of developing countries.

Lau et al. [11] analysed the case of a remote residential area in Malaysia and used HOMER to analyse the economic viability of a hybrid system. The study uses a hypothetical case of 40 households with a peak demand of 2 kW. The peak demand is 80kW and the base demand of around 30 kW is considered in the analysis. Although such high rural demand can be typical for Malaysian conditions, it is certainly not true for others. The study also does not consider any productive use of electricity.

Similar case studies are presented in other studies as well. For example, Himri et al. [12] present a study of an Algerian village; Nandi and Ghosh [13] discuss the case of a Bangladeshi village, while Nfah et al. [14] and Bekele and Palm [15] provide case studies of Cameroon and Ethiopia respectively. Table 1 summarises the technology choices, demand focus and country of application of these studies.

Table 1: Selected examples of hybrid technology analysis using HOMER

Reference	Technology application	Country of application	Supply duration/ type
Givler and Lilienthal [8]	PV-battery - diesel	Sri Lanka	Basic needs
Hafez and Bhattacharya [10]	PV, Wind, Hydro, Diesel, Battery	Hypothetical	24 hour service but unrealistic demand profile for a rural area of developing countries.
Lau et al. [11] (2010)	PV-diesel hybrid	Malaysia	24 hour service but uses a high demand profile for a rural area and does not use any productive load.
Himri et al. [12]	Wind-diesel hybrid	Algeria	Adding wind turbine to an existing diesel-based supply; Limited technology options.
Nandi and Ghosh [13]	Wind-PV-Battery	Bangladesh	Solar and wind hybrid; no productive demand
Nfah et al. [14]	PV, Micro-hydro, LPG generator, battery	Cameroon	Diesel as main generator supplemented by PV and micro-hydro, load based on grid-connected urban households of Uganda was used.
Bekele and Palm [15]	PV-wind hybrid	Ethiopia	PV and wind hybrid, randomised load profile from hypothetical load data.

It can be seen that the hybrid options have often considered a limited set of technologies. Moreover, most studies concentrate on supplying electricity merely for domestic purposes and do not take into account the electricity demand for agricultural, irrigation, community purposes and for small-scale business units for the socio-economic development of the whole region. The load profiles are also not carefully considered in many cases. These issues are considered in the present study, thereby bridging the knowledge gap.

3. Methodology

3.1 Introduction

This study uses the HOMER software package developed by NREL for designing micro-power systems but complements it by undertaking pre- and post- HOMER analyses. This is indicated in Fig. 1. In the Pre-HOMER analysis phase, a detailed assessment of the village load, site layout and available resources in the selected village is conducted. This is carried out outside HOMER and data is fed into the software. In the HOMER analysis the hybrid RET system is designed, followed by a techno-economic analysis. It compares a wide range of equipment with different constraints and sensitivities to optimize the system design. The analysis is based on the technical properties of the system and the life-cycle cost (LCC) of the system. The LCC comprises of the initial capital cost, cost of installation and operation costs over the system's life span. HOMER performs simulations to satisfy the given demand using alternative technology options and resource availability. Based on the simulation results, the best suited configuration is selected. In the Post-HOMER phase, the business-related analysis is performed to a limited extent (see section 5), which we intend to strengthen in the future.

We have considered a combination of the following technologies, namely small hydropower (SHP), wind turbines, solar PV (SPV) systems, batteries, and a bio-diesel generator (BDG) for back-up (see Fig. 2 for a schematic system configuration diagram). In the hybrid system the demand from the village is AC-coupled, the SHP and the BDG are connected to the AC side of the network and the SPV, wind turbine and the batteries are connected to its DC side. Usually a conventional back-up diesel generator (DG) is used to supplement the RE system for peak loads and during poor resource periods. In this study, a BDG (B100) is used instead, making the whole system a sustainable, clean and carbon neutral system, not only for the purpose of electricity generation but also for working effectively towards GHG emissions mitigation by not burning any fossil fuels. This makes the study different from others.

Fig. 1: Framework of analysis

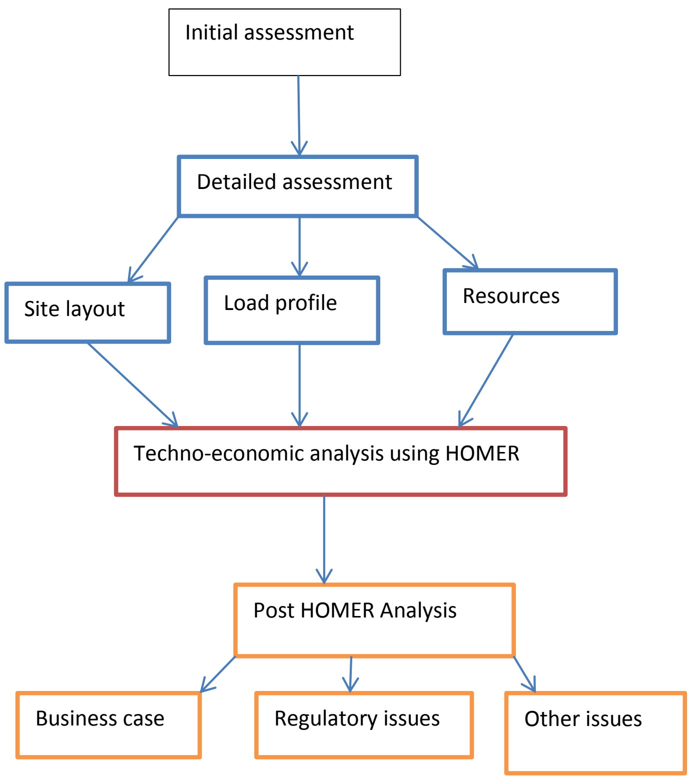
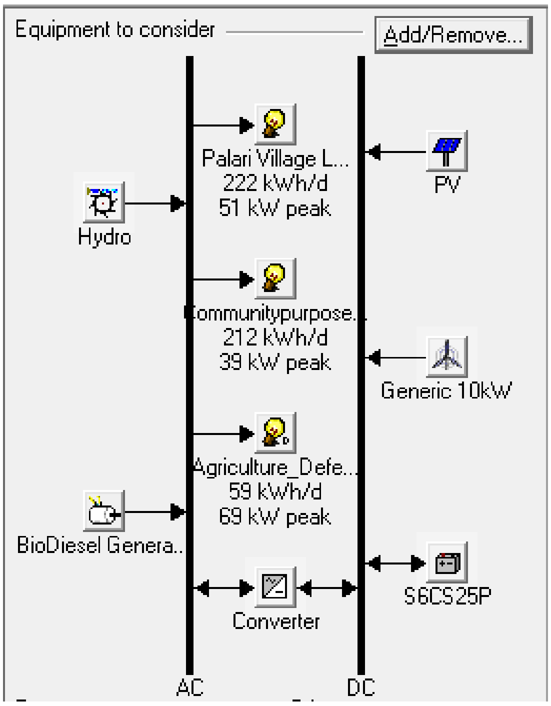


Fig. 2: Design of the selected RET's for the hybrid system



3.2 System Modelling

The selected off-grid remote rural village for this study is Palari, a small village in Bastar district in the Indian state of Chhattisgarh. The details of the village are listed in table 2. The nearest town is Kondagaon, which is about 15 to 20 kilometres away, both Kodagaon and Palari are located in close proximity to the national highway 43 (NH-43). The area around the village is partially hilly with flat plains constituting the rest. The village has water and drinking water facilities in the form of water-wells and hand pumps. The village has no access to grid electricity, which offers an opportunity for off-grid electrification of the village.

Table 2: Details about the selected village

Particulars	DETAILS
Village Name	Palari
Sub-District	Kondagaon
District	Bastar
State	Chhattisgarh
Country	India

Latitude	19°635'N
Longitude	81°672'E
Elevation (in meters)	587
Area of Village (in hectares)	370
Unirrigated area (in hectares)	> 200
Forest land (in hectares)	14
Culturable waste (in hectares)	7
Rivers Available	1
Water-wells	1
Grid Electricity	0
Number of households	304
Total Population	1,624
No. of Males	764
No. of Females	860
Education facilities (Primary School)	1
Medical Facilities (Primary Health Subc entre)	1
Post Office	1
Total Income (per annum)	Rs. 1,75,100 / $ 3892
Total Expenditure (per annum)	Rs. 1,13,400 / $ 2520

Source: Census 2001. (http://www.censusindia.gov.in/)

3.2.1 Village Load Assessment

In a remote rural village the demand for electricity is not high compared to urban areas. Electricity is demanded for domestic use (for appliances like radio, compact fluorescent lamps, ceiling fans, and table fans), agricultural activities (such as water pumping), community activities (such as in community halls, schools, and clinics) and for rural commercial and small-scale industrial activities (such as cold storage, small milk processing plants and cottage industries).

In this study, the village energy load requirement is carefully estimated considering existing load profile data available in state government records for similar rural areas. We have also consulted previously published literature on Indian villages and triangulated with expert opinions and personal judgements. The demand has been estimated separately for two distinct seasons prevailing in this area, namely summer (April to October) and winter (November to March) considering the appliance holding and use patterns for households, potential commercial activities, and energy use in productive applications. Table 3 provides the summary of estimated demand for summer and winter seasons. Clearly, the demand estimation is a crucial element of the entire system design and further improvement is possible here by incorporating social information of the users as well as their preferences.

Table 3: Estimated electricity demand for Palari village

S. No.	LOAD	No. in use	Power (watts)	SUMMER (April - Oct.)		Winter (Nov. - March)	
				Hrs/Day	Watt-hrs/Day	Hrs/Day	Watt-hrs/Day
	Domestic Purposes						
1	Low-energy lights (CFL)	1	20	6	120	7	140
2	Low-energy lights (CFL)	1	20	6	120	7	140
3	Low-energy lights (CFL)	1	11	5	55	6	66
4	Radio	1	10	3	30	4	40
5	Ceiling Fan	1	30	15	450	0	0
6	Table Fan	1	15	9	135	**0**	0
	TOTAL				**910**		**386**
A	**No. of Houses**	**304**			**276640**		**117344**
	Industrial/ Commercial/Community Purposes						
1	Shops	10	500	8	40000	7	35000
2	Community Centre	1	1000	8	8000	6	6000
3	Small Manufacturing Units	5	3000	12	180000	10	150000
4	Street Lights (CFL)	5	30	10	1500	12	1800
B	**TOTAL**				**229500**		**192800**
	Agriculture & Irrigation Purposes						
1	water pump	8	745.6	5	29824	3	17894.4
2	Irrigation pump	4	1491.2	6	35788.8	4	23859.2
3	well	1	745.6	4	2982.4	2	1491.2
C	**TOTAL**				**68595.2**		**43244.8**
	Medical Centre						
1	Low-energy lights (CFL)	4	20	4	320	6	480
2	Ceiling Fan	4	30	6	720	0	0
3	Refrigerator	1	600	20	12000	16	9600
D	**TOTAL**				**13040**		**10080**
	School						
1	Compact Fluorescent Lights	5	20	2	200	4	400
2	Ceiling Fan	2	30	6	360	0	0
3	Computer (desktop)	1	300	2	600	2	600
4	Television	1	100	2	200	2	200
E	**TOTAL**				**1360**		**1200**

Knowing that the load factor in such locations tends to be poor, some demand has been distributed strategically over the 24 hour period to improve the system load factor. The village load has been divided into three important categories:

1) Primary Load 1 – This includes the domestic load, medical centre and school demand. The load demand is approximately 222kWh/day and 51.2 kW peak. It has a load factor of 0.181 (see Fig. 3).

2) Primary Load 2 – This includes the demand load for the community centre, shops, local business and small manufacturing units. It is approximately 212kWh/day and 39.4 kW peak. It has a load factor of 0.224 (see Fig. 4).

3). Deferred Load – This includes the agricultural load of the village. The scaled annual average deferred load is 58.6kWh/day and has a peak load of 68.6kW. It has a storage capacity designed for 30 kW and is also connected on the AC side.

Fig. 3: Load profile of primary load 1

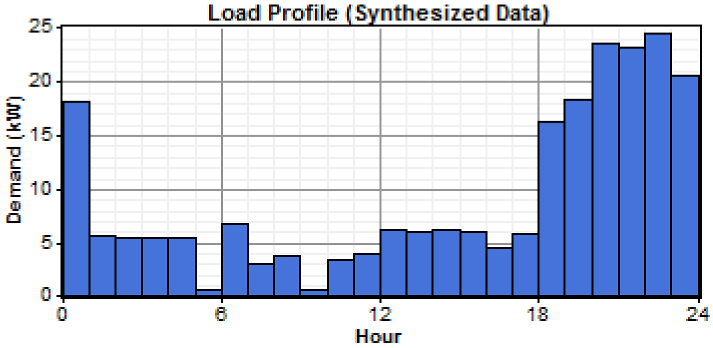
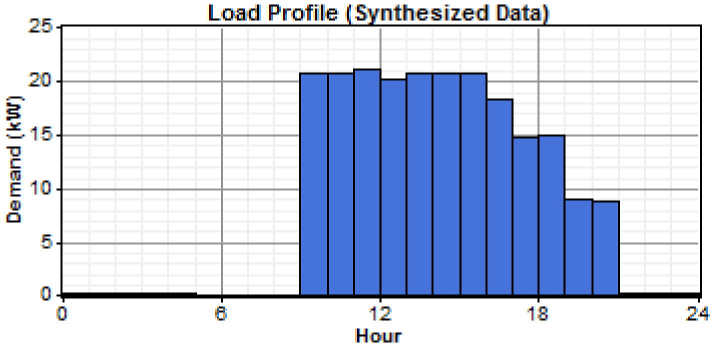


Fig. 4: Load profile of primary load 2



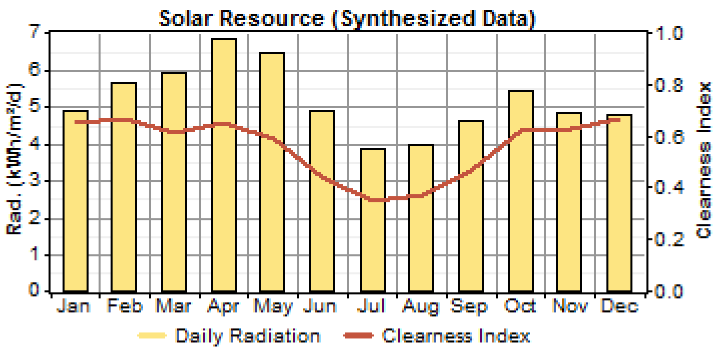
The load assessment was done in Excel worksheet, using customised data templates for this purpose. This is an area of further work which can produce a generic pre-HOMER tool for wider applications.

3.2.2 Resources Assessment

We have considered solar, wind, micro-hydro and bio-diesel resources in this simulation. The resource assessment is presented below.

The solar resource used for Palari village at a location of 19°59' N latitude and 81°59' E longitude was taken from NASA Surface Meteorology and Solar Energy website[2]. The annual average solar radiation was scaled to be 5.17kWh/m^2/Day and the average clearness index was found to be 0.548. The solar radiation is available throughout the year; therefore a considerable amount of PV power output can be obtained (see Fig. 5).

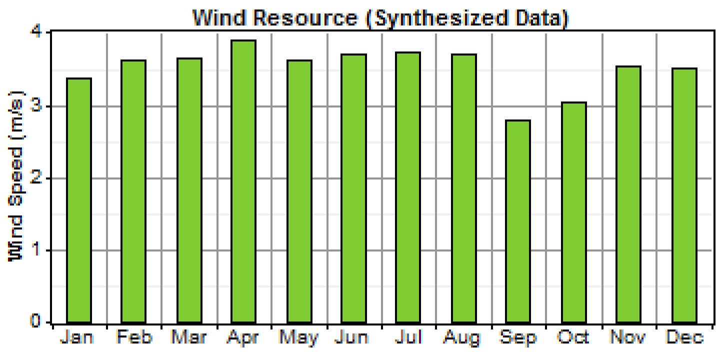
Fig. 5: Solar energy profile at the selected village



The monthly average wind resource data from an average of ten years was taken from the above NASA resource website based on the longitude and latitude of the village location. The annual average wind speed for the location is 3.5 m/sec with the anemometer height at 50 meters. The wind speed probability and average monthly speed throughout the year is also observed. It shows that there are 15 hours of peak wind speed. The wind speed variation over a day (diurnal pattern strength) is 0.25 and the randomness in wind speed (autocorrelation factor) is 0.85 (see Fig. 6).

[2] http://eosweb.larc.nasa.gov/sse/

Fig. 6: Wind energy resource at the selected village



The Alternate Hydro Energy Centre (AHEC), India, has identified a number of locations for the development of Small Hydropower projects in Chhattisgarh [18]. One of the projects, Kondagaon on Narangi River near Palari village, is identified with a potential output of 500kW at 5 meters head. The monthly average flow has been carefully estimated based on the average precipitation, average temperatures and topography of the region. The residual flow was assumed to be 4000 l/s. The flow in the river drops from September to May, and rapidly increases up to 58,000 l/sec in August due to heavy rainfall in the area. Hence power generation from the hydro source varies depending on the water availability during the year.

Biodiesel is a bio fuel predominantly made from vegetable oil and sometimes animal fat. Biodiesel can be used to run diesel engines with minor engine modifications (if required). In India, with the help of extensive agricultural research, Jatropha Curcas oilseed was chosen as main feedstock for the biodiesel production in India's Biodiesel programme. The most commonly available are B20 (containing 20% of biodiesel and 80% petroleum diesel in the blend), and B100 which is pure biodiesel. Biodiesel has a shelf life of 6 months, after which it has to be tested again.

As there is a biodiesel plant in the neighbouring city of Raigarh, it is assumed that the fuel will be available from this plant. The fuel price is considered to be 0.6 $/L. The current market price of biodiesel in India is about 0.58 $/L, though it varies regionally due to tax and other costs.

3.2.3 Components Assessment

In a micro-power system, a component generates, delivers, converts and stores energy. In this HOMER analysis, solar PV, wind turbines, and run-off river hydropower are the intermittent resources and the bio-diesel is kept for backup. Batteries and Converter are for storing, converting electricity respectively. The grid connection in this study is only used as a comparison for the analysis and determination of the economic distance to grid (EDL). The performance and cost of each of the system's components is a major factor for the cost results and the design[3].

The SPV panels are connected in series. The power generated by SPV is more than wind turbines at this location due to better solar insolation. The capital cost and replacement cost for a 1kW SPV is taken as $6000 and $5000 respectively. As there is very little maintenance required for PV, only $10/year is taken for O&M costs. Like for all other components considered in the following paragraphs, the costs per kW considered include installation, logistics and dealer mark-ups. The SPV is connected to a DC output with a lifetime of 20 years. The de-rating factor considered is 90% for each panel to approximate the varying affects of temperature and dust on the panels. The panels have no tracking system and are modelled as fixed titled south at 19°59' N latitude of the location with the slope of 45°.

A Generic 10kW horizontal-axes wind turbine is considered. The amount of electricity generated by the wind turbine greatly depends on the availability of and variations in the wind speed. The G10 wind turbine selected gives a 10kW of DC output. The cost of one unit is taken as $40,000, while the replacement and the maintenance cost are considered to be $32,000 and $200/year respectively. The wind turbine has a hub height of 25 meters and a lifetime of 25 years.

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[3] The components' technical and cost parameters for this study are based on data collected from The Ministry of Non-Conventional Energy Sources (GoI), The Energy Research Institute (TERI) in India, previous published literatures, information from personal sources of Indian manufactures, and assumptions.

The SHP is designed for a power output of 30kW depending on the village load. The turbine is designed for a net head available of 5m and has a design flow of 815 l/s. The turbine efficiency is 75% and has a pipe head loss of 5.68%. The SHP gives an AC output and has a lifetime of 25 years. The capital cost for a 30kW SHP is taken as $42,000 while the replacement cost and O&M cost are considered to be $35,000 and $4,000 respectively.

The capital cost, replacement cost, O&M costs of a 1kW BDG are taken as $1200, $1000, and $1.03/hr respectively.[4] A normal old DG can be used as well, but it might need certain modifications. The per kW costs are for a new modern DG that can be used for biodiesel as fuel as well and include the costs of installation, logistics and dealer mark-ups. The generator is connected to an AC output with a lifetime of 15,000 operating hours. The minimum load ratio is taken to be 30% of the capacity; moreover, HOMER requires the partial load efficiency to simulate this component. HOMER calculates the total operating cost of the generator based on the amount of time it has to be used in a year.

Batteries are used as a backup in the system and to maintain a constant voltage during peak loads or a shortfall in generation capacity. The battery chosen for this study is Surrette 6CS25P. It is a 6V battery with a nominal capacity of 1,156 Ah (6.94 kWh). It has a lifetime throughput of 9,645kWh. The capital cost, replacement cost and O&M costs for one unit of this battery were considered as $1000, $800, and $50/year respectively.[5] HOMER models the batteries on charging and discharging cycles.

The capital cost, replacement cost and O&M costs of the converter for 1kW systems were considered as $700, $550, and $100/year respectively [16]. The lifetime of the converter is 15 years, inverter efficiency of 90% and rectifier efficiency of 85%.

[4] The prices considered are an interpolation of data (quotations) obtained from local Indian manufactures and distributors.

[5] The prices considered are an interpolation of data (quotations) obtained from local Indian manufactures, distributors and previous published literatures.

3.2.4 Sensitivity of Inputs

The key variables for the micro-power system are, however, often uncertain. This is a major problem to be overcome in the designing of the system. Here the uncertainties in the RES (wind, hydro, solar and biomass) have been taken into account. The sensitivities entered for the Biodiesel price in $/l are 0.60, 0.714, and 0.804. For wind speed 3.5m/s and 5.0m/s are the two values entered. Similarly for the design flow rate 815 l/s and 0 l/s were entered for the SHP.

3.3 Economic Modelling

As HOMER aims to minimise the total net present cost (NPC) both in finding the optimal system configuration and in operating the system, economics play a crucial role in the simulation. The indicator chosen to compare the different configurations' economics is the life-cycle cost (LCC), and the total NPC is taken as the economic figure of merit. All economic calculations are in constant dollar terms.

3.4.1 Economic Inputs

The project's lifetime is considered to be 25 years with an annual discount rate of 10%. The system fixed capital cost is considered to be $10,000 for the whole project and the system fixed O&M cost is estimated to be $500/year for the project lifetime.[6] The system fixed capital costs include various civil constructions, logistics, labour wages, required licenses, administration and government approvals and other miscellaneous costs.

3.4.2 The Grid

In this study the grid is used as standard benchmark by HOMER, to be compared with the technical and cost parameters of the off-grid hybrid RETs system. Therefore the cost of grid extension is taken in the analysis to see whether a grid extension is viable or an off-grid system is more appropriate. The capital cost of grid extension per kilometre for the

[6] These costs are an interpolation from previous literature, estimates from TERI and quotations from local Indian civil contractors.

Palari village terrain is considered to be $8000/km. The annual O&M cost per kilometre is considered to be $1500/year/km[7] and the grid power price is assumed from an interpolation as $0.44/kWh [17].

3.4.3 Analysis

HOMER performs the simulation for a number of prospective design configurations. After examining every design, it selects the one that meets the load with the system constraints at the least life cycle cost. HOMER performs its optimization and sensitivity analysis across all mentioned components and their resources, technical and cost parameters, and system constraints and sensitivity data over a range of exogenous variables. The competitiveness of the best suited hybrid RET system for rural electrification is compared with the conventional option of grid extension, based on the COE for both options and based on this the economic distance limit (EDL) is determined. The cost of low tension transmission distribution lines within villages has been excluded, since it is the same in all the cases.

4. Results and discussion

This section presents the results of our analysis. First, the optimisation results are presented, which is followed by the outcomes of our sensitivity analysis. The economic and environmental aspects are also considered.

4.1 Optimization results

The optimal combination of RET system components for our case study is a 20kW PV-Array, 30kW SHP, 10kW BDG, 40 Surrette 6CS25P Batteries, 20kW Inverter and a 20kW Rectifier with a dispatch strategy of cycle charging. No wind turbine is selected at this site

[7] The costs are an estimated assumption based on the interpolation from previous publishes literatures.

(see Fig. 7). This system is considered at 3.5m/s of wind speed, $0.6/l of biodiesel cost and 815 l/s of design flow rate for the SHP. The total net present cost, capital cost and the cost of electricity (COE) for such a hybrid system are $673,147, $238,000 and $0.420/kWh, respectively. The COE of $0.420/kWh from this hybrid system is cheaper than that of $0.44/kWh from grid extension as considered for this study. Therefore grid extension does not appear to be a viable option to meet the village load. But, if the cost of electricity from the grid supply falls below $0.420/kWh, grid extension becomes viable.

Fig. 7: Optimal least cost hybrid system for the case study

Cost summary

Total net present cost	$ 673,147
Levelized cost of energy	$ 0.420/kWh
Operating cost	$ 47,939/yr

System architecture

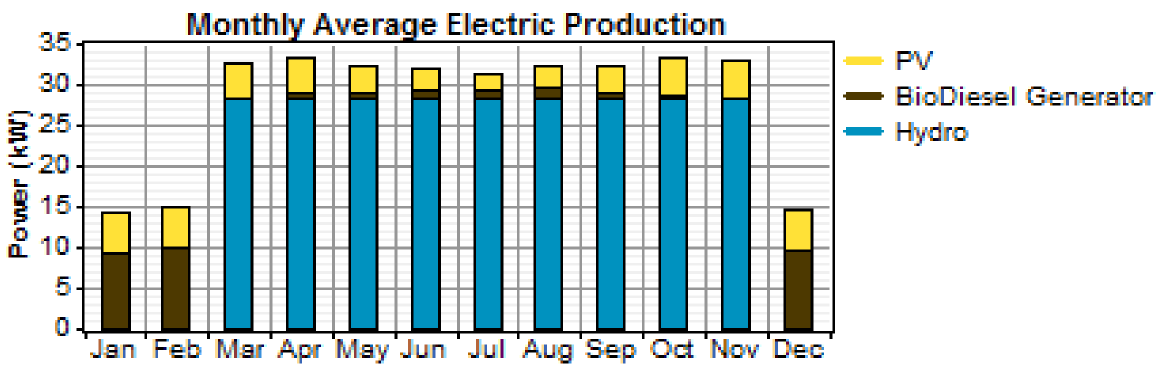
PV Array	20 kW
Hydro	30 kW
Biodiesel Generator	10 kW
Battery	40 Surrette 6CS25P
Inverter	20 kW
Rectifier	20 kW
Dispatch strategy	Cycle Charging

Electrical

Component	Production (kWh/yr)	Fraction
PV array	34,439	14%
Hydro turbine	186,649	76%
Biodiesel Generator	25,294	10%
Total	246,382	100%

Figure 8 shows the monthly distribution of the electricity produced in kW by the SPV, SHP and BDG. From December to February, the biodiesel generator is mostly used combined with SPV as hydropower is unavailable due to low flow in the river. Also, from June to August the peak load is met by SPV and BDG.

Fig. 8: - Monthly average electricity production from the best hybrid configuration system.



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It is evident from Fig. 8 and table 4 that small hydro station dominates the electricity output in this case. The SHP operates at full load for 9 months and produces 186,649 kWh/year, achieving a capacity factor of 71%. At this level of operation, the levelised cost of hydro-only system becomes just 4.62 cents/ kWh. Only during the winter months when water is inadequate, bio-diesel plant becomes the dominant producer. For the selected system the biodiesel plant operates for 2663 hours (capacity factor 28.9%), produces 25,294 kWh/year and consumes 13,646 litres of bio-fuel. However, this is a costlier option than hydropower and the marginal cost of electricity from the bio-diesel plant is $0.21/ kWh. The penetration of solar energy reduces the biodiesel output, particularly outside winter months. The solar panels produce 34,439 kWh/year, operating for 4357 hours (or recording a capacity factor of 19.7%). The levelised cost of solar electricity turns out to be $0.415/kWh.

Table 4: - Techno-Economic details of the three hybrids system configurations

Configurations	Unit	Best Hybrid	2nd best Hybrid	3rd best Hybrid
Wind Speed	m/s	3.5	3.5	5
Bio Diesel-(B100) Price	$/L	0.6	0.6	0.6
Design Flow Rate	L/s	815	0	0
Solar PV	kW	20	100	120
Wind Turbine (G10 kW)	no.	0	0	6
Hydro	kW	29.98	0	0
Bio D	kW	10	20	10
Batteries - Surrette 6CS25P		40	180	200
Converter	kW	20	50	70
Dispatch Strategy	no.	CC	CC	CC
Total Capital Cost	$	2,38,000	8,49,000	12,31,000
Total NPC	$	6,73,147	19,84,485	18,98,258
Total Annual Capacity Cost	$/yr	26,220	93,533	1,35,617

Total Annual Replacement Cost	$/yr	3,623	14,232	17,815
Total O&M Cost	$/yr	36,129	89,701	47,937
Total Fuel Cost	$/yr	8,188	21,161	7,759
Total Annual Cost	$/yr	74,159	2,18,627	2,09,127
Operating Cost	$/yr	47,939	1,25,094	73,511
COE	$/kWh	0.42	1.23	1.192
PV Production	kWh/yr	34,439	1,72,196	2,06,636
Wind Production	kWh/yr	0	0	53,004
Hydro Production	kWh/yr	1,86,649	0	0
Bio D Production	kWh/yr	25,294	63,719	22,950
Total Electrical Production	kWh/yr	2,46,382	2,35,916	2,82,589
AC Primary Load Served	kWh/yr	1,55,444	1,56,290	1,54,027
Deferrable Load Served	kWh/yr	21,308	21,383	21,350
Renewable Fraction	%	0.9	0.73	0.92
Capacity Shortage	kWh/yr	4,393	2,805	5,522
Capacity Shortage Fraction	%	0	0	0
Unmet Load	kWh/yr	3,056	2,144	4,440
Unmet Load Fraction	%	0.02	0.01	0.02
Excess Electricity	kWh/yr	62,412	25,258	73,398
BioDiesel-(B100)	L/yr	13,646	35,268	12,932
Breakeven Grid Extension Distance	km	-2.09	58.58	54.59

62,412 kWh/year of electricity which is 25% of total electricity generated goes unused due to low demand and is fed to dump loads. This is particularly high in summer months when the hydro plant operates fully. This shows that this system has the capability in meeting the demand growth in the future. The demand can also be increased by serving the demand of other nearby villages, because as the demand increase the load factor increases and hence the cost per kWh will decrease.

Fig. 9: Cash flow summary based on the selected components

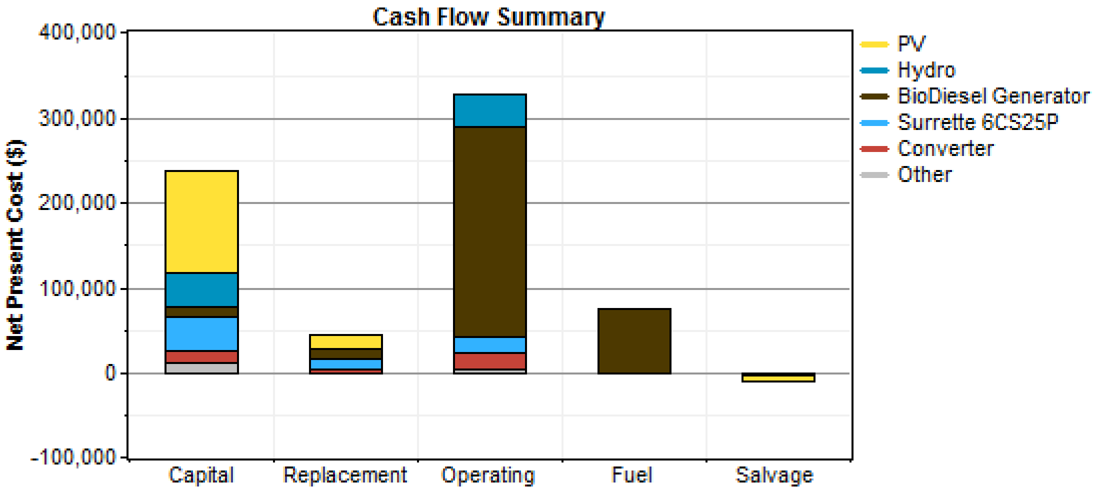


Figure 9 shows the cash flow summary for the optimal system. The capital cost of the bio-diesel generator makes up only 5% of the system's total capital cost, whereas almost 50% of the initial investments go to the SPV arrays. Once installed, however, SPV is cheap to maintain and operate compared to the BDG, which in the end is responsible for 51.5% of the system's total annual cost of $74,159. Small hydro plant on the other hand is relatively cheaper and contributes less to the overall cost.

4.2 Sensitivity Results

Sensitivity analysis eliminates all infeasible combinations and ranks the feasible combinations taking into account uncertainty of parameters. HOMER allows taking into account future developments, such as increasing or decreasing load demand as well as changes regarding the resources, for example fluctuations in the river's water flow rate, wind speed variations or the biodiesel prices. Here, various sensitive variables are considered to select the best suited combination for the hybrid system to serve the load demand.

If the hydropower option is not available, the second-best hybrid configuration will comprise of 100kW SPV, 20kW BDG and 180 batteries and will have a cost of electricity of $1.230/kWh. This hybrid system has an economic distance to grid of 58.6 kilometres and generates 25,258 kWh/year of excess electricity. This configuration can be used at off-grid locations where hydropower is not available. The third hybrid configuration adds wind turbines to the configuration when the wind speed increases from 3.5m/s to 5m/s and no hydro is available. Hence with an increasing number of components the capital cost and total NPC also increase. The third hybrid configuration of wind turbines, SPV, BDG and batteries has a COE of $1.192/kWh[8]. Table 4 shows all the relevant techno-economic details considering the best three hybrid system configurations considered on HOMER for this paper.

This shows that the system configurations without SHP tend to be more costly than other renewable technologies. Even if the wind speed increases, generating more electricity from the wind turbine, the system costs do not reduce (see Fig. 10). The surface plot for the levelized COE with total NPC superimposed is presented in Fig. 10. The biodiesel price is fixed at $0.6/l, the hydropower design flow rate is depicted on the x-axis and wind speed variation on the y-axis. It can be observed that as the design flow rate increases, the power output from SHP increases and hence there is a reduction in total NPC. As the total NPC decreases, the system's COE decreases as well. This shows that with a change in sensitivity variables the capacity of an individual component increases and hence the configuration of the system changes. Therefore a hybrid system with SHP proves to be the cheapest option compared to other RETs.

[8] HOMER ranks options by net present value and not by cost of electricity.

Fig. 10: Surface plot of cost of electricity

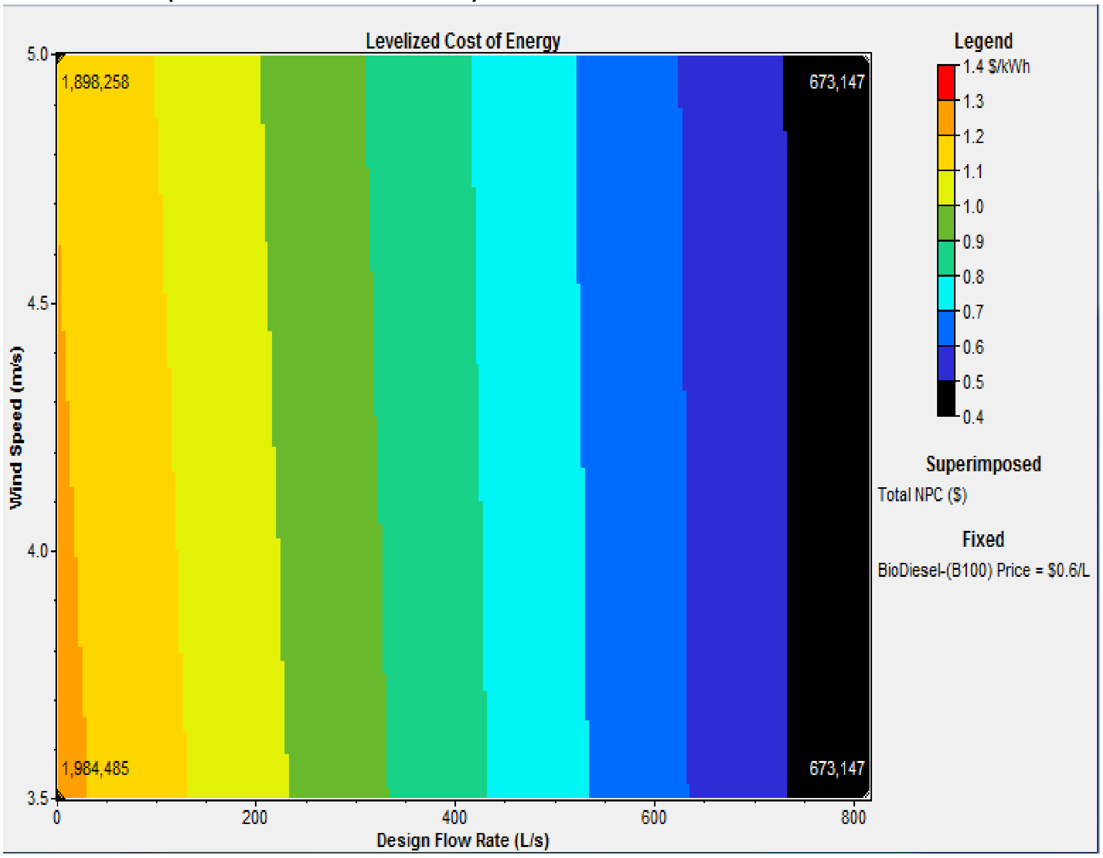
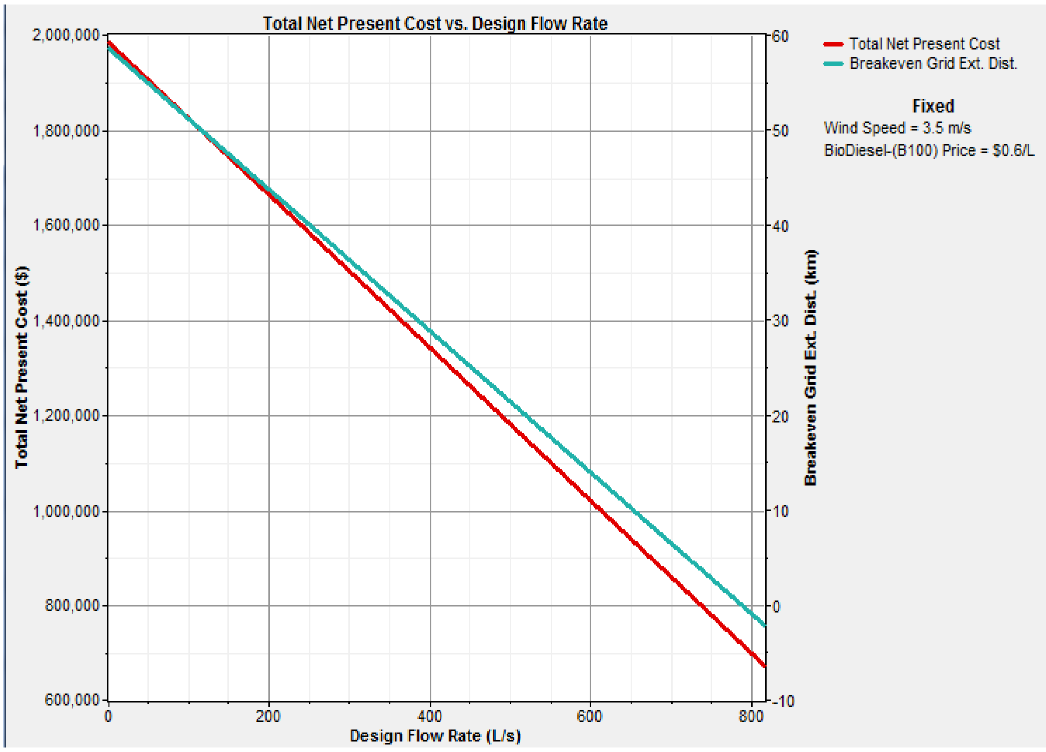


Figure 11 shows the result for the breakeven distance for grid extension (or EDL). It shows that the distance varies from a negative value to 60kms depending on the total NPC and levelized COE. For the selected hybrid configuration of SPV, SHP, BDG, and batteries the EDL comes out be a negative value as mentioned earlier. It is clearly evident from the line graph that as the design flow rate increases with wind speed and biodiesel cost at a fixed value of 3.5m/s and $0.6/l respectively, the total NPC of the system decreases. At 100l/s of design flow rate the EDL comes out to be 50kms and at 800l/s the EDL comes out to be negative distance of -2kms. Hence the total NPC and levelized COE of a system determine the EDL with respect to the input parameters.

Fig. 11: - Line graph for total NPC vs. Design flow rate and Breakeven Grid Extension distance.



4.3 Emissions

The optimal hybrid RET system would save 33,832 kg/yr of CO_2 over one year in operation compared to a central power generation plant or a stand-alone DG system. In addition, emission of particulate matters and nitrogen oxides will be reduced due to reliance on renewable energy systems (see table 5).

Table 5: Emission reduction

Pollutant	**Emissions (kg/yr)**
Carbon dioxide	33,832
Carbon monoxide	44.3
Unburned hydrocarbons	0.688
Particulate matter	4.68
Sulphur dioxide	0.576
Nitrogen oxides	894

Based on the above analysis, it can be concluded that a hybrid system becomes a viable option in an off-grid location in India. If small hydro power potential exists, it can offer economically attractive power supply. In the absence of small hydro potential, the cost of supply increases and interventions by the government may be required to make the investment socially desirable.

5.0 Post HOMER Analysis

The optimal hybrid electricity supply system requires development of 60 kW of power generating capacity (30 kW small hydro, 10 kW biodiesel and 20 kW solar PV) in a remote location and arrange for necessary distribution to 304 households and other customers in the village. Although HOMER suggests technical feasibility of such a system and indicates the break even cost at which the investment can be recovered, the business dimensions are generally not covered. The post HOMER analysis is required to develop a complete understanding of the business case. In the following paragraphs, some such issues are highlighted.

The first question that arises relates to financing of the investment. For example, in the optimal case, an investment of $238,000 will be required for a 60 kW system (or an average of $400 per kW approximately). Although the investment volume is not large either for any conventional lender (such as banks) or for any utility investor, significant risks are involved in the investment. First, a part of the investment is not re-deployable (e.g. the investment for SHP). If the project does not succeed for any reason, the investment will be a sunk cost for the investor and will represent a bad investment. Second, the electricity market in the area is not developed and the assumptions related to the demand may not materialise, or take longer to realise. This will adversely affect the cost recovery process. Third, the business environment may be affected by political, regulatory and governance challenges, thereby affecting such investments. Fourth, there are practical difficulties (e.g. availability of skilled manpower, managing supply logistics, and poor transport facilities) that can add to costs, delay project delivery and reduce profitability of the projects. In such cases, appropriate incentives and support mechanisms will play an important role to attract investment and mitigate risks. In the state of Chhattisgarh, capital grant is available for solar, wind and biogas plants. Also, the state renewable energy agency is actively promoting off-grid electrification and has trained technicians who work in rural areas. Therefore, some risk mitigation is already underway.

A related issue that requires careful consideration is the choice of an appropriate business model for delivering the project. While a private investor brings expertise and innovative ideas, the cost of supply can be higher. Moreover, a private investor will essentially be profit-driven and unless the business case suggests profitability, it is unlikely that private investment will flow. On the other hand, state utility services have not been successful in providing electricity in the remote areas and therefore such agencies are unlikely to be interested in off-grid electricity delivery. A middle path may be found in the form of local co-operatives or private-public partnership projects where both the social dimension and the business-like approach are combined. In our particular case, the state renewable energy agency is proactive in building joint ventures and promoting private investment but further work is required to decide a specific business model.

Clearly, the tariff issue will play a crucial role but remains a challenging task in the rural context due to the following factors. First, investors will be interested in recovering the investment over a shorter period of time and very few lenders will consider a loan period of 25 years. As the cost recovery period reduces, the cost of supply will increase, which may in turn make the project less attractive to the users. Second, the discount rate used for business decisions depends on the investor. For example, a private investor is likely to use a higher discount rate to reflect the cost of capital, riskiness of the investment and its desire to recover the investment quickly. On the other hand, state agencies or local communities may use a low discount considering the social nature of the investment. The tariff will accordingly depend on this. Third, the grid-based electricity supply in other areas may be subsidised and consumers in the off-grid area may expect similar tariff treatments. However, the cost of supply for the off-grid case may be quite different from the grid-based supply and the consumer base is significantly small. Therefore, there is very limited cross-subsidy potential in the off-grid case and unless there is direct subsidy support from the government, price parity with the grid-based supply can only jeopardise the viability of the project. In this particular case, the state allows subsidy for rural areas and the support is available for off-grid consumers at a fixed rate ($0.5 per household per month). While this may reduce the tariff burden on the consumer, it is unclear whether this level of subsidy is sufficient for cost recovery or not and whether the subsidy will be available over the entire life of the project.

Finally, the issue of regulating the off-grid supply through a mini-grid system as is envisaged in the case study requires careful consideration. The business will not function effectively unless the rules of the game are clearly laid out and the compliance with the rules is monitored through a supervisory system. As the consumers are likely to be illiterate and vulnerable, protecting them against any monopoly abuse, health and safety risks and other unfair treatments assumes greater importance. Simultaneously, the investor needs to be protected and encouraged to provide the desired level of service. However, unclear regulatory environment and lack of regulatory capacity can hinder developing such projects. This is an area of concern for the present case study where no specific regulatory arrangement exists for mini-grids.

6. Conclusion

Our search for a technically feasible and economically viable hybrid solution for off-grid electricity supply to a remote village such as Palari resulted in a least-cost combination of small hydro power, solar PV, bio-diesel and batteries that can meet the demand in a dependable manner at a cost of $0.420/kWh. Given the availability of small hydro power in this location, most of the electricity in the optimal solution comes from the hydro plant and it provides a cheap source of power to the locality. However, the system reliability cannot be ensured due to variable nature of water availability and lack of adequate water flow in winter unless other technology options are considered. The bio-diesel plant and the solar PV plants contribute 10% and 14% respectively to electricity generation but being costlier options than small hydropower, they raise the overall cost of electricity. If the small hydro plant is not available (or no hydro resources are available), the electricity demand can be met with a hybrid system comprising of solar PV, small wind turbines and bio-diesel plants. But the cost of electricity supply will increase three folds, thereby making the system less attractive to users. Thus three main lessons from this case study are: 1) where hydro potential exists, it is important to take advantage of the resource; 2) a combination of technologies improves supply reliability and hence makes better business sense; 3) the cost of supply of renewable-energy based electricity may not always be a cost effective option for remote applications unless appropriately supported by the government.

Although our work is based on a standard software HOMER, it goes beyond the conventional applications of the software by systematically considering the pre and post application phases. In the pre-HOMER stage, we have considered the local demand in detail and have included multiple types of users (residential, institutional, commercial, agricultural and industrial) and considered seasonal variation in the demand. As HOMER takes the demand as given and finds the least cost combination of supply options to meet the demand, realistic demand estimation assumes an important role. Our study contributes in this area by highlighting this aspect and incorporating a detailed demand analysis feature in the study. In the post-HOMER phase we highlight the business-related dimensions that influence the project delivery. We have briefly considered the financing challenge, business model selection, tariff issue, and the regulatory concerns. This is an attempt to go beyond the techno-economic analysis.

Surely further work is required in both pre and post HOMER areas. We believe that a standard template can be designed for a systematic estimation of demand for off-grid areas and to capture the stakeholder perspectives. Even demand scenarios can be included to take the simulations to another level of iteration. Similarly, a systematic approach of considering the business case of the optimal solution and its delivery-related issues can enhance the overall appreciation of the micro-energy systems.

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OASYS South Asia project

The Off-grid Access Systems for South Asia (or OASYS South Asia) is a research project funded by the Engineering and Physical Sciences Research Council of UK and the Department for International Development, UK. This research is investigating off-grid electrification in South Asia from a multi-dimensional perspective, considering techno-economic, governance, socio-political and environmental dimensions. A consortium of universities and research institutes led by De Montfort University (originally by University of Dundee until end of August 2012) is carrying out this research. The partner teams include Edinburgh Napier University, University of Manchester, the Energy and Resources Institute (TERI) and TERI University (India).

The project has carried out a detailed review of status of off-grid electrification in the region and around the world. It has also considered the financial challenges, participatory models and governance issues. Based on these, an edited book titled “Rural Electrification through Decentralised Off-grid Systems in Developing Countries” was published in 2013 (Springer-Verlag, UK). As opposed to individual systems for off-grid electrification, such as solar home systems, the research under this project is focusing on enabling income generating activities through electrification and accordingly, investing decentralised mini-grids as a solution. Various local level solutions for the region have been looked into, including husk-based power, micro-hydro, solar PV-based mini-grids and hybrid systems. The project is also carrying out demonstration projects using alternative business models (community-based, private led and local government led) and technologies to develop a better understanding of the challenges. It is also looking at replication and scale-up challenges and options and will provide policy recommendations based on the research.

More details about the project and its outputs can be obtained from www.oasyssouthasia.dmu.ac.uk or by contacting the principal investigator Prof. Subhes Bhattacharyya (subhesb@dmu.ac.uk).

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