CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081020

Optimal Design and Techno-economic Analysis of Off-grid Hybrid Renewable Energy System for Remote Rural Electrification: A Case Study of Southwest China

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Demand for electricity in remote areas is a key bottleneck for development of these areas. Challenges of grid extension to remote areas have been identified, such as difficult terrain for construction and vast investment. Fast development of decentralized renewable energy production technologies provides opportunity for tackling the challenges. The study aims to demonstrate the techno-economic feasibility of off-grid hybrid renewable energy system for sustainable remote rural electrification via a case study of a village in Southwest China. In order to determine the most cost competitive configuration whilst ensuring a reliable power supply for residential, community and agricultural demand of the village, different combinations of PV panels, wind turbine and biogas generator are modelled and optimized in HOMER. Daily and seasonal characteristics of energy supply and demand sizes and patterns of remote rural areas are considered. Comparison of grid extension and an off-grid hybrid power system has been carried out. Results show that a hybrid power system comprising solar, wind and biomass is a reliable and cost-effective option for remote rural electrification whilst achieving environmental benefits.

1. Introduction

Remote area electrification is a vital requirement for development of the remote rural areas so as to obtain economic growth, poverty elimination, and improvement of livelihood of the villages (Rajbongshi et al., 2017). Conventional methods of power supply in remote areas include grid extension and using diesel generators. Utility grid extension to the remote rural community is sometimes practically infeasible and economically unattractive due to geographical inaccessibility, difficult terrain, and high economic investment (Haghighat et al., 2016). Using diesel generators is another alternative, however, rapid depletion of fossil fuel resources on a global scale, environmental pollution, and high transportation costs for remote area make it a less attractive option. Considering the challenges, the penetration of local renewable resources has attracted extensive attention worldwide with the advantages of pollution reduction, and usually local abundance for sustainable electricity availability of remote areas. However, in order to ensure system reliability, standalone renewable energy based systems often lead to oversizing issues of components due to intermittent and uncertain nature of renewable resources, which makes the system costly.

To tackle these aforementioned challenges, hybrid renewable energy system (HRES) which combines different renewable resources together with batteries or a generator can provide reliable and cost-effective power supply for communities far from the grid (Odou et al., 2020). Studies on off-grid or grid-connected HRESs including various configurations are reviewed in the literature (Shivarama and Sathish, 2015). One of the most important issues of hybrid renewable energy system is optimal design of the components so that the optimization objective are minimized/maximized whilst the set constriants are satisfied. To properly size hybrid renewable energy systems and their integrations, it is of vital importance to characterize daily and seasonal characteristics of energy supply and demand sizes and patterns. Previous studies have not pay enough attention on load patterns of remote rural areas by featuring power loads for different purposes and considering future load growth at a community level, which is an important issue to be considered in the study

Paper Received: 30/03/2020; Revised: 27/05/2020; Accepted: 05/06/2020
Please cite this article as: Li J., Liu P., Li Z., 2020, Optimal Design and Techno-economic Analysis of Off-grid Hybrid Renewable Energy System for Remote Rural Electrification: A Case Study of Southwest China, Chemical Engineering Transactions, 81, 115-120 DOI:10.3303/CET2081020

whilst doing optimal design. To do optimal design and to analyze the performance and reliability of hybrid renewable energy systems, researchers have been using various tools or programs (Fathima and Palanisamy, 2015). Hybrid optimization model for electric renewables (HOMER) developed by National Renewable Energy Laboratory (NREL) is one of such tools, which is widely used for various studies worldwide for the optimal planning of off-grid or grid-connected power system. A review of the state-of-the-art of researches which use HOMER for optimal planning of HRES is presented in the literature (Bahramara et al., 2016).
To the best of authors' knowledge, there is no comprehensive study on the HOMER of off-grid hybrid power system comprising solar, wind and biomass energy, which featuring residential, community and agricultural loads in remote rural areas of Southwest China, and give a cost-effective, reliable and sustainable solution for the electrification of residential entities. As a result, the main idea of the study is to do optimal design and analyze the techno-economic feasibility of off-grid HRES in remote areas. In the case study, techno-economic analysis of different system configurations is performed, whilst comparison of the off-grid hybrid power system and grid extension has been carried out. Future load growth is also considered through sensitivity analysis.

2. Methodology

This study aims to analyze the techno-economic feasibility of the off-grid hybrid power system comprising solar, wind, and biomass energy, which featuring residential, community and agricultural power loads. First, a remote village in Southwest China is identified. Then for the design of the HRES, detailed assessment of the load profile and renewable resources availability in the village are obtained. According to local conditions, appropriate components are selected and modelled, whilst techno-economic parameters of the components are assessed. To make decisions about the configuration of the hybrid power system and properly size their components, the optimization objective is set to minimize the net present cost (NPC) of the system. The operation of the system is simulated by making energy balance calculations in each time step of the year, in order to determine whether a configuration is feasible whilst satisfy the set constraints (i.e., whether it can meet the electric demand under the conditions specified). For each feasible system configuration, results are obtained including capacity of components and techno-economic performance. HOMER is used to develop the hybrid power system configurations aiming to obtain the optimal solution whilst satisfying the constraints. Future user load growth is considered through sensitivity analysis.
For the techno-economic analysis of the hybrid power system, economic indicators such as NPC and cost of energy (COE) are taken into account. Comparison of grid extension and the off-grid hybrid power system has been carried out, and breakeven grid extension distance (BGED) is determined. NPC, COE and BGED are demonstrated in detail as follows.The total NPC of the HRES is the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its life time. Costs include capital costs, replacement costs, Operation&Maintianance (O&M) costs, fuel costs, emissions penalties, and the costs of buying power from the grid if grid connected. Revenues include salvage value and grid sales revenue if grid connected. The total NPC is calculated by summing the total discounted cash flows in each year of the project lifetime, which is described as the following equation.

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{1}$$

where C_{NPC} is total net present post in \$, $C_{ann,tot}$ is total annualized cost in \$/y, CRF is capital recovery factor, i is interest rate in %, R_{proj} is project life time in years.
The levelized COE is defined as the average cost per kWh of useful electrical energy produced by the system, using the following equation:

$$COE = \frac{C_{ann,tot}}{E_{primary} + E_{deferrable}} \tag{2}$$

where COE is cost of energy, $C_{ann,tot}$ is total annualized cost in \$/y, $E_{primary}$ is primary load served (AC and DC) in kWh/y, $E_{deferrable}$ is deferrable load served in kWh/y.
The BGED is the distance from the grid that makes the NPC of extending the grid equal to the NPC of the off-grid system, which is calculated as Eq(3)

$$D_{grid} = \frac{C_{NPC} \cdot \mathrm{CRF}(i, R_{proj}) - c_{power} \cdot E_{demand}}{c_{cap} \cdot \mathrm{CRF}(i, R_{proj}) + c_{om}} \tag{3}$$

where C_{NPC} is total NPC of the stand-alone power system in \$, CRF is capital recovery factor, i real discount rate in %, R_{proj} is project lifetime in years, E_{demand} is total annual electrical demand (primary plus deferrable) in kWh/y, c_{power} is cost of power from the gird in \$/kWh, c_{cap} is capital cost of grid extension in \$/km, c_{om} is O&M cost of grid extension in \$/y/km.

3. Case study

3.1 Site description

In this study, a village Minghe in mugu town, Huili county, Liangshan autonomous prefecture of Sichuan province of China is considered. The latitude and the longitude of the selected village are 26°22.4′N and 102°13.5’E. The elevation of the village is 1,713 m, with hilly and flat plain around. The area where the village located belongs to subtropical humid monsoon climate, with abundant solar and wind resources. The total population of the village is 2,824, and number of households is 612. The village is dominated by agriculture and animal husbandry, insufficient and unreliable power supply restricts the development of new agriculture and local economic development. The village is 22.4 km away from the mugu town.

3.2 User load assessment

The village load requirement is carefully estimated considering existing load profile data available in town government committee of similar rural area. Personal judgements of local residents are also taken into account.The damand has been estimated for three different seasons prevailing in this area namely summer, monsoon and winter by considering the power and utilization time of the appliance holding for households, community, potential commercial and industrial activities, and energy use in agricultural applications. Depending on the purpose of electricity demand and considering its characteristics, the selected village load has been divided into primary load and deferrable load.
(i) Primary load includes residential load, community and commercial load, and productive activities, which must be met instantly. Electricity is demanded for residential purpose for appliances like compact fluorescent lamps, TV, radio, fridge and others; for community and commercial purpose for a range of infrastructure, such as street lights, community center, school, medical center, post office, shops and others.
(ii) Deferrable load is defined as the electrical demand that can be met anytime within a defined time interval. These loads allow certain flexibility when the power supply is insufficient. The deferrable load is second in priority after the primary load, but ahead of charging the batteries. If the power produced exceeds the primary load, the surplus can serve the deferrable load. Irrigation pumps are typical examples of deferrable loads.
The primary load demand is approximately 372 kWh/d for domestic use and 175 kWh/d for community and commercial purpose in summer. Average annual primary load demand is 514 kWh/d and 75 kW peak. The average deferrable load is 50 kWh/d and has a peak load of 60 kW peak, with a storage capacity designed for 30 kWh and connected on the AC side.

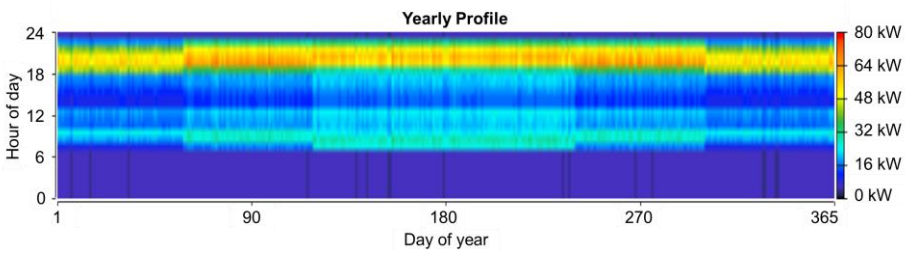

Figure 1: Yearly primary load profile

The yearly primary load profile considered for the simulation is shown in Figure 1. The daily primary electric load profile shows a small base value for street lights covering early morning and night hours, a higher level extending in the morning and midday time, due to productive and community infrastructure consumptions, and an evening peak load covering home services, generally two to three times of the midday electric demand. Seasonal loads are mainly water pumps, irrigation pumps and agricultural related productive activities.

3.3 Resources assessment

Wind, solar, hydro and biomass resources are abundant in the selected village. However, the utilization of small scale hydro energy is limited due to the local government’s policy, solar, wind and biomass are considered as the primary renewable energy resources. The resources assessment are presented as follows.

3.3.1 Solar energy source

The solar radiation and temperature at a location of 26°22.4′N latitude and 102°13.5’E longitude is taken from NASA Surface Meteorology. The annual average solar radiation is approximately to be 4.71 kWh/m^2/d, scaled from 3.85 kWh/m^2/d with clearness of 0.407 in September to 6.25 kWh/m^2/d with clearness of 0.601 in April. Based on the solar radiation and ambient temperature obtained, hourly energy output of the solar can be calculated according to the following equation:

$$P_{PV} = Y_{PV} f_{PV} (\frac{G_T}{G_{T,STC}})[1 + \alpha_P (T_c - T_{c,STC})] \tag{4}$$

where Y_{PV} [kW] is the related capacity of the PV array, meaning its power output under standard test conditions (STC, which is a radiation of 1 kW/m^2, a cell temperature of 25 °C, and no wind) ; f_{PV} [%] is the PV derating factor; G_T [kW/m^2] is the solar radiation incident on the PV array in the current time step; $G_{T,STC}$ [1 kW/m^2] is the incident radiation at STC; α_P [%/°C] is the temperature coefficient of power, considered as -0.5 in this case; T_c [°C] is the PV cell temperature in the current time step, and $T_{c,STC}$ [25 °C] is the PV cell temperature under STC.

3.3.2 Wind energy source

The monthly average wind resource data is obtained from local government measurement data for the area where the village located. Annual average wind speed is 6.9 m/s, with the altitude above sea level 1,450 m and the anemometer height 70 m. The diurnal pattern strength (wind speed variation over a day) is 0.25, the 1 hr. autocorrelation factor (randomness in wind speed) is 0.85 and hour of peak wind speed is 15 m/s.
The calculation of power output of the wind turbine in each time step uses a three-step process. First, wind speed at the hub height of the wind turbine is calculated according to the following equation.

$$U_{hub} = U_{anem} \frac{\ln(z_{hub} / z_0)}{\ln(z_{anem} / z_0)} \tag{5}$$

where U_{hub} [m/s] is the wind speed at the hub height of the wind turbine, U_{anem} [m/s] is the wind speed at anemometer height, z_{hub} [m] is the hub height of the wind turbine, z_{anem} [m] is the anemometer height, and z_0 [m] is the surface roughness length.
After the U_{hub} [m/s] is determined, it refers to the wind turbine's power curve to calculate the expected power output from the wind turbine at that wind speed under standard conditions of temperature and pressure (STP). If the U_{hub} is not within the range defined in the power curve, the turbine produces no power. Finally, to adjust to actual conditions, power output value is calculated as Eq(3).

$$P_{WTG} = P_{WTG,STP} \left(\frac{\rho}{\rho_0} \right) \tag{6}$$

where P_{WTG} [kW] is the wind turbine power output, $P_{WTG,STP}$ [kW] is the wind turbine power output at STP according to power curve, ρ [kg/m^3] is the actual air density, and ρ_0 [1.225 kg/m^3] is the air density at STP.

3.3.3 Biomass resource

In the selected village, biomass is easily available in the form of manure. The utilization of biomass energy takes the form of converting manure into biogas through anaerobic fermentation unit, which small-size biogas power generation is the most widely used utilization form of biomass with better technological economy characteristic in China rural area. The village rear approximately 1,200 sheep and 800 pig, biogas production potential from manure is very huge and local abundant, and supply of biogas is relatively stable throughout the year. According to the local utilization form, low heat value (LHV) of the produced biogas is around 25.0 MJ/kg, biogas consumption rate of biogas fueled diesel generator (BDG) is approximately 0.05 m^3 /kWh.

3.4 Design specification

For the design and techno-economic analysis, costs and technical details of the system components are major factors, which are assessed in HOMER pro version 3.13.3 as follows. The technical and cost parameters of the components for the study are based on data collected from previous published literature, information from personal sources of China manufactures and assumptions.
The solar system is connected to a DC output with a life time of 25 y, the capital and replacement cost for 1 kW solar power generation is taken as $1,000 and $950, O&M cost is considered as $10/y/kW, due to very little maintenance required for PV panels (Gebrehiwot et al., 2018). Derating factor is considered as 85 % for each flat PV panel to account for reduced output in real-world operating conditions compared to the conditions which the PV panel is rated. Panels have no tracking system and the slope is modeled as 26.5 °. A generic 10 kW horizontal axis wind turbine with $11,000 capital cost and $10,000 replacement cost is connected to AC output, which O&M cost is $50/y (Halabi and Mekhilef, 2018). The wind turbine has a lifetime is 20 y and a hub height of 24 meters. To fulfill the electricity demand during evening peak, a BDG is considered and connected to AC output due to abundant biomass resource in the village. BDG will guarantee the stability and reliability of the hybrid power system due to intermittent and uncertainty characteristics of wind and solar modules. Capital cost, replacement cost and O&M cost of a 1 kW BDG are taken as $550, $500, and $0.1/h with a lifetime of 15,000 h (Muh and Tabet, 2019). The optimized search capacities are: 0, 30, 40, 50, 60, 70, 80 kW. Batteries

are used as back facility in the system. 1 kWh Lead Acid is chosen for this hybrid system, with 12V nominal voltage and lifetime throughput of 800 kWh. The battery has round trip efficiency of 80 %, capital and replacement cost of the battery are considered to be $260 for one unit of the battery (Ayeng'o et al., 2018). The batteries are modeled on charging and discharging cycles. For AC/DC converter, the capital, replacement and O&M costs are considered as $300/kW and $300/kW (Akhtari and Baneshi, 2019). The lifetime of the converter is 15 y, with inverter efficiency of 95 % and the rectifier efficiency of 90 %.

The project's lifetime is considered to be 25 y with a nominal discount rate (NDR) set to 8 %, expected inflation rate at 2 %, whilst the real interest rate is calculated as 5.88 %. In this study, the economy of off-grid hybrid power system is compared with grid extension. Considering the conditions of minghe village, the capital cost, O&M cost of grid extension is considered as $8,000/km and $1,800/km. With government subsidies, the villagers can purchase grid power at the price of $0.1/kWh under grid extension.

4. Results and discussion

Operation of the system with different configuration is simulated by making energy calculation according to the user load and energy supply in each time step of the year. Then configurations which met the constraints specified are ranked according to the NPC, the optimal system configuration with the lowest NPC can be selected. BGED is calculated to compare the economy of the standalone system with grid extension. Future laod growth is considered through sensitivity analysis.

4.1 System optimization results

The optimization results of the HRES is shown in Table 1, which each one is the lowest NPC representative of each system configuration. All the systems use 100 % renewable energy with 0 % unmet load.

Table 1: System optimization results of the hybrid renewable energy system

Rank	Architecture						Costs				System
		PV (kW)	Wind turbine (10 kW)	BDG (kW)	Battery (kWh)	Converter (kW)	NPC ($)	COE ($/kWh)	O&M ($/yr)	Initial Capital ($)	BGED (km)
1	PV/Wind/ BDG/Battery	144	8	70	387	82	691,427	0.285	22,852	396,008	13.6
2	PV/BDG/ Battery	214		60	480	90	744,181	0.307	26,764	398,189	15.29
3	Wind/BDG/ Battery		21	40	590	88	811,960	0.335	29,322	432,900	17.45

The hybrid PV/Wind/BDG/Battery is the least cost system with NPC of $691,427, whilst the NPC of PV/ BDG/Battery and Wind/BDG/Battery are $744,181 and $811,960. The system with the lowest NPC comprises PV of 144 kW, 8 Wind turbines of 10 kW, BDG of 70 kW, 387 Batteries of Generic 1 kWh Lead Acid, 82 kW converter. Cost summary of the PV/Wind/BDG/Battery configuration by category is shown in Figure 2.

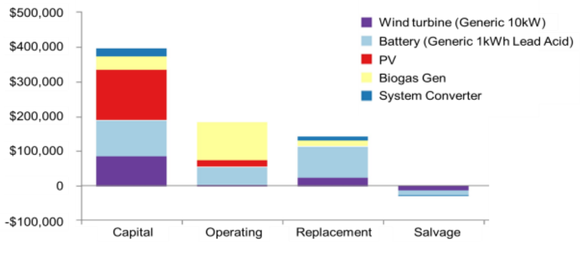

Figure 2: Cost summary of Solar/wind/biogas gen/battery hybrid system by category

The COE, initial capital cost, O&M cost of the PV/Wind/BDG/Battery are $0.285/kWh, $396,008, $22,852/y. Due to local policy, government will subsidy the initial capital and O&M costs of the hybrid power system in support of the village development. Compared with grid extension, the PV/Wind/BDG/Battery system is cost-effective with a BGED of 13.6 km, which is shorter than the village's distance to the nearest grid mode (22.4 km).

4.2 Sensitivity analysis results

Future load growth of the village is considered through sensitivity analysis by changing scaled annual average load demand, from the current baseline of 515 kWh/d to 600, 700, 800 KWh/d. With the increasing load demand, results show that PV/Wind/BDG/Battery remains the least-costly system considering NPC, system configuration for different annual average load are listed in Table 2. Increasing the capacity of system components can respond to load demand growth, which is more flexible than capacity expansion of power grid.

Table 2: Optimal system configuration for different annual average load

Annual average Load (kWh)	Architecture					
	Optimal system type	PV (kW)	Wind turbine (10 kW)	Biogas gen (kW)	Battery (kWh)	Converter (kW)
515	PV/Wind/BDG/Battery	144	8	70	387	82
600	PV/Wind/BDG/Battery	138	11	70	486	101
700	PV/Wind/BDG/Battery	161	9	60	666	118
800	PV/Wind/BDG/Battery	129	16	60	846	128

5. Conclusions

The study aimed to demonstrate the techno-economic feasibility of off-grid hybrid renewable energy system for sustainable remote rural electrification via a case study of a village in Southwest China. By performing techno-economic analysis, the simulation results showed that the most cost-effective and reliable system for the off-grid hybrid power system would be composed of 144 kW PV modules, 8 Wind turbines of 10 kW, 70 kW BDG, 387 kWh storage batteries and 82 kW convertor, which could generate about 434,448 kWh/y making the village independent of the grid with a reasonable COE of $0.285/kWh. The PV/wind/BDG/Battery system is economically viable than grid extension (BGED is 13.6 km). Considering solar, wind, biomass are usually local abundant in remote rural areas, utilization of the HRES is cost-effective, reliable whilst achieving environmental benefits. The sustainability of the proposed HRES not only reflects in economy and environment aspect, but also integrates social aspect. With more government dedications through establishment of conductive policies, incentives for villagers and funding mechanisms, the hybrid renewable energy system provides sustainable solutions for remote rural electrification and development in the long run.

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