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Modelling and Optimization of Hybrid Distributed Energy Systems for Remote Area Electrification: A Case Study in West China

Jinze Li*, Pei Liu, Zheng Li

Tsinghua BP Clean Energy Research and Education Centre, Department of Themal Engineering, Tsinghua University, Beijing 100084, China
ljz17@mails.tsinghua.edu.cn

Electricity availability of remote areas is a key bottleneck for development of these areas. Increasing electricity availability of remote areas has previously been severely constrained by connection conditions to a main electricity grid, including line distance, geographical conditions for construction, and size and pattern of loads. Increasingly cost-effective renewable energy, together with fast development of distributed energy production technologies, provides opportunities for tackling this challenge. However, due to the unique characteristics of energy supply and demand sizes and patterns of remote areas, design of distributed energy systems in these areas pose great challenges compared with existing ones for urban areas. In this paper, we propose a modelling and optimization framework for design of distributed energy systems in remote areas, featuring residential, small industrial, commercial and agricultural power loads, off-grid network, and solar, wind, and biomass as primary energy sources. We then implement the optimal design framework in HOMER, and illustrate the capability of the proposed framework via a case study of a village in West China. Results show that a hybrid distributed energy system comprising solar, wind, biomass energy is a cost effective, sustainable and environmentally friendly option for remote areas.

1. Introduction

Remote area electrification has been an essential development agenda for many developing countries given the fact that estimated 1.2 B people, about 17 % of the world's population, lack access to electricity (World Energy outlook, 2015). Conventional methods of energy supply in remote areas include grid extension and using diesel generators. For grid extension, many challenges are identified, such as distance from national or regional electricity grids, difficult terrain, and harsh weather conditions. Though using diesel generators is another alternative, the shortage of fossil fuel, environmental pollution, and high transportation costs for remote area make it a less attractive option. Considering these challenges, the penetration of local renewable resources has attracted extensive attention worldwide for the electricity availability of remote areas, with the advantages of sustainable and easily available resources, pollution reduction, and usually local abundance (Liu et al. 2018). However, the high renewable energy penetration systems lead to instability risk and oversizing issues because of intermittent and uncertain nature of natural resources.
To tackle these aforementioned challenges, cleaner and more efficient decentralized hybrid energy systems have provided long-term solutions for rural electrification process (Gizem and Selin, 2018). Vast researches on off-grid hybrid distributed energy systems, which integrate two or more types of renewable sources and storage modules as back up facilities are reviewed in the literature (Bajpai and Dash, 2012). One of the important issues in hybrid distributed energy system is optimal planning of its component so that the objective functions are minimized/maximized whilst all constraints are satisfied. To properly size hybrid renewable energy systems and their integrations, it is necessary to characterize not only the electricity consumption but also the fluctuations of demand along the day. For remote areas, the characteristics of energy demand sizes and patterns have difference with existing ones of urban areas. Previous studies have not pay enough attention on load patterns

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of remote areas by featuring power loads for different purposes at a whole community level, which is an important issue to be considered in this study while doing optimal design.

To do optimal design and to analyse the performance and reliability of hybrid distributed energy systems, researchers have been using various tools or programs (Fathima and Palanisamy, 2015). Hybrid optimization model for multiple energy resources (HOMER) developed by NREL (National Renewable Energy Laboratory, USA) is one of such tools. Description of HOMER and researches on optimal planning of hybrid renewable energy systems using HOMER are comprehensively reviewed in the literature (Bahramara et al., 2016).

To the best of author's knowledge, there is no comprehensive study on the HOMER which featuring residential, small industrial, commercial, agricultural power loads, off-grid network in remote areas of west China, and give a cost effective, reliable and sustainable solution for the electrification of residential entities by maximizing the utilization of local renewable energy sources. As a result, the main idea of this study is to provide a modelling and optimization framework for design of hybrid renewable energy systems in remote areas based on identifying the distinctive features of these areas. In the case study, electricity load, solar radiation data, biomass resource and wind speed data of a village in west China are used to apply techno-economic analysis by using HOMER simulation and optimization considering sensitivities.

2. Methodology

By providing a modelling and optimization framework for design of hybrid renewable energy system in remote areas, this study aims to demonstrate the techno-economic feasibility of the off-grid energy system comprising solar, wind, biomass energy. In order to present and illustrate the capability of the proposed modelling and optimal planning framework for the remote area, the study has considered the electricity load characteristics and local resources condition of a typical village in west China, but the framework is generalized in nature.

First, a remote village in west China is identified. Then for the design of hybrid renewable energy system, a detailed assessment of the electricity load profile and the available resources in the selected village are obtained. According to user load and available resources, appropriate components are selected. HOMER is used to develop the renewable energy based hybrid energy system configurations and techno-economic analysis aiming to obtain the optimal solution whilst satisfying the given load demand and constraints. The robustness of the system is also analysed by sensitivity studies of variable parameters of the system, which provides the basis for verifying the selection of optimal solution. After this HOMER based analysis, the final suitable configuration is decided based on the local conditions and government incentive policy.

2.1 User load assessment

In this study, a village Leopard Beach in Hongsibao district in Wuzhong city, Ningxia province of China is considered. The latitude and the longitude of the selected village are 37°29.0′N and 106°16.8’E. The elevation of the village is 1,272 m, with hilly and flat plain around. The total population of the village is 2,112, with 1,141 male and 971 female, and number of households is 408.

The load profile data is taken from village committee record, and electricity demand has been estimated by considering the power and utilization time of each equipment for three different seasons like summer, monsoon and winter. Compared with urban areas, electricity demand in a remote rural village is not high. 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 domestic load and industrial/commercial load, which must be met instantly. Electricity is demanded for domestic purpose for appliances like compact fluorescent lamps, fans, TV, washer, fridge and others; for industrial and commercial purpose for a range of infrastructure, such as small industry, post office, community center, school, medical centers, shops and others. The primary load demand is approximately 600 kWh/day for domestic use and 135 kWh/day for industrial /commercial purpose, with 75 kW peak in summer. Average annual primary load demand is 480 kWh/day and 68kW peak.

(ii) Deferrable load is defined as the electrical demand that can be met anytime within a defined time interval. Irrigation pumps and battery-charging are typical examples of deferrable loads. These loads allow certain flexibility when the power supply is insufficient. If the power supply produced ever exceeds the primary load, the surplus can serve the deferrable load rather than waste. The average deferrable load is 60 kWh/day.

The load profile considered for the simulation is shown in Figure 1. The typical daily primary electric load profile in Figure 1a shows a small base value covering morning and night hours, a higher level extending in the morning and midday time, due to productive and social infrastructure consumptions, and an evening peak load covering lighting and other home services, generally four to five times of the midday electric demand. As shown in Figure 1b, electric demand of monsoon and winter have obvious distinction with summer, associated to use of fans and fridges. Duration and utilization time of certain equipment have slight differences between monsoon and winter.

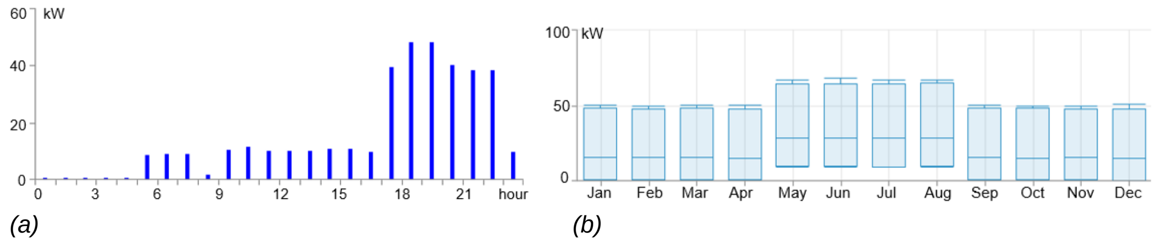

Figure 1: load profile. (a) Daily primary electric load profile. (b) Seasonal profile

2.2 Resources assessment

Hybrid solar/wind/biomass electric system is considered in this case. Converters and batteries are used as back up facilities because of the intermittent nature of renewable natural resources. The energy resources assessment is presented as follows.

2.2.1 Solar energy source

The solar radiation and temperature at a location of 37°29.0′N latitude and 106°16.8′E longitude is taken from NASA Surface Meteorology. The annual average solar radiation is approximately to be 4.54 kWh/m^2/day, scaled from 2.69 kWh/m^2/day with clearness of 0.633 in December to 6.08 kWh/m^2/day with clearness of 0.525 in June, which is evident that solar radiation in the selected village can be utilized almost throughout the whole year.
Based on the solar radiation and ambient temperature obtained, hourly energy output of the solar can be calculated according to the following equation,

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

where Y_{PV} [kW] is the related capacity of the PV array, meaning its power output under standard test conditions (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 standard test conditions; 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 standard test conditions.

2.2.2 Wind energy source

The monthly average wind resource data is obtained from NASA resource website for the selected village. Annual average wind speed is 6.02 m/s, with the altitude above sea level 1,272 m and the anemometer height 50 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.

$$U_{hub} = U_{anem} \frac{\ln(z_{hub} / z_0)}{\ln(z_{anem} / z_0)} \tag{2}$$

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, z_0 [m] is the surface roughness length, and ln(..) is the natural logarithm.
After the hub height wind speed 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 wind speed at the turbine hub height is not within the range defined in the power curve, which is wind speed below the minimum cutoff or above the maximum cut-out wind speed, the turbine produces no power. Finally, to adjust to actual conditions, power output value is calculated as equation (3).

$$P_{WTG} = P_{WTG,STP} \left(\frac{\rho}{\rho_0}\right) \tag{3}$$

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.

2.2.3 Biomass resource

In the village being studied, biomass is available easily in the form of maize straw. The cultivated land area is 350 hectares, which maize covers 180 hectares. Maize is harvested in autumn and considering decentralized collection and other losses, the maize straw could be used as fuel is approximately 3,000 ton/year. The utilization of biomass energy takes the form of converting maize straw into biogas, which small-size biogas power generation is the most widely used utilization form of biomass with better technological economy characteristic in China. Carbon content of local maize straw is 40 %, according to the local utilization form, gasification ratio is supposed to be 24 %, and low heat value (LHV) of biogas is 17.0 MJ/kg.

2.3 Techno-economic assessment

For the cost benefits and technical design, costs and performance details of the system components are major factors. According to the amount of available resources and load profile, appropriate equipment is selected roughly as follows.

The solar system is connected to a DC output with a life time of 20 years, the capital and replacement cost for 1 kW solar power generation is taken as $1,000 and $850 respectively. Derating factor is considered as 80 % for each flat PV panel to account for reduced output in real-world operating conditions compared to the conditions which the PV panel was rated. Panels have no tracking system and the slope is modeled as 37.5°.

A generic 10 kW horizontal axis wind turbine with $10,000 capital cost and $5,000 replacement cost is connected to AC output, which O&M cost is $50/year, lifetime is 20 years and hub height of the wind turbine is 24 meters. Weibull *k* value is parameter that reflects the breadth of a distribution of wind speeds. In the selected village, we use a Weibull *k* value of 2, which is typical of many wind scenarios.

To fulfill the requirement of the domestic sector during the night, a biogas fueled generator of 50kW is selected and connected to AC output. Biogas fueled generator will guarantee the stability and reliability of the hybrid renewable system due to intermittent and uncertainty characteristics of wind and solar modules. With abundant biomass resource, small size biogas fueled generator is easily available in the selected village with low capital, replacement and O&M costs. Capital cost, replacement cost and O&M cost of the generator (Generic 50kW) are $70/kW, $50/kW, and $0.03/operating hour respectively with a lifetime of 15,000 hours.

The main purpose of the batteries is to store the PV and wind turbine output during the day time to be used in the absence of solar radiations and wind. 50 Li-ion, 6.0 V batteries of 167 Ah are connected to DC in this hybrid energy system. Data sheet available in the HOMER indicates that the battery has round trip efficiency of 90 % and lifetime of 15 years, capital and replacement cost of the battery are considered to be $300/ generic 1 kWh Li-ion. For AC/DC converter, the capital, replacement and O&M costs are considered as $20/kW, $15/kW, $3/kW respectively, with a lifetime of 25 years, inverter efficiency of 95 %, and the rectifier efficiency of 90 %.

2.4 Analysis criteria

The selected design configurations in this case are (i) Wind/ Biogas Gen/Battery (ii) Solar/Biogas Gen/Battery (iii) Solar/Wind/Biogas Gen/Battery. Energy balance calculations for each system configuration are performed in HOMER and the feasible ones are selected. Feasible combinations of renewable energy systems are compared and analyzed based on Net present cost (NPC) and Cost of energy (COE) to get optimal solution.

The total NPC of a system 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, O&M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue. For this case, emissions penalties and power exchange with the grid (because the system is off-grid) are neglected. 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.

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i,R_{proj})} \tag{4}$$

where C_{NPC} is total net present post in $, $C_{ann,tot}$ is total annualized cost in $/year, *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:

$$COE = \frac{C_{ann,tot}}{E_{primary} + E_{deferrable}} \tag{5}$$

where *COE* is cost of energy, $C_{ann,tot}$ is total annualized cost in $/year, $E_{primary}$ is primary load served (AC and DC) in kWh/year, $E_{deferrable}$ is deferrable load served in kWh/year.

3. Results and discussion

HOMER simulates the operation of a system by making energy balance calculation according to the load profile in each time step of the year. For each time step, the electric demand in that time step is compared to the energy that the system can supply in that time step, whilst how to operate the fuel-powered generators and whether to charge or discharge the batteries are decided. Then configurations meet the constraints specified are ranked according to the NPC and the feasible ones with the lowest net present cost are presented by category as the optimal system configuration. System is also analysed by considering different sensitivity parameters.

3.1 System optimization results

The optimal simulation results of the hybrid renewable energy system are shown in table 1, which each one is the lowest NPC representative of each energy combination and all the systems use 100% renewable energy. From the NPC and COE view, there is little difference among the four kinds of combination, the NPC and COE of the energy system with Solar/Wind/Biogas gen/Battery are \$164,860 and \$0.0647 respectively, which is \$3178 and \$0.0013 larger than the least cost energy system with Biogas gen/Battery. And the Solar/Wind/Biogas gen/Battery system has the most initial capital cost of \$38,779 and least operating cost of only \$9,753/year, which is \$1,258/year smaller than the Biogas gen/Battery system with operating cost of \$11,011.

Table 1: Optimal simulation results of the hybrid renewable energy system

Architecture					Cost			
PV (kW)	Wind turbine (10kW)	Biogas gen (kW)	1kWh Li	Converter (kW)	NPC (\$)	COE (\$)	Operating cost(\$/yr)	Initial capital (\$)
		50.0	51	26.8	\$161,682	\$0.0634	\$11,011	\$19,336
1.06		50.0	51	25.9	\$162,622	\$0.0638	\$11,003	\$20,381
	1	50.0	49	29.1	\$163,969	\$0.0643	\$10,457	\$28,783
10.0	1	50.0	49	27.9	\$164,860	\$0.0647	\$9,753	\$38,779

Due to local policy, government will pay for the initial capital cost of the energy system in support of the development of village, whilst villagers undertake operating cost. The lifetime of the energy system is taken as 25 years, considering future electricity demand growth and economic benefits of villagers comprehensively, the combination of a 10 kW PV, 10 kW wind turbine, 50 kW biogas fuelled generator and 49kWh Li battery is the final optimal choice. Cost summary of the Solar/Wind/Biogas gen/Battery configuration is shown in Figure 2.

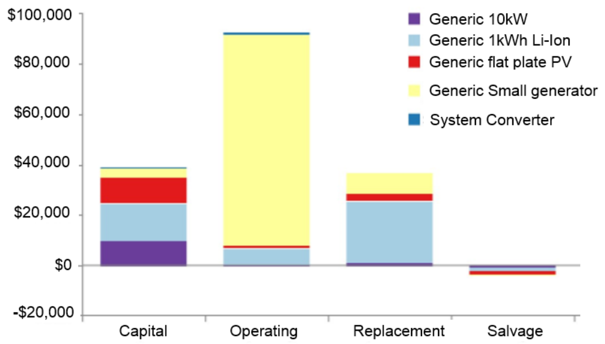

Figure 2: Cost summary of Solar/wind/biogas gen/battery hybrid system by category

3.2 Sensitivity analysis results

For the designed system of the selected village, changes in solar radiation and wind speed are considered for the sensitivity analysis. Price and amount of biomass are neglected as biomass is available in the form of maize straw free of cost and the amount obtainable is much bigger for the 50 kW biogas fueled generator needed.
For sensitivity analysis, available solar radiation is varied from 4.1 kWh/m^2/day to 4.6 kWh/m^2/day, wind speed is varied from 5.7 m/s to 6.1 m/s considering changes in climatic conditions. Results obtained from the sensitivity analysis of the hybrid system are shown in Figure 3, which illustrates the optimal system type due to the variation in solar radiation and wind speed according to NPC. Through the results, it can be observed that by increasing the solar and wind utilization, system combined of the Solar/wind/biogas gen/battery outperforms the other

combinations, characterized by lower NPC. When the solar radiation is 4.54 kWh/m^2/day and annual average wind speed is 6.02 m/s, considering sensitivity analysis, Solar/wind/biogas gen/battery is the optimal solution, with the net present cost of $160,238.2, which also provides evidence for the selection of optimization results.

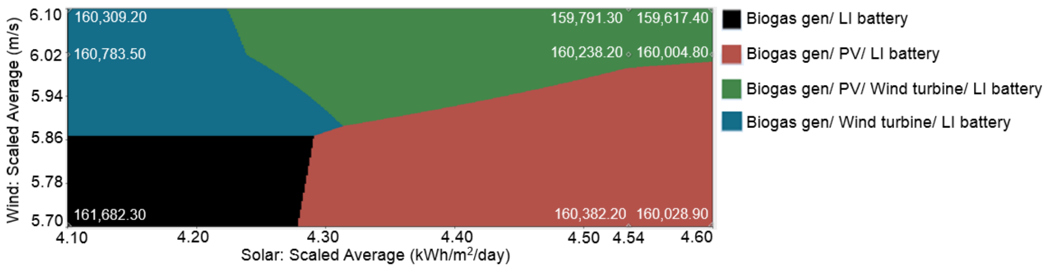

Figure 3: Optimal system type of sensitivity analysis

Optimal system type of sensitivity analysis also provides selection basis of suitable hybrid distributed energy system when changes occur in the availability of natural resources. For other villages with the similar load characteristics and available resources, it can also serve as a reference basis.

4. Conclusions

This study provides a modelling and optimization framework based on sensitivity analysis for design of off-grid hybrid distributed energy system in remote areas. The techno-economic evaluation of various configurations for the selected village of west China is analysed in HOMER by simulating dynamic hybrid model, and further research is done through sensitivity analysis using parameters like solar radiation and wind speed. The combination of 10 kW PV modules, 10 kW wind turbine, 50 kW biogas fuelled generator, 49 kWh storage batteries and 28 kW convertor is the final selected optimal solution for this case study with initial capital investment of $38,779 and operating cost of $9,753/year. This hybrid energy system generates about 204,831 kWh/year making the village independent of grid, which provides electricity to the consumers at a low cost of $0.0647/kWh. Moreover, the system has reasonable total net present cost (NPC) of $164,860, the period of the project is 25 years and estimated payback period is 8.96 years. According to simulation results and further analysis, the hybrid renewable energy based configuration which comprising solar, wind, and biomass energy are cost effective and reliable, which can be employed in the remote area to make them independent of grids.

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