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Energy Procedia 158 (2019) 688–693

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Optimal Design of Standalone Hybrid Renewable Energy Systems with Biochar Production in Remote Rural Areas: A Case Study

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Abstract

For remote agriculture-based rural areas, utilizing the local renewable resources such as biomass, wind, and solar energy could be potentially more efficient than long-distance transmission of electricity. In this paper, a multi-objective optimization model for the design of standalone hybrid renewable energy systems (HRES) in remote rural areas is proposed. The objective is to maximize the profits and the carbon abatement capability of the system by optimal process selection and sizing of HRES components including solar, wind, and biomass generation systems. A case study for the design of an HRES on the Carabao Island in the Philippines is conducted. The result shows a 122 kW solar power plant, a 67 kW onshore wind farm and a 223 kW biomass pyrolysis system constitute the optimal configuration of the hybrid energy system, generating a daily profit of US$ 940. The greenhouse gas emission of the optimal system is -3,339 kg CO_2 eq/day, indicating good carbon sequestration performance.

Keywords: Hybrid renewable energy system; Negative emission technologies; Cost and benefit analysis; Life cycle assessment; Optimization

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1. Introduction

One of the Sustainable Development Goals (SDGs) of the United Nations Development Program is to achieve universal access to affordable electricity by 2030 [1]. However, supplying power to remote regions, such as a remote island, through power grid transmission may result in considerable loss of electricity in the transmission process and can be very costly [2]. In this case, building a standalone microgrid locally based on the concept hybrid renewable energy system (HRES) can be an alternative to electrify the area efficiently and economically. HRES is able to

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10.1016/j.egypro.2019.01.185

generate electricity using a combination of different renewable resources, such as solar, wind, and bioenergy [3]. Utilizing local renewable resources rather than importing fossil fuels is environmentally friendly and could be used to develop self-sustained methods to cope with the problems of fossil fuel depletion and climate change in the long run.

Bioenergy is a type of renewable energy derived from biological sources (biomass) by various biochemical and thermochemical processes, through which biomass can be converted into syngas, bio-oil and biochar [4]. In this study, we especially look into bioenergy as the work focuses on the design of the HRES for an off-grid agriculture-based island, where there are abundant biomass resources in the form of agricultural residues available throughout the year, apart from solar and wind resources. Thermochemical methods including combustion, gasification, and pyrolysis have been widely used to convert agricultural residues into electricity. As a carbon-rich solid residue derived from gasification and pyrolysis, biochar has been recognized as an effective carbon abatement tool upon its application to soil. The application of biochar for soil remediation could also potentially increase crop productivity [4]. Choices of feedstock and processing techniques for biomass conversion critically determine the yield of products and thus the level of profitability and environmental impacts. Therefore, it is feasible to maximize the economic and environmental performance while meeting the product demand by optimizing the choice of feedstock and processing techniques.

However, there is limited knowledge regarding the combined economic and environmental benefits of biochar-based HRES for remote rural areas. In this paper, a multi-objective optimization method for the design of a standalone HRES considering the effects of biochar production on an agriculture-based island is proposed. To demonstrate the method, a case study on the optimization and application of HRES on Carabao Island in the Philippines is carried out. In the following sections, the method for designing the HRES will be presented in Section 2, the background of the case study on Carabao Island will be shown in Section 3, the results and discussion of the case study will be provided in Section 4, and conclusion given in Section 5.

2. Methodology

As shown in Figure 1, the first step in the proposed method is data compilation regarding local renewable energy resources for the stand-alone system, which are usually featured by temporal fluctuations or seasonality. The data required depend on the energy conversion models. In this case, wind speed and temperature are required to calculate the maximum potential of power generated from the wind, while solar radiation and temperature are used to estimate the maximum possible power generation derived from solar energy. The availability of biomass waste is utilized to assess the maximum production of electricity and biochar from different thermochemical processes. The maximum resource availability is used as the resource constraints in the following optimization process. In this study, the hourly demand and weather data for each day throughout the year is converted into the hourly data for one day (24 hours). In the optimization model, the actual electricity and biochar production for each time interval (1 hour) serves as the input for the assessment of the economic and environmental performances of the system. The actual electricity and biochar production is calculated using the conversion model from the number of wind turbines, solar

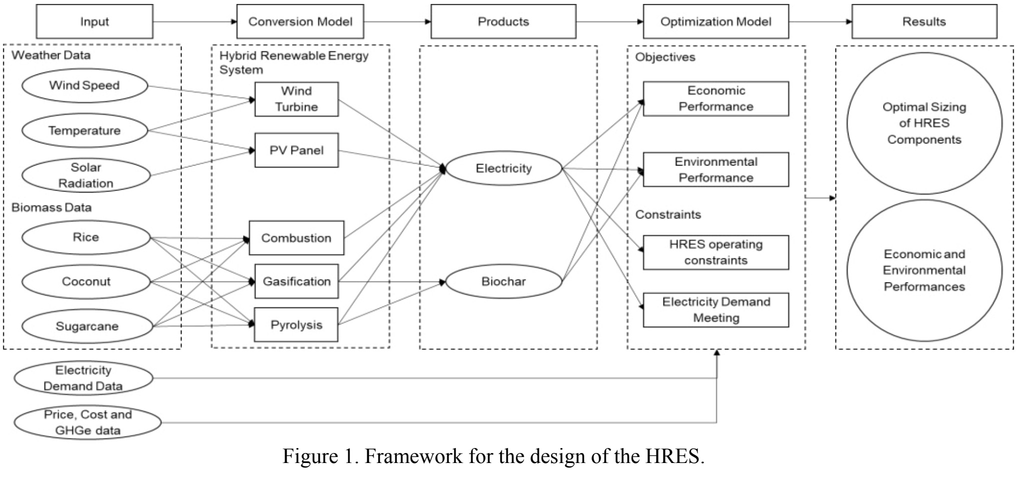

Figure 1. Framework for the design of the HRES.

panels, and the feeding rates of biomass, which are the decision variables that determine the size of each components of the HRES. Finally, the optimal decision variables can be returned and the results of the optimal sizing of each component and corresponding economic and environmental performances of the HRES are obtained. Details about the conversion model and optimization model are provided in the following subsections.

2.1. Conversion Model

Combustion, gasification, and pyrolysis are considered in this study as the alternative technologies for biomass conversion. It is assumed that biochar produced from the processes is used for soil amendment, while the syngas and bio-oil products are consumed for electricity production. Therefore, the mass production rate of the biochar and the power produced from the processes are calculated based on the following mass and energy balances in Eq. (1)-(2):

$$m_{biochar} = x_{biochar} \cdot F \tag{1}$$

$$P_{biomass} = \begin{cases} F \cdot LHV_F \cdot \eta, & \textit{direct combustion} \\ (F \cdot LHV_F - m_{biochar} \cdot LHV_{biochar}) \cdot \eta, & \textit{gasification and pyrolysis} \end{cases} \tag{2}$$

where $m_{biochar}$ is the mass production rate of biochar (kg/h), $x_{biochar}$ is the yield of biochar (kg /kg feed), F is the feeding rate of the biomass (kg/h), $P_{biomass}$ is the power generated by the biomass conversion technologies (kW), LHV_F is the lower heating value of the feed (kJ/kg), $LHV_{biochar}$ is the lower heating value of the biochar (kJ/kg), and η is the efficiency of the different biomass conversion technologies.

The electricity generated from the wind turbine and the solar panel are estimated using Eq. (3)-(5) [5].

$$P_w = \begin{cases} 0, & v \le v_{ci} \text{ or } v \ge v_{co} \\ \frac{1}{2} \cdot \rho \cdot C_p \cdot A \cdot v^3, & v_{ci} \le v \le v_r \\ P_r, & v_r \le v \le v_{co} \end{cases} \tag{3}$$

$$P_s = U \cdot I \tag{4}$$

$$I_l - I_d \{\exp[\alpha \cdot (U + R_{se} \cdot I) - 1\} - \frac{U - R_{se} \cdot I}{R_{sh}} - I = 0 \tag{5}$$

where P_w and P_s are the power generated by the wind turbine and the solar panel (kW), ρ is the air density (kg/m^3), C_p is the wind power coefficient, A is the area swept by the rotor blades of the wind turbine (m^2), v is the wind speed (m/s), v_{ci}, v_r, and v_{co} are the cut-in speed, rated speed, and the cut-out speed of the wind turbine (m/s), P_r is the rated power of the wind turbine (kW), U is the voltage of the solar panel (V), and I_l is the light current (A).

2.2. Optimization model

The objective of the model is to maximize the daily cash flow (CF) and minimize the daily greenhouse gas (GHG) emissions, subject to the demand satisfying, resource availability, as well as the operating constraints of the system. Assuming the system operates continuously through the year, the startup of the HRES system is not considered. The overall optimization model is shown in Eq. (6). The calculation of the cash flow is carried out by Eq. (7). The evaluation of the greenhouse gas emission is through Eq. (8). This is formulated as a multi-objective linear programming problem and solved by the the Gurobi solver in Matlab using a weighted sum method.

$$\begin{aligned} & \textit{Maximize } (CF,\ -GHG) \\ & s.t. \quad \sum_i \mathrm{P}(i,t) - S_{in}(t) + S_{out}(t) \ge D(t) \qquad \sum F(j,t) \le F_r(j,t) \\ & \qquad N_i \cdot A_i \le L_i \qquad P_{sell} \le D \\ & \qquad S_{out}(t) \cdot \Delta t \le E(t) \qquad S_{in}(t) \cdot \Delta t \le E_{\max} - E(t) \\ & \qquad \Delta x \le dP_x \ (x = P(i,t), P_{sell}(t),\ S_{in}(t), S_{out}(t)) \qquad N_w, N_s, F(j,t), P_{sell}(t),\ S_{in}(t), S_{out}(t) \ge 0 \\ & \qquad t = 1,\dots,24 \qquad i = \textit{solar, wind, combustion, gasification, pyrolysis} \qquad j = \textit{type of the biomass feed} \end{aligned} \tag{6}$$

where CF is the daily cash flow in US dollar (\$/day), GHG is the greenhouse gas emission (kg CO_2 eq/day), P is the power generated by the HRES (kW), S_{in} is the energy storage charging power (kW), S_{out} is the energy storage discharging power (kW), D is the demand (kW), N_i is the number of each HRES component, A_i is the land area occupied by one unit of the HRES component (m^2), L_i is the available land area for each HRES component (m^2), P_{sell} is the power sold (kW), $\Delta t = 1$ is the time interval (h), E is the accumulated energy of the energy storage system (kWh), Δx means the change of the time dependent variable x during the time interval, dP_x is the maximum changing rate of the variable x, F is the feeding rate of the biomass (kg/h), F_r is the maximum feeding rate of the biomass (kg/h), subscript *max* denotes the maximum value of the parameter or variable.

$$\begin{aligned}
&CF = \sum_{t=1}^{24} (Revenue(t) - OPEX(t)) - \frac{CAPEX}{365} \cdot \frac{r \cdot (1+r)^T}{(1+r)^T - 1} \\
&Revenue(t) = c_{elec} \cdot P_{sell}(t) + c_{biochar} \cdot m_{biochar}(t) \qquad OPEX(t) = OPEX_{\mathrm{var}}(t) + OPEX_{fixed}(t) \\
&OPEX_{\mathrm{var}}(t) = c_{VOM}(i) \cdot P(i,t) + c_{storage\_VOM} \cdot (S_{in}(t) + S_{out}(t)) \qquad OPEX_{fixed}(t) = c_{FOM} \cdot P(i,t) + c_{storage\_FOM} \cdot (S_{in}(t) - S_{out}(t)) \\
&CAPEX = c_{CAPEX}(i) \cdot P_{\max}(i) + c_{storage\_CAPEX\_P} \cdot S_{\max} + c_{storage\_CAPEX\_E} \cdot E_{\max} \\
&E(t) = (\sum_{t=1}^{t} \mathrm{S}_{in}(t) \cdot \Delta t) - (\sum_{t=1}^{t} \mathrm{S}_{out}(t) \cdot \Delta t) - \frac{\eta}{2}(\sum_{t=1}^{t} \mathrm{S}_{in}(t) \cdot \Delta t) - \frac{\eta}{2}(\sum_{t=1}^{t} \mathrm{S}_{out}(t) \cdot \Delta t)
\end{aligned} \tag{7}$$

$$GHG = \sum_t \sum_i (ghg_p(i) \cdot P(i,t) - ghg_{biochar} \cdot m_{biochar}(i,t)) \tag{8}$$

where $Revenue$ is the total revenue of the HRES (\$/h), $OPEX$ is the operating and maintenance cost (\$/h), r is the interest rate, T is the lifespan of the HRES system, and c_x is the unit cost or selling price depending on the context, ghg_p is the unit greenhouse gas emission for the HRES components (kg CO_2 eq/kW), $ghg_{biochar}$ is the greenhouse gas absorption by biochar (kg CO_2 eq/kg) which is proportional to the stable carbon content of the biochar.

3. Input for the case study

Carabao Island, a 5th class municipality in Romblon, Philippines, is a rural island with a population of 10,881 and an area of 22.05 km^2 [6]. There exists investment potential to develop eco-tourism on the Carabao Island as it is next to the touristy Boracay Island [7]. However, the power infrastructure on the island is not well established currently, and the electricity supply is only available from 2 pm to 6 am [8]. Cobrador Island, another island in Romblon, has achieved a 24-hour energy supply from the hybrid solar-diesel system [9]. Therefore, one feasible investment plan is to utilize multiple renewable resources to power the island. This case study looks into the feasibility of installing a stand-alone HRES on the Carabao Island, which is potentially consisting of solar, wind, and biomass generation components. Rice, sugarcane and coconuts are the three major crops produced in the country. The annual yields of the agricultural wastes from these crops in the Philippines and the estimated hourly biomass feeding rate on the Carabao Island are shown in Table 1. As the input of the study, the data of the local demand and resources, including the average daily wind, solar, and temperature information, are also collected. The maximum allowance of the number of wind turbines and solar panels are assumed to be 50 and 2000, respectively. Figure 2-3 show the demand curve and the maximum power and biochar production estimated from the available resources.

Table 1. Annual biomass waste availability [10] and the their corresponding lower heating values (LHV) [11].

	Sugarcane waste	Bagasse	Rice husk	Rice straw	shell	coconut coir	Coconut frond
Yield in the Philippines (ton/yr)	5,322,970	5,322,970	3,122,631	4,270,000	2,419,819	1,547,479	6,950,000
Hourly yield (kg/ha/h)	0.05	0.05	0.03	0.04	0.02	0.01	0.06
LHV (MJ/kg)	15.52	15.62	11.1	14.92	19.26	17.79	17.79

Table 2. Parameters for bioenergy conversion. *Assumed based on [2] and [12].

LHV of Biochar (MJ/kg) [11]	31.91	Biochar yield from gasification*	10%
Fixed carbon in the biochar*	80%	Biochar yield from pyrolysis*	20%
Biochar yield from combustion	0	Efficiency of the combustion, gasification, and pyrolysis systems*	0.27, 0.3, 0.3

Table 3. Cost of the HRES components [13][14].

	CAPEX ($/kW)	Fixed OM (% of CAPEX/yr)	Variable OM ($/MWh)		CAPEX ($/kW)	Fixed OM (% of CAPEX/yr)	Variable OM ($/MWh)
Combustion	3,070	3.2	4.56	Solar	1,600	9.53 ($/kW/y)	0
Gasification	3,920	4.5	4.08	Wind	2,300	23.82 ($/kW/y)	0
Pyrolysis	3,920	4.5	4.08	Energy storage	583.96 ($/kW) 556.55 ($/kWh)	10.11	1.07

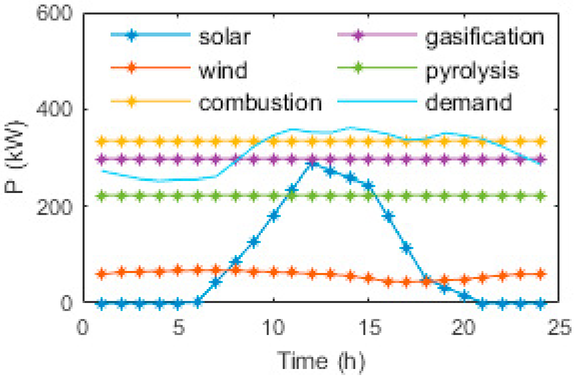

Figure 2. Demand curve and the maximum power generated from the technologies.

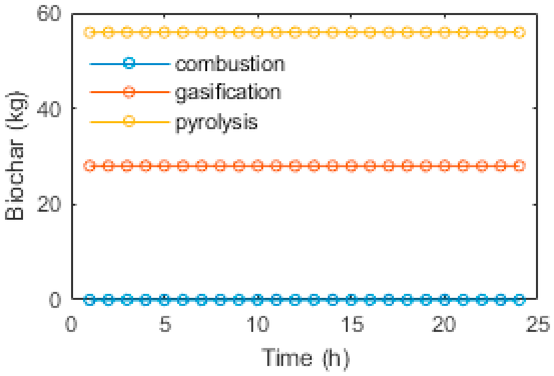

Figure 3. Maximum biochar production.

4. Results and discussion

According to the optimization, the optimal solution for minimizing the greenhouse gas emissions and maximizing the cash flow are the same, resulting in one optimal solution for the multi-objective optimization. The optimal power generation and storage performing profile meeting the constraints are returned by Matlab, as shown in Figure 4-5. The optimal configuration of the HRES consists of a 223 kW pyrolysis process, a 122 kW solar power plant with 843 PV panels (1.24 m^2 each), a 67 kW onshore wind farm with 50 wind turbines (blade diameter = 7m), and a 67 kW vanadium redox flow battery (VRB) energy storage system. Consequently, the optimal daily cash flow or profit is 940 US$/day. The operation of the optimal HRES is carbon negative, with an optimal daily greenhouse gas emission of -3,339 kg CO_2 eq/day (or carbon sequestration of 3,339 kg CO_2 eq/day).

Pyrolysis is the most preferable technology under the current objectives and constraints. All types of feedstocks are suggested to be treated through pyrolysis. This is because it has the highest levelized profit (profit per unit electricity generated) among the technologies in this study, followed by wind power generation. The root cause is

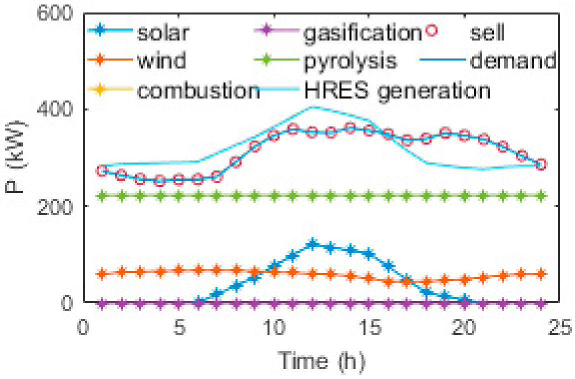

Figure 4. Optimal power generation curve.

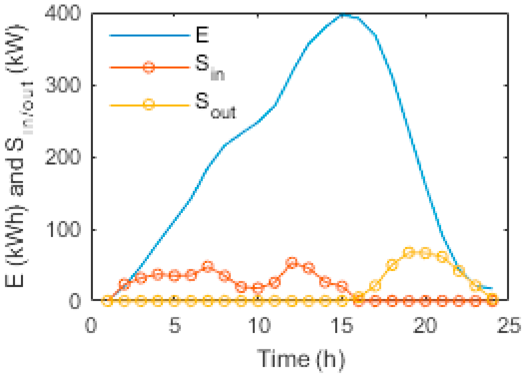

Figure 5. Operation profile for the energy storage.

that for each unit of electricity generated and sold, pyrolysis and gasification gain extra benefits from the sales of biochar and the former has a higher biochar production and benefit. However, pyrolysis is only economically preferred when the excess generated power cannot generate revenue, which is true for a stand-alone system. In the case when all the local excess electricity generation can be sold to other markets, gasification becomes the most profitable and preferred technology among the bioenergy conversion methods considered in this study because it has a higher profit per unit biomass consumed. Lastly, it is also worth mentioning that the pyrolysis based system always has the largest GHG reduction because of its highest biochar production.

5. Conclusions

A multi-objective optimization method for the design of standalone hybrid renewable energy systems in remote rural areas has been proposed and a case study for the Carabao Island has been conducted. The result indicates that building a HRES on the Carabao Island is profitable and carbon negative. The current study demonstrates how to use the current model to do a preliminary design of the HRES. The proposed method can also be applied to studies with a different timeframes and location. To enhance the practical significance of the design, future resources and demand can be estimated and imported into the model. As a promising prediction method, machine learning methods can be used to achieve this goal. Alternatively, demand data can be estimated using bottom-up models. Stochastic optimization can be used to take into account the uncertainty of the prediction. More detailed modeling of the systems such as the exact modeling and simulation of the biomass conversion process can be adopted to make the model more realistic and reliable. Apart from the economic and environmental objectives considered in this study, further studies incorporating other factors, such as social and ecological effects, can also be carried out by adding additional constraints and objectives to the model. To be more comprehensive, adding other energy systems such as geothermal and ocean energy is also feasible based on the current optimization model.

Acknowledgements

The authors thank the MOE AcRF Grant in Singapore for financial support to the project R-279-000-537-114.

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