Techno-economic study of a distributed hybrid renewable energy system supplying electrical power and heat for a rural house in China

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Abstract. Energy saving and emission reduction have become targets for modern society due to the potential energy crisis and the threat of climate change. A distributed hybrid renewable energy system (HRES) consists of photovoltaic (PV) arrays, a wood-syngas combined heat and power generator (CHP) and back-up batteries is designed to power a typical semi-detached rural house in China which aims to meet the energy demand of a house and to reduce greenhouse gas emissions from the use of fossil fuels. Based on the annual load information of the house and the local meteorological data including solar radiation, air temperature, etc., a system model is set up using HOMER software and is used to simulate all practical configurations to carry out technical and economic evaluations. The performance of the whole HRES system and each component under different configurations are evaluated. The optimized configuration of the system is found

1. Introduction
The energy crisis and the climate change have become major concerns and are gaining significant attention in China and the world. Energy cost and environmental effect is making energy management, optimization and utilizing more renewables a crucial issue in building operations and maintenance. Actually, prior to the development of coal in the mid 19th century, nearly all energy used was renewable. Over the years, many new technologies have come out trying to shift the conventional low-efficiency fossil fuel-fired energy mode to other alternative and efficient options. In 1954, Bell laboratories first successfully brought the silicon solar module which provided the 6% conversion efficiency to the outdoor [1]. During the early 20th century, gasification had been an important and common technology. However, using woods to generate electricity, they must be gasified first and then cleaned (eliminate the particles and char) and cooled down (remove the moisture) the producer gas, i.e. syngas before being burned in the engine [2]. Technology like heat recovery is a method to improve the efficiency of the whole system which is quite often implied in the Rankine Cycle (RC) or Organic Rankine Cycle (ORC) [3]. In the early 21st century, the emergence of distributed generation (DG) technologies carved out the new way for optimizing the energy consumption configuration [4]. Moreover, hybrid renewable energy systems (HRES) which terms to the complementary incorporation of several different renewable energy generations have been proved to be more reliable and efficient...
than single power system [5]. It is acknowledged that some of these technologies are quite mature while others are still developing.

Based on the technologies mentioned above, a distributed hybrid renewable energy system (HRES) consists of photovoltaic (PV) arrays, a wood-syngas combined heat and power generator (CHP) and back-up batteries is designed for a rural house, which is located in a mountainous area in China where power grid is hard to reach.

2. Proposed Conformation

For mountainous area, grid construction is highly expensive. Therefore, distributed generation is a perfect approach to solve the problem. More importantly, some local sources such as solar radiation and wood biomass are available for building an ideal HRES. As shown in Fig. 1, a stand-alone power system needs to satisfy the thermal and electrical load for a household. Without the support of the grid, the system should be flexible enough to adjust the power output according to the load change. Accordingly, energy storage system is designed and implemented. If the generation is more than load requirement, it has to be stored in the energy storing device. If the load is high and the generation is less, the storage device has to discharge [6].

3. Cost estimation

HOMER (Hybrid Optimization Model for Electric Renewables) is a simulation software and is developed by National Renewable Energy Laboratory. HOMER first assesses the technical feasibility of the hybrid microgrid system to make sure it can meet the load demand. It can simulate the operation of the system for an entire year. Second, it estimates the total net present cost (NPC) of the system which terms to the life-cycle cost including initial set-up costs, component replacement costs, and the purchasing power costs from the grid, operation and maintenance costs. NPC is given by the following formula [7],

\[
NPC = \frac{C_{tot}}{CRF(i,T_p)}
\]  
(1)

where \(C_{tot}\) is the total annualize cost of the system (USD/year), \(i\) is the annual real interest rate (%), \(T_p\) is the project lifetime (10 years in this project), \(CRF(,\) is the capital recovery factor, which is given by the following formula:

\[
CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n+1}
\]  
(2)

where \(n\) is the number of years.

In HOMER, the salvage costs (SC), which indicates the residual values of the components at the end of the project lifetime, are also taken into account in the estimation of the NPC, Homer gives the following formula:
where $C_{RC}$ is the replacement cost of the component (USD), $T_{rem}$ is the remaining life of the component (year), $T_{com}$ is the lifetime of the component (year).

In Homer, the levelized cost of energy (COE) is given by:

$$\text{COE} = \frac{C_{tot}}{E_{tot}}$$

where $E_{tot}$ is the total electricity consumption per year (kWh/year).

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- The text should be set to single line spacing.
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4. Cost study

4.1. Style and spacing

A typical rural house in Hubei province, south China (Latitude 30.7°N, Longitude 111.28°E) has been used as the case study to investigate and validate the efficacy of the proposed methodology. The load demand of the house including thermal and electric load is estimated by a four years average as shown in Fig. 2 and Fig. 3 respectively. It is understandable that the peak of the electric load appears in summer when the air condition starts to work while the peak of the thermal load is in winter. The specific data are gathered in Table I.

| TABLE I | SPECIFIC LOAD DEMAND |
|---------|-----------------------|
| Thermal load | Electric load |
| Average(kWh/d) | 39.5 | 2.18 |
| Average(kW) | 1.65 | 0.0907 |
| Peak(kW) | 11.5 | 1.06 |
| Load factor | 0.143 | 0.0856 |

**Figure 2.** Monthly thermal load data

**Figure 3.** Monthly electric load data

**Figure 4.** Average daily radiation and clearness index near the house

4.2. Sources Available

From the National Aeronautics and Space Administration (NASA) database on the RETscreen webpage, some basic information was acquired. Fig. 4 shows the daily solar radiation ranged from 2.31kWh/m² to 4.52kWh/m². Searching the mountains around the house, it turned out about 10 tons
wood biomass available for use yearly (redundant branches and leaves in winter). Wood biomass is a necessary source for fueling the boiler (wood gasifier) and wood gas generator.

5. Model Simulation
The core concept of this study, in simple words, is to use the local sources to feed its own demand. As shown in Fig. 5, components consist of PV modules, T-105 battery which stand on the DC side and wood gasifier, wood gas generator which stand on the AC side. The converter plays a role of converting direct current or alternating current. To choose an appropriate battery for the energy storage system, the balance between generation and demand should be achieved. So,

\[
\text{Required storage capacity} = \text{Max} \int \Delta P \text{dt} - \text{Min} \int \Delta P \text{dt} \tag{5}
\]

\[
\text{Number of batteries} \geq \frac{C_{\text{Wh}}}{\text{DOD}} \times \text{rated capacity of each capacity} \tag{6}
\]

Where, \(\Delta P\) is the magnitude difference between generated power \((P_{\text{gen}})\) and the demand \((P_{\text{dem}})\), \(C_{\text{Wh}}\) is the batteries total capacity, DOD is the depth of discharge [8].

The exhausted heat from the engine and the boiler is utilized to generate hot water and then supply to users. It can be achieved by installing some heat exchangers on the way of flowing exhausted wood gas. This can be considered as a typical small CHP system.

The control model in HOMER software includes load following (LF) model and cycle charging (CC) model [9].

6. Result and discussion
A total of 3780 \((9 \times 7 \times 6 \times 5 \times 2)\) cases are made which the number is corresponding to the combinations of different sizes of components (generator \(\times\) PV \(\times\) converter \(\times\) battery \(\times\) control model).

6.1. Mechanical Result
Many cases can satisfy the demand of the household. From the results of HOMER, it is found that the system of case 1 with 0.5kW of PV arrays, 0.65kW of wood gas generator, 3 unit batteries each of 1.35kWh and 0.5kW sized power converter in CC model obtains the best effectiveness, as shown in Table II and the details shown in Table III and table IV. Firstly, the lowest NPC and COE were achieved in this result (see in section B). Secondly, the whole system run perfectly to meet the demand of the household, which the unmet thermal load is 0 and the unmet electric load is small enough to be ignored. Thirdly, the excess thermal and electricity are the lowest.

6.2. Economic Result
On the economic side, attentions often be paid on the COE and NPC. These two factors calculated automatically by the HOMER represent the economic feasibility of the whole system. The economic
optimization result is shown in Table II. The lowest NPC and COE are 3572 USD and 0.351 USD/kWh respectively. It should be noted that Chinese government is promoting the development of distributed renewable energy [10] and matched preferential policies have been introduced including levy-refund and discount taxable income. So the real cost is much lower.

6.3. Emission Result
For the economic-optimal system shown in Table II, some important indicators of pollutant can be acquired by simulation which is shown in Table V. However, the biomass like wood could be considered renewable in a life cycle because the CO2 emitted by burning woods this year can be partly absorbed by the growing of new boughs next year through photosynthesis [11].

6.4. Sensitivity analysis
If we enhance the proportion of the PV arrays, for example, choosing the system of case 2 with 0.75kW PV and 0.65kW generator which electricity generated by PV takes 55% of the whole system, the emissions of the pollutant will have a slight decrease as shown in Table VI.

| Options | PV (kW) | Generator (kW) | battery | Converter (kW) | PV (kWh/yr) | Generator (kWh/yr) | Initial capital (USD) | Operating Cost(USD/yr) | NPC (USD) | COE (USD/kWh) |
|---------|---------|----------------|---------|----------------|-------------|-------------------|----------------------|----------------------|-----------|--------------|
| Case 1  | 0.5     | 0.65           | 3       | 0.5            | 518         | 618               | 1856                 | 134                  | 3572      | 0.351        |
| Case 2  | 0.75    | 0.65           | 3       | 0.5            | 777         | 587               | 2292                 | 134                  | 4000      | 0.393        |
| Case 3  | 0.25    | 1              | 3       | 0.5            | 259         | 755               | 2072                 | 176                  | 4320      | 0.425        |

Table III Thermal demand and supply

| Thermal production (kWh/yr) | 16155 |
| Boiler output fraction (%) | 83    |
| Generator output fraction (%) | 16    |
| Excess thermal (kWh/yr) | 1738  |
| Unmet thermal load (kWh/yr) | 0     |
| Wood consumption (kg/yr) | 3852  |

Table IV Electric demand and supply

| Electric production (kWh/yr) | 1136 |
| PV output fraction (%) | 46    |
| Generator output fraction (%) | 54    |
| Excess electricity (kWh/yr) | 190   |
| Unmet electric load (kWh/yr) | 3.13 × 10^{-7} |
| Capacity shortage (kWh/yr) | 0.568 |

Table V Emissions of Economic Optimization System

| Pollutant | Emissions (kg/yr) |
|-----------|-------------------|
| Carbon dioxide (CO2) | 6490     |
| Carbon monoxide (CO) | 4.23     |
| Particulate matter (PM) | 0.427    |
| Sulfur dioxide (SO2) | 3.83     |
| Nitrogen oxides (NOX) | 1.39     |

Table VI Emissions of PV-enhance System

| Pollutant | Emissions (kg/yr) |
|-----------|-------------------|
| Carbon dioxide (CO2) | 6407     |
| Carbon monoxide (CO) | 4.10     |
| Particulate matter (PM) | 0.414    |
| Sulfur dioxide (SO2) | 3.78     |
| Nitrogen oxides (NOX) | 1.34     |

Emission of carbon dioxide drops about 1.3%, carbon monoxide about 3.1%, particulate matter about 3.2%, sulfur dioxide about 1.3%, nitrogen oxides about 3.7%. However, the COE of this PV-enhanced system has a 12.0% increase. In fact, lower emissions always mean higher costs. Therefore, it is important to strike a balance between the profit making and environment protection.

7. Conclusion
In order to meet the target of promoting renewable energy in remote rural areas, this investigation of the feasibility of building a distributed HRES for a rural house was conducted in mountainous area of south China.
To find the optimized configuration, HOMER software was utilized to simulate all viable combinations in two different modes. The results had demonstrated that PV/wood gas generator/battery system with CC mode was evaluated to possess the lowest COE (0.351USD/kWh) and NPC (3572USD) for SAPS.

As for emissions, though the CO2 reaches 6490 kg/yr in the economic optimization system, the net emission can be thought as zero in a life cycle according to the properties of renewable biomass energy.

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