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Comparative analysis of hybrid systems for on-grid and off-grid applications in central China: Case study of university dormitory in Ma'anshan

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Comparative analysis of hybrid systems for on-grid and off-grid applications in central China: Case study of university dormitory in Ma'anshan

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Abstract. In order to compare the design of hybrid energy systems for on-grid and off-grid applications, a university dormitory in central China is selected and investigated to achieve the target of a zero energy dormitory. The building is modeled in DeST and hybrid system design optimization is performed in HOMER. Results show that the on-grid hybrid system under time-of-use rate policy is much more economic than that under single rate policy for on-grid case. The total net present cost is 230,534 $ and the levelized cost of energy is 0.124 $/kWh. The off-grid system with generators is more economical than system without them, and the cost is found to be about 6 times than on-grid system. Sensitivity analysis is performed by considering sell-back price and diesel price, it is found that NPC and COE can be increased by 9.7% and 12.7% for the decreased sell-back price and doubled diesel price respectively.

1. Introduction

Recent years, the frequent occurrence of hazy weather in China has attracted much more attention on environment protection and thus largely boosts researches on the application of environment-friendly renewable energy (RE) resources. Building energy consumption accounts for a total energy consumption of about 35% [1], and urban residential electricity use has more than tripled between 2001 and 2014, from 123 billion kWh to 408 billion kWh [2]. Many countries have adopted policies to support electricity generation from renewable energy resources with the aim of achieving a sustainable development [3].

Hybrid energy systems (HES), combining two or more renewable energy resources like wind or solar, seem to be more reliable and cost effective due to the complementary nature of various resources. Huang et al. [4] proposed a new type of wind-solar hybrid system and the results showed that, at low wind speed, the multi-turbine wind-solar hybrid system has more power production than the reference system. Li et al. [5] discussed the economics, sensitivity and PV module tilt angle analysis of the proposed hybrid photovoltaic/wind turbine/battery (PV/WT/BA) power system for a household in Urumqi, China using the Hybrid Optimization Model for Electric

Renewable(HOMER)software. The feasibility of achieving smart/near-zero energy buildings (ZEB/nZEB) has been widely studied in case studies including commercial, residential and public buildings. Aksamija [6] discussed that this commercial building is able to meet net-zero energy use after multiple renewable energy sources and appropriate design manipulations. Krarti [7] found that the annual energy use could be achieved by 50% compared to the current design practices of homes through most countries in the MENA region. Some papers take into account the advantages and disadvantages of grid connection and off-grid system. The evaluations showed that grid connected hybrid RE systems have a higher probability of adaptation than off-grid system (100% renewable system) configurations [8]. The study of Rajbongshi et al. [9] concluded that the cost of energy (COE) for an on-grid hybrid system was lower compared to an off-grid hybrid system for rural electrification under similar load profiles.

The concept of zero energy universities must have broad prospects since it can be designed as a standalone system or grid connected system. This study aims to identity and compare the two design case (on-grid and off-grid system) for applications in central China.

2. Methodology

2.1. Optimization process

Firstly, the cooling/heating load of the studied building can be obtained by DeST simulation. And the building load profile is obtained by summing the HVAC power load and other equipment load. Secondly, the meteorological data, proposed hybrid system configuration and search spaces of renewable energy system are determined and set for simulation in HOMER. Thirdly, exhaustive searching method in HOMER is used to find the optimal design option for the studied building considering two scenarios, i.e. the on-grid zero energy dormitory and off-grid zero energy dormitory. Finally, sensitivity analysis is performed on specific variables in the on-grid and off-grid systems, respectively.

2.2. Input parameters

2.2.1. Building load. In this study, a student dormitory at Anhui University of Technology, located in Ma’anshan city of central China, is selected to be designed as a zero energy dormitory. The dormitory has 6 stories with a height of 19.9 m and it covers a total floor area of 10292 m^2. The building consists of 312 rooms, each with an area of 24.15 m^2. In general, energy consumption of this building is mainly composed of electricity to power the lighting, an air conditioner and small power appliances. In this study, the building is modeled in DeST software and the cooling/heating load is obtained by simulation, as shown in figure 1. The other electricity load per hour is assumed according to the actual situation and the annual average daily load data of a student dormitory is finally obtained as shown in figure 2.

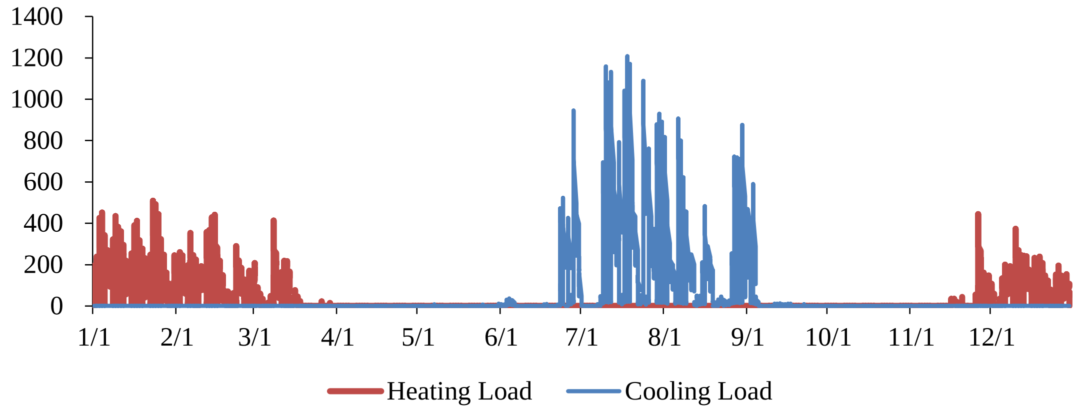

Figure 1. Cooling/heating load profile of the dormitory.

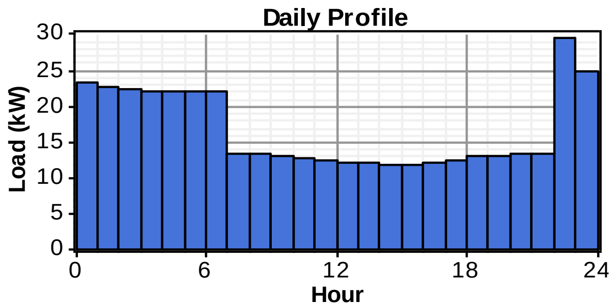

Figure 2. Daily load profile.

2.2.2. Solar irradiation and Photovoltaic modules. The monthly solar radiation data of this region as presented in Figure 3. In general, the average daily solar radiation and clearness index for Ma'anshan is found to be 3.75 kW h/m^2/day and 0.437 respectively. The initial cost of PV modules, replacement cost, and operating cost are 1600 $/kW, 1100 $/kW, and 10 $/year, respectively. Assuming PV lifetime of 25 years and a derating factor of 0.8. The PV design angle is 31.9° regardless of temperature effects.

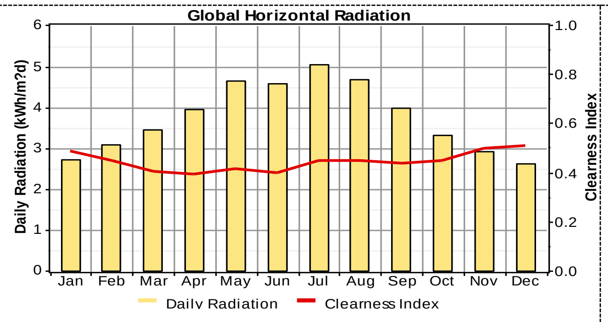

Figure 3. Global solar irradiation of the region.

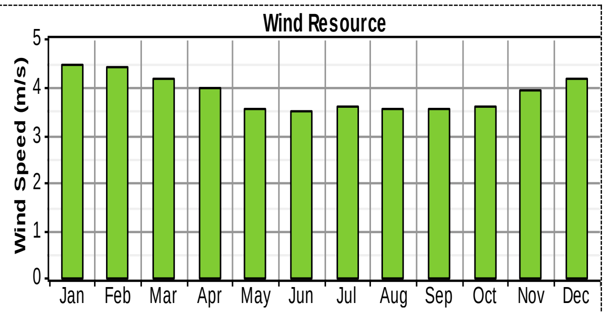

Figure 4. Average wind speed of the region.

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2.2.3. Average wind speed and wind turbine. The annual wind speed variation for Ma'anshan is shown in Figure 4. The monthly average wind speed is varied between 3.48 and 4.49 m/s. The annual average wind speed is 3.87 m/s. The wind turbine used in this paper is G10. The initial cost, replacement cost and operation cost are 7000 $, 6000 $ and 100 $/year respectively. Assume that the life of a wind turbine is 15 years.

2.2.4. Diesel and Diesel generator. The current price of diesel in Anhui is about 5.6 CNY/liter (i.e. 0.8 $/per liter). The diesel price is usually varied according to its region, transportation cost and economic conditions. The initial cost, replacement cost and operation cost are 400 $, 400 $ and 2 $/year respectively. Assume that the life of a wind turbine is 15000 hours.

2.2.5. Storage battery. Battery storage is used for storing excess power when the total output of all hybrid energy systems exceeds the load demand. On the other hand, when the load demand is greater than the available energy generated, the battery bank will release energy under discharging state to satisfy the load demand. The initial cost, replacement cost and operation cost are 250 $, 250 $ and 1 $/year respectively. Assume that the life of a wind turbine is 12 years.

2.2.6. Converter. Any system that contains both AC and DC elements requires a converter. The initial cost, replacement cost and operation cost are 225 $, 225 $ and 10 $/year respectively. Assume that the life of a wind turbine is 15 years.

2.2.7. Grid. In HOMER, the grid is modeled as a component from which the building can purchase/sell AC electricity. According to electricity policy in Ma'anshan, users can choose two different electric utility charges for energy purchased from the grid, i.e. single rate policy (SRP) or time-of-use rate policy (TRP). SRP refers to power purchase from the grid at 0.125 $/kWh throughout the day (24 hours). TRP means that the peak power price is 0.13 $/kWh in AM 8:00-PM 22:00 (14 hours), the trough power price is 0.09 $/kWh in PM 22:00-AM 8:00 (10 hours). Thanks to the country's strong support for renewable energy applications, subsidies for the sell-back of power to the grid are available at 0.145 $/kWh in Anhui province.

3. Results and discussion

3.1. Analysis of on-grid hybrid system

3.1.1. On-grid hybrid system configuration for the student dormitory. PV/WT/grid hybrid system is proposed for the student dormitory. This type of hybrid energy system can be used for both purchasing powers from the grid when the load demand is higher than the generation from the hybrid system at the apartment, and selling power back to the grid when there is excess electricity generation from the hybrid system. Grid is 100% reliable and available in HOMER simulation tool. The search space alternatives used in the simulation are shown in Table 1.

Table 1. Search space alternatives used in the on-grid PV/WT hybrid system.

Components	PV (kW)	G10 (Quantity)	Grid (kW)	Converter (kW)
Search space	0-150 (interval of 10)	0-50 (interval of 10)	Max: 1000	0-400 (interval of 50)

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3.1.2. Design optimization under two different electric utility charges. As the hybrid system is assumed to be connected to the grid, two different electric utility charges (i.e. SRP and TRP) from the grid are concerned based on grid policies applied in Ma'anshan city.

Under the SRP, the optimal hybrid system is obtained to be configured with the grid with the ability of purchasing/selling 1000 kW, wind turbines with the number of 10, solar panel of 130 kW and a converter of 100 kW. The NPC of this system is 263,830 $, the COE is 0.142 $/kWh. This optimal hybrid system reduces carbon dioxide emissions of 36,439 kg.

Under the TRP an optimal hybrid system is found to configure with the grid with the ability of purchasing/selling 1000 kW, wind turbines with the number of 10, solar panel of 120 kW and a converter of 100 kW. The NPC of this system is 230,534 $, the COE is 0.124 $/kWh (12.6% lower than that of the system under SRP), as shown in Table 2. This hybrid system reduces carbon dioxide emissions of 30,458 kg (16.4% lower than that of the system under SRP).

Table 2. Comparisons of optimal hybrid systems under two electric utility charges.

Charges	PV (kW)	G10 (Quantity)	Converter (kW)	NPC ($)	COE ($/kWh)	Net purchases (kWh/yr)	CO_2 (kg/yr)
SRP	130	10	100	263,830	0.142	-57,657	-36,439
TRP	120	10	100	230,534	0.124	-48,193	-30,458

3.2. Analysis of off-grid hybrid systems

3.2.1. Off-grid hybrid system configuration for the student dormitory. The off-grid hybrid system is also investigated for supplying electricity for the student dormitory. Two types of hybrid system are considered in this study, i.e. PV/WT/battery (PV/WT/BA) and PV/WT/generator/battery (PV/WT/GE/BA). The search space alternatives used in the simulation are shown in Table 3.

Table 3. Search space alternatives used in the off-grid simulation.

Search space	PV (kW)	G10 (Quantity)	Battery (Quantity)	Generator (kW)	Converter (kW)
PV/WT/BA	0-150 (interval of 10)	0-50 (interval of 10)	1900-2200 (interval of 10)	-	0-400 (interval of 50)
PV/WT/GE/BA	0-150 (interval of 10)	0-50 (interval of 10)	400-550 (interval of 10)	0-500 (interval of 100)	0-400 (interval of 50)

3.2.2. Design optimization under different hybrid systems. The optimal combination of PV/WT/BA for the building is found to be solar panels of 140 kW, 10 kW Generic wind turbines with the number of 30 and Surrette 4KS25P Batteries with the number of 2090, a converter capacity of 350 kW. The NPC of this system is 1,527,943 $, the COE is 0.821 $/kWh (Table 4). Besides, the unmet load is 0 kWh and carbon dioxide emissions are 0 kg. However, there is always excess electricity produced under the design of the PV/WT/BA system since both PV and WT are passive generation system which cannot controlled based on the building load.

Under the designed PV/WT/GE/BA for the building, optimal size is found to be solar panels of 60 kW, 10 kW Generic wind turbines with the number of 20, a generator of 200 kW, Surrette 4KS25P Batteries with the number of 500 and a converter of 150 kW. The NPC of this system is 967,126 $, the COE is 0.519 $/kWh (36.7% lower than that of the PV/WT/BA system) (Table 4). The consumption of diesel in diesel generator cause carbon dioxide emissions of 43,768 kg, which is a less friendly option compared with PV/WT/BA systems in terms of CO_2 emissions. However, the diesel generators have the advantage of flexible power supply and can largely reduce the areas required for installing the PV and WT.

Table 4. Comparisons of the two hybrid systems for off-grid dormitory.

Systems	PV (kW)	G10 (Quantity)	Converter (kW)	Battery (Quantity)	Generator (kW)	NPC ($)	COE ($/kWh)	CO_2 (kg/yr)
PV/WT/BA	140	30	350	2,090	-	1,527,943	0.821	-
PV/WT/GE/BA	60	30	150	500	200	967,126	0.519	43,748

3.3. Sensitivity analysis

3.3.1. Effects of sell-back electricity rate on the grid-connected system. In recent years, China has greatly promoted the application of the sustainable energy and many incentives have been made for different regions. For example, the policy of increasing sell-back price of power to grid power aims to facilitate the widespread of renewable energy. However, the state finance subsidies are supposed to decrease with the popularity of hybrid power generation. Thus, it is meaningful to investigate how the sell-back price affects the design of hybrid energy system.

For the on-grid hybrid system, the sell-back price of power to the grid is considered as sensitivity variable, and five price are investigated, i.e. 0.145, 0.14, 0.135, 0.13 and 0.125 $/kWh. It can be found that both NPC and COE of the design system under TRP are much cheaper than that under SRP. Therefore, sensitivity analysis is only performed on the TRP system.

Under the TRP, a similar trend for variations of the system NPC and COE is found as shown in Figure 5. The total NPC for PV/WT/grid is increased from 230,534 $ to 252,566 $ and COE is increased from 0.124 $/kWh to 0.136 $/kWh When the sell-back rate is decreased from 0.145 $/kWh to 0.125 $/kWh. It can be found that both NPC and COE of the design system under TRP are much cheaper than that under SRP. In addition, COE is found to be lower than 0.124 $/kWh when the sale-back rate is higher than 0.145 $/kWh, indicating that it is possible for the on-grid building designed with HES to be more economic than traditional buildings without any HES.

3.3.2. Effects of diesel price on the off-grid system. Fuel price is also a fluctuate parameter according to the time which should be analyzed for the hybrid system including the diesel generator. Therefore, diesel price is chosen as the sensitivity variable which is varied from 0.8 $/L to 1.6 $/L with an interval of 0.2 $/L. The effect of diesel price on the COE and NPC of hybrid power system is shown in Figure 6. The NPC for off-grid PV/WT/GE/BA system is increased from 967,126 $ to 1,089,839 $ and COE is increased from 0.519 $/kWh to 0.585 $/kWh when the diesel price is doubled. That is to say both the NPC and COE are increased at a ratio of 12.7 %.

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As the diesel price is increased, the required amount of diesel will be reduced which results in a decrease generation from the generator. An increase of PV size, from 60 kW to 140 kW, is therefore needed for generation balance. Accordingly, the penetration of PV generation is increased from 27% to 49% while the contribution of diesel generator is reduced from 17% to 8%. In addition, CO_2 emissions are decreased by 36.6% under the variation range of diesel price.

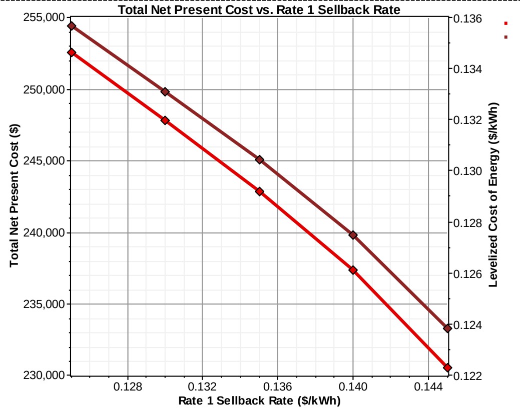

Figure 5. NPC and COE against sell-back rate in PV/WT/grid system under TRP.

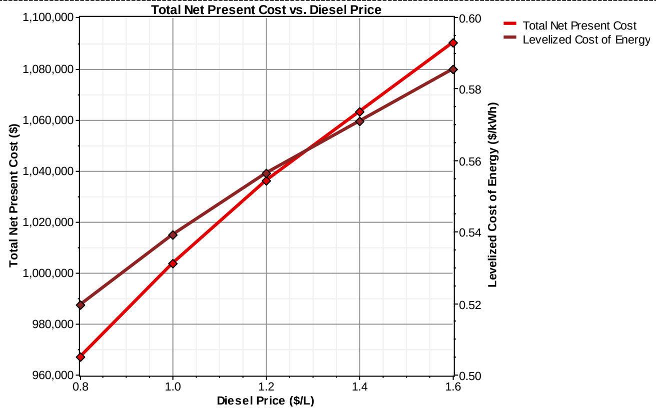

Figure 6. NPC and COE against diesel price in off-grid system.

4. Conclusion and implications

(1) PV/WT hybrid systems are considered for designing the on-grid zero energy university dormitory, a lower NPC and lower COE are obtained under the local time-of-use rate policy (TRP) compared with that under the single rate policy (SRP). In general, the cost of generating energy from this optimal hybrid system is 0.124 $/kWh, thus it is possible for the on-grid building designed with HES to be more economic than traditional buildings without any HES. However, the results also depend on the local government financial resources and strong political support.

(2) PV/WT/BA and PV/WT/GE/BA are considered and compared for designing an off-grid university dormitory. Results show that PV/WT/GE/BA hybrid systems are more economic than off-grid PV/WT/BA hybrid configurations. Compared with the on-grid case, an oversized hybrid system is required to ensure reliable supply for the standalone case. The energy cost of off-grid PV/WT/BA is 0.825 $/kWh, about 6 times than that of off-grid PV/WT/GE/BA, which is mainly caused by the high cost of battery.

(3) The sell-back price and diesel price are investigated in terms of the effects on the design of hybrid energy systems by sensitivity analysis. When the sell-back price is decreased from 0.145 $/kWh to 0.125 $/kWh, and the NPC and COE of the designed system are increased by 9.7% under TRP. When the diesel price is doubled from 0.8 $/L to 1.6 $/L, it is found that the size of PV is largely increased and the NPC and COE of the designed system are increased by 12.7%.

(4) The initial investment cost and source dependency of the renewable energy system is considered to be a major obstacle to large-scale promotion of these technologies. Furthermore, the cost of the land has not been taken into account but the large land area required for installing PV and WT is a practical problem for application. Future study can be conducted by taking the land costs of each region into account based on local policies.

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