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Technoeconomic Analysis on a Hybrid Power System for the UK Household Using Renewable Energy: A Case Study

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Abstract: The United Kingdom has abundant renewable energy resources from wind, solar, biomass and others. Meanwhile, domestic sector consumes large amount of electricity and natural gas. This paper aims to explore the potentials of a hybrid renewable energy system (HRES) to supply power and heat for a household with the optimal configuration. A typical house in the United Kingdom is selected as a case study and its energy consumption is collected and analysed. Based on energy demands of the house, a distributed HRES including wind turbine, solar photovoltaic (PV) and biogas genset is designed and simulated to satisfy the power and heat demands. Hybrid Optimization Model for Electric Renewable (HOMER) Software is used to conduct this technoeconomic analysis. It is found that the HRES system with one 1-kW wind turbine, one 1-kW sized biogas genset, four battery units and one 1-kW sized power converter is the most feasible solution, which can supply enough power and heat to meet the household demands. In addition, the HRES system has the lowest net present cost (NPC) of $14,507 and the lowest levelized cost of energy (LCOE) of $0.588 kW^{-1}·h^{-1}. The case study is also quite insightful to other European countries.

Keywords: hybrid renewable energy system; HOMER; NPC; LCOE

1. Introduction

Environmental pollution of fossil fuel-based electricity generation and depletion of natural resource have drawn burgeoning attentions, which initiate clean and renewable energy technologies for zero carbon emission [1]. Solar and wind power generation technologies could be good candidates for the places where electricity is cost effective [2]. It is worth noting that solar and wind power generation are much related to the weather conditions. Thus, hybrid renewable energy system (HRES) could be an effective approach to reduce the consumption of fossil energy resources for future sustainable development. Many researchers have investigated autonomous hybrid renewable power systems for various applications by using different mathematic models. Celik [3] conducted a optimization analysis on a hybrid system which was composed of PV and wind power components based on average daily electrical load. However, the transient working performance cannot be predicted. Markvart [4] investigated a hybrid photovoltaic (PV) and wind power system. The battery is integrated for electricity storage. Similarly, Diaf et al. [5] studied an PV and wind power system from a technoeconomical perspective. Later, their research team [6] optimized the hybrid power system to supply the electricity for a household. The detailed composition of the system was determined. Jeyaprabha and Selvakumar [7]

also conducted an investigation on the hybrid system in India which was composed of PV, diesel and battery. The artificial intelligence techniques (AIT) was adopted. Results indicated that the life cycle cost (LCC) was remarkably reduced when compared with single system.

Apart from the above representative mathematical procedures, Hybrid Optimization Model for Electric Renewable (HOMER) is a common software to handle the various technologies for both steady and transient simulation. To have a general review, some representative case studies using HOMER are presented in Table 1. It is demonstrated that quite a few studies in different places are conducted to investigate autonomous PV/wind/diesel/battery electric power systems. Most of these aims to investigate the viability and performance in remote areas where solar or wind energy resources are relatively abundant, e.g., South East Asia or Africa Island. Except the reference [8], the rest of research studies are all hybrid power systems which aim to satisfy the requirements by only using renewable electricity. Even for the studies in the reference [8], heating loads were not completely investigated and separated from electricity load. To meet the extra heat demands, the biogas generator is usually used to supply the heat and electricity. It has an influence on renewable electricity and heat from boiler, and the optimization will also be altered. Although various studies, such as feasibility, optimal sizing methodologies and technoeconomic analyses of hybrid PV/wind power systems, have been conducted using HOMER, a very few researchers paid attentions to a technoeconomic feasibility study on a hybrid system for a urban domestic household utilization, which may reveal vast potentials in real applications [9,10]. Additionally, heating and electricity loads are rarely considered together in the previous references [11,12], which could be found and compared with the information in the last row of Table 1. However, the cogeneration system and storage system are gathering momentum [13,14]. Thus, the research gap of the studies on the hybrid system is that various energy demands should be considered in the real application. Under this scenario, this paper is to give a feasible solution for household only using renewable energy resources, which aims to meet both heating and power demands in the cheap way. The implementation of the system could be not only conducive to individual but also contributes to the environment for low or zero carbon emissions.

Table 1. The relevant researches on hybrid systems by using Hybrid Optimization Model for Electric Renewable (HOMER).

Reference	Technology	Application Place	Research Findings
Himri et al. [15] 2008	Wind/diesel	Algeria	Combining wind turbine with a diesel-based supply; limited technology options.
Nfah et al. [16] 2008	PV/microhydro/ diesel/battery	Cameroon	Diesel as main generator supplemented by PV and microhydro based on grid-connected urban households.
Zamani et al. [17] 2008	PV/wind/battery	Hypothetical	A new method developed for exact calculation of the variable-speed wind turbine output power.
Bekele and Palm [18] 2010	PV/wind	Ethiopia	PV and wind; randomized load profile from hypothetical load data.
Lau et al. [19] 2010	PV/diesel	Malaysia	24 h service but a high demand profile for a rural area.
Nandi et al. [20] 2010	PV/wind/battery	Bangladesh	Solar and wind hybrid; no productive demand.
Hafez et al. [21] 2012	PV/wind/hydro/diesel/ battery	Hypothetical	24 h service but unrealistic demand profile for rural area in developing countries.
Ngan et al. [22] 2012	PV/wind/diesel	Southern Malaysia	Seven different system configurations, e.g., system with and without battery storage.
Li et al. [23] 2013	PV/wind/battery	Urumqi, China	The economical, sensitivity and PV module tilt angle analyses of the proposed system are discussed.
Hiendro et al. [24] 2013	PV/wind/battery	Indonesia	Wind turbine and battery are the most important components of the PV/wind hybrid system.
Sen et al. [25] 2014	PV/microhydro/wind /biogenerator/battery	India	The optimal off-grid option is identified and compared with conventional grid extension.

Table 1. *Cont.*

Reference	Technology	Application Place	Research Findings
Yahiaoui et al. [26] 2016	PV/diesel/battery	South Algeria	Utilization of hybrid energy system could minimize operational cost and reduce CO_2 emission.
Maatallah et al. [27] 2016	PV/wind/diesel	The northernmost city in Africa	Potential operation of hybrid PV/wind turbine/diesel system with batteries storage is verified.
Bentouba et al. [28] 2016	PV/wind/diesel	South of Algeria	100% of the electricity demand could be supplied to the town by using a hybrid configuration.
Sarker [29] 2016	Bio/PV/wind/battery/capacitor	Southern Norway	Biomass is used for hybrid system and proves its feasibility.
Sagani et al. [8] 2017	PV/diesel/battery	Northwest Greece	Hybrid system for power and heat is proposed; a cost-effective alternative is obtained to conventional type.
Present study	PV/wind/battery/ biogas	Northeast United Kingdom	Both heating and electrify loads are considered. The optimal off-grid option is identified among eight cases.

A technoeconomic case study of a hybrid renewable wind/PV/biogas-genset/boiler power and heat system scheme with battery storage is proposed and analysed based on its demands and local weather conditions in Newcastle, UK. Results of the present research work are expected to provide useful information of HRES in urban household application, which is quite insightful to the other European countries with the similar household energy consumption structure. The framework of paper is illustrated as follows. The measured household loads, weather conditions, and system design are presented in Section 2. Technical and economic results are shown in Section 3 followed by the conclusions in Section 4.

2. Methodology

2.1. Description of the Case Study

In general, there are over 27 million dwellings in the United Kingdom and 80% of them are houses. It can be categorized into five types: detached, semidetached, terraced houses and bungalows and flats. The average occupancy is 2.4 persons per household [30]. The main energy consumption in the UK domestic household sector is electricity and heating (natural gas). As shown in Figure 1, the detached house built in 1970s was chosen as a case study in Newcastle, UK. It was a four-bedroom house with total floor area of 90 m^2, and its energy supply was based on electricity and natural gas (for heating). The metered interval of energy consumption data was measured in 30 min to keep the consistency and accuracy of the generated load profile with the real-time consumption. Meanwhile, in order to simulate an accurate annual profile, the typical daily data were selected in March, June, November and December.

Figure 1. The selected case-study house in Newcastle, UK.

2.2. Renewable Energy Potentials in Newcastle, UK

Newcastle is located on the North East of England, and it is around $114\,km^2$. The mean temperature in winter is around 3 °C, while the temperature in summer climbs up to 14.5 °C. Thus, sunshine received in the UK land is relatively insufficient. On the contrary, the United Kingdom is abundant with wind resource, particularly in North East of England where its geography and wind patterns play a vital role in the promotion of delivering wind power to reach renewable energy targets. The potential of domestic microgeneration is estimated to contribute mostly 40% of the UK electricity demand by 2050 [31]. Central and local governments have further recognized the significant role of distributed electricity generation to fulfil its renewable energy targets [32,33]. In order to encourage the penetration of small-scale and low-carbon technologies applied in electricity generation, the fixed rate Feed-In Tariffs (FITs) was introduced to the United Kingdom in 2010 to reward generators within a size up to 5 MW. The gross output of the generator including the surplus part would export back to the grid [34,35]. To carry out this technoeconomic study on a hybrid power system using renewable energy, HOMER was selected as a tool to simulate various renewable energy generation systems (REGS). It is a micropower optimization model which was developed by NREL (National Renewable Energy Laboratory) in the United States, and it has two algorithms for optimization. The first search algorithm simulates and finds all of the feasible system configurations; and the second one is a derivative-free algorithm, which is used to find the least costly system. It displays all configurations in the order of net present cost. The users can analyse the results to compare options of the system design [36]. Thus, it has been used as a tool to find optimal design of the hybrid renewable energy systems, which include solar PV, microhydropower, wind turbine and biofuel generators [37]. In the optimization process, many different system configurations were simulated to find the one that satisfies the technical constraints at the lowest life cycle cost.

2.3. Data Collection and Analysis

2.3.1. Electricity and Heat Consumption of the Selected House

Figure 2a,b shows the typical daily energy consumption in summer and winter, respectively. It was observed that no distinct electricity demand of appliances associated with occupants' activities was found between 0:00 and 6:00 a.m. since it was the bedtime. Thus, the load in this zone stayed smaller than 100 Wh, which could be basically attributed to Wi-Fi router and refrigerator. From 6:00 a.m. to 10:00 a.m., as occupants woke up, the load went to the first peak time in the morning. The use of the kettle, toaster and microwave system increased the overall loads. From 10:00 a.m. to 16:30 p.m., since major occupants had left house, it remained at certain load. From 16:30 p.m. to 19:30 p.m., it came to the second peak time during the day due to the fact that dwellers come back and then started their dinner cooking and evening activities. Kitchen wares such as heaters, entertainment devices and the washing machine could be involved in pulling up the load. The collected data indicated that the peak demand within 24 h varies from 30 to 710 Wh. Based on the measured daily load, the annual consumption was calculated to be 1679 kWh. Thereby the annual average demand was 4.60 kWh per day and the maximum demand was 7.370 kWh per day as the scaled annual average demand for the designed system. The monthly electricity consumption is evaluated within a year which is shown in Figure 3a. In a similar measurement, heat consumption is indicated in Figure 3b, which is recorded from the smart meter installed in the house. It is demonstrated that the yearly heat consumption could reach 10,040 kWh, which ranged from around 159 kWh in August to 1462 kWh in January. The average heat consumption was 837 kWh per month.
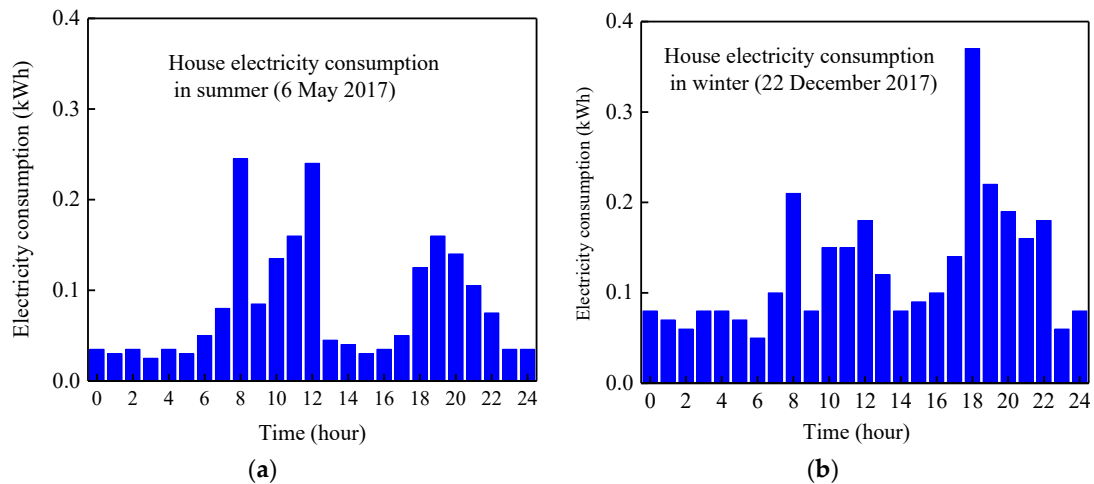
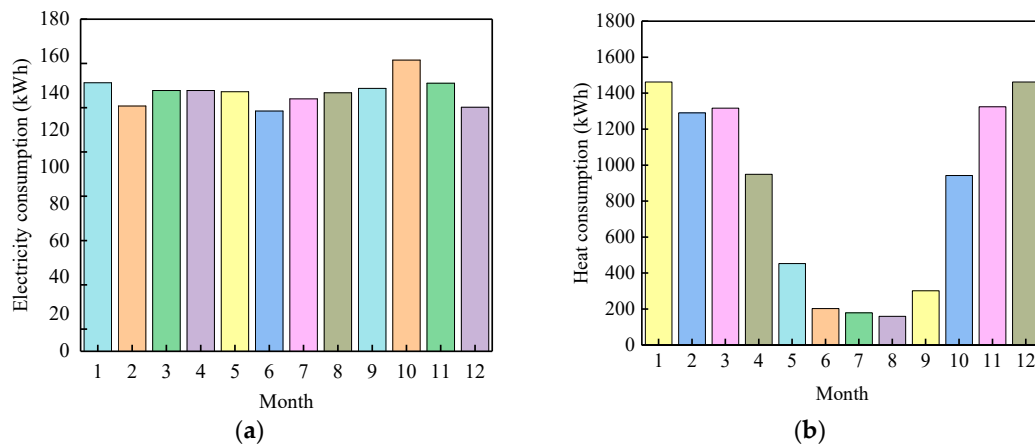**Figure 2.** Typical daily profile of electricity consumption (**a**) in summer and (**b**) in winter.

Figure 3. Monthly average energy consumption in 2017 (**a**) electricity and (**b**) heat.

2.3.2. Weather Data

Considering physical properties of silicon as the main material for PV, operating temperatures of PV modules are directly influenced by ambient temperature which has a profound correlation with the performance and thermal characteristic. A field experiment in the United Kingdom reveals that the peak power would decline 1.1% for each degree rising of a residential PV module once the temperature arrives to 42 °C [38]. Therefore, the ambient temperature is quite notable for the simulation. We used the data from the National Aeronautics and Space Administration (NASA) database on Renewable Energy Technology (RET) screen webpage. Figure 4a depicts monthly ambient temperature within a year. It can be noticed that the ambient temperature ranges from 10 to 16 °C in summer. In winter, the temperature is in the range from 4 to 6 °C. These ranges could ensure the efficient operation of the PV arrays. The wind speed data in Newcastle was also collected from RET screen webpage. It is the 10-year average monthly wind speed data as shown in Figure 4b. It was observed that the wind speed ranged from 4.8 m·s^{-1} in June to 7.4 m·s^{-1} in January. The annual average wind speed was 6.4 m·s^{-1}. The wind speed from October to March indicates that the favourable wind condition is more than half of a year. The site solar radiation data are acquired similarly, which are shown in Figure 4c. The daily solar radiation ranged from 0.469 to 4.73 kWh·m^{-2}·day^{-1}, whereas the clearness index varied from 0.350 to 0.449. The annual average global horizontal radiation was estimated to be 2.61 kWh·m^{-2}·day^{-1}. In addition, it is worth noting that more sufficient solar energy source appears from April to September, while less solar radiations are expected on the rest months though this trend is approximately opposite to the load profile.
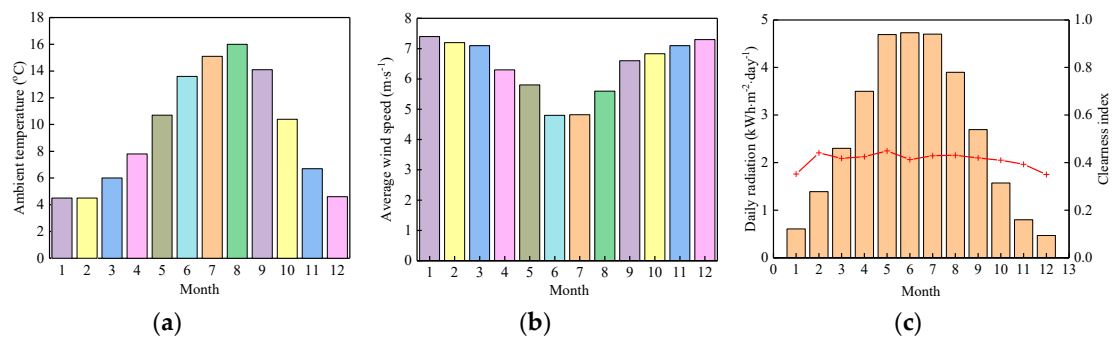
Figure 4. Monthly (**a**) ambient temperature, (**b**) wind speed and (**c**) solar radiation and clearness in Newcastle.

2.4. System Design and Configuration

2.4.1. System Design

Based on the above house energy consumption, it can be found that electrical and heat loads are varied due to the weather variation in different seasons/months. In order to meet the varied demands of electricity and heat (natural gas), a HRES was designed (Figure 5). It was composed of wind turbine, PV arrays and a biogas engine generator (also called genset) as well as a battery bank. The biogas genset was selected and used to generate power when there was no wind and/or sunshine. Meanwhile, the biogas genset that supply heat and batteries were used to store extra power. The genset was fuelled with biogas, which was produced from an anaerobic digester using the local biowastes such as grass, food wastes and cow wastes nearby. Whether connecting to the on-grid or off-grid systems may lead to the differences in selecting and sizing each specific component. The charge controller was essential only if the system was equipped with batteries to regulate respective power source that could feed those batteries properly. The set voltage of the DC bus was 48 V, which met the concerning demands. In addition, the controller was required for DC–AC conversion and overspeeding protection [39]. It is worth noting that a hybrid wind and solar charging controller or a single DC/AC controller can be used based on the different working conditions [40]. For DC–AC conversion, the batteries were adopted in offline use. For online system, bidirectional inverters were used to render the conversion. It behaved in two modes: power supply mode from distributed generators (PV and wind turbine) to the load and the rectification mode with power from the generators to the batteries when needed.
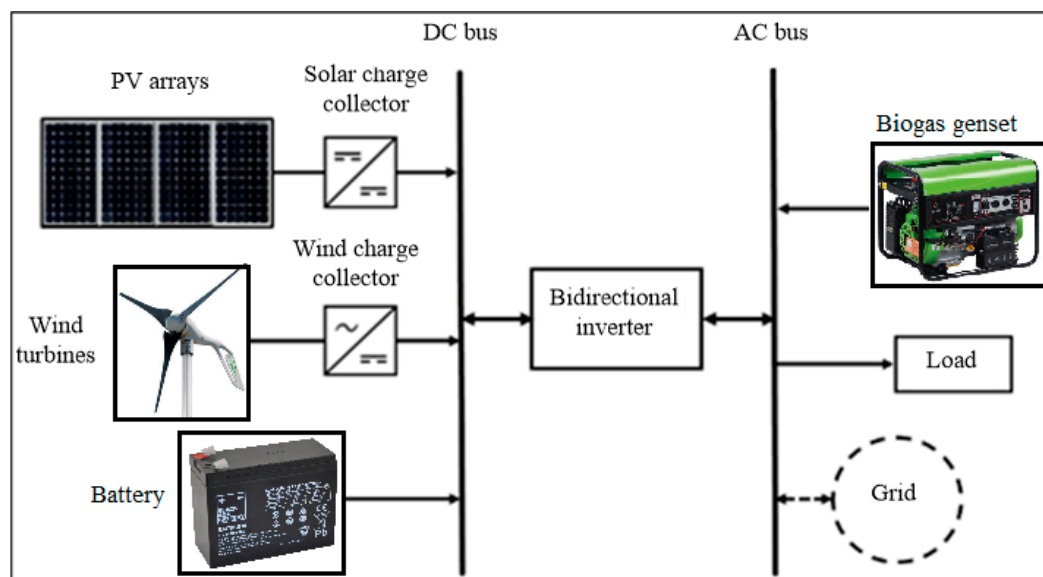

Figure 5. Design of the hybrid renewable energy system (HRES) applied to the house.

2.4.2. System Components

Base on system design above, this section presents the performance of each component according to weather conditions. With regard to load profiles, PV, wind and biogas generator were evaluated for the electricity, whereas biogas and boiler were for heat supply, which are, respectively, simulated in the rest of this subsection.

Electricity Supply

For solar PV, since total floor area of the house was 90 m², the roof area was estimated for less than 45 m². Given that each PV module occupied 1.245 m², the maximum panel number was limited to 36, which may harvest 30% of the maximum daily power demand, based on the solar resource available in the case study area [38]. This size is used as a constraint condition to judge the simulation results which is not considered as a fixed PV input. These panels would be mounted as fixed and tilted south at an angle of 52 degree. The realistic power output of PV array can be calculated as Equation (1).

$$P_{\text{PV}} = f_{\text{PV}} P_{\text{STC}} \frac{G_A}{G_{\text{STC}}} (1 + (T_C - T_{\text{STC}}) C_T \tag{1}$$

where f_{PV} is the PV derating factor, P_{STC} is the nominal PV peak power under the standard test condition, G_A is the global solar radiation illuminating on PV arrays, while G_{STC} is the global solar radiation. T_{STC} is nominal temperature upon the STC condition (25 °C), while C_T refers to the temperature coefficient of PV panel. T_c is the cell temperature, which can be computed from ambient temperature T_a and global solar radiation in the horizontal surface G via Equation (2). NOCT is the normal operating cell temperature which is generally set as 48 °C.

$$T_c = T_a + \frac{NOCT - 20}{0.8} G \tag{2}$$

Figure 6a shows the mean output of 10-modules PV arrays at the targeted house monthly. It was indicated that the highest PV output could reach 0.15 kW on May due to the relatively high solar radiation and low ambient temperature. The monthly PV output ranged from 0.06 to 0.15 kW. The cost of 1 kW PV unit was $1900·unit^{-1}.

Considering wind power, the maximum of the wind speed is limited to 6.4 m·s^{-1} even though wind resource is abundant when compared to the solar resource [41]. Thus, a low cut-in speed wind turbine is selected to obtain a better utilization of wind resources. Based on power conversion law, the output power generated by the wind can be estimated by Equation (3).

$$W_{\text{wind}} = \frac{1}{2} n C_{\text{p}} \rho l \pi r^2 v h^3 \eta \left(\frac{P}{P_{\text{N}}} \right) \tag{3}$$

where n is the number of turbines, C_{p} is the aerodynamic efficiency (assumed at the Betz limit 0.593), ρ is the air density as 1.225 kg·m^{-3}, r is the radius of the turbine rotor, v(h) is the wind speed that varies with the height h, η is the efficiency of the generator, and P_{N} is the nominal power of the generator. In ideal condition, η equals to 1.

Then, the estimated outputs of wind turbines on a monthly basis are presented in Figure 6b. In this case, API-1 kW and API-500 W wind turbines were selected as the candidates. The API-1 kW, at wind speed of 6.4 m·s^{-1}, had the better performance of providing a daily output from 0.46 to 1.16 kW. Comparably, electricity produced by API-500W ranged from 0.4 to 0.64 kW. The costs of wind turbines were $1400·unit^{-1} for the 1 kW unit and $1300·unit^{-1} for 0.5 kW unit, respectively.
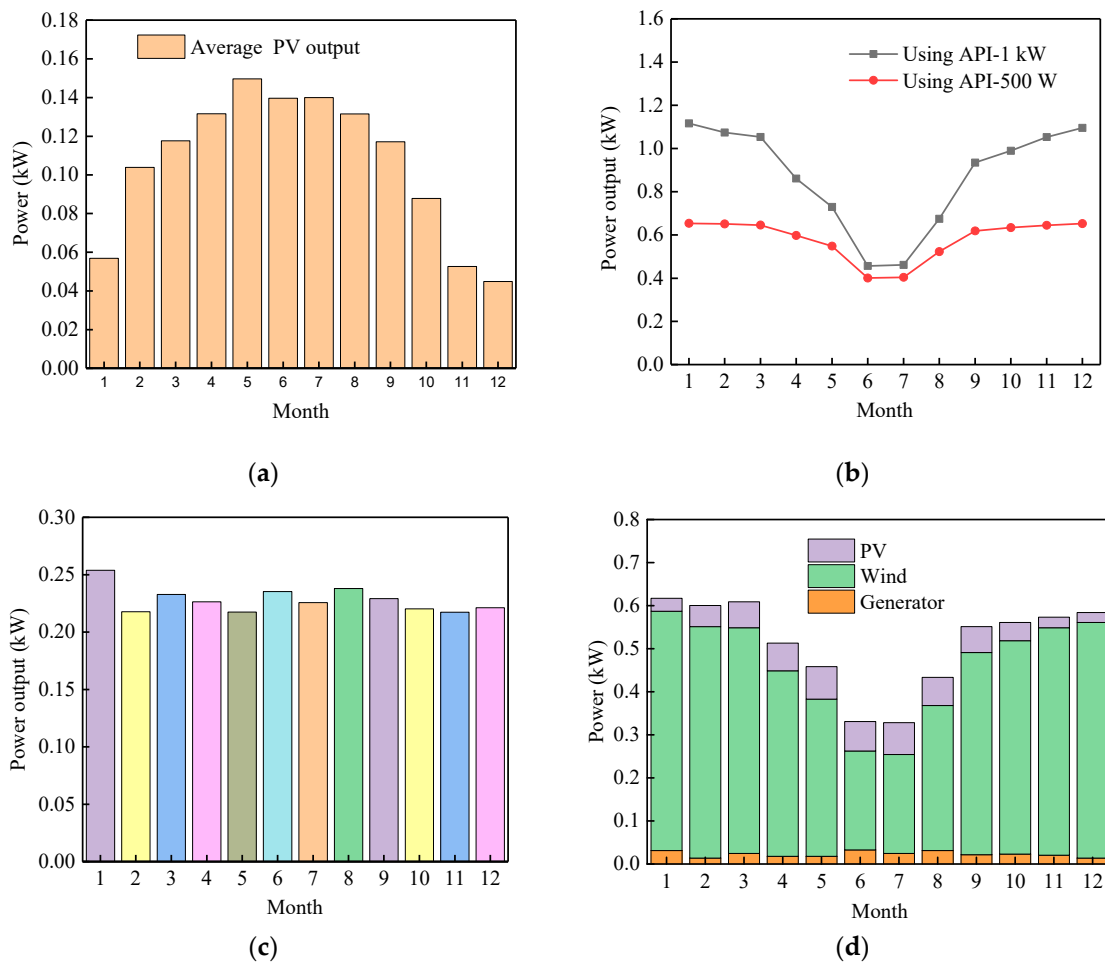
Figure 6. Simulated electricity output on a monthly basis: (**a**) photovoltaic (PV) only, (**b**) wind only, (**c**) biogas generator only and (**d**) average electricity production.

In order to meet the demand of power and heat consumption throughout a year in case the renewable solar and wind were insufficient, a biogas engine genset (1 kW, 220 V) was selected and supplemented to power the house. With the aim of minimizing net carbon dioxide and other gas emissions, biogas produced from biowaste was selected as the renewable fuel input. The generator was used to run at 1 kW capacity, with the average thermal efficiency of 20%. Notably, 50% of the waste heat from the engine genset was utilized to provide part of the heat to meet the heating demands together with a boiler. A 15 m^3 anaerobic digester that can produce biogas of 8.83 m$^3 \cdot$day^{-1} (3221 m$^3 \cdot$year^{-1}) was selected to produce biogas for the generator and the boiler. Annual electrical energy from the biogas generator could refer to Equation (4) [42].

$$E_{\text{gen}} = F_{\text{ann}}/F_{\text{spec}} \tag{4}$$

where F_{ann} is annual generator fuel consumption (L·year^{-1}) and F_{spec} is average specific fuel consumption of the genset (L·kWh^{-1}).

Cost of energy from the biogas genset can be divided into two parts. The first part is the fixed cost per hour of energy when the genset is running without generating electricity, which can be calculated by Equation (5).

$$C_{\text{gen,fixed}} = C_{\text{o\&m,fixed}} + \frac{C_{\text{rep,gen}}}{R_{\text{gen}}} + F_0 \, Y_{\text{gen}} \, C_{\text{fuel,eff}} \tag{5}$$

where $C_{\text{o\&m,fixed}}$ is the operation and maintenance (O&M) cost ($\$\cdot h^{-1}$), $C_{\text{rep,gen}}$ is the replacement cost ($\$$), R_{gen} is the generator lifetime (h), F_0 is the fuel curve intercept coefficient ($L\cdot kWh^{-1}$), Y_{gen} is the capacity of generator (kW), and $C_{\text{fuel,eff}}$ is the effective price of fuel ($\$\cdot L^{-1}$).

The second part of the cost of energy per hour is the additional cost per kilowatt-hour of generating electricity from the genset, which is expressed as Equation (6).

$$C_{\text{gen,mar}} = F_1\, C_{\text{fuel,eff}} \tag{6}$$

where F_1 is the fuel curve slope ($L\cdot kWh^{-1}$) and $C_{\text{fuel,eff}}$ is the effective price of fuel ($\$\cdot L^{-1}$).

The costs of the biogas generator and the digester used are $600 and 4000\cdot$unit^{-1}, respectively. Figure 6c demonstrates the simulated monthly electricity output produced by only a biogas generator. It is indicated that the highest electricity output happens on January. From January to December, the electricity output ranged from 0.217 to 0.254 kW. Figure 6d shows the monthly average electricity production. It is indicated that the majority of the electric power is generated by wind turbine followed by solar PV. The genset was used to produce power when no wind and no sunshine.

Heat Supply

The heat is supplied from the boiler and the waste heat of biogas generator. A condensing boiler (Worcester Greenstar 25i Combi Boiler) was used in the house, and thus, it was also used in the simulation, which was assumed to be fuelled with biogas. Figure 7 shows the simulated monthly heat output in which Figure 7a is the heat produced only by the gas boiler. Figure 7b is the heat produced by the biogas generator together with the boiler when the electricity supply is only from the biogas genset. Results showed that for the combined heating mode, biogas generator takes a leading role while the boiler compensates the remained heat. When the heat was supplied only by the boiler, it ranged from 0.23 to 1.96 kW. When the heat was supplied via the combined mode, it ranged from 1.6 to 2.7 kW. It is indicated that more heat will be supplied than the demand.
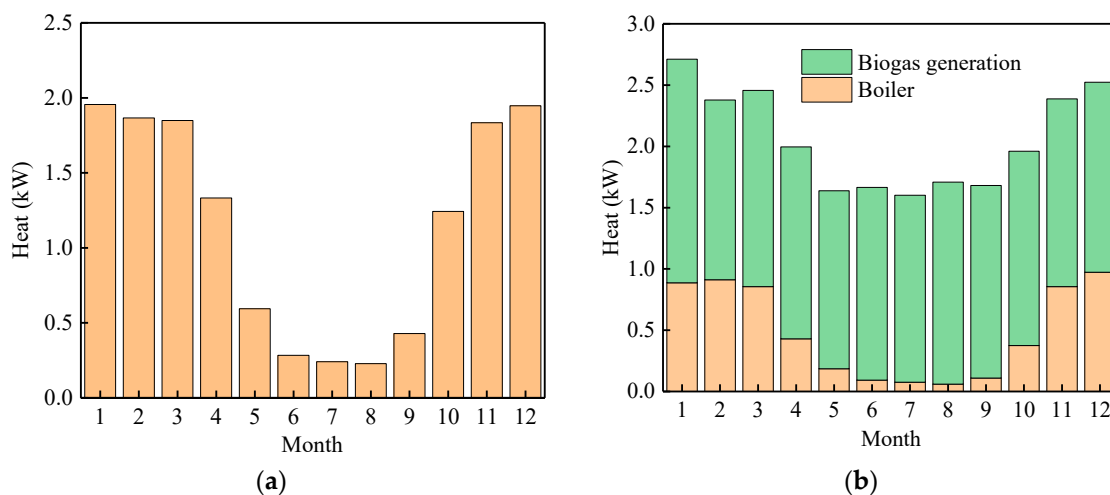

Figure 7. The simulated heat output on a monthly basis: (**a**) boiler only and (**b**) biogas generator and boiler.

Storage Battery

In off-grid and stand-alone renewable hybrid system, battery bank is undoubtedly the most commonly used component. The power generated by the renewable sources will become totally meaningless if there is no storing device to store those generated power safely and efficiently. As the power generated by the renewable source is unpredictable in nature, there may be shortage of generated power. In this study, the power stored in battery was originally from the wind power, PV and/or the genset when they produced excess power during low demand period of the house. Figure 8 shows

the normal load profile in 1 day. The battery played a prominent role to eliminate the mismatch between the domestic load and supply from the renewables by charging/storing the surplus electricity during off-peak time and discharging during peak time to increase the operation reliability. To fulfil these objectives, it experienced three modes, i.e., charging, storage and discharging. In this study, Trojan L16P battery was selected due to its low cost. The model was a 420 amp-hour, 6-volt deep cycle battery and could be used in homes, cabins and renewable energy systems. The costs of the battery was \$420·unit^{-1}.

(a)

(b)

Figure 8. Daily load profile for energy storage system: (**a**) daily load and (**b**) state of charge of batteries.

The battery charging could be calculated by Equation (7).

$$P_b(t) = P_b(t-1) \times (1-\sigma) + [P_{bh}(t) - P_{bl}(t)/\eta_{bi}] \times \eta_{bb} \qquad (7)$$

The battery discharging is calculated by Equation (8).

$$P_b(t) = P_b(t-1) \times (1-\sigma) + [P_{bh}(t)/\eta_{bi} - P_{bl}(t)] \qquad (8)$$

where P_b is the battery energy in time interval, P_{bh} is the total energy generated by either wind turbine, biogas genset or PV panel, P_{bl} is the load demand in time interval, η_{bi} is the efficiency of inverter, η_{bb} is the battery charging efficiency, and σ is the factor of self-discharging.

Figure 8a shows the daily load profile for the energy storage system (battery). The function of battery was used to store the extra power during the off-peak periods and to supply power during the peak time. Figure 8b indicates the state of charge (SoC) of the batteries from January to December. It was demonstrated that batteries were in charging and discharging frequently. The SoC varied around 40–100% dynamically, which means that the batteries were running in its safe region.

DC and AC Converter

In order to store extra power (charging) during off-peak demand and supply power during peak demand, a bidirectional inverter was employed in this stand-alone system. Selection of the inverter was based on a comprehensive consideration of the nominal load, the maximum DC input current and the voltage of the battery [20]. The costs of the converter was $450·unit^{-1}. The related details are presented in Table 2.

Table 2. Hybrid inverter/charger-230 V/50 Hz model.

Electrical Specifications	XW6048-230-50	XW4548-230-50
Continuous output power (kW)	0.006	0.0045
Surge rating (kW)	0.012	0.009
Surge current (Arms)	53	40
Perak efficiency (%)	95.4	95.6
AC output voltage (%)	230 ± 3	230 ± 3
DC current at rated power (A)	131	96
DC input voltage range (V)	44–64	44–64

2.5. Economic Evaluation

Economic evaluation of the renewable system with the optimal configuration was to calculate and compare the total net present cost (NPC) of different combinations. The NPC represents the life-cycle cost of the system, which includes all the costs during the system lifetime, i.e., the initial capital investment, component replacement, operation and maintenance and fuel as shown in Equation (9).

$$NPC = \frac{C_{ann,tot}}{CRF\left(i\ R_{proj}\right)} \tag{9}$$

where $C_{ann,tot}$ is the total annual cost ($·year^{-1}), i is the annual interest rate (%), R_{proj} is the project lifetime (year), and *CRF* is the capital recovery factor and can be calculated from Equation (10).

$$CRF\ (i,\ N) = \frac{i\ (1+i)^N}{(1+i)^N - 1} \tag{10}$$

where N is the number of years.

Initial capital costs of the components are used to calculate the total installed cost of those components at the beginning of the renewable system, which could refer to Equation (11).

$$C_{acap} = C_{cap} \times CRF_{proj} \tag{11}$$

where C_{acap} is the annualized capital cost and CRF_{proj} is the CRF of the project.

Levelized cost of energy (LCOE) is defined as the average cost of per kWh of useful electrical energy produced by the renewable system during its lifetime. LCOE is the annualized cost of the electricity dividing by the total useful electric energy production, which can be calculated using Equation (12).

$$LCOE = \frac{C_{ann,tot} - C_{boiler}\ E_{thermal}}{E_{prim,AC} + E_{prim,DC} + E_{def}} \tag{12}$$

where $C_{ann,tot}$ is total annualized cost of system ($·year^{-1}), C_{boiler} is the boiler marginal cost ($·kWh^{-1}), $E_{thermal}$ is the total thermal load served (kWh·year^{-1}), $E_{prim,AC}$ is the AC primary load supplied (kWh·year^{-1}), $E_{prim,DC}$ is the DC primary load served (kWh·year^{-1}), and E_{def} is deferrable load served (kWh·year^{-1}); since it is a distributed system, there is no grid sale. The project lifetime was set to 25 years and the discount rate was 8.0%.

3. Results and Discussion

In order to optimize the energy distribution, the above design of the hybrid PV-wind-biogas-genset-battery system was simulated. Technical and economic analysis of the proposed hybrid system were carried out. Two system configurations were adopted for comparison in terms of different wind turbines due to the good wind source in Newcastle. The simulation results were sorted into categories according to different rates of the wind turbine with API-1 kW and API-0.5 kW (Table 3). The simulation results of LCOE under two configurations of the hybrid renewable systems are indicated here. Each configuration included 8 cases, which were presented as a sensitivity analysis when considering different combinations of the hybrid system and the number of units. For example, Case 1 of configuration 1 includes one unit of wind turbine (API 0.5 kW model), zero unit of PV panel, one unit of biogas genset, five units of batteries and one unit of converter. A boiler for heating was assumed in place without extra investment. Compared with the electricity output of the hybrid system, the heat was more predictable. This was the reason to use one unit of biogas genset for two configurations. For the battery in the configuration with 1 kW wind turbine, the charging and discharge rate were 284 and 242 kWh·year^{-1}, respectively. The loss was 42 kWh·year^{-1}. For the battery in the configuration with 0.5 kW wind turbine, the charging and discharging rate were 358 kWh·year^{-1} and 304 kWh·year^{-1}, respectively. The loss was 54 kWh·year^{-1}. It means that the system can harvest more and store less electric power into the battery with a large wind turbine.

Table 3. Two configurations of the hybrid systems.

System Configurations (Off-Grid)								
Case Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Configuration 1	**Number of Unit**							
Wind turbine (API-0.5 kW)	1	1	2	1	0	0	0	0
PV	0	1	0	1	1	0	0	1
Biogas genset	1	1	1	1	1	1	1	1
Battery	5	4	0	0	7	7	0	0
Converter	1	1	0	0	1	1	0	0
Configuration 2	**Number of Unit**							
Wind turbine (API-1 kW)	1	1	1	1	0	0	0	0
PV	0	0	1	1	1	0	0	1
Biogas genset	1	1	1	1	1	1	1	1
Battery	4	0	3	0	7	7	0	0
Converter	1	0	1	0	1	1	0	0

Figure 9 presents the results of simulated energy supply of the hybrid system using 0.5 kW wind turbine, in which Figure 9a,b indicates the electricity and heat output, respectively. It can be seen that the best scenario was Case 1 (hybrid wind turbine with biogas genset), which could generate enough power (2335 kWh from the wind turbine and 475 kWh from the biogas genset) and heat (3108 kWh heat from the biogas genset and 8489 kWh from the boiler) to meet the demands. Results also showed that the advantage using this scenario (Case 1) was that the LCOE was 0.645 $·kWh^{-1}, which was the lowest one in this group of eight cases. Besides, the waste heat from the genset could be utilized for heating the house. Case 2 that combines a wind turbine, a solar PV with a biogas genset, was the second-best solution among the eight cases, with the LCOE 0.726 $·kWh^{-1}. The other cases were more expensive though they were also technically feasible.
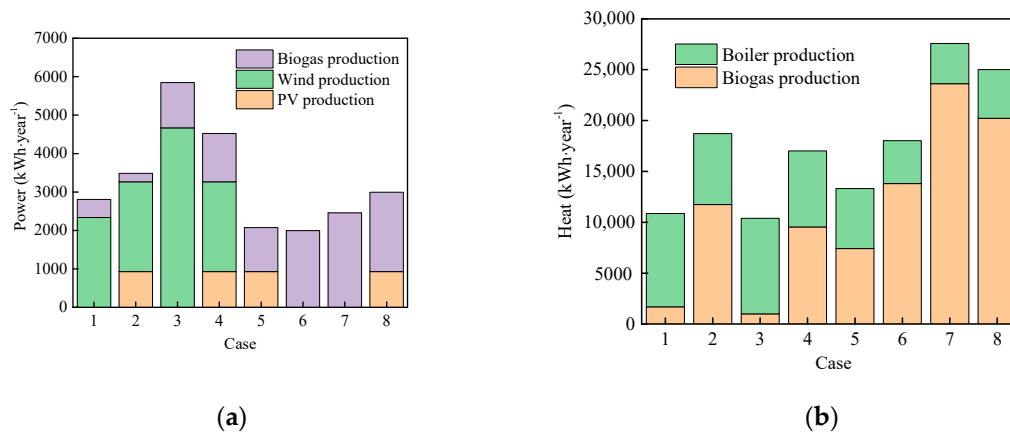
Figure 9. Computed generation profiles (0.5 kW wind turbine, PV and biogas genset): (**a**) power and (**b**) heat.

Figure 10 indicates total capital cost (TCC) and total net present cost (NPC) of Configuration 1. It can be observed that Case 1 had a low NPC of $15,735, which was lower than the other systems. Additionally, it is worth noting that all of eight cases can produce enough electricity and heat to meet the demands of the house. In Cases 1–4, wind turbines produced the majority of electrical power, whereas PV and biogas genset produced much less proportions. As wind turbines cannot produce heat directly, boiler consumes more fuel in order to supply the heat that is required for the house. In Cases 5–8, electricity was mainly produced from biogas genset with limited supply from solar PV. In these cases, the waste heat from the biogas genset was used to provide majority of the heat for the house with a very small amount of heat from the boiler. This reveals the advantage of using biogas genset.
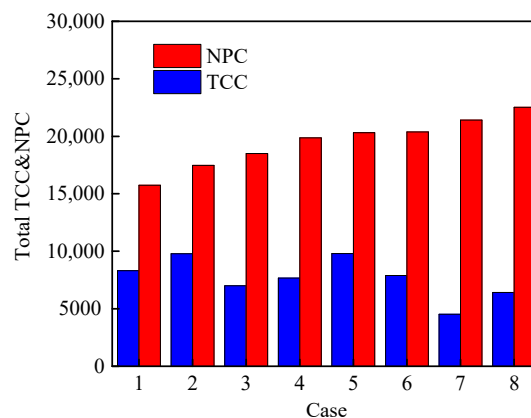

Figure 10. Computed total capital cost (TCC) and total net present cost (NPC) (0.5 kW wind turbine, PV and biogas genset).

Similar trends can be obtained from Figures 11 and 12. Case 1 of configuration 2 included one unit of wind turbine (API 1 kW model), zero unit of PV panel, one unit of biogas genset, four units of batteries and one unit of converter and a boiler. From Figure 11, it is indicated that Case 1 was the best scenario, which generated enough power (3826 kWh from the wind turbine and 341 kWh from the biogas genset) and heat (2277 kWh heat from the biogas genset, which was 19.9% of total heat, and 8937 kWh from the boiler) to meet the demands. The LCOE was 0.588 $·kWh^{-1}. The other cases were more expensive than that of Case 1. In Figure 12, it is demonstrated that Case 7 of Configuration 2 had the minimum TCC and a relatively high NPC. This is because the system needs to invest the biogas genset only. For Case 1 of Configuration 2, though the TCC was higher than that of Case 7, the total NPC was $14,507, which was the lowest in the Configuration 2.
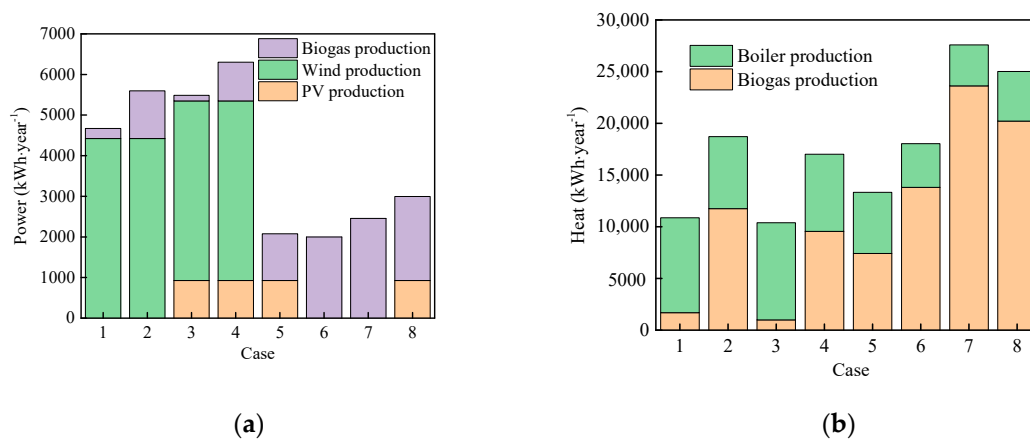
(**a**)   (**b**)

Figure 11. Computed generation profiles (1 kW wind turbine, PV and biogas genset): (**a**) power and (**b**) heat.
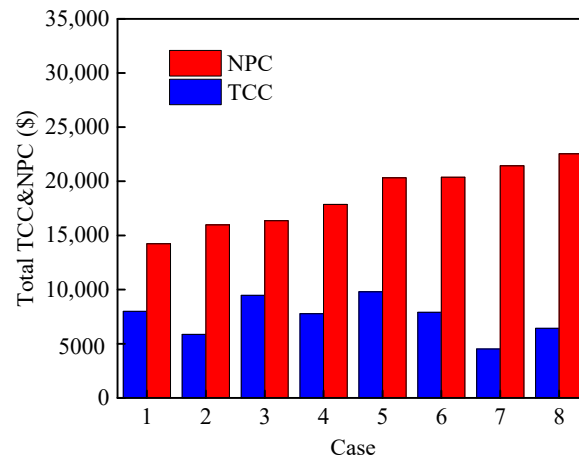

Figure 12. Computed TCC and total NPC (1 kW wind turbine, PV and biogas genset).

It can be realized that two common configurations are preferred, i.e., the wind-turbine (1 or 0.5 kW)/biogas-genset/battery systems with a 1-kW capacity for its converters. These two systems can satisfy the possible peak power as their NPC or initial capital is the least in two groups of configurations. Thereby the most optimal configuration is composed of API-1 kW wind turbine, and the one with API-0.5 kW is regarded as the second choice.

In order to have a comprehensive understanding, total costs in terms of the initial capital, total NPC and LCOE for all targeted alternatives are summarized and compared in Table 4. NPC is an equivalent value based on the present cash flow within the project lifetime. The replacement cost as well as operation and maintenance (O&M) cost indicated how much it will consume after installation. It can figure out the most optimal configuration which combined one 1 kW rated wind turbine, one biogas engine generator, four batteries and one inverter. It had cost of $7992 for the initial capital investment and the total NPC of $14,507 that may be accepted by middle-income families. These numbers for the second and third options were $8307 and $5870 for the total capital costs and the total NPC, respectively. The second one that referred to the combination of a biogas genset, 5 batteries, an inverter and the 1 kW rated wind turbine may indicated that the most optimal power rate for wind turbine was API-1 kW wind turbine. Besides, the LCOE was more extensively and effectively used to evaluate the HRES. The results showed that the best configuration was Case 1 in the Configuration 2 (with 1 kW wind turbine), which was composed of the 1 kW wind turbine, biogas genset, the batteries and the inverter. Moreover, the second best one was the No. 1 configuration with the participation of the 0.5 kW wind turbine even though its COE was $0.057 higher than that of the best one, which was 9.7% higher than the best one.

Table 4. Total cost data under two configurations.

Case Number	1	2	3	4	5	6	7	8
Configuration 1: Wind Turbine (API-0.5 kW)								
Total capital cost ($)	8307	9789	7010	7667	9800	7900	4524	6424
Total NPC ($)	15,735	17,470	18,497	19,860	20,307	20,379	21,416	22,526
LCOE ($·kWh^{-1})	0.645	0.726	0.774	0.837	0.858	0.862	0.91	0.962
Configuration 2: Wind Turbine (API-1 kW)								
Total capital cost ($)	7992	5870	9474	7770	9800	7900	4524	6424
Total NPC ($)	14,507	16,473	17,025	18,616	20,307	20,379	21,416	22,526
LCOE ($·kWh^{-1})	0.588	0.68	0.705	0.779	0.858	0.862	0.91	0.962

It is demonstrated that the best configuration above, i.e., the hybrid wind turbine and biogas genset together with batteries to power the household has its advantage from the environmental and economic viewpoint. This configuration is considered to be the most appropriate one with net zero carbon emissions because the system can supply enough electrical power and heat to meet the demand of the house from the renewables of wind and biowastes. Currently electric power generations in the United Kingdom are mainly from conventional steam power plants and combined cycle gas turbine power plants which provide 47% of the electric energy [43]. It is desirable to utilize the low-grade heat of power plant for domestic heating. However, as large power plants are located far away from residential buildings, the waste heat cannot be directly utilized. Under this scenario, utilization of small generators nearby buildings would be a solution. It is reported that using small power generator to supply power and heat will save around one-third of the fuel [44]. If the proposed system is applied to the houses in villages or in the rural areas where there is abundant wind and biowastes nearby, it will help the UK house/building sector to reduce their carbon emissions, which is recognized as one of the "difficult" sectors to achieve the UK government target. The only disadvantage is that the proposed system has a COE of $0.588 kW^{-1}·h^{-1}, which is around two times of the current electricity prices from the power electricity suppliers. Thus, a government policy or a propaganda is required in the future.

4. Conclusions

This paper investigates a hybrid power system using renewable energy to meet electricity and heating demands of a selected household in Newcastle, UK. The hybrid system includes wind turbine solar PV and biogas genset together with batteries and converter. A model is set up in HOMER software and used to carry out the study to find the optimal configurations of such system. The conclusions are yielded as follows.

(1) Applying a hybrid distributed HRES, to meet the dynamic electrical power demand of a household, is feasible and rewarding since the power and heat are all supplied from renewables, i.e., wind bioenergy and solar.

(2) The wind (1 kW capacity)-biogas-genset-battery system is the most optimal choice with appropriate NPC ($14,507) and the lowest COE ($0.588 kW^{-1}·h^{-1}). The system can also provide the heat of 2227 kWh from the biogas genset, which can save 19.9% of the total heat supply by the boiler.

(3) Because of the abundant wind resources in the United Kingdom, especially in Newcastle area, wind turbines have an overwhelming contribution to the electricity supply from the HRES. Comparably, due to the less solar radiation available (rainy and cloudy weather at Newcastle area), solar PVs have less contribution to the HRES.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

AIT	Artificial intelligence techniques
C	Cost (\$·year^{-1})
CRF	Capital recovery factor
C_{p}	The aerodynamic efficiency
E	Load served or supplied (kWh·year^{-1})
FIT	Feed-in tariff
f	PV derating factor
F	Fuel consumption (L·year^{-1}); Average specific fuel consumption (L·kWh^{-1}); Fuel curve intercept coefficient (L·kWh^{-1}) of the genset
G	Global solar radiation (kW·m^{-2})
HOMER	Hybrid optimization model electric renewables
HRES	Hybrid renewable energy system
h	Height (m)
i	Annual interest rate (%)
LCC	Life cycle cost
LCOE	Levelized cost of energy
NASA	National aeronautics and space administration
NOCT	Normal operating cell temperature (°C)
NREL	National renewable energy laboratory
NPC	Net present cost (\$)
n	Number of turbines
N	Number of years
O&M	Operation and maintenance
P	Power (kW); Energy in time interval
PV	Photovoltaic
RET	Renewable energy technology
TCC	Total capital cost (\$)
r	Radius (m)
R	Lifetime (year)
SOC	State of charge
T	Temperature (°C)
v	Wind speed (m·s^{-1})
Y	Capacity of generator (kW)
Greek letters	
ρ	Density (kg·m^{-3})
η	Efficiency of the generator; Efficiency of inverter
σ	Factor of self-discharging
Superscripts	
N	Number of years
Subscripts	
A	PV array
a	Ambient
ann	Annual
anntot	Total annual; Total annualized

Subscripts

acap	Annualized capital
b	Battery
bb	Battery charging
bh	Total energy generated by either wind turbine biogas genset or PV panel
bi	Inverter
bl	Load demand in time interval
boiler	Boiler
c	Cell
def	Deferrable load served
fueleff	Effective price of fuel ($\cdot$L^{-1})
gen	Generator
1	Fuel curve slope (L$\cdot$kWh^{-1})
0	Fuel curve intercept
O&M	Operation and maintenance
primAC	AC primary load
primDC	DC primary load
proj	Project
PV	Photovoltaic
repgen	Replacement of genset
spec	Average specific fuel consumption of the genset
STC	Standard test condition
thermal	Thermal

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