Chapter

Energy, Economic and Environmental (3E) Assessments on Hybrid Renewable Energy Technology Applied in Poultry Farming

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Abstract

This chapter aims to design, construct and test a new and renewable heating system for fulfilling the energy demand and ameliorating the interior environment of poultry farming in the UK. This system consists of a photovoltaic/thermal module attached to the polyethylene heat exchanger integrated with a geothermal copper pipe array and heat pump. The thermal and electrical energy performance of the hybrid renewable heating system is investigated based on a numerical model and experimental test. Moreover, the economic analysis (and environmental assessment are conducted. It is concluded that the electrical energy production from the photovoltaic array could reach 11867 kWh per annum whereas the heat pump thermal output is about 30210 kWh per annum. Meanwhile, the overall gas and electrical cost of the hybrid renewable heating system are £320 and £129, which are much less than that of the gas burners system and could save £763 and £750, respectively, resulting in less than 6-year of payback period. The energy consumption of the hybrid renewable heating system could decrease about 28873 kWh, resulting in a reduction in total CO_2 emission of approximately 8.3 tons, in comparison with the gas burners system.

Keywords: poultry farming, photovoltaic/thermal array, geothermal copper pipe array, energy efficiency, economic and environmental assessments

1. Introduction

The poultry industry is a significant economic part, supplying energy, meat, eggs and livelihoods to an increasing human population. Nevertheless, it is highly exposed to global-scale warming and climate change caused by human activities [1]. The direct impacts on poultry farming involve the growth, breeding, health and welfare whereas the indirect influences are owing to the global warming on the productivity of forage crops, pastures and feeds [2]. Poultry farming makes up a large proportion of the world's entire requirement for family livestock, meanwhile, the global population is going up continuously, which results in a growth in the need for poultry providing over the upcoming decades. To be more specific, compared with 2010, the consumption of poultry meat is anticipated to enhance from 330 to 455 million tons per annum in 2050 [3].

Traditional farming solutions are not the capability of fulfilling this demand, in particular for the broiler breeding. This is because the indoor temperature needs to be controlled with accuracy for achieving optimum growth [4, 5]. And also, the health status of the chicken extremely depends on the ambient temperature inside the poultry shed. In the heating season, it is necessary to sustain indoor air temperature in the range of 21–32°C for broiler birds, while in the cooling season, it should avoid the overheating and heat stress on chicken. What is more, there is major pollutant gas including carbon dioxide (CO_2) and ammonia (NH_3) emitted from poultry facilities that must be maintained underneath the critical concentration levels of $\sim$2500 ppm and $\sim$ 25 ppm, respectively [6].

Although, indoor ambient temperature and harmful gases emission should be controlled effectively, the energy consumption and overall expenses still need to be decreased. Energy is utilized for environmental control including lighting, ventilation cooling and heating, preparation and distribution of feed as well as manure management [7, 8]. Specifically, broiler breeding farming for indoor temperature control makes up 96.3% and 75.5% of the entire thermal and electrical energy demands, respectively. Meanwhile, in laying hen sheds, the power output for indoor condition control and ventilation demand is 58.9% and 43.7%, respectively [9, 10]. Additionally, the electricity expense involving heating, lighting, ventilation and cooling is the biggest part for poultry farmers [11].

Water is a vital input for poultry meat and eggs production and plays an important role in guaranteeing chicken health. The traditional water sources, such as rivers, lakes, rainfall, aquifers and snowmelts are not sufficient to fulfill the minimum water demands. Currently, 61% fresh water is obtained from seawater desalination processes, 21% from brackish water as well as 8% from river water. In general, 90% of fresh water is attained from these three sources and the remaining is extracted from brine, wastewater and other sources. Desalination is regularly utilized to produce freshwater eliminating salts, pollutants and minerals from brackish water [12]. However, desalination technology requires considerably higher energy, cost and greenhouse gas (GHG) emissions compared to traditional water treatment approaches. Currently, two mature technological solutions are employed include thermal and membrane approaches. It is found that the thermal-based approach has much higher energy-intensive compared to membrane-based ones [13, 14]. Specifically, Ahmed et al. [15] found that the desalination capacity across the globe based on the membrane desalination method makes up about 73% whereas the thermal-based solutions account for merely 27% until 2016. Moreover, the membrane approaches require high operating pressure ranging from 55 to 70 bar, by comparison, the normal pressure for the brackish water desalination varies from 15 to 30 bar [16]. Integrating the desalination technologies with renewable energy sources have the potential to produce fresh water for future development. This mainly includes three merits, namely, energy sustainability, future fresh water sustainability and environmental sustainability. Renewable energy technologies like solar photovoltaic (PV), solar photovoltaic/thermal (PV/T) and geothermal heat pumps are state-of-the-art and could become feasible and economically promising for different areas. Nevertheless, when the technologies continue to enhance, the fresh water becomes scarce and fossil fuel energy price increases, thereby renewable energy desalination suits more viable economically. Additionally, the CO_2 emission is the major factor by the operation of desalination processes. It is reported [17, 18] that the CO_2 emission is over 1500% and it is predictable to increase to 2200% by 2040. Herein, the efficiency enhancement of water and electricity, is vital to regulate CO_2 emission to protect the environment.

Hence, to ensure energy sustainable development, decrease cost as well as GHG emission in poultry farming, sustainable energy development in poultry production and reduce cost and GHG emissions, there is a strong incentive to explore energy conservation and deployment of renewable energy technologies for improving energy conversion efficiency for heating and cooling and replacing the utilization of fuel. In comparison with conventional oil and gas energy resources, renewable energy technology shows massive potential owing to its excellent quantity and environmental friendliness.

To be more specific, solar energy technologies including photovoltaic (PV), solar thermal collector and solar photovoltaic/thermal (PV/T) are the ideal solutions for warming poultry shed. This is because they are both inexpensive and efficient to operate and could solve fossil fuel-oriented environmental matters, compared to traditional energy sources such as gas and oil. Gad et al. [19] built a solar energy heating system for poultry shed to assess the energy efficiency and system cost. It is observed that the thermal and electrical efficiencies could achieve 71.6% and 12.5%, respectively. The electricity cost of renewable technology is about 1.12 US $/kg which is less compared to 1.46 US $/kg of the conventional power operating system. Mirzaee Ghaleh et al. [20] built a solar thermal collector system for heating a poultry shed in Iran, and demonstrated that the system could fulfill at least 20% of the energy demand in the heating season. Bazen et al. [21] carried out an economic evaluation of a solar PV system for Tennessee's poultry farm in USA, and concluded that the effects of initial cost, installed expense and tax credit on the net present value could reach 35%, 10.6% and 15%, respectively. Fawaza et al. [22] performed a techno-economic assessment of a solar heating system for broiler breeding in Lebanon. The results illustrated that the hybrid system can achieve 74% of energy-saving and overlay 84% of heating load demand in the heating season. Moreover, annual operating cost saving is approximately $3389, resulting in a 4.6-year' payback period. Chen and Sheng [23] proposed a solar thermal vacuum tube collector system for warming poultry shed, and found that the system can save around 148.6 kg of CO_2 emissions.

Geothermal energy is a potential heat source to provide space heating for a chicken shed owing to the comparatively constant temperature of the soil. And also it has minimal maintenance during the long operation period. As a result, the influences of the GHP poultry shed on indoor temperature control and energy efficiency assessment are investigated in some case studies [24, 25]. Specifically, Kharseh and Nordell [24] developed an integrated solar-geothermal system for evaluating the energy demand for a poultry shed in Syria. It is concluded that this hybrid unit can generate 92 MWh of heating and 13 MWh of cooling, respectively. Choi et al. [25] applied a GHP unit for heating a broiler in Korea. It is demonstrated that the maximum and minimum indoor temperatures could be maintained in the range of 26.4°C-33.5°C and 22.4°C-30.9°C, respectively.

Green poultry shed is a wise choice for resolving basic and applied problems in connection with livestock production in an economic and ecological way. There is still currently a research gap in the area of investigating the energy, economic and environmental (3E) evaluation to study conversion efficiency, economic and GHG emission elements for design and performance estimation of the renewable energy unit in poultry shed. The major novelty of this work is to utilize the techno-economic evaluation approach to predict the annual electrical and thermal energy output and calculate system electrical and thermal energy cost savings, net present value, payback period and GHG emission.

2. System description

Figure 1 illustrates the fundamental design schematic of the hybrid renewable heating system. To be more specific, the hybrid system could produce highly efficient heating by solar photovoltaic/thermal (PV/T) array with a novel category of cheap polyethylene heat exchanger (PHE) loop assisted a heat pump and couple to a low expense geothermal copper pipe array. The PV/T module can simultaneously produce electrical energy for driving the running of heat pump compressor and thermal energy for inputting to the heat pump evaporator along with the geothermal pipe array. In the meantime, geothermal energy can offset the heat source production from the PV/T module for heat pump condenser, such as in the absence of solar radiation or nighttime. The fan coil as a recirculation device is utilized to provide space heating to the poultry shed.

2.1 JWL poultry farm

This hybrid heating renewable system is installed in an actual poultry farm called John Wright Ltd. (JWL), located in Newark-on-Trent of Nottinghamshire in the East Midlands of England, UK. It has four poultry houses with 40,000 chickens in at a time. **Figure 2(a)** presents an actual photo of JWL. The dimension of shed 1 is 62 × 8 × 2 m (L × W × D) which is selected for the hybrid heating system because it is the smallest one on-site and thus needs the least heating demand in winter as given in **Figure 2(b)-(d)**. The photo of young birds, the control unit and 66 kW gas burner are shown in **Figure 2(e)-(g)**, respectively. Additionally, in shed 1, the indoor temperature should be maintained in the range from 32–20°C. The relative humidity (RH) varies from 50–70%. Two 66 kW gas burners are utilized to warm the poultry shed in winter.

2.2 Meteorological data

Meteorological data are crucial for assessing the thermal and electrical energy output and shed heating load. **Figure 3** describes the average ambient temperature,

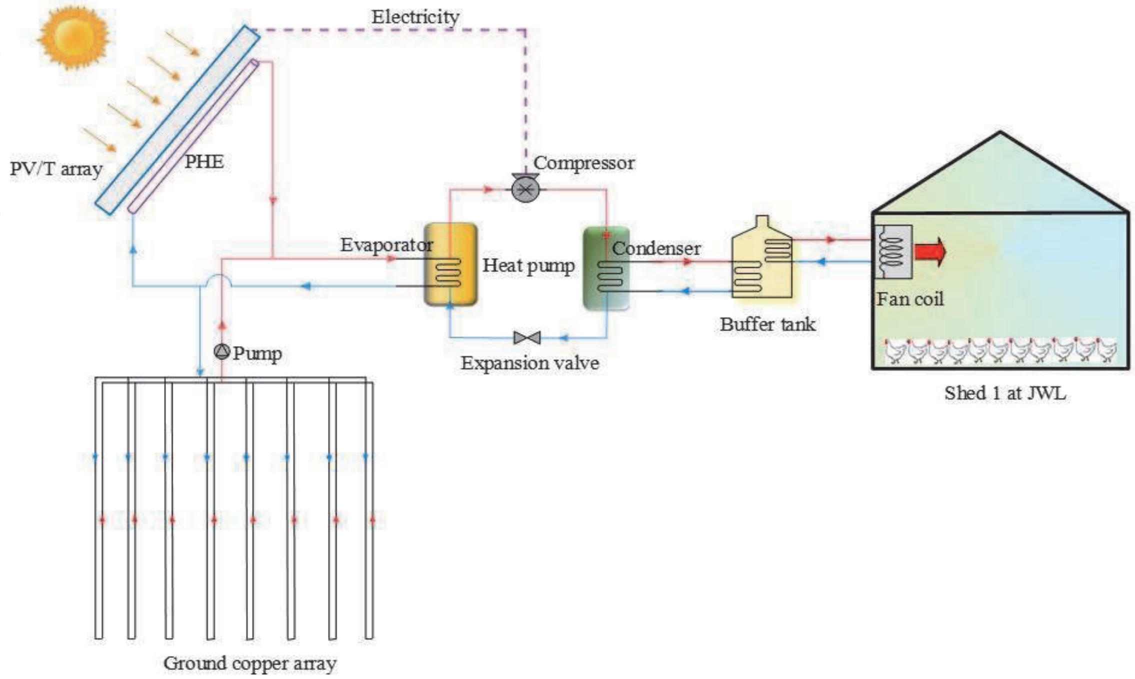

Figure 1.
Schematic diagram of hybrid renewable heating system.

Figure 2.
JWL photos: (a) satellite view; (b) south view; (c) back view; (d) front view; (e) young birds; (f) heating control unit; (g) 66 kW gas burner.

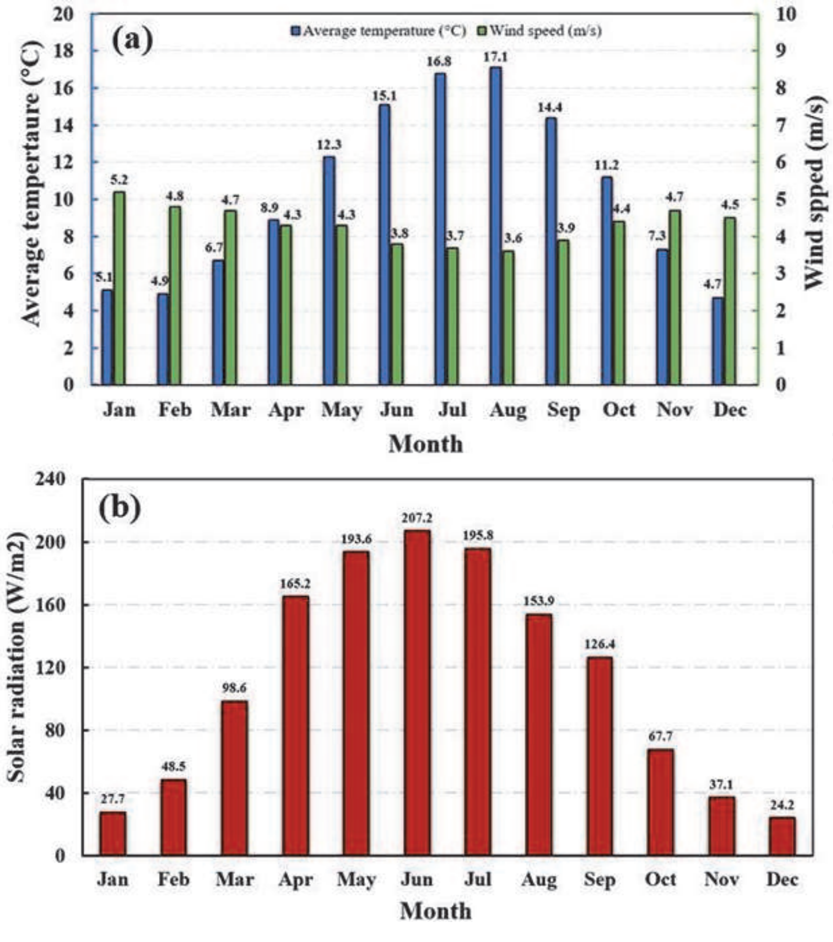

Figure 3.
Weather conditions: (a) average air temperature and wind velocity; (b) solar radiation in Newark over a year.

wind velocity as well as solar radiation [26]. Specifically, the highest average ambient temperature is 17.1°C in August whereas the lowest reaches 4.7°C in December. The monthly wind speed varies from 3.6 m/s to 5.2 m/s on average. Meanwhile, the highest and lowest solar radiation are 207.2 W/m^2 in June and 24.2 W/m^2 in December.

2.3 Experimental description

Figure 4 depicts the layout of the hybrid heating system installation. Because the survey presented that there are not any poultry sheds in JWL which are fit for the installation of the PV/T array. Hence, only the workshop, which is located next to shed 1 as presented in **Figure 4(a)** is fulfilled the requirement of the structural reinforcement. The energy output from the PV/T module is piped down the side of the workshop, under the entrance road and through shed 1 to the plant room as exhibited in **Figure 4(b)**. Moreover, 52 (260Wp) Canadian solar PV panels [27] and four 1 × 12 m PHE mats are mounted on the roof of the workshop with 15° oriented to the south for enhancing solar energy harvesting. The solar PV inverter is placed on the external wall of the workshop as displayed in **Figure 4(c)-(d)**. A 15 kW F1145 NIBE heat pump [28] with R407C refrigerant is designated as it is the biggest capacity the consortium and can afford almost the required thermal energy input from the PV/T and ground copper pipe arrays as given in **Figure 4(e)**. The heat pump system could be employed in reverse to supply cooling in summer if

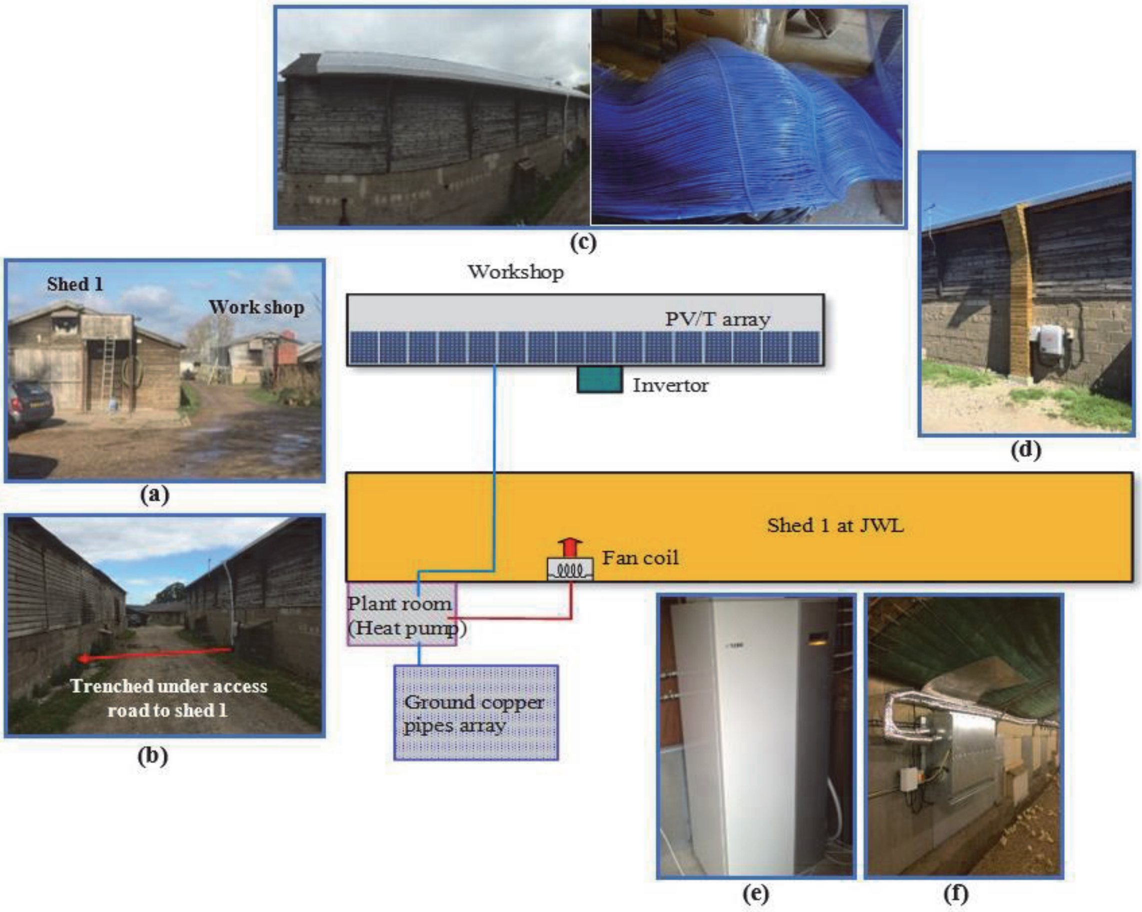

Figure 4.
Hybrid renewable energy heating system installation: (a) workshop and shed 1; (b) trenched under access road to shed 1; (c) PV/T installed on the workshop roof; (d) inverter along with the external wall; (e) NIBE F1145 heat pump; (f) fan coil.

required. Additionally, the fan coil is mounted vertically on the south internal to provide spacing heating for shed 1 as shown in **Figure 4(f)**. Furthermore, there are fifty ground copper pipes with 15 mm diameter and their dimension size is 2.5 × 5 m (length × deep). The overall surface region of the geothermal pipe array is approximately 10 × 10 m. The vertical copper pipes are connected and run back to the plant room.

3. Numerical model

3.1 Energy model

3.1.1 PV/T array

Thermal energy conversion is classified into two processes including solar radiation conversion into thermal energy and transferring collected thermal energy towards PHE. Hence, this dynamic model is expressed by:

$$\frac{\partial Q_t}{\partial t} = m_{PV/T} C_{PV/T} \frac{\partial T_{PV/T}}{\partial t} = Q_{abs} - Q_{PV/T-loss} - Q_{ele} \tag{1}$$

where Q_t is the overall thermal energy (kW); $m_{PV/T}$ is the mass of PV/T (kg); $C_{PV/T}$ is the heat capacity of PV/T (J/ (kg·K)); $T_{PV/T}$ is the temperature of PV/T (°C); t is the time (s); Q_{abs} is the solar energy absorbed (kW); $Q_{PV/T\text{-loss}}$ is the overall thermal loss (kW); Q_{ele} is the power output (kW).

$$Q_{abs} = \tau_c \alpha_{abs} A_{eff} I \tag{2}$$

τ_c is the transmittance of PV/T; α_{abs} is the absorptivity of PV/T; A_{eff} is the effective area of PV/T (m^2); I is the solar radiation (W/m^2);

$$Q_{PV/T-loss} = Q_{conv,c} + Q_{c,sky} + Q_{conv,pl,heo} + Q_{pl,heo} \tag{3}$$

$$Q_{conv,c} = h_{cv}(T_c - T_a) \tag{4}$$

where h_{cv} is the forced convection coefficient ($W/m^2{\cdot}K$), which is written as:

$$h_{cv} = 5.7 + 3.8 \cdot V_{wind} \tag{5}$$

$$T_c = 30 + 0.0175 \times (\mathrm{I} - 300) + 1.14 \times (\mathrm{T_a} - 25) \tag{6}$$

where V_{wind} is the wind velocity (m/s); T_c is the PV surface temperature (°C); T_a is the air temperature (°C);

$$Q_{c,sky} = \varepsilon_c \cdot \sigma \cdot \left(T_c^4 - T_s^4\right) \tag{7}$$

$$T_s = 0.037536 \cdot T_a^{1.5} + 0.32 T_a \tag{8}$$

where ε_c is the emissivity of PV/T cover layer; σ is the Stefan-Boltzmann's constant, $5.67 \times 10^{-8}\ W/m^2{\cdot}K^4$; T_s is the sky temperature (°C).

$$Q_{conv,pl,heo} = h_{air} \cdot \left(T_{pl} - T_{heo}\right) \tag{9}$$

where h_{air} is the convective heat transfer coefficient ($W/m^2{\cdot}K$); T_{pl}, T_{heo} are the temperature of the EVA layer and PHE wall temperature, respectively (°C).

$$h_{air} = \frac{N_u \cdot \lambda_{air}}{\delta_{air}} \tag{10}$$

where λ_{air} is the air thermal conductivity (W/m K); δ_{air} is air gap thickness between the surface cover and PV module (m).

Nu is the Nusselt number as expressed:

$$N_u = \left[0.06 - 0.017\left(\frac{\beta_s}{90}\right)\right]\mathrm{Gr}^{1/3} \tag{11}$$

where β_s is the title–angle of PV panels; Gr is the Grashoff number given as:

$$Gr = \frac{g \cdot \left(\mathrm{T}_{pl} - T_{heo}\right) \cdot \delta_{air}^3}{\nu_{air}^2 \cdot T_{air}} \tag{12}$$

$$Q_{pl,heo} = \varepsilon_{pl} \cdot \sigma \cdot \left(T_{pl}^4 - T_{heo}^4\right) \tag{13}$$

where ε_{pl} is the emissivity of EVA layer;

$$Q_{ele} = \eta_e A_{eff} I \tag{14}$$

where η_e is the electrical efficiency of PV array (%); A_{eff} is the effective area of PV array (m^2).

The overall heat production is written as:

$$Q_t = A_{eff} \cdot h_t \cdot (T_a - T_w) \tag{15}$$

where h_t is the overall heat transfer coefficient between the water and PV module ($W/m^2 \cdot K$); T_w is the water temperature within the PHE (°C).

$$\eta_t = \frac{Q_t}{A_{eff} \cdot I} \tag{16}$$

where η_t is the thermal efficiency (%).

3.1.2 Ground copper pipe array

To supply an adequate heat source for the evaporator of the heat pump unit, a low expense geothermal copper pipe array is developed. In lights of the heat transfer fields, it is categorized into solid and fluid regions [29].

3.1.2.1 Solid field

The solid field contains soil and pipe wall as presented:

$$\rho_{soil} c_{soil} \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{\mathrm{soil}} \frac{\partial T_s}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{\mathrm{soil}} \frac{\partial T_s}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_{\mathrm{soil}} \frac{\partial T_s}{\partial z}\right) \tag{17}$$

$$\rho_{pipe} c_{pipe} \frac{\partial T_p}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{pipe} \frac{\partial T_p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{pipe} \frac{\partial T_p}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_{pipe} \frac{\partial T_p}{\partial z}\right) \tag{18}$$

where ρ is the density (kg/m^3); c is the thermal capacity (J/kg·°C); λ is the thermal conductivity (W/m·K).

3.1.2.2 Fluid field

The energy balance equation of the inlet pipe is given as:

$$\rho_{fluid} c_{fluid} \frac{\partial T_{inlet}}{\partial t} + (\rho c v)_f \frac{\partial T_{inlet}}{\partial z} = \lambda_{fluid} \frac{\partial^2 T_{inlet}}{\partial z^2} + b_{ig} \left(T_{grout} - T_{inlet} \right) \tag{19}$$

The energy balance equation of the outlet pipe is expressed as:

$$\rho_{fluid} c_{fluid} \frac{\partial T_{outlet}}{\partial t} + (\rho c v)_f \frac{\partial T_{outlet}}{\partial z} = \lambda_{fluid} \frac{\partial^2 T_{outlet}}{\partial z^2} + b_{og} \left(T_{grout} - T_{outlet} \right) \tag{20}$$

3.1.3 Heat pump

The heat source of the heat pump is provided by PV/T and geothermal copper pipe to offer a comfortable climate for the shed in the heating season. Hence, a heat pump model is expressed as [30]:

$$m_r = V_c \omega \rho_{r,suc} \cdot \left[1 + C_v \left(1 - \frac{\mathrm{P}_{\mathrm{r},cond}}{\mathrm{P}_{\mathrm{r},evap}} \right)^{\frac{1}{n}} \right] \tag{21}$$

$$\Delta \xi_{comp} = \xi_{r,dis} - \xi_{r,suc} = \frac{n}{n-1} \cdot \frac{\mathrm{P}_{\mathrm{r},evap}}{\rho_{r,suc}} \cdot \left[\left(\frac{\mathrm{P}_{\mathrm{r},cond}}{\mathrm{P}_{\mathrm{r},evap}} \right)^{\frac{n-1}{n}} - 1 \right] \tag{22}$$

$$Q_{el} = \frac{m_r \Delta h_{comp}}{\eta_{comp}} \tag{23}$$

where m_r is the refrigerant mass flow rate (kg/s); V_c is the compressor swept volume (m^3); ω is the compressor rotational speed (rev/s);

The coefficient of performance (COP) is given as:

$$COP_h = \frac{Q_{heating}}{Q_{el}} \tag{24}$$

3.2 Economic model

Economic policy has a vital effect on the life cycle cost (LCC) analysis in lights of the hybrid renewable heating system. Hence, the LCC is given as [31, 32]:

$$LCC = E_{IC} + \sum_{i=1}^{n} (E_{SEC} + E_{ME} + E_{PC} + E_{ITS}) \tag{25}$$

where LCC is the system lifetime expense (£); E_IC is the original expense (£); E_SEC is the system energy cost (£); E_ME is the maintenance cost (£); E_PC is the system periodic cost (£); E_ITS is the system income tax savings (£).

The payback period (PBP) is employed to determine the time required to recoup the fund expended in an investment [33, 34].

$$PBP = X + \frac{Y}{Z} \tag{26}$$

where X is the number of years of final recovery (£); Y is the balance amount to be recovered (£); Z is the cash inflow (£).

4. Results and discussion

4.1 Model validation

Before performing the prediction of the annual thermal and electrical energy output, it is necessary to validate the accuracy of the numerical model. Hence, the comparisons between numerical and experimental results, in terms of the PV electrical energy production, PHE and thermal energy output from the heat pump, are analyzed based on the error analysis model from 01/Nov/2016 to 31/Jan/2017.

$$Error = \left| \frac{T_{numerical} - \mathrm{T}_{\exp erimental}}{T_{numerical}} \right| \tag{27}$$

4.1.1 Electrical energy production from PV array

Figure 5 displays the comparison of daily electrical energy output from PV array based on the simulation and test results. It is concluded that the error is up to 14.93% occurred at the termination of the operating phase, the mean error reaches 9.26%. Moreover, the experimental data demonstrated that the total electrical energy production could achieve 1125.89 kWh from 01/Nov/2016 to 31/Jan/2017 (228 days), by contrast, the numerical result exhibits close proximity of value, achieving 1247.51 kWh within a 10% error. This means that the numerical result is in very good agreement with experiment data, which validates the reliability of the numerical model.

4.1.2 Thermal energy output from PHE

It can be observed from **Figure 6** that the temperature variation between the experimental data and the numerical result has a similar trend. The highest thermal fluid temperature within the PHE reaches 15.75°C on 10/NOV/2016, by comparison, the lowest one is 0.75°C on 25/JAN/2017. And also, the minimum temperature difference was around 3.29% on 31/DEC/2016, the mean one being 9.11%, while the maximum temperature difference is approximately 14.72% on 14/NOV/2016.

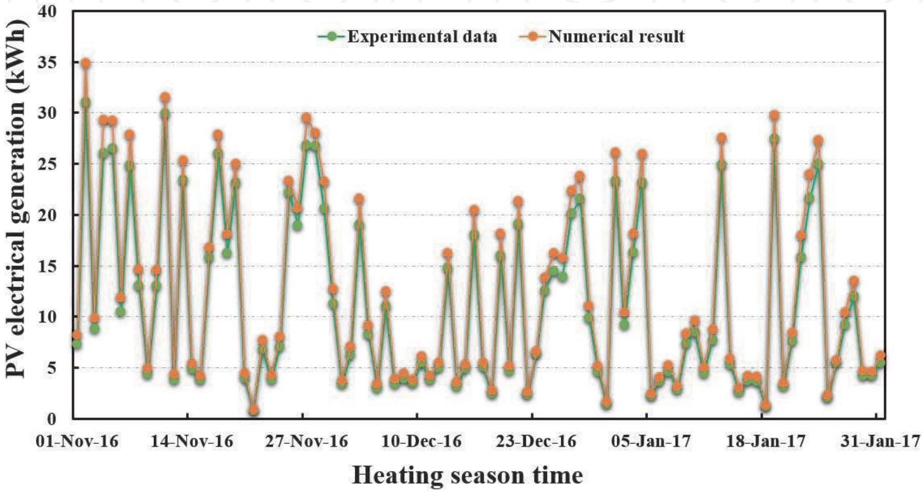

Figure 5.
Electrical energy output from PV array.

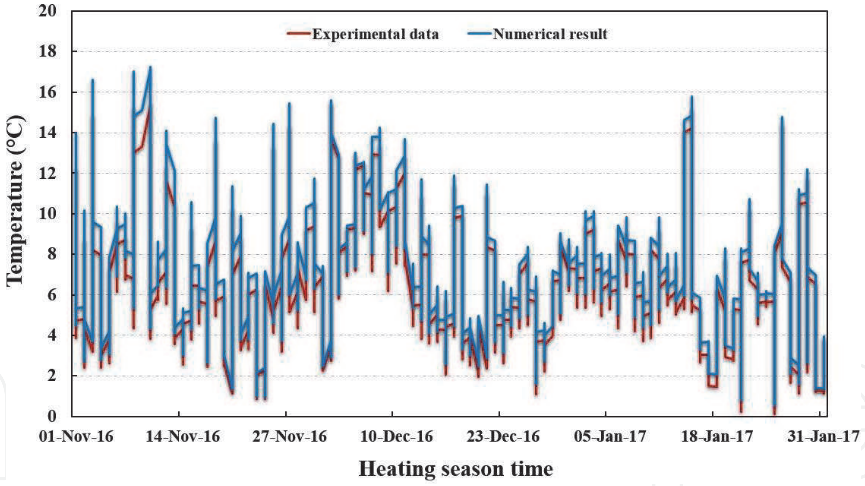

Figure 6.
Thermal energy output from PHE.

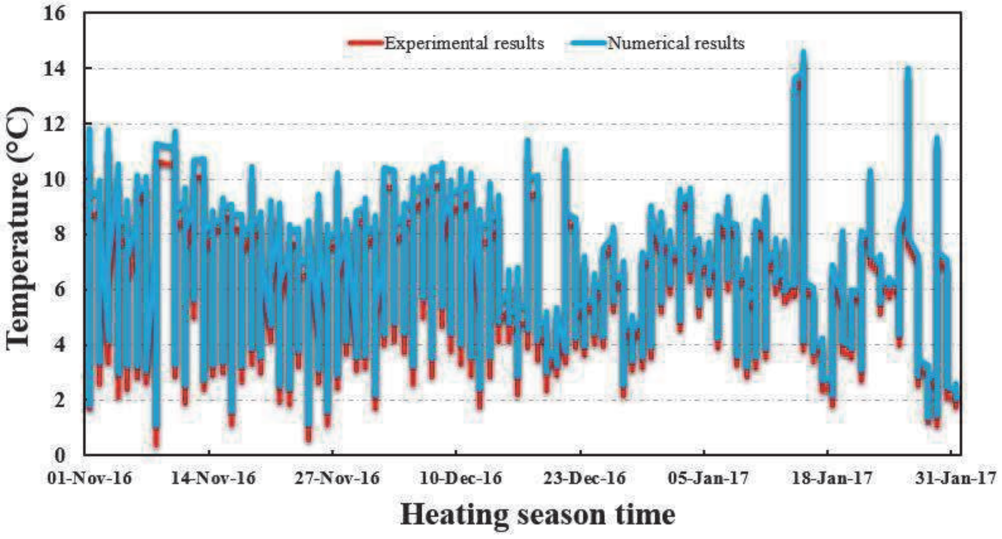

Figure 7.
Heat production from ground copper pipe.

4.1.3 Thermal output from ground copper pipe

Figure 7 displayed a similar temperature change tendency between the simulation and test results. Specifically, the temperature of the test could realize up to 14.23°C on 15/JAN/2017 whereas the lowest temperature could reach 0.89°C on 08/NOV/2016. Additionally, the maximum, minimum and average relative errors are 11.33% on 16/DEC/2016, 2.40% on 15/JAN/2017 and 6.36%, as clarified in **Table 1**.

4.1.4 Thermal energy output from the heat pump

Figure 8 compared the thermal energy output from the heat pump system, and found that the daily maximum and minimum differences are about 9.30% appeared on 16/JAN/2017 and 5.49% occurred on 05/DEC/2016, respectively. Consequently, the numerical model could be employed to assess the annual thermal and electrical energy output of the hybrid renewable heating system over a year.

Table 1 illustrated the relative error analysis of PV electrical, thermal, geothermal thermal and heat pump outputs between simulation results and experimental data. It is found that all error values are less than 15% which fulfill the requirement.

Date	PV electrical output (%)	PHE thermal output (%)	Geothermal thermal output (%)	Heat pump output (%)
03/NOV/2016	14.84	12.39	8.07	7.01
14/NOV/2016	4.15	14.98	7.07	6.33
28/NOV/2016	9.05	11.86	6.73	5.94
15/DEC/2016	8.22	9.75	14.79	5.49
23/DEC/2016	3.48	8.78	6.12	9.01
31/DEC/2016	14.88	3.29	4.98	8.28
08/JAN/2017	14.93	8.50	4.47	8.86
21/JAN/2017	8.45	8.91	2.40	9.30
26/JAN/2017	5.38	3.49	2.57	9.13

Table 1.
Relative error analysis of PV electrical, thermal, geothermal thermal and heat pump outputs.

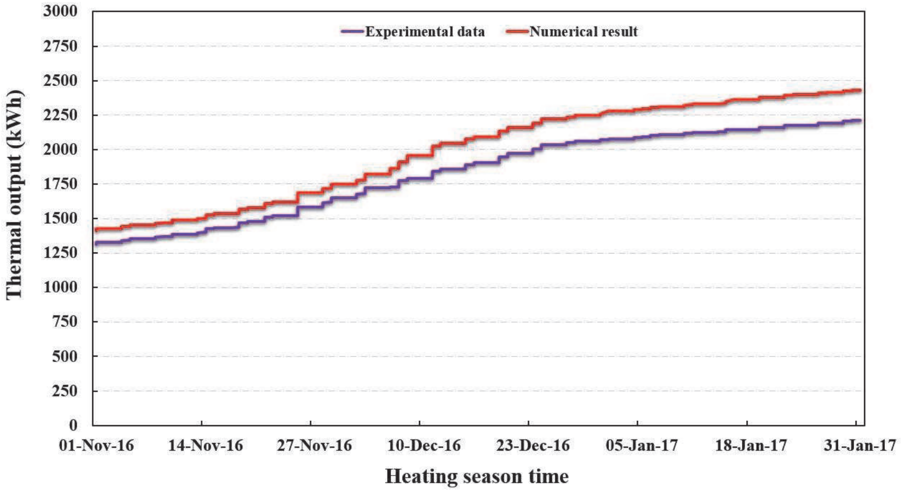

Figure 8.
Thermal energy output from the heat pump system.

4.2 Year-round system performance assessment

Figure 9 depicts the monthly power energy production and efficiency from the PV array. It can be concluded that the minimum and the maximum monthly electrical energy generation are around 335.81 kWh with the lowest efficiency (about 14.85%) in December and 1830.35 kWh with the highest efficiency (about 15.9%) in June, respectively. And also, the overall electrical energy obtained from the PV array could reach 11,867 kWh during a year. This means that it not only can meet the power demand of the poultry shed, but also could supply around 43.5% power requirement of the heat pump compressor operating.

Additionally, diminishing the PV surface temperature contributes to increasing the voltage and electrical efficiency. The PHE under the PV array could help to decrease the PV surface temperature resulting in a PV electrical efficiency enhancement. **Figure 10** exhibits the monthly thermal energy output and COP variation of the heat pump unit. Results show that the highest and the lowest monthly thermal energy output could achieve 3848.77 kWh in July and 1610.77 kWh in February, respectively. And also, the overall thermal energy output is about 30210.98 kWh per annum. This means that some capacity of the gas burners would

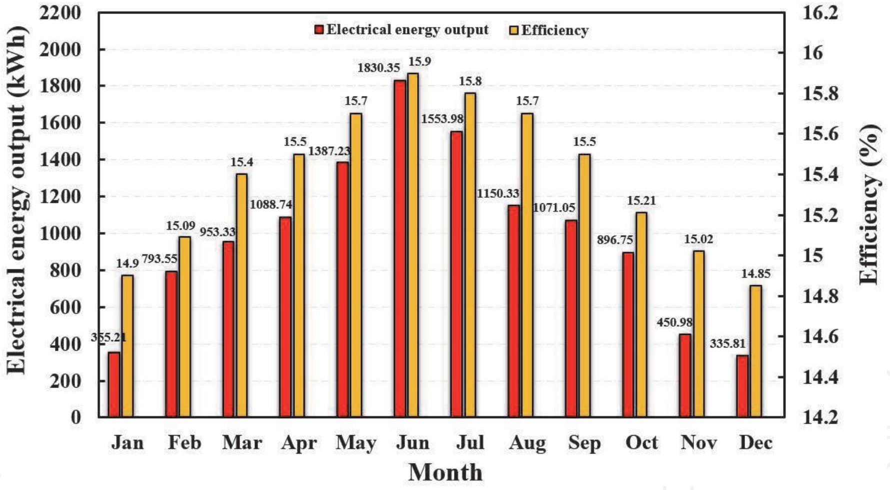

Figure 9.
Monthly PV electrical energy production and efficiency.

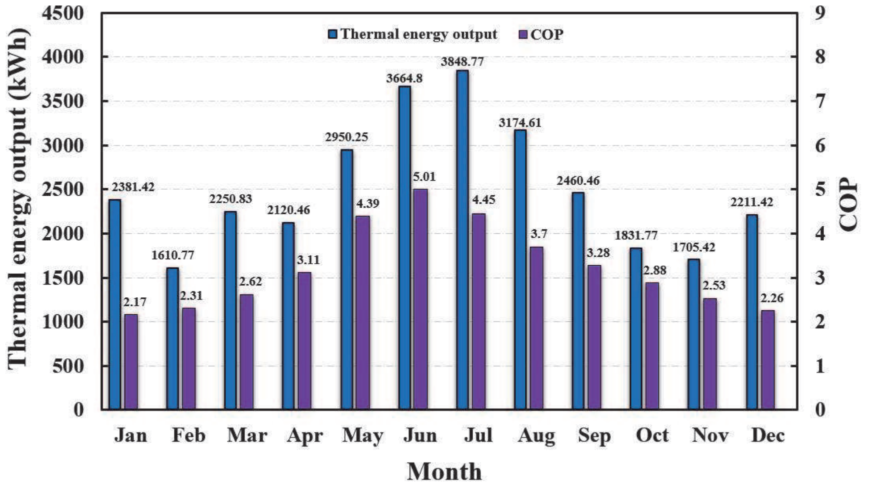

Figure 10.
Monthly thermal energy output and COP of heat pump system.

be needed alongside the heat pump to warm the shed sufficiently, especially from December to February.

Furthermore, the highest and lowest PV/T thermal efficiency could reach 28.3% in June and 7.3% in December. When the PV/T operates in conjunction with the geothermal copper pipe array, the COP of the heat pump could achieve up to 5.01 in June, while a minimum COP of 2.17 can be achieved in December.

4.3 Economic assessment

It can be observed from **Figure 11** that the comparison of gas and electricity cost between the current system and PV/T and heat pump system each period. Notably, the overall cost of the PV/T with heat pump system is lower than the gas burners system. To be more specific, the gas cost of the PV/T with heat pump system is approximately £319.74, which is significantly lower than that of the gas burner system (approximately £1083), saving about £763. Similarly, the electrical cost of the PV/T with heat pump system is approximately £128.52, which is lower compared to the gas burner system (approximately £893), saving about £750. Additionally, the payback period is about 5.5 years.

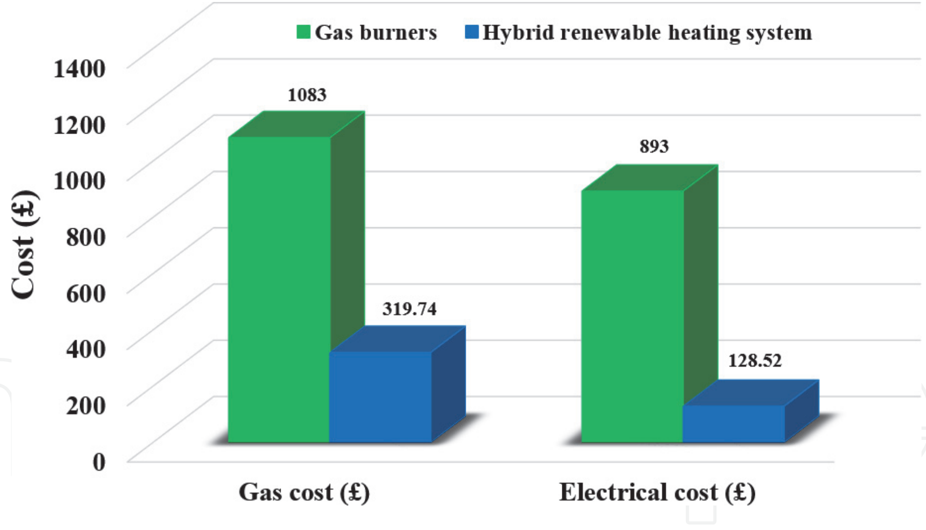

Figure 11.
Comparison of gas and electrical cost between gas burners and hybrid renewable heating systems.

4.4 Environmental evaluation

To perform the environmental evaluation, the CO_2 emissions related to gas and electricity prices are needed, as applied to the UK. Therefore, the values assigned to the parameters in this study are provided [34, 35] including 0.5246 kg CO_2 (e)/ kWe h for electricity and 0.1836 kg CO_2 (e)/kWth h for gas. Additionally, in the UK, the electricity price at Feed-In Tariff (FIT) and the renewable heat incentive (RHI) are £0.1097/kWh and £0.052/kWh, respectively [36, 37]. Results confirmed from **Figure 12** that the gas burners system produces energy consumption of about 39,851 kWh resulting in about 10.27 tons CO_2 emission, while the hybrid renewable heating system has an only energy consumption of 10,978 kWh which is equivalent to 2.026 tons CO_2 emission. This indicates that the novel hybrid system could save about 28,873 kWh energy consumption, making for a reduction of total CO_2 emission of approximately 8.3 tons. **Table 2** describes the calculation processes of energy consumption, CO_2 emission and operating cost of the gas burners and PV/T with heat pump systems.

4.5 Summary

To sum up, the hybrid renewable energy heating system could save 28,873 kWh of thermal and electrical energy consumption, £1528 of operating cost with

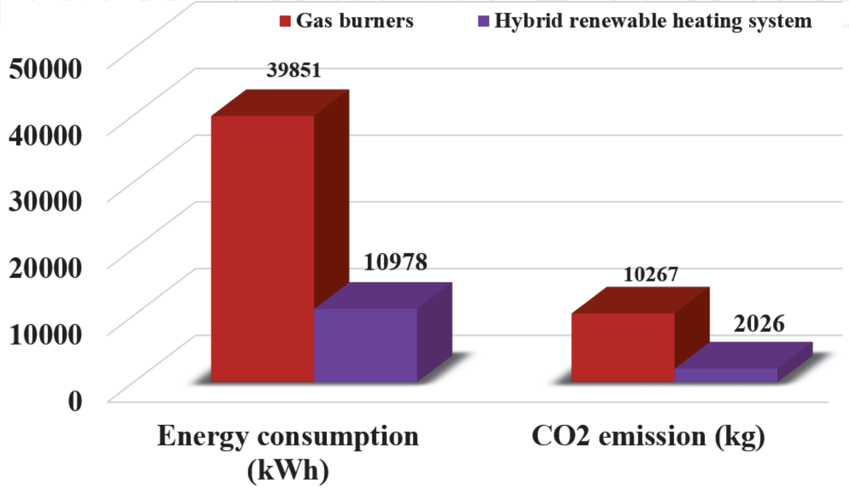

Figure 12.
Comparison of energy consumption and CO_2 emission between gas burners and hybrid renewable heating systems.

System/items	Gas burners system	PV/T with heat pump system	Saving
Total energy consumption, kWh (228 days)	31,199 + 8652 = **39,851**	10946.57 + 31.21 = **10,978**	28,873 kWh
CO_2 emission, tons per (228 days)	31,199 × 0.1836 + 8652 × 0.5246 =10266.98/1000 = **10.27 tons**	10946.57 × 0.1836 + 31.21 × 0.5246 =2026.16 kg/1000 = **2.03tons**	8.3 tons
Operating cost (£) (228 days)	£1083 + £893 = **£1976**	£319.74 + £128.52 = **£448.26**	£1528

Table 2.
Calculation process of energy consumption, CO_2 emission and operating cost between gas burners and PV/T with heat pump systems.

5.5 years' payback period and 8.3 tons of CO_2 emission. Additionally, the electrical output of the PV/T array could achieve approximately 11,867 kWh per annum whereas the thermal energy output is about 30,210 kWh per annum.

According to previous studies [19, 22, 25, 38], it is observed that the hybrid of solar and geothermal energy systems used in a poultry house is rare. Specifically, Fawaz et al. [22] demonstrated that the solar-assisted localized heating system could save approximately 74% of the energy demand and exhibit a 4.6 years of payback period. To improve the chicken meat and eggs production, Gad et al. [19] concluded that the thermal efficiency of the solar heating system is about 71.6% whereas the PV electrical efficiency is 12.5%. Choi et al. [25] designed, constructed and tested a geothermal heat pump system for ameliorating the interior environment of the poultry shed. It is demonstrated that the average interior air temperature could be kept in the range from 24.8 to 32.2°C whereas the relative humidity varies from 45.2 to 72.6%. Moreover, the GHP poultry house could save about 92% of the overall energy expense in comparison with the normal poultry shed. And also, the concentration of CO_2 in the GHP poultry house could be decreased by 3299 ppm, by comparison, in the conventional shed, it is decreased by 4945 ppm. Uzodinma et al. [38] assessed the performance of a solar thermal collector with a phase change materials system for poultry incubating chamber, and observed that the temperature of the chamber could be kept in the range from 36 to 39°C, meanwhile, an average egg hatchability could reach 62.37%.

Herein, this proposed hybrid PV/T with heat pump system could allow taking the benefit of high solar irradiation rates and soil heat, thus improving system performance, ameliorating the interior environment of poultry shed and boost meat and eggs production.

5. Conclusions

In this chapter, a novel PV/T with PHE array coupled to a low expense geothermal copper pipe array and heat pump system is installed in the JWL poultry farm. A numerical model is established and has a good agreement with experimental data within a 15% error. In the meantime, the yearly system energy output is predicted based on the Newark-on-Trent of Nottinghamshire, UK weather conditions. Moreover, the comparisons of the gas cost, electrical cost and CO_2 emission are investigated between the gas burners and hybrid renewable heating systems. Some significant outcomes are obtained as below:

- The electrical production from the PV array could realize 11,867 kWh per annum. It not only meets the power requirement of the poultry shed, but also supply around 43.5% power needed for the heat pump compressor operation.

- The heat pump thermal energy output is about 30,210 kWh per annum, which indicates that some capacity of the gas burners would be required alongside the heat pump to warm the shed adequately in winter.

- When the PV/T operates in conjunction with the geothermal pipe, the COP of the heat pump could reach up to 5.01 in June, while a minimum COP of 2.17 could be achieved in December.

- The overall gas and electrical cost of the hybrid renewable heating system are £320 and £129, which are much less than that of the gas burners system saving £763 and £750, respectively, resulting in less than 6 years of payback period.

- In comparison with the gas burner, the energy consumption of the hybrid renewable heating system can decrease about 28,873 kWh, making for a decline of total CO_2 emission of approximately 8.3 tons.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acronyms and Abbreviations

CO_2	carbon dioxide
COP	coefficient of performance
FIT	feed-in tariff
GHG	greenhouse gas
GHP	geothermal heat pump
LCC	life cycle cost
NH3	ammonia
PBP	payback period
PHE	polyethylene heat exchanger
PV	photovoltaic
PV/T	photovoltaic/thermal
RH	relative humidity
RHI	renewable heat incentive
WelChic	welfare enhanced living conditions for healthier chickens
3D	three-dimensional
3E	energy, economic and environmental

Nomenclature

A	area (m^2)
c	thermal capacity (J/kg·K)
H	depth (m)
h	heat transfer coefficient [W/(m·K)]
λ	thermal conductivity [W/(m·K)]
r	radius (m)
T	temperature (°C)

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