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Solar-assisted poultry production in small-scale farms: a case study in the Bekaa semi-arid region, Lebanon

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Abstract

Background In Lebanon, poultry production is one of the major components of the agricultural sector; however, it suffers from increasing energy costs necessary to cover poultry heating requirements. This affects the profits of brooding farms, namely, small-scale farms in rural areas. Few studies have addressed the use of renewable energy in the poultry industry in Lebanon, with most having focused on modelling ventilation and air quality requirements in poultry houses. Therefore, there is a need to investigate the efficiency of renewable energy sources in providing heating requirements for poultry production. Accordingly, this study evaluates the performance of a solar-assisted, localized heating system in providing heat requirements for chicks in a renovated green poultry house in the Bekaa semi-arid rural region in Lebanon. For this aim, two brooding cycles were conducted during the warm and cold seasons in a greenhouse and were later replicated in a conventional poultry house.

Results The energy inputs in the green and conventional houses, respectively, were 33,995.39 and 40,656.97 MJ (1000 birds)$^{-1}$ in the warm season, and 37,058.25 and 45,770.05 MJ (1000 birds)$^{-1}$ in the cold season. Calculated energy efficiency values for the green and conventional poultry houses were, respectively, 0.58 and 0.50 in the warm season, and 0.46 and 0.41 in the cold season. The net return was negative for both systems and the benefit-to-cost ratio from broiler production was calculated to be 0.49 and 0.50 in the green and conventional houses, respectively. Life cycle cost analysis showed that adopting the green heating system in the studied farm would entail an 18.89% increase in cost over a period of 20 years as compared to the conventional system.

Conclusion It was concluded that poultry production is not profitable in small-scale farms in the studied area in Lebanon. The use of renewable energy might be more suited for large-scale broiler operations to achieve their purpose in reducing overall production costs. Optimization of the green system to fully satisfy the poultry energy requirements would render it more economically competitive.

Keywords Broiler production, Renewable energy, Solar-assisted heating, Energy analysis, Economic analysis

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Background

In Lebanon, poultry production is considered one of the major components of the agricultural sector. The country is home to more than 10 large poultry producers and some 2000 poultry farms, with poultry constituting 50% of the meat consumption [1]. The production of broiler meat in Lebanon has been steadily increasing over the past years. According to statistics reported by the Food and Agricultural Organization [2], the sector witnessed a growth rate of 23% between the years 2015 and 2019. In 2019, Lebanon produced a total of 52,010 metric tons of poultry meat, with broiler meat accounting for the majority of the production at 44,780 metric tons.

While meeting local demand, the Lebanese poultry industry is vulnerable to foreign competition. This is particularly challenging given the high cost of energy, which constitutes a burden on the farmers and decreases their profitability in this sector. Indeed, major electricity shortages in Lebanon, bad performance in the electricity sector, and the necessity to rely on high-cost private generators affect the competitiveness of businesses in Lebanon and lead to lost economic opportunities [3]. Electricity shortages in Lebanon are listed as the second constraint to economic competitiveness after political instabilities [3]. In addition, the limited adoption of new technologies and modern farming practices poses a major challenge for small farms in Lebanon. This obstacle hampers the progress of the agro-processing industry, thereby creating significant barriers for small farms to enhance their productivity, increase their income, and actively contribute to the growth and development of the agro-processing sector [4].

The electricity supply in Lebanon is characterized by chronic shortages, uneven distribution, and high costs, all of which are aggravated in rural areas where the bulk of electricity needs are met through diesel generators [5]. With Lebanon benefitting from 300 sunny days a year and an average solar radiation of more than 2100 kWh/m^2, solar energy offers a sustainable alternative to energy cuts and diesel generators. In 2010, the Ministry of Energy and Water (MoEW) committed to reaching 12% of electric and thermal supply from renewable energy by 2020, one-third of which was to be by solar energy. In 2018, the Government of Lebanon further pledged to switch to natural gas and renewable energy and extended the target to 30% of electricity and heat consumption through renewables by 2030 [6].

Energy sustainability is an essential component of a resilient and sustainable future [7]. Accordingly, promoting energy sustainability in the agricultural sector is crucial for ensuring long-term food security, reducing greenhouse gas emissions, and achieving sustainable development goals [8]. The integration of renewable energy sources into small-scale poultry production can improve energy efficiency, reduce production costs, and enhance the sustainability and resilience of small-scale poultry farming systems [9]. Renewable energy technologies such as solar, wind, and biogas have been successfully applied in small-scale poultry production, demonstrating their potential to improve energy efficiency and reduce operating costs for farmers [10, 11].

Since 2007, UNDP-CEDRO has implemented in Lebanon more than 100 small-scale PV and solar water heaters (SWHs) projects in schools, clinics, and municipalities nationwide [5, 6, 12]. In 2018, CEDRO completed the 'Village 24' Initiative the first community-led renewable energy system in Lebanon entirely powered by 250 kWp solar PV coupled with diesel generators [6]. By the end of 2018, Lebanon's total PV installed capacity was 56.37 MWp, of which only 10% pertained to the agricultural sector and was mostly (9%) used in solar PV pumps for irrigation purposes [5, 12, 13]. Enhancing the use of renewable energy across the agriculture sector, namely, in poultry production operations, would contribute to decreasing the overall operating costs in this sector and render it more competitive.

Research has shown that the integration of renewable energy sources with energy conservation measures in poultry production can lead to significant reductions in energy consumption [14–16]. In their review on the use of advanced renewable and sustainable heating systems in poultry farming, including photovoltaic (PV), solar collector, hybrid PV/thermal, thermal energy storage, ground/water/air sources heat pumps, lighting and radiant heating, Cui et al. [17] found that up to 85% energy savings can be achieved as compared to the traditional poultry houses. The authors calculated a payback time of the used technologies of 3–8 years.

Bazen and Brown [18] investigated the impact of alternative energy programs, grants and other incentives on the feasibility of solar PV systems in several solar regions within Tennessee's poultry industry. The authors showed that incentives exceeding current levels before the adoption of solar PV systems would be financially beneficial. Van Dyne [19] studied, using a simulation model, the economic feasibility of the use of solar heating in Maryland's poultry houses, and showed that solar energy could cover up to 42% of the heating requirements, presenting a cost-effective heating source as compared to the commonly used propane gas.

In addition, Firouzi [20] conducted an energy audit in 25 broiler farms in Northern Iran and reported an energy efficiency during the warm season of 26%, with feed and diesel fuel constituting the highest energy inputs of 43.44% and 33.43%, respectively. The efficiency dropped to 20% in the cold season, with an energy input of 51.58%

from diesel fuel, and 31.73% from the feed. Amini et al. [21] evaluated energy consumption and conducted an economic analysis of traditional and modern farms for broiler production. The fuel and feed were the major contributors to the energy inputs in both farms. Energy efficiencies in the traditional and modern farms were 0.16 and 0.17, respectively.

Moreover, in the Arab region, Kharseh and Nordell [22] studied the implementation of geothermal source heat pumps in chicken farms in Syria, and results showed that the system decreased coal consumption by 57% and had a payback period of 5 years. El Zanaty et al. [23] studied the application of a renewable energy heating system in Egypt that includes solar PV system in addition to a biodigester of chicken manure and found that such implementation is beneficial from an economic perspective as compared to the fossil fuel systems adopted in traditional farms. Emirates Modern Poultry Company installed solar power that is expected to cover 60% of it is electricity consumption, making it the first solar-powered poultry farm in the UAE [24].

In Lebanon, few studies have addressed the use of renewable energy in the poultry industry and were mostly focused on ventilation in poultry houses. Fawaz et al. [25] carried out 3-D simulations to model the performance of a localized ventilation system and reported energy savings of 74% as compared to the conventional fully mixed system. Moreover, coupling the proposed system with a solar heating system saved 84% in the winter flock. El-Mogharbel et al. [26] assessed the implementation of solar-assisted localized heating in poultry houses using computational simulations and reported a decrease in the energy consumption by two-thirds as compared to the energy consumed using conventional heating. Alassad et al. [27] assessed the performance of a dew-point evaporative cooler in a poultry house located in a semi-arid climate and reported a 6.8% reduction in cost as compared to the direct evaporative cooling, with better compliance to poultry house thermal and air quality requirements. The cost was further reduced by 4.7% when localized ventilation instead of conventional was combined with the dew point apparatus.

This study aims to experimentally evaluate the use of renewable energy in poultry production to decrease the dependency of this sector on fossil fuels and increase the profit of broiler farms in rural areas in Lebanon. For this aim, a poultry house located in the semi-arid region in Lebanon was renovated and equipped with a solar-assisted localized heating system to ensure heating requirements in broiler production. The greenhouse was used to conduct two broiler production cycles during the warm and cold seasons. An energy analysis was conducted to assess the profit from using renewable energy, and an economic analysis was performed to assess the economic feasibility of the implementation of the studied system in small-scale poultry farms in the studied area.

Methods

Study location

The study was performed in a poultry farm at AREC (Advancing Research Enabling Communities Center) in the Beqaa semi-arid region in Lebanon (33° 55′ 29.0″ N 36° 04′ 25.8″ E). The climate in this region is continental, characterized by wet, often snowy winters with temperatures as low as −1 °C, and dry warm summers attaining 40 °C.

System description

A renovated green poultry house (GPH) at AREC equipped with a solar-assisted localized heating system and photovoltaic panels was tested in poultry production. A conventional poultry house (CPH) operated on conventional electricity was used as a control house. The houses were north-facing structures with their sidewalls facing east and west. The poultry houses' dimensions were 15 m × 9.5 m × 3 m ($L*W*H$), with a gable height of 0.5 m. Heating in the CPH was ensured by 10 compact electric heaters (25 × 25 × 44 cm), with a heating output of 6825 BTU/hour each, distributed systematically in the poultry house. Pictures and layouts of the GPH and CPH are provided in Additional file 1: Figures S1–S3. A description of the GPH solar heating system and photovoltaic system is shown in Fig. 1.

Solar-assisted localized heating system

The heating system in the GPH (Fig. 1) is composed of 16 solar collectors with a total absorber area of 36.42 m^2. The system uses the Superline high-performance flat plate solar collectors, with panel dimensions of 1.891 m × 1.204 m × 0.099 m, each. The collectors have a thermal efficiency rating of 0.76 and a heat transfer fluid capacity of 1.8 L. The collectors are installed on the roof of the poultry house at an inclination of 45° to maximize exposure to sun irradiation. The solar collectors are connected to a 1000-L thermal water heating storage tank equipped with a coil heat exchanger and a built-in electrical backup heater. A 50-L gravity storage tank is installed to drain the solar panels in extremely cold periods, preventing freezing problems. Solar-heated water circulates into 8 fan coil units (YHK 25–2/CR 03-2R HB) distributed in the broiler area of the poultry house and placed at 1 m elevation from the ground. Hot water circulating in the fan coil units heats the surrounding air and provides the required temperature at the chicks' level. The fan coil units have a flow rate

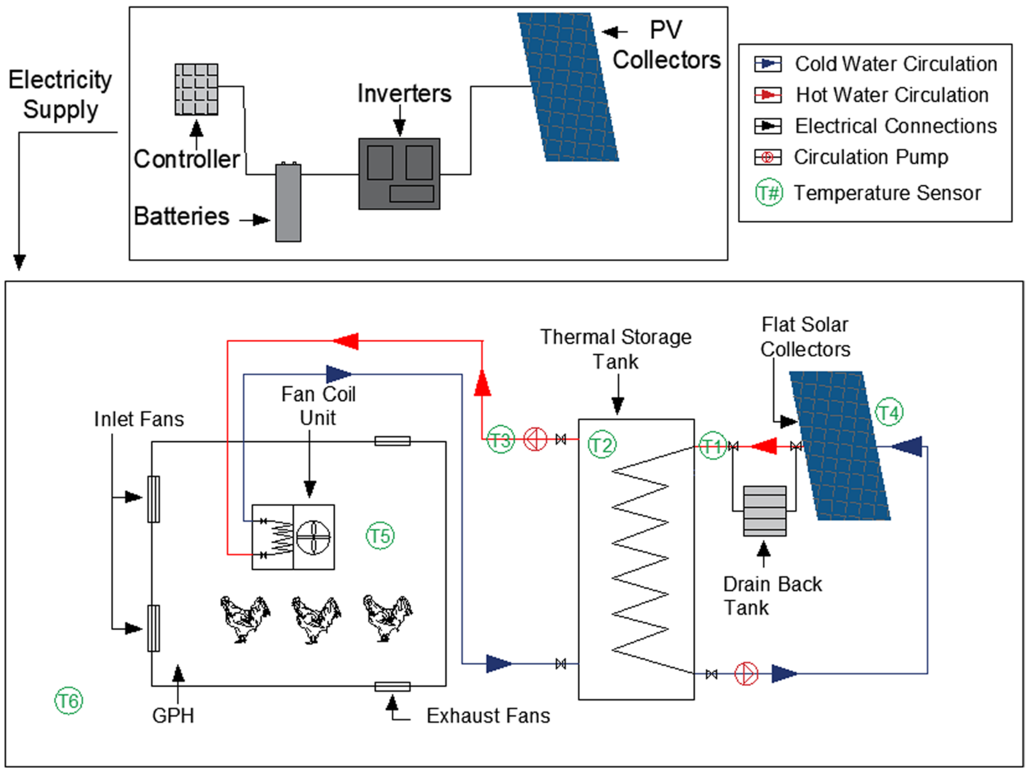

Fig. 1 Solar-assisted heating system, photovoltaic system, and system controller in the green poultry house

of up to 310 m^3/h. The fan flow rate was adjusted at different stages of the broiler production cycle to ensure adequate airflow in the poultry house for optimal broiler growth and productivity. The design of the heating system was based on findings from previous studies that investigated the efficiency and performance of a solar-assisted localized heating system for chicken brooding in a prototype poultry house representative of the tested house in this study [25, 26]. The studies performed numerical simulations using computational fluid dynamics to calculate the required localized heating load and to assess the performance of the heating units [25, 26].

Photovoltaic system

A total of 16 photovoltaic (PV) panels are installed on the top of the GPH to provide the electric energy required to run the green system. The PV panels used in the system are STP280—24/Vd with a capacity of 280 Watts. They have an efficiency rating of up to 16.8% and a maximum power voltage of 31.5 V and are designed to withstand harsh weather conditions. Electricity produced by the PV cells is stored in 24 batteries (OPzS Cell batteries with a total capacity of 656 Ah). A Studer 4000W interactive inverter is used to convert the electricity from the solar modules for use in lighting the GPH (total power of 300W) and operating the system pumps and controllers.

Controllers and data acquisition system

A programmable controller (Resol Germany) able to read 12 temperature measurements was used. Thermocouple temperature sensors were employed and distributed across the entire system. In addition, OM-EL-USB-2-LCD omega temperature loggers were placed in different locations inside and outside the poultry houses to provide additional temperature readings. The temperature inside the poultry house was maintained at the required value through a preset program ensuring the synchronized operation of the different components of the system. The preset temperature values inside the poultry house were varied throughout a given cycle experiment to satisfy temperature requirements at different periods during the production cycle. The location of the different temperature sensors and pumps used in the system is shown in Fig. 1. The detailed operation program is provided in Additional file 1: Table S1.

Broiler production cycles

Two broiler production cycles were conducted during the warm and cold seasons to assess the green system's performance in providing the required heating under various weather conditions. In each experiment, 1000 newly hatched chicks [28] were raised in each of the GPH and the control CPH until they became of sufficient weight to be delivered to the market. The warm and cold seasons cycle experiments lasted for 37 and 35 days, respectively.

Before starting the broiler production cycle, the temperature in the green and conventional poultry houses was maintained at 32 °C, which is required during the first two days of broiler brooding. This was achieved using heaters in the CPH and through the operation of the solar heating system in the GPH, aided by heaters when necessary (during the cold season). The temperature was then varied throughout the production period to satisfy temperature requirements at each stage of the chicks' development. Additional file 1: Table S2 provides temperature requirements during the production cycle of Ross broilers. Inside and outside temperatures of the poultry houses were recorded in the data logger every 1 min. The temperature was checked regularly during the day, and heaters were used in both the GPH and CPH according to needs. In addition, ventilation in the poultry houses was ensured using adjustable ventilation fans. The ventilation rate was regulated according to the guidelines of the National Chicken Council, which recommends maintaining a ventilation rate between 3 and 8 cubic feet per minute (cfm), depending on the weather conditions.

During the broiler production cycle, several parameters were recorded to monitor the overall performance of the chicks and the system. Production recording sheets were filled daily, recording the bird's mortality, feed consumption, vaccine administration, and any other remarks on each broiler's health status. Chicks were weighed 5 times during the cycle, based on a 12% representative sample. In addition, humidity measurements inside and outside the poultry houses were performed daily using OM-EL-USB-2-LCD data loggers that measure and store relative humidity data for continuous monitoring. Humidity inside the poultry houses should be maintained between 50 and 75% to avoid respiratory disorders due to high or low humidity levels [28]. Renewable and conventional electricity consumption was also recorded throughout the broiler production cycle using electricity meters. A detailed description of the broiler production cycle operations, maintenance of the poultry houses, and vaccination schedule of the broilers is provided in Additional file 1.

Energy analysis

Heating load supply by the green system

Before conducting the broiler production cycles, testing of the green system was performed in the cold season in the absence of chicks. This allowed calculating the fraction of the heating load supplied by the solar-assisted localized heating system in the absence of supplemental heating sources (electric heaters) used to attain the required heating during the broiler production cycles. The heating coverage by the green system was estimated by comparing the difference in temperature between the inside and outside of the poultry house (ΔT achieved) relative to the overall required increase in temperature (ΔT required) as determined by the set temperature inside the poultry house. Hourly temperature data were used to estimate the heat coverage by the green system during the day-time and night-time over the duration of the testing period, which lasted 42 days.

In the experiments, the green system heating coverage was calculated with reference to the control house, which was fully operating on conventional energy. In this case, the contribution of the green system in heating the poultry house was equal to the difference between the total energy used in heating the CPH and the fraction of supplemental conventional energy used in the GPH to cover the shortage in heating.

Input–output energy analysis

In order to assess the benefits of the green system, input–output energy analysis was performed on the GPH under both tested weather conditions and was compared to that of the CPH. Energy indicators were then computed based on the energy equivalents of inputs and outputs.

The inputs included the newly hatched chicks, feed, machinery, electricity, and human labour. The outputs included the broilers and the manure [20, 21, 29–32].

The energy of newly hatched chicks is calculated as in Eq. (1):

$$E_{\mathrm{ch}} = n_{\mathrm{ch}} \times \mathrm{ec}_{\mathrm{ch}} \times w_{\mathrm{ch}}. \tag{1}$$

E_{ch} is the total energy from the chicken input (MJ), n_{ch} is the number of chicks, $\mathrm{ec}_{\mathrm{ch}}$ is the energy equivalent of chicks (MJ Kg^{-1}), and w_{ch} is the average weight of newly hatched chicks.

The energy of the feed depends on the diet composition and the energetic values of each feed ingredient component. It is calculated as the summation of energy of the feed components and is expressed in terms of metabolizable energy per unit weight of feed (MJ Kg^{-1}). The composition of the feed used in this study is provided in Additional file 1: Table S3. The energy of the feed is calculated as in Eq. (2):

$$E_{\mathrm{F}} = \sum W_{\mathrm{ci}} \times \mathrm{ec}_{\mathrm{ci}}. \tag{2}$$

E_{F} is the total energy from the feed input (MJ), i is the number of components, w_{ci} is the weight of the component ingredient i of the feed, and $\mathrm{ec_{ci}}$ is the energy equivalent of component ingredient i (MJ $\mathrm{kg^{-1}}$).

The energy of machinery is the energy equivalent of the raw material of the equipment used during a broiler production cycle. In this study, those included the feeders, drinkers, pumps, and electrical fans, and their average energy equivalents were assumed from the literature [21, 32].

The energy of electricity included AREC's electric grid used for lighting the poultry houses and operating the evaporative coolers. It was measured using electricity meters. The energy of electricity used from the storage batteries of the PV system constitutes a renewable form of energy and was not included in the energy analysis. It is worth noting that energy input from diesel fuel combustion (MJ per litre), a major energy source in broiler production, was absent in this study and was substituted by the grid power where applicable (full operation of the CPH and complemental energy source in the case of the GPH).

The energy consumed by human labour is calculated as in Eq. (3):

$$E_{\mathrm{la}} = h \times n_{\mathrm{d}} \times n_{\mathrm{la}} \times \mathrm{ec_{la}}. \tag{3}$$

$\mathrm{E_{la}}$ is the total energy from the human labour input (MJ), h is the number of work hours spent per day, n_{d} is the number of workdays during the cycle, n_{la} is the number of human labourers, and $\mathrm{ec_{ch}}$ is the energy equivalent of human labour (MJ $\mathrm{h^{-1}}$).

The output energy included chicken meat and manure. The former was defined by the total weight of broilers sold, and the latter was calculated by multiplying the weight of the produced manure during a given cycle by its energy equivalent coefficient. Energy equivalents used to estimate the energy inputs and outputs are summarized in Table 1.

Table 1 Energy equivalents of inputs and outputs in broiler production [29]

Inputs/outputs	Units	Energy equivalent (MJ/unit)
Inputs		
Chick	kg	10.33
Human labour	h	1.96
Machinery		
Polyethylene	Kg	46.3
Galvanized iron	Kg	38
Steel	Kg	62.7
Electric motor	Kg	64.8
Feed		
Maize	kg	7.9
Soybean meal	kg	12.06
Di-calcium phosphate	kg	10
Minerals and vitamins	kg	1.59
Fatty acid	kg	9
Electricity	kWh	3.6
Outputs		
Broiler	kg	10.33
Manure	kg	0.3

Energy indicators

Energy indicators were computed based on the energy equivalents of inputs and outputs and included: energy use efficiency or energy ratio (4), which is the ratio of the output and input energy; energy productivity (5), which is the amount of yield produced per 1 MJ of input energy; specific energy (6), which is the amount of input energy per each kg of output yield; and net energy (7), which is the difference between the input and output amounts of energy. The indices were calculated as follows:

$$\text{Energy use efficiency} = \frac{\text{Energy output}\left(\mathrm{MJ(1000\ bird)^{-1}}\right)}{\text{Energy input}\left(\mathrm{MJ(1000\ bird)^{-1}}\right)}, \tag{4}$$

$$\text{Energy productivity} = \frac{\text{Yield}\left(\mathrm{kg(1000\ bird)^{-1}}\right)}{\text{Energy input}\left(\mathrm{MJ(1000\ bird)^{-1}}\right)}, \tag{5}$$

$$\text{Specific energy} = \frac{\text{Energy input}\left(\mathrm{MJ(1000\ bird)^{-1}}\right)}{\text{Yield}\left(\mathrm{kg(1000\ bird)^{-1}}\right)}, \tag{6}$$

$$\begin{aligned}\text{Net energy} =&\text{energy output}\left(\mathrm{MJ(1000\ bird)^{-1}}\right)\\ &- \text{energy input}\ \mathrm{(MJ(1000\ bird)^{-1}}.\end{aligned} \tag{7}$$

Economic analysis

Economic analysis of broiler production using conventional and renewable sources of energy was done by a survey of the economic indices and performance of a life cycle cost (LCC).

Economic indices

Calculated economic indices included: gross production value (8); gross return (9); net return (10); benefit–cost ratio (BC) (11); and productivity (12). These economic indices depend on broiler yield, gross production value, variable cost production, fixed cost production, and total production cost. They were calculated over a one-year operation period considering an average of 8 broiler production cycles per year of 1000 chicks each. Economic indices were calculated as follows:

$$\text{Gross production value} = \text{yield}\left(\text{kg}(1000\ \text{bird})^{-1}\right) * \text{broiler price}\left(\$(\text{kg})^{-1}\right), \quad (8)$$

$$\text{Gross return} = \text{Gross production value}\left(\$(1000\ \text{bird})^{-1}\right) - \text{variable production value}\left(\$(1000\ \text{bird})^{-1}\right) \quad (9)$$

$$\text{Net return} = \text{gross production value}\left(\$(1000\ \text{bird})^{-1}\right) - \text{total production value}\left(\$(1000\ \text{bird})^{-1}\right), \quad (10)$$

$$\text{BC} = \frac{\text{Gross production value}\left(\$(1000\ \text{bird})^{-1}\right)}{\text{Total production value}\left(\$(1000\ \text{bird})^{-1}\right)}, \quad (11)$$

$$\text{Productivity} = \frac{\text{Broiler yield}\left(\text{kg}\ (1000\ \text{bird})^{-1}\right)}{\text{Total production value}\left(\$(1000\ \text{bird})^{-1}\right)}, \quad (12)$$

where the gross production value is the wholesale price of broilers produced per cycle of 1000 birds, the yield is the total weight of broilers produced per cycle of 1000 birds, and the broiler price is the market-selling price of 1 kg of broiler. The variable production value is the cost inquired per broiler production cycle of 1000 birds and includes the cost of the chicks, feed, vaccines, wood shavings, labour, electricity, and other items necessary during the chick growing period, which values may vary from one cycle to another depending on the market prices. The total production value is the sum of the variable production cost inquired per broiler production cycle of 1000 birds and the capital cost of the project.

Life cycle cost (LCC) analysis

In order to assess the economic feasibility of implementing renewable energy in poultry production, a life cycle cost analysis was performed for both the green and conventional heating systems. It consisted of calculating the total cost of each system over a defined service time, according to the following Eq. (13) [33]:

$$\text{LCC} = C_0 + \left[\sum_{t=1}^{T}\frac{\text{OC}_t}{(1+i)^t} + \sum_{t=1}^{T}\frac{\text{MC}_t}{(1+i)^t} + \sum_{t=1}^{T}\frac{\text{RC}_t}{(1+i)^t}\right] - \sum_{t=1}^{T}\frac{\text{SV}_t}{(1+i)^t}. \quad (13)$$

C_0 is the initial investment cost at time 0, OC is the operating cost, MC is the maintenance cost, RC is the replacement cost, SV is the salvage value, T is the time period of the analysis, and i is the rate used to discount future values.

Statistical analysis

Factorial experiments were designed to study the effect of weather conditions (warm vs cold weather) on the performance of the tested renewable system. For this aim, two broiler production cycles were conducted in the green poultry house during the warm and cold seasons. In each case, the experiments were replicated in a conventional control poultry house to compare the effect of renewable vs conventional energy sources in providing heat requirements for the chicks, and consequently on broiler production and performance. Statistical analysis was conducted using the t-test in Minitab 17.1.0. to test for significant differences in achieved indoor temperatures in the poultry houses during both the warm and cold seasons. A T-test was also used to check for significant differences in humidity inside the poultry houses, as well as differences in feed consumption and birds' weight and mortality in the green and conventional poultry houses. The analysis was carried out with a significance level of less than 0.05 ($p < 0.05$).

Results

Performance of the solar-assisted heating and PV systems

Before conducting the broiler production cycle experiments, testing of the green system was performed in the winter season in the absence of chicks. In this case, outside temperatures averaged 12.8 °C, reaching a maximum of 20 °C during the day-time and dropping to as low as 4 °C during night-time. The test revealed a significant contribution of the localized heating system in satisfying the required heating demand. During the day-time, the system provided on average 43.92 ± 16.59% of the heating load, with a heating share as high as 87.15% being attained. During night-time, the average system heating contribution was 44.06 ± 8.03% with a maximum heating load of 64.62%.

Similar results were attained during the actual production cycle conducted in the cold season. During this cycle, outside temperatures averaged 12 °C, reaching a maximum of 25 °C during the day-time and dropping to as low as 3.2 °C during night-time. The heating load provided by the localized heating system was calculated with reference to the CPH which was fully operational on conventional energy. The average heating load from the green system measured 63.69 ± 39.04% during the day-time and 43.5 ± 24.37% during night-time, with heating coverage of 100% being attained during sunny days. Most of the time, electric heaters were used as additional heating sources to meet heating requirements.

Measured temperatures in the greenhouse were significantly different ($p < 0.05$) than those achieved in the conventional house. In both houses, temperatures were statistically different ($p < 0.05$) from the required values for healthy chicks' development, with an average temperature difference of 1.2 °C and 2.2 °C in the GPH and the CPH, respectively, as compared to set temperatures during the production cycle. The lower temperature difference in the case of the GPH is due to the system automation allowing better temperature control as compared to the CPH where workers were responsible for monitoring the inside temperature in the house and ensuring its compliance with the required values. A 2 °C difference in temperature is allowed in poultry houses. However, higher temperature variations cause health problems for the chicks, especially if the thermal stress lasts for a period [28]. Temperature data at different locations in the system are provided in Additional file 1: Table S4.

During the cold broiler production cycle, total electricity consumption in the conventional house was 4344 kWh. It was used mainly to operate the heaters and was provided by AREC's grid. In the greenhouse, total electricity consumption by the electric heaters, as auxiliary conventional heating source, was 2184 kWh. An additional 432 kWh were provided by the PV system to ensure the green system operation and the lighting of the poultry house.

During the broiler production cycle conducted in the warm season, the outside temperature averaged 27 °C, increasing above 35 °C during the day-time to attain 41 °C on very hot days. During the night-time, outside temperatures dropped to values as low as 17 °C, early during the brooding cycle. During the first week of the brooding cycle, when heating temperatures up to 32 °C where necessary, the localized heating units were providing heating requirements for the healthy development of the chicks, especially during the night-time when temperatures decreased. Electric heaters were not used in this case and 100% heating coverage was ensured by the solar-assisted localized heating system. Beyond week one, when temperature requirements inside the poultry house dropped below 28 °C, heating was not necessary.

Total electricity consumption in the conventional house was 1898 kWh. It was used to operate the heaters at the beginning of the cycle especially during the night-time, as well as the ventilation fans and cooling pads, to maintain the required temperature. In the greenhouse, solar power could not achieve the electricity demand to operate the cooling system. In this case, supplemental electricity (44 kWh) from AREC's grid was used in addition to the 643 kWh provided by the PV system.

In both broiler production cycles, reported average chick weight, c mortality, and feed consumption were conformed to the Aviagen management handbook for chicken development [28]. No significant difference ($p > 0.05$) between the recorded chick's weight, mortality, and feed consumption was reported between the green and conventional poultry houses throughout the broiler production cycles. Data on chicks' mortality, average chick weight by the end of the broiler production cycles, feed consumption, the production efficiency factor, and the food conversion ratio are available in Additional file 1: Table S5.

Energy analysis

Input–output energy analysis

Input–output energy analysis was conducted on the conventional and green poultry houses. Table 2 shows the energy equivalents of inputs and outputs in both houses during the warm and cold seasons of broiler production cycles.

Energy indices

Energy indices were calculated for both the GPH and CPH for the two conducted broiler production cycles. Table 3 summarizes energy indices values and the share of energy forms in the green and conventional poultry houses during the warm and cold seasons of broiler production cycles.

Economic analysis

Economic indices

In order to estimate productivity and analyse the efficiency of introducing renewable energy in broiler production in small farms in Lebanon, a budgetary analysis was performed and economic indices were calculated for both GPH and CPH in the warm and cold seasons. Descriptive statistics was used to analyse data collected from the green and conventional houses. The economic analysis was based on an average of 8 broiler production cycles, assumed to be carried out all year round. Table 4 represents the economic results for a one-year operation of the poultry houses.

Table 2 Energy equivalents (EE) and % share of inputs and outputs in broiler production

	GPH-WS[a]		CPH-WS[a]		GPH-CS[a]		CPH-CS[a]	
	Total EE (MJ/1000 birds)	Share (%)	Total EE (MJ/1000 birds)	Share (%)	Total EE (MJ/1000 birds)	Share (%)	Total EE (MJ/1000 birds)	Share (%)
Inputs								
Chick	454.89	1.34	442.08	1.09	424.89	1.15	433.27	0.95
Human labour	217.56	0.64	217.56	0.54	294	0.79	294	0.64
Machinery	200	0.59	200	0.49	200	0.54	200	0.44
Feed	32,964.53	96.97	32,964.53	81.08	28,276.96	76.30	29,204.37	63.81
Electricity	158.4	0.47	6832.8	16.81	7862.4	21.22	15,638.4	34.17
Total energy input	33,995.39	100	40,656.97	100	37,058.25	100	45,770.05	100
Outputs								
Broiler	19,666.23	99.45	20,179.04	99.45	17,012.81	99.45	18,870.80	99.45
Manure	108.52	0.55	111.35	0.55	93.88	0.55	104.13	0.55
Total energy output	19,774.75	100	20,290.38	100	17,106.68	100	18,974.93	100

[a] GPH and CPH refer, respectively, to green and conventional poultry houses. WS and CS refer, respectively, to the warm and cold seasons of broiler production cycles

Table 3 Energy indices values and share of energy forms in broiler production

Items	Units	GPH-WS	CPH-WS	GPH-CS	CPH-CS
Energy use efficiency	–	0.582	0.499	0.462	0.415
Energy productivity	kg MJ^{-1}	0.578	0.496	0.459	0.412
Specific energy	MJ Kg^{-1}	1.729	2.015	2.178	2.425
Net energy	MJ $(1000 \text{ birds})^{-1}$	− 14,220.64	− 20,366.59	− 19,951.57	− 26,795.12
Direct energy	%	1.106	17.341	22.009	34.809
Indirect energy	%	98.894	82.559	77.990	65.190

Table 4 Economic analysis indices

Outcomes	Unit	GPH	CPH
Broilers sale price	$	15,067	15,953
Broilers weight	kg	14,202.92	15,120.94
Gross production value	$/(10,000 bird)	15,067	15,953
Variable production cost	$/(10,000 bird)	28,926.56	31,205.84
Fixed production cost	$/(10,000 bird)	1750	500.00
Total production cost	$/(10,000 bird)	30,676.56	31,705.84
Total production cost	$/kg	2.04	2.06
Gross return	$/(10,000 bird)	− 13,859.37	− 15,252.9
Net return	$/(10,000 bird)	− 15,609.37	− 15,752.9
Benefit to cost ration	–	0.49	0.50
Productivity	Kg/$	0.46	0.47

Table 5 LCC parameters

Parameter	Green heating system	Conventional heating system
Service time	20 years	20 years
Investment at year zero	35,000 $	1000 $
Maintenance cost	2%	2%
Salvage cost	4.5%	4.5%
Discount rate	5%	5%
Replacement cost	20 years	2 years
Conventional electricity consumption[a]	8900 kwh/year	25,000 kwh/year

[a] Electricity tariff in Lebanon is 0.13$/kwh. The average electricity consumption during the warm and cold seasons was multiplied by 8 broiler production cycles/year

Life cycle cost analysis

LCC analysis including initial investment and yearly operational and maintenance costs was conducted for both renewable and conventional heating systems. The green heating system consisted of the PV system, the solar-assisted localized heating system, and the controllers and data acquisition system. The conventional system consisted of 10 electrical heaters used in the control house. In both cases, the electric power consumption of the heaters, lamps, evaporative cooling systems, ventilation fans, and circulating pumps was

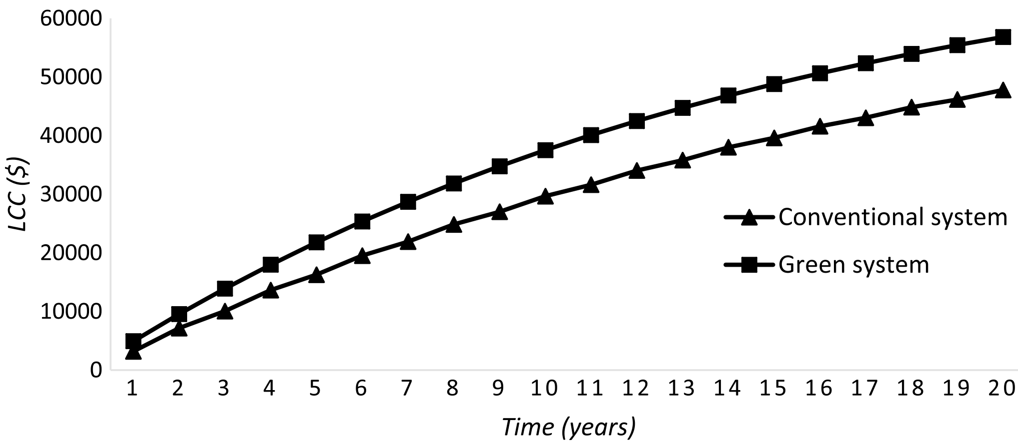

Fig. 2 Yearly variation of the LCC ($) for the green and conventional heating systems

added to the overall operational cost. This constitutes the bulk of the operation cost of the CPH fully operating on conventional electricity, but only a part of the operational cost of the GPH where energy was mostly provided in renewable form with relatively minimal auxiliary input from the conventional electricity source. Table 5 presents the different variables used in the LCC analysis, and Fig. 2 illustrates the yearly variation of the LCC ($) for the two systems.

Figure 2 shows a lower LCC for the conventional system throughout the time period of the analysis.

Discussion

Performance of the solar-assisted heating and PV systems

The assessment of the green system's performance during the cold and warm seasons showed that the system achieved partial success in meeting its objectives, with some shortcomings observed during peak hot and cold weather conditions. In these cases, conventional auxiliary energy was necessary to satisfy temperature requirements in the green poultry house. Nonetheless, the green system successfully achieved substantial savings in electricity consumption during both cold and warm seasons contributing to the decrease in the overall broiler production cost. Despite these limitations, the broiler production cycles were successful in both the green and conventional houses and during both cold and warm seasons. Indeed, the recorded temperature levels throughout the production cycles were favourable and supported the healthy development of the broilers. In addition, the target broilers' weight was achieved in both houses indicating that the broilers received adequate nutrition and thermal comfort and grew at an appropriate rate. The production efficiency factors for the greenhouse were 258.32 and 279.88 in the cold and warm seasons, respectively, and were slightly lower than the values calculated for the conventional house (Additional file 1: Table S5), namely due to the system vulnerabilities during peak weather conditions. Importantly, the results did not show any significant differences between the green and conventional poultry houses in the recorded average chicks' weight, chicks' mortality, and feed consumption, which conformed to the Aviagen management handbook for broilers development. The findings highlight the need to optimize the green system to become fully autonomous and able to meet the required energy loads.

Energy analysis

Input–output energy analysis

Analysis of input–output energy showed a slightly higher total energy consumption during the cold season and was associated with increased electricity consumption in both poultry houses during this period. Broilers' feed ranked first in energy inputs in both houses and under both climatic conditions, followed by electricity consumption, except in the GPH during the warm season where minimal electricity input was recorded. Similar results were reported by Heidari et al. [29] and Amid et al. [32], where feed and fuel had the highest share of energy consumption. In the absence of the use of diesel fuel in this study, the calculated energy input values under the different production conditions were lower than those reported in the literature. The implementation of the green system resulted in 19.03% energy input conservation in the cold season and 16.38% in the warm season, as compared to the conventional poultry house. Energy outputs from the CPH and GPH were comparable during the warm and cold seasons. The slightly lower output in the latter case was associated with the lower average broiler weight measured during the cold season.

Energy indices

Energy indices were calculated for both the GPH and CPH for the two conducted broiler production cycles. Energy use efficiency in broiler production was estimated to be 0.582 and 0.499 for the green and conventional houses, respectively, during the warm season, and 0.462 and 0.415, respectively, during the cold season. These values indicate a higher efficiency in energy use in the green poultry house. The lower ratios computed during the cold season are associated with a higher electricity consumption in this case. Amini et al. [21] reported energy use efficiency of 0.16 and 0.17 for traditional and modern farms, respectively. In a study conducted by Amid et al. [34] on the economic and energy analysis of broiler production in farms of different sizes, the energy use efficiency averaged 0.18 with higher values reported for larger farms. The higher energy efficiency values reported in this study are mainly due to the absence of the use of diesel fuel associated with high-energy input.

In addition, calculated energy productivity was 0.578 and 0.496 kg MJ^{-1} for the green and conventional houses, respectively, during the warm season, and 0.459 and 0.412 kg MJ^{-1}, respectively, during the cold season. Amid et al. [34] reported an average energy productivity of 0.02 kg MJ^{-1} in broiler farms of different sizes in Iran, substantially lower than the values reported in this study. The authors associated the measured low energy productivity with the use of fuel for heating the broiler production rooms, as well as to the use of old equipment that favours high fuel energy consumption. Baxevanou et al. [35] developed and applied an energy audit procedure to poultry chambers of various sizes and technology levels, to assess the energy performance of broiler facilities located in lowland and mountainous areas of Epirus Greece. The authors reported energy productivity varying between 0.578 and 1.111 kg MJ^{-1} (or specific energy varying between 0.25 and 0.48 kWh/kg) depending on the chamber technology level (insulation, automatic control of internal microclimate, etc.) and the location where the unit was installed (lowland vs mountainous areas). Chambers with advanced technology levels showed energy performance improvement by 27–31%. In this study, the absence of reliance on fuel as an energy source, and the use of relatively new equipment to ensure heating and ventilation requirements, resulted in an average energy productivity of 0.537 and 0.435 in the green and conventional poultry houses, respectively, with 12.5% energy performance improvement in the former case. A higher energy performance associated with the use of the proposed solar-assisted heating system is expected in large-scale farms where higher yield is expected per unit of energy input. It is also important to note that geographical variations and the type of poultry houses (open, semi-enclosed, closed) significantly affect energy performance [36].

A negative net energy was reported for both systems indicating that energy was wasted during broiler production under both tested conditions. Higher energy losses were computed in the case of the CPH, being 30.17 and 25.54% higher than energy losses in the GPH, in the warm and cold seasons, respectively.

Moreover, direct and indirect energy forms were quantified. Direct energy (DE) includes human labour and electricity. According to a recent review by Li et al. [37], heating and ventilation are the two main contributors to DE use in poultry housing but vary considerably based on geography and climate. Similarly, Paris et al. [36] report heating as the largest on-farm direct energy-consuming activity, followed by ventilation and lighting. Indirect energy (IDE) covers energy embodied in chick, machinery, and feed used in broiler farm production. Indirect energy constituted a higher share (>65%) of energy use in both green and conventional houses during both the cold and warm seasons. Heidari et al. [28] recorded a higher share of direct energy (59.2%) due to the excessive use of diesel fuel. Similarly, Amid et al. [34] reported a higher share of direct energy (64.62%) in broiler production in farms of different sizes, reporting fuel as the most influential factor. In this study, the absence of the direct use of fossil fuel for heating and ventilation purposes, as well as the high-energy input of the feed, resulted in a higher share of indirect energy use. In their review of energy use in the EU livestock sector including broiler production, Paris et al. [36] reported animal feed as the main energy input category. The authors indicated that 75% of the total energy use in broiler production in the EU is associated with feed.

Economic analysis of broiler production

Budgetary analysis of broiler production in the studied small-scale farm showed a slightly higher total production cost in the case of the CPH, attributed to higher electricity usage in this case. However, the higher total weight of the produced broilers in the CPH contributed to a relatively higher gross production value and resulted in insignificant differences between the productivity and BCR in both houses. The negative return values and BCR < 1 indicate that, under the tested experimental conditions, broiler production was not lucrative for both renewable and conventional systems. Heidari et al. [29] conducted an econometric analysis in large-scale broiler production farms and reported a positive net return of 1386.53 \$ (1000 $bird^{-1}$), and a benefit-to-cost ratio of 1.38, revealing a profitable meat production in the studied area. Bashir [38] conducted an economic analysis of broiler production in environment-controlled houses in the Faisalabad district in Pakistan, with an average flock size of 29, 210 birds. The author reported a profitability index of about 0.30 and a capital turnover of about 1.50, concluding that broiler production is a moneymaking business in the studied area. Azeez and Akbay [39] conducted an economic analysis of broiler production on 180 farms with a mean capacity of 14,000 birds in the northern region of Iraq and reported a benefit-to-cost ratio of 1.28. In this study, small-scale rural poultry production was considered. The results show that, despite achieving energy savings through using solar energy for heating the house, poultry production is not profitable at such a small-scale (1000 chicks) in the studied area. Al-Khraisa [40] conducted an economic analysis of poultry production in small, medium, and large-scale farms in the Amman and Ibrid districts in Jordan. The author reported that productivity is not promising for investors in this sector in the case of small farms that are unable to reap the benefit of economies of scale.

Life cycle analysis showed a lower LCC for the conventional system throughout the time period of the analysis (Fig. 2). Hence, the conventional system is more economically profitable than the green system and achieves an 18.89% reduction in cost in 20 years of operation. Optimization of the green system to fully satisfy the energy requirements in the poultry house would render it more economically competitive. The inclusion of the social and environmental impacts of the introduction of renewable energy in broiler production would also permit a better assessment of the economic profitability of such initiatives.

Conclusions

In this study, the introduction of renewable energy in broiler production in small-scale farms with an average flock size of 1000 birds was assessed. Broiler production cycles were conducted in a green poultry house equipped with a localized solar heating system and photovoltaic panels, and energy consumption was compared to a control house operated on conventional electricity. The average heating load from the green system measured $63.69 \pm 39.04\%$ during the day-time and $43.5 \pm 24.37\%$ during the night-time, with heating coverage of 100% being attained during sunny days. Energy analysis showed a higher energy use efficiency in the GPH, in both warm and cold seasons. However, economic analysis showed that broiler production was not profitable for both green and conventional systems under the studied conditions. LCC analysis demonstrated a higher economic profitability of the conventional system over a period of 20 years. While the green system showed promises from an energy perspective in reducing energy costs in small-scale poultry farms, optimization of the system to fully support energy requirements in broiler production cycles remains necessary to ensure the economic profitability of introducing renewable energy in small-scale poultry farms, which are mainly family-based poultry operations in the studied rural area. Such green systems would be more suited for large-scale broiler operations to achieve their purpose in reducing the overall production costs.

Supplementary Information

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Additional file 1: Figure S1. The GPH shown from the outside and inside. **Figure S2.** The inside of the conventional poultry house. **Figure S3.** Layout of the green poultry house.

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Author contributions

DAS: conceptualization, methodology, validation, analysis, investigation; resources, data curation, writing, review and editing, visualization, supervision, project administration, funding acquisition; STS: investigation, analysis, data curation, writing, visualization; NG, KAG and GC: conceptualization, methodology; ND, YD: advising on brooding operations; NH: contribution in green system operation and maintenance. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated and analysed during this study are included in this published article and its supplementary information files.

Declarations

Ethics approval and consent to participate

Broiler production operations adhered to a high standard (best practice) of veterinary care to maintain flock health and welfare and achieve good flock performance.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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