Evaluation of the solar contribution in a hybrid incubator of avian eggs

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Abstract: Solar thermal energy has been widely employed by the agro food industry with the objectives of reducing conventional sources of energy and achieving a reduction in greenhouse gas emissions. The focus of this manuscript is to evaluate a medium scale commercial incubator (for 9072 red-legged partridge (Alectoris rufa) eggs) supported with solar thermal energy under detailed monitoring. In this sense, an evacuated solar collector with an absorbing area of 0.99^{m2} and 163 L of water accumulation (with an auxiliary 80 L water tank) was coupled to the original emergency cooling system of the incubator. The hybrid system, using an automated control system, showed higher thermal stability (std=0.12 ℃) than the standard control system of the incubator (std=0.18 ℃). The area of the polygon defined by the phase space (PS) diagram, involving >90% of the data for the experiments with solar contribution (Experiments 1 to 3), was among 27% to 35% of that of commercial incubations, which is because of the high stability in the temperature. The computed performance (0.44 to 0.85) of the evacuated tube collector was in the same range as the theoretical performance provided by the manufacturer (0.60). The solar contribution was up to 60.4% per day, which indicates a saving of 806 MJ of electricity in a standard incubation.

Keywords: solar thermal energy, red-legged partridge, evacuated tube collector, incubations

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1 Introduction

Meeting the demand for a high quality food supply against a background of climate change and the need to reduce our greenhouse gas emissions presents a major challenge for the farming community (Caslin et al., 2011). The management of energy resources plays a key role for avoiding environmental problems, and thus, the combination of energy efficient improvements and the development and implementation of renewable-type energies has to be accepted by the agro food industry (Quijera et al., 2011). Using renewable energy sources during the incubation process will help reduce greenhouse gas (GHG) emissions through the production chain in the poultry industry (Pelletier, 2008). The use of solar energy for incubation can be especially relevant for game farms due to their location on isolated rural areas where solar heating will not only save energy but also help dealing the farm with energy supply incidences. The evaluation of a solar heating system for the incubation of red-legged partridge eggs is presented in this study demonstrating its potential of use for a relevant sector in countries such as Spain, accounting 2200 farms that raise red-legged partridge (MAGRAMA, 2016), but also France, Portugal, England and Italy (Gonzalez-Redondo et al., 2010). In the cited study, the authors characterized the red-legged partridge farms in Spain, identifying a first period, before 1997 where most of the established farms were small complete-cycle farms and 1997 onwards were complete-cycle farms increased their size and offered additional products and services. Eighty-four percent of

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the red-legged partridge game farming subsector is composed by complete-cycle farms that incubate their own eggs (Gonzalez-Redondo et al., 2010), something that highlights the relevance of the incubation process.

The location, type of collector, working fluid, size of the system and storage volume are the factors that need to be considered for specific solar heating applications to determine the heat exchanger size and the load (Kalogirou, 2003; Mekhilef et al., 2011). To increase the efficiency of solar thermal systems, solar collectors are applied to heat air or water as the medium of heat transfer. However, each collector is dedicated to a specific application. A flat plate type collector and an evacuated solar collector are designed to be used in low or medium temperature applications (30℃-200℃). Solar thermal technology has been widely employed to heat buildings; to dry vegetables (Correa-Hernando et al., 2011), fruits, and meats; and to heat broiler chickens. The earlier manuscripts of Brewer et al. (1975); Brewer et al. (1978); Flood et al. (1979); Brewer et al. (1981); Flood et al. (1981) and Reece (1981) showed the potential use of solar thermal energy in poultry houses. In a recent work, Fawaz et al. (2014) showed that solar-assisted localized ventilation for poultry houses lead to energy savings of up to 74%. Poultry incubation needs low temperatures (36.5℃-38.5℃), which can be easily reached using solar heating systems. Solar supported egg incubation is an especially suitable solution for small countryside farms. In this sense, several studies have been carried out on the design and construction of solar supported incubators (Bolaji, 2008; Kuye, 2008; Kisaalita et al., 2010). Nevertheless, there is a lack of experience with the exhaustive monitoring of incubator operation.

The high frequency monitoring of key parameters, such as temperature, is essential to better understand and evaluate the incubation system. Thermal stability is a factor that is very important in the incubation process because hatchability is dramatically reduced when the operation temperature is 2℃ over or under the recommended temperature (Deeming and Ferguson, 1991; French, 1997). Phase space (PS) has recently been demonstrated as a useful tool for representing the dynamic behavior and thermal stability. This article focuses on the evaluation of a commercial incubator supported with a solar thermal subsystem under detailed monitoring. Better understanding of the energy inputs and storage and their effects on the incubator temperature could help with the implementation of a fuzzy controlled hybrid system for increasing operation efficiency.

2 Material and methods

2.1 Farm characteristics

The farm where the system was installed and evaluated was established in 1998, it is a complete-cycle farm with 692 pairs in the breeding flock that is maintained by the yearly substitution of the eldest 1/3 of the flock, thus being composed by 1/3 of one year old, 1/3 of two years old and 1/3 of three years old partridge pairs laying eggs from the end of February to the beginning of June incubating 24000 eggs on average per season with 54% of hatchability. The eggs are stored from one to 21 days prior to incubation at temperatures ranging from 10℃ to 15°C. This small-scale farm was established in a period where most of the new established farms have switched to a more industrial production structure either with an increase of their breeding flocks or by eliminating them and focus on the chicks growing.

2.2 Factory design of the incubator and modified solar-electric hybrid design

The factory design of the incubator (VICTORIA I-36, VICTORIA srl, Guanzate, Italy) comprises two heating resistors (1700 W total) working simultaneously that are controlled by a temperature controller. Additionally, the incubator is equipped with an emergency cooling circuit that operates in case of overheating and consists of a heat exchanger fed by water. Heat exchange between the incubator and the described elements is forced by ventilation by means of a fan located in front of the radiating elements, as shown in Figure 1.

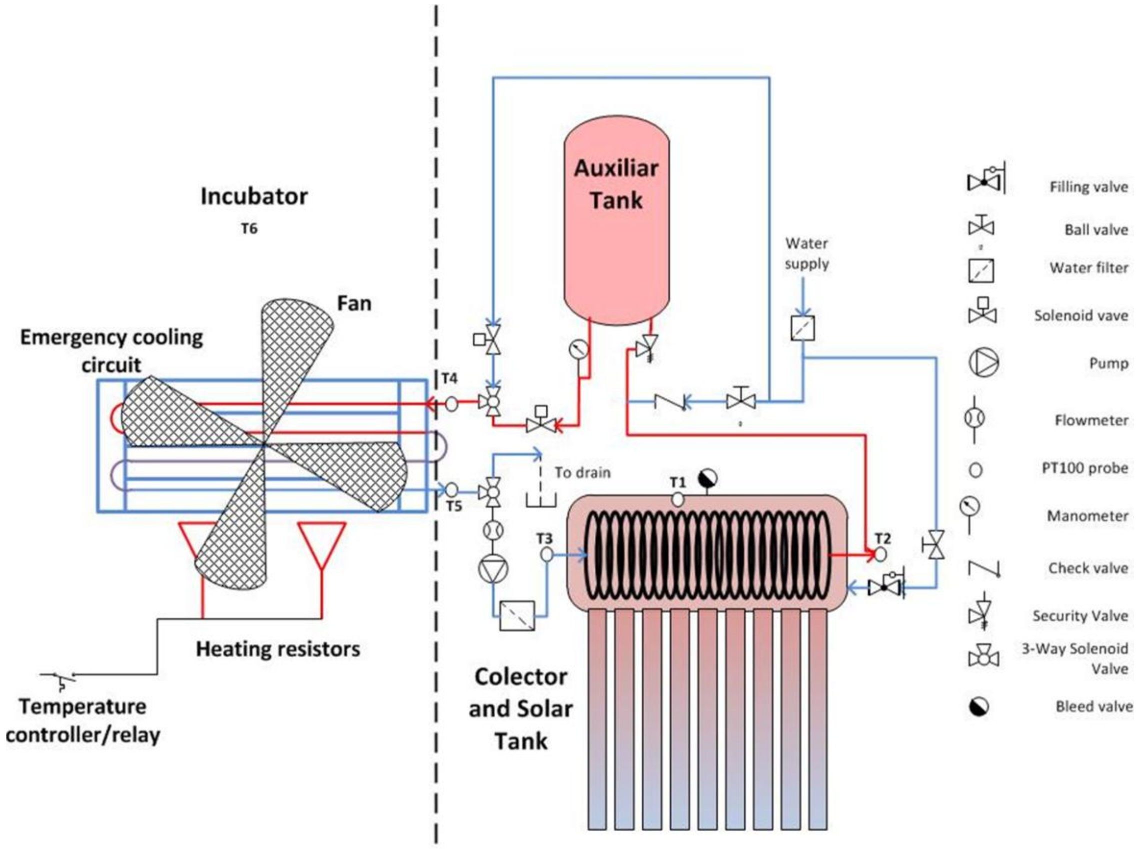

Figure 1 Left side of the figure corresponds to the factory design of the commercial incubator. The heating resistors have a total power of 1.7 kW. The right side of the figure shows the hydraulic diagram of the solar heating system and the coupling to the commercial incubator.

The emergency cooling system was modified to be fed with hot water from the solar panel, allowing for the combined electrical and solar heating of the incubator and the circulation of water in a closed circuit (Figure 1).

The solar collector (Solar Electric SD-165HE, Solar Electric España, Madrid, Spain) has 15 evacuated tubes, 0.99 m^2 of absorbing area and a 163 L total water capacity, accounting for a 130 L deposit. According to the manufacturer's information, the performance, η, of the solar collector is indicated by Equation (1. The system includes a secondary deposit with a capacity of 80-L, which can be used in series or can be bypassed.

The thermal performance of the collector based on the manufacturer's data is:

$$\eta = -23.06 \cdot T_0^2 - 0.170 \cdot T_0 + 0.645 \quad \textbf{(1)}$$

where $\boldsymbol{T_0=(T_1-T_e)/G}$. T_1(℃) and T_e (℃) are the mean temperature of the collector and the environmental temperature, respectively. G is the average solar radiation (W/m^2) during sunshine hours.

Six Pt-100 sensors monitored the temperatures at the inlet (T_3), the outlet (T_2), at the solar collector tank (T_1), at the heat exchanger inlet (T_4) and outlet (T_5), and at the incubator (T_6). All Pt-100 sensors were connected to a 6-channel Resistance Temperature Detector (RTD) sensor input module (model ICP 7015, ICP DAS CO., LTD, Taiwan, R.O.C.) that digitalizes and sends this information to the control PC. The pump (DAB model VSA 35/130, Dab Pumps Spa, Padova, Italy) and the solenoid valves (Solar Orkli models 30212200 and 40212200, Solar Orkli S. Coop, Ordizia, Spain) were controlled by a PC through a relay module with 8 channels (model ADAM 4068, Advantech Co., Beijing, China) using TestPoint® v7 software (Capital Equipment Corporation, Massachusetts, USA).

2.3 Experimental design

Five experiments were carried out over three years (Table 1). The first trials corresponded to the supervision of two standard incubations to analyze the base-truth values of the thermal variation during the first phase of the incubation with eggs turning (21.4 and 21.1 days). The rest of incubation, until 23 days (corresponding to the hatching phase in a hatcher) was not supervised. Experiments 1 and 2 incorporated the solar circuit to evaluate the stability of heat control, while the last experiment (hybrid strategy, Experiment 3) verified the stability of the solar-electric hybrid control of the incubator at different loads.

Table 1 Summary of the experiments

	Standard Incubations		Experiment 1	Experiment 2	Experiment 3
	1	2	Solar unloaded	Hybrid unloaded	Hybrid 69% loaded*
Start date	14/04/14	10/05/13	10/07/13	19/07/13	16/06/14
Experiment duration, days	21.4	21.1	7	5	1.5
Eggs, n	9020	9072	-	-	-
Hatchability, %	70.5	74.1	-	-	-

Note: *90L of water in bottles that corresponds to the content of water of 6260 partridge's eggs (69% of the maximum capacity of the incubator)

2.4 Evaluation of the thermal stability

Following Eckmann and Ruelle (1985), the best way to reconstruct the PS from a time series is using time delays. The technique is as follows. Let there be a time series (t(k), y(k)) with a fixed time step. Then, we can construct the N-dimensional PS (Y_1, Y_2,…,Y_N) from the time series by Y_i=y(k +Δ_i) with i =1, 2,…, N and Δ_1=0, where each Δi defines a time delay given by td_i=t (k+Δ_i)−t (k). Note that the time delay does not depend on step k because the time step is fixed. That is, we represent the time series versus itself delayed in time. The value of the optimal time delays is obtained by heuristics, 9 in our case.

Figure 2 shows the PS representation of the incubator temperature for Experiment 2. A polygon including the majority of data (>90%) was selected for every dataset, and its area was determined as an indicator of temperature stability (Villarroel et al., 2011). For Experiment 2, the only experiment that has a significant number of observations for solar and electric contribution; this area selection was performed for each period (solar vs. electric contribution). Previous works (Jiménez-Ariza et al., 2014) have shown that the area in a PS diagram is appropriate for the diagnosis of temperature under transport conditions for long and short container shipping. In this work, it has been used as an estimator of temperature stability during egg incubation.

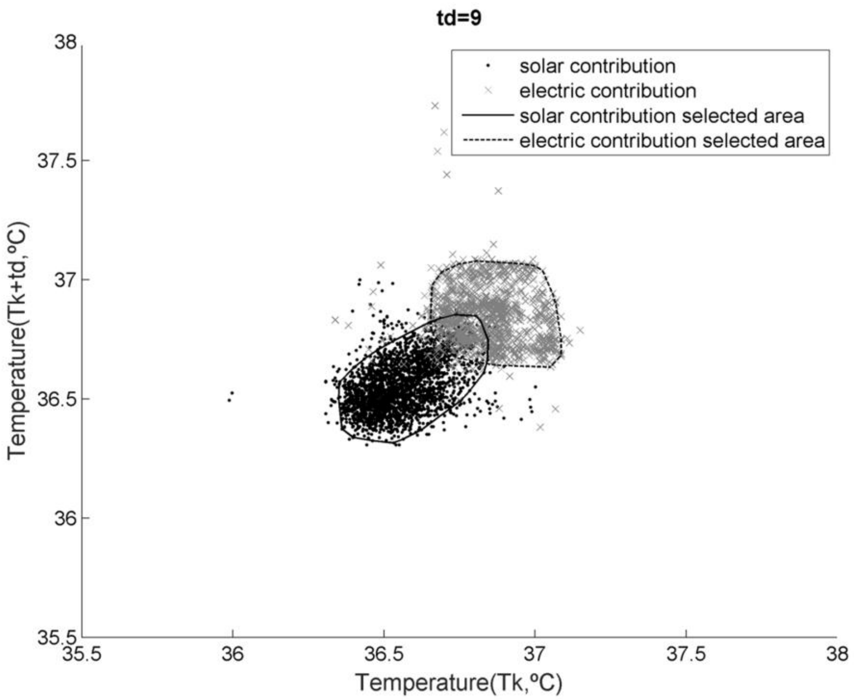

Figure 2 Phase space representation of the incubator temperature for Experiment 2.

2.5 Solar and electric contribution

The electric energy contribution (kWh) is computed based on the total time (hours) that electrical resistors are switched on and on their rated power (1700 kW). Information about the status of the electrical heating resistors is only available for the experiment with hybrid control and the incubator loaded at 69% (Experiment 3). Thus, for the other experiments, the status of the resistors was estimated based on the incubator temperature derivative by assuming that when the resistors are switched, this derivative is positive.

The solar contribution was computed based on the experimental data recorded in the thermal circuit. The measured water flow ($\dot{V}_w$) is 0.0025 m^3/min when the pump is activated and the density (ρ_w) of the water at 45 ℃ is 990.22 kg/m^3. The water mass flow rate, $\dot{m}_w$, was calculated from Equation (2:

$$\dot{m}_w = \rho_w \cdot \dot{V}_w \qquad \textbf{(2)}$$

The heat gain rate ($\dot{Q}$) was computed using Equation (3:

$$\dot{Q} = \dot{m}_w \cdot Cp \cdot \Delta T \qquad \textbf{(3)}$$

The specific heat capacity (C_p) of the water at 45 ℃ is 4.180 kJ/kg/K. The cumulative heat gain (Q) from start up to any time was obtained (Equation (4) by integrating the total useful heat gain for the period (Enibe, 2002):

$$Q = \int_0^t \dot{Q} \cdot dt = \int_0^t \dot{m}_w \cdot C_p \cdot \Delta T \cdot dt \qquad \textbf{(4)}$$

The total mass of water measured by the flowmeter at the end of the day (M_w) was used instead of the water mass flow ($\dot{m}_w$) as Equation 5:

$$Q = M_w \int_0^t C_p \cdot \Delta T \cdot dt \qquad \textbf{(5)}$$

The heat gain in the solar panel was estimated by the temperature difference between the outlet and the inlet (T_3-T_2). On the other hand, the heat transferred from the exchanger into the incubator was computed based on the corresponding temperature differences (T_5 -T_4).

The MATLAB function trapz(X,Y) computes an approximation of the integral of Y via the trapezoidal method.

The fact that the heat accumulation in the auxiliary tank (80 L) affects the final heat transfer has to be taken into account. This device is intended to mitigate the high dynamic changes of the solar contribution (i.e., fast shading of the panel). Moreover, surplus solar energy can be accumulated in this extra water volume, allowing for the extension of incubator heating when solar radiation decreases, as shown in Figure 4 (22:00 h to 0:00 h).

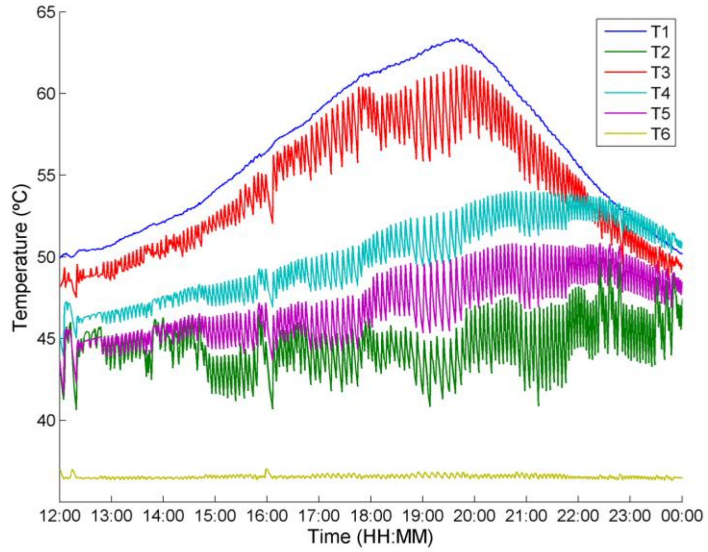

Figure 3 Temperature evolution during the solar contribution period for Experiment 1. Temperature monitoring at five locations of the solar circuit and the incubator

Solar radiation data were obtained from a weather station located at 40°30'08" N, 3°58'01" W and 653 m above sea level at a distance of 12 km from the farm (40° 34′ 42″ N, 4° 00′ 07″ O and 880 m above sea level). The total solar radiation per day in this location was in the range of 5695 MJ/m^2 (January 2014) and 27768 (June 2014) MJ/m^2.

3 Results

3.1 Temperature dynamics under electric and solar heating

The supervised incubation period covered the first 21 days where eggs were turned 45° from the vertical line to 135° every one hour. Figure 5 shows the thermal dynamics of two standard incubations (21.4 and 21.1 days). The average temperatures inside the incubator were 36.9℃ (ranging from 36.4℃ to 37.7℃) and 36.7℃ (ranging from 36.1℃ to 37.3℃), respectively, while the average temperatures inside the building were 16.4℃ and 13.5℃ (ranging from 8.5℃ to 26.5℃). The thermal heating in both cases was fully electric. Though according the manufacturer data, the incubator design was developed considering a building temperature of 20℃, the wide range of variation in the room temperature does not seem to affect the thermal stability inside the incubator.

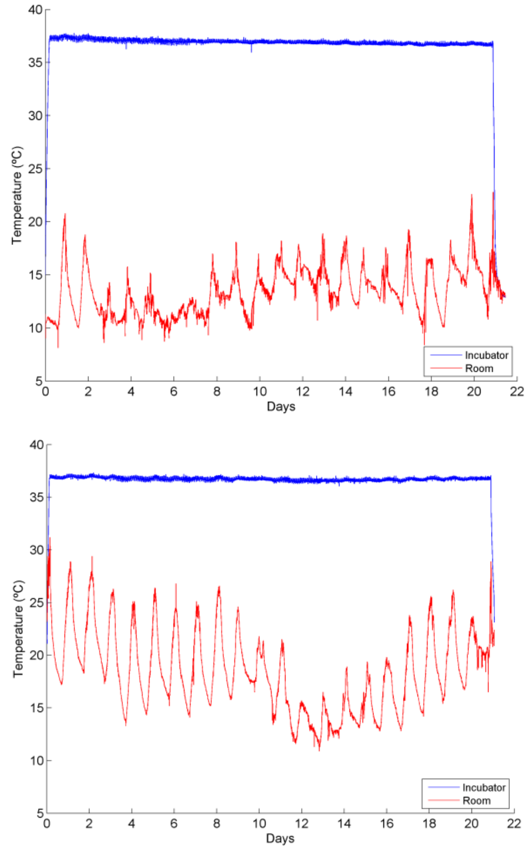

Figure 5 Thermal characterization of the standard incubations: 21.4 days, 9020 eggs, and 21.1 days, 9072 eggs.

Figure 6 summarizes the average temperature and corresponding standard deviation inside the incubator and room for electric and solar heating. A very stable temperature in the incubator is found regardless of the type of heating, solar or electric.

Table 2 Summary of the incubator and room temperatures during the tests

Test	Period indicated on Figure 5, Figure 7 and Figure 9	Incubator Temperature, ℃			Room Temperature, ℃		
		Mean/Std	Max	Min	Mean/Std	Max	Min
Standard Incubation 1		36.9 / 0.4	37.7	36.4	13.4 / 3.6	22.2	8.5
Standard Incubation 2		36.7 / 0.3	37.3	36.1	17.9 / 6.1	26.5	11.5
Experiment 1: Solar heating unloaded incubator	1	36.0 / 0.1	36.2	35.6	29.6 / 1.7	31.6	26.0
	2	36.1 / 0.1	36.4	35.8	31.0 / 2.5	34.2	26.4
	3	36.0 / 0.1	36.2	35.8	28.9 / 1.5	30.7	26.0
	4	36.0 / 0.1	36.3	35.8	29.7 / 2.0	32.1	26.2
	5	36.0 / 0.1	36.4	35.8	30.6 / 1.7	32.9	27.2
	6	36.1 / 0.2	36.5	35.8	31.4 / 2.6	34.6	27.0
	7	36.1 / 0.2	36.5	35.8	31.9 / 2.8	35.5	26.7
Experiment 2: Hybrid system unloaded incubator	1	36.6 / 0.1	36.9	36.3	33.2 / 2.2	36.2	29.0
	A	36.8 / 0.1	37.2	36.6	27.3 / 0.9	29.2	25.5
	2	36.6 / 0.1	37.0	36.3	32.2 / 1.9	34.7	28.9
	B	36.8 / 0.1	37.1	36.6	26.4 / 1.3	29.0	24.8
	3	36.5 / 0.1	36.8	36.3	31.7 / 1.6	33.7	28.3
	4	36.6 / 0.1	36.8	36.3	31.9 / 2.1	34.5	28.2
	5	36.6 / 0.1	36.9	36.3	32.0 / 2.2	35.1	28.1
Experiment 3: Hybrid system loaded incubator, 69%	A	36.9 / 0.1	37.3	36.6	22.4 / 1.5	26.9	19.9
	1	36.5 / 0.2	37.5	34.8	27.7 / 1.2	30.2	24.7
	B	36.9 / 0.1	37.3	36.5	22.7 / 1.4	26.6	20.8

Differences on average temperatures between electric and solar heating are attributable to the calibration of the sensors commanding each heating system.

Figure 6 shows the temperatures recorded in the incubator and in the solar circuit for a five-day period with an empty incubator. There was a two-day period where the hybrid system was successfully working, before accidental disconnection of the electrical heating. During times of sunshine, where solar irradiance is enough to heat the water in the collector to above 50℃, the temperature inside the incubator was well maintained by the solar heating system (periods 1, 2, 3, 4 and 5) regardless of the electric contribution.

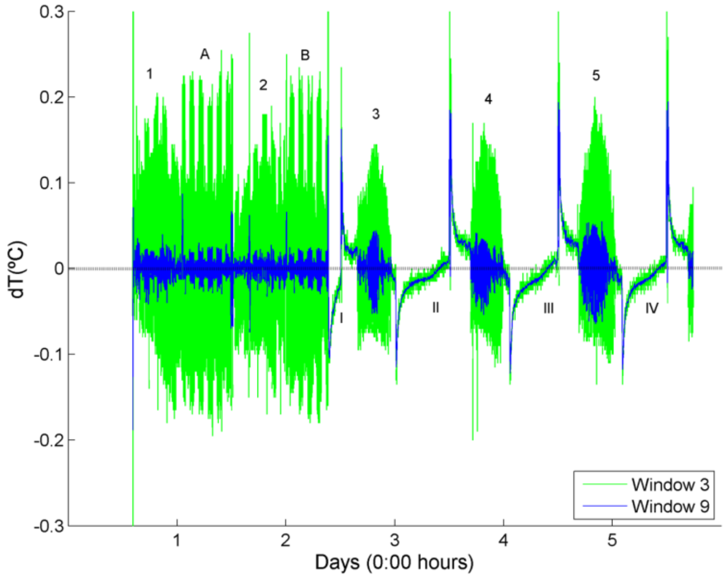

Figure 8 Representation of the smoothed derivative of the temperature inside the incubator using the Savitzky-Golay algorithm for windows of three and nine elements

Figure 9 provides some features regarding the variability of the temperature inside the incubator in Experiment 2, the hybrid system unloaded incubator. The temperature derivative is smoothed by application of the Savitzky-Golay algorithm for window sizes of three and nine elements. In this figure, the periods corresponding to solar heating (1, 2, 3, 4 and 5) are addressed and the intervals for electric heating are highlighted (A, and B). There were also four periods without solar heating, where the electric resistors are deactivated (I, II, III and IV). The main feature points to different dynamics of solar and electric heating, the latter is being much more predictable than the former. It can also be highlighted that the temperature derivative inside the incubator during solar heating increased when the electric heating was not active at night (3, 4 and 5) compared to 1 and 2. The naked eye can observe a significant effect with larger thermal disturbances than for hybrid control.

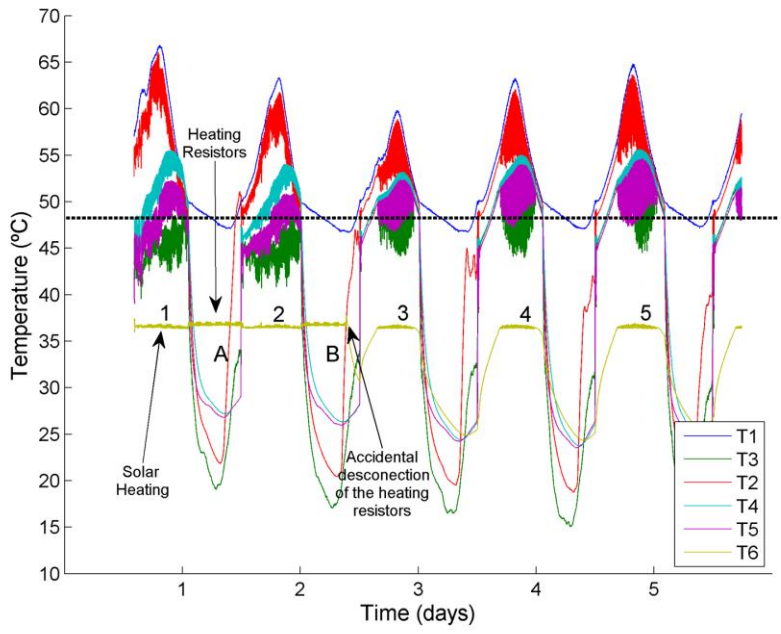

Figure 7 Experiment 2 temperatures on the solar circuit and inside the incubator. During the 2nd night (period B) the electrical power of the incubator was accidentally disconnected.

Figure 7 shows the temperature records in the incubator and in the solar circuit for a 1.5 day period with a loaded incubator (90 L of water, equivalent to 69% of the full load capacity). In this case, the hybrid control is set. An interval with solar heating is found (1) with two corresponding periods of electric heating (A and B). The effect of the thermal inertia of the load can be derived by the larger interval the heating circuit was active in. Again, the average temperature with solar heating (36.5℃) was below that of electric heating (36.9℃). The total solar contribution reached 31.5 % (453 min).

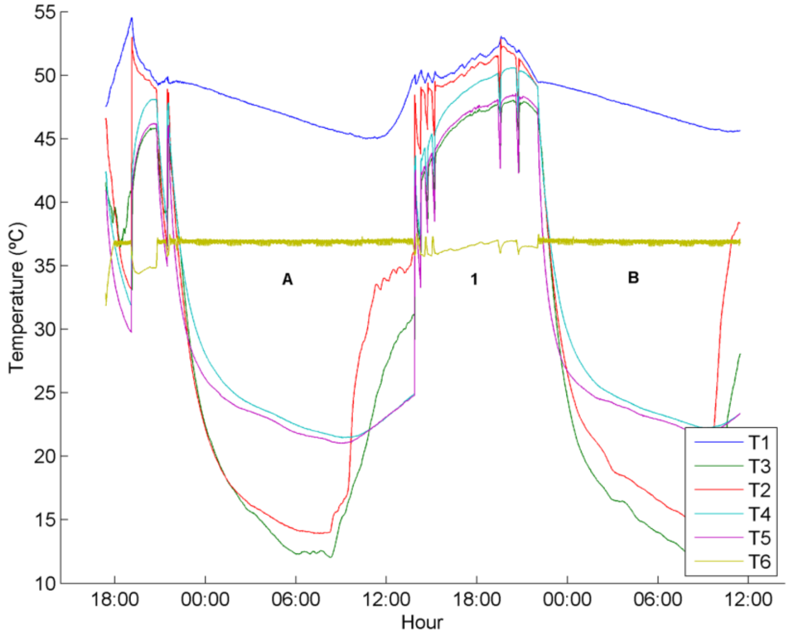

Figure 10 Experiment 3 temperatures. ‘A’ and ‘B’ are periods with electrical heating. During the ‘A’ period, there is solar heating.

Figure 8 displays the thermal stability in all five experiments (2 commercial incubations and 3 solar tests) based on the PS theory. The thermal stability is evaluated in terms of the polygon area (Villarroel et al., 2011), the lower the area covered by the data, the higher the thermal stability. Considering the region that gathers 90% of the points for each experiment, the area obtained for the solar experiments (experiments 1 to 3) is among 27% to 35% of that of commercial incubations, which refers to the high stability of the temperature. The experiment with the loaded incubator (Experiment 3) and full hybrid control (in black in Figure 8) fell within the range of commercial incubations (red and yellow in the same Figure).

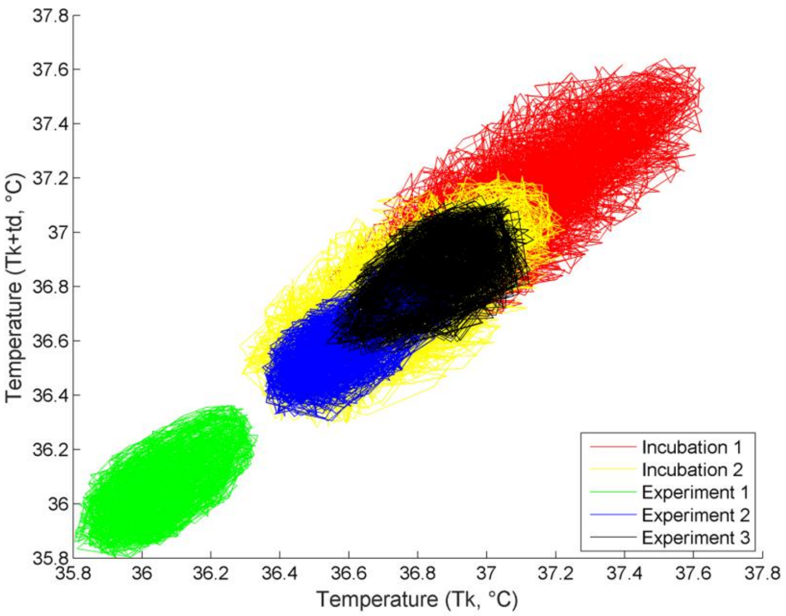

Figure 11 Phase space diagram of the 5 tests carried out. Standard incubations are indicated by the diagrams with largest areas

The area containing the majority of points is related to the thermal stability, its length is related to the temperature range and its width to the variation frequency. This result can be seen in Figure 2, where, for the solar contribution, the temperature range was wider, but the frequency of the variations was lower. For the electric contribution period, the frequency of the temperature variation was higher, but the variation range was lower.

3.2 Analysis of the electrical and solar contribution and efficiency

As indicated before, the electrical contribution was computed on the basis of resistor activation. Table 4 shows the electrical heating period compared to the true activation, which was between 41.5% and 51.5%. The comparison between the real status (measured) of the heating resistors (ON/OFF) and the estimation (calculated as described previously) for available data of the Experiment 3, allows to estimate the resistors activation time for the other experiments and incubations. In the two standard incubations, the electrical heating period agrees with the total duration of the process. The mean of the fraction of time in which the resistors were actually activated was 41.68% during the standard incubations, yielding 210 h for a 21 days incubation period. Thus, the total electrical consumption of the heating resistor during standard incubation was 357 kWh (1285.2 MJ).

Table 3 Computation of the period in which the heating resistors are activated

	Period indicated on Figure 5 and Figure 7	Electrical heating period, min	Resistors active (measured time, min)	Resistors active (estimated time, min)	Resistors active (corrected estimation time, min)	Fraction of time of resistors activated, %
Standard Incubation 1		29 622	-	14 309	12 294	41.50
Standard Incubation 2		29 841	-	14 538	12 491	41.86
Experiment 2: Hybrid system unloaded incubator	A	562	-	292	251	44.64
	B	448	-	226	194	43.34
Experiment 3: incubator at 69% load	A	768	415	473	406	52.92
	B	547	220	275	236	43.19

The net production of CO_2 in the energetic sector of Spain was 259 g/kWh in the year 2014 (Sources: UNESA, REE, IDAE, CNMC and MAGRAMA[2]). Therefore, each standard incubation poured into the air at an equivalent of 92.5 kg of CO_2. Figure 12 shows the thermal evolution of an empty incubator with 100% solar heating. The maximum temperature inside the solar collector always stayed below 70 ℃.

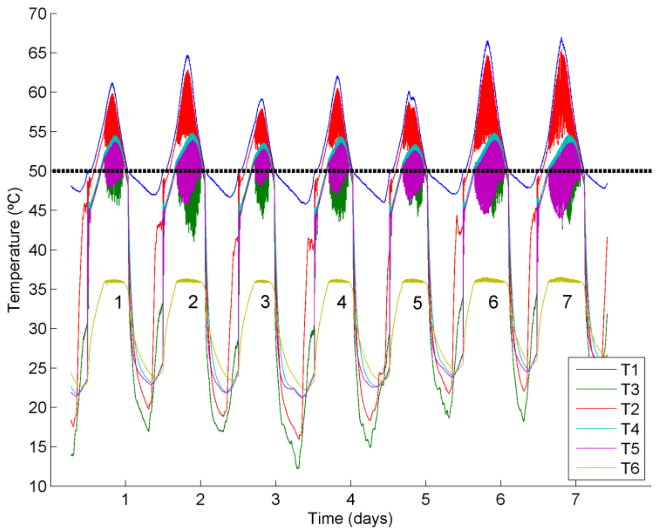

Figure 12 Experiment 1 temperatures on the solar circuit and inside the incubator**.** In the last two days of the experiment, there was enough heat accumulated to extend the use of hot water

Table 5 reflects the daily duration of solar heating, which ranged from 31.5% to 60.4% (between 453 and 870 min). Full solar heating refers to the period where the temperature was in the range of the set-point temperature. The total solar contribution is the sum of full solar heating and the time where solar energy is being used to increase the temperature to the set point temperature. The described effect on the differences of set-point temperatures for solar (between 36.0 ℃ and 36.1 ℃) and electric heating (ranging from 36.8 ℃ to 36.7 ℃) can be observed in this experiment.

Table 5 Solar contribution during experiments 1, 2 and 3

	Period indicated on Figure 5, Figure 7, and Figure 9	Full solar control, min	Total solar contribution, min	Total solar contribution, % per day
Experiment 1: Solar heating unloaded incubator	1	414	714	49.6
	2	519	765	53.1
	3	341	650	45.2
	4	400	673	46.7
	5	427	682	47.4
	6	629	838	58.2
	7	642	870	60.4
Experiment 2: Hybrid system unloaded incubator	1	647	647	45.0
	2	713	713	49.5
	3	479	708	49.2
	4	515	781	54.2
	5	589	833	57.9
Experiment 3: Hybrid system loaded incubator, 69%	1	453	453	31.5

Taking into account that a standard incubation (with the features described above) consumes an average of 1285.2 MJ, using a hybrid solar-electrical heated incubator can save between 404.8 MJ and 776.3 MJ of electric energy.

The efficiency of the collector was estimated (tems and industrial processes).) from the ratio between the heat gain inside the collector (Equation (5), kWh) and the mean solar radiation for this location and this period of the year (kWh). This value was of the same order as that computed from the theoretical curve supplied by the collector manufacturer (Equation (1). In almost all cases, the estimated efficiency was higher than the theoretical performance (approximately 60%). The evacuated tube collectors showed good performance for intermediate temperature applications (air conditioning systems and industrial processes).

[2] UNESA: Asociación Española de la Industria Eléctrica (Spanish association of electric industry) ;REE: Red Eléctrica de España (Spanish electricity distribution network); IDAE: Instituto para la Diversificación y Ahorro de la Energía (Institute for the diversification and energy saving); CNMC: Comisión Nacional de Mercado y Comercio (Trade and market national comission); MAGRAMA: Ministerio de Agricultura, Alimentación y Medio Ambiente de España (Ministry of agriculture, food and environment of Spain)

Table 6 Analysis of the temperature, heat and performance of the solar heating circuit. The average collector tank and the average environmental temperatures (T_1 and T_e, respectively) are computed for sunshine periods

Experiment	Period indicated on Figure 5, Figure 7 and Figure 9	T_1, ℃	T_e, ℃	M_w, kg	Heat transferred into incubator, kWh	Heat gain in collector, kWh	Computed performance of solar collector, %
Experiment 1: Solar contribution unloaded incubator	1	55.4	30.26	1255	1.60	5.47	66.56
	2	56.8	32.11	1098	1.75	7.03	85.51
	3	54.6	30.12	1271	1.38	5.48	66.65
	4	55.8	33.11	1100	1.48	5.79	70.51
	5	55.1	35.60	1047	1.43	4.74	57.69
	6	57.6	35.29	1037	1.85	6.36	77.42
	7	57.8	34.56	1012	1.88	6.88	83.75
Experiment 2: Hybrid System unloaded incubator	1	60.3	35.19	352	1.40	5.16	62.74
	2	56.46	34.76	565	1.93	6.42	78.17
	3	54.59	34.14	1104	1.34	4.19	51.03
	4	55.92	33.81	1237	1.72	5.19	63.22
	5	56.61	35.57	1258	1.96	5.43	66.05
Experiment 3: Hybrid system loaded incubator	1	51.22	32.03	1065	2.22	3.93	44.37

4 Discussion

In previous studies, such as those by Gomez-de-Travecedo et al. (2014), González-Redondo et al. (2012) and Mourão et al. (2010), the set-point temperature inside the incubator was 1℃ higher (37.8℃) than the temperatures recorded in the standard incubations described in this study. The set-point value is a matter of expert decision and may vary from place to place. Mean hatchability of the farm (54%) is comparable with the obtained on the aforementioned references (ranging from 41% to 53%) but clearly lower than the obtained by Mourão et al. (2010) (80%). A possible factor explaining part of this difference is the previous storage of the eggs, identified as relevant by Gomez-de-Travecedo et al. (2014). The higher hatchability observed in small batches of incubation eggs incubated by the farm (corresponding to incubations not monitored) suggests the occurrence of this storage influence.

The temperature range for the hybrid system was narrower (0.9℃) than that for the commercial equipment under exclusive electric heating (1.3℃) and also compared to other studies described in the literature. For example, Bolaji (2008) used a temperature range of 2.5℃, while the studies reported by Kuye (2008) and Kisaalita et al. (2010) did not include incubation monitoring. It has to be said that this higher temperature stability should be attributable to the room temperature, which is closer to the set-point temperature for the incubator during operation. Comparing electrical to solar heating periods at the hybrid control experiments shows narrower temperature ranges for the electric heating periods. The solar contribution, with a slower response time, is nevertheless more stable when operating regime is reached and thus it will benefit from a fuzzy control system that allows better temperature control as well as energy savings.

The potential energy savings of the hybrid solar system (404.8 MJ and 776.3 MJ per incubation in our system) have not been estimated in the references. Comparing the temperature of the heat transfer fluid at the collector outlet (up to 67℃ in our system), Bolaji (2008) reports temperatures on the collector outlet of up to 85℃ using a solar air heating flat plate collector with an effective area of 0.66 m^2, while Enibe (2002) obtains temperatures of 45℃ for the outlet air using a flat plate collector with an effective area of 1.34 m^2.

Nevertheless, the actual solar energy transferred to the incubator is low compared to the energy captured in the collector, as derived from reusing a circuit designed for cooling and not for heating. Moreover, the volume of water in the solar circuit can be further optimized to avoid storing an excessive amount of solar energy.

However, the stability of the temperature inside the incubator and the long period of use of the solar collector (up to 61.8%) suggest this possibility to be a true economic potential at our latitudes.

5 Conclusions

The incubation of the eggs of game species (i.e., partridge) is a quasi-professional activity that makes use of small scale commercial incubators (9000 partridge eggs per incubation). In this paper, a 8 m^3 incubator has been adapted to accomplish solar and electric heating in a hybrid strategy to decrease the actual energy requirements by 357 kWh (1285.2 MJ) over 20-21 days.

The solar contribution can account for 42% of the energy demands in our geographical conditions for a set-point temperature inside the incubator of 36.8℃ without challenging the temperature stability. The PS theory could be a useful tool to quantitatively assess the stability of the temperature during incubations. Hybrid control incubations are expected to show comparable temperature stability to fully electric heating.

The use of solar heating on commercial incubations has demonstrated its potential as temperature stability achieved is comparable to conventional energy sources (electric). The introduction of solar heating systems would not only save energy and prevents some of the negative effects of power outages but also would allow the use of smaller cheaper incubators that enable a better management of the egg storage prior to incubation.

The performance of the solar collector (44%-85%), according to the thermodynamic computations, stayed within the range reported by the manufacturer under our conditions (61%). The installation of a limited number of sensors, with the incorporation of physical models, allowed for the precise monitoring of the process of egg incubation with large energy efficiency. The effect of control strategies, such as fuzzy controls, should be analyzed in the future.

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