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Research article

Smart agriculture through using cost-effective and high-efficiency solar drying

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ABSTRACT

Background: Challenges must be handled in an integrated manner when addressing food security and climate change. More efficient designs for food production systems, as well as their logistics, are needed in order to increase food production and to reduce emissions intensity. Specifically, any enhancements done on this purpose would contribute to mitigating climate change. Five important dimensions are being considered in smart agriculture: food security, availability, accessibility, utilization, and stability.

Scope and approach: Food supply-demand chain can seriously be effected by uncontrolled population growth. Thus, any perspective to solve these uncontrolled conditions can have a positive impact. Especially giving emphasis on reduction of food losses via expoloring various ways of production, or increasing productivity, or ensuring food security are effective ways for solutions. For example, the use of solar drying for agricultural, marine or meat products is very important for preservation, thus minimizing food losses. However, traditional sun drying is a relatively slow process. Also, the product quality worsens due to several factors: microorganism growth, enzymatic reactions, insect infestations. It is known that utilizing solar energy involves several factors that need attention. Thus, a lot of effort is directed toward improving solar energy technology for drying processes.

Key findings and conclusion: This study presents a smart agriculture design for drying using low cost and highly-efficient solar selective absorber. The system is based on an air heating flat plate solar absorber. Levelized cost of heat (LCOH) for the prototype using solar renewable energy is calculated and compared with the fossil fuel energy sources; natural gas, electricity, and liquified petroleum gas (LPG). In addition; a comparison of the costs for air collectors using various selective absorbers; unglazed or glazed, is presented. It is shown that solar energy, in the long run, will be more advantageous compared to fossil fuels.

1. Introduction

Economical aspects and technological developments are important for massive production and a thorough investigation is necessary. However, environmental and social aspects are the other important issues that need to be handled carefully. Especially, with the growing interest in corporate sustainability, recognizing and using greener systems are becoming a priority [1].

Since energy is one of the most demanded needs and this demand continuously grows, a lot of various researches on energy in the literature exist. Especially, many various investigations are taking place on renewable energy technologies since going greener is also another important aspect to realize [1, 2, 3]. So, solar energy is one important resource that can overcome sustainability requirements in energy. Thus, studies on numerous applications of solar energy are continuously taking place in different areas such as; cooking, space heating/cooling, low-temperature industrial fluids heating, drying agriculture, etc. [4, 5]. Not only technological developments for systems using solar energy are investigated but also performance and economic analysis of these systems were as well investigated. In these studies, it was presented that the energy balance is positive and that energy payback times are in the order of several years to two decades depending on which type of conventional method it was being compared [2, 4, 5, 6, 7, 8, 9].

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In the last years, not only economical and technological aspects were the only two sound matters to be analyzed comprehensively, but also environmental and social aspects. The latter two aspects started to become very important in the last decade and their importance is continuingly increasing. A comprehensive life cycle assessment (LCA) of the system under study can give the required ecological information [10, 11]. Process stages like raw material extraction, transportation, manufacturing, waste management, etc. can be chosen to set the boundaries in order to define environmental burdens accordingly [10].

A full LCA was taken into account in previous research conducted by the authors for the selective surface used in the absorber investigated in this study [11]. The authors showed in their study that producing energy from the thermal collectors specifically using the selective surface produced with a continuous system would have much lower energy demands, greenhouse gas emissions (lower carbon emissions), and environmental impact compared to producing the same amount of energy using conventional resources [11]. This analysis can be crucial to be used as an enabling condition to solve the challenge that the solar thermal markets face today; since economic pressure keeps rising from other renewable technologies. The present study aims to address this issue, by giving a special focus to the economic aspects of solar thermal systems.

To have a more reliable and efficient living media, become more and more important. Demands toward a more efficient kind of living style become a priority. For this sustainable management takes into account using systems comprised of renewable energy or hybrid systems. Through these systems reduction of environmental burdens, social burdens, and economical burdens can be controlled and designed [1]. For example, in agriculture, one of the highest-burden is generated via energy consumption during food drying. Solar thermal collectors can be one of the solutions that can be used to cover a significant portion of this energy demand.

Since solar radiation can be transformed as internal energy. Thus once can treat solar collectors as heat exchangers [12]. The process can be summarized as: the transform is realized as a simple absorption process where the solar radiation is absorbed by a collector surface and then is converted to heat. The absorbed heat by the collector is transferred to transport fluid (usually air, water or oil). Last, the fluid with higher energy is used for various thermal applications via conduction and convection mechanisms.

There are mainly two important producers of solar selective coatings in the European market: Alanod and Almeco-Tinox. The main problem for efficient solar collectors is the cost. However, they have high absorption (α_s) of the incident radiation and low heat emission (ε_T). This high cost is caused by the deposition methods used during manufacturing that require high vacuum installation and deposition of many layers in order to get good adhesion properties, high absorption, low heat emission, and durability. The development of low cost and efficient solar thermal collectors could help the market to reach a critical mass. Considering the components of a solar collector (glazing, absorber, heat insulation, casing), the solar absorber is drastically influencing the collectors' efficiency as well as the cost.

The long-term stability of the solar absorber materials should be assessed as the manifold micro-climatic conditions can significantly deteriorate the material's performance. The minimum lifetime of a solar thermal system is estimated to be 20–25 years. Thus, the materials should maintain optical performance within this period.

The reality is that even though much research has been performed previously in the field of solar energy towards performance and economic analysis, there is still much improvement that needs to be made. For this purpose, an economic analysis of a prototype that uses the cost-effective and high-efficiency low carbon steel selective solar absorber manufactured by Selektif Teknoloji was conducted and the results are presented in this study. The system of interest in this study is manufactured for the first time as a prototype to dry fresh apple. For this goal, a series of experiments were conducted repeatedly at different climate conditions in order to carry out the feasibility studies.

2. Results

Selective surfaces are one of the most important parts of high-efficiency solar collectors. Not only for commercial applications but also residental applications, a selective absorber should have good optical properties, low cost, good thermal stability, and ease of large-scale production [13, 14, 15]. With knowing the importance of these properties, a new method was developed by Selektif Technology Co. Inc. for the selective surface coating on the low carbon steel via continuous roll to roll production of [16]. Spectroscopic and the stability of the selective surfaces for bare coatings and selective surface coating are measured and presented in Figures 1 and 2, respectively.

The main characteristic of spectrally selective coatings for solar absorbers is the difference between their solar absorbance and thermal emittance. While high solar absorbance, with α-values of 0.94–0.95, are relatively easy to achieve, more effort needs to be devoted to achieving low emittance (ε) of coatings with high stability against environmental conditions. The protective selective coating contains a functionalized composite application by coil coating [16]. Thus, absorbers holding higher emission and low emittance values are incorporated into the design to be used in solar air collectors to generate more energy. This enhancement is incorporated via efficiency.

The thermal stability of selective surfaces used in the manufacturing of the prototype is measured and accredited by Institut für Solartechnik (SPF), Rapperswil, CH in 2011. Changes in optical properties at 280 °C are given in Table 1. As can be seen from Table 1, stability against humidity is tested after an anti-corrosion coating over the selective surface using coil coating.

Further stability tests were carried out using a harsher environment (3% NaCl solution) than the ambient. To see the effect of protected selective surfaces, both non-protective and protective selective surfaces were soaked in the salty environment for a period of 60 h. Figure 3a and 3b show the electron microscopy images of non-protected and protected selective surfaces, respectively. As a result, no fractures were observed on the coating having protected selective surface after 60h of being soaked in a 3% NaCl solution. On the other hand, a non-protective surface showed cracks as is observed in Figure 3a. It is worth mentioning here that the more stable the absorber is the more cost-effective it will be on the process for the long-term use. This positive effect of the absorber is incorporated by considering a low maintenance costs value.

Other advantages of the design in interest are the low investment cost, low operation cost and low environmental impact [10, 16, 17, 18]. A fully automated process may also facilitate smart fabrications.

Dehydrating temperatures for food that is required for quality as raw once dried, are typically between 40-50 °C. Solar air collector reaches this temperature easily.

For the purpose of the study, a solar drying prototype system comprising all the above-mentioned advantageous was designed and manufactured. The picture of the prototype system can be seen in Figure 4. In this pilot system, a channeled duct in the air collectors was chosen. It provided more efficient air heating then the conventional pipes [19].

The designed system consisted of four main parts:

1. a three-level low carbon steel oven embedded in hardboard (as seen in Figure 4)
2. selective surface made with roll to roll technology
3. porous oven plates in each level
4. data output control unit

With the goal being to dehydrate the fruits in this study, the air was used as the heat transport medium. This type of collector is the simplest type and used for low-temperature applications [19]. The transfer of solar energy to the transport medium occurs in the duct. The duct is the volume where air flowing from inlet to outlet is in contact with the

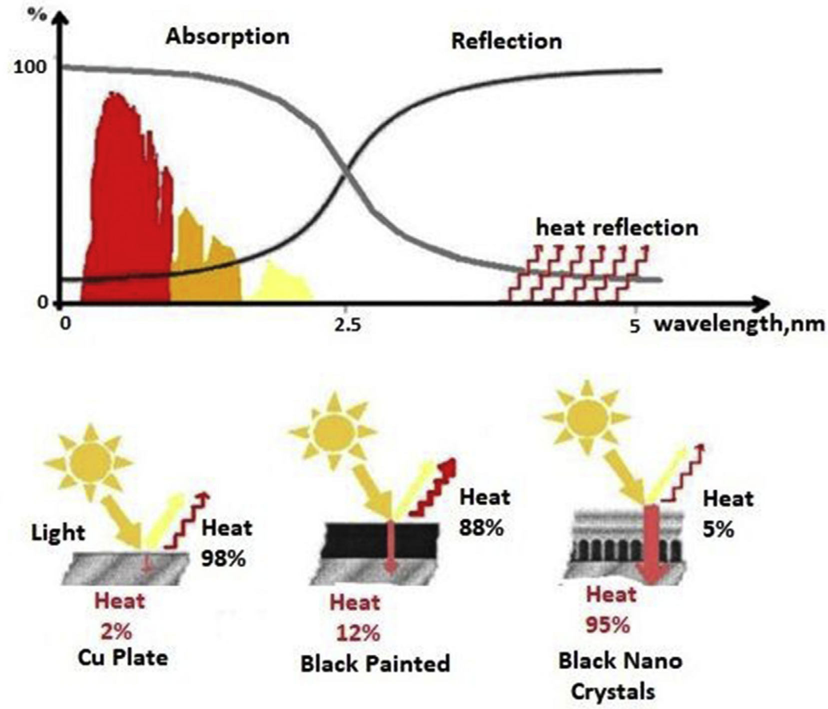

Figure 1. Spectral properties of selective surfaces.

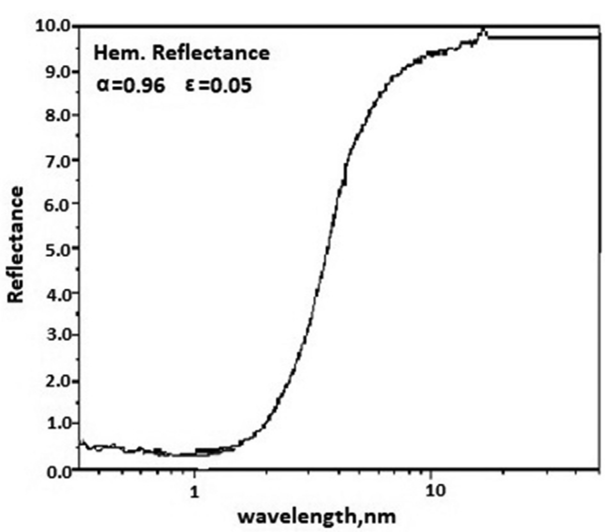

Figure 2. Reflection spectrum of SELEKTIF®.

absorber. While heat transfer occurs between air and absorber, all other surfaces except glazing were insulated to prevent heat loss (Figure 4).

One of our goals is to reduce the cost of the prototype in order to be used in rural areas. Thus, priority is given to the operational cost rather than investment cost. To achieve operational cost reduction, the natural heat transfer type was selected in the design stage. As well as, simple to use and easy to control, maintenance-free systems are the properties that are demanded by the villagers, thus these objectives were also taken into considerations in developing the prototype dryer [20]. However, there are drawbacks in these types of flat plate solar air heaters due to properties of air and design of the oven plates used in drying. But this cost minimization was not the only reason to select such a process type, also the other important initiating force was the need to find a solution to major issues regarding the performance of flat plate solar air heaters. These drawbacks are due to the properties of air. Reduced heat transfer properties of air results in the limitation of the heat transfer from the absorber plate to air and causes low efficiency of heaters. In addition, due to the low density of air, large volumes are needed to handle.

Another solution in the literature that fixed this limitation stated above came by introducing a turbulent flow regime of air to take advantage of the increased forced convective heat transfer coefficients in this regime [21]. A turbulent flow regime achieved with high flow rates. But this solution was not what we aimed since it requires electricity consumption to realize the forced convection ending with increased operational cost. In this study, the improvement of heat transfer performance ensured by changing the design of oven plates that are used to hold the apples. The experimental results of the trials for drying apples with traditional oven plates are not shown here due to its bad performance. However, when the design of the plates was changed to porous

Table 1. Thermal stability results.

Sample	Changes in properties at 280 °C sample temperature								
	150 h			300 h			509 h		
	$-\Delta\alpha_s$	$\Delta\varepsilon_{100}$	PC	$-\Delta\alpha_s$	$\Delta\varepsilon_{100}$	PC	$-\Delta\alpha_s$	$\Delta\varepsilon_{100}$	PC
1	-0.006	-0.002	-0.007	-0.006	0.007	-0.002	-0.008	0.005	-0.005
2	-0.002	-0.002	-0.003	-0.003	0.009	0.002	-0.004	0.005	-0.002
3	-0.004	0.001	-0.004	-0.004	0.008	0.000	-0.004	0.007	-0.001
mean	**-0.004**			**0.000**			**-0.002**		

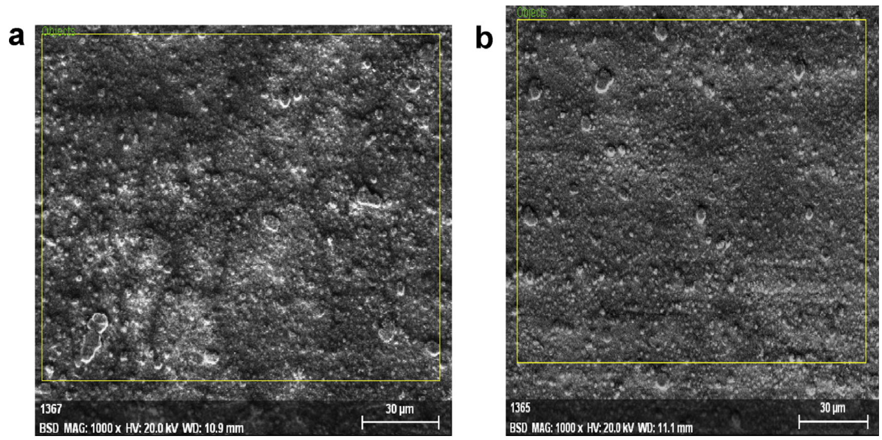

Figure 3. a. Non protected surface awaited 60h in 3%NaCl. b. Protected surface image awaited 60h in 3%NaCl.

Figure 4. Cost-effective and high-efficient solar drying pilot system prototype.

type and including manual rotating fan at the top of the flue pipe, drying effectiveness improved dramatically.

Another, action taken by the authors in the production stage of the dryer prototype was to build the dryer section using hardboard materials instead of low carbon steel. The main reason was to save time in system manufacturing, and especially not the speed of drying. However, in the later LCOH calculations, which are shown in detail, the effect of low carbon steel walls was taken into account.

During the drying process, the removal of the moister from the apples is achieved by passing the air through the porous plates up towards the flue pipe. The capacity of the oven was set to be 2 kg of apples on each layer. Apples were dried between sunrise and sunset. The weight change of the fruits was tracked by weighing the samples before the drying process and at the very end. Temperatures of each layer were measured between 10:00 am and 06:00 pm at intervals of two hours. These experiments were carried out at two different times in the spring season. The first trial was conducted on April 28, 2016, the second trial on May 7, 2016. In Table 3 global radiation values of Istanbul are presented. Successfully dried apples were produced with having either leathery or crisp sides with no moist centers.

The costs of the materials used to finalize the assembly of the prototype drying system can be seen in Table 2 (the list of the investment cost). The prices collected in various time periods are always converted to Euro (€) Currency in this study for the sake of avoiding the Turkish Lira (TL) inflation. This conversion can be a more accurate and updated way to show the feasibility results due to the fact that from 2015 or 2017 to today, inflation increase rate and €/TL parity increase rate are nearly very close.

Table 2. Manufactured pilot dryer system total investment cost.[a]

Materials	Price (in euro)
1200 × 2400 mm^2 galvanized plate with 1.5 mm thickness	43.85
560 × 1100 mm^2 hardboard with 18 mm thickness	102.64
500 × 2000mm^2 selective surface	10.35
6 mm thick flat glass	22.27
3 pieces of TFA 30.3049 Dostmann brand thermometer and moister meter	116.10
30 cm long flue pipe	22.43
3 pieces of porous oven plates	81.44
30cm thick 1m^2 rock wool	1.33
1 piece of 250 × 900mm^2, 1 piece of 275 × 900mm^2 lid	10.93
For support 10mm^2 wooden	20.93
Labor cost	120.00
Total İnvestment Cost	552.27

[a] The cost excludes the low carbon steel price since the manufacturing was completed realized using hardboard.

For LCOH calculation, one needs to calculate the first system capacity (per day kWh-day). For this daily radiation, information is needed. From Table 3, the global radiation for the month of May is read to be 5.57 kWh/m^2-day [22]. Before starting the calculations, a concise description of the proposed system should be explained. As can be seen in Figure 4, the system comprises a black colored surface collector where the surface is on the wall and a solar collector coated with the selective surface where the collector is integrated into the prototype with an angle. In this particular case, the energy is assumed to be produced by these two different collectors. Due to the shape and location of the oven, an accurate estimation of the area exposed to daily solar irradiation is needed [23]. Our initial evaluations showed us that the black painted surface collector on the wall was found to have sun exposure on an area of 1.44 m^2 during the drying process period. The high-efficiency selective surface coated solar collector, on the other hand, has an area of 1 m^2.

To further carry on the calculation, efficiency information of the surfaces is needed. Black painted surface had an efficiency of 63%; whereas, the selective surface had an efficiency of 71% and this value on the absorber was measured by SPF, Rapperswil, CH in 2011. The efficiency of the absorber is calculated according to two standards; International Solar Thermal Testing Standard (ISO 9806) and Solar thermal collectors (EN12975) [24,25]. The results are given in Table 4 below.

Table 3. Global radiation values in Istanbul [20].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Global Radiation ($kWh/\ m^2 - day$)	1.40	2.19	3.13	4.36	5.57	5.92	5.74	5.22	4.09	2.74	1.62	1.19

Table 4. Calculated efficiency of the absorber under study.

Efficiency based on reference area (Selektif-Sera)	
η_0 (-) (Efficiency)	0.711
a_1 (W/m^2K)	4.27
a_2 (W/m^2K^2)	0.0072

Table 5. Calculated levelized cost of heat.

ST System Category	Solar System	Natural Gas	Electricity	LPG
LCOH (€-cent/kWh) (for 20 years)	0.014	0.025	0.059	0.069
LCOH (€-cent/kWh) (for 25 years)	0.012	0.024	0.064	0.076

Calculations of energy productions from these two various solar collectors can be seen below in Eqs. (1), (2), and (3):

$$5.57kWh - day\ x\ 1.00m^2\ x\ 0.71 = 3.95kWh - day \tag{1}$$

the energy coming from the selective surface collector

$$5.57\ kWh - day\ x\ 1.44\ m^2\ x\ 0.63 = 5.05\ kWh - day \tag{2}$$

the energy coming from the black painted surfaces on the walls.

Overall, the total daily energy amount obtained from the sun is calculated to be:

$$3.95kWh - day + 5.05kWh - day = 9kWh - day \tag{3}$$

The calculations are widened such that the comparison of solar energy-based data can be made with conventional fossil fuels or electricity demanded systems. Eventually, calculations are carried backward starting from the total daily energy generated by the solar system.

The calculated energy is first converted to kJ/day as shown in Eq. (4):

$$\frac{9kWh}{day} x \frac{3600kJ}{1kWh} = 32400\ kJ \Big/ day \tag{4}$$

Then daily energy demand value is taken so that the cost of generating 4184 kJ (1000 kcal) of energy using natural gas, electricity, and liquefied petroleum gas (LPG) can be calculated as presented in Eq. (5), Eq. (6), and Eq. (7). Daily operational cost values for natural gas, electricity, and LPG consumptions were found from literature as 0.161369TL/4184 kJ (0.02634 €/4184 kJ), 0.668916 TL/4184 kJ (0.10919 €/4184 kJ), and 0.820707 TL/4184 kJ (0,13397€/4184 kJ), respectively (euro currency was taken on 2nd of Jan 2019) [26].

$$32400 \frac{kJ}{day} x \frac{0.02634€}{4184\ kJ} = 0.20\ € \Big/ day \quad \text{for natural gas} \tag{5}$$

$$32400 \frac{kJ}{day} x \frac{0.010919€}{4184\ kJ} = 0.85\ € \Big/ day \quad \text{for electricity} \tag{6}$$

$$32400 \frac{kJ}{day} x \frac{0.13397€}{4184\ kJ} = 1.04\ € \Big/ day \quad \text{for LPG} \tag{7}$$

To further compare these results, and give them more meaning, the Levelized cost of heat (LCOH) values are calculated. The LCOH values are presented in Table 5.

In Table 5, the heat generation LCOH values are presented for today and the prediction for the year 2030. In the LCOH calculations investment capital, operation, maintenance, and yearly interest are taken into account. The LCOH values tend to increase in the order of more than 2 or higher depending on which conventional energy source was being used. Due to having lower maintenance costs and operational costs, where especially no bills are generated during the usage of renewable energy, LCOH for the system of interest found to be the lowest. Where on the other side, no matter which conventional energy source is being used, there will always be an additional monthly operational cost due to consumption. So even with this integration of the innovative selective surface characteristics, the prototype showed promising low-cost high-efficiency characteristics.

Another calculation was carried out to reflect the experimental setup conditions. As mentioned before, the walls during the conduction of the experiments were not manufactured with the black painted solar collector. So, using only the energy production capacity coming from the solar collector of an area of 1.44 m^2 are repeated. The capacity of the two various systems generated daily and over the total period is given in Table 6. Glazed surface generates 13% more energy due to comprising higher efficiency.

A comparison of the LCOH of glazed and unglazed surfaces along with the conventional energy sources are presented in Table 7. As can be seen from these results, even for a shorter period, switching to incorporate renewable energy sources reduces costs dramatically. The

Table 6. Solar air collector tests results given for apple drying in Istanbul.

Collector size/m^2, Efficiency (%)	Required heat energy for apple drying in Istanbul	Period	Required Total Energy
1.44 m^2, Eff. 63% (for unglazed surface)	5.05 kWh/day-m^2	180 days/10 years	9090 kWh/1800 days
1.44 m^2, Eff. 71% (for glazed surface)	5.70 kWh/day-m^2	180 days/10 years	10260 kWh/1800 days

Table 7. Economic analysis based of system cost and comparison with other energy sources.

LCOH for 10 years (€-cent/kWh)				
Natural gas	Electricity	LPG	Solar Thermal	
			Glazed solar air collector	Unglazed solar air collector
7	7.65	133	4.6	4.0

Table 8. Targeted cost policy for solar heat given by IEA.

Cost in €-cent per kwh	Today		2030	
	Central Europe	Southern Europe	Central Europe	Southern Europe
Solar thermal	7–16	5–12	3–6	2–4
Natural gas	8.5–29		17–58	
Electricity	7–33		14–66	

same behavior can be observed when Tables 5 and 7 are compared. The cost of solar energy incorporated system being the lowest followed by natural gas comprised the system and LPG comprised system being the far highest.

As can be seen in Table 8, predicted the unit cost of generating work from natural gas and electricity are 8.5–29 €-cent/kWh and 7–33 €-cent/kWh, respectively. When the prices are compared with solar prices changing from 5-16 €-cent/kWh, it is becoming more attractive. However, the International Energy Agency (IEA) predicted that in the future the cost of the solar system will decrease in contrast to the increasing costs of fossil fuels. This prediction also coincided with our calculations.

As noted above, solar thermal markets are facing challenging times partly caused by increasing economic pressure from other renewable technologies. To address this, a special focus is given to the economics of solar thermal systems. The cost data shown can be referred by the end-user (customer). However, in these calculations, prices exclude value-added tax (VAT). Furthermore, it should be kept in mind that the solar fraction and climatic conditions play an important role.

3. Conclusion

In this study, a special focus is given to the economics of solar thermal systems. Calculations were carried out for a drying prototype manufactured using solar collectors with two various coating surfaces; unglazed and glazed. Cost-effectiveness was successfully presented via LCOH calculations. There are competing factors in the first installation and investment cost of renewable energy at the present time. However, predictions of increasing costs of conventional energy will overcome those factors. It is predicted that by the time the cost of renewable energy will decrease. A comparison of LCOH for the manufactured prototype is given for two different time periods: 20 and 25 years. It was found that the system comprised of solar energy technology showed the lowest LCOH whereas for the systems comprised of natural gas, electricity, and LPG showed a factor of 2, 4, and 5 times higher values, respectively. The cost data shown in this study can be used as a guide by the end-user (the prices exclude VAT). Furthermore, the solar fraction and the climatic conditions play an important role and always should be considered in a feasibility study.

Declarations

Author contribution statement

G. A. Ciftcioglu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

F. Kadırgan: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

M. A. N. Kadırgan: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

G. Kaynak: Conceived and designed the experiments; Performed the experiments.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

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