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Sustainability and performance analysis of a solar and wind energy assisted hybrid dryer

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ABSTRACT

In this study, energy, exergy and sustainability analysis of the solar and wind energy assisted hybrid drying system were discussed. The drying process was carried out by solar dryer. Wind energy was used to provide the electrical energy required for the operation of the fan in the drying unit. So, no external energy source was required for the drying process. The main purpose of the study was to contribute to the development of an economical and environmentally friendly drying system that was operated using only two different renewable energy sources. The drying characteristics of banana slices were determined in the experiments. It was found that the exergy efficiency of the dryer was in the range of 68.04–83.89%, as a result of the experiments. The system was also examined in terms of waste exergy rate, improvement potential and environmental sustainability. The evaluations showed that the hybrid dryer had 57.7% and 21.52% higher exergy efficiency compared to other conventional solar dryers and solar assisted- hybrid dryers, respectively. Moreover, the energy payback period was determined as 1.36 years. This result clearly indicated that the system can recover the energy it consumed in approximately 38.18% shorter time compared to other solar dryers.

1. Introduction

Nowadays most of the fresh fruits and vegetables deteriorate in a short time due to the amount of moisture they contain. This leads to significant wastage of fruits and vegetables. Drying process is one of the most important methods used to prevent this waste. In this way, the moisture in the fruit or vegetable is removed from the product so that the product can remain intact for a long time. In the literature, there are many studies on the development of drying technologies with high energy efficiency.

An important part of these studies is solar energy assisted drying systems. Especially in the studies carried out in recent years, the performance, economic and environmental impact analyses of indirect solar dryers is at the forefront. Benhamza et al. [1] determined the optimal geometric and operating parameters of the finned solar assisted drying system for food drying. In the study, the optimum operating parameters of the system were determined as a result of experimental studies based on energy, exergy analysis, improvement potential values and outlet temperatures. It was observed that the optimum design parameters obtained increased the thermal efficiency by 15.76% and the improvement potential value by 19.33%. Mugi and Chandramohan [2] carried out energy and exergy analysis of drying of okra (Abelmoschus esculentus) under forced and natural convection in an indirect solar dryer and compared their results for better evaluation of dryer performance and optimization of drying. The average drying efficiencies were found as 74.98% and 24.95%, respectively, under forced convection, and 61.49% and 20.13%, respectively, under natural convection. The exergy loss for the drying chamber varied between 0.062- 21.99 W and 0.394–24.99 W under forced and natural convection, respectively. Singh and Gaur [3] examined the economic feasibility and environmental impact of the new greenhouse dryer with vacuum solar collector. In this developed hybrid drying system, it was aimed to dry high humidity agricultural and non-agricultural products. In experimental studies, tomato slices were dried from 94.6% (wb) to 10% (wb) moisture content in 10 h. In line with the data obtained, it was determined that the payback period of the dryer was 1.73 years and it can reduce 169.10 tons of CO_2. In recent years, studies on the thermal performance of solar dryers came to the fore. The thermal efficiency values for these systems were mostly determined experimentally [4,5]. In some studies, the thermal performance of

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the dryer was handled with experimental and numerical analyzes [6]. Researches usually concentrated on the drying and energy performance of solar dryers [7–9]. In the studies carried out on the developed solar dryers, as well as the energy efficiency, drying performances were also investigated experimentally [7,8]. In addition, solar dryers were operated in different modes and their thermal performances were compared [10]. Solar assisted systems operating in active and passive modes were developed and analyzed experimentally, especially in the form of greenhouse dryers [11]. Considering the performance of the greenhouse dryers developed in these systems, it was observed that the drying time was shortened by 37% on average [12,13]. In other studies on solar assisted dryers in the literature, it was concluded that the energy and exergy efficiency of solar dryers were generally higher than conventional dryers, and that the drying time was significantly reduced, in terms of drying performance [14,15]. In addition, in recent studies, economic, environmental impact and sustainability analyzes of solar dryers were examined, and the experimental results clearly showed that these systems also provided positive contributions in terms of economy and environmental impact [16,17].

A significant amount of research studies showed that solar assisted dryers were used in conjunction with energy storage systems to improve performance and availability. Energy storage systems with latent heat storage capacity, in which various phase change materials were used, had a large place in the literature. Glycerol [18], lauric acid [19], paraffin RT-42 [20] and paraffin wax [21,22] were used as phase change materials in the studies. In studies on latent heat storage medium with phase change materials, the performance analyzes of the systems were usually examined experimentally and compared with conventional solar drying [23] and operating with the situation without energy storage medium [24]. The obtained results clearly revealed that significant savings were achieved in systems where PCM energy storage medium were integrated in terms of both drying performance and energy efficiency. Apart from this, the use of energy storage systems with sensible heat storage capability, which used materials such as pebbles as energy storage material, in solar assisted drying applications was becoming common. Thermal performances [25,26], energy and exergy efficiencies [27] and economic analysis [28] of sensible heat storage systems were mainly discoursed in the studies. In some of the studies in the literature, it was observed that the sensible and latent heat storage systems integrated into solar dryers were compared in terms of thermal and economic aspects [29,30]. The obtained results generally indicated that the usage time and performance of the solar dryers supported by the energy storage system increased significantly, compared to the conventional solar dryers.

In recent years, hybrid dryers assisted with solar energy have a very important place in the literature. The dryer types that occupied the largest space in this area were the solar assisted heat pump dryers. An important part of the researches were emphasized on the performance analysis of these systems [31,32]. In some studies, it was observed that energy-based economic evaluations were also performed together with performance analyses [33,34]. On the other hand the performance and environmental effects of hybrid dryers developed using solar energy and different energy sources were also examined. In these studies, mainly LPG [35], biomass [36] and electric heaters [37], heat pump-assisted hybrid photovoltaic-thermal systems [38] were used in a hybrid way with solar energy. In a study conducted in this area, Hadibi et al. [39] investigated the performance of a solar assisted-electric hybrid drying system. In the study, the CO2 reduction of the system was detected as 72.61 and 140.81 tons for 4.1 and 6.9 m/s air velocities, respectively. In another study, Singh and Gaur [40] compared the hybrid active solar assisted greenhouse dryer in terms of performance and economy by drying three different products such as tomato, ginger and gourd with conventional dryers. Compared to conventional dryers, it was observed that the developed dryer reduced the drying time of gourd, ginger and tomato by 61.90%, 34.09% and 47.36%, respectively. It was also predicted that the energy payback period of ginger, gourd and tomato could be approximately 1.79, 2.87 and 0.69 years less than conventional dryers. In a different study, Leon and Kumar [41] developed a solar-biomass hybrid air heater and provided hot air at a constant temperature (60 °C) and flow rate. In this developed system, pepper was dried from 76.7% (wb) moisture content to 8.4% (wb) moisture content in 32 h. As a result of the experiments, it was observed that the drying time was reduced by 66% compared to drying in the open sun and the temperature remained constant at 60 ± 3 °C for 21 h. Zoukit et al. [42] developed a new hybrid solar-flue gas dryer and also performed CFD analysis of the system. The results obtained from simulation and experimental studies showed close values to each other and dryer efficiencies for flue gas mode, solar mode and hybrid mode were determined as 37%, 42% and 40%, respectively.

In this study, a new hybrid drying unit operating with two different renewable energy sources such as wind and solar energy was developed. All of the electrical energy required by the system was encountered from wind energy. There were many studies on the performance evaluation of solar assisted drying systems in the literature. The drying performance and energy and exergy efficiency of the solar assisted dryers were mainly focused on in the performed researches. In a significant part of these studies, in order to increase the performance of solar dryers and shorten the drying time, they were generally used in a hybrid way with other energy sources such as energy storage systems, heat pumps, biomass and microwaves. However, since the drying process is performed at low temperature, it usually needs a high and quality energy source. Therefore, it was observed that additional energy sources such as electrical energy continued to be used in the operation of these developed systems. In this study, however, the drying process was carried out using only wind and solar energy, and no additional energy source such as electrical energy was required during the experiments. In this way, as no additional energy source was used during the operation of the system, it was provided to significantly reduce the energy consumption for the drying process compared to other drying technologies. This situation clearly revealed the difference of the developed hybrid drying system from other drying technologies in the literature. The study, at the same time, evidently indicated that sufficient electrical energy was obtained from wind energy to perform the drying process. In brief, the main purpose of this study was to carry out the drying process using only clean and renewable energy sources, and by this means, providing to bring a new drying system with low energy consumption, cheap, environmentally friendly and sustainable to the literature. Thus, it was plainly observed that the hybrid dryer with wind and solar energy, which was developed, compared to other drying technologies, had a considerably high performance and was a sustainable system.

2. Materials and method

2.1. Preliminary examination of the dried product

In each experiment performed in this presented study, the drying characteristics of banana slices with different thicknesses were determined. The most important purpose in choosing different thicknesses was to determine the optimum drying time for the system. The drying behavior of banana slices was studied in the literature using different drying techniques. Tunnel type electric dryer [43,44], solar and heat exchanger assisted hybrid solar dryer [45], microwave freeze drying method [46], microwave and microwave-infrared combination [47], and a thin-layer indirect solar dryer [48] were among the preferred drying technologies in the literature to determine the drying characteristics of banana slices. In the studies, banana slices were generally sliced at a temperature of 40–60 °C, with an average thickness of 5–7 mm, and dried from 75 to 77% (wb) moisture content to 16.8–27% (wb) moisture content. Before drying, banana slices with a thickness of 5–7 mm were subjected to 4 different pre-treatments such as lemon juice, honey dipping, ascorbic acid and salt solution [44]. In the experiments carried out in the presented study, the banana slices were sliced with a different thickness (from 4 mm to 7 mm, respectively) in each experiment, without any pre-treatment, and dried by placing them on the drying tray.

2.2. Drying unit

The flow diagram of the solar and wind energy supported hybrid drying system, which was designed and developed, was shown in Fig. 1. The system was placed in a location that can receive both solar and wind energy. The drying process was carried out with heat energy obtained from solar energy. The hot air coming from the collector was blown into the system with the help of the fan, and moving from the upper part of the system to the lower part, it evaporated the moisture of the product in the tray inside the cabinet with heat, and provided it to mix to the drying air. After a certain period of time, the drying air lost its ability to absorb moisture and became heavier and went down. In this case, the flap located on the upper part of the drying unit was opened and the interior drying air was discharged to the atmosphere. In the system, electrical energy was needed only for the operation of the fan. This electrical energy required for the operation of the fan was encountered by wind energy. For this, before the experimental studies, wind energy was stored in the gel battery as electrical energy. In addition, a separate resistance was placed at the bottom of the system. In this way, it is planned to activate the resistance placed at the bottom of the system for times when the solar energy is insufficient and to carry out the drying process at a constant temperature of 45 °C. It is thought that the electrical energy consumed by the resistance can be compensated by the wind energy stored in the gel battery. Some photographs of the wind and solar assisted hybrid drying system were indicated in Fig. 2.

The drying unit consists of collector, fan, resistance and drying chamber. An air collector was placed on the system which is 0.5 m wide and 0.4 m long. The main body of the collector was made of

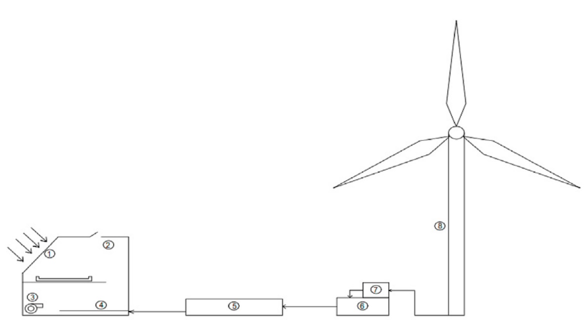

Fig. 1. Flow diagram of the hybrid dryer.

stainless steel, sun-collecting black aluminum sheet, isolation material (rock wool) and two-ply glass strata and both of the two ends were completely left open. The outer part of the drying unit was formed by bending stainless steel material. In the intermediate part of the drying unit, rock wool was used as insulation material and the insulation material was covered with stainless steel sheet. The drying unit consisted of a single shelf. The fan, which provides air flow in the system, is placed in the inner front of the drying unit. In addition, a resistance was placed at the bottom of the system and the resistance was deactivated during drying with solar energy. The wind turbine was placed on a 1.5 m long pole made of stainless steel material. The body and blade sections of the wind turbine were made of composite material. The energy obtained from the wind was stored as AC current in the gel battery with the help of a charge controller and converter. The design features of the drying unit, wind turbine, charge controller equipment and gel battery were shown in Table 1. Temperature, relative humidity, air speed, wind speed, solar radiation, weight and electricity measurement values in the drying unit were transferred to the computer environment via datalogger at certain periods. Sensitivity data for the measuring devices were indicated in Table 2. Temperature, relative humidity and air velocity values were monitored during the experimental studies by means of temperature, humidity sensors and anemometer placed at the inlet and outlet of the drying unit. The value of the wind speed was also measured with a similar anemometer used. Moreover, solar radiation, product weight changes and the amount of electrical energy stored in the gel battery were determined with a pyranometer, precision scale, and digital multimeter, respectively.

2.3. Analysis of drying unit

2.3.1. Design and energy analysis of solar air collector

The total amount of heat required to remove moisture from the product in the drying system consists of the amount of heat obtained from the air solar collector (Q_u) and the heat required to evaporate moisture from the product (Q_{evp}).

$$Q_{Total} = Q_u + Q_{evp} \tag{1}$$

The amount of heat obtained from the air solar collector can be calculated with the following equation [49]:

$$Q_u = A_c F_R [I - U_L(T_i - T_0)] \tag{2}$$

Here, F_R and U_L can be expressed as heat loss factor and heat loss coefficient, respectively, and can be determined as follows [49]:

$$F_R = \frac{\dot{m}C_p}{A_c U_L}\left(1 - \exp\left(A_c U_L F' / \dot{m}C_p\right)\right) \tag{3}$$

Where;

$$F' = \left[1 + \frac{U_L}{h + [(1/h) + (1/h_r)]^{-1}}\right]^{-1} \tag{4}$$

$$U_L = \frac{I(\tau\alpha_a)}{T_i - T_0} \tag{5}$$

Collector efficiency can be detected with Eq. (6):

$$\eta = \frac{Q_u}{A_c I} \tag{6}$$

The amount of heat required to remove moisture from the product can be found using the following equation [18]:

Fig. 2. Some photographs related to the hybrid dryer.

Table 1
Wind turbine and solar dryer design parameters.

Components of Solar Dryer	Dimension
Collector Length[m]	0.4
Collector Width [m]	0.5
Drying Chamber Length [m]	0.75
Drying Chamber Width [m]	0.6
Drying Chamber Height [m]	0.6
Components of Wind Turbine	
Wind Turbine Weight [kg]	5
Blade Weight of Wind Turbine[kg]	0.66
Blade Rotor Diameter [m]	0.22
Blade Length[m]	0.107
Initial Wind Speed[m/s]	3
Optimum Wind Speed[m/s]	12.5
Wind Speed of Shear[m/s]	45
Maximum Power[W]	500
Available Power[W]	400
Electrical Power Value	40 amp/12 V-AC
Power of Gel Battery	12 V/100Ah
Power of Modified Sinus Inverter	12 V/1000 W

Table 2
Sensitivity data of measuring equipments.

Equipment of Measurement	Measurement Type	Precision
Datalogger	Data switching equipment	–
Anemometer	Air speed/Wind speed	±0.03
Temperature sensor	Temperature (^{0}C)	±0.3
Humidity sensor	Relative humidity (%)	±%1
Pyranometer	Solar radiation (W/m^2)	±%5
Precision Balance	Moisture and weight loss (gr)	0.01
Digital multimeter	Current, voltage,resistance (%)	0.5

$$Q_{evp} = W_W L \tag{7}$$

2.3.2. Design and energy analysis of wind turbine

In this study, the wind turbine was used to provide the necessary electrical energy on the purpose of operating the fan in the drying unit. Therefore, the wind turbine was considered independent of the drying unit. The electrical energy obtained from the wind turbine was stored in the gel battery and the drying unit was directly connected to the gel battery. The maximum power that can be obtained from the wind turbine can be determined using Betz's law [50]:

$$P = \frac{1}{2} CF \rho A V^3 \tag{8}$$

As expressed in Eq. (8), the power obtained from the wind turbine depends on the density of the air (ρ), the area swept by the wind (A) and the turbine speed (V).

The drying characteristics of banana slices were handled in this study. Banana slices were examined separately for 4 different thicknesses (4, 5, 6 and 7 mm). Drying times were determined as 4 h on average for 4 mm thickness and 5.5 h on average for 7 mm thickness. Hence, drying times for the product of different thicknesses varied between 4 and 5.5 h. In order to determine the maximum wind turbine power, the experiment in which the drying behavior of 7 mm thick banana slices was examined was based. First of all, the turbine was positioned in a place where it can receive maximum wind. The amount of energy required to operate the fan in the 5.5-h experiment was used Eq. (1), Eq. (2) and Eq. (7), as the total of 0.96 kWh was determined. This value corresponded to approximately 80% of the energy stored in the gel battery. According to the region where the wind turbine was located, the minimum wind speed was 3 km/h and the air density was 1.215 kg/m^3 in the evening hours when the gel battery was stored. In this case, it is possible to express the CF value, which is defined as the Betz limit, as the ratio of the power (P) obtained from the wind turbine to the actual power (P_0) in the wind [18,51]:

$$\frac{P}{P_0} = 0.5\left(1 - \left(\frac{v_2}{v_1}\right)\right)^2 \left(1 + \left(\frac{v_2}{v_1}\right)\right) \tag{9}$$

During this experiment, the power value obtained from the dryer was equalized to Eq. (8) and Eq. (9) and the area swept by the wind was figured out as 0.0085 m^2.

2.3.3. Drying performance analysis

Moisture content of banana slices by wet basis was calculated with Eq. (10) [52]:

$$M_w = \frac{M_i - M_f}{M_i} * 100 \tag{10}$$

Drying rate can be defined as the basic expression of the amount of moisture removed from a kg of dry product per unit time period and can be expressed as follows [18]:

$$D_r = \frac{M_a - M_{a-1}}{\Delta t} \tag{11}$$

The basic drying efficiency depends on the specific energy consumed. The expression that gives the amount of specific energy consumed can be defined as the specific moisture absorption rate (SMER). This value can be found as follows:

$$SMER = \frac{w}{Q_{Total}} \tag{12}$$

The ratio of moisture that is one of the most important parameters of the drying process can be determined with Eq. [13,53,54]:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{13}$$

2.3.4. Exergy analysis of the hybrid dryer

Exergy, also defined as useable energy, can be expressed as one of the most basic indicators of the performance analysis of a system. The general exergy analysis of the hybrid dryer developed within the scope of this study, it was determined using the following basic equation [55]:

$$Ex = \dot{m}_a C_p \left[(T - T_a) - T_a ln \frac{T}{T_a}\right] \tag{14}$$

Starting from this relation, the input and output exergy values were obtained as follows [49,55]:

$$Ex_{in} = \dot{m}_a C_{p,a} \left[(T_{in} - T_a) - T_a ln \frac{T_{in}}{T_a}\right] \tag{15}$$

$$Ex_{out} = \dot{m}_a C_{p,a} \left[(T_{out} - T_a) - T_a \ln \frac{T_{out}}{T_a}\right] \tag{16}$$

It is possible to calculate exergy loss and exergy efficiency using Eq. (17) and Eq. (18), respectively:

$$Ex_{loss} = Ex_{in} - Ex_{out} \tag{17}$$

$$Ex_{eff} = 1 - \frac{Ex_{loss}}{Ex_{in}} \tag{18}$$

2.3.5. Sustainability analysis of the hybrid dryer

Sustainability is one of the most important factors showing the continuity of exergy efficiency [46]. Exergy plays an active role in drying technology and in the use of energy with high efficiency, sustainable, economic and environmental impact in many industrial areas. Studies show that the sustainability index (SI), improvement potential (IP) and waste exergy rate (WER), which are known as the main sustainability factors, are completely related to exergy values [56,57]. Sustainability analysis was carried out for the wind and solar energy assisted hybrid drying system developed within the scope of this study. The main sustainability indicators can be determined by Eqs. [18–20] depending on the input and output exergy values, exergy loss and exergy efficiency [58,59]:

$$SI = \frac{1}{1 - Ex_{eff}} \tag{19}$$

$$IP = \left(1 - Ex_{eff}\right) Ex_{loss} \tag{20}$$

$$WER = \frac{Ex_{loss}}{Ex_{in}} \tag{21}$$

The daily energy consumption value, on the other hand, can be expressed with Eq. (22), taking into account the total operating time of the dryer and the consumed power value [18]:

$$E_{day}(kWH) = \frac{Moisture\ evaporated(kg)*L(J/kg)}{3.6x10^6} \tag{22}$$

"E_{day}" refers to the amount of energy consumed daily. The latent heat of evaporation (L) was taken as 2395 kJ/kg for an average drying temperature of 45 °C.

It is possible to calculate the energy payback period with the following [60]:

$$EPPT = \frac{Embodied\ Energy(kWh)}{E_{annual}\ \left(\frac{kWh}{year}\right)} \tag{23}$$

Embodied energy refers to the total amount of energy contained in the materials that make up the system. The total embodied energy for the developed wind and solar assisted hybrid dryer was determined as 287.75 kWh. The annual energy output can be calculated with the following equation:

$$E_{annual} = E_{day} * n_{wd} \tag{24}$$

Where, "E_{annual}" refers to the annual thermal energy output. "n_{wd}" indicates the number of days the dryer is operated in a year. Assuming that the dryer is operated on sunny days, this value is accepted as 190 days for Bursa/Turkey.

3. Results and discussion

3.1. Energy and performance analysis of the dryer

A hybrid drying system was developed using two different renewable energy sources such as wind and sun in this study. The drying process was carried out by transferring the hot air coming from the solar collector into the drying cabin with the help of a fan. All of the electrical energy needed to operate the fan in the system was encountered from wind energy. Wind energy was converted into electrical energy, stored in the gel battery, and provided the necessary electrical energy for the fan to operate. Therefore, the wind turbine did not have a direct effect on the product drying properties and was only used on the purpose of providing the electrical energy needed by the drying system. The process of storing wind energy as electrical energy was realized the night before the drying experiments and the electrical energy used to operate the fan was kept ready in the gel battery before the drying experiments. The wind speed values shown in Fig. 3 were gauged with an anemometer, during the storage of wind energy in the gel battery. For this reason, the measurements of the wind speed were started at 2 p.m. when the wind started to be effective and continued until the gel battery was fully charged. The time to fully charge the gel battery, on the other hand, continued maximum 20 h depending on the wind activity and drying time. During the daylight hours when the charging process was started, the wind speed value was measured at regular intervals and it was observed

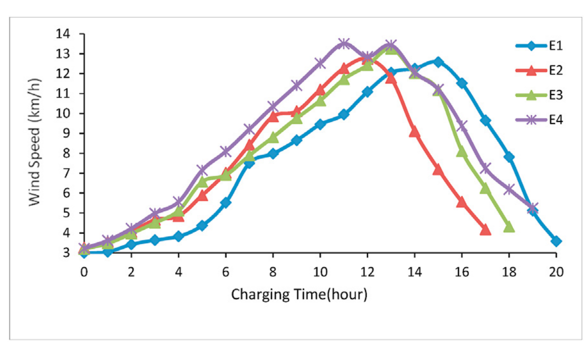

Fig. 3. The change of wind speed during the charging time of the gel battery.

that the wind speed changed between 3 and 5 km/h depending on the weather conditions until 5 p.m. It was found that the wind speed reached up to a maximum of 13.50 km/h, especially in the evening, due to the increase in the effect of the wind, and it changed between 3.00 and 13.50 km/h depending on the weather conditions.

Experimental studies were performed during 4 days in September and in each experiment, the drying characteristics of banana slices of different thicknesses (1st Exp. 4 mm, 2nd Exp. 5 mm, 3rd Exp.6 mm, and 4th Exp. 7 mm) were examined. It is possible to say that the main reason for using different thicknesses in each experiment is to determine the optimum thickness and drying time for drying the banana slices. The temperature and relative humidity changes in the drying unit during the experimental studies were indicated in Fig. 4. The results revealed that there was no big difference between the inlet and outlet temperatures and relative humidity values due to have the small scale of the drying unit. However, it was observed that the maximum temperature value that can be measured in the drying unit, depending on the outdoor temperature, showed different results in each experiment and generally varied at 45–55 °C. Similarly, it was determined that the relative humidity values in the drying unit also changed by considering the outdoor relative humidity value, but this change was not at extreme levels. During the drying experiments, the solar radiation values measured with the pyranometer and the air velocity values in the cabin gauged by the anemometer were demonstrated in Fig. 5 and Fig. 6. Considering the solar radiation data, it was observed that the lowest solar radiation values were obtained during the experiment conducted on the 4th day, while the highest solar radiation values were observed during the experiment conducted on the 1st day. In the experiments, it was detected that the solar radiation data ranged between 300 and 632 W/m^2. As stated in Fig. 6, it was observed that the values of air speed in the drying unit varied between 0.82 and 2.81 m/s depending on the outside air data during the experiments for 4 days.

The basic parameters for the energy and drying performance obtained during the experiments were shown in Table 3. As can be seen in Table 3, the banana slices were dried until they were reduced from 75 to 77% moisture content to 16–17% moisture content according to the wet basis. Drying times varied between 4 and 5.5 h depending on the thickness of the product. The developed hybrid dryer was compared with other solar assisted hybrid dryers in the literature with regards to drying time. Considering that the drying process in other solar assisted hybrid dryers continued for an average of 10 h, it was observed that the developed hybrid dryer with solar and wind energy support reduced the drying time by an average of 45%. The variation of moisture content with drying time was demonstrated in Fig. 7. Moreover, the amount of electrical energy consumed by the fan according to the drying time was also measured with a multimeter during the drying period and the results were expressed in Fig. 8. The results indicated that the lowest consumption with 0.72 kWh was obtained in the 1st experiment where 4 mm thickness banana slices were dried. Similarly, it was observed that the highest consumption occurred with 0.96 kWh in the 4th experiment, in which 7 mm thickness banana slices were dried. In addition, in the measurements made with a digital multimeter, it was detected that the total amount of power stored in the gel battery was 1.2 kWh. In the experimental studies, drying times varied depending on the thickness of the product. This change in drying times also affected the storage time of wind energy in the gel battery. The maximum power consumed by the fan, depending on the duration of the drying process, was determined as 0.96 kWh. When the storage times of the gel battery were examined, on the other hand, it was observed that the shortest and longest storage times were realized before the 2nd and 1st experiment, respectively. Considering that the charging process was performed one day before the experimental studies, it was determined that the gel battery reached the maximum amount of power stored for the first experimental study after 20 h. In the experimental study carried out on the first day, 60% of the energy obtained from the wind turbine and stored in the gel battery was used for the drying process. For the drying experiment carried out on the second day, the maximum power value was reached after 17 h of charging time, since 40% electrical energy was present in the gel battery. In the experiments performed on the other days, the operating time of the wind turbine also stretched as the drying time increase depending on the product thickness compared to the first day. Considering this

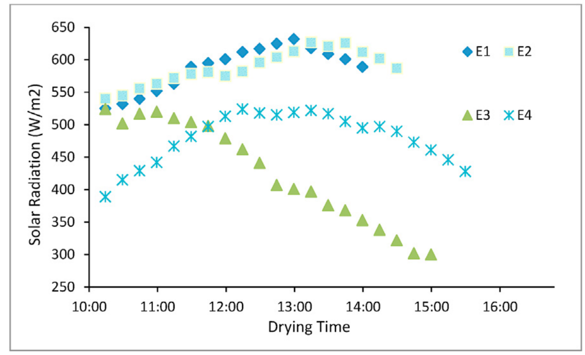

Fig. 5. The change of solar radiation.

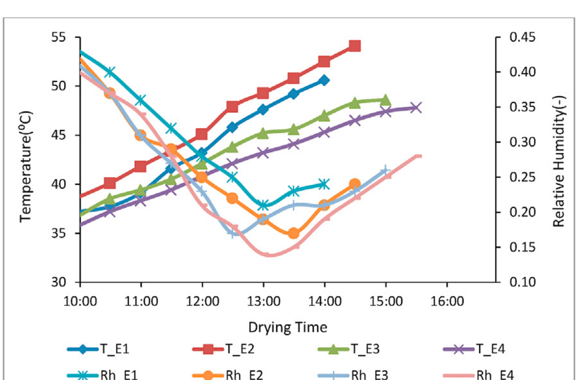

Fig. 4. Temperature and relative humidity changes in the drying unit.

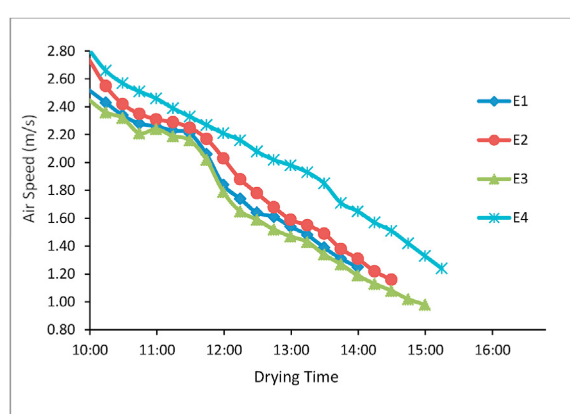

Fig. 6. The change of air speed in the drying unit.

Table 3
Basic parameters for energy and drying performance.

Parameters	Unit	Exp_1 (4 mm Thickness)	Exp_2 (5 mm Thickness)	Exp_3 (6 mm Thickness)	Exp_4 (7 mm Thickness)
Consumed energy for drying process	kWh	1.38	1.44	1.51	1.62
Consumed energy by fan	kWh	0.72	0.78	0.85	0.96
Dried product (banana)	kg	2	2	2	2
Average amount of water removed from product	kg	1.673	1.674	1.675	1.678
Specific moisture extraction rate(SMER)	Kg_w*KWh^{-1}	1.212	1.163	1.109	1.036
Average ambient temperature	°C	28.3	28.1	27.5	27.1
Average temperature of drying unit	°C	45.4	46.4	43.2	42.3
Average relative humidity of drying unit	%	30.2	26.7	26.0	25.1
Total drying time	Hour	4	4.5	5	5.5
Moisture content(initial)	(%wb)	75	75.73	76.25	75.60
Moisture content(final)	(%wb)	16.07	16.33	16.67	16.76
Range of the solar radiation	W/m^2	524–632	528–626	300–524	362–522

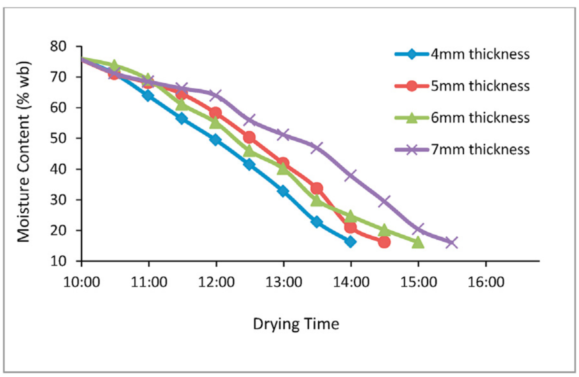

Fig. 7. The change of moisture content (wet basis) according to the drying time.

situation, it was clearly observed that the thickness of the product affects not only the drying time and the amount of energy consumed, but also the storage time of the gel battery and therefore the operating time of the wind turbine. It was found that the main reason for this was the drying times that vary depending on the product thickness. The results clearly indicated that the energy stored in the gel battery provided the necessary energy to operate the fan in the drying system, and there was no need for an additional external electricity source.

3.2. Exergy analysis of dryer

In this study, the exergy performance of the wind and solar assisted hybrid dryer was also discussed. During the experiments, the input-output exergy values of the system were determined using Eqs. 15 and 16. As a result of the experimental data, it was observed that the input exergy values change between 0.01286 and 0.14894 kW. Similarly, it was detected that the exergy output values vary between 0.00875 and 0.11456 kW. Exergy input-output values calculated with the experimental data were demonstrated in Fig. 9. In line with these data, the lowest exergy loss of 0.00411 kW was obtained during the third experiment in which 6 mm thick banana slices were dried. It was determined that the highest exergy efficiency value with 83.89% was found in the first experiment where 4 mm thick banana slices were dried. During the experiments, it was determined that the exergy loss values varied between 0.00411 and 0.03329 kW, and the exergy efficiency was between 68.04 and 83.89%. In addition, the lowest exergy efficiency was obtained in the 4th experiment in which 7 mm thick banana slices were dried. The results revealed that the product thickness and external environment values directly affected the exergy efficiency and as the product thickness increased and the solar radiation value decreased, the exergy loss increased and the exergy efficiency decreased. The variation of exergy loss and exergy efficiency with drying time was indicated in Fig. 10. During the experiments, it was observed that the highest exergy loss occurred towards the end of the drying process. In addition, the exergy efficiency of the system was compared with the exergy efficiency of other drying techniques in the literature. It was determined that the average exergy efficiency of solar assisted drying systems was around 45%. It was observed that the exergy efficiency was in the range of 60–65% on average, especially in studies dealing with solar-assisted hybrid dryers. The average exergy efficiency of the wind and solar assisted hybrid dryer developed within the scope of this study was determined as 76.46%. As a result of the evaluations, it has been determined that the developed hybrid dryer provides a significant advantage of %57.7 and %21.52, respectively, in terms of exergy efficiency compared to other conventional solar dryers and solar-hybrid dryers.

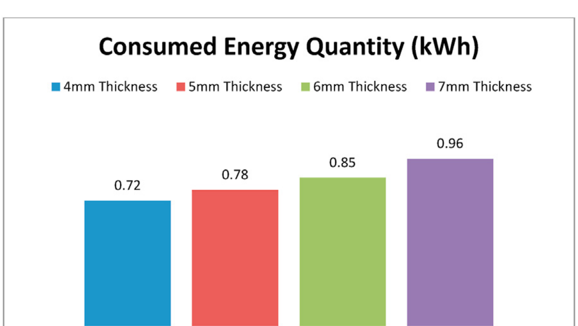

Fig. 8. The amount of electrical energy consumed by the fan according to the drying time.

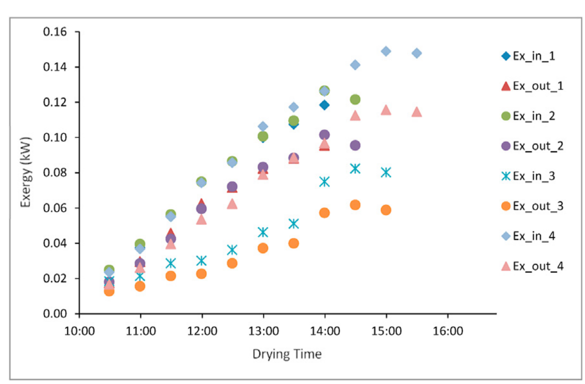

Fig. 9. Exergy input-output values calculated with experimental data.

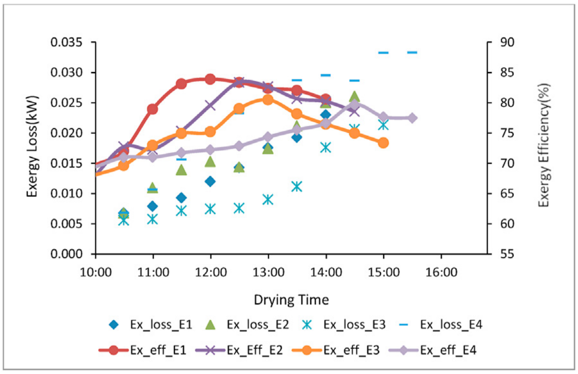

Fig. 10. The change of exergy efficiency and exergy loss with respect to drying time.

3.3. Sustainability analysis of dryer

In addition to the energy and exergy performance of the wind and solar powered hybrid drying system developed within the scope of this study, sustainability analysis were also examined. As sustainability values, the waste exergy rate, sustainability index, improvement potential and energy payback period of the system were determined. The waste exergy ratio can be expressed as the ratio of the exergy loss in a system to the inlet exergy value. Because it was observed that exergy was lost to the surrounding environment with moisture during the drying process. Waste exergy ratio was calculated separately for each experiment, taking into account the inlet exergy and exergy lost values, during the experiments. Depending on the temperature and air velocity in the drying unit, it was observed that the waste exergy ratio values were highest at the beginning of the drying process, decreased in the middle, and reached equilibrium towards the end of the process. The maximum waste exergy ratio value was obtained as 0.335 in the 2nd experiment that the banana slices with a thickness of 5 mm were dried. The variation of the waste exergy ratio according to the drying time was illustrated in Fig. 11. The sustainability index is generally expressed a function of exergy efficiency. Considering that the product thickness and solar radiation values have a direct effect on exergy efficiency, for the sustainability index, it was observed that the highest average value of 4.967 occurred in the 1st experiment, while the lowest average value of 3.924 occurred in the 4th experiment. The variation of the sustainability index according to the drying time was indicated in Fig. 12. Another basic parameter is the improvement potential determined depending on the exergy efficiency and exergy loss. The main purpose of determining this value is to reduce the exergy loss. For this reason, it was determined in the experiments that the improvement potential values had the lowest value at the beginning of the drying process and increased continuously during the drying period. Accordingly, considering the average improvement potential values, it was detected that the lowest value was occurred with 0.002597 kW in the 1st experiment, on the other hand, the highest value was obtained with 0.005383 kW in the 4th experiment. The change of the improvement potential values according to the drying time was shown in Fig. 13. In addition, it was concluded that the energy payback period was 1.36 years, depending on the annual amount of energy consumed during the drying process and the amount of embodied energy of the hybrid dryer. In the performed evaluations, the developed wind and solar energy supported hybrid drying system was compared with other conventional solar dryers in the literature and especially with solar energy supported hybrid drying technologies in terms of energy payback time. In the studies, it was observed that the average energy payback times for conventional solar dryers operating in passive and active modes varied between 1.6 and 2.5 years. In the researches carried out for solar- hybrid dryers, on the other hand, it was concluded that the average energy payback period was about 2.2 years. The results revealed that the drying unit can recover the energy consumed in approximately 38.18% shorter time compared to other conventional solar dryers and solar- hybrid dryers.

4. Conclusions

Energy, exergy and sustainability analyses of the wind and solar powered hybrid drying unit were performed in this study. Wind energy was utilized on the purpose of providing the necessary electrical energy for operating the fan in the drying unit. For this, the wind energy was stored as electrical energy in the gel battery before a day of the drying process. The total storage capacity of the gel battery was 1.2 kWh, maximum 80% of this stored energy was used to operate the fan in the drying unit, and the required electrical energy was provided in this way. Thus, the drying process was carried out without the need for any external energy source.

In each of the experimental studies, the drying performance of banana slices of different thickness was determined. So, the effect of product thickness on drying performance and drying time was detected. The results indicated that the thickness of the product had a significant effect on the drying performance and the amount of energy consumed. Moreover, the specific moisture extraction rate, which is accepted as the basic drying performance efficiency, was determined as 1.212, 1.163, 1.109, 1.036 Kgw*KWh^{-1} for 4, 5, 6 and 7 mm thicknesses, respectively. The specific moisture extraction rate decreased as the product thickness increased. However, the main reason why this value was above 1 was that the specific energy consumption of this hybrid drying system was much lower

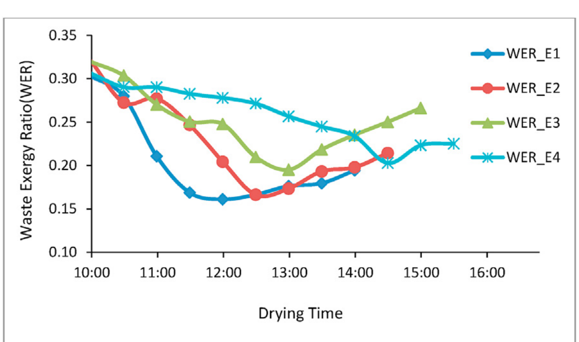

Fig. 11. The variation of waste exergy ratio with respect to drying time.

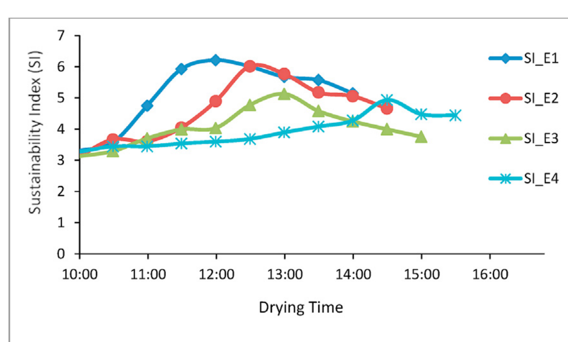

Fig. 12. The change of sustainability index according to drying time.

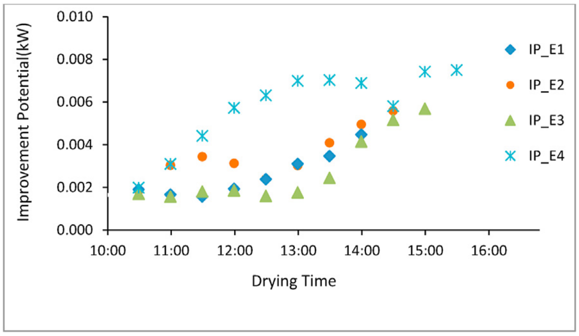

Fig. 13. The variation of improvement potential as regards drying time.

compared to other drying technologies in the literature. As a result of the experiments, it was observed that the highest performance and sustainability values were obtained during the experiments in which banana slices of 4 and 5 mm thickness were dried. Therefore, it is possible to say that the ideal thickness values for dried banana slices are 4 or 5 mm.

The findings obtained from the experimental studies revealed that the exergy efficiency of the system varies between 68.04 and 83.89%. This result clearly showed that a drying system that operates using only two different renewable energy sources such as wind and sun without the need for any additional energy source had a very high energy efficiency compared to other drying techniques.

In addition, this developed system was also handled in terms of sustainability factors such as waste exergy ratio, sustainability index and improvement potential which were examined on the basis of energy and exergy efficiency. The obtained data revealed that the energy payback period of this hybrid drying unit, which had high exergy efficiency and low exergy loss, was 1.36 years.

As a result, the development of new hybrid drying technologies with high energy efficiency and energy saving, by using clean and cheap renewable energy sources, can both reduce the costs of the farmers significantly and contribute to the prevention of fruit and vegetable waste.

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CRediT authorship contribution statement

Halil Atalay: Conceptualization, Writing – original draft, Review, Methodology, Analyzed the Data. **Nur Yavaş:** Investigation, Technical Drawings, Writing& editing, Analyzed the Data. **M. Turhan Çoban:** Conceptualization, Writing – review & editing.

Declaration of competing interest

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

Nomenclature

A	Swept area (m^2)
A_c	Area of collector (m^2)
C_p	Specific heat capacity ($J*kg^{-1}*K^{-1}$)
$C_{p,a}$	Specific heat capacity of air($J*kg^{-1}*K^{-1}$)
CF	Betz limit
D_r	Rate of drying
E_{annual}	Annual consumed energy($kWh*year^{-1}$)
E_{day}	Daily consumed energy(kWh)
Ex	Exergy (kW)
Ex_{in}	Inlet exergy(kW)
Ex_{out}	Outlet exergy(kW)
Ex_{loss}	Loss of exergy(kW)
Ex_{eff}	Efficiency of exergy (%)
F_R	Factor of heat removal
F'	Factor of efficiency
h	Heat transfer coefficient ($W*m^{-2}*K^{-1}$)
hr	Heat transfer coefficient for radiation($W*m^{-2}*K^{-1}$)
I	Radiation of solar ($W*m^{-2}$)
L	Latent heat of vaporization ($J*kg^{-1}$)
$\dot{m}$	Flow rate of mass ($kg*s^{-1}$)
$\dot{m}_a$	Flow rate of air mass ($kg*s^{-1}$)
M	Moisture content
M_a	Moisture content at any drying time on wet basis
M_e	Moisture content of equilibrium on wet basis
M_f	Mass of final sample (kg)
M_i	Mass of initial sample (kg)
M_0	Moisture content of initial on wet basis
M_w	Moisture content on wet basis
n_{wd}	Number of operated days of dryer
P	Extracted power of wind turbine (W)
P_0	Actual power of wind turbine(W)
Q_{evp}	the amount of heat required for evaporated the moisture of the product (kWh)
Q_{total}	Total amount of heat required for drying process (kWh)
Q_u	Consumed useful heat (kWh))
t	Time(s)
T	Temperature(^{0}C)
T_a	Air temperature in the system(^{0}C)
T_0	Outside air temperature(^{0}C)
T_i	Inlet air temperature(^{0}C)
T_{in}	Inlet temperature of drying unit(^{0}C)
T_{out}	Outlet temperature of drying unit (°C)
U_L	The coefficient of total heat transfer ($W*m^{-2}*K^{-1}$)
V	Velocity($m*s^{-1}$)
v_1	Intact wind speed ($m*s^{-1}$)
v_2	Speed of wind after exceeding the rotor plane ($m*s^{-1}$)
w	Mass of expelled moisture
W_v	Mass of evaporated water (kg)

Greek Symbols

η	Collector efficiency (dimensionless)
ρ	Density of air ($kg*m^{-3}$)
α_a	Coefficient of absorption
Δt	Time period (s)

Subscripts

E	Experiment
EPPT	Energy payback period time
IP	Improvement potential
MR	Moisture ratio
Rh	Relative humidity
SI	Sustainability index
SMER	Specific moisture extraction rate
WER	Waste exergy ratio
wb	Wet basis (%)

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