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Energy, Exergy and Economic Analysis of a Mixed-mode Natural Convection Solar Tunnel Dryer for Banana Slices

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Abstract

The energy, exergy and economic analysis of a mixed-mode natural convection solar tunnel dryer for drying banana slices is presented. The collector, drying chamber and chimney energy and exergy are analysed for a load of 3.75 kg of fresh banana slices. Further, the economic analysis in terms of Net Present Value (NPV), Profitability Index (PI), the Payback Period (PB) and the Discounted Payback Period are presented. Drying experiments were done in a period of two days. During the experiment, solar radiation varied from 206.1 W/m^2 to 934.5 W/m^2; drying chamber temperature varied from 51.7ºC to 81.84ºC while the ambient temperature varied from 21.7ºC to 31.9ºC. The relative humidity ranged from 4.63% to 28.46% for the drying chamber and, 14.9% to 31.8% for the ambient. Under these conditions, the moisture content of the bananas was reduced from 73.89% to 14.27% in seven hours of drying on the first day. Energy and exergy efficiencies ranged from 5.56% to 57.32%, and 0.33% to 2.81%, respectively on Day 1. For Day 2 the energy and exergy efficiencies were from 14.15% to 59.16%, and 0.75% to 3.76%, respectively. For the drying chamber, the efficiency increased gradually in the first two hours to a maximum of 5.36%, corresponding to the period when there was maximum evaporation. The chimney, which is a bare flat plate type without glazing and insulation, lost heat from its surfaces. Nonetheless, it generated enough buoyancy to move air through the dryer. With the solar dryer lifespan of 10 years and the Discounted Payback Period of four years, the project is attractive and worth investing in.

Keywords: energy exergy and economic analysis, mixed-mode, natural convection, solar tunnel dryer, banana slices

1. Introduction

A major obstacle faced by farmers in Africa and many developing nations revolves around post-harvest losses, which are approximated to account for 30-40% of their agricultural yields (AGRA, 2015, Aboud, 2013). Matavel et al., (2021) identified insufficient techniques for food processing as one of the main contributors to the losses of food and high prevalence of hunger in Sub-Saharan Africa. They identified solar drying of agricultural products as having great potential to address the insufficient techniques for food processing in Sub-Saharan Africa. According to Musembi et al., (2016) the present direction towards utilisation of renewable energy sources due to worries about the effects of fossil fuels on climate change, energy expenses, and the necessity to reduce post-harvest losses, solar power is anticipated to have a significant role in food processing within the broader food systems context.

Based on the mode of heat transfer from the sun to the drying food, natural convection solar dryers, also known as passive solar dryers, can be classified into three main groups as: direct solar dryers, indirect solar dryers and mixed-mode solar dryers (Simate & Ahrné 2006). These dryers can further be classified according to their design e.g. Cabinet, Greenhouse, Tunnel type, and others (Srinivasan & Muthukumar, 2021). The mixed mode solar dryer has been found to have higher drying rate, more uniform moisture content and better temperature distribution in drying the food than the other types of solar dryers (Simate 2020, Simate 1999). Further, the greenhouse type of mixed mode natural convection solar dryer, with its large capacity, has been found to greatly enhance the shelf life of food and address the existing constraints associated with other solar dryers (Matavel et al., (2021). Garg et al., (1998) reported on a tunnel type mixed-mode solar dryer that had an inclined collector and a drying chamber assembly arranged in series and having the air in the dryer circulating by natural convection. The air in the tunnel flowed over, other than through the product, thus improving the drying rate. Berinyuy et al (2012) reported on a type of mixed-mode solar tunnel dryer that had a horizontal collector-drying chamber assembly and, a vertical chimney that created airflow in the dryer. The drying experiments using cabbage, amaranth, bitter leaf, and pepper demonstrated that the utilization of this solar drying setup resulted in a notable decrease in drying duration and an enhancement in the quality of the products. Cherotich and Simate (2016) investigated the thin layer drying process of mango slices using a mixed mode natural convection solar tunnel dryer. Their findings revealed that the Midilli-Kucuk model provided the most accurate description of mango drying behaviour in this specific type of dryer. In another study, Mukanema and Simate (2023) conducted a Computational Fluid Dynamics (CFD) simulation of banana drying within a mixed mode natural convection solar tunnel dryer. Their goal was to analyse the temperature distribution and airflow patterns within the dryer. By identifying specific areas that could be optimized, they aimed to enhance the overall performance of the dryer.

Kumar et al., (2017) reported that numerous investigations have been conducted regarding the exergy of various kinds of solar dryers and that these endeavours sought to minimize losses, enabling the optimal utilization of resources and ultimately reaping economic advantages. Their findings indicated that exergy analysis provides an improved means of assessing the performance of solar dryers, yielding crucial insights into processes, losses, and factors contributing to inefficiencies. Dincer and Rosen, (2007) noted that, although there are challenges in quantitatively grasping drying procedures due to nonlinear physical processes and moisture content-temperature reliant material transport characteristics, exergy analysis proves adept at furnishing optimal solutions for drying-related issues. Akpinar (2018) observed that the exergy efficiency of solar drying systems is commonly used as a measure of their sustainability, as it reveals how effectively the exergetic inputs are utilized within the process.

Despite extensive investigations into mixed-mode natural convection solar tunnel dryers, there exists a research gap concerning their energy, exergy, and economic aspects due to insufficient prior research in these domains. A comprehensive examination of these dryers would reveal areas with notable energy and exergy losses and suggest potential improvements. Additionally, an economic analysis would assess the viability of investing in such dryers, which significantly impacts their adoption by farmers and, consequently, reduces post-harvest losses. Consequently, this study investigates the energy, exergy, and economic performance of a mixed-mode natural convection solar tunnel dryer equipped with a simple bare flat plate chimney for drying banana slices.

2. Method

2.1 Natural Convection Solar Tunnel Dryer

The Natural Convection Solar Tunnel Dryer used in the study comprises three major sections: a flat plate solar collector, a drying chamber and, a bare flat plate chimney. The collector and drying chamber have equal floor dimensions of 1 m length by 0.75 m width and a depth of 0.1 m, while the chimney is 0.75 m high by 0.75 m wide and 0.1 m deep. Both the collector and the chimney were painted matt black to improve the absorption of solar radiation and are covered with a 200-micron thick greenhouse plastic. The collector and the drying chamber form a tunnel that allows air to flow from the collector to the drying chamber. Air from ambient enters the collector in an upward direction, then makes a 90º turn and passes through the collector and drying chamber in a horizontal direction and finally, makes another 90º turn and moves up through the chimney before exiting at the rear top of the chimney. The Schematic of the solar dryer and experimental setup are shown below in figure 1. As the air passes through the three sections of the dryer, there is transfer of heat between the air and the sections of the dryer to varying degrees. In addition to this, in the drying chamber, the air picks up moisture that has evaporated from the drying bananas and takes it out of the dryer through the exit at the back of the chimney.

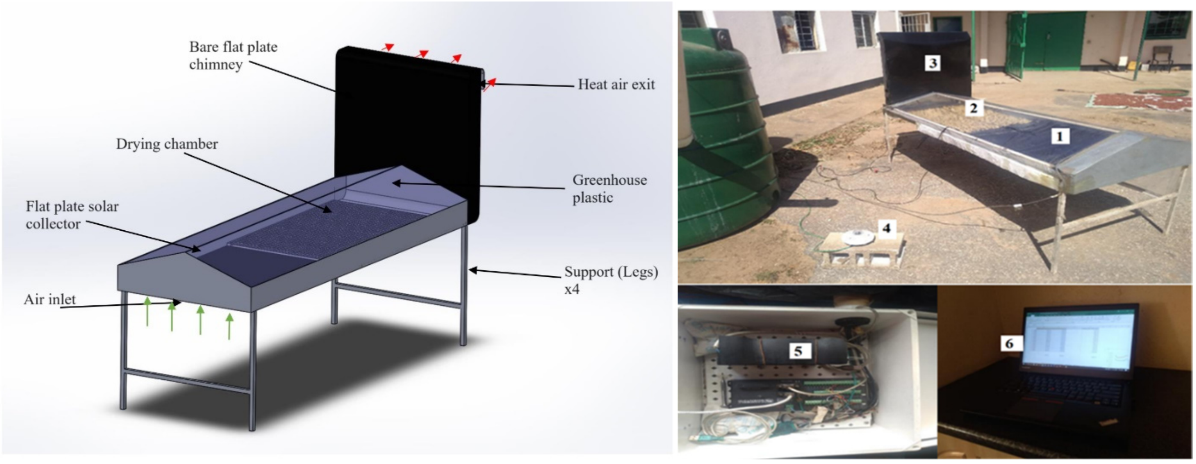

Figure 1. Schematic of the solar dryer and Experimental set-up of the solar dryer and the equipment: (1) Collector unit, (2) Drying unit, (3) Bare flat-plate chimney unit, (4) Solar pyranometer, (5) Data logger, (6) Computer

2.2 Experimentation

The solar drying experiments were carried out at the University of Zambia's Department of Agricultural Engineering field station which has coordinates: 15.3°S latitude and 28.3°E longitude. The solar tunnel dryer was placed on a level and uncovered area that receives sun shine the whole day. Figure 1 gives an illustration of the setup used in the experiments.

A multi-probe data logger, CR 1000 model, Campbell Scientific Inc., was linked to the solar tunnel dryer through several sensors that collected data which was recorded in the data logger and displayed on the computer screen. This setup captured solar radiation and air temperature and humidity data. For solar radiation measurement, a Kipp & Zonen Delft BV, model: CM11 pyranometer, with irradiance range: 0–1,400 W/m^2, sensitivity: 4 to 6 μV/Wm^2, placed on a horizontal surface near the solar tunnel dryer was used. For temperature, thermocouple-type temperature probes (Campbell Scientific Inc. 108 – L model, range: -5°C to +95°C, accuracy ±0.01°C), were used to collect air temperature data. The sensors measured air temperature in the ambient, and at the collector exit, drying unit exit and, chimney exit. The collector air inlet temperature and relative humidity were measured using a combined temperature/relative humidity probe (Campbell Scientific Inc. model: HMP60-L) for the range of temperature -40°C to 60°C and humidity range of 0 to 100%. Finally, the airflow was measured by inserting the probe of a digital air flow meter (Keonders Instruments BV, The Netherlands, μP 2308, measurement: 0–30 m/s, accuracy: <20 m/s = ±2%, ≥20 m/s = ±5%) into a hole in the back of the chimney to measure the upward flow of air in the chimney. The data collected fluctuated throughout the day as dictated by the solar radiation, ambient temperature, relative humidity and wind conditions, and played a crucial role in defining the product drying process.

Before the start of the drying experiment, ripe but firm bananas were peeled then sliced 3 mm thick (Reducing the slice thickness results in shorter drying time and increased drying rate; therefore 3 mm dimension was deemed reasonable/appropriate especially when considering shrinkage) and then they were loaded on a polythene net positioned on top of the wire mesh of the tray. The tray size was 0.75 m^2 and was fully loaded with 3.75 kg of fresh banana slices. For the purpose of monitoring the weight loss of the bananas with drying time, three small samples were weighed at one-hour intervals using a digital weighing balance (model: PE 3000, Mettler Instruments BV, Switzerland, maximum weighing capacity: 3,100 g, accuracy, ±0.1 g). The experiment was conducted from 09:00 hours to 16:00 hours for two consecutive days. For the initial moisture content of the banana, the standard method of moisture content determination (AOAC, 2005) was used.

2.3 Energy and Exergy

2.3.1 Solar Collector

The energy received by the collector (ENC_{in}) is a product of the incident solar radiation energy onto the collector and the collector area, and is given by equation (1) (Duffie & Beckman, 2013).

$$\mathrm{ENC_{in}} = \mathrm{A_{collector}} * \mathrm{R_{solar}} \tag{1}$$

Where:

$A_{collector}$ is the area of the solar collector, m^2

R_{solar} is the incident solar radiation, W/m^2

The solar collector useful gain (ENC_{out}) is based on the difference between the air outlet and inlet temperatures of the collector. It is given by equation (2) (Duffie & Beckman, 2013),

$$\mathrm{ENC_{out}} = \mathrm{M_a} * \mathrm{C_p}\ (\mathrm{TC_{exit}} - \mathrm{TC_{in}}) \tag{2}$$

Where:

M_a is the mass air flow rate, kg/s

C_p is the specific heat capacity of air, J/kg °C

TC_{in} is the collector inlet temperature, °C

TC_{exit} is the collector exit temperature, °C

During its operation, the solar collector loses some of the energy it receives from the sun to the ambient through radiation and convection. Consequently, the energy efficiency of the solar collector ENC_{eff} can be determined using equation (3).

$$\mathrm{ENC_{eff}} = \mathrm{ENC_{out}}/\mathrm{ENC_{in}} \tag{3}$$

For the exergy content of the transferred heat, Bejan (2016) reported that this is described by the boundary and the atmospheric reservoir temperatures, and the transferred energy. Therefore, the solar radiation component of the inlet exergy into the collector (EXC_{solar}) is described by equation (4)

$$\mathrm{EXC_{solar}} = \mathrm{A_{collector}} * \mathrm{R_{solar}}(1 - (\mathrm{T_{am}}/\mathrm{T_{solar}})) \tag{4}$$

Where:

T_{am} is the ambient temperature, K

T_{solar} is the surface temperature of the sun and a value of 5,500°C (NASA, 2022), is used in this analysis.

Dincer and Rosen (2007) described the exergy of flowing matter as comprising of the following exergy components: potential, kinetic, physical and chemical. The exergy of the flowing matter EXM_{flow} is given by equation (5).

$$\mathrm{EXM_{flow}} = \mathrm{EXM_{potential}} + \mathrm{EXM_{kinetic}} + \mathrm{EXM_{physical}} + \mathrm{EXM_{chemical}} \tag{5}$$

Considering an ideal gas, the specific flow exergy is given by equation (6), which is a simplified version of equation (5) (Benjan, 2016).

$$\mathrm{EX_{specific}} = \mathrm{c_p}\left(\mathrm{T} - \mathrm{T_o} - \mathrm{T_o}\ln\frac{\mathrm{T}}{\mathrm{T_o}}\right) + \mathrm{RT}\ln\frac{\mathrm{P}}{\mathrm{P_o}} \tag{6}$$

Equation (6) is further simplified by considering that the change between inlet and outlet pressure of the solar collector is negligible. Further, the mass air flow is incorporated, resulting in a simplified equation (7), which was then used to calculate the exergy of air at the inlet and outlet of the solar collector.

$$\mathrm{EXC_{air}} = \mathrm{M_a}\ \mathrm{C_p}\ [\mathrm{T_{air}} - \mathrm{T_{am}} - \mathrm{T_{am}}\ \ln\left(\mathrm{T_{air}}/\mathrm{T_{am}}\right)] \tag{7}$$

Where EXC_{air} and T_{air} are respectively, the exergy and temperature of air at the point of consideration, i.e. inlet or outlet of the solar collector.

The solar collector exergy efficiency (EXC_{eff}) is given by Zhong et al, (2014) as the ratio of the exergy increase of air flow to the solar radiation exergy input into the collector (EXC_{solar}). It is given by equation (8).

$$\mathrm{EXC_{eff}} = (\mathrm{EXC_{air-out}} - \mathrm{EXC_{air-in}})/\mathrm{EXC_{solar}} \tag{8}$$

2.3.2 Drying Chamber

The energy entering the drying chamber has two components; the first one is due to direct solar radiation on to the drying chamber and is equal to that on the solar collector (ENCin), while the second one is that of hot air coming from the solar collector i.e. the collector useful gain (ENC_{out}). Therefore equations (1) and (2) also apply to the drying chamber as it has exactly the same dimensions and is covered by the same greenhouse plastic as the solar collector. This mixed heating of the drying chamber classifies this dryer as a mixed mode solar dryer.

For the exergy input into the drying chamber, two components are identified, i.e. that due to hot air from the collector and that due to solar radiation received directly by the drying chamber. The exergy input of hot air from the solar collector into the drying chamber (EXD_{air}), and that due to direct solar radiation (EXD_{solar}), are given below by equations (9) and (10), respectively. Equation (9) is also used to calculate the exergy of air at the outlet of the drying chamber.

$$EXD_{air} = M_a C_p [T_{air} - T_{am} - T_{am} \ln \left({T_{air}}/{T_{am}} \right)] \quad (9)$$

$$EXD_{solar} = A_{drying} * R_{solar}(1 - (T_{am})) \quad (10)$$

Where A_{drying} is the drying area, m^2.

The total exergy entering the drying chamber ($EXD_{chamber}$) is equal to the sum of the product exergy ($EXD_{product}$) arising from the heating of the food to evaporate the moisture, the exergy destruction ($EXD_{destruction}$) arising from internal irreversibility and, the exergy emitted with waste to the outside of the dryer (EXD_{waste}) (Dincer & Rosen, 2007).

$$EXD_{chamber} = EXD_{product} + EXD_{destruction} + EXD_{waste} \quad (11)$$

The combination of exergy destruction due to internal irreversibility ($EXD_{destruction}$) and the exergy emitted with waste to the outside of the dryer (EXD_{waste}) constitute the exergy loss in the drying chamber (EXD_{loss}).

Kumar et al, (2017) gives the product exergy ($EXD_{product}$) as the rate of heat used in evaporating moisture from product in the drying chamber, which in this case is the banana slices. Equation (12) is used to determine the product exergy in the drying chamber,

$$EXD_{product} = Q_{evaporation} \left(1 - {T_{am}}/{T_{drying\ chamber}} \right) \quad (12)$$

Where: $Q_{evaporation}$ is the heat used for evaporating moisture from the banana slices, J/s. It is given by equation (13).

$$Q_{evaporation} = m_{evap} h_{fg} \quad (13)$$

m_{evap} is the moisture evaporation rate, kg/s.

h_{fg} is the latent heat of vaporisation, J/kg; evaluated at the temperature of the drying chamber, which is assumed to be the same as the temperature of the banana slices, $T_{drying\ chamber}$.

The drying chamber exergy efficiency ($EXD_{efficiency}$) is the ratio of the product exergy for moisture evaporation from the banana slices to the total exergy entering the drying chamber ($EXD_{chamber}$) (Hepbasli, 2008, Dincer & Rosen, 2007); It is given by equation (14),

$$EXD_{efficiency} = EXD_{product}/EXD_{chamber} \quad (14)$$

2.3.3 Changes in Air Exergy in the Collector, Drying Camber, and Chimney

The function of air in a drying process is twofold: to supply heat for evaporating moisture from the food, and to carry away the evaporated moisture to the outside of the dryer. It is therefore important to know the behaviour of air in the dryer in terms of its exergy as it moves from one section to another. This can reveal the sections that may need improvements so as to make the dryer more efficient. For this reason, the exergy of air (EX_{air}) at the inlets and outlets of the three sections of the dryer (Collector, Drying Chamber, and Chimney) were determined using equation (15).

$$EX_{air} = M_a C_p [T_{air} - T_{am} - T_{am} \ln \left({T_{air}}/{T_{am}} \right)] \quad (15)$$

Where EX_{air} and T_{air} are the exergy and temperature of air respectively, at the points of consideration.

3. Results and Discussion

3.1 Drying Performance, Energy and Exergy

The variation of solar radiation and temperature inside and outside of the dryer with time of the day is shown in Figure 2. Solar radiation ranged from a minimum of 206.1 W/m^2 to a maximum of 934.5 W/m^2 during the two days of the drying experiment. The air from ambient is heated as it passes through the collector, and its temperature increases by a maximum of 36.8ºC, increasing its capacity to pick moisture from the banana slices in the drying chamber. On Day 1, the Collector Outlet/Drying Chamber In temperatures are of the same magnitude as the Drying Chamber Out/Chimney In temperatures, despite more heating of the air as it passed through the drying chamber which received additional heating from solar radiation through the transparent cover. The additional heat through the transparent cover of the drying chamber could have been used in the evaporation of moisture from the bananas as the sample still had a lot of moisture. On Day 2, there was a marked difference between the two temperatures, reaching a maximum difference of about 15ºC at 12:00 hours. It can be noted that on Day 2, the bananas had lost significant amount of moisture and therefore the demand for heat was less, resulting in the increase in the temperature of air in the drying chamber, reaching a maximum value of 81.84ºC. According to Boudhrioua, et al., (2002), banana slices become stiff and brittle if they are dried for a duration of 4, 6 or 8 hours at 80ºC, as this temperature is higher than the glass transition temperature. In another study Leite, et al. (2007) carried out banana drying experiments to determine the effect of drying temperatures of 60ºC and 70ºC on the quality of the dried bananas. Their results showed that the chemical composition of the bananas was not affected by the drying temperature, but sensorial analysis showed that lower drying temperatures produced better-accepted products. From the foregoing studies, in order to produce good quality dried banana slices, it is necessary to have a way of regulating the temperature in the drying chamber to around 60ºC and avoid the undesirable effects of higher temperature. Figure 2 also shows the chimney temperature, which is lower than the drying chamber temperature but higher than the ambient temperature. For airflow to take place, there should be buoyancy in the chimney arising from the difference between the chimney and the Ambient temperatures. It should be noted that although the front area of the chimney is painted mat black to absorb radiation and thus provide further heating of the air and contribute to improved air flow, its front has no glazing and its back and sides are not insulated and loose heat to the ambient. It can therefore be envisioned that an insulated and glazed chimney would have given higher airflow than the current one.

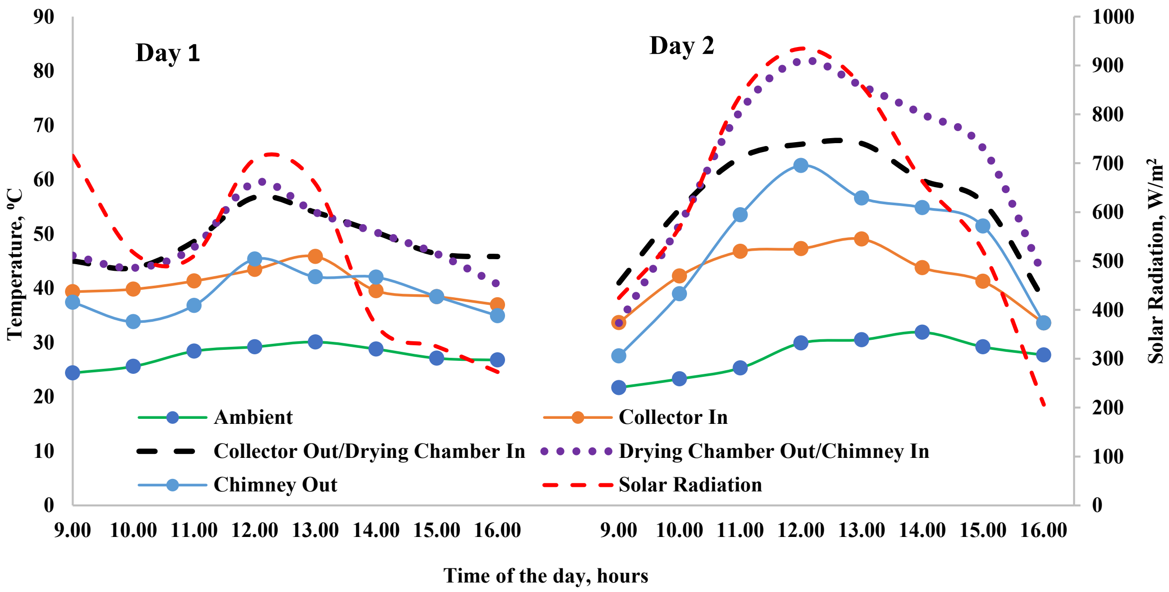

Figure 2. Temperature in the Ambient and in the Solar Dryer

Figure 3 shows the relative humidity in the ambient and in the solar dryer. The relative humidity in the ambient is higher than that in the collector and in the drying chamber. As the air moves from ambient through the collector, its temperature is increased resulting in a reduction of the relative humidity and making the air have a higher moisture carrying capacity. It can be seen that the relative humidity in the drying chamber is higher than that in the collector due to the moisture that has been picked from the bananas in the drying chamber.

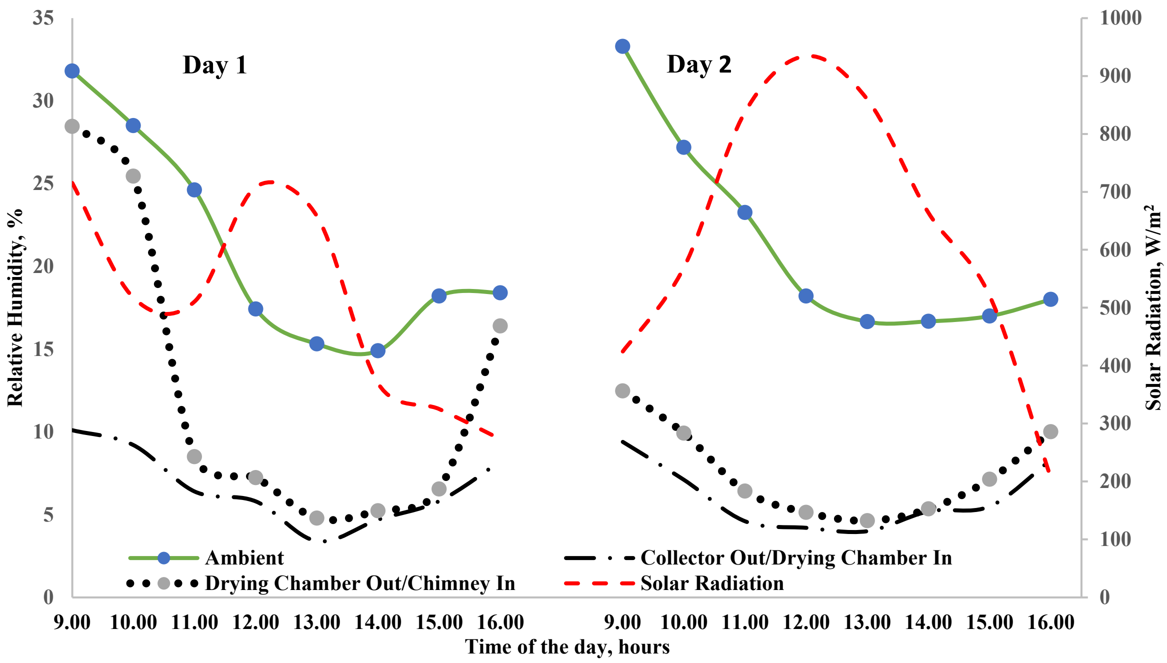

Figure 3. Relative Humidity in the Ambient and in the Solar Dryer

The airflow in the solar dryer is shown in figure 4 with the values ranging from 0.005 kg/s and 0.006 kg/s for the first and second day, respectively at 09:00 hours, to maximum values of 0.015 m/s and 0.016 m/s for the first and second day respectively at 15:00 hours. Since the airflow is by natural convection, the temperature difference between of the air inside the dryer and that in the ambient largely dictates the magnitude of the airflow. The airflow values determined in this work are comparable to what other researchers found. These include 0.0021 to 0.0123 kg/s (Othieno, 1987), 0.006 to 0.1 kg/s (Bala & Woods, 1994), 0.0029 kg/s (Berinyun et al. 2012) and 0.0043 – 0.0119 kg/s (Simate, 2020).

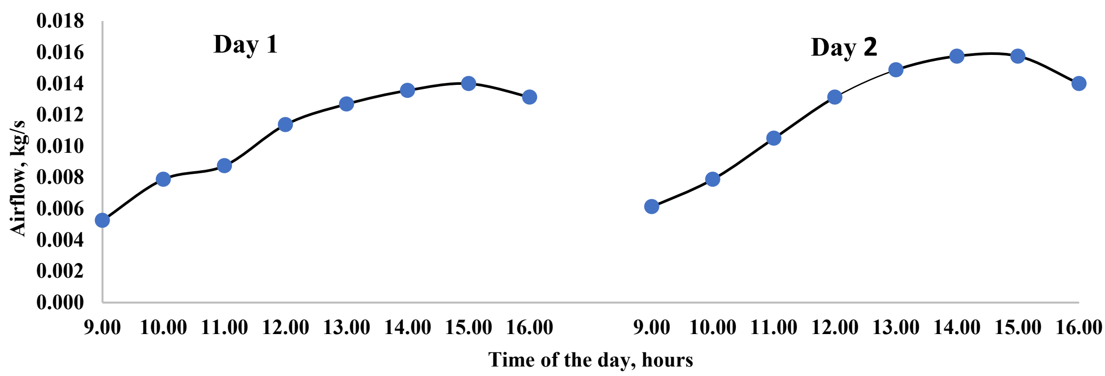

Figure 4. Airflow in the Solar Dryer during the drying period

Figure 5 shows the moisture content variation with time of the day. Most of the drying takes place on the first day with the moisture content reducing from 73.89% to 14.27% wet basis. At the start of the drying experiment, moisture is readily available on the surfaces of the fresh banana slices and is easily evaporated. However as drying progresses, less moisture is available for evaporation thus reducing the drying rate as can be seen in the drying curve for Day 2. During the last three hours of the second day, the moisture content remained constant as no more moisture could be removed from the slices; and the experiment could even have been stopped earlier.

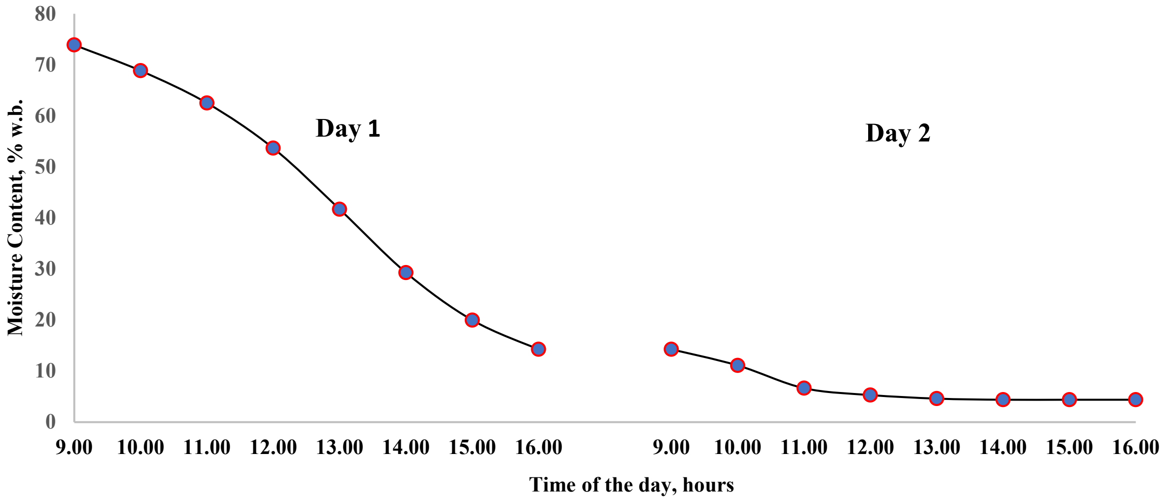

Figure 5. Moisture Content changes during the drying period

The energy output from the solar collector with respect to time of the day is shown in Figure 6. The variation of the energy output typically follows that of the solar radiation with maximum values on both days happening around mid-day. The energy ranged from 29.81 J/s to 152.16 J/s on the first day, and 45.06 J/s to 263.26 J/s on the second day.

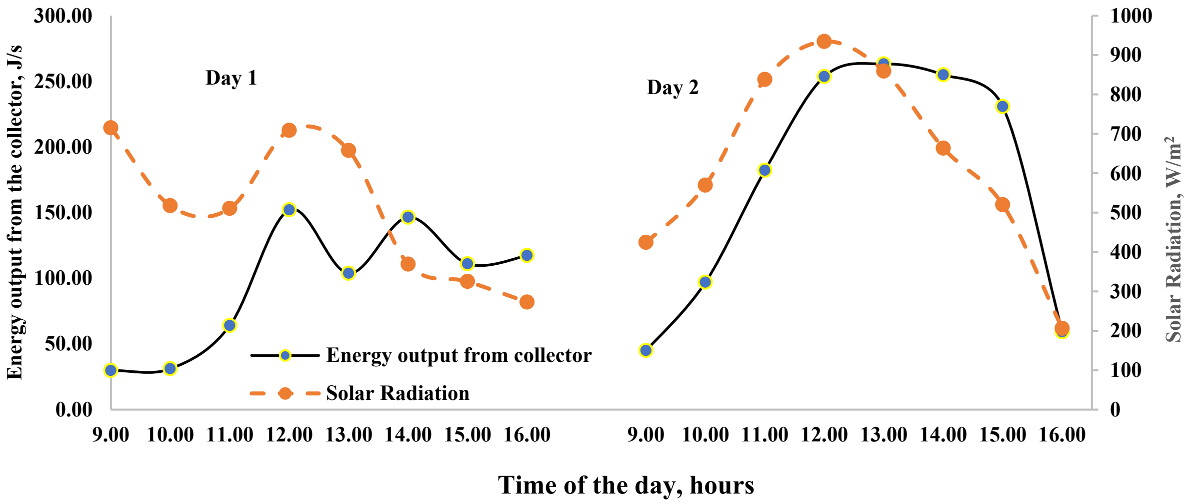

Figure 6. Energy output from the Solar Collector

Figure 7 shows the energy and exergy efficiencies of the solar collector. Energy and exergy efficiencies range from 5.56% to 57.32% and 0.33% to 2.81%, respectively on Day 1. For Day 2 the energy and exergy efficiencies are from 14.15% to 59.16% and 0.75% to 3.76%, respectively. Mugi and Chandramohan (2021) found a collector efficiency of 53.84% when drying chilli in an indirect-mode natural convection solar dryer, which is within the range of efficiency that has been found in the current study. Fudholi et al., (2016) found an average collector efficiency of 41% for an average solar radiation of 540 W/m^2 during the drying of jewfish in a hybrid solar dryer. Simate (2021) found the collector energy efficiency range of 32% to 49.7% and attributed the lower values to energy being used to heat the collector during the early stage of drying. Oztop et al., (2013) in their review of solar air heaters incorporating various enhancement techniques to improve heat transfer, reported energy efficiencies in the range of 47% to 89%, which is higher than what has been found in this study where a flat plate collector without any enhancements was used. Therefore, incorporating heat transfer techniques in the solar collector could improve the energy efficiency. For the exergy efficiency, the values in this study are much lower than the energy efficiencies. According to Tiwari et al., (2009) and Subramani et al., (2020), irreversibility destroys some of the input exergy in the collector.

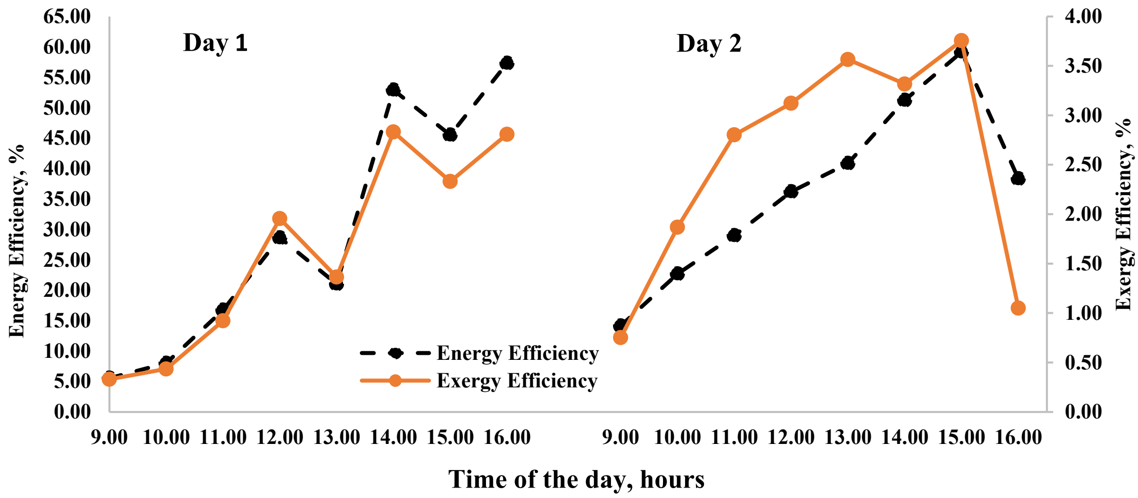

Figure 7. Energy and Exergy Efficiencies of the Solar Collector

The energy entering the drying chamber is shown in Figure 8. The total energy entering the drying chamber is a sum of the energy from the solar collector and the energy from direct solar radiation onto the banana slices on the drying tray. The average contribution of hot air from the collector to the energy entering the drying chamber is 29.54%.

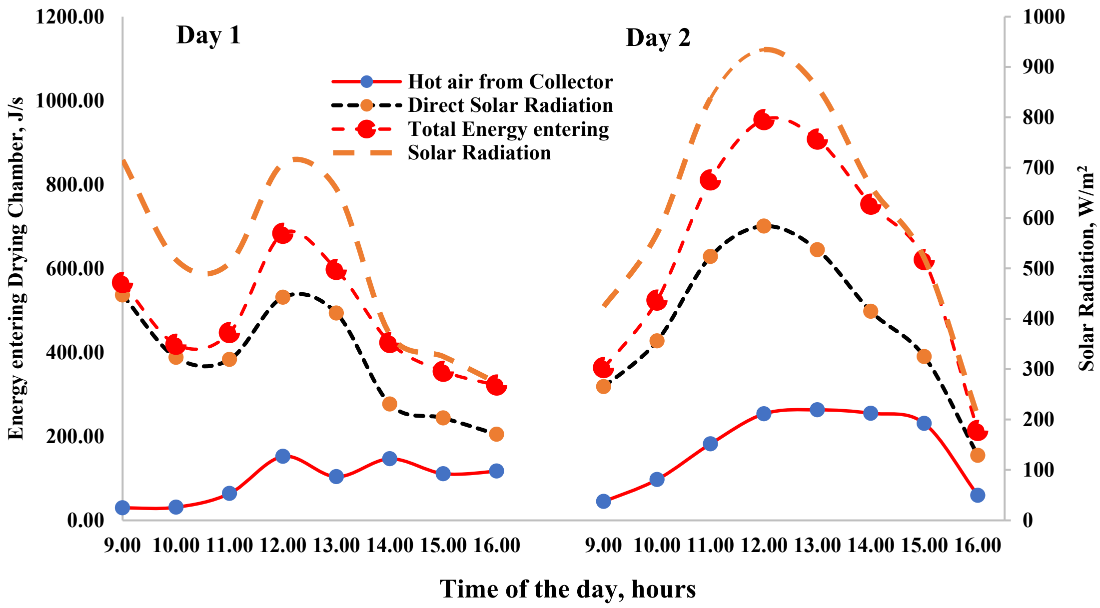

Figure 8. Energy entering the Drying Chamber

Figure 9 shows the exergy in the drying camber, that entering, that in the product (due to evaporation of moisture from the drying bananas), and lastly the one lost. The exergy entering the drying chamber is a sum of the exergy of air from the collector and the exergy due to direct solar radiation into the drying chamber. The exergy loss is very high ranging from 95% to 100% of the exergy entering the drying chamber. The exergy loss comprises that in the waste emission and that destroyed due to internal irreversibility. The maximum exergy in the product is 24.78 J/s and is observed at the beginning of the drying process when there is maximum moisture evaporation from the bananas. As the drying progressed, product exergy decreased continuously until there was no more evaporation from the bananas during the period from 14:00 hours to 16:00 hours.

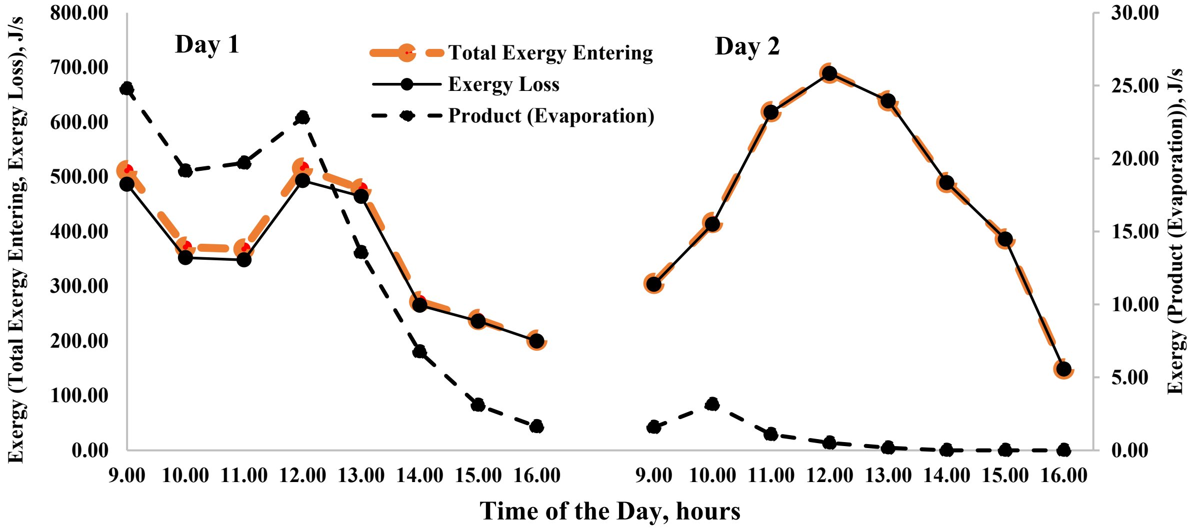

Figure 9. Exergy in the Drying Chamber

Figure 10 shows the exergy efficiency of the drying chamber. The efficiency increases gradually in the first two hours to a maximum of 5.36% at 11:00 hours. During this period, high evaporation of moisture from the bananas is experienced, resulting in a reduction of 41% in the water content. A steep reduction in the exergy efficiency is seen from 11:00 hours to 16:00 hours on Day 1, whereas very minimal reduction is experienced on Day 2 due to reduced evaporation.

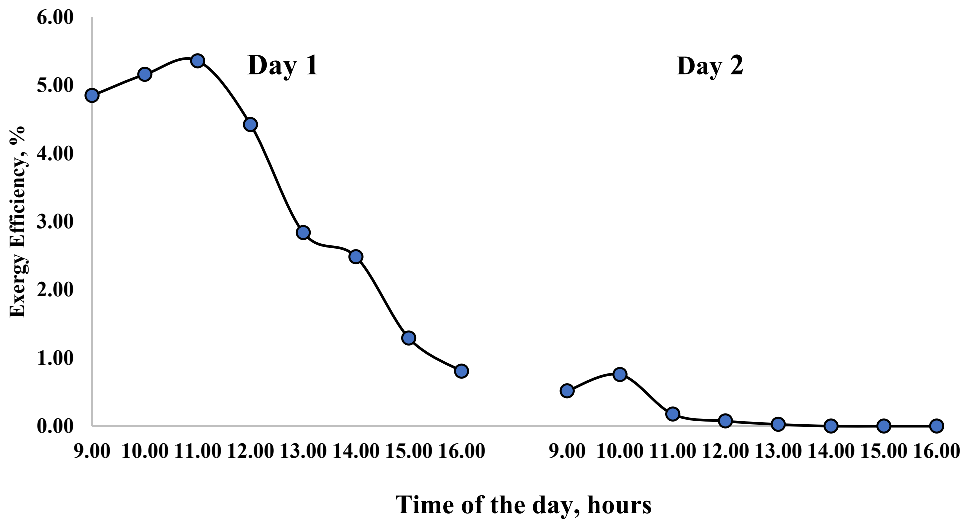

Figure 10. Exergy Efficiency of the Drying Chamber

As the air moves through the three sections of the solar tunnel dryer, i.e. the collector, drying chamber and lastly the chimney, its exergy changes as it is exposed to the different conditions in these sections. Figure 11a, 11b and 11c show the changes in the exergy of air in the collector, drying chamber and chimney, respectively. In the collector (Figure 11a) the air is heated and leaves the collector with a higher exergy than when it entered, thus it has more capacity to provide heat to evaporate moisture and to carry the moisture away. The variation of exergy with time typically follows the pattern of the solar radiation.

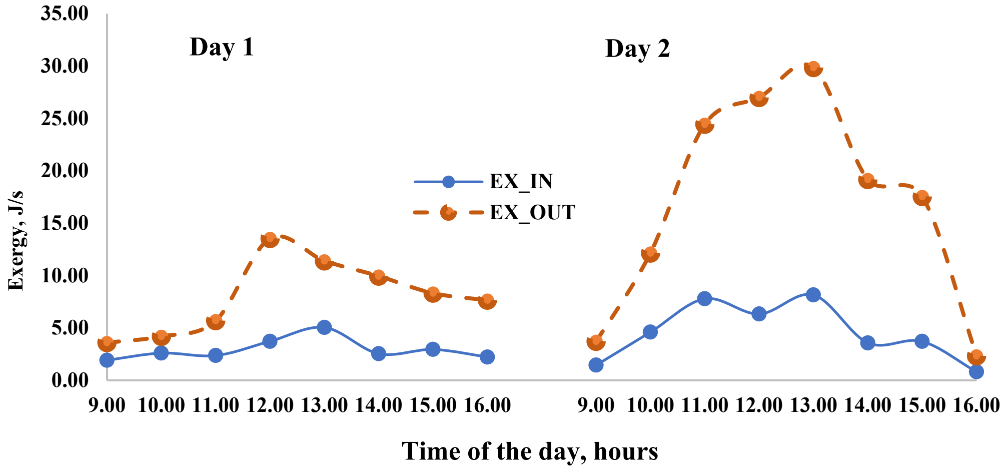

Figure 11a. Exergy of Air in the Collector

Figure 11b shows exergy of air in the drying chamber. On Day 1, the exergy of air entering the drying chamber is almost equal to its exergy when leaving the drying chamber, differing by an average of 1.03 J/s. It can be inferred from this observation that the evaporation of moisture from the bananas is largely met by the direct solar radiation on the banana slices. On the contrary on Day 2, the exergy of air at drying chamber exit is higher than that at inlet, with the difference between the two exergies reaching a maximum value of 25.76 J/s at 12:00 hours. This can be attributed to the fact that on Day 2, most of the moisture from the bananas has been evaporated and therefore the combined heat from the collector and the direct solar radiation, is less utilized in the evaporation of moisture from the banana slices resulting in increased temperature and higher exergy of air coming out of the drying chamber.

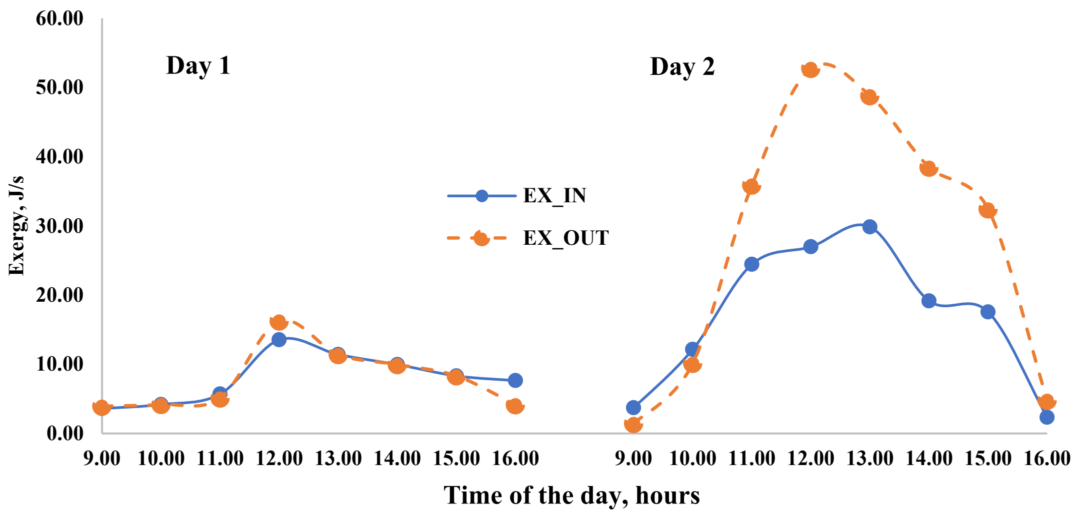

Figure 11b. Exergy of Air in the Drying Chamber

The exergy of air in the chimney is shown in Figure 11c. Contrary to what has been observed in the collector and drying chamber, the exergy of air entering the chimney is higher than that at the exit. The total exergy entering the chimney is a sum of the exergy of air from the drying chamber and that due to direct heating of the chimney surface by solar radiation. Some of the exergy in the chimney is used to create buoyancy for airflow through the dryer while the rest is exergy loss, comprising of internal irreversibility and waste to the outside of the chimney. The chimney is a bare flat plate type without glazing on the side that faces the sun. In addition to this, its back and sides are not insulated, and therefore could have a lot of heat loss. A more detailed exergy analysis of the chimney would give the magnitude of the exergies involved, i.e. total exergy entering the chimney (from direct solar radiation and hot air from drying chamber) and exergy loss through irreversibility and waste.

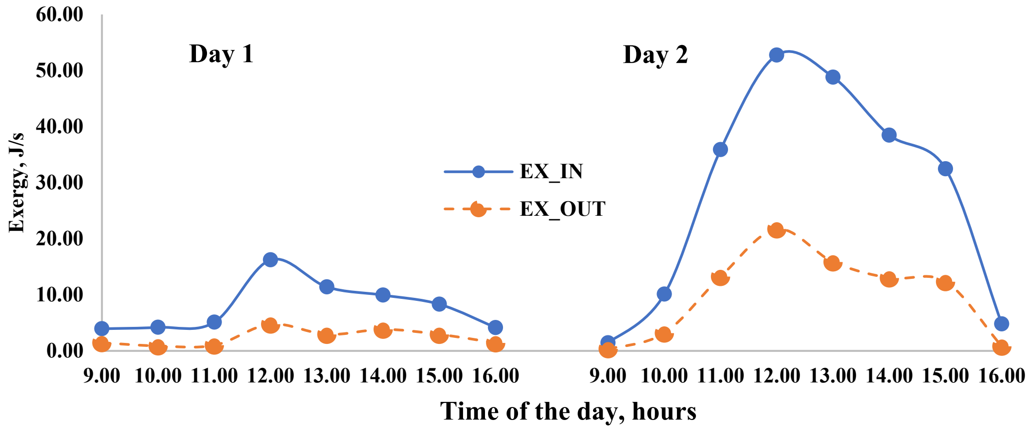

Figure 11c. Exergy of Air in the Chimney

Despite the chimney not having glazing and insulation as discussed in the previous section, the average temperature of air in the chimney, as shown in Figure 12, was higher than that in the ambient. This condition created thermal buoyancy that was sufficient to move air through the dryer.

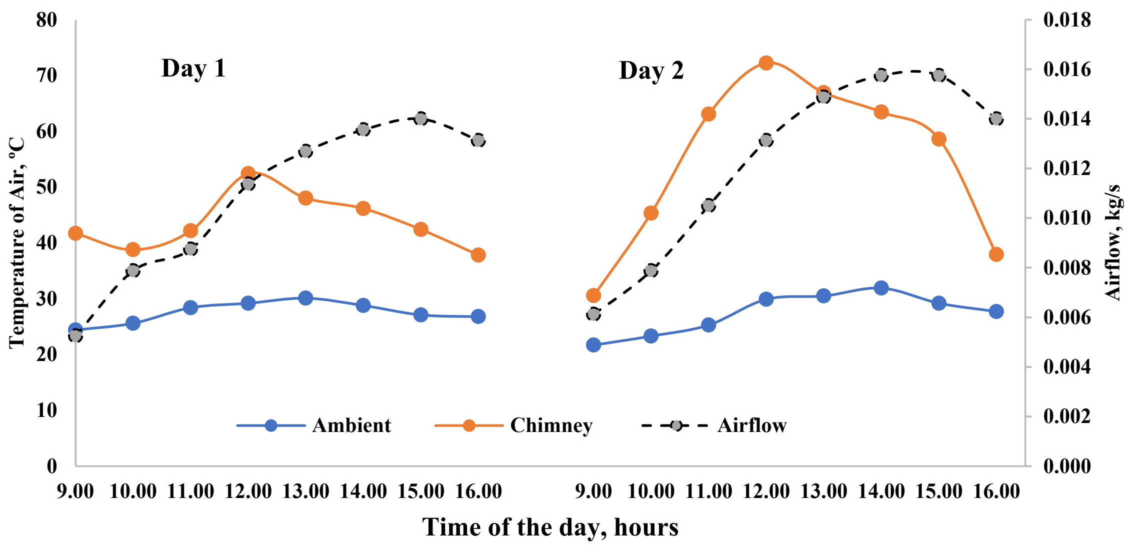

Figure 12. Average temperature in the Chimney and in the Ambient in relation to the Airflow in the dryer

3.2 Economic Analysis

Economic analysis of the natural convection solar tunnel dryer for drying bananas was done in order to provide some information on how feasible it is to invest in this drying venture. The economic analysis includes the Net Present Value (NPV), Profitability Index (PI), the Payback Period (PB) and the Discounted Payback Period.

3.2.1 Net Present Value (NPV)

The investment profitability of a project can be quantified by the present value of the cash inflows less the present value of the cash outflows during a certain period of time. This is referred to as the Net Present Value (NPV). The difference between the cash inflows and the cash outflows has to be greater than zero in order for the project to be considered profitable (Adams et al., 2019).

This project has one initial investment (cash outflow) at the beginning, followed by cash inflows. The Net Present Value for this project is calculated using equation (16);

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{\mathrm{FC_t}}{(1+r)^t} - \text{Initial Investment} \tag{16}$$

Where FC_t is the funds or revenue received at time t, r is investment rate of return, t is the specific year of investing, and n is the total number of years investing.

Table 1 shows the Net Present Value calculation. The cash out at Year 0 is the initial investment, comprising mainly of materials and labour to build the solar dryer. The overhead and maintenance costs are estimated to be 2% of the initial investment. The Cash Out comprises the cost of fresh bananas and the remuneration for the worker involved in the processing. The Cash In comes from the sales of dried bananas, and the selling price of ZMW150/kg, was obtained from a local supermarket that sells dried bananas. Using an average inflation rate in Zambia of 10.83% (average from 2005 to 2023) (Trading Economics, 2023), the annual running cost is projected to increase at a rate of 10.83%. (The figures are in Zambian Kwacha, ZMW. The exchange rate is USD1.00 = ZMW22.30 as of 3rd November, 2023 (Bank of Zambia, 2023). The dryer is considered to have a lifespan of 10 years. In the 11th year, at the end of the project, the dryer is sold at a sum of ZMW1,500.00, which is the estimated scrap value. The NPV of ZMW19,101.43 is realised at the end of the project and since this is greater than 0, we accept this project as it shows that investing in it can be viable. Akowuah et al., (2021) carried out financial as well as economic analysis of a hybrid maize solar dryer and found that the investment in the dryer was profitable and that it would create jobs and reduce on the postharvest losses of maize. For our current study, investing in the project would create employment for the local communities, add value to the bananas as well as increase the shelf life of these fruits.

Table 1. Net Present Value calculation (NPV)

Year	Cash In	Cash Out	Net	DF@10.83%	PV
0			-5,300.00	1	-5,300.00
1	21,900.00	5,300.00	2,741.34	0.90228	2,473.46
2	24,090.00	19,158.66	3,015.47	0.8141	2,454.90
3	26,499.00	21,074.53	3,317.02	0.73456	2,436.55
4	29,148.90	23,181.98	3,648.72	0.66278	2,418.30
5	32,063.79	25,500.18	4,013.60	0.59802	2,400.21
6	35,270.17	28,050.19	4,414.96	0.53958	2,382.22
7	38,797.19	30,855.21	4,856.45	0.48685	2,364.36
8	42,676.90	33,940.73	5,342.10	0.43928	2,346.68
9	46,944.59	37,334.81	5,876.31	0.39635	2,329.07
10	51,639.05	41,068.29	6,463.94	0.35762	2,311.63
11	1,500.00	45,175.12	1,500.00	0.3227	484.05
				NPV	19,101.43

3.2.2 Profitability Index (PI)

Profitability index (PI) is a financial metric that is used to measure the attractiveness of a project or an investment. To determine the PI, the present value of future expected cash flows is divided by the investment amount at the start of the project. The PI is given by equation (17) (Chen, 2023);

$$\text{Profitability Index} = \frac{\text{Present Value of Future Expected Cash Flows}}{\text{Investment at Start of Project}} \tag{17}$$

For a project to be considered a good investment, its PI should be greater than 1.0, while more attractive projects would have higher values of PI. A value of 4.6 is obtained in this project. Since PI is greater than 1.0, we invest in the project as it will be profitable. Further, since profitability index is greater than 1.0, it means that the project will generate more benefits than costs. The PI can be compared with other projects that may be competing for the same funding. According to Shimpy et al., (2023), the design of the solar dryer, its material cost and its efficiency in drying the food, can be used to improve the PI, by reducing the cost of the dryer, improving efficiency, and optimizing the design.

3.2.3 Payback Period

The payback period is the time it takes to recover the cost of an investment. It is determined by dividing the initial investment with the average cash flows. A payback period that is shorter, makes an investment more attractive than one that is longer. The payback period is useful when making investment decisions even though it does not consider the time value of money (Kiran, 2022).

Table 2 shows the Payback Period calculation. The payback period is 2 years. Akowuah et al., (2021) found that the initial capital investment and the drying charge affect the payback period of a maize solar dryer. They found a payback period of 2.7 years for the drying charge per bag of $2.11. Philip et al., (2022) describes the analysis of a greenhouse solar dryer with 100 kg capacity that was designed to produce high-quality dried products. They found that the dryer had a payback period of 1.5 to 2.1 years.

Table 2. Payback Period

Year	Cash Flow	Cumulative Cash Flow
0	-5,300.00	-5,300.00
1	2,741.34	-2,558.66
2	3,015.47	456.81
3	3,317.02	3,773.84
4	3,648.72	7,422.56
5	4,013.60	11,436.15
6	4,414.96	15,851.11
7	4,856.45	20,707.56
8	5,342.10	26,049.66
9	5,876.31	31,925.96
10	6,463.94	38,389.90
11	1,500.00	39,889.90

3.2.4 Discounted Payback Period

The Discounted Payback Period is the time it takes for the present value of cash inflows to equal the initial investment. It is useful in evaluating the profitability and timing of cash inflows of a project or investment. The shorter the time the discounted payback takes, the faster the project generates cash inflows and breaks even. The discounted payback period is determined by deducting discounted cash flows that occur during each year of the project from the initial cost (Kiran, 2022). Table 3 shows the Discounted Payback Period, this happens in the 4th year.

Table 3. Discounted Payback Period

Year	Cash Flow	Cumulative Cash Flow	DF@10.83 %	Discounted Cash Flow	Cumulative Discounted Cash Flow
0	-5,300.00	-5,300.00	1	-5,300.00	-5,300.00
1	2,741.34	-2,558.66	0.90228	-2,308.63	-7,608.63
2	3,015.47	456.81	0.8141	371.89	-7,236.74
3	3,317.02	3,773.84	0.73456	2,772.11	-4,464.63
4	3,648.72	7,422.56	0.66278	4,919.52	454.90
5	4,013.60	11,436.15	0.59802	6,839.05	7,293.95
6	4,414.96	15,851.11	0.53958	8,552.94	15,846.89
7	4,856.45	20,707.56	0.48685	10,081.48	25,928.36
8	5,342.10	26,049.66	0.43928	11,443.09	37,371.46
9	5,876.31	31,925.96	0.39635	12,653.86	50,025.31
10	6,463.94	38,389.90	0.35762	13,729.00	63,754.31
11	1,500.00	39,889.90	0.3227	12,872.47	76,626.78

4. Conclusion

The energy efficiency of the collector ranged from 5.56% to 57.32% and 14.15% to 59.16% on the first and second day respectively. This efficiency may be considered low but could be improved by incorporating heat transfer techniques in the solar collector. An efficient solar collector can be constructed to be smaller than a less efficient one and can impact positively on the cost of the solar dryer.

The dryer was effective in reducing the moisture content of the bananas from 73.89% to 14.27% in seven hours of drying on the first day, showing that it is effective. However, the maximum temperature reached in the drying chamber of 81.84ºC, can result in brittle slices as it is higher than the glass transition temperature. Therefore, putting in place a mechanism that limits the maximum temperature to 60ºC, would ensure quality dried product.

The chimney is a bare flat plate type without glazing and insulation, thus has high heat loss from its surfaces. Although it generated enough buoyancy to move air through the dryer, it could benefit from having glazing and insulation in place. A more detailed exergy analysis of the chimney would give how much improvement can be realised after the addition of the glazing and insulation.

The economic analysis included the Net Present Value (NPV), Profitability Index (PI), the Payback Period (PB) and the Discounted Payback Period. With the solar dryer lifespan of 10 years and the Discount Payback Period of four years, the project is attractive and worth investing in.

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