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Performance of Flexible PV Film Technology as an Auxiliary Energy Source in a Solar-Electric Hybrid Greenhouse Dryer

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Abstract Solar drying is an economical way to preserve agricultural produce. The intermittent nature of solar radiation necessitates use of supplementary energy for improved airflow rates and to supply heat during periods of low solar radiation. This study evaluated the performance of low-cost, flexible and lightweight solar PV film developed by Power Roll Limited (UK) for food drying application. Two tests were conducted (Trial 1: with fans only on; Trial 2: with fans and electric heater on) using a forced convection solar-electric hybrid greenhouse dryer at no load (empty drying beds). Test results shows that for Trial 1 the PV was able to run throughout the day, while Trial 2 the system run for 6 hours. Further, about 95% of the PV load power was used to run the fans, with the two fans using 144.1 ± 3.0 W and the maximum fan cumulative power was 961 Wh for Trial 1. For Trial 2, the PV load (1510-1524 W) was higher than the PV charge rate (304-694 W), hence the PV power declined to 30%. Further analysis showed that dryer temperatures increased by 5.05ºC at a radiation of 800 W/m^2 due to the heater. The results on drying of African nightshade (*Solanum scabrum*) indicated this 5.05ºC temperature increase realized through the auxiliary energy from the PV system improves drying substantially. The cost benefit analysis shows that usage of the PV system led to energy saving of about US$ 1.6 from 8.5 kWh of energy used within the 6 hours of PV system deployment.

Keywords Auxiliary energy, greenhouse dryer, performance, PV film, solar radiation.

1. Introduction

There are a large number of applications in which solar energy can be utilized directly by exploiting its heat characteristic, and according to Bhuttoa et al. [1], solar thermal technologies are comparatively simple, relatively low cost and easy to adopt for such purpose. The potential applications of solar thermal technologies include its use in drying agricultural products under controlled temperatures. This is more so given that energy consumed for drying is substantial and was estimated to be 10–15% of the total world industrial energy consumption [2]. The high price of energy in many countries makes the drying process relatively expensive. This has led scientific and technological research to look for the alternative sources of energy and optimum manner of consuming energy during the drying process.

Solar drying systems (where produce is contained in an enclosed space) are a better option to preserve agricultural produce, for example through drying, as they have a number of advantages; they are economic to install, have low cost of operation, and are efficient when compared to sun drying (where produce is exposed to directly to solar radiation) [3], [4]. However, solar systems have not been well adopted in developing countries where they have been promoted; with major challenges contributing to this including; technical challenges including limitations in capacities and low efficiencies, and financial challenges [5]. Another major challenge in use of solar energy is the intermittent nature of solar radiation and particularly during the low intensity periods of solar radiation [6]. This is because most convectional systems use solar energy with no backup. According to Akarslan [4], unreliability is the biggest retarding factor for extensive solar energy utilization, this is due to the intermittent nature of solar radiation.

One way to overcome the challenge of intermittent nature of solar radiation is to use backup energy. Various systems have been used to supply alternative energy in greenhouse dryer; with Kiburi et al. [7] and Gunasekaran et al. [8] indicating that backup energy provides supplemental heat to solar drying in an overcast day that raises the drying air temperature with magnitudes similar to those achieved on a clear day. The provision of backup energy to solar systems is meant to supply heat during times when solar radiation is low, for example when it is cloudy or when the ambient temperatures are low due to cold weather. Solar drying can also be improved through improved airflows, and according to Zomorodian and Dadashzadeh [9], forced convection not only significantly reduces drying time but also improves the quality of the dried products.

Review of literature shows that the use of solar energy, including from photovoltaic (PV) films, to run electric heaters for food drying using solar dryers (including greenhouse dryers), is limited. Most of the reviewed solar dryers have alternative source of energy such as biomass [7], [8], [10], [11], or heat collection systems such as stones or rock bed storage as back heat [12], [13]. In these and other designed dryers, solar is used in form of electric power to drive fans. According to Bennamoun [2], the main application of PV cells is their use in direct and indirect type forced convection dryers, generally for food and herb drying. According to this researcher PV cells have not been used sufficiently in the past particularly for solar drying due to their high prices and low efficiencies. This is a challenge the developers of PV films are trying to address.

The few applications that have used PV technology to run electric heaters in solar dryers have been for systems different from the one under this study. Reviewed literature indicates that most applications have been in enclosed and insulated cabinet dryers [14]–[16]; and mainly involving small dryers. Different heating systems have also been used in these studies; for example, trials by Ferreira et al. [15], used PV powered incandescent bulbs to provide the supplementary heat in a solar dryer; not an optimal application of PV given that up to 13% of energy in such bulbs goes to lighting [17], and given the short life span of such bulbs compared to electric coils. [18], studied application of solar where two PV modules (glass to glass) were used for thermal heating of a greenhouse dryer through greenhouse effect and also to run DC fans under forced convection.

A greenhouse dryer normally has no insulation on the walls; but according to a study by Mohammed et al. [19], the greenhouse warming effect in such dryers was responsible for boosting both the internal thermal solar energy and drying air temperature within the tested solar dryer, implying even without insulation such systems are able to realise high inside air temperatures. According to Hussein et al. [14], the efficiency of such dryer can be increased through use of combination of solar and heating element coil powered by PV, but points out that cost per unit of drying might be high in such systems; calling for a need to investigate technical economical prices of the deployed PV systems. This study is to investigate the deployment of a thin PV film in a commercial greenhouse dryer, and to monitor dryer and PV system parameters that would inform on future deployments of the PV films that are being developed. The PV film used in this study is one such system under development.

Use of grid electricity, liquefied petroleum gas (LPG), biomass or other artificial energies as backup energy to supply heat can be expensive. This is however the conventional energy used to run the fans and heaters in processing plants, including in dryers and even as backup energy in such systems. Most of these also have negative impact to the environment. According to IRENA [20], by 2050, solar technology is expected to be among the cheapest sources of power available, particularly in areas with excellent solar irradiation. Solar-run heater can therefore provide a cheap and environmentally friendly way of providing such energy [21]. Use of solar panels can be an option, but the systems require substantial space and are heavier and this pose challenges in their utilisation. Also, according to Hossam El-din [22] among the three common types of solar cells, amorphous thin-film has the lowest cost per watt, compared to monocrystalline and polycrystalline types. The amorphous thin-films or the PV films have been developed to overcome this challenge with use of solar cells. Information on usage of these films in solar drying is limited, but their application in industrial systems like drying would be ideal given their advantages.

The worldwide estimated projection for thin-film PV technology production capacity was more than 5000 MW by 2010 [23] and according to the report, improvement of the films has been ongoing for sometimes. Power Roll Limited (UK) has developed a low-cost, flexible and lightweight solar PV film as an alternative to existing PV technology. According to the company [24], the film has been produced at \$0.03/W and this according to the company is much cheaper than existing flexible PV solutions and delivers the lowest levelised energy cost of any solar technology.

A thin-film solar cell is a second generation solar cell that is made by depositing one or more thin layers, or thin-film of PV material on a substrate, such as glass, plastic or metal. PV module converts incident sunlight into electricity. Thin-film technologies continue to be developed over the years; they differ in performance and costs. There exist different types of films; the Amorphous silicon that existed in 1980 and continues to be improved, with today's best cell efficiencies being about 12%; the cadmium telluride whose efficiencies are high (almost 16% in the laboratory); the copper indium diselenide (and related alloys) cells that have reached nearly 18% efficiency under standard test conditions; Chalcopyrites with which highest efficiency of 19.9% for small area devices have been realised; and the film silicon and dye-sensitized cells that attempt to combine the strong performance of crystalline silicon devices with the attractive economic advantages of thin-film manufacture through large-area processing and reducing the thickness of silicon to lower cost of the film. However, these thin low thickness films have not achieved efficiencies of more than 11% [25], [26].

The drive to actualize clean energy sources in tropical countries like Kenya through use of solar technologies is inspired by these countries strategic location along the Equator. In many countries the problems such as the high initial cost, installation and maintenance expense, and the low efficiency of solar cells are still obstacles in realizing the solar energy as an alternative energy. As a result, according to Rukini et al. [27], Hamakawa [28] and Makrides et al. [29], thin film based PV are gaining attention in the market because of their lower price, are less bulky, and come in flexible and transparent form. However, despite these advantages and the potential of thin films due their performance improvements and cost reductions in recent years, thin-film technology remains lowly adopted and by 2018 it accounted for only 5% of the global solar PV market [20]. The low usage is still attributed to the technology high production cost, expensive commercialization, limited diversification in their uses and lack of information on their reliability.

Research to reduce costs continues to be undertaken, but also there is need to improve the reliability and undertake performance characterization of PV systems and subsystems by collecting, analysing and disseminating information on their technical performance and failures, providing a basis for their assessment, and developing practical recommendations for sizing purposes. Although thin-film PV modules have been in production for decades, the characterization of their performance including in outdoor conditions remains a topic of active research. This is because the field contains a diverse set of environmental conditions [30].

With continued research, the availability of numerous PV cell technologies in the market has necessitated the performance comparison and the viability of these technologies in actual weather conditions. According to Makrides et al. [29], for each PV technology type, manufacturers normally provide typical rated performance parameter information that include maximum power point power, efficiency and others, all at standard test conditions of solar irradiance 1000 W/m^2, air mass of 1.5 and cell temperature of 25°C. This combination of environmental conditions rarely occurs outdoors, and specification provided by manufacturer are therefore not sufficient to accurately predict PV technology operation under different climatic conditions and outdoor performance monitoring and evaluations of the technology is necessary [29]. Testing of such systems has mainly been conducted for PV modules, and this has been undertaken to evaluate how they perform in different environmental conditions [31]–[34].

Analysis of performance of hybrid solar systems also requires estimating the effects, to the drying condition, of the direct solar energy received through the glazing material. The relationship between temperature inside a solar dryer and solar radiation has been researched and reported by various authors. Condor et al. [35] and Condorí and Saravia [36] obtained linear relations between the solar dryer outlet temperature and the solar radiation. Similar findings have been realised by Ronoh et al. [37] and Tarigan [38]. Benhamoua et al. [39] assessed temperatures at different parts of a solar dryer at different solar irradiance and after several attempts they got different equations of different degrees and chose a quadratic equation, as it was the one that gave the highest coefficient of determination (R^2) closer to one.

It is evident from the foregoing review that a number of studies have been undertaken to test PV cells in different environmental setting to assess their performance. The literature review indicates that not enough work on testing of PV films in different settings has been undertaken, and documentation of such studies in Kenya was not identified from literature. The review also shows that there is limited application of PV films as auxiliary energy for heat supply in solar dryers, and particularly in greenhouse dryers. The review also points at the possibility of the stored energy, in the hubs, of supplying continuous drying during periods of low or no solar radiation. This study was commissioned to assess this potential of usage of a flexible PV technology in powering the forced convection and heating systems of a solar-electric hybrid greenhouse dryer.

2. Materials and Methods

2.1 Experimental Setup

The study was conducted at Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya (situated at 37.05 °E, 1.19 °S and altitude of 1550 m). A solar-electric hybrid greenhouse dryer (Fig. 1) measuring 4 m long, 2 m wide and 1.6 m high was used. The dryer had two AC fans rated 33-35 W and 100-110 W and an electric heater rated 1.5 kW. The centre part of the dryer is 2.1 m high. It is a gothic or gable roof type and covered with a 200-micron polythene cover material.

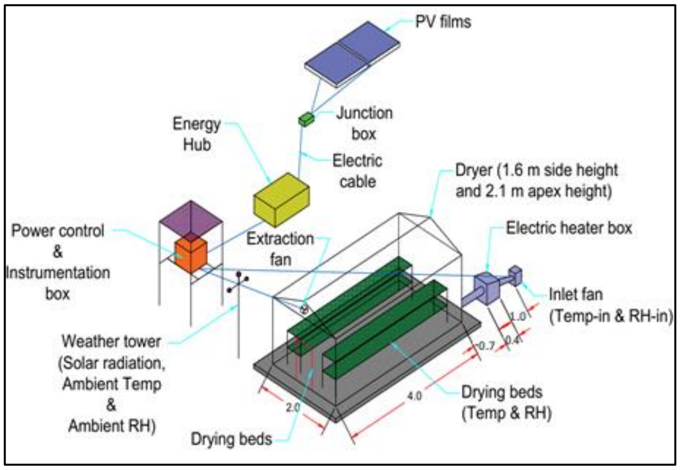

Fig. 1. Schematic diagram of an experimental setup

The dryer has a concrete base mixed with black oxide paint. It has internal ducts of 0.15 m diameter made of galvanized material. The ducts are 3.7 m long and are located below the two rows of drying beds. In each row, there are two drying layers and hence a total of four drying beds, each bed measuring 3.5 m long by 0.5 m wide. The distance from the dryer wall to the heater is 0.6 m, and from the heater to the outside fan is 1 m. The dryer has a blower (inlet) and an exhaust (outlet) fan to guarantee even distribution of the drying air [40]. The blower fan drives air through the heater, the ducts and the ducts openings; while the exhaust fan removes the air from the drying chamber. The inlet fan has two speeds and is rated 1380-1700 cfm and 100-110 W, while the outlet one is rated 547-800 cfm and 33-35 W. The fans provided average airflow rates of 1.7 m/s at the outlet; enough flow rates to sustain efficient drying.

Two fast-fold PV thin films, each with a peak power of 1 kW, were used for the tests undertaken in this study. Each PV film measured 5.5 m long, 2.267 m wide and 4 mm thick. The flexible solar modules are bonded to a high strength PVC-coated polyester fabric. Reinforced high frequency (HF)-welded hemmed border with steel eyelets are used for securing the mat. The PV films are connected to a fast-fold energy hub with quick release, secure IP68 cable. The energy hub (FFENERGYHUB-10, Renovagen, UK) measured 0.545 m wide by 0.863 m high, and weighed 125 kg. The energy hub has 10 kWh nominal battery capacity, 8 kWh usable battery capacity and maximum PV open circuit of 145 V and 70 A.

The dryer has been designed to dry agricultural produce such as fruits and vegetables. It has been designed and tested to dry African nightshade (*Solanum scabrum*).

The mass of water M_W (kg) to be removed was calculated based on what was stated by Olaniyan [41], as in (1).

$$M_W = M_f \left(\frac{MC_1 - MC_2}{100 - MC_2}\right) \tag{1}$$

where, M_f (kg) is the initial mass, MC_2 is the final moisture content (% w.b) and MC_1 is the initial moisture content (% w.b). The quantity of heat Q (kJ) required to be removed was estimated using the equation, as in (2), by Ajala et al. [42].

$$Q = m_p C_{pveg} \Delta T + 4.186 \times 10^3 \ \{597 - 0.56(T_{pr})\} \tag{2}$$

where, m_p is the mass of product (kg), C_{pveg} is specific heat of African nightshade (kJ/kg°C), ΔT is the change in temperature and T_{pr} is the product temperature (°C) taken as the average of maximum and minimum temperatures. A minimum temperature of 19°C, and an ideal maximum temperature for drying vegetables of 60°C were selected.

The amount of power or quantity of heat required per time was worked out based on a desired drying time of 6 hours as suggested by Tchiengue and Kaptouom [43].

With a capacity of 14 kg based on a loading of 2 kg/m^2 as reported by Shahi et al. [44], the required heater was found to be 1.5 kW, for an initial moisture content of 86.7% (w.b) reported by Gordon [45] for the African nightshade, and a final moisture content of 10% (w.b) for 60^{o}C [46]. With a thermal efficiency adjustment of 100%, the heater selected was 3.0 kW.

The PV film deployed was supplied with limited peak power capacity of 1.0 kW for each of the two films. The heater supported by the PV film was therefore expected not to achieve the maximum design temperature of 60^{o}C for lower temperature conditions, given the lower energy supply by the film. The study therefore assessed this change.

The fan selection was based on the equation by Ichsani and Dyah [47], as in (3).

$$m_a C_{pa}\left(T_i - T_f\right) = M_w L \tag{3}$$

where, m_a is the mass of drying air (kg), C_{pa} is the specific heat capacity of air at constant pressure (J/kg^{o}C), T_i and T_f are the initial temperature and final temperature of drying air, respectively (^{o}C), and L is the latent heat of evaporation of free water from the product (J/kg). The mass of air was calculated according to the formula stated by Ichsani and Dyah [47], as in (4).

$$m_a = \frac{M_w}{(\Delta W_{fi} \times n)} \tag{4}$$

where, ΔW_{fi} is change in humidity ratio which is the moisture that can be removed by the heated air; and n is the pickup factor, given as 0.25 by Ichsania and Dyah [47]. Using a minimum average temperature of 19^{o}C and average relative humidity of Juja as 70%, then ΔW_{fi} was determined using the psychometric charts. The volumetric flow rate was determined as a minimum of 0.16 m^3/s (340 cfm), and this was used to select suction fans in the market; the identified fans had a power rating of 33-35 W.

The ducts friction loss was calculated using an equation, as in (5), for galvanized steel circular duct [48].

$$\Delta p = 0.109136 q^{1.9} / d_e^{5.02} \tag{5}$$

where, Δp is friction or pressure loss (inches water gauge/100 ft of duct), q is air volume flow (cfm - cubic feet per minute) and d_e is equivalent duct diameter (inches).

A length of 3.7 m for the 0.15 m diameter double ducting and 1 m of a 0.3 diameter for the outside duct was used. The equivalent length method was used to estimate the pressure drops for the ducting bends and an L/D value = 20 was selected as stated by Wilson [49]. The total pressure drop was factored in inlet fan selection, and a fan of 0.35 m^3/s (741 cfm) was selected, and used to select a fan in the market with power rating of 100-110 W.

The PV heater was expected to drive these fans, as their combined power rating (a maximum of 145 W) was small.

2.2 Data Collection and Analysis

Two tests were conducted (Trial 1: with fans only on; Trial 2: with fans and the electric heater on). No-load data was collected during both tests. The instantaneous battery capacity, the PV system load (the total power being drawn from the hub) and PV charge data were collected from the PV hub system status and configuration panel. Data on solar radiation was collected using a pyranometer (LI-200R M200). Instantaneous and cumulative power usage by the heater and fans were measured using an AC-100A LCD panel digital power meter (FTVOGUE) and an electricity energy saving analyser (Zhengzhou Paiji Technology), respectively. Temperature and relative humidity were recorded using an E&E 071 sensor. Temperatures at various points of drying beds were monitored using Type K thermocouples, while the outlet air velocity was measured using a R.M. Young Wind Sentry anemometer (Model 03101, from Campbell Scientific). The data was logged using a CR1000 logger supported by a 32-channel relay multiplexer, both from Campbell Scientific.

Radiation and temperature data from the two tests were analysed using SPSS Version 20 and the corresponding relations established. The relations were used to assess the increase in temperature due to the backup energy.

3. Results and Discussion

3.1 Use of PV System for Running Dryer Fans

The PV film system was able to run the solar-electric hybrid greenhouse dryer under the two arrangements; with fans only and with fan and heater running. The solar radiation was not high (as is common in the month of September in Kenya) during days of trials. In the first trial (fans only) the PV was able to operate throughout the day, while in the second trial (heater and fans) the PV was able to run the system for six (6) hours. Figs. 2-4 show trends of the data from the two tests.

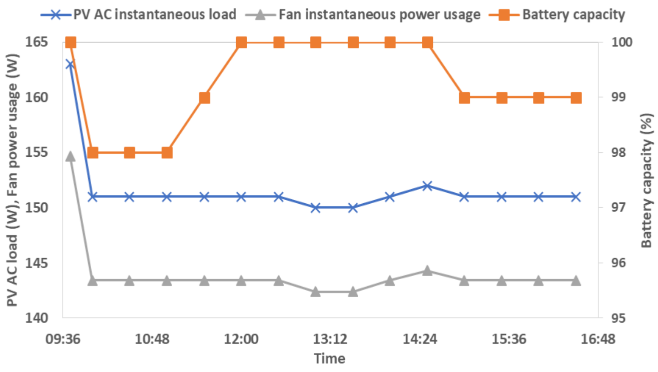

Fig. 2. Variation of PV AC load, fan power usage and battery capacity with time for Trial 1

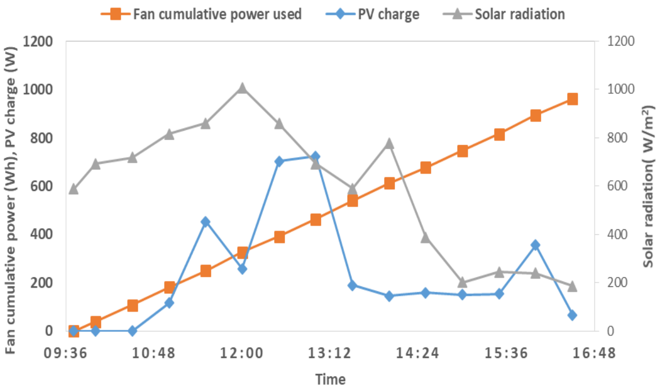

Fig. 3. Variation of fan cumulative power and PV charge with time for Trial 1

As depicted in Fig. 2, the PV system was able to maintain and sustain the charge at between 98 and 100% power. More specifically, 20, 33.3 and 46.7% of the total experiment time had power maintained at 98, 99 and 100% battery capacity, respectively. It was noted that 95% of the PV load power was used for running the dryer fans, and the two fans mostly used about 144.1±3.0 W of power. The rest of the power was used to run the hub, especially the hub cooling fan. Fig. 3 shows that the maximum fan cumulative power used by the fans during the period was 961 Wh. Radiation levels ranged between 185.9 to 1007 W/m^2 with an average of 570.8±272.5 W/m^2 (with ± being the standard deviation); this is lower than the daily average radiation in Kenya of 700 W/m^2. The PV instantaneous charge at the end of the indicated time ranged from 0 to 724 W, while the battery power at the end of the experiment was 99%. The PV load, that was in most cases 151.7±3.2 W, was not high to exhaust the battery power.

3.2 Use of PV System for Running Dryer Fans and the Heater

As shown in Fig. 4, the PV system was able to charge and sustain 30-95% of the system maximum power. The two fans consumed 136.3 to 140.2 W of power, and 800 Wh cumulatively. The average radiation ranged from 619.6 to 1062 W/m^2 with an average of 885.3±130.6 W/m^2 (Fig. 5); this is higher than the daily average solar radiation in Kenya. The PV instantaneous charge at the end of the indicated test period ranged from 304 to 694 W. The battery power at the end was 30%, which led to automatic switch-off of the PV system. The PV load ranging between 1510 and 1524 W or the combined instantaneous power of heater (that ranged from 1327 to 1331 W, as shown in Fig. 5) and fan (that ranged between 136.3 to 140.2 W, as shown in Fig. 4) was higher than the charge rate of the PV. This caused the PV power to decline to 30% and after 7675 Wh of power had been consumed by the heater. The heater cumulative power usage is shown in Fig 5.

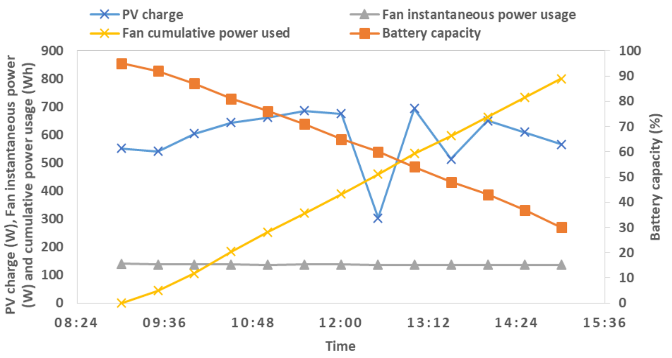

Fig. 4. Variation of PV charge, fan instantaneous and cumulative power usage, and battery capacity with time for Trial 2

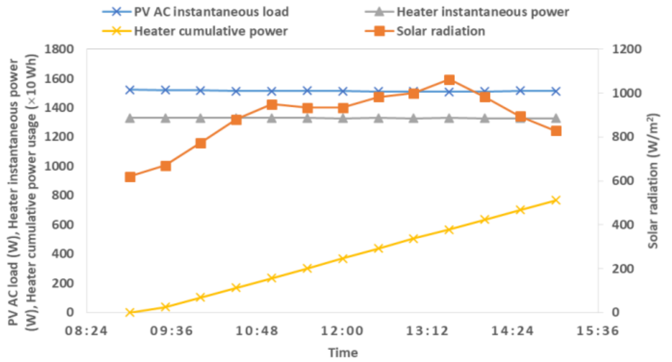

Fig. 5. Variation of PV AC load, heater instantaneous and cumulative power usage, and radiation with time for Trial 2

3.3 Variation of Temperature and Solar Radiation with Time

The changes in temperature and solar radiation during the test period are illustrated in Figs. 6 and 7. As presented in the figures, the temperatures in both systems increased with increase in solar radiation. The temperatures when the heater was used as a backup energy to solar radiation were more stable than for the solar energy only condition (Trial 1: 38.7±6.2°C; Trial 2: 50.2±4.7°C). The average solar radiation levels for Trials 1 and 2 were 570.2±275.9 W/m^2 and 857.2±143.7 W/m^2, respectively.

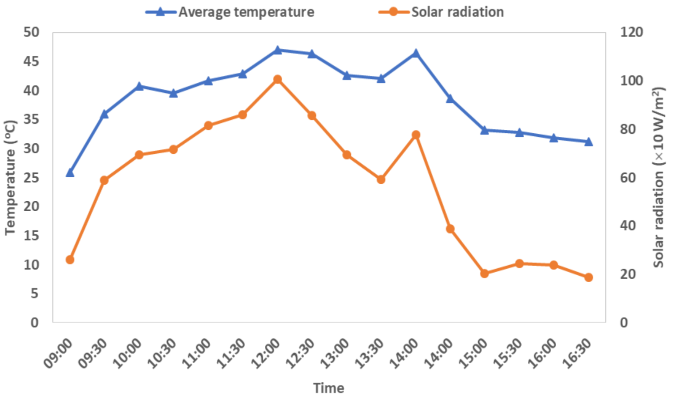

Fig. 6. Variation of temperature and radiation with time for Trial 1

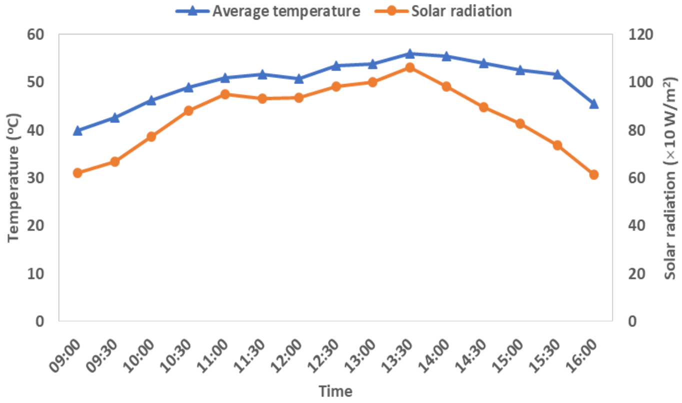

Fig. 7. Variation of temperature (inside the dryer) and radiation with time for Trial 2

The variation of inlet and heated air temperature (in the duct and after the heater) during the test period is shown in Fig. 8. The average inlet temperature was 29.1±2.1°C, while the corresponding average heated air temperature after the heater was 44.2±4.8°C. Generally, the electric heater was able to increase the ambient temperature by 52%.

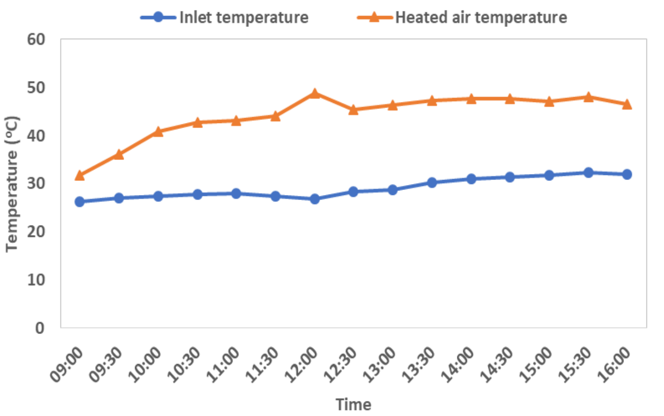

Fig. 8. Variation of ambient and heated air temperature (in the duct and after the heater) with time for Trial 2

3.4 Variation of Dryer Temperature and Ambient Temperature with Solar Radiation

Since the two experiments were done under different conditions, equations were selected to predict the increase in temperature due to the heater. Linear and nonlinear regression analyses were used to select the best relationship between the dryer temperature, ambient temperature and solar radiation data for the two experiments. The nonlinear regression was run for some polynomial equations with either or both of the radiation and ambient temperature values cubed or squared, or one of these values being raised to power one. The linear equation and the equation of the form, as in (6), gave the highest values of R^2 of 0.971 and 0.974, respectively for Trial 1, and 0.976 and 0.977, respectively for Trial 2.

$$T_d = a\,{T_{amb}}^2 + b\,R + c \tag{6}$$

where, T_d is the dryer temperature (°C), T_{amb} is the ambient temperature (°C), R is the solar radiation (W/m^2), a, b and c are coefficients.

Equations (7) and (8) were selected to predict dryer temperatures under Trial 1 and Trial 2, respectively. The two gave the highest R^2 of 0.974 and 0.977, respectively. Ronoh et al. [37] similarly performed regression analyses relating the temperature inside a tent dryer to the open sun temperature and solar radiation, and found a strong linear relationship with R^2 of 0.98.

$$T_d = 0.0278\,{T_{amb}}^2 + 0.0139\,R + 9.584 \tag{7}$$

$$T_d = 0.0186\,{T_{amb}}^2 + 0.0286\,R + 9.828 \tag{8}$$

Solar radiation data from 500 to 1200 W/m^2 were fitted into the two equations (i.e., (7) and (8)) under a selected average ambient temperature of 27.5°C, which is the average temperature in Trial 1. The trend is presented in Fig. 9. As seen in the figure, for radiation ranging from 500 to 1200 W/m^2, there was an increase in temperatures (0.64 to 10.93°C) due to usage of the backup energy. The increase in temperature at 800 W/m^2, which is approximate to the average solar radiation during Trial 2, was 5.05°C. The small difference in temperature from the two tests for lower values of radiation (less than 500 W/m^2 can be explained as being due to the estimation of Trial 2 equation using higher values of solar radiation (more than 612.1 W/m^2); therefore, leading to the selected equations' less explanation of the relationship between dryer temperature, ambient temperature and radiation for the lower radiation values.

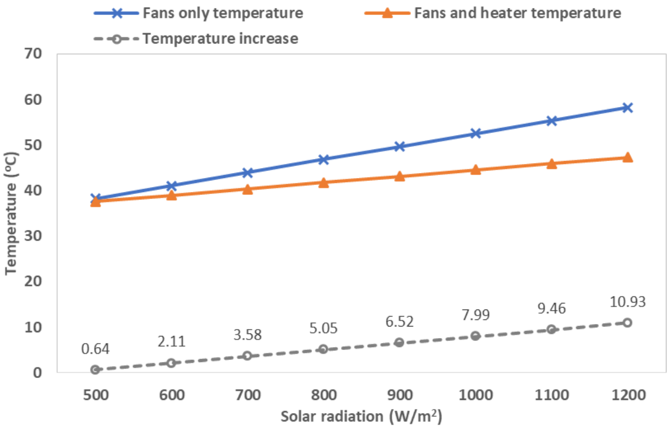

Fig. 9. Estimation of increase in temperature using the two prediction equations

The variation of ambient air temperature and relative humidity during the test period (Trials 1 and 2) is shown in Fig. 10. The average ambient temperatures for Trials 1 and 2 were 27.5±2.2°C and 29.1±2.1°C, respectively. The corresponding average ambient relative humidity were 37.6±6.5% (Trial 1) and 27.2±6.2% (Trial 2). The results demonstrated the inverse relationship between ambient air temperature and relative humidity.

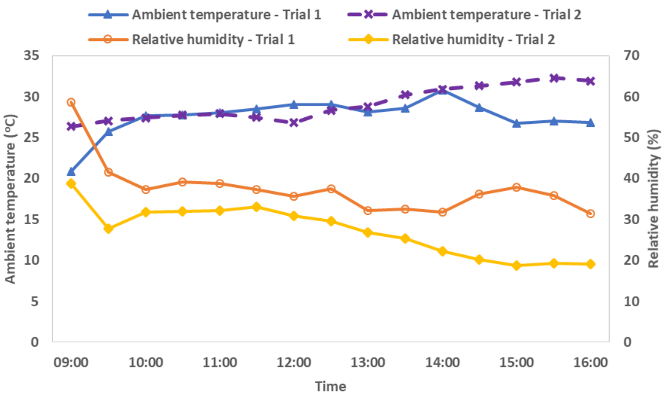

Fig. 10. Variation of ambient air temperature and relative humidity with time for Trial 1 and Trial 2

3.5 Effects of Improved Temperatures on Drying

Test results from the same solar-electric hybrid greenhouse dryer used in this study, and which was run on an electric heater that utilised grid electricity, show that slight improvement in temperatures results into improved drying (Fig. 11). African nightshade (*Solanum scabrum*) was dried under varied temperatures in the hybrid greenhouse dryer for 7 hours. The mean radiation levels for days 1 and 2 were 362.4±161.8 W/m^2 and 474.0±258.4 W/m^2, respectively.

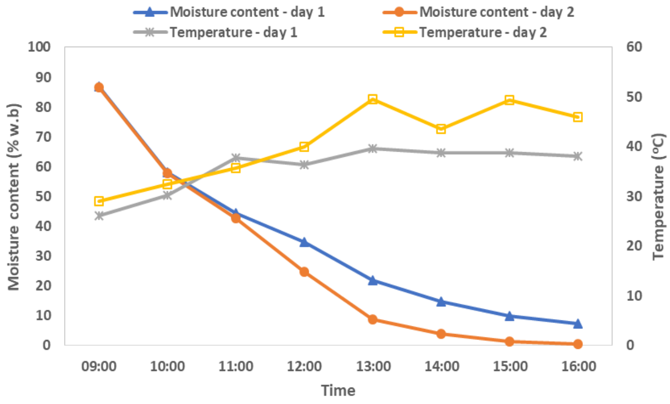

Fig. 11. Comparison of change in moisture content under different temperatures in the dryer.

As illustrated in Fig 11, at temperature of 40.7°C, the nightshade dried to a moisture content of 0.38% w.b, compared to 7.38% w.b when dried at 35.7°C. To attain a moisture content of about 9% w.b, it took approximately 5 hours to dry the produce at a temperature of 40.7°C and 7 hours at 35.7°C. This shows that drying of agricultural produce such as nightshade can improve substantially if temperatures increase by even 5°C; almost the same average increase realised through the auxiliary energy from the PV system. A faster drying rate of the produce on the second day can also be attributed to the high mean radiation levels compared to the first day.

4. Conclusion

The findings show that the PV film can be used as an alternative to other energy sources as backup energy to solar dryers and to run fans in solar drying. This capacity of the PV system used in this study is ideal for usage in agricultural activities in systems that utilise about 1 kW of power for the whole of daytime; about 10 hours. Larger capacity systems would be required where power requirement is higher than 1 kW.

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References

[1] A.W. Bhuttoa, A.A. Bazmi, and G. Zahed, “Greener energy: Issues and challenges for Pakistan – Solar energy prospective”, vol. 16(5), pp. 2762-2780, 2012.

[2] L. Bennamoun, “Integration of photovoltaic cells in solar drying systems”, *Drying Technology*, vol. 31(11), pp. 1284-1296, 2013.

[3] C. L. Hii, S. V. Jangam, S. P. Ong, and A. S. Mujumdar, *Solar drying: Fundamentals, applications and innovations*. Transport Phenomena Group, Singapore, 2012.

[4] F. Akarslan, “Solar-energy drying systems”, Department of Textile Engineering, Engineering and Architectural Faculty, Süleyman Demirel Univercity, Isparta Turkey, 2012.

[5] S. Karekezi, “Renewable energy development”, Paper presented in the Workshop for African Energy Experts on Operationalizing the NEPAD Energy Initiative, 2003.

[6] M. Y. H. Othman, and K. Sopian, “Options for solar drying systems: Perspective in Malaysia”, *JITE*, vol. 1(12), pp. 55-66, 2011.

[7] F. G. Kiburi, C. L. Kanali, G. M. Kituu, P. O. Ajwang, and E. K. Ronoh, “Performance evaluation and economic feasibility of a solar-biomass hybrid greenhouse dryer for drying banana slices”, *Renewable Energy Focus*, vol. 34(00), pp. 60-68, 2020.

[8] K. Gunasekaran, V. Shanmugam, and P. Suresh, “Modeling and analytical experimental study of hybrid solar dryer integrated with biomass dryer for drying *Coleus forskohlii* stems”, IPCSIT, 28, IACSIT Press, Singapore, 2012.

[9] A. A. Zomorodian, and M. Dadashzadeh, “Indirect and mixed modesolar drying mathematical models for Sultana grape”, *J. Agric Sci Technol*, vol. 11, pp. 391-400, 2009.

[10] O. Odhiambo, “Development of solar dryers for orange flesh sweet potato drying”, A GIZ Food Security and Drought Resilience Program Technical Report, 2015.

[11] S. N. Ndirangu, E. K. Ronoh, C. L. Kanali, U. N. Mutwiwa, and G. M. Kituu, “Design and performance evaluation of a solar-biomass greenhouse dryer for drying of selected crops in western Kenya”, *Agricultural Engineering International: CIGR Journal*, vol. 22(3), pp. 219-229, 2020.

[12] M. Nemś, A. Nemś, and P. Pacyga, “A granite bed storage for a small solar dryer”, *Materials*, vol. 11(10), pp. 1-16, 2018.

[13] G. B. Tchayaa, J. H. Tchamib, M. Kamtab, and C. Kapseub, “Solar energy storage in an indirect solar dryer (ISD) with stone for drying”, *Journal of Solar Energy Research*, vol. 3(1), pp. 81-85, 2018.

[14] B. Hussein, M. A. Hassan, S. A. Kareem, and K. B. Filli. “Design, construction and testing of a hybrid photovoltaic (PV) solar dryer”, *International Journal of Engineering Research and General Science*, vol. 3(5), pp. 1-14, 2017.

[15] A. G. Ferreira, A. Charbel, and J. G. Silva, “Experimental analysis of a hybrid dryer”, *Thermal Engineering*, vol. 6(2), pp. 3-7, 2007.

[16] O. Taşkın, N. İzli, and A. Vardar, “Analysis on photovoltaic energy-assisted drying of green peas, *International Journal of Photoenergy*, vol. 2016, Article ID 3814262, pp. 1-8, 2016.

[17] D. C. Agrawal, H. Leff and V. J. Menon, “Efficiency and efficacy of incandescent lamps, *American Journal of Physics, vol.* 64 (5), pp. 649-654, 1996

[18] P. Barnwal and A Tiwari, “Design, construction and testing of hybrid photovoltaic integrated greenhouse dryer”, *International Journal of Agricultural Research*, vol. 3(2), pp. 110-120, 2008.

[19] S. Mohammed, N. Fatumah, and N. Shadia, “Drying performance and economic analysis of novel hybrid passive-mode and active-mode solar dryers for drying fruits in East Africa”, *Journal of Stored Products Research*, vol. 88(3), 101634, 2020.

[20] IRENA, “Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects”, A Global Energy Transformation: paper, *International Renewable Energy Agency, Abu Dhabi*, 2019.

[21] C. Kanali, G. Kituu, U. Mutwiwa, J. Mung’atu, E. Ronoh, S. Njuguna, M. Kamwere, and L. Mulamu, “Energy efficient rural food processing utilising renewable energy to improve rural livelihoods in Kenya”, RE4Food (Renewable Energy for Food Processing) project funded by Engineering and Physical Sciences Research Council (EPSRC), UK, Published by Jomo Kenyatta University of Agriculture and Technology, Kenya, 2017.

[22] A. A. Hossam El-din, C. F. Gabra, and A. H. H. Ali, “A comparative analysis between the performances of monocrystalline, polycrystalline and amorphous thin film in different temperatures at different locations in Egypt”, in 1st Africa Photovoltaic Solar Energy Conference and Exhibition, Durban, March 2014.

[23] H. S. Ullal, “Overview and challenges of thin film solar electric technologies”, Paper presented at the World Renewable Energy Congress X and Exhibition 2008, Glasgow, Scotland, United Kingdom, 2008.

[24] Power Roll (2020, September 24). Power Roll has developed a new way to generate and store energy [Online]. Available: https://www.powerroll.solar.

[25] K. Zweibel, “Thin film photovoltaics” Report Presented at the Technology's Critical Role in Energy and Environmental Markets conference Albuquerque, New Mexico October 18-21, 1998 NREL/CP-520-25262, 1998.

[26] A. Jäger-Waldau. “Status and perspectives of thin film photovoltaics”, in *Thin Film Solar Cells: Current Status and Future Trends*, Chapter 1, Publisher: Nova Science Publishers, Inc., 2011.

[27] A. Rukini, L. Suhaimi, A S. Pradhipta, and M. Anggara, “An analysis of potential utilization of low cost Cu2ZnSnS4 thin film based photovoltaic in Sumbawa”. IOP Conference Series: Earth and Environmental Science, vol. 396, 012011, pp. 1-10, 2019.

[28] Y. Hamakawa. Thin-film solar cells. Next generation photovoltaics and its applications. Published by Springer-Verlag

Berlin Heidelberg New York. ISSN 1437-0379. ISBN 978-3-642-07879-8, 2004.

[29] G. Makrides, B. Zinsser, M. Norton, and G.E Georghiou, Performance of photovoltaics under actual operating conditions, third generation photovoltaics, Dr. Vasilis Fthenakis (Ed.), ISBN: 978-953-51-0304-2, InTech, (2012). Available from: http://www.intechopen.com/books/third-generationphotovoltaics/performance-of-photovoltaics-under-actual-operating-conditions. Accessed on 8th September, 2021.

[30] T J. Silverman, U. Jahn, M. Apolloni, A. Louwen, W. Sark, M. Schweiger, G. Belluardo, J. Wagner, A. Tetzlaff, P. Ingenhoven, and D. Moser, Characterization of performance of thin-film photovoltaic technologies. International energy agency photovoltaic power systems programme. Report IEA-PVPS T13-02:2014. ISBN 978-3-906042-17-6 (2014).

[31] J. Kurnik, M. Jankovec, K.Brecl and M. Topic, "Outdoor testing of PV module temperature and performance under different mounting and operational conditions". *Solar Energy Materials and Solar Cells*, vol. 95(1), pp. 373-376, 2011.

[32] M. A. Bashir, H. M. Ali, S. Khalil, M. Ali, and A.M. Siddiqui, "Comparison of performance measurements of photovoltaic modules during winter months in Taxila, Pakistan", *International Journal of Photoenergy*, vol. 2014, Article ID 898414, pp. 1-8, 2014.

[33] L. Premalatha and N. A. Rahim, "The effect of dynamic weather conditions on three types of PV cell technologies – A comparative analysis', *Energy Procedia*, vol. 117, pp. 275-282, 2017.

[34] A. Zdyb, and S. Gulkowsk, "Performance assessment of four different photovoltaic technologies in Poland", *Energies*, vol. 13(1), 196, pp. 1-17, 2020.

[35] M. Condorí, M. R. Echazú, and L. Saravia, "Solar drying of sweet pepper and garlic using the tunnel greenhouse drier", *Renewable Energy*, vol. 22(4), pp. 447-460, 2001.

[36] M. Condorí, and L. Saravia, "Analytical model for the performance of the tunnel-type greenhouse drier", *Renewable Energy, vol*. 28(3), pp. 467-485, 2003.

[37] E. K. Ronoh, C. L. Kanali, J. T. Mailutha, and D. Shitanda, "Modeling thin layer drying of amaranth seeds under open sun and natural convection solar tent dryer", *Agricultural Engineering International: the CIGR Ejournal*, Manuscript 1420. vol. XI., 2009.

[38] E. Tarigan, "Mathematical modeling and simulation of a solar agricultural dryer with back-up biomass burner and thermal storage", *Case Studies in Thermal Engineering*, vol. 12, pp.149-165, 2018.

[39] A. Benhamoua, F. Fazouane, and B. Benyoucef, "Simulation of solar dryer performances with forced convection experimentally proved, *Physics Procedia*, vol. 55, pp. 96-105, 2014.

[40] A. Tiwari, "A review on solar drying of agricultural produce", *Journal of Food Processing and Technology*, vol. 7(9), pp. 1-12, 2016.

[41] A. M. Olaniyan, "Conceptual design of a charcoal-fired dryer", Proceedings of International Conference of Agricultural Engineering, Zurich, 06-10.07.2014.

[42] A. S. Ajala, P. O. Ngoddy, and J. O. Olajide, "Design and construction of a tunnel dryer for food crops", 21st SAAFoST Biennial International Congress & Exhibition, 6-9 September 2015, Southern Sun Elangeni/Maharani Complex, Durban, South Africa, 2015.

[43] E. Tchiengue, and E. Kaptouom, "Influence of technological factors on the rate of drying of vegetables using solar thermal energy. Solar drying in Africa", in Proceedings of a workshop held in Dakar, Senegal, 1987.

[44] C. Shahi, A. Singh, and A. E. Kate, "Development of solar poly house tunnel dryer (STD) for medicinal plants", *World Academy of Science, Engineering and Technology, International Journal of Agricultural and Biosystems Engineering*, vol. 9(12), pp. 1269-1275, 2015.

[45] Y. Gordon, "Food Drying", in Proceedings of a workshop held at Edmonton Alberta, 1981.

[46] U. Singh, and V. R. Sagar, "Quality characteristics of dehydrated leafy vegetables influenced by packaging materials and storage temperature". *Journal of Scientific & Industrial Research, v*ol. 69, pp. 785-789, 2010.

[47] D. Ichsani, and W. A. Dyah, "Design and experimental testing of a solar dryer combined with kerosene stoves to dry fish", *American Society of Agricultural and Biological Engineers*, pp. 1-3, 2002.

[48] Engineering Toolbox (2003, April 26). Friction loss in air ducts - online calculator [Online]. Available: www.engineeringtoolbox.com/duct-friction-pressure-loss-d_444.html.

[49] H. Wilson (2014, April 26). Equivalent lengths of pipe fittings and valves: Tables of equivalent lengths in plastic and steel pipe. Katmar 2014-2020 Software [Online]. Available: https://www.katmarsoftware.com/articles/pipe-fitting-equivalent-length.htm.