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Comparative Analysis of Hybrid Photovoltaic Thermal (PV/T) Solar Dryer

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Abstract: As the world's population is increasing, the demand for food is also increasing. Drying techniques increase the life and quality of crop and industrial food products. It also improves the economic condition of farmers. Drying reduces the water stored within the product by evaporation. It can be done by the use of conventional energy and different methods. Sun radiation is used for open sun drying around the globe. Open sun drying has many disadvantages in comparison to other drying techniques. Solar drying is comparatively clean and effective. Solar dryers are of mainly four types: 1) direct solar dryer; 2) indirect solar dryers; 3) mixed mode solar dryer and 4) hybrid solar dryers.

Because electric and heat energy demand is increasing day by day worldwide, PV/T solar dryer becomes an interesting and upcoming interest of research nowadays. In this review article basics of different kinds of solar dryers and recent advancements in hybrid PV/T dryers have been presented. Results for drying grapes, medicinal herb, tomato, and wood using PV/T solar dryer are discussed in this study. Variations of drying time, energy consumption, efficiency with different air temperatures, air flow rate and RH are discussed. The use of different solar collectors, solar air heater and heat storage materials with hybrid PV/T dryer have also been reviewed.

Key words: Drying, solar dryers, greenhouse drying, photovoltaic thermal (PVT), conventional PVT systems.

Introduction

Solar energy is the oldest source of energy ever known to us. The sun was worshiped as God by many civilisations. Almost all natural phenomena are related to the Sun in one or another way (Kalogirou, 2004). Plants maintain life on Earth by converting carbon dioxide and sunlight in the presence of water and air into food and oxygen. Sun's energy is extracted in the form of electricity and heat by PV cells and solar thermal collectors (Tiwari, 2012). A solar system that produces electricity, as well as heat, collectively is called a photovoltaic thermal system (PV/T system) (Kumar et al., 2015).

Solar energy is non-conventional, environment-friendly and abundantly available free of cost energy resource on the Earth (Tiwari et al., 2009). Several domestic, commercial and industrial processes require drying. The drying process involves two steps in water removal:

1. Taking the moisture out from the object to the outer layer.
2. Migration of water from the outer layer to the environment in the form of water vapours (Belessiotis and Delyannis, 2011).

In industry, a huge part of the energy is utilised in drying objects. In the timber industry, more than

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50% of used energy is consumed only for drying the wood (Piratesh et al., 2014). Drying is used in various industries such as textile, clay brick production, cement, wastewater treatment, wood, biomass fuel, dairy industry, drying crops to preserve them and drying herbs, drying fruits, etc. Conventional dryers in industries use fossil fuels and energy from conventional power grids, which generate a high amount of greenhouse gas emissions. Utilising the sun's energy conversion system and regaining the unused heat could reach zero-carbon emission goals for industries. Solar dryers are arrangement that uses energy from the sun's radiation for drying the product.

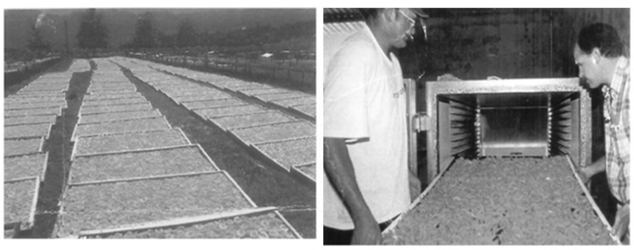
In this work, different classifications of the solar dryer are discussed with a focus on the utilisation of a solar photovoltaic thermal system because it produces heat as well as electricity simultaneously.

Classification of Solar Dryers

Solar thermal dryers are broadly categorised into categories: open sun, direct, indirect, mixed, passive mode, and active mode.

Open Sun Drying

In open sun drying (OSD), a thin layer of the crop is spread over the ground and is under direct sun for drying in ambient conditions (Jain and Tiwari, 2000). Traditional OSD has many disadvantages such as deterioration by rainwater, insect infestation, human and animal invasion and air blown trash which result in the contamination of crops (Fargali et al., 2008). To keep the good quality of the product in OSD as per international standards is almost impossible. Figure 1a shows the halves of peaches kept for drying, in south Africa (Belessiotis and Delyannis, 2011). The peaches are kept outdoors for open sun drying, in Figure 1b. OSD is replaced by a small chamber hot air dryer operated by electricity. The alternative of open sun dryer on the other hand consumes energy from conventional sources and hence increases carbon dioxide emission and the cost of the process of drying.



(a) (b)

Figure 1: Peach drying in South Africa: (a) By OSD and (b) in electric dryer (Belessiotis and Delyannis 2011).

Direct Solar Dryer

The temperature of the drying product increases with the absorption of the sun's radiation which is the working principle of this kind of solar dryer. Othieno (1986) designed the simplest solar cabinet dryer as shown in Figure 2. A simple wooden box was used for the cabinet. The size of this box is 2m × 1m. The bottom of this dryer could be portable and could be made from a sheet of metal or wood. To cover the dryer polyethylene sheet was used, the polyethylene sheet was transparent. For the circulation of air, holes are cut in the side of the dryer.

Minka (1986) concluded that temperatures inside the direct cabinet dryer, as shown in Figure 3, increased by about 30°C from the ambient temperature. A variety of crops can be dried from the cabinet dryer.

Cabinet dryer has many limitations as follows: (1) due to direct exposure to the Sun discolouration of the dried product, (2) transmittivity of the glass cover reduces due to vapour condensation on the inner surface and (3) due to its limited capacity, it is applicable for small scale application.

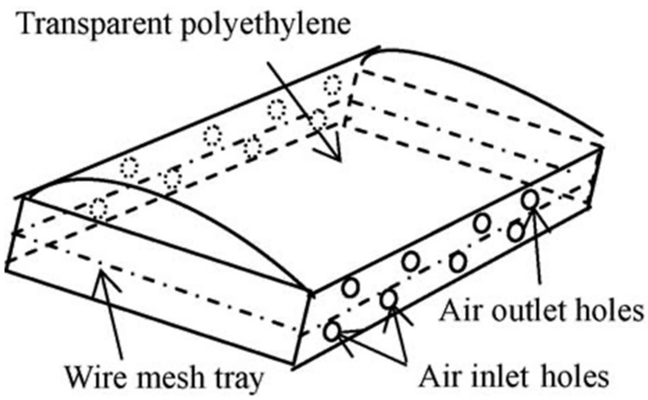


Figure 2: Direct solar dryer (tray type) (Othieno, 1986).

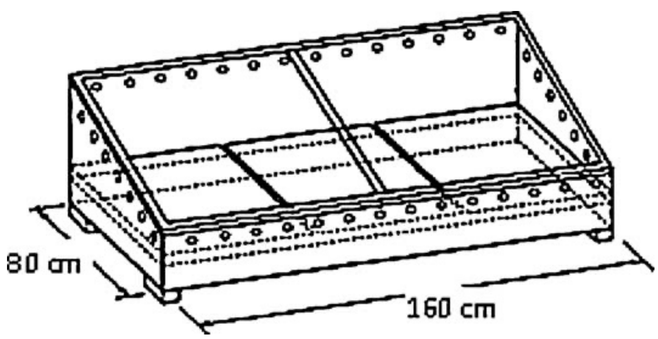


Figure 3: Direct cabinet dryer (Minka, 1986).

Indirect Solar Dryer

To reduce discolouration and cracks on the surface of the crop, indirect solar dryers are used. The solar radiation transmitted by the glass cover is absorbed by collectors and applied to the cabinet of the dryer (Goyal and Tiwari, 1996). Air is circulated for drying the crop. Air goes out of the dryer from the exhausting vent. Goyal and Tiwari developed a dryer based on this concept as shown in Figure 4

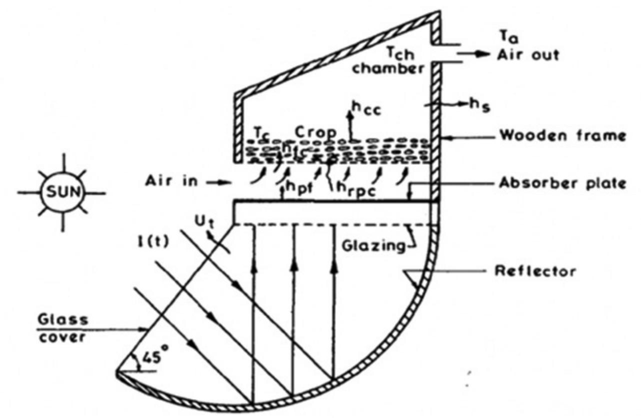


Figure 4: Basic diagram of reverse absorber cabinet dryer (Goyal and Tiwari, 1996).

Mixed Mode Solar Dryer

Sun's radiation as well as heated air both are used for drying the crop in mixed mode solar dryer. A lot of studies have been carried out by many researchers recently on mixed-mode solar dryers. Figure 5 shows a mixed mode solar dryer used for rubber sheets. The quality of rubber sheets dried in mixed mode solar dryer was much better than sheets dried in the open sun

Figure 5: Experimental set up of mixed mode solar dryer (Andharia et al., 2020).

Hybrid Solar Dryer

In hybrid solar dryer heat and electricity are produced by the solar thermal collector as well as by some auxiliary means and hence called a hybrid solar dryer. A hybrid solar dryer is useful under all weather conditions as it can be operated with only non-conventional or only convectional or with both types of energy sources (Lamrania et al., 2019).

Figure 6 shows the medicinal herb dryer. This is a hybrid system that has a solar heat collector as well as a biogas heater system. A controlled medicinal herb drying system using PV to feed the electrical load of the dryer and solar thermal and biogas fuel for heating drying air was proposed and developed by Fargali et al. (2008).

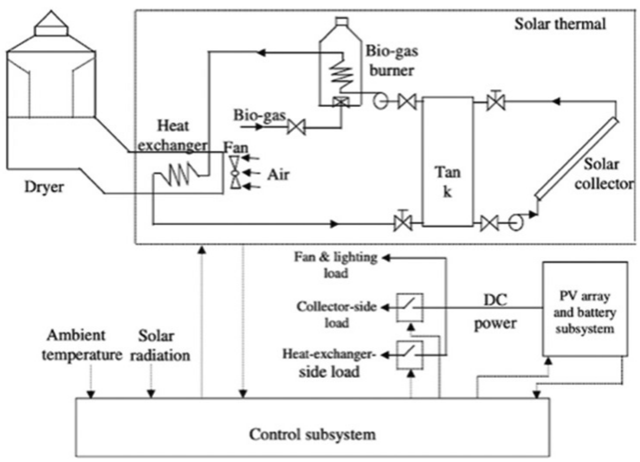


Figure 6: The medicinal herb dryer system (Fargali et al., 2008).

Passive and Active Mode Solar Dryer

Air in the solar dryer can be circulated naturally or by artificial methods. When air is circulated naturally, the dryer is known as working in passive mode and when air is circulated by using a fan it is known as an active mode solar dryer. Baranwal and Tiwari (2008) and Pawar et al. (1995) found that the quality of the product is better in forced mode than in natural mode drying.

Table 1 depicts findings from various research on solar dryers.

Photovoltaic Thermal System for Solar Dryers

Photovoltaic module converts the sun's radiation into electrical energy directly. The photovoltaic module has very low efficiency and converts only up to 20% of strike energy into electricity, part of the remaining

Table 1: Results of various solar dryer

Category of solar dryer	*Reference*	*Key finding*
Direct Solar dryer	Bentayeb et al. (2008)	Wood solar dryer could be used in Morocco.
	Onuigboet al. (2017)	The rate at which the product is dried in OSD was not satisfactory as compared to solar dryer.
	Ondier et al. (2010)	Drying rate can be increased by dehumidification of drying air.
Indirect Solar dryer	Goyal and Tiwari (1997)	Performance of indirect solar dryer was better.
	Lamrani and Draoui (2020)	With use of PBES system with an indirect solar dryer decreases the wood drying time by 15% in comparison of conventional indirect solar dryer
	El-Sebaii et al. (2002)	Storage of energy and chemical pretreatment of crop reduces the time of drying too much.
Mixed Mode Solar Dryer	Simate (2003)	The cost of drying of mixed mode dryer was less in comparison to indirect mode solar dryer. The distribution of moisture in dry crop was uniform in mixed mode solar dryer.
	Tiwari and Tiwari (2016)	This greenhouse dryer works well in all weather conditions.
Hybrid Solar Dryer	Barnwal and Tiwari (2008)	For ripened grapes the convective heat transfer coefficient is higher than GR-I grapes and hence fast drying.
	Lopez-Vidanaet al. (2013)	The hybrid drying system consumes 20 % less fuel in comparison to LPG drying system without compromising the quality of dried product.

energy is converted into heat, reflected and transmitted through the module. With increasing temperature solar cells' efficiency decreases. Excess heat can be extracted and used for low heat application by circulating fluid (air/water). Refrigerants, phase change material, heat pump, nanofluid set care other heat removal methods. In this study, different uses of PV/T technology in solar dryers are discussed and shown.

Grape Drying

Figure 7 shows hybrid photovoltaic thermal greenhouse dryer developed by Barnwal and Tiwari (2008) for drying grapes.

Figure 7: Hybrid PV/T integrated greenhouse dryer (Baranwal and Tiwari, 2008).

A transparent polyethylene sheet has been used for green house. Two PV module was used on the south roof of the dryer. The modules provide the dc power for the active operation of the dryer as well as the heating of the greenhouse (Baranwal and Tiwari, 2008). Figures 8 and 9 shows the grapes before drying and after drying. Figure 9 shows the result of drying in a greenhouse, shade and open sun.

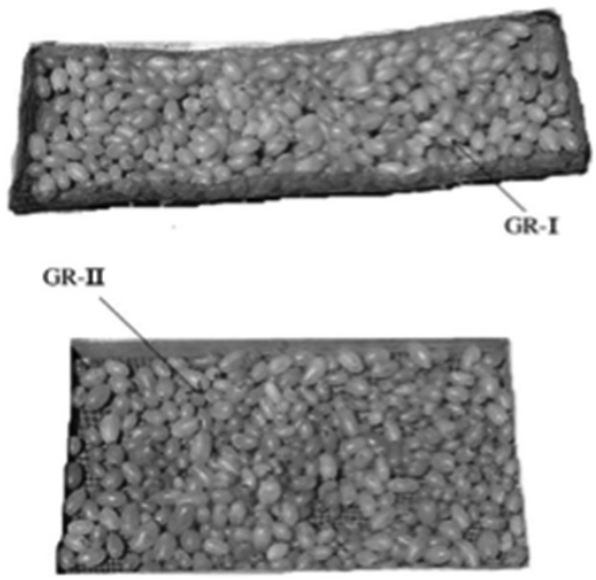


Figure 8: Grape picture before experiment (GR-I and GR-II) (Baranwal and Tiwari, 2008).

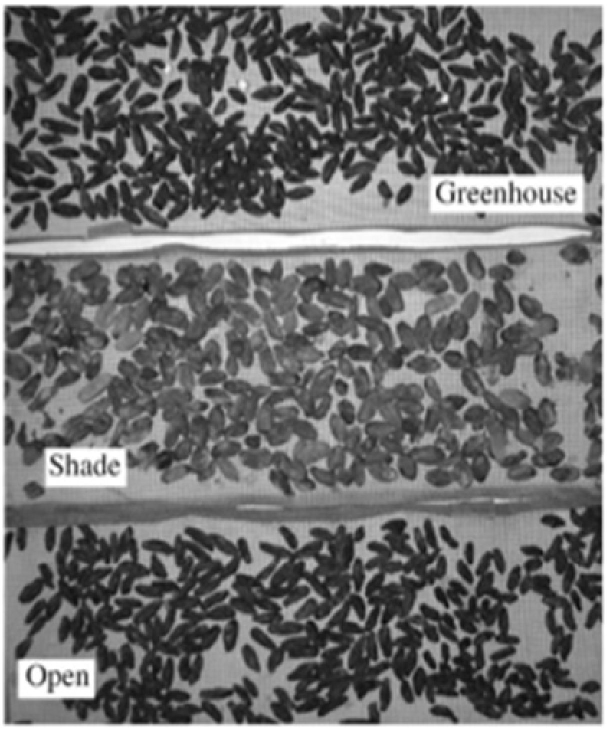


Figure 9: Grape picture after experiment (GR-I) (Baranwal and Tiwari, 2008).

Saffron Drying

Saffron flower has a very beautiful colour, smell, and flavour. Saffron is cultivated in many countries around the world. Saffron spice is made by drying fresh saffron stigma. Figures 10 and 11 show the schematic representation and experimental set up of the dryer designed by Mortzapour et al. (2012).

This dryer consists of two basic parts a PV/T panel and a heat pump unit, the experimental set up is designed to create a closed cycle of air flow. A 120 W PV panel is used, and the glass sheet is used as the cover of the collector. R134a refrigerant is used as it is easily available and clean in use. 10 cm diameter air duct is used for air flow by a dc fan supplied by a 12 V battery. Hot and humid air from the dryer outlet is dehumidified and cooled in the evaporator and supplied to the solar collector to absorb heat from the PV panel which is further heated by heat recovered by the condenser (Mortzapour et al., 2012). Figures 12 and 13 show the effect of air flow rate, heat pump, and drying air temperature on energy consumption and dryer efficiency. Increased air flow rate and drying air temperature result in a decrease in energy consumption because of a reduction in drying time. Energy consumption decreases with the use of heat pump units because of the recovery of waste heat and reduced drying period.

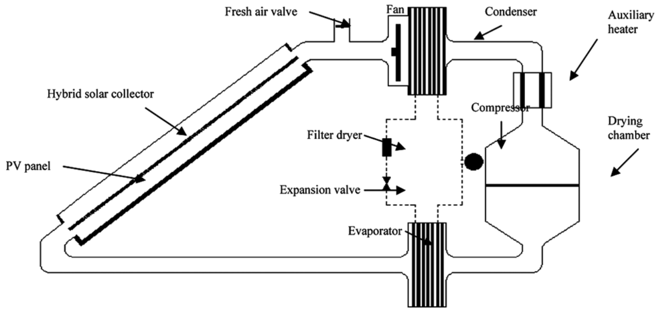


Figure 10: Saffron dryer schematic diagram (Mortzapour et al., 2012).

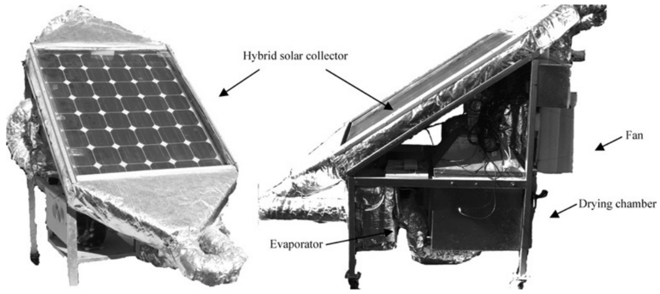


Figure 11: Experimental set of fabricated dryer (Mortzapour et al., 2012).

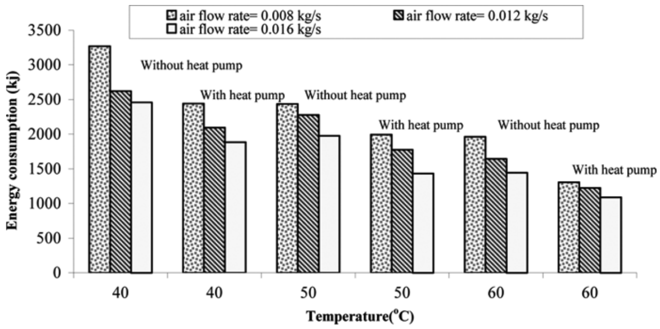


Figure 12: Comparison of energy consumption under different condition (Mortzapour et al., 2012).

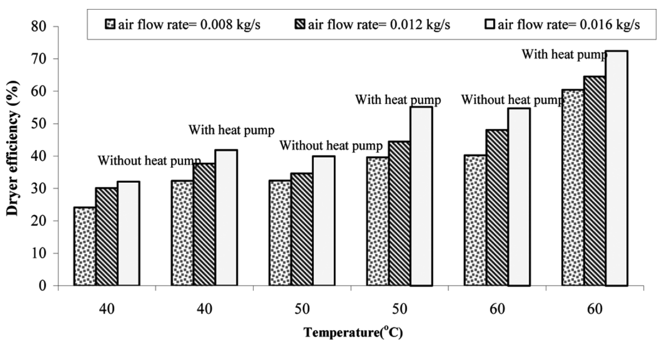


Figure 13: Comparison of dryer efficiency air flow rate, heat pump, and drying air temperature (Mortzapour et al., 2012).

Tomato Drying

In solar dryers, exhaust air still has thermal energy which can further be extracted to improve the efficiency of solar and decrease the energy payback time of the system. The hot air from the exhaust of the solar dryer is recirculated into the system again. The relative humidity of circulating air is increased in this process which results in a decrease in vapour absorption capacity of air (Dorouzi et al., 2018). In this experiment, an indirect solar dryer having a liquid desiccant bed and a photovoltaic thermal desiccant regeneration system is used. Figure 14 depicts an experimental photograph of the study.

A 500 gm of good quality tomatoes were used, washed with chlorinated water, drained, and kept in a refrigerator. A 5 mm thick slice of tomato was dried in a solar dryer. Three different temperatures and three RH values were selected. Figure 15 a,b shows the picture of the tomato before and after drying.

The time taken for dry tomato at different drying conditions is shown in Figure 15c. The graph shows that drying time is reduced by 10% when the temperature increases from 60°C to 70°C. Also drying time was reduced by 27% when applying the activation RH of 18% instead of 28%.

Figure 15d shows the variation of redness of dried tomato. Redness reduces with an increase in the RH, it is because of the long drying time at elevated RH in the dryer.

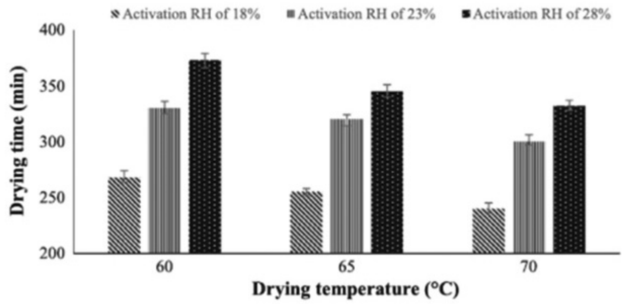


Figure 15c: Drying time at different conditions of RH and temperature (Dorouzi et al., 2018).

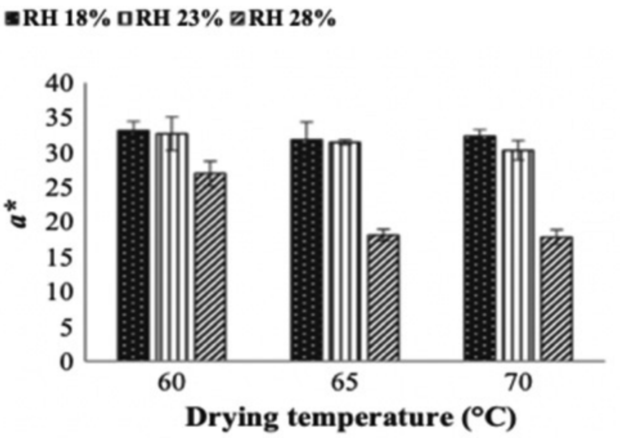


Figure 15d: The colour changes of tomato slices at different RHs and temperatures of solar drying process as given by redness (Dorouzi et al., 2018).

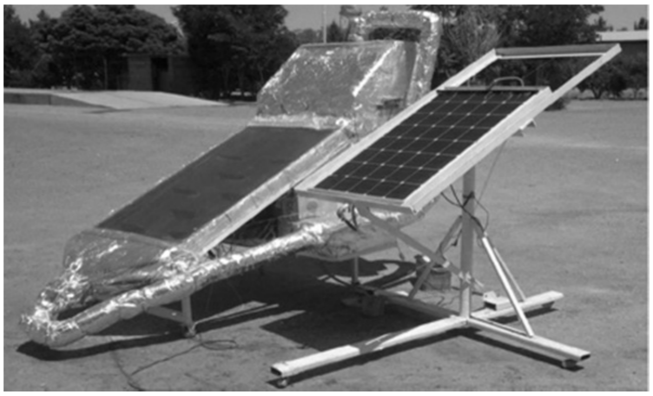


Figure 14: A photograph of liquid assisted solar dryer (Dorouzi et al., 2018).

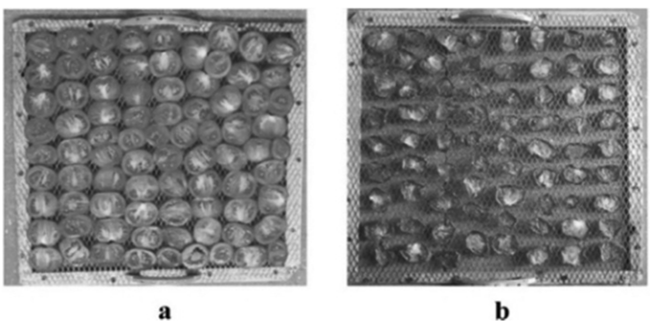


Figure 15: The picture of tomato (a) before and (b) after drying (Dorouzi et al., 2018).

Wood Drying

Making the wood drying system energy efficient and reducing carbon dioxide emission is a very crucial aspect of wood drying (Johnsson et al., 2019). Simo-Tagne and Bennamoun (2018) designed a direct solar dryer with a solar absorber on the roof of the drying chamber. Drying time was found high as 30 days in African weather conditions. The indirect solar dryer is most widely used in the wood drying industry with a flat plate collector as an air heater (Simo-Tagne and Bennamoun, 2018). To increase the profit, drying time must be as minimum as possible (Lamrani et al., 2021). The photovoltaic thermal solar system provides electrical as well as thermal energy so it can be efficiently used in the wood drying industry (Joshi and Dhoble, 2018; Pang et al., 2020). Exhaust air heat can be recovered hence system efficiency can further be increased (Khouya, 2020; Minea, 2012).

Lamrani et al. (2021) designed a hybrid indirect solar dryer with PV/T solar air collector and heat recovery system. The numerical model was designed and compared with the experimental readings available. Figures 16-18 depict the schematic layout of the proposed dryer system, cut section of PV/T solar air heater and heat recovery system, respectively.

Figures 19 and 20 show the result of this work. Figure 19 shows the change in energy consumption in the city of Ajaccio (France). During summer energy consumption is the minimum for all types of dryers and maximum during winter. This issue is further resolved with the use of a heat recovering system with effectiveness of 0.5 and 0.8. Figure 20 shows the mitigation of carbon dioxide emissions by using various types of dryer during different times of the year.

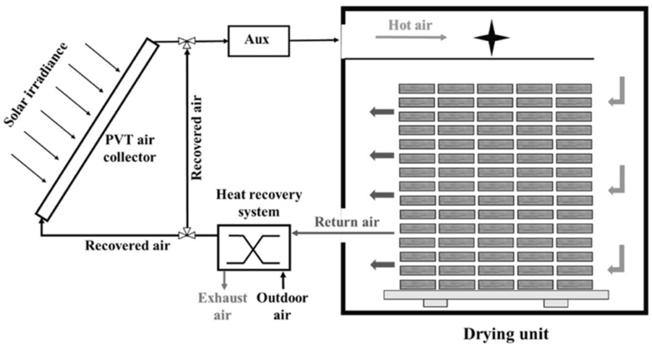


Figure 16: Systematic layout of dryer system for wood (Lamrani et al., 2021).

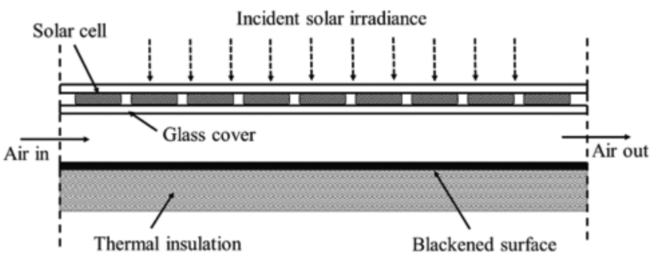


Figure 17: Cut section of glass-to-glass PVT solar air heater (Lamrani et al., 2021).

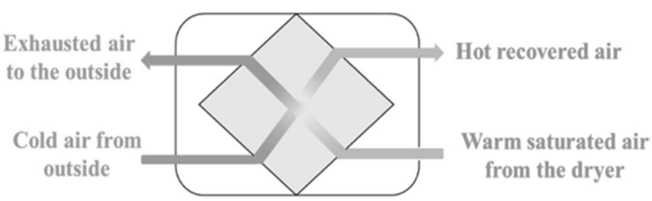


Figure 18: Heat recovery system (Lamrani et al., 2021).

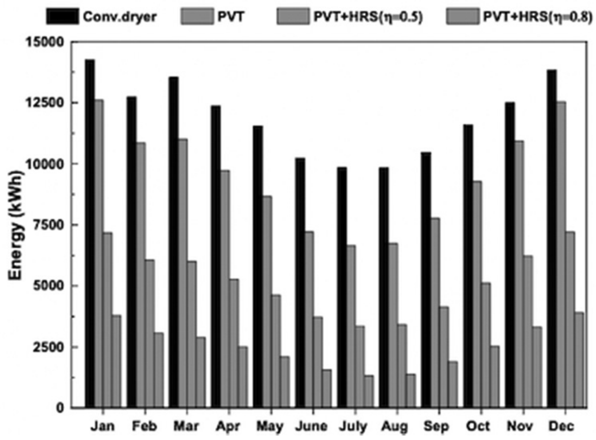


Figure 19: Monthly change of total dryer energy consumption for various case studies (Lamrani et al., 2021).

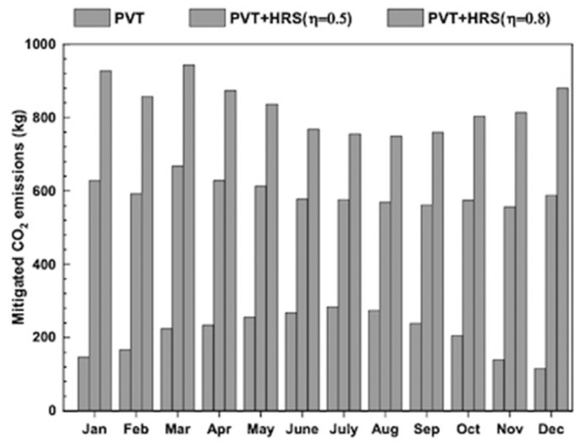


Figure 20: Mitigation of carbon dioxide emission by using various types of dryer during different times of year (Lamrani et al., 2021).

Table 2 shows different types of the solar dryer with Photovoltaic thermal systems as an integral part. It has been found that solar dryer with PV/T system is efficient, and effectively produces good quality dried product in less time.

The hybrid photovoltaic thermal solar dryer can also supply excess generated electricity to the power grid. Gupta et al. (2018) concluded that because of intermittent supply from the PV system voltage is affected at the point of common coupling and harmonics distort the current and voltage waveform (Gupta et al., 2018). Excess generated electricity by the PV system can also be stored for later use in off-sun hours. In off-grid PV system, it is essential to use energy storage

Table 2: Various solar dryer with photovoltaic thermal system

Name of product	*Study year/Name of Researcher/ Type of study*	*Type of PV/T dryer*	*Key findings*
Grapes	P. Baranwal G.N Tiwari (2008) Experimental study	Hybrid Photovoltaic thermal greenhouse Dryer of maximum 100 kg Capacity, Forced Convection mode	It has been found that the convective heat transfer coefficient for grapes (GR-I) varies between 0.26 and 0.31 w/m^2.K for greenhouse and 0.34-0.40 w/m^2 K for OSD condition.
Medicinal herb	Hanna M Fargali Abd El Shafy (2008) Dynamic modelling for different component in solar thermal system	Controlled drying method	PV/T are the main energy sources during day. Biogas and stored electricity in battery are only used in cloudy/off sun hours. Results shows highly effective drying.
Saffron	Hamid Mortezapour Barat Ghobadian Saeid Minai and Mohammad hadi Khostaghaza (2012) Experimental Study	Hybrid photovoltaic thermal solar dryer equipped with heat pump	Drying time decrease as air temperature increases. Overall efficiency of hybrid solar collector improves with air flow rate and energy consumption is reduced. Electrical efficiency increases with heat pump and drying time is reduced.
Tomato	Mahdiyesh Dorozi, Hamid Mortezapour , (2018) Experimental study	Indirect solar dryer Liquid Desiccant assisted solar dryer coupled with a photovoltaic thermal regulation	60°C temperature and activation RH of 23% was find best for drying of tomato slices for good color quality of dried tomato for sufficient electricity production.
Wood	Bilal Lamrani Abdeslam Draoui Frederic Kuznic (2021) Transient Model study	Indirect solar Dryer Hybrid solar wood dryer with Photovoltaic thermal air collector and heat recovery system	During winter and summer, the energy consumption by integrated PV/T, heat pump solar dryer is decreased by 73.5% and 86.5%, respectively.

for the continuous operation of the system (Tharani et al., 2020). Various types of batteries are used with the photovoltaic thermal system, Lithium-ion batteries are the best suitable kind for the off-grid PV system (Tharani et al., 2020).

Conclusion

In developing countries with less availability of electricity in remote areas, open sun drying is mostly used for crop drying or otherwise, and fossil fuels are used for drying products in agriculture and industries. The solar dryer is cost-effective and efficient for producing the best quality of dried items. Based on the present review, the following conclusion can be drawn:

1. Heat and electricity are the basic need of solar dryers to maintain quality, colour and aroma of dried products by drying product quickly in a controlled environment.
2. Weather dependent (only used in the day time) solar dryer has been improved a lot from the direct solar dryer to hybrid (all weather, Day /Night, only conventional sources) solar dryer.
3. According to the material to be dried, location and availability of money, different kinds of solar dryer can be designed and used to reduce dependency on a conventional dryer.
4. The solar PV/T system has higher overall efficiency than only solar PV or solar thermal systems. PV/T system supplies hot air as well as electricity to operate the fan/auxiliary heater/recharge liquid desiccant bed.

Profit from the final dried product can be increased and reduction in carbon dioxide emission can be decreased by using hybrid PV/T solar dryers.

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