International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 11, No. 2, June 2020, pp. 1011~1018
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v11.i2.pp1011-1018

Energy-economic-environmental analysis of solar drying system: a review

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Article Info

Article history:

Received Jan 30, 2019
Revised Jul 8, 2019
Accepted Jan 30, 2020

Keywords:

Drying materials
Renewable energy
Solar dryer
Solar energy

ABSTRACT

Solar drying is an emerging technology to preserve wide range of products from agriculture to animal-based products. The application of solar dryers, however must be evaluated to determine its benefit and effectiveness. In the evaluation of solar dryer performance, three criteria which are most important to look at are thermal performance, economic cost and environmental implications. Therefore, this paper attempts to review the thermoeconomic analysis and environmental evaluation on various solar drying system. Performance equations in energy–economic–environment analyses for solar drying syistems evaluation are presented. The CO2 emission, carbon mitigation, and earned carbon credit of various solar drying syistem are also presented.

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1. INTRODUCTION

In the recent years of energy research, renewable sources are gaining much attention as the world is shifting from fossil fuel to alternative energy. One of the reasons that drives this shift is due to the increasing demand for energy in the future, that initiate the exploration for a more sustainable energy sources to last to the end of human lifetime. The alarming scene of environmental degradation and pollution is also another main reason that pushes for cleaner, and more responsible energy generation. Solar energy is the most accessible, readily available, and highly potential as renewable source of energy generation. The amount of solar radiation intensity that reaches the outer atmosphere is 1,360 W/m^2, and after accounting for natural losses, the global radiation that reaches the ground is still high at the range of 800-1000 W/m^2 , on a clear sky sunny day in summer [1]. Due to its energetic potentials, solar energy is converted into useful applications in the form of thermal and electrical energy. Solar energy is widely used in solar thermal technology such as in solar collector systems [2-4], in photovoltaic/thermal systems [5-16] and in solar drying systems [17-21].

The role of solar thermal is theorized to be able to lower the burden on scarce renewable resources and also to supply renewable energy in conditions where no alternatives are available [22]. While the application for solar thermal systems is widely known in domestic sector, it also provides huge potential for industries to benefit from. Kylili et al. conducted a life-cycle assessment (LCA) on industrial solar thermal system (ISTS) in the Europe, and found significant energy and carbon savings from its application, which ranges from 35 – 75 GJ and 2 – 5 tonnes of CO$_2$ per kWth depending on the geographical location, respectively [23].

2. SOLAR DRYING PRINCIPLE AND MECHANISMS

Drying is a method of food preservation that has been practiced for centuries. It is a common practice to extend the shelf life of different kind of food products, from fruits, herbs, and animal and marine based products. In drying, excess moisture from food products are removed due to thermal action. The resulting end products with moisture reduction inhibits microbial growth which enables them to be stored for future use. During moisture removal, simultaneous process of mass and heat transfer take place within the sample, outer surface and heating air. However, despite its reliability to preserve food products, drying process is highly energy intensive which consumes about 50% energy of the food processing industry [24]. The energy requirement for drying process is high because of the latent heat of vaporization involved to vaporize excess moisture from the products.

Solar drying provides an alternative to the conventional drying process. In contrary to sun drying, where food products are being exposed to dry directly under the sun, solar drying utilizes heat entrapment mechanism to enhance the moisture removal process. The application of solar dryer converts solar energy using solar collector unit into useful thermal energy. Thus, solar dryer systems are capable to increase the operating temperature to 50-60 °C which resulted in perfect drying and product quality [25]. Due to higher drying temperature, solar dryer minimizes the area needed to expose the products to hot air. Solar dryer is also less dependent on sunshine availability, as it can utilized thermal energy storage systems and auxiliary heating unit for heat supply. Construction of solar dryers includes drying chamber, which isolates the products from ambient surroundings. Thus, final products from solar driers are less susceptible to contamination from dust, insects, and microbial growth.

Primarily, solar dryer can be categorized into four groups; direct solar dryer, indirect solar dryer, mixed-mode solar dryer, and hybrid solar dryer [26]. The working principle of each dryer is different in terms of solar energy conversion to thermal energy. In direct solar dryer, heat is generated by direct absorption of solar irradiation on the product as sun rays penetrate through transparent chamber, while indirect dryer utilizes solar radiation on collector unit to heat up air, which indirectly dry the materials [27]. Mixed-mode dryer utilizes both direct mode in drying chamber, and indirect mode in its collector unit, where as hybrid dryer on the other hand refers to the usage of supplementary source of energy i.e. biomass, diesel engine, photovoltaic integration to supply heat.

3. EXPERIMENTAL EVALUATION

Due to wide availability of solar drying systems in practice, the development of solar dryer technologies needs to be based on empirical knowledge of its energy profile and the anticipated performance over its expected life-time. The information acquired from empirical evaluations is relevant to determine and improve the plant and operation costs, energy conservations, fuel versatility and pollutants [28]. In addition, selection of the right dryers must take into consideration the user's need and the end use of dried products, thus require the evaluation the following domains: social, technical and economic functions [29].

3.1. Energy Analysis

Solar dryers take into application of energy conversion from solar to useful thermal energy for drying process. For this purpose, numerous methods and processes were developed and their effectiveness can be evaluated on many merits, such as energy efficiency, time to dry and product quality. In solar drying, thermal performance is a reliable indicator to study the system merits and can be quantified using energy analysis. Energetic performance is based on the first law of thermodynamics, which takes in to account the quantity of energy and the energy change in respect to the change in surroundings [30]. However, the drawbacks of energy analysis is that it only considers energies at inlet and outlet of the system, and sometimes is redeemed as insufficient for system optimization as it neglects the irreversibility and thermodynamic losses [31-33].

In general, energetic analysis on solar dryers can be done on two main components; the drying systems and the drying materials. Drying systems of solar dryers includes the solar absorber unit, drying chamber, and movement of heated drying air throughout the system. In short, energy analysis of solar dryer components is commonly done by applying heat transfer and energy balance based on the principle of energy conservation of the first law of thermodynamics. Determination of thermal performance of solar dryers are important to achieve maximum moisture removal while using minimum amount of energy [28].

In literature, there are several indicators that are commonly used to evaluate the thermal capacity of solar dryer components, especially for solar collector unit. The amount of useful heat that can be harness from solar collector can be calculated using heat removal factor, F_R and the incident solar radiation, I_t. Q_u value is depended on the material of construction used for collector, as well as the surface area, as suggested by (1) [34].

$$Q_u = F_R A_c [I_t(\tau\alpha) - U_L(T_i - T_a)] \tag{1}$$

The energy used for moisture evaporation can be calculated as [35]

$$E_{vap} = M_{water} H_{fg} \tag{2}$$

Thermal efficiency of solar collector is the ratio of heat gain by air passing through the collector to the energy gained due to solar irradiation, given by [36–38].

$$\eta_c = \frac{mc(T_{out} - T_{in})}{A_c I} \times 100\% \tag{3}$$

Another indicator commonly used in energetic analysis is the thermal efficiency of solar dryers, η_d. Essentially, η_d is the ratio of energy required to evaporate product's moisture to the energy consumed for the drying process. In short, thermal efficiency of the drying system is the ratio of the energy used for moisture evaporation to the energy input to the drying system.

$$\eta_d = \frac{E_{evap}}{E_{input}} \tag{4}$$

In passive convection dryers, dryer efficiency calculation is based on the air movement due to natural buoyancy, whereas active dryers takes into account the energy input through electrical fans or blowers, given by respectively [39], [40]. Depending on the type of solar drying system, the energy consumed for drying process would need to account for all source of energy generated in the system. In hybrid system, usually photovoltaic-thermal (PVT) hybrid dryers, electrical efficiency of solar collector is quantified as the system takes electricity into energy generation.

$$\eta_{d,P} = \frac{mL_v}{A_c I t_d} \tag{5}$$

$$\eta_{d,A} = \frac{mL_v}{A_c I + P_f} \tag{6}$$

The relationship between energy input to solar dryer and amount of water evaporated can also be used to define the performance of the dryer and to compare performance of the dryers. is Specific moisture extraction rate (SMER) in kg kWh^{-1} relates how much moisture can be removed per unit of energy, whereas specific energy consumption (SEC) is the reciprocal of SMER with units of kWh kg^{-1} [41]

$$SMER = \frac{Amount\ of\ moisture\ evaporated}{Energy\ input\ to\ the\ dryer} \tag{7}$$

$$SEC = \frac{Energy\ input\ to\ the\ dryer}{Amount\ of\ moisture\ evaporated} \tag{8}$$

Pickup efficiency, or moisture removing efficiency of drying air is the efficiency measure on moisture extraction using hot air, and it can be calculated using

$$\eta = \frac{h_o - h_i}{h_{as} - h_i} = \frac{W}{v\rho(h_{as} - h_i)} \tag{9}$$

In hybrid systems where energy source comes from other than solar energy, solar fraction is determined to quantify the ratio of energy extraction of heat from solar collector to the overall energy available for the drying process [35]. Solar fraction can be expressed by

$$SF = \frac{Q_s}{Q_t} = \frac{Heat\ gain\ at\ collector}{Total\ heat\ supplied\ to\ dryer} \tag{10}$$

From the drying material components, effectiveness of drying can be associated with moisture reduction within the samples. The mass of water removed (W) from a wet product can be calculated by [28]

$$W = \frac{m_o(M_i - M_f)}{100 - M_i} \tag{11}$$

Moisture ratio, which is a dimensionless form of moisture content explains the ratio of remaining moisture to be removed at time *t* over initial total moisture present. In the study of drying, MR is an important tool to understand the kinetics and drying profile as they vary from one material to another. In fact, MR is found to be mostly adequate to describe the drying behavior of some fruits and vegetables as it translates to drying constant, *k* (s^{-1}). This is an important parameter widely used in thin-layer modelling, to obtain drying curve as a function of time [42].

$$MR = \frac{(M - M_e)}{(M_o - M_e)} \tag{12}$$

3.2. Economic Analysis

While energy analysis is a common approach used to minimize thermodynamic efficiencies within dryer system, thermoeconomic is a different take to estimate the cost-optimal structure and the optimal values of thermodynamic efficiencies in each component [43]. Thermoeconomic is viewed as a promising diagnostic tool, even for complex system [32]. Through economic analysis, solar dryer application has been proved to have undeniable improvement on carbon footprint reduction associated with the energy-intensive drying process. In a review article by Mathew et al., solar dryers are highly effective device with low investment to produce good quality of dried products. The unit cost of useful energy for solar dryers were found to vary from 0.0034 to 0.015 USD per MJ of energy for different types of drying products [44].

El-Hage et al. conducted an economic study to evaluate monetary savings due to application of industrial solar dryers under Lebanese climate. The energy cost saving is determined on monthly basis, where it is dependent on the percentage of time where solar dryer is used, Pr, the dryer energy consumption for operation E_{month}, and the cost of electricity for one unit of kWh, P_{kWh}. Depending on the Pr value which ranges from 0.1 to 1, the energy cost reduction records savings between \$130 to \$4160 per month for drying of 120kg of various vegetable samples.

$$SM = P_r \times E_{month} \times P_{kWh} \tag{13}$$

From the determined SM and capital cost of the solar dryer, simple payback period (PP) for the dryer system was determined as follows

$$PP = \frac{C_{dryer}}{SM} \tag{14}$$

A more detailed economic analysis was performed by ELkhadraoui et al. who evaluated the economics of chapel-shaped greenhouse for red pepper and grape drying in Tunisia [45]. The payback period for the dryer system was determined to be short at 1.6 years. The calculation used takes into account the capital cost of the dryer C_{cc}, inflation rate i, interest rate on long term investment d, and the saving during first year of the dryer S_1. This method of calculation is also used by [40], [46].

$$PP = \frac{\ln\,[1 - \frac{C_{cc}}{S_1}(d-i)]}{\ln\,(\frac{1+i}{1+d})} \tag{15}$$

Another approach for economic analysis is the incorporation of cost-benefit analysis to compare cost and benefits of solar drying to other means by taking into consideration the size, materials for construction, efficiency, operation, sophistication and sustainability of the driers which vary from countries to country. Past study on economic analysis on solar drying systems as show in Table 1.

3.3. Environmental Analysis

In practice, percentage of reductions on fuel consumption depends on the type and solar dryer system. The range of savings recorded can vary from 20-40 percent in hybrid systems, to total fuel elimination in natural ventilation greenhouse solar dryer [50]. Past study on environmental analysis on solar drying systems as shown in Table 2. CO_2 mitigation is a tool to measure climate change potential with the opportunity to reduce greenhouse effect emission by capping total annual emissions and letting the market assign a monetary value to any shortfall through trading [51]. In carbon credit model, monetary incentives allow transactions among businesses and individuals to get involve in carbon footprint reduction and at the same time funds reduction schemes globally. Carbon credit is the component of energy analysis. A carbon credit is a generic term for any tradable certificate or permit representing the right to emit one tone of carbon or carbon dioxide equivalent. Carbon trading is also an application of an emission trading approach [22].

Table 1. Past study on economic analysis on solar drying systems

Ref.	Year	Solar Dryer Type	Drying materials	Indicator	Findings
[45]	2015	Mixed mode greenhouse SD	Red pepper and grape	Annualized cost of dryer Annualized capital cost (Cac) Annual electricity cost for fans Annual savings (Sj) for drying the typical product in the jth year Payback period	Dryer capital cost is 660 USD, and Payback period is 1.6 years compared to 20 years of lifetime.
[40]	2016	Modified greenhouse dryer	Potato chips	Payback period	Payback period is 1.11 years.
[47]	2018	Indirect cabinet SD	Carrot, Corn, Mushrooms, Potatoes, Apples, Banana, Cherries, Peaches	Amount of saved money Payback period (PP)	The capital cost of dryer is 8000 USD, and savings recorded range from 1400 USD to 12500 USD depending on mass and type of drying sample and percentage of dryer utilization. From this, the payback period range from 0.9 to 62 months.
[48]	2005	Unknown SD	Various agri-produce	Capital cost of dryer Unit cost of drying Unit cost of useful energy Valuation of benefits	
[49]	2014	Low cost SD - Direct and indirect passive dryers	Fish	Fixed cost - constructiona and maintenance cost Qualitative performance evaluation	
[23]	2018			Carbon savings	Life-cycle assesment on environmental performance of industrial solar thermal system (ISTS). Large- scale ISTS applications were found to achieve energy and carbon savings ranging from 35 – 75 GJ and 2 – 5 tonnes of CO2 per kWth, depending on the geographical location.
[44]	2018	Various			The economic analysis of different driers has been discussed in this article.

Table 2. Past study on environmental analysis on solar drying systems

Ref.	Year	Solar Dryer Type	Drying materials	Indicator	Findings
[51]	2011	Hybrid PVT Greenhouse	Mint leaves	CO2 mitigation over the lifetime Net mitigation over lifetime Earned carbon credit	CO2 mitigation is 140.97 tons and earned credit of 704.85 - 2819.4 USD.
[40]	2016	Modified greenhouse dryer	Potato chips	Embodied energy Energy payback time CO2 emission CO2 mitigation per kWh Earned carbon credit	Embodied energy is 480.277 and 628.73 kWh for passive and active mode, respectively. Annual CO2 emission is 13.45 and 17.6 kg for passive and active mode, respectively. The average EPBT, carbon mitigation, and earned carbon credit for passive dryer is 1.04 year, 32.36 tons, and 375 USD while active dryer is 1.3 year, 33.9 tons, and 393 USD, respectively.
[46]	2014	modified greenhouse dryer under active mode	Tomato	EE EPBT CO_2 emission Carbon mitigation Earned credit	Embodied energy is 628.7287 kWh. Low EPBT of 1.14 years. Annual CO2 emission is 17.6 kg, with net CO2 mitigation of 38.06 tons. Earned carbon credit varies from 176 - 706 USD.
[52]	2017	Indirect SD	Fenugreek	EE EPBT CO_2 emission CO_2 mitigation Carbon credit	Embodied energy of the dryer is 1081.8 kWh. EPBT of 4.36 years, annual CO2 emission of 85.46 kg, and CO2 mitigation of 391.52 kg. The earned carbon credit ranges from 660 - 2061 USD.
[47]	2018	Indirect cabinet SD	Vege and fruits	Amount of CO_2 produced Amount of CO_2 reduction	Range of CO2 reduction from 20500 - 40300 kg per month for different crop at 120 kg and 960 kg.

Embodied energy (EE) is the total energy required to produce any items, things, or services [40]. It is a variable commonly used in environmental analysis, to determine how much energy is associated with producing a unit of system by taking into account the energy used in extraction, processing, manufacturing, and transporting of the materials [52]. The calculations on EE serve as an indicator of the overall environmental impacts of materials and systems, as the energy consumed correlates to CO_2 production which contributes to GHG emission. In analysis, EE calculation requires the quantification of the materials used in the construction and maintenance of the dryer over its entire life time. The mass values of the different materials were then multiplied by the embodied energy coefficients of the corresponding materials (EEC), usually expressed in MJ kg^{-1} to give the total EE for the overall equipment [53].

Energy Payback Time (EPBT) is the time required to pay back the EE, can be calculated as

$$EPBT = \frac{Embodied\ Energy}{Annual\ Energy\ Output} \tag{16}$$

Carbon credit is a tool that represents any tradable certificate or permit that grants the right for businesses or industries to emit one tone of carbon or carbon dioxide equivalent, which is essential in the application of emission trading approach [54]. They provide a way to reduce greenhouse effect emissions on an industrial scale by capping total annual emissions and letting the market assign a monetary [51]. Carbon credit model is commonly used to calculate the carbon mitigation involved with the usage of solar dryers, as well as the earned carbon credit associated. The overall CO_2 mitigation over dryer lifetime is calculated as the difference of total CO_2 mitigation and total CO_2 emission

$$\begin{aligned} Net\ mitigation\ of\ \mathrm{CO2}\ over\ lifetime &= Total\ CO2\ mitigation - Total\ CO2\ emission \\ &= [E_a \times n \times X - EE]\ kg \end{aligned} \tag{17}$$

where E_a is the annual thermal output energy of the dryer, n is the dryer lifetime, and X is the CO_2 mitigation per kWh of the dryer. The equation for X is given as follows

$$X = \frac{1}{1-L_a} \times \frac{1}{1-L_{td}} \times 0.98 \tag{18}$$

where the first term accounts for power consumption loss, L_a (10%), and second term for energy loss due to transmission and distribution, L_{td} (45%). Therefore, at given L_a and L_{td}values, the amount of CO_2 mitigation of the system, X is determined to be 2.01 kg.

From the quantified net lifetime CO_2 mitigation of the dryer system, earned carbon credit can be calculated by multiplying the value with the cost of carbon credit, D which ranges from USD 5-20 per ton of CO_2.

$$Carbon\ credit = Net\ mitigation\ of\ CO2\ over\ lifetime\ \times D \tag{19}$$

A simpler environmental analysis was performed by Elhage et al. who studied the amount of CO_2 reduction in relation to percentage of solar dryer usage, mass of drying sample and type of food being dried under Lebanese climate. By quantifying the amount of energy consumption per month of the dryer E_{month}, the amount of CO_2 produced $M_{produced,CO2}$ and amount of reduction in CO_2 emission $M_{reduced,CO2}$ by the system is quantified as

$$M_{produced,CO2} = E_{month} \times M_{\frac{CO2}{kWh}} \tag{20}$$

$$M_{reduced,CO2} = Pr \times M_{produced,CO2} \tag{21}$$

where $M_{\frac{CO2}{kWh}}$ is the amount of CO_2 produced from 1 kWh electricity which differs from one place to another.

4. CONCLUSIONS

Solar drying is a highly potential application of solar thermal technology. The use of solar dryers for drying of agricultural produce as well as poultry and marine products results in higher product quality through better control of drying process. One approach to evaluate the thermal performance of solar dryers is done through energy analysis which is discussed in detail in this review. Solar dryers also contribute to environmental conservation, as it reduces the energy demand in the food post-harvesting sector. To evaluate the financial savings and environmental impact, economic and environmental analysis suitable for solar dryer systems were outlined in this review.

ACKNOWLEDGEMENTS

The authors would like to thank the UKM for funding UKM-Simedarby (KK-2014-014).

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