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ANALYSIS OF ECONOMIC AND ENVIRONMENTAL FACTORS OF SOLAR DRYER INTEGRATED WITH A HYBRID PHOTOVOLTAIC-THERMAL AIR HEATER

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ABSTRACT

Hybrid photovoltaic-thermal (PV/T) solar systems provide an improved method of cogenerating electric energy and thermal energy from the solar energy. In the present work, a double pass hybrid PV/T air heater was developed and tested. The hybrid PV/T system was integrated to an indirect active solar dryer for drying of amla (*Phyllanthus emblica*). Experiments were done to determine the drying characteristics of the fruit. Annualised cost method is used to find the economic benefits. Payback period comes to 9.3 years and Benefit-Cost ratio, 1.61. Ecological sustainability of the developed technology is measured using energy matrices. Energy payback time is calculated as 2.25 years. Considering the value of $ 14.5/tCO_2, for a carbon credit, environmental cost reduction per annum is Rs. 1003. Thus hybrid photovoltaic-thermal system with enhanced heat dissipation methods are technologically feasible and economically a viable option for sustainable use of the solar energy.

KEY WORDS : Solar dryer, Hybrid photovoltaic thermal, Carbon credit, Ecological sustainability

INTRODUCTION

The economic development of nations necessitated large scale exploration and consumption of energy and fossil fuels dominated the world energy market for a long time since the dawning of the industrial revolution. The excessive dependence of fossil fuels to meet the energy requirements of expansive life styles of the modern urban populace has severely damaged the global ecological stability (IEA, 2014).

The threat of a probable ecological disaster instigated by the global warming compelled the policy makers to focus the attention towards renewable energy sources in recent times. Notwithstanding the adverse impacts of global warming on the environment, the ambitious plans of developing countries to add more energy resources is unlikely to tame in future since the influential relationship between quality of life as measured by Human Development Index and the consumption of energy is fairly established (Fanchi, 2004). Reliable sources of non-polluting energy are necessary for the nations in order to ensure quality of life for their citizens by advancing the economy. Solar energy is the most prominent renewable source of energy as it is practically inexhaustible, abundantly available in large part of the world. It is a clean and non-polluting energy source. Solar energy technologies require less maintenance and the operation is noiseless.

Even though solar energy is abundantly available in nature the need for evolving technically brilliant and economically viable methods to extract the energy into usable forms is paramount. Mainly two distinct technologies which harvest solar energy for domestic and industrial applications are available: (i) solar thermal technology and (ii) solar photovoltaic (PV) technology. Solar thermal technology converts solar energy into heat. A solar collector is the essential unit for this conversion. The heat generated is either used directly or stored for several applications like space heating, crop drying and supplying warm water (Kalogirou, 2004). Solar PV technology converts solar energy directly into electricity which is the most usable variety among all the energy forms. The basic component of photovoltaic technology is a photovoltaic cell which works on the photovoltaic effect. The inherent disadvantage of solar PV technology is the high economic costs due to the low electrical conversion efficiency of the solar cells.

Hybrid photovoltaic-thermal (PV/T) systems are developed to offer a practical method to extract the waste heat from the solar panels and thus to improve the electrical efficiency of the photovoltaic panels. It is the end result of several attempts to combine solar thermal technology and solar photovoltaic technology to harness the advantages of both the distinct methods of solar energy conversion. Hybrid PV/T systems have many attractive features of both solar thermal technology and solar photovoltaic technology. Basically a hybrid PV/T system improves the economic viability of the schemes by simultaneously generating both electrical energy and thermal energy.

Application of solar energy in food processing sector is an economically feasible and environmentally sensible concept. Providing sufficient, nutrient rich and affordable food to the ballooning world population is a great challenge to nations. Increasing the food production is not the only way forward to achieve the objective of feeding the entire people of the world with quality meals fit for human consumption. Systematically reducing food losses by injecting benefits of technology into the entire supply chain of food production is another significant initiative to ensure the nutritional security to all. In the conservation point of view also, crop spoilage is a major risk that generally policy makers tend to overlook but exert great pressure on scarce resources like water and energy. The spoilage of agricultural produce is a major environmental hazard since (i) fresh water consumed for the production of food is miserably squandered in a world where access to potable water is deprived to millions, (ii) the energy, mainly released from the combustion of fossil fuels is ultimately wasted and (iii) hectares of land are deforested to expand agriculture (CSRJ, 2015).

In the present work, economic and environmental factors associated with solar drying of crops using the hybrid PV/T air heater are discussed. Economics plays a crucial role in the endeavour of nations to replace conventional technologies with clean technologies. So a thorough understanding of the economic factors involved in the consumer preference in a competitive market scenario of energy alternatives is imperative. There are some established methods to forecast the economic viability of the projects. Ultimately, the propagation of clean technologies based on solar energy is pivotal in the long term goal of reducing carbon emissions for preventing the global warming. There are major energy savings derived from the use of solar systems but the production of system components itself consumes lot of energy. So the net savings of the energy is determined by considering the embodied energy and the actual savings. The relevant economic and environmental feasibility analysis methods are thus discussed.

Many studies have been carried out in the field of hybrid technology during the last two decades. Pioneering works have been done by Kern and Russel (1978) who developed a hybrid PV/T system for generating both electrical and thermal energy using water or air as heat removal medium. Hottel-Willier analytical model (Hottel, and Willier 1958) for flat plate collectors was modified by Florschuetz (1979) to suit the PV/T collectors. Raghuraman (1981) developed numerical methods for predicting the performance of liquid and air PV/T collectors. Othman *et al.* (2007) developed a mathematical model of a PV/T air heating system attaching fins on the back-side of the absorber plate and results were presented. The results showed a marked improvement of total efficiency of the system.

A parametric study of a hybrid PV/T water/air heating system was conducted by Tiwari and Sodha (2006). A thermal model of a combined photovoltaic and thermal solar water/air heating system has been studied. Numerical computations have been carried out for different configurations of the integrated system. It is reported that overall thermal efficiency of the developed system is 65% and 75% for summer and winter conditions, respectively.

Drying is a proven post-harvest method for the preservation of the crops. Even though open sun drying is the cheapest and oldest method while harvesting the solar energy, drying using simple devices like solar cabinet dryers eventually evolved to improve the quality of the final product. Many researchers turned their attention in the area.

Dissa *et al.* (2011) experimentally studied the drying characteristics of *Amelieand Brooks* mangoes using a solar cabinet dryer with four trays. The experiments were carried out under the weather conditions of fruit harvest period. The solar drying curves thus obtained were fitted using 10 mathematical models and simulated with direct solar drying model. Reyes *et al.* (2013) studied the dehydration effects of mushroom (Paris variety) using a hybrid solar dryer with a solar panel and electric heater. Effective diffusivity was determined which was in agreement with literature. It is reported that input solar energy resulted in a saving of 3.5-12.5% of total energy.

The experimental study of drying fenugreek leaves using a multi shelf dryer with intermediate heating of air in-between trays was reported by Singh *et al.* (2004). The dryer used in the experiment was capable of drying under shade or otherwise as per the requirement. The performance of the dryer was evaluated. The shelf life of the product was determined to be more than one year.

The researchers of the Solar Energy Group in the Universiti Kebangsaan Malaysia (Othman *et al.* 2006) developed and studied four different types of solar driers: (i) a V-groove solar collector, (ii) a double pass solar collector with integrated storage system, (iii) a solar assisted dehumidification system and (iv) a photovoltaic thermal air heater. It is reported that the common problems associated with the common driers have been overcome by the proposed dryers. These dryers have the benefits of heat storage and auxiliary energy source to facilitate for the drying of a wide range of crops.

Sreekumar *et al.* (2008) developed a solar dryer suitable for drying vegetables and fruits. For collecting the solar radiation and for spreading the products to be dried, the developed dryer has two separate compartments. The dryer was loaded with 4 kg of bitter gourd of moisture content 95% and the final moisture content of 5% was achieved in 6 hours. Economic analysis was also performed using annualised cost method, present worth of annual savings and present worth of cumulative savings. Using a multi-shelf domestic solar dryer, Singh *et al.* (2006) dried fenugreek leaves and presented the economic implications of using the developed dryer using three methods: (i) annualised cost method, (ii) life cycle costing and (iii) payback period. A very low pay back period compared to the lifespan of the dryer is reported.

Agrawal and Tiwari (2015) presented the results of a study on the carbon credit potential of glazed hybrid photovoltaic thermal air collector. Using an annualised unit cost method adopted, the analysis was done based on both annual thermal energy and exergy basis. The performance of the hybrid system is analysed using three parameters namely, energy payback time (EPBT), the energy production factor (EPF) and the life cycle conversion efficiency (LCCE). Singh and Kumar (2013) conducted experimental study of cylindrical potato samples using mixed mode solar dryer and performance was analysed for a wide range of operating conditions. Mathematical frame work was developed to determine drying efficiency, specific energy consumption, CO_2 emissions mitigation and carbon credits earned. The results show that the developed dryer is capable of mitigating carbon emissions in all the operating conditions.Economic viability of the solar energy systems is essential for the greater market penetration of the products. PV/T technology is more economical due to the better thermal and electrical performance. Axaopoulos and Fylladitakis (2013) have evaluated the performance and economic viability of a hybrid PV/T system for residential applications. In the work, the researchers presented the results of the analysis of the hybrid system for the production of electricity and domestic hot water using a commercially available PV/T system. Net Present Value (NPV) analysis was carried out and the economic spider diagrams were presented. Spider diagram indicates the effect of legislation and fuel prices on the value of the solar systems.

Unchecked carbon emission seriously damages the global ecological balance in an unprecedented manner. Qi Zhu (2017) studied the effect of government regulations on the carbon emission trading market. The study showed that the government policies can encourage enterprises to participate in the carbon emission trading. It was reported that there was a negative relation of supervision cost and the trading price. Shivkumar (2013) conducted experimental studies of a hybrid photovoltaic thermal active solar still. Thermal and economic analysis was done considering the effect of subsidy, inflation, tax benefits and maintenance costs. Annualised costing method was adopted. CO_2 emission mitigation and revenue from carbon credits were calculated. The payback period calculated was 4.2 years. Agarwal and Tiwari (2013) conducted experimental study on glazed hybrid photovoltaic thermal collector. Energy payback time, electricity production factor, and life cycle conversion efficiency have been calculated. The annual carbon credits earning potential of the system was also calculated. It was reported that the environmental cost of the overall thermal energy is $36.97 per annum and for overall exergy is $8.55 per annum.

The present work envisages a detailed experimental study on drying of different fruits using a hybrid PV/T air dryer and the analysis of economic and environmental factors associated with solar hybrid drying.

MATERIALS AND METHODS

Solar dryer with hybrid PV/T air heater

The solar hybrid dryer on which experiment was conducted basically consisted of two main parts: the hybrid PV/T air heater and the cabinet dryer. The dryer used the hot air that was delivered by the hybrid air heater.

Solar dryer

The inner core of the cabinet type solar dryer (dimensions 280mm x 280mm x 400mm) was fabricated using marine plywood of thickness 6mm and outer frame was made using galvanized iron sheets of 20 SWG. The gap between inner core and outer frame was filled with polystyrene sheets of thickness 50 mm to reduce heat losses. The indirect type active solar dryer consists of four trays made of metallic mesh to keep the crops. The dryer was provided with a door for loading and unloading the crops.

Hybrid PV/T air heater

The design of a hybrid PV/T solar collector basically resembles the features of a solar air heater. The pictorial view of the proposed hybrid photovoltaic-thermal solar air heater is shown in Fig.1. The outer and inner frames of the double pass PV/T air heater were fabricated using mild steel (MS) angles and the sides and bottom of the inner frame except front side were covered flawlessly by welding the galvanized iron (GI) sheet of gauge 20 SWG. An expanding type conduit was made using GI sheet and MS angles for smooth and separate entry and exit of the air and fixed in the front side. Photovoltaic panel of rating 100 Wp (area 0.8 m^2) was fixed in the middle of the frame. The sides and bottom of the air heater were insulated by polystyrene sheets of thickness 50 mm. A glass sheet of thickness 6 mm was fixed at the top channel of the hybrid PV/T collector. The setup was made inclined at an angle of 12.25^o to the horizontal facing towards the south. The blower in the set up ensured the forced circulation of air into the PV/T air heater.

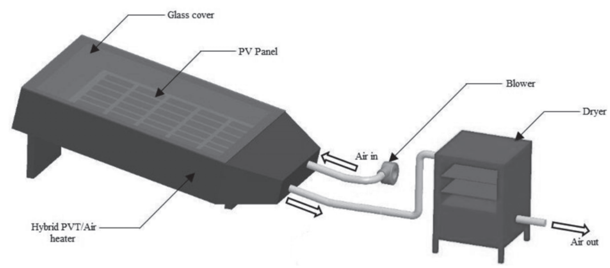

Fig. 1. Pictorial view of the hybrid photovoltaic thermal solar air heater

Salient features of design

The length and width of the solar photovoltaic panel are respectively 1210 mm and 660 mm. The outer dimensions of the solar collector are 1460 mm length, 780 mm width and 340 mm height. The inner length of the box is about 1400 mm which makes a gap for incoming air to turn to the lower channel from the upper channel. This arrangement forms two passages, above and below of the PV panel, thus formed a double pass collector. The performance of the double pass hybrid PV/T solar air heater was further improved by attaching simple and cost effective heat extraction devices in the absorber plate. In this model, five slats of length 1160mm and height 120 mm were attached perpendicular to the absorber plate in the lower channel (Fig. 2). The enhanced heat dissipation from the solar panel improves the electrical efficiency and the extracted heat in used in a beneficial way subsequently.

Solar dryer with electric heater

The performance of the hybrid solar dryer was compared with the performance of a similar dryer

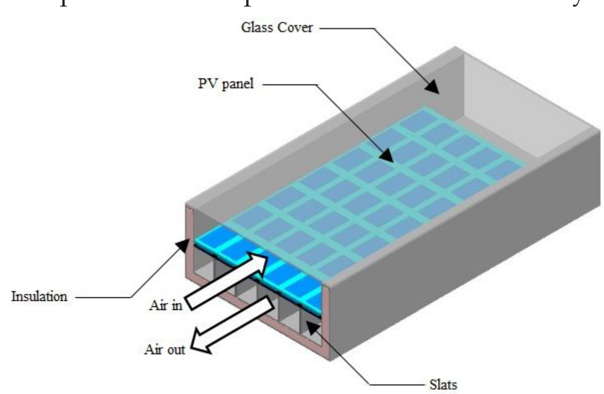

Fig. 2. Inner details of hybrid PV/T air heater

using an electric heater. The electric heater was fabricated with provision for heating at four different power ratings. In the present work a power rating of 500 W was used (Fig. 3). The cabinet type dryer could be attached to the electric heater. Like in the previous case, a blower was provided for the circulation of air. The pressurised air from the blower was passed through the heater so that hot air emanates from it. This hot air enters the dryer for the dehydration of the fruit samples.

Fig. 3. Photograph of the solar dryer with electric heater

Experimental procedure

In this work, the economic analysis of drying of amla or Indian gooseberry (*Phyllanthus emblica*) is conducted. As amla is a rich source of vitamin C, the dried product has lot of market potential. First, experiments were conducted to study the drying characteristics of amla using two types of the drying system: (i) solar dryer with PV/T air heater and (ii) solar dryer with electric heater. The experiments were conducted in Solar Energy Centre of National Institute of Technology Calicut, Kerala, India. From the local market of Calicut, fresh amla was procured. The seed of the fruit was removed after slicing the flesh. 1 kg of the sample was placed in the dryer. First drying experiment was conducted using the PV/T air heater. Weight of the sample was measured periodically using an electronic balance. The experiment was continued till the required moisture removal was obtained. The experiment was repeated using the electric heater also.

Various measuring instruments were used to analyse the performance of the dryer. The solar radiation intensity was measured using a pyranometer (make-EMCON). Relative humidity was measured by humidity meter (make-Huger) and air velocity, by an anemometer (make-Lutron AM-4201). Voltage and current of photovoltaic cell were measured by the voltmeter and ammeter (make-MECO). Photovoltaic panel was loaded using a rheostat for maximum power point. The ambient temperature, glass cover temperature, top and bottom temperature of the panel, temperatures of the bottom plate, inlet and outlet temperatures of air, dryer temperature etc. were measured using J-type thermocouples.

Economic Analysis

A robust economic model is necessary for the analysis of solar energy systems. The market penetration of the renewable energy technologies is ultimately based on the economic paybacks by using the solar thermal systems. Economic feasibility of two projects can be compared in different ways. In the present work, following models are used for studying the economic feasibility of the developed hybrid solar energy system compared with an electric system.

Annualised cost method

Consider an end of the year uniform amount R for a period of 'n' years for a single present value of P as shown in the diagram, Fig. 4 (Tiwari, 2002).

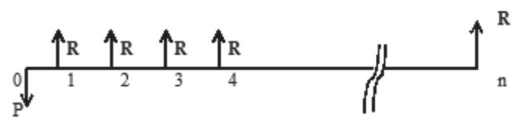

Fig. 4. Uniform cost of the present value

Present value, $P = R\frac{(1+i)^n-1}{i(1+i)^n}$ .. (1)

where 'i' is the interest rate and 'n' is the life span of the system

The capital cost is a single one time investment but that can be annualised for the analysis using the above method. In the annualised cost method, all the costs associated with both types of drying are taken in an annual basis.

Annualised uniform cost is defined as a product of the present value of the system and capital recovery factor (CRF)

So the annualised capital cost, ACC = Capital cost x CRF

where $CRF = \frac{i(1+i)^n}{(1+i)^n-1}$ .. (2)

Annual cost of production = Annualised Capital Cost (ACC) + Cost of electricity+ Cost of maintenance + cost of raw amla .. (3)

Maintenance cost is taken as 2%.

Payback period

Payback period is the time needed to recoup the capital investment by the cumulative savings.

Considering the interest rates and inflation,

Payback period is, $n_p = \frac{\ln[1-\frac{C}{S}(d-i)]}{\ln(\frac{1+i}{1+d})}$ .. (4)

where C is the capital investment, S is the annual savings, and 'd' is the discount rate.

Discount rate is the rate of return on the long term investment.

Benefit-Cost analysis

Benefit-cost (B/C) ratio analysis is a basic tool to determine the feasibility of a project based on advantage versus disadvantage analysis. A project is considered to be economically viable if the savings accrued from the project exceeds the associated costs.

$$B/C = \frac{\text{Net benefits}}{\text{Net costs}} \quad .. (5)$$

Life cycle savings

The solar energy technologies penetrate into the market when the economic viability of using the technology exceeds that of non-solar options. The economic viability can be determined in several ways. In the life cycle analysis, time value of money and detailed account of complete range of costs are taken into account (Kalogirou, 2004). This analysis gives clear insight to the long term economic feasibility of a system as it accounts all the benefits and costs over the life span of the system.

Life cycle costs (LCC)

Life cycle cost is the sum of all costs associated with a system over its life span, at the present value of money. In the LCC analysis, all the future costs are brought back to the present day cost.

Life cycle savings (LCS)

Life cycle savings of a solar energy system is defined as the difference between the LCC of a conventional fuel-only system and LCC of a solar energy system. In the present work, life cycle savings by using a hybrid PV/T integrated dryer is compared with an electric dryer for drying of amla.

Environmental Cost Analysis

Energy is a fundamental requirement for the existence and growth of human societies. The unbridled exploitation of all possible forms of energy resources irrespective of the environmental consequences is a serious threat to the fragile ecological balance. To assess the environmental viability of the system, two methods are used here in the analysis of solar hybrid PV/T drying system.

Energy matrices

The appropriateness of the energy technologies with respect to the ecological sustainability is analysed using energy modelling. Many basic techniques are evolved in this area. The performance of the dryer integrated with the solar PV/T system is analysed using two basic parameters as shown below.

Energy Pay Back Time (EPBT)

Energy payback time is the time needed to redistribute the embodied energy of the system by the energy savings by using the system. It is the ratio of the embodied energy to the total energy savings per annum (Agrawal and Tiwari, 2015).

$$EPBT\,(years) = \frac{E_{in}(kWh)}{E_{savings}(kWh/year)} \quad .. (6)$$

The concept of embodied energy has emerged as a latest tool to assess the environmental impact by using a product of service. This concept is widely used in the building technology field to reduce the total carbon foot print. Embodied energy is the total quantity of energy required for the production of goods or services considering all the energy requirements directly or indirectly needed for the process as if this energy is a part of the product or 'embodied' in it. Thus the basic idea of the embodied energy analysis is to determine the quantity of energy consumed in the production of a system. The energy involved in the production of the raw materials, manufacturing of the products, installation and maintenance of the components etc. are taken into consideration.

Energy production factor (EPF)

The overall energy performance of the hybrid PV/T drying system can be easily assessed by the energy production factor which is the ratio of total energy input to total energy output. It is the reciprocal of EPBT. It is defined in two ways.

(i) On annual basis

$$EPF_a = \frac{E_{out}}{E_{in}} \text{ or } EPF_a = \frac{1}{EPBT} \quad .. (7)$$

If *EPFa* approaches unity, the project becomes viable ecologically.

(ii) On life time basis

$$EPF_l = \frac{E_{out}\times n}{E_{in}} \quad .. (8)$$

Carbon credits

Major attraction of the solar energy is its environmental friendly nature. The remarkable progress of the world economy since the decades from 1970 has brought unprecedented prosperity to the world. But the excessive dependence on the fossil fuels for driving this growth over several decades has severely damaged the global ecological balance. In order to overcome the challenges posed by global warming and related environmental matters, scientific community and policy makers have finally turned their attention towards renewable energy. The enviroeconomic analysis is a powerful tool to evaluate a project for its environmental friendliness based on the CO_2 emission into the environment. Electricity is produced widely from coal which is a cheap fuel but not environmental friendly. 960 gCO_2/kWh is the average CO_2 equivalent intensity for electricity generation from coal. The other factors such as transmission and distribution losses in India (20%) and loss due to inefficient electric equipment (20%), the total figure reaches to1.34 $kgCO_2$/kWh. CO_2 mitigation potential of the hybrid PV/T dryer is an important indicator for the adaptation of the technology. CO_2 mitigation per annum is determined as,

$$\tau_{co_2} = \frac{\delta_{co_2}\times E_{overall}}{10^3} \quad .. (9)$$

where τco_2 is CO_2 mitigation per annum (tCO_2/annum), δco_2 is the average CO_2 equivalent intensity for electricity generation from coal (1.34 kg CO_2/kWh) and $E_{overall}$ is the annual overall energy savings (kWh) by using the hybrid PV/T dryer system.

RESULTS AND DISCUSSION

The experiments were conducted in Solar Energy Centre of NIT Calicut. The performance of the PV/T hybrid drying using solar energy as input is compared with that of drying similar crops using electrical energy. The PV/T dryer took 12 hours for drying 1 kg of amla while the electric heater took 10 hours for the same moisture removal. The enviroeconomical analysis is conducted to study the overall benefits of solar energy systems. The pertinent costs and parameters considered for the study is given in Table 1.

Economic analysis

Annualised capital cost method

The capital cost of the hybrid PV/T dryer system is worked out to be about Rs. 30000. This includes the cost of 100 Wp solar panel, material and labour cost for fabricating PV/T air heater, cost of dryer, cost of blower and other transportation and labour charges for the installation of the PV/T system. The capital cost of the electric drying system is Rs. 13000. This is the cost for the electric heater, air blower, dryer and other conveyance and labour charges for the installation of the system. The annualised capital cost of the solar hybrid PV/T drying system is calculated using Eq. (2) to be Rs. 2407. Annualised capital cost of the electric system is Rs.1740. On an average 250 sunny days are available in a year for the solar energy applications. In a drying day, 9 hours of useful drying was performed. For calculating the annual cost of production, running cost of blower, maintenance charges and cost of raw amla were taken as per Eq. (3). Total production capacity of the PV/T dryer is 37 kg of dried amala/year. The PV/T dryer uses an electric blower which consumes a total energy of 626.63 kWh/year. Total

Table 2. Common parameters

Sl. No	Parameter	Value
1	Unit cost of electricity	Rs. 5.5/unit
2	Cost of raw amla	Rs. 40/kg
3	Number of sunny days per year	250 days
4	Discount rate	5%

Table 1. Costs and parameters

Sl. No	Parameter	PVT dryer system	Electric dryer system
1	Capital cost	Rs. 30000	Rs. 13000
2	Life span	20 years	20 years
3	Interest rate	5%	12%
4	Maintenance charges	2%	2%
5	Total time required for drying of 1 kg amla	12 hours	10 hours
6	Electric power requirement	278.5 W	694.1W

electricity production from the solar photovoltaic panel is worked out to be 90 kWh/year. Considering a 95% earning from this production, total cost while using a solar energy system is Rs. 2976 per annum. The electricity cost of the electric drying system is Rs. 7139 per annum. Using these factors, total cost of drying of 1 kg of amla using the solar thermal system is worked out to be Rs. 349 per kg of dried amla. While using the electric heating system, the cost is Rs. 454 per kg of dried amla. So there is an annual savings of Rs. 3885 per year.

Payback Period

Payback time is the time needed for the cumulative savings to balance the initial investment. Initial investment of the solar drying system is Rs. 30000 and the life span is 20 years.

Simple payback period (SPB) = Investment costs/ Net benefits

It is calculated to be 7.72 years. But considering the interest rate and discounting the actual payback period is calculated using Eq. (4) to be 9.3 years. Considering the total life span of 20 years, this project can be treated as a viable one. In the present analysis, savings using a solar thermal system is determined in comparison with the expenses incurred for an electric heating system while the actual cash flow from the sales of the dried products is not considered.

Benefit-Cost Ratio

Benefit-cost (B/C) ratio analysis is a simple tool for selecting a project based on the economic viability. If the B/C ratio exceeds unity, the project is viable because net benefits exceed the costs. In the present analysis annualised costs are considered for the comparison. The net benefit of using the developed solar dyer compared with the electric heating system is considered. The B/C ratio is worked out to be 1.61. As it is above one, the adaptation of solar energy system can be considered as a viable option.

Life cycle savings

The life cycle cost savings by using the developed solar drying system is analysed (Table 3).

In this analysis, 10% of the capital cost is treated as the down payment and the rest is taken as a loan from a bank with an interest rate of 5% for 10 years. Provision for fuel inflation is given as 3%. The total

Table 3. Life cycle cost calculation

Year	Interest (Rs.)	Principal paid (Rs.)	Principal balance (Rs.)	Extra mortgage payment(Rs.)	Fuel savings (Rs.)	Solar savings (Rs.)	PW of solar savings (Rs.)	cumulative solar savings (Rs.)
0.00			27000			-3000.00	-3000.00	-3000.00
1.00	1350.00	2146.62	24853.38	-3496.62	3885.00	388.38	359.61	-2640.39
2.00	1242.67	2253.95	22599.42	-3496.62	4040.40	543.78	466.20	-2174.19
3.00	1129.97	2366.65	20232.77	-3496.62	4202.02	705.39	559.96	-1614.23
4.00	1011.64	2484.99	17747.78	-3496.62	4370.10	873.47	642.03	-972.20
5.00	887.39	2609.23	15138.55	-3496.62	4544.90	1048.28	713.44	-258.76
6.00	756.93	2739.70	12398.85	-3496.62	4726.70	1230.07	775.15	516.39
7.00	619.94	2876.68	9522.17	-3496.62	4915.76	1419.14	828.06	1344.45
8.00	476.11	3020.51	6501.66	-3496.62	5112.39	1615.77	872.95	2217.40
9.00	325.08	3171.54	3330.12	-3496.62	5316.89	1820.27	910.59	3127.99
10.00	166.51	3330.12	0.00	-3496.62	5529.57	2032.94	941.65	4069.63
11.00					5750.75	5750.75	2466.40	6536.03
12.00					5980.78	5980.78	2375.05	8911.08
13.00					6220.01	6220.01	2287.08	11198.17
14.00					6468.81	6468.81	2202.38	13400.54
15.00					6727.56	6727.56	2120.81	15521.35
16.00					6996.67	6996.67	2042.26	17563.61
17.00					7276.53	7276.53	1966.62	19530.23
18.00					7567.59	7567.59	1893.78	21424.02
19.00					7870.30	7870.30	1823.64	23247.66
20.00					8185.11	8185.11	1756.10	25003.76
				Solar savings			25003.76	

life cycle savings is found to be Rs. 25,004.

Energy matrices

Energy Pay Back Time (EPBT)

There is substantial energy savings by using the solar thermal system compared with the electric system for drying of amla. In the energy payback analysis, the time period required to balance the embodied energy of the solar energy system with the cumulative energy savings by the use of it. The total energy savings by the solar thermal system is 761.34 kWh/year compared with an electric heating system considering the electricity production by the PV panel. The total embodied energy of the solar system is calculated as given in Table 4.

$$\text{EPBT (years)} = \frac{E_{in}(\text{kWh})}{E_{savings}\,(\text{kWh/year})} \quad \text{.. (10)}$$

i.e, EPBT = 1865.98/761.34 = 2.45 years

Energy production factor (EPF)

(i) On annual basis

$$EPFa = \frac{E_{out}}{E_{in}} = 763.34/1865.98 = 0.41$$

(ii) On life time basis

$$EPFl = \frac{E_{out} \times n}{E_{in}} = 0.41 \times 20 = 8.2$$

On an annual basis the energy production factor for a solar PV/T drying system is calculated to be 0.41. On a life time basis, the energy production factor is 8.2. A near unity value of EPF indicates that the energy savings by the solar energy system is at par with the total embodied energy of the system. So ecologically, a value near unity of EPF is ideal. Considering the total life span of the project, EPF for life is calculated.

Carbon credits

Only source of energy for a human during the period "primitive" was food (Fanchi, 2004). Historical per capita energy consumption estimated for a 'primitive' period is 2 x 10^3 kcal. As societies advanced over the millennia, the requirement of energy has been increased exponentially. The estimate of per capita energy consumption in the modern technological period is 230 x 2 x 10^3 kcal. Energy consumption since the beginning of industrial age has been driven by fossil fuels. Due to the excessive dependence on the fossil fuels, the CO_2 emission also tremendously increased during this period. During the last 50 years, emission of CO_2 has been doubled (IEA, 2017). This poses a serious challenge to the fragile environmental equilibrium. The after effect of the unprecedented carbon emission is the global warming which means the increase of average temperatures of near the surface of the Earth. The alarming proportion of the threat to the environment is noticed by the nations and an international environmental treaty was adopted by the United Nations Framework Convention on Climate Change (UNFCC) at the Earth Summit, Rio de Janeiro in 1992. The UNFCC objective was to reduce the concentration of greenhouse gases in the atmosphere. In 1997, the Kyoto Protocol was established to reduce greenhouse gases by developed countries by legally binding obligations. In an effort to reduce the emissions of greenhouse gases, a mechanism called carbon trading was

Table 4. Embodied energy of the components of the solar PV/T dryer

Sl. No.	Component	Quantity	Energy density (kWh/kg)	Total embodied energy (kWh)
1	PV panel	0.8 m^2	980 kWh/m^2	784
2	MS frame and structure	23.36 kg	8.89	207.67
3	GI sheet	63.67 kg	9.67	615.69
4	Glass cover	13.16 kg	4.42	58.16
5	Polystrene	1.5 kg	32.52	48.78
6	Paint	2 kg	25.11	50.22
7	Plywood	1.65 kg	2.89	4.77
8	Blower			
9	Plastic	0.7 kg	19.44	13.61
10	Copper wire	0.3 kg	19.61	5.88
11	Iron	1 kg	8.89	8.89
			Total	**1865.98**

developed (Tiwari, 2002; Tyagi and Kaushik, 2012). Kyoto protocol signatory nations are obliged to reduce the carbon emission in a phased manner. When the target on schedule cannot be achieved, a nation can assign its industries to purchase emission permits or carbon credits, mostly from developing countries to meet its targets. Carbon credits are gathered by enterprises in developing countries when polluting technologies are replaced with clean technologies (IEA, 2017). Carbon credits are defined as "a key component of national and international emissions trading schemes that have been implemented to mitigate global warming". Credits are traded in the international market at the prevailing market rates. The rate of one carbon credit is taken as per 2017 value is \$14.5/tCO_2 (Sahota *et al.,* 2017).

Total overall electrical energy savings per annum = 761.34 kWh/year

CO_2 emission for each unit of power consumed = 1.34 $kgCO_2$/kWh

CO_2 emission reduction per annum = 1.02 tCO_2/year

Environmental cost reduction per annum= 1.02 x \$ 14.5= \$14.79/year

(CO_2 mitigation price per annum) = Rs.1002.76/year

(1 US dollar = Rs.67.8)

CONCLUSIONS

Hybrid photovoltaic thermal technology is an ingenious way of harnessing solar energy for domestic and industrial applications. In the present work, the heat extracted from the photovoltaic panel is used for drying of amla (*Phyllanthus emblica*). The performance of the hybrid PV/T collector was enhanced by attaching slats in the absorber. The performance of the developed solar dryer with PV/T air heater combination was compared with solar dryer with electric heater combination. The economic and environmental characteristics were analysed. The payback time of the hybrid PV/T solar dryer is estimated as 9.3 years. The analysis was done considering a savings compared with the use of an electric dryer. The life cycle savings is found to be above Rs.25000. The energy payback time is 2.45 years. Energy production factor is 0.41 on annual basis and 8.2 on life time basis. Considering the value of \$ 14.5/tCO_2, for a carbon credit, environmental cost reduction per annum is Rs.1003.These factors clearly establish the economic viability and environmental sustainability of the suggested system of hybrid PV/T powered solar dryer.

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