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Economic and Environmental Sustainability of Various Solar Thermal Devices

Surendra Poonia and A.K. Singh

ICAR-Central Arid Zone Research Institute, Jodhpur 342 003, India

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***Correspondence**
Surendra Poonia
surendra.poonia@icar.gov.in

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Abstract: The development of a region depends on energy utilization. The use of traditional energy sources, such as coal, oil, and natural gas cause pollution by releasing greenhouse gases into the atmosphere. To solve these environmental problems, it is important to switch to cleaner, more energy-efficient sources such as renewable energy (solar, wind, hydro, geothermal) and reduce electricity use. ICAR-CAZRI, Jodhpur has designed and constructed many new solar thermal and photovoltaic systems to provide green solutions to energy problems in arid regions. PVT (Photovoltaic-Thermal) with great potential to add energy includes hybrid and tilt-type solar dryers, trackless solar cookers, animal feed solar cookers and solar desalination units. To start a new business, the profitability of the business should be evaluated separately based on economic analysis. Banks provide loans according to the economic characteristics of the project. For this reason, the economic evaluation of solar thermal devices were carried out to evaluate the feasibility of solar technology investment in order to guide new entrepreneurs. Therefore, the cost-economics of these devices have been carried out. The high cost of business characteristics such as benefit-cost ratio (BCR), net present value (NPV), annual income, rate of return (IRR) and low cost of payback period indicate that the use of solar energy is profitable. . It also keeps the environment clean by eliminating carbon dioxide emissions.

Key words: Eonomic analysis, solar thermal devices, business model

The global population is experiencing rapid growth, resulting in an increased demand for energy due to industrialization, urbanization, and the use of energy-intensive technologies. However, the use of scarce resources such as coal, oil and natural gas in electricity production and use has led to environmental problems such as air pollution and climate change. It is projected that these resources may be depleted within the next 50 to 100 years if current consumption rates persist. Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs, including access to clean and reliable energy. Renewable energy sources such as solar, wind and biomass offer an environmentally friendly alternative to fossil fuels. Solar cooking, drying, and desalination are simple, viable, and attractive options for utilizing solar energy, particularly in developing countries (Pande *et al.* 2009; Poonia *et al.*, 2018a; Singh *et al.* 2020a). These methods produce no greenhouse gas emissions or air pollution, making them environmentally friendly and reducing reliance on fossil fuels. They are particularly suitable for rural areas in developing countries where access to electricity and clean cooking fuels may be limited. Traditional cooking methods that rely on open fires or poor-quality stoves create indoor air pollution that can cause respiratory problems. The impact of fuel wood burning on the ecosystem has been documented in several kinds of literature (Tingem and Rivington, 2009; Panwar *et al.,* 2011; Poonia *et al.,* 2017b and 2023). In India, each person needs 0.4 tons of fuel wood annually. The firewood situation in rural areas is even more serious than the oil price increase. If cow dung is utilized as manure rather than burned for cooking, it can meet one-third of India's fertilizer needs (Panwar *et al.,* 2011). Fruits and vegetables are often dried outdoors. Although this drying method is low-cost, it also brings problems such as dust pollution, bacterial contamination, precipitation and uneven drying (Fudholi *et al.* 2010; Poonia *et al.,* 2017a, 2018a). Solar dryers can enhance food security and income generation by allowing farmers to preserve and sell their crops when prices are higher (Poonia *et al.,* 2021 and Poonia *et al.,* 2022 a, b). Solar thermal devices not only reduce the environmental impact of cooking and food preservation but also alleviate the drudgery associated with traditional methods, ultimately contributing to a better standard of living in rural areas (Panwar *et al.*, 2013). In comparison to the rest of the country, the arid and semi-arid regions of the country receive significantly greater radiation 6.0 $kWhm^{-2} day^{-1}$ mean annual daily solar radiation with 8.9 average sunshine hours a day at Jodhpur (Poonia *et al.,* 2022c).

Any solar energy device is useless unless it can be used for a reasonable price. Economic feasibility should be low during solar thermal device optimization under defined design conditions because it is strongly correlated with cost variables such as material, maintenance, manufacturing, and operating costs. The main issues with solar devices are their high cost of manufacture, operation, maintenance, and interest. The success of solar thermal devices is purely dependent on the drastic reduction of capital cost in the solar thermal system of construction. Research initiatives aimed at reducing the price of these units ought to be continued. Without compromising their functionality, research, and development into more affordable, durable, locally obtainable materials for drying unit construction should continue (Selvanayaki and Sampathkumar, 2017). The development of the solar energy sector is very beneficial in terms of employment generation in India. It not only generates income, it creates employment and reduces CO_2 emissions. Therefore, solar energy installation in the manufacturing industry needs to be evaluated financially. These products can add energy to create new jobs, and business opportunities should be evaluated based on analysis and marketing (Singh *et al.,* 2020a and 2022; Poonia *et al.,* 2023). Banks provide loans based on the economic results of the project. Therefore, the present study was carried out to assess the viability of establishing enterprises focused on developing solar thermal energy devices, aimed at providing guidance to aspiring entrepreneurs in their pursuit of establishing new ventures.

Materials and Methods

Economic evolution of solar thermal devices

Economic analysis of solar thermal devices is essential to assess their cost-effectiveness and overall viability in comparison to other energy sources. The economic evaluation is based on life cycle cost (LCC) and life cycle benefit (LCB). Additionally, other economic factors such as benefit-cost ratio (BCR), net present value (NPW), annual income (A), rate of return (IRR), payback period (PBP) and carbon mitigation potential were also determined of the devices.

Life cycle cost (LCC)

It refers to the total cost incurred throughout the life of the solar thermal device. It includes initial capital costs (such as purchase and installation), operation and maintenance costs, and disposal or decommissioning costs. LCC helps in determining the overall cost of the device over its lifetime (Poonia *et al.,* 2018a, 2020, 2021 and 2022a and Singh *et al.*, 2020a).

The LCC is given as:

$$\text{LCC (Unit)} = \text{Initial cost per unit } (P_i) + P_w \text{ (O \& M cost including labour)} - P_w \text{ (SV)} \quad \text{... (1)}$$

$$= Pi + Pw\frac{X(1-X^n)}{1-X} - SV(1+i)^{-n}$$

where,

P_i = Initial investment (Rs.); P_w= Operational & maintenance expenses, including replacement costs of damaged components (Rs.); n = Useful life of solar devices, year; P_w (SV) = Present worth of salvage value of the devices at the end of life (Rs.); e = Annual escalation in cost (fraction), and i = Interest or discount rate (in fraction).

Life cycle benefits (LCB)

LCB represents the total economic benefits generated by the solar thermal device over its operational life. This includes savings in energy costs, reduced greenhouse gas emissions, and any other tangible benefits associated with its use (Poonia *et al.,* 2018a, 2020 and 2022a and Singh *et al.*, 2020). The LCB is as follows:

$$LCB = R\frac{X(1-X^n)}{(1-X)} \quad \text{... (2)}$$

where,

R is the annual benefit (Rs.) and $X = \frac{1+e}{1+i}$

Benefit-cost ratio (BCR)

Benefit-cost ratio (BCR) is a financial measure used to evaluate the economics of a solar product or project. It is calculated by dividing the total benefit (often referred to as the "LCB" of the "lifetime benefit") by the total cost (often referred to as the "LCC" of the "cost of living"). The calculation formula of BCR is as follows (Poonia *et al.,* 2018a, 2020, 2021 and 2022b and Singh *et al.*, 2020b):

$$Benefit - cost\ ratio(BCR) = \frac{Life\ cycle\ benefits\ of\ solar\ devices}{Life\ cycle\ cost\ of solar\ devices}$$

$$BCR = \frac{R\frac{X(1-X^n)}{(1-X)}}{P_i + P_w - P_w(SV)} = \frac{LCB}{LCC} \quad \text{... (3.1)}$$

The benefit-cost ratio of a solar cooker is expressed as the ratio of initial cost and current price to initial cost as follows:

$$BCR = \frac{E\sum_{n=1}^{15}\frac{1}{(1+a)^n}}{C + M\sum_{n=1}^{15}\frac{1}{(1+a)^n}} \quad \text{... (3.2)}$$

Net present worth (NPW)

NPW is the net present value (total profit minus total cost) of the asset discounted to its present value over its useful life. A positive NPW indicates that the investment is financially sound, while a negative NPW indicates that the investment is not economically sound. NPW is a crucial financial tool for assessing the feasibility of an investment in a solar thermal device. It helps investors and decision-makers determine whether the project will add value to their financial goals and whether it's a wise financial choice.

$$NPW = LCB - LCC \quad \text{...(4)}$$

The NPW for solar cooker has been computed by using the following relation, respectively (Nahar, 2001; Mahavar *et al.,* 2012 and Poonia *et al.,* 2020)

$$NPW = \frac{(E-M)}{(a-b)}\left[1 - \left(\frac{1+b}{1+a}\right)^n\right] - C \quad \text{...(5)}$$

where, C = Cost of solar cooker (Rs.), E = Annual energy savings (Rs.) by using solar cooker compared to other fuels (oil, coal, kerosene, LPG and electricity), M = Annual maintenance cost of solar cooker (Rs.), a = Annual compound interest, b = Inflation rate in energy and maintenance per annum, n = Number of years.

Annuity (A) : Annuity represents the equal annualized cash flow that would result from an investment in the solar thermal device. It takes into account both the initial investment and the net benefits over the device's life (Poonia *et al.,* 2018a, 2020 and 2022 and Singh *et al.*, 2020b).

$$(\text{Annuity}) = \frac{NPW}{\sum_{t=1to10}\left(\frac{1+e}{1+i}\right)^n} \quad \text{...(6)}$$

Payback period

The payback period is the time it takes for the profit to equal or exceed the initial investment. A shorter payback period is generally preferred because it indicates a faster return on investment. The payback period is shown in years and parts of the year (Poonia *et al.,* 2018b, 2020 and 2022a,b and Singh *et al.*, 2020a). The shorter the return on investment, the lower the risk. The payback period can be determined by the following formula:

-LCC+LCB = 0

The payback period of solar cooker is calculated by calculating the balance of other fuels such as kerosene, coal, gasoline, liquefied petroleum gas. (LPG) and electricity. The payback periods for non-tracking solar cooker have been computed by using the following relations, respectively (Nahar, 2001; Poonia *et. al,* 2020):

$$N = \frac{\log\left[\frac{(E-M)}{(a-b)}\right] - \log\left[\left(\frac{E-M}{a-b}\right) - C\right]}{\log\frac{(1+a)}{(1+b)}} \quad ...(7)$$

N: Payback period in years, a: Compound interest rate per annum, b: Inflation rate in energy and maintenance per annum, C: Cost of the solar cooker (Rs.), E: Energy savings per year (Rs.), M: Maintenance cost per annum (Rs.).

Internal rate of return (IRR)

Internal rate of return (IRR) is the most important factor used to evaluate the profitability of an investment in solar solar thermal devices. It represents the discount rate at which the net present value (NPV) of cash flows from the investment is zero. In other words, it is the ratio of the initial investment to the income that the investment will generate in the future. Higher IRR is generally better (Poonia *et al.*, 2018 a, 2020 and 2022 and Singh *et al.*, 2020).

$$IRR = lower\ DR + \frac{Difference\ of\ DR\ x\ NPWat\ lower\ DR}{(NPW\ at\ lower\ DR\ - NPW\ at\ higher\ DR)} \quad ...(8)$$

where, DR is discount rate

Carbon mitigation potential

The carbon footprint of solar thermal devices or systems is a measure of the amount of carbon dioxide (CO_2) emissions and it helps avoid or reduce when compared to conventional fossil fuel-based energy generation. CO_2 emissions include net emissions from the production of materials for photovoltaic systems. A solar power plant emits an average of 0.98 kilograms of carbon dioxide every time it produces electricity. The emission factor is a value that indicates the amount of carbon dioxide emissions produced per unit of energy produced by a particular method. For example, fossil fuels like coal or natural gas have high emission factors because they release a significant amount of CO_2 when burned to generate energy.

$$CO_2 \text{ emission per year} = \frac{E_{em}\ (kWh)\ \times\ 0.98}{n\ (years)} \quad ...(9)$$

where,

E_{em} = embodied energy of the system, n = lifetime of the solar devices

Net CO_2 reduction was monitored under the Kyoto Protocol with an emission credit of 21 € (euro) (where 1 € = INR 82) per t CO_2 e (European Climate Exchange, 2008). The current value of carbon credit by the PV system is calculated as follows:

$$\frac{0.98 \times 21 \times 82 \times Net\ CO_2\ mitigation}{1000\ \sum_{n=1}^{n=25}(1-d\ )^n \times \left[\frac{(1+e)}{1+i)}\right]^n} - 21 \times 82 \times\ 0.98\ \times \frac{E_{em}}{1000} \quad ...(10)$$

The social cost of carbon for India is reported to be the highest across the globe at US$ 86 per ton of CO_2-equivalent (CO_2-eq) (Ricke *et al.* 2018). This means that for every additional ton of CO_2 emissions in India, it is estimated that there are economic damages equivalent to US$ 86. A lower carbon footprint indicates a more environment-friendly energy generation system, as it results in reduced CO_2 emissions for the same amount of energy produced.

Results and Discussion

The fundamental principle of solar energy technology involves harnessing incoming solar radiation through transparent glass collectors to generate heat, which can be utilized for various purposes such as drying, heating, and cooking. Based on this principle, various types of solar energy thermal devices have been developed for post-harvest processing and value addition of agricultural products, boiling of animal feeds and desalination of salt water (Poonia *et al.*, 2017a; 2018; Singh *et al.*, 2020). For example, PV/T hybrid solar dryers, inclined type solar dryers, solar cookers, solar water heaters, solar desalination, etc. Overall, solar energy technology provides a profitable benefit for rural communities, especially in arid regions where sunlight is abundant, by providing a continuous and sustained solution to various agricultural and post-harvest processes.

Economic analysis of solar thermal devices involves assessing the financial viability and cost-effectiveness of these technologies for various applications (Bhattacharyya *et al.*, 2022). Many factors need to be taken into account before a solar thermal gadgets installation and solar power plant is designed and installed. These include field research, market research, logistics management, demand management, policy and marketing. Such analyses are necessary for the success of solar energy projects (Prakash *et al.*, 2017). Economic analysis is crucial in determining the feasibility and viability of solar energy projects. The primary objective of economic analysis is to maximize the net benefit or minimize costs while achieving specific benefits. It's important to note that what may be technically efficient from an engineering standpoint may not always be financially efficient.

Solar dryer

Compared to traditional methods such as open sun drying, solar dryers are the best solar energy products for drying fruits, vegetables and grains. In addition, since it is protected from rain, there is little chance of damage or deterioration from pests during the sun drying process. Among the various types of solar dryers inclined solar dryer and phase change material-based PV/T solar dryer are the most commonly used devices. Each type of solar dryer has its own advantages and may be better for certain applications or areas depending on conditions such as weather, capacity and type of dry goods. Overall, solar drying is an environmentally friendly and cost-effective way to preserve foods.

PCM-based PV/T hybrid solar dryer

The PCM-based PV/T hybrid solar dryer with a glass collection area of 1.06 m^2 can dry 10 to 12 kg of fruits and vegetables in 12 to 48 hours, depending on the moisture content of the product (Fig. 1). The cost of dried fruits and vegetables depends on many factors, including the initial cost of the solar dryer, operating costs (maintenance, labor, etc.) and the cost of dry arid food produce. The price of the dried produce will vary depending on the type and market value of the fruits and vegetables processed. The initial investment (P_i) of PCM based PV/T hybrid solar dryer is Rs. 14,000. The annual operation and maintenance (O&M) cost, including labour, is Rs. 4,000. The salvage value was taken as 10% of the initial investment.

Fig 1. PCM-based photo voltaic thermal (PV/T) hybrid solar dryer.

The annual benefit was obtained by using the dryer for 10 drying cycles each for Indian jujube and Indian cherry (*Cordia myxa* L.). The 18 kg of ber was processed through 10 drying cycles, resulting in a total weight of 180 kg. With a price of Rs. 20 per kg, the cost amounts to approximately Rs. 3,600. The dried ber fruit weight is 60 kg and is sold at Rs. 150 per kg, generating a revenue of Rs. 9,000 and a profit of Rs. 5,400. Similarly, drying 180 kg of Indian cherries increases revenue by Rs. 30 per kg, increasing to Rs. 5,400. Therefore, the total annual income from dry produce, ber and Indian cherries is Rs. 10,800. The total cost incurred over the entire life cycle of the dryer, including initial investment, annual operation and maintenance and other related costs, is Rs. 42,191. The total revenue generated over the entire life of the dryer from selling dried products is Rs. 80179. The present value of the dryer's total revenues and expenses is calculated as the result of the discount rate for the entire project. NPW of the dryer is reported to be Rs. 37,988. The present dryer based on NPW have been determined to be more economical in terms of production compared to solar biomass hybrid dryer (Dhanushkodi *et al*., 2015) and hybrid photovoltaic/thermal greenhouse crop dryer (Barnwal and Tiwari, 2008).

The benefit-cost ratio is calculated by dividing the present value of the benefit (LCB) by the present value of flow cost (LCC), which is 1.90 for the dryer. A BCR greater than 1 suggests that the project is economically viable. Annual income of dryer shows that the average annual return of dryers is Rs. 5118. The payback period is 2.08 years, which is lower than the payback period of the dryer, which is approximately 10 years. The discount rate that causes the NPW of the project's cash flows to fall to zero. The IRR of 64.6% is a good indicator of the economics and attractiveness of the project. The thermal efficiency of this dryer is 16.7%. In addition to the economic benefits, using a hybrid solar dryer can save approximately 1850 MJ/year of energy compared to conventional open sun drying. Furthermore, by replacing a conventional electricity-operated oven dryer, a solar dryer can also reduce CO_2 emissions by approximately 503 kg $year^{-1}$. Overall, the economic analysis suggests that investing in the PCM-based PV/T hybrid solar dryer unit is a financially sound decision compared to the alternatives mentioned in the reference studies.

Inclined Solar dryer

The inclined solar dryer (1280 mm × 980 mm) based on the natural convection working principle, is made of a rectangular box made of galvanized steel sheet (22 gauge) and two drying trays. The collector area of inclined dryer is 1.25 m^2 and the average thermal efficiency of dryer is 18%. The initial investment of an dryer is Rs. 9000 and the annual cost of operation and maintenance (O&M), including labor, is Rs. 4000. The SV (salvage value) is 10% of the initial investment. The annual return was obtained by using 10 trials each of ber and seedless lasoda/gonad using a dryer. The dry weight of ber is around 120 kg and its price is around Rs. 2400. The weight of the dried ber is about 40 kg and at Rs 150 per kg Rs. 6000/- was obtained. Earn income from benefit is Rs. 3600. Similarly, thirty seedless lasoda/ gonda samples were dried to 120 kg gonda for a profit of Rs. 30/kg unseeded seeds, totaling about Rs. 3600 and six months experimental drying of tomatoes, spinach and carrots added about 360 kg @ 10 Rs. per kg. Guaranteed profit of Rs. 3600. Therefore, the total annual profit from dried produce is approximately Rs. 10,800. Considering an interest rate of 10% and 10-year life of the dryer, the cost of living and life-cycle benefits show that the LCC and LCB of the dryer are Rs. 38,349 and Rs. 80,179 respectively.

The net present worth (NPW) of investment in the dryer is Rs. 41,830, which means the dryer makes a good profit over its life. The profit-cost ratio is 2.09; this means that for every Rs. 1 invested, there is a return of Rs. 2.09. The annuity of the dryer is Rs. 5635, which represents the average net annual return. The payback period is 1.42 years, which is shorter than the expected life of a dryer. This indicates a quick return on investment. NPW of discount rate variable shows that at 10% interest rate NPW is positive at Rs. 41830. But if the interest rate is higher, say 60%, the NPW comes down to Rs. 3516.44. NPW at 90% interest varies negatively at Rs. 804.93. This shows the sensitivity of the project's financial potential to the discount rate.

Overall, the tilt-type solar dryer seems to be a good investment, with a good NPW, a benefit-cost ratio greater than 1, and a payback period that lags the life of the dryer. The high IRR of 84.4% also indicates a strong return on investment. However, it is important to consider the discount rate when assessing the financial sustainability of a project. Besides the economic benefits, using a solar dryer saves approximately 1584 MJ energy $year^{-1}$ compared to open sun drying. Additionally, by replacing conventional dryers, solar dryers can reduce CO_2 emissions by approximately 431 kg $year^{-1}$.

Fig. 2. Inclined solar dryer.

Solar cooker

Solar cooker is another useful solar powered thermal device for cooking purposes and can replace cooking gas or liquefied petroleum gas (LPG), firewood, agricultural waste, and cow dung cake (Nahar 1998; Poonia *et al*., 2017a, Poonia *et al*., 2017b, Poonia *et al.,* 2020). There are different types of solar cookers available, such as animal feed solar cooker, high insulation hot box type solar cooker, and non-tracking solar cooker. The non-tracking and animal feed solar cooker does not require frequent adjustments to keep it facing the sun.

Non-tracking solar cooker

The double-glazed non-tracking solar cooker with a reflector designed and fabricated at the workshop of ICAR-CAZRI, Jodhpur, is an innovative solar cooking device based on the hot box principle. The dimensions of this cooker are 1090 × 285 × 150 mm. The aperture area of cooker is 0.30 m^2 with an an optimal ratio of 3.8:1 to achieve the maximum amount of radiation and eliminate the need for tracking (Fig. 3). Experimental results show that the first

Fig. 3. Non-tracking solar cooker.

figure of merit (F_1), second figure of merit (F_2), and standardized cooking power (Ps) are 0.121, 0.401, and 46.50 W, respectively, indicating that the produced cooking gadget is marked A class according to ASAE and BIS standards (Poonia *et al.*, 2020). The thermal efficiency of the solar cooker is 25.2%.

The initial cost of a non-tracking solar cooker is Rs. 9000.00 and the expected lifespan of the solar cooker is more than 15 years. The payback periods have been computed from equation (7) concerning different fuels shown in Table 1. The payback period is the time it takes for the savings from using solar cooker to reach the initial cost. The shortest payback period for firewood is 1.58 years, and the longest payback period for kerosene is 6.00 years. Net present worth (NPW) varies depending on the type of fuel used. NPW price varies between Rs. 3,060 to Rs. 38,006. The payback period increases for fuel: fire, electricity, electricity, liquefied petroleum gas and kerosene. The short payback period shows that the use of solar cooker is economical, especially when compared to traditional cooking methods such as firewood, LPG and gasoline. In addition to the economic benefits, the use of non-tracking solar cooker saves approximately 644 MJ energy year^{-1} compared to fuel. Additionally, the non-tracking solar cooker is in a position to replace 100 percent biomass, saving approximately 175 kg of CO_2 on an annual basis, if it replaces firewood.

Fig. 4. High-insulation box-type solar cooker.

High-insulation box-type solar cooker

High insulation box type solar cooker is designed and manufactured at ICAR-CAZRI, Jodhpur. The outer box is made of galvanized steel sheet (22 SWG) and the inner box is made of aluminum sheet. The outer box size is 610 × 610 × 200 mm, the inner box is 355 × 355 mm, the height is 80 mm and the aperture area is 0.126 m^2 (Fig. 4). This solar cooker has high F_1 and F_2 value in different seasons of the year (F1>0.12, F2>0.40), which shows that the performance of this cooker is good and works well in various climates and seasons (Poonia *et al.,* 2019). The overall efficiency of box type solar power is to be 26.5%. A higher efficiency percentage means that the solar cooker effectively converts sunlight into cooking energy.

The solar cooker costs is Rs. 4500.00 and the expected lifespan of the solar cooker is > 10 years. The payback period is calculated

Table 1. NPV and payback periods of non-tracking solar cooker

Type of fuel	Calorific value (MJ kg^{-1})	Efficiency (%)	Cost (Rs.)	Energy saving (Rs.)	Net present worth (Rs.) n = 10	Payback period (yr.)
Firewood	19.89 MJ kg^{-1}	17.3	9.00 kg^{-1}	6768	38006	1.58
Coal	27.21 MJ kg^{-1}	28.0	15.00 kg^{-1}	5094	25552	2.19
Kerosene	45.55 MJ L^{-1}	48.0	17.50 L^{-1}	2071	3060	6.00
LPG	45.59 MJ kg^{-1}	60.0	40.00 kg^{-1}	3784	15805	3.12
Electricity	3.6 MJ kWh^{-1}	76.0	6.00 kWh^{-1}	5674	29869	1.93

Table 2. NPV and payback periods of high insulation box-type solar cooker

Type of fuel	Calorific value ($MJ\ kg^{-1}$)	Efficiency (%)	Cost (Rs.)	Energy saving (Rs.)	Net present value (Rs.) n = 10	Payback period (yr.)
Firewood	19.89 $MJ\ kg^{-1}$	17.3	9.00 kg^{-1}	3384.0	19002.9	1.49
Coal	27.21 $MJ\ kg^{-1}$	28.0	15.00 kg^{-1}	2547.0	12775.7	2.42
Kerosene	45.55 $MJ\ L^{-1}$	48.0	17.50 L^{-1}	1035.5	1530.0	6.99
LPG	45.59 $MJ\ kg^{-1}$	60.0	40.00 kg^{-1}	1892.0	7902.5	3.12
Electricity	3.6 $MJ\ kWh^{-1}$	76.0	6.00 kWh^{-1}	2837.2	14934.5	1.94

according to equation (7) for different fuels as shown in Table 2. In case of firewood, the payback period is the shortest at 1.49 years, and in the case of kerosene is the longest at 6.99 years and net present value (NPV) varies from 1530 to 19003 Rs., depending on the fuel type (Table 2). The NPV is very high for firewood, indicating that low-efficiency cooking fuels like firewood are more expensive in the long run. It also reveals that the value of NPV is very high for firewood i.e. these low-efficiency cooking fuels purchased by the poor mass population in urban areas are much more expensive in the long run. The box-type solar cooker are a smart financial choice, especially when compared to cheaper and more expensive energy sources like firewood and kerosene. The solar cooker save 1293 MJ energy $year^{-1}$; this is equivalent to the annual energy consumption of other fuels and firewood. This cooker is in a position to replace 100% of biomass and reduce carbon dioxide emissions by 222 kilograms per year, if it replaces firewood. The use of solar cooker will help save firewood in rural areas of India and traditional energy sources such as LPG, kerosene, electricity and coal in urban areas. Conservation of firewood would help in preserving the ecosystem thereby increasing the forest area.

Animal feed solar cooker

Animal feed solar cookers, mostly used to boil animal feed, are another type of solar thermal device used by farmers (Nahar 1994; Nahar *et al.,* 1996; Poonia *et al.,* 2017). The purpose of this device is to increase milk yield and quality by cooking feed before it is fed to milch animals. Traditionally, the feed for milch animal is boiled by burning firewood, cow dung cake and farm waste to increase the quantity and quality of milk. Commercially available box-type solar cookers have a smaller capacity and usually need to face the sun. Keeping this in mind, ICAR-CAZRI, Jodhpur designed, developed and tested a better solar energy system based animal feed solar cooker. The design is based on the length-to-width ratio of glazing and the reflector was kept as 3:1 to receive the maximum amount of reflected radiation. The installation of the solar cooker has a brick wall (0.1 m) plastered with cement sand in a ratio of 1:6. The dimensions of the solar cooker are 1980 × 760 × 100 mm, the internal dimensions are 1870 × 650 × 50 mm (Fig. 5). The depth of the cooker kept 300 mm, half of which was filled with pearl millet hull to provided 150 mm insulation from the bottom. The animal feed solar cooker was used to successfully boil different types of animal feed, including crushed barley (*Jau Ghat*), split cluster beans (*guar korma*), cluster bean powder, cotton seed, and gram churi. The device can boil animal feed in 4 to 5 hours, which is a relatively fast process, and the thermal efficiency of the animal feed solar cooker is around 21.8%. By using this cooker, farmers can improve the quality of cattle feed, thus increasing the quality and quantity of milk. It also reduces the need for traditional fossil fuels, which are expensive and harmful to the environment.

The animal feed solar cooker is estimated to save 2250 MJ of conventional energy annually considering the efficiency of the solar cooker as 30%, respectively. Animal feed solar cooker is in aposition to replace 100 percent biomass

Fig. 5. Animal feed solar cooker.

Table 3. Economic attributes and annual CO_2 emission saving of solar thermal devices

Attributes economics	Animal feed solar cooker	Non-tracking solar cooker	High-insulation box-type solar cooker	Inclined solar dryer	PCM-based PV/T hybrid solar dryer	Solar desalination device
Benefit-cost ratio (BCR)	2.40	1.80	1.71	2.09	1.90	2.46
Payback period (PBP) years	1.90	1.58	1.49	1.42	2.08	0.65
Energy saving/year (MJ)	2250	644	1293	1584	1850	7200
CO_2 mitigation (kg/year)	612	175	222	431	503	1077

(firewood) and save about 612 kg of CO_2 on an annual basis if it replaces firewood. Based on the above points, legislators and the government of India should consider supporting such devices, perhaps through financial assistance, which would go a long way in solving social, economic and environmental technical problems. Therefore, the use of animal feed solar cookers will help save traditional fuels such as firewood in rural areas of India and LPG, kerosene, electricity and coal in urban areas. The introduction of animal feed solar cookers in rural and urban areas of India can benefit the economy and health by protecting the environment, reducing carbon emissions, promoting sustainable development and reducing pollution. This change is in line with international efforts to combat climate change and protect ecosystems.

Solar desalination device

Basin type solar desalination unit was constructed using bricks masonry at ICAR-CAZRI, Jodhpur. The condensation cover of the distiller is made of 3.5 mm thick flat glass. The condensing cover is tilted 20° to the horizontal to optimize the capture of solar radiation. The absorber has an area of 4.2 square meters and is responsible for absorbing solar radiation and heating salt water (Fig. 6). The average distillate production of this unit is 8540 ml d^{-1} and its average efficiency is 30.25%, respectively (Singh *et al.,* 2019). Distilled water from the solar desalination unit should be mixed with salt water in proportions suitable for drinking. In fact, with a solar desalination plant, up to 20 L/d of drinking water (150 ppm TDS) can be produced per day from raw water containing 300 ppm TDS.

Fig. 6. Basin-type solar desalination device.

Based on the distillate output performance the economic analysis of the bricks masonry solar thermal desalination device was carried out by computing the living cost (LCC) and life benefit (LCB) of the device. The life cycle cost (LCC) of a desalination device is the sum of all costs associated with solar desalination energy over its lifetime, representing the value of time available, also calculated by the time value of money. The initial investment (P) in the desalination unit is Rs.9,000. The annual operation and maintenance (O&M) cost, including labour, is Rs. 8000 per year. The results were calculated by producing 7.5 liters of desalination per day for 300 days per year at a cost of Rs. 10 per litre. The residual value is considered to be 10% of the initial investment. The R value (annual) value is derived from desalination output of 7.5 liters per day for 300 days per year at a cost of Rs. 10 per litre. The annual income guaranteed by solar still is around Rs. 22,500.

LCC is the sum of the total cost of solar desalination device over its life cycle, including time cost of Rs. 68,197 and LCB is the sum of all costs, benefits or revenues from the system over its life cycle of Rs. 167,468 units. BCR is a measure of a project's profitability and is calculated by dividing the LCB by the LCC. BCR is 2.46, which means the project produces more benefits than it costs. The annual cost of the desalination unit is Rs. 13,372. This represents the average annual return on investment. The payback period is 0.65 years, which is lower than the expected life of the desalination device, which is approximately 10 years. Currently, the average rate of return (IRR) is 151%, which is quite high for the funded project. The solar desalination device is economical, has a good cost-effectiveness ratio, a short return on investment period and a very high rate of return. These results demonstrate the economic and environmental benefits of the project. The economic benefits of solar energy products, namely benefit-cost ratio (BCR), investment payback period (PBP), energy savings and carbon dioxide emissions reduction, are shown in Table 3.

Conclusion

The economic analysis of various solar thermal devices has been carried out. On the basis of economic attributes of the devices it is concluded that these devices can save not only conventional energy but also reduce carbon emission as save is the bigger source of renewable energy. The benefit cost ratio (BCR) of solar thermal devices varies from 1.71 to 2.46 and pay back period of solar devices is 0.65 to 2.08 years. The annual energy saving varies from 644 MJ to 7200 MJ per year and reduction in CO_2 emission varies from 175 kg/year in non-tracking solar cooker to 1077 kg/year in solar desalination device. These devices can go a long way to supplement conventional electricity. In addition, to reduce CO_2 leading to increased use of green energy. The present economic analysis of solar devices is very useful for entrepreneurs and farmers of the arid region of Rajasthan. Entrepreneurs should come forward for taking the manufacturing of these devices in the urban and rural areas for providing employment to skilled worker and contributing to a self -sustaining growth with ensured environmental protection.

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