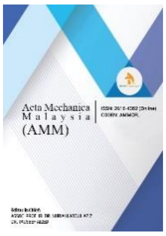
Acta Mechanica Malaysia (AMM)

DOI: http://doi.org/10.26480/amm.02.2024.175.182

ISSN: 2616-4302 (Online)
CODEN: AMMCFL



RESEARCH ARTICLE

EVALUATION AND THERMAL-ANALYSIS OF A SOLAR-ASSISTED DRYING-SYSTEM: ECONOMIC ANALYSIS

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ARTICLE DETAILS

Article History:

Received 23 August 2024
Revised 18 September 2024
Accepted 07 October 2024
Available online 09 October 2024

ABSTRACT

In this last part, of the work on the thermal analysis of the solar-assisted drying-system for agriculture products, an economic analysis is carried out. The evaluation is based on the data collected from solar drying-experiments carried out using Roselle as drying-product. The results showed that the annual operating cost; revenue, profit, and energy saved is RM15047, RM23129, RM8082, and RM1976, respectively. The payback-period of the total system-cost is 5.86 years, and the rate-of-return is 23%.

KEYWORDS

Solar-drying system; Economic-Analysis; ROR; PBP; NPV, Roselle

1. INTRODUCTION

The global population is on the rise and is estimated to be (in year 2050), 9 Billion, 9.7B, and 9.8B as in Philip et al., (2022), WPP, (2022), and Daliran et al., (2023); Taki et al., (2016), respectively. This show the critical challenge in food security, and sustainable development. The escalating demand for food has led to increased energy-consumption across the food-supply-chain. This results in increased fossil fuel consumption (Chahartaghi et al., 2019). In 2030, the global demand for energy and food will rise by 40% and 50%, respectively (Daliran et al., 2023; Taki et al., 2018), that requires another 70% increase in food production (Philip et al., 2022).

The global reserves of fossil fuels dwindling, the demand for energy is on the rise, a trend that's likely to continue into the future (Dini and Putra, 2021; Nazari et al., 2022). Nowadays, several factors are driving the decrease in the use of fossil fuels (Razmjoo et al., 2021; Hassan et al., 2023). Owing to their non-renewable nature and environmental concerns such as global warming, ice melting, and the disruption of Earth's natural ecosystem, limit their use (Chahartaghi et al., 2019). Carbon emissions and environmental pollution remain major global concerns (Hassan et al., 2023; Naqvi et al., 2022).

The increase of the world population and industrial activities, in addition to the excessive usage of fossil fuels has been worldwide caused chain environmental consequences (Kalogirou, 2004a; Kaldellisa et al., 2005). Therefore, energy conservation becomes a hot topic around people (Chan et al., 2006). One of the most effective solutions to the problem is the use of renewable-energy resources, such as the use of solar energy (Reddy, 1995). Besides, such energy systems provide economic and physical diversity without any chemical combustion, which causes environmental pollution.

In the current economic, renewable energy sources are increasingly used due to their enduring nature, safety, and environmental friendliness (Fan et al., 2021; Cai et al., 2021; Fan et al., 2022). The global trend is shifting towards the exploration of alternative energy sources (Kachare and Shinde, 2019). Solar energy, being abundant and sustainable, holds the greatest potential among renewable sources (Wang et al., 2021; Kumar et al., 2023). It stands out as a significant part of renewable energies (Kachare and Shinde, 2019). Harnessing solar power effectively is vital for reducing the adverse effects of traditional energy consumption (Kumar et al., 2023; Pandey et al., 2021). Solar thermal technology primarily focuses on harvesting solar energy by converting it into heat (Kachare and Shinde, 2019).

Drying is among the most energy-intensive operations (Tiris et al., 1996; Barbosa et al., 2023). It consumes, 10-15% of total industrial energy demand (Chua et al., 2000), ≈10% of fuel consumption in developed nations, and about 12% of total industrial energy used in China (Xie et al., 2021). The drying process accounts for up to 70% of energy usage in wood product manufacturing, 50% in textile finishing, over 60% in maize farming (Xie et al., 2021), up to 20% of the industrial sector's total energy usage, and can constitute as much as 90% of processing costs (Barbosa et al., 2023).

Economic and environmental considerations make it imperative to refine drying processes. Yet, the dominance of non-renewable energy sources persists in many nations, propelling the quest for solar-powered dryers to the forefront (Barbosa et al., 2023; Bekkioui et al., 2020). Solar-powered dryers are increasingly popular, as the solar energy is plentiful and free-to-use energy source. However, traditional fossil fuel-based dryers and kilns remain prevalent despite their impending environmental hazards. While the economic and environmental merits of solar dryers are established, research are ongoing to fine-tune the gathering, transformation, and utilization of solar energy. Such optimization ensures quicker drying times and the capacity to dry more products using the same amount of energy (Barbosa et al., 2023).

Simple design tool for sizing solar-assisted crop dryers based on drying load, climate, and economic data, is not existing (Santos et al., 2005). However, to study the economic feasibility of a solar system, different terms and methods are applied to evaluate different figures of merit. Some of these are the life-cycle cost (Garg and Prakash, 2002), net present-value, internal-rate-of return (Brenndorfer et al., 1985; Kablan, 2004), payback-period (Sukhatme, 2002), utility-expense rate, equivalency of annual income (Kayali, 1998), and life cycle savings (Duffie et al., 2020).

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Website:
www.actamechanicamalaysia.com

DOI:
10.26480/amm.02.2024.175.182

Cite the Article: I.E. Saeed, Zulkhairi Zainol Abidin (2024). Evaluation and Thermal-Analysis of A Solar-Assisted Drying-System: Economic Analysis. *Acta Mechanica Malaysia, 7(2): 175-182.*

Moreover, the goal of the economical-analysis of solar-energy systems is to determine the least-cost-method of providing the energy-needs, bearing in mind the solar, together with non-solar substitutions (Duffie et al., 2020; Haralambopoulos et al., 1997).

The life savings' analysis, or Life cost analysis involves the effects of interest, inflation, and tax rates (Kalogirou, 1996; Moran and Tsatsaronis, 2000). Solar processes are generally characterized by low and high, initial and operating, costs, respectively. Accordingly, the simple financial challenging is of matching an initial-identified investment with prospected operational-costs (Duffie et al., 2020; Kalogirou, 1996). The difficulty of getting a low-cost solar-system design is multi-factor decision, where the most important components are the collector-area and storage-capacity (Haralambopoulos et al., 1997). Utilization of solar heaters has rapidly expanded and producing solar-water-heaters is becoming a new industry with annual production of >$1.2billion (Xia et al., 2004; Runsheng et al., 2006).

The dried products are becoming a highly attractive alternative to marketing fresh products (Yaldiz and Ertekyn, 2001). Due to altering life-regimes, there is a pronounced request for a varied high-value dry-produces with worry about the fresh-ness/convenience (Baysal et al., 2003). Dry fruits and vegetables represent a wholesale market in North America of about 3billion dollars annually, while dry snack meats account for another billion dollars in sales (Durance and Wang, 2002).

Roselle, (*Hibiscus. sabdariffa.* L.), commonly, is given various-names (e.g., Karkade, sorrel, etc.). It is grown in many tropical and sub-tropical countries, as high-volume specialities botanical products in international commerce. Apart from global-markets, there are substantial-local and regional-markets where it's transformed into both hot and cold herbal-drinks, jellies, sweets, and other items (Plotto, 2004). The aim of the last part, of the work on the evaluation of solar-assisted-dehumidification drying-system for agriculture products, is to conduct an economic-analysis, which is based on experimental data-experimental from solar-drying of Roselle.

2. MATHEMATICAL MODELLING

Initial Cost (*IC*): is a cost of purchasing equipment and installing them (Sukhatme, 2002), which is summation of 2 terms; the first is proportional to collector-area, while other is independent of collector-area (Duffie et al., 2020):

$$IC = C_c + C_o = C_c A_c + C_o = k_p A_c + C_o \tag{1}$$

Annual Cost (*AC*): for both solar and non-solar systems, it is total of factors, which can be summarized as (Sukhatme, 2002; Duffie et al., 2020):

$$AC = Fuel\ expense + Repayment\ on\ loan\ Maint.\,\&\ Inurance\ charges\ + Electric\ bill + Materials\ costs + Local\ taxes - Tax\ deductions \tag{2}$$

Mortgage Payment: is the annual value of money required to cover the funds borrowed at the beginning to install the system, which includes interest and principal payment. It can be estimated by dividing the amount borrowed by the present-worth-factor (*PWF*). The *PWF* is predicted using an inflation-rate = zero (i.e., equal-payments), besides taking a market discount-rate = mortgage-interest-rate. The *PWF* is given in tables or be calculated as follows (Kalogirou, 2004a; Duffie et al., 2020):

$$PWF = \tfrac{1}{d}\left[1 - \left(\tfrac{1}{1+d}\right)^n\right] \tag{3}$$

Total Cost or expenses (*TC*) can be written as (Kayali, 1998):

$$TC = \frac{C_o + C_t - SV_n}{(1+i)^n} \tag{4}$$

If the rate of interest is zero:

$$TC = C_o + C_1 + C_2 + \cdots + (C_n - S_n) = C_o + C_o + \textstyle\sum_{t=1}^{n} C_t - C_n \tag{5}$$

If the rate of the interest is greater >zero, C_t and S values must be added to C_o, after their values are reduced to the real-rate of interest, then:

$$TC = C_o + \textstyle\sum_{t=1}^{n} (C_t/(1+i)^t) - (S_n/(1+i)^n) \tag{6}$$

If the values of C_1, C_2...C_n are equal to each other, the conversion of the annual payments is calculated as follows:

$$C = C_o\big(((1+i)^n - 1)/((1+i)^n + 1)\big) \tag{7}$$

Here, the *TC* can be given as:

$$TC = C_o + C - (S_n/(1+i)^n) \tag{8}$$

Fuel Cost (*c_f*): can be estimated as (Haralambopoulos et al., 1997):

$$c_f = \frac{K_D}{(\eta_e\ HHV)} \tag{9}$$

Fuel Savings (*F_s*) in the (jth) year is given by (Sukhatme, 2002):

$$F_s = c_f\,(1+i)^{j-i}\ \ F.E_a \tag{10}$$

Solar Savings (*SS*): is the difference between the costs of the conventional energy system minus the costs of the solar-energy system (savings can be negative; they are then losses) (Duffie et al., 2020).

Annual Solar Savings (*ASS*) can be calculated as:

$$ASS = Fuel\ saving - Repayment\ on\ loan - Maintenance\ charges\ - Electric\ bill - Loacl\ taxes + Tax\ deductions \tag{11}$$

Cumulative Solar Savings (*CSS*) (Sukhatme, 2002):

$$CSS = \left(\textstyle\sum_{j=1}^{n} (ASS)j\right) - (IDP) \tag{12}$$

Life Cycle Savings (LCS): is the difference between the life cycle costs (*LCC*) of the conventional fuel-only system and solar-plus-auxiliary energy system, or the cumulative-solar-savings calculated over the lifetime (n_t) of a system plus the resale value (*RV*) of the system at the end of its lifetime (Duffie et al., 2020; Sukhatme, 2002):

$$LCS = CSS_{nt} + RV = \left(\textstyle\sum_{j=1}^{nt} (ASS)j\right) - (IDP) + (RV) \tag{13}$$

Salvage Value (*SV_N*) or **Market value (*MV*):** is the system's estimated-value at the completion of its useful-life. Considering a linear depreciation of the system with time, the salvage value (*SV*) at a time *n* can be expressed as (Kablan, 2004):

$$SV_N = IC - (D\,.\,n) \tag{14}$$

The depreciation rate *D* (*MR/year*) is given by (Wsmojo, 2024; Sullivan et al., 2015):

$$D = (IC - SV)/n \tag{15}$$

Solar-Contribution or fraction (*f*) (Duffie et al., 2020; Kalogirou, 2004b): the fractional-reduction of purchased-energy (with energy quantities integrated over the year) is:

$$F_e = (L_o - L_A)/L_o = L_s/L_o = \left(\textstyle\sum_{yr} f_i\ L_{o,i}\right)/\left(\textstyle\sum_{yr} L_{o,i}\right) \tag{16}$$

Present-Worth (Value) (*P*) (Duffie et al., 2020; Ozsabuncuoglu, 1995):

$$P = F(1+d_i)^{-n},$$

$$F = P(1+d_i)^n \tag{17}$$

If, A_1, A_2,.., A_n are the payments due after *1*, *2*,..., *n* years, then the present worth of these payments is $A_1/(1+d)$, $A_2/(1+d)^2$,..., $A_n/(1+d)^n$, respectively, and the sum is given as (Sukhatme, 2002):

$$S = \textstyle\sum_{j=1}^{n} A_j/(1+d)^j \tag{18}$$

Frequently, the payments are related and increase at a constant rate (*i*), thus, $A_2 = A_1\ (1+i)$, $A_3 = A_1\ (1+i)^2$. Then, (*S*) becomes:

$$S = A_1 \textstyle\sum_{j=1}^{n} (1+i)^{j-1}/(1+d)^j \tag{19a}$$

$$= A_1/(d-i)[1 - ((1+i)/(1+d))^n]\ \ ;\ if\ i \neq d \tag{19b}$$

$$= (A_1 n)/(1+i)\ \ ;\ if\ i = d \tag{19c}$$

Payback-Period (*PBP*)

This term is defined in many ways. It is defined as the required time for the cumulative-fuel-savings to equal the total-initial-investment (Sukhatme, 2002, Duffie et al., 2020). As well, as a needed-time for operational-cash inflow (Brenndorfer et al., 1985) or the cumulative savings (Duffie et al., 2020) to equal the total initial cost of the system. It is also defined as the time period to recovery the investment or the capital (Peterson and Fabozzi, 2002). The *PBP* (years) can be given without discounting as:

$$PBP = ln\left(((i.T_c)/(c_f FE)) + 1\right)/\,ln(1+i) \tag{20a}$$

and with discounting as:

$$PBP = \frac{ln\left(1-\left(C(d-i)/(c_f FE)\right)\right)}{ln\left((1+i)/(1+d)\right)} \quad ; for\ i \neq d \tag{20b}$$

$$= T_c(1+i)/\left(c_f FE\right) \quad ; for\ i = d \tag{20c}$$

If the cash flows are the same every year (P_n), (Omni, 2024; Investopedia, 2024), or the average annual profit (P_a) (Brenndorfer et al., 1985; Mohammed et al., 2020) is used, then *PBP* is given as:

$$PBP = C_o/P_n = C_o/P_a \tag{21}$$

If the initial investment is spread out over several years, or the benefits change over time, then the *PBP* is calculated by looking at the net-benefits (Wsmojo, 2024; Omni, 2024):

$$PBP\ =\ A_y +\ (B/C) \tag{22}$$

Where, B= (the total-amount to be paid-back minus the total-amount paid-back at the beginning of the last payback year). C= (the amount paid-back at the end of the last-payback year minus the amount paid-back at the start of that).

Rate-of-Return (*ROR*): *ROR* or return-on-investment (*ROI*), is the rate- of the increase in future average net-cash-flow, to the initial increase in required-investment (Brenndorfer et al., 1985). It is a measure of how productive an investment is, and a percentage (or interest rate) that describes the merit of an investment. Therefore, it is the ratio of money-gained or lost on an investment relative to the amount of money-invested (Wikipedia, 2024). A general equation is given as:

$$ROR = (O - D)/(IC) \tag{23}$$

Net-Present-Value (*NPV*): is a standard method for the financial-appraisal of long-term projects. It is used for capital-budgeting, and widely throughout economics. It measures the additional or shortage of cash-flows in present-value (*PV*) terms, once financing-charges are met (Wikipedia, 2024). The goal of the *NPV* is to determine the value created from the underlying-investment, and can be given by (Brenndorfer et al., 1985; Peterson and Fabozzi; 2002, Investopedia, 2024; Farr and Faber, 2019):

$$NPV = IC + \sum_{t=1}^{t} \frac{(Cash\ flows\ year_t)}{(1+i)^t} = \sum_{t=1}^{t} \left(\frac{C_t}{(1+i)^t}\right) - C_o \tag{24}$$

The major problem with this technique is the selection of an appropriate rate of return. A pragmatic solution is usually to take the real-rate of interest at which money can be raised on the money-markets (Brenndorfer et al., 1985). If the project can yield return that more than cover the total cost, in addition to the cost of borrowing the money, then its *NPV* would be positive, and thus it is accepted.

3. RESULTS AND DISCUSSIONS

In installing solar-drying systems, the economic-factors must be considered, besides the engineering efficiency-process. The economical-analysis is conducted aiming to depict the economic aspects associated with the installation of the solar-assisted drying-system for agricultural-products. The analysis is performed to obtain the life-cycle cost (*LCC*), the life cycle savings (*LCS*), rate-of-return (*ROR*), payback-period (*PBP*), and net-present-value (*NPV*). The calculations are carried out using experimental-data from solar-drying of Roselle under this system. The details and discussions on the thin-layer solar-drying experiments, energy/exergy analyses, and the description of the system and its operation, can be read in parts I-II of this work.

The drying-processes are continued day and night until the Roselle's weights, are not varied significantly with the increment in the drying-time. The moisture-content is then taken as the equilibrium-moisture-content. However, the drying process could be stopped at moisture content of 15%*wb* (0.178db), as this is the save-grad moisture-content for Roselle (≤16%db) (Tahir, 2008). The 15%wb moisture-content of Roselle is achieved, for instant, in 56 and 58 hours of drying at 55°C and air velocity of 1.5m/s and 3m/s, respectively. The equilibrium-moisture-content (E_{MC}) at these air conditions is 11%*wb* and 9.76%*wb*, respectively (Table 1).

Table 1 presented the drying-load (Q_{load}) in kWh, and energy fraction supplied from the solar (Q_{solar}) during the drying-experiments. In addition, the Table showed the drying-air-conditions and the moisture-content (*MC*) as %wb; where S for save-to-stop the drying process (i.e. 15% wb).

As it clears from the Table, drying of Roselle at 35 and 45°C are not led to the save-moisture content, as the minimum value reached is 17% wb; despite that long-drying-times are tested (78-143 hours). It is also obvious that the highest value of energy load is used by heater1 (H_1= 29%), which is used for regeneration of the silica gel. The second consumption is used by the air-blowers (B_1 =21% and B_2 =12%); where B_1 is related to the regeneration process, and B_2 is used for the drying process. Heater$_1$ (H_1) and B_{1+2} constituted the major portion of the overall-energy in all the experiments with an average of 62%. This is followed by heater$_2$ (H_2) at the inlet of the drying chamber (13%), and 5% for water pumps (P_{1+2}), while the average solar-energy provided is 20%.

Table 1: Energy loads distribution

Drying experiment					Q_{Load} (*kWh*)					
T	Vel.	Time	MC (*wb%*)		$Q_{Electricity}$				Q_{Solar}	*f*
°C	*m/s*	*hrs*	*S*	E_{MC}	H_{1+2}	P_{1+2}	B_{1+2}	*Total*	*kWh*	*%*
35	1.5	143	-	29	186	16	122	317	47	15
	3.0	103	-	22	127	12	106	239	35	15
45	1.5	96	-	21	132	14	81	221	29	13
	3.0	78	-	17	129	12	80	216	46	21
55	1.5	56	15	11	88	05	46	133	15	11
	3.0	58	15	10	115	06	41	156	66	42
60	1.5	55	15	04	96	06	27	123	47	38
	3.0	43	15		97	03	44	138	23	16
65	1.5	38	15	05	61	07	28	90	09	10
	3.0	41	15	06	95	07	43	139	31	22
Aver.		71		14	112	09	62	177	35	20
Max		143		29	186	16	122	317	66	42
Min		38		04	61	03	27	90	09	10

The scenario used in the calculation is that, the drying experiments at 55°C are chosen for the analysis. This is the mid temperature in the tested range. Besides, in drying at 35°C and 45°C, moisture content of 15% is not achieved, and drying at 60 or 65°C may alters some essential components in Roselle.

About 10 kg of Roselle is dried in each run, which is equivalent to ≈ 30% of the system capacity (35 ± 5 kg) depending on the size of the Roselle-flowers, where two varieties are grown in Malaysia; the Sudanese (or *Arab*), and Terengganu varieties. The first one is big-flowers with dark-red colour, while the latter is small and pale in colour. Table 2 described the items used in the calculations, where all the values are given in Malaysian Ringgit (*RM*).

Table 2: Description of the items used in the calculations

No.	Parameters	Value	Units
1	Roselle: Initial-moisture-content	90.7	%wb
2	Roselle: Final-moisture-content	15.2	%wb
3	Roselle/batch	10/20	kg
4	Batches/year	148/154	-
5	Fresh-Roselle	1.05	RM/kg
6	Dried-Roselle	85	RM/kg
7	Drying-air velocity	1.5/3.0	m/s
8	Average drying-time (hrs/batch)	57	hr
9	Operation-time	360	days/year
10	Silica-gel regeneration-	60	°C
11	Initial-costs (as in Table 3)	-	RM
12	Initial-cost paid	100	%
13	Fuel-only system	Electricity	-
14	Insurance	1	%
15	Maintenance	1	%
16	Labour	20	RM/day
17	Electricity-rate	0.218	RM/kWh
18	Discount-rate	7	%
19	Period of economic-analysis	15	years
20	Salvage -value (at end of 15	10	%

10 kg of Roselle provide 154 and 148 (batch/360days), for drying at 55°C, and air velocity of 1.5m/s and 3.0m/s, respectively. In addition to these two cases, an assumption for drying 20kg per batch (about 60% of the system capacity) at the same temperature (55°C) and air velocities (1.5m/s and 3.0m/s), constituted the four cases of the analysis. The cases can be summarized as follows: Case1 = (55°C, 1.5m/s, 10kg Roselle); Case2 = (55°C, 3.0m/s, 10kg Roselle); Case3 = (55°C, 1.5m/s, 20kg Roselle); Case4 = (55°C, 3.0m/s, 20kg Roselle). The major terms used in the initial costs (*IC*) calculations are given in Table 3. The costs are due to the conventional and solar components; summing up the two represented the total-cost of the system. The total initial cost (*IC*) is paid once at the beginning (i.e.100% down-payment).

Table 3: Initial costs of solar assisted dehumidification drying system

No.	Equipment	RM
	Conventional system components:	
1	Absorber columns (2 units)	1500
2	Desiccant (silica gel)	2450
3	Concrete building and drying chamber	6500
4	Air blowers (2 units)	1600
5	Electric air-heaters (2 units)	350
6	Circulating system and installation	1500
	Subtotal$_1$	**13900**
	Salvage value of conventional components (%10)	1390
	Solar components:	
1	Flat plate solar-collector (5 panels)	8000
2	Heat exchangers (2 units)	3450
3	Water storage tank (1 unit)	800
4	Water pumps (2 pumps)	550
5	Water circulation system	1200
	Subtotal$_2$	**14000**
	Salvage value of solar components (%10)	1400
	Total initial cost: of the solar-assisted drying-system	**27900**
	Salvage value of the solar assisted drying system (%10)	2790

The solar-collector contributes, significantly, to the cost of solar-systems (Sukhatme, 2002; Duffie et al., 2020). It is clear from the Table3, that 57% of the total initial-cost, of installing the solar components, and 29% of the total-system costs are due to the cost of the collector. The annual-cost (operating-cost) of the installed solar-system is the addition of the material (Roselle) cost, labour cost, maintenance, and insurance of the system, and cost of electric-energy consumed by subsidiary equipment like pumps, blowers, etc., as shown in Table 4. Moreover, the annual cost of the system is accepted to be constant and paid at the end of each year during (zsabuncuoglu, 1995).

The annual-cash-flow statement for solar-assisted dehumidification drying-system is shown in Table 4. The annual profit is equal to the revenue-amount (benefit) minus the cost, in the operating-year. The minimum net-profit is RM2681, and the maximum is RM13796 per year. The magnitude of the fuel saved is dependent on the solar-fraction, which in turn depends-on various-factors; such as, the drying load, solar-irradiation, specifications of the collector, water-storage-tank, heat-exchanger, and circulating-system.

Table 4: Annual cash-flow statement

No.	Economic parameters	Case1	Case2	Case3	Case4
1	Labour	7,200	7,200	7,200	7,200
2	Fresh Roselle	1,628	1,554	3,255	3,108
3	Electricity	4,021	2,904	7,990	5,808
4	Maintenance	140	140	140	140
5	Insurance	140	140	140	140
6	Fuel saved	507	2,129	1,007	4,259
7	Dried Roselle	15,810	15,096	31,416	30,192
8	Total cost	13,129	11,938	18,725	16,396
9	Revenue	15,810	15,096	31,416	30,192
10	Net profit	2,681	3,158	12,691	13,796

The solar annual savings are converted into present-worth-values, which are added up to obtain the life-cycle-savings (*LCS*). The system will be viable if life cycle savings; which represent the money saved by installing the solar system instead of buying the fuel, is positive (Duffie et al., 2020). Table 5 shows the cumulative money from the amount of energy-saved each year, by installing the solar components; assuming that the amount saved is constant each year. The values are discounted, using a discounting factor at 7% interest rate, to the present-values. The salvage-value (*SV*) or lifetime of a solar-water-heating system is the time-period between the installation and the time at which it becomes uneconomical to restore the equipment to working order, because of general-deterioration (Reddy et al.,1995). The SV of the solar and conventional components, and the whole system, can be directly subtracted from the initial-cost without compounding first and then discounting (zsabuncuoglu, 1995), as it would give the same value. Table 6 shows the initial-costs (*IC*), the salvage-values (*SV*), and the depreciation-rate (*DR*).

Table 5: Cumulative amount of the energy saved (*CSS*) and *LCS*

Year	Case1	Case2	Case3	Case4
0	0.00	0.00	0.00	0.00
1	474	1990	941	3980
2	885	3720	1759	7439
3	1241	5215	2466	10429
4	1364	5732	2711	11463
5	1807	7591	3591	15183
6	2016	8471	4006	16942
7	2209	9282	4390	18564
8	2360	9915	4689	19829
9	2481	10424	4930	20847
10	2576	10824	5119	21648
11	2649	11129	5264	22257
12	2700	11346	5366	22691
13	2734	11488	5434	22976
14	2752	11561	5468	23122
15	2755	11576	5475	23151
CSS	2755	11576	5475	23151
SV	1011	1011	1011	1011
LCS	3766	12587	6486	24162

Table 6: Initial cost (IC), salvage values (SV), and depreciation rate (DR)

Parameters	Solar	Conventional	System	Unit
IC	14000	13900	27900	RM
SV	1400	1390	2790	RM
***DR* (6%)**	840	834	1674	RM

Cumulative-net-profits (*CNP*) and depreciated-values (*DV*) of the solar and conventional components, and the whole system are shown in Table 7. The depreciation rates are RM 840, 834, and 1674 per annum of the initial-costs of the solar components, the conventional components, and the whole system, respectively.

Table 7: Cumulative net profits, and depreciated values

Year	CNP				DV		
	Case1	Case2	Case3	Case4	Solar	Convent.	System
0	0.000	0.000	0.000	0.000	14000	13900	27900
1	2681	3158	12691	13796	13160	13066	26226
2	5363	6316	25382	27593	12320	12232	24552
3	8044	9475	38073	41389	11480	11398	22878
4	10726	12633	50763	55186	10640	10564	21204
5	13407	15791	63454	68982	9800	9730	19530
6	16089	18949	76145	82779	8960	8896	17856
7	18770	22108	88836	96575	8120	8062	16182

Cite the Article: I.E. Saeed, Zulkhairi Zainol Abidin (2024). Evaluation and Thermal-Analysis of A Solar-Assisted Drying-System: Economic Analysis. *Acta Mechanica Malaysia, 7(2): 175-182.*

Table 7 (Cont.): Cumulative net profits, and depreciated values

8	21452	25266	101527	110372	7280	7228	14508
9	24133	28424	114218	124168	6440	6394	12834
10	26815	31582	126909	137965	5600	5560	11160
11	29496	34741	139600	151761	4760	4726	9486
12	32178	37899	152290	165558	3920	3892	7812
13	34859	41057	164981	179354	3080	3058	6138
14	37541	44215	177672	193151	2240	2224	4464
15	40222	47374	190363	206947	1400	1390	2790

The ROR, is the rate- of the increase in future-average net-cash-flow, to the initial increase in required-investment, i.e. the total-capital employed or all expenditure in the preoperational years, in addition to the working-capital. The revenue minus the operational-cost would give the profit on which the ROR could be calculated. Table 8 showed the values of *ROR* (%) on the solar and conventional components, and the whole system. The values are calculated after the annual-cash-flows have been depreciated.

Table 8: Rates of return (*ROR*) %

Components	Case1	Case2	Case3	Case4	Average
Solar	13.2	16.6	84.6	92.5	51.7
Convention	13.3	16.7	85.3	93.3	52.1
System	03.6	05.3	39.5	43.4	23.0

However, there are some complications in this technique. For instance, the question of whether the return should be calculated before or after taxes and allowances. Therefore, it could produce a wide variety of rates of return from the same basic-data. An example of the variation is given in Table 9, where the *ROR* is calculated without considering the depreciation effect. Obviously the values are higher compared to those presented in Table 8.

Table 9: Rates of return (without depreciation)

Components	Case1	Case2	Case3	Case4	Average
Solar	19.15	22.56	90.65	98.55	57.73
Convention	19.29	22.72	91.30	99.26	58.14
System	09.61	11.32	45.49	49.45	28.97

Payback-period (*PBP*) is simply the answer to the question of how-long it will take to get the invested money back. However, it doesn't tell much about the investment after the break-even point, and it ignores any benefits that occur after this point and time-value of the money as well (Wsmojo, 2024; Omni, 2024; Investopedia, 2024). Moreover, it does not measure the profitability, and this is a major weakness since a shorter payback-period for one project does not mean that it should be preferred to another, as the main objective in investing is profit, not the recouping of the initial-capital (Brenndorfer et al., 1985). Nevertheless, it gives some indication of the level of risk of a project by separating projects that require a short-time to recover their investment from those that require a longer-period (Sullivan et al., 2015). The method is particularly valuable when used in combination with a robust financial analysis-tool such as the net-present-value (*NPV*) (Omni, 2024).

Table 10 presents the Payback-period (in years) for the solar and conventional components, and the whole system. The values are calculated by having the cash-flows to be the same every year (Omni, 2024, Investopedia, 2024). Subsequently, the payback-period is given by dividing the total costs over the annual-profits or annual operational-cash-inflow (Brenndorfer et al., 1985). Although, other definitions for the payback-period will result in different values.

Table 10: Payback period

Components	Case1	Case2	Case3	Case4	Average
Solar	5.22	4.43	1.10	1.01	2.94
Convention	5.18	4.40	1.10	1.01	2.92
System	10.40	8.83	2.20	2.02	5.86

A greenhouse solar-dryers with a total cost of $2361, and payback period between 1.5 and 2.1 years is built by (Philip et al. 2022). A dryer with payback-period of 0.48years, is reported by (Sethi et al., 2021), while payback-period of 2.24 and 1.38 years, are reported by (Mugi and Chandramohan, 2022), for passive and active mode indirect solar-dryers, respectively. A low-priced forced-convection solar-dryer (initial-investment of $670), with calculated payback-period of 0.65 years, is developed by (Lakshmi et al., 2019). A firewood solar-drier with initial-investment of $4600, and a payback-period of 1.89 years is developed by (Merlin and Azese, 2021).

Net-present-value (*NPV*) is the present-value of current and future income streams, minus initial investment (Investopedia, 2024; Vcexperts, 2024). It is sensitive to the reliability of future cash-inflows that will yielded by the investment (Investopedia, 2024). The technique assumes that, there is minimum-desirable ROR that would make the project acceptable. Thus, all expected future cash-flows are discounted- to the present using minimum-desirable rate (Brenndorfer et al., 1985). Then the project is accepted only when the result is positive (Sullivan et al., 2015).

Table 11 shows the present (discounted) values (*PV*) of the net profits, and the discount factor (*DF*) at the interest-rate of 7%. It is clear from the Table that all the cases produced a positive *NPV*, except case1 where the *NPV* is negative, and it could be eliminated.

Table 11: Present-value (*PV*), Salvage-value (*SV*), Net-present-value (*NPV*)

End of year	***DF***	**Present values (*PV*)**			
	7%	**Case$_1$**	**Case$_2$**	**Case$_3$**	**Case$_4$**
0	1.000	-27900	-27900	-27900	-27900
1	0.935	2506	2952	11861	12894
2	0.873	2342	2758	11084	12050
3	0.816	2189	2578	10360	11262
4	0.673	1804	2125	8540	9284
5	0.713	1912	2252	9049	9837
6	0.663	1778	2094	8414	9147
7	0.623	1670	1967	7903	8591
8	0.582	1561	1838	7386	8030
9	0.544	1458	1718	6903	7504
10	0.508	1363	1605	6451	7013
11	0.475	1274	1500	6029	6555
12	0.444	1191	1402	5635	6126
13	0.415	1113	1311	5267	5726
14	0.388	1040	1225	4922	5350
15	0.362	972	1145	5610	6011
SV	0.362	1011	1011	1011	1011
NPV	-	-2717	1581	88523	98489

Table 12 presented the cumulative-costs (*CC*), cumulative-revenues (*CR*), cumulative-net-profit (*CNP*), and lifetime-profit (*LTP*). The cumulative-net-profit is equal to cumulative-revenues minus the cumulative-costs ($CNP = CR - CC$), while the lifetime-profit is equal to the cumulative-net-profit plus the salvage-value of the system (*SV*) minus the initial-total-cost (*IC*) of the system ($LTP = CNP + SV - IC$). In addition, the present-worth (*PW*) of the cumulative net profit, salvage-value, and the lifetime-profit are given.

Table 12: Cumulative (cost, revenue, and net profit), PW, and LTP

Year	Case1		Case2		Case3		Case4	
-	***CC***	***CR***	***CC***	***CR***	***CC***	***CR***	***CC***	***CR***
1	13129	15810	11938	15096	18725	31416	16396	30192
2	26257	31620	23876	30192	37450	62832	32791	60384
3	39386	47430	35813	45288	56175	94248	49187	90576
4	52514	63240	47751	60384	74901	125664	65582	120768
5	65643	79050	59689	75480	93626	157080	81978	150960
6	78771	94860	71627	90576	112351	188496	98373	181152
7	91900	110670	83564	105672	131076	219912	114769	211344
8	105028	126480	95502	120768	149801	251328	131164	241536

Table 12 (Cont.): Cumulative (cost, revenue, and net profit), PW, and LTP

9	118157	142290	107440	135864	168526	282744	147560	271728
10	131285	158100	119378	150960	187251	314160	163955	301920
11	144414	173910	131315	166056	205976	345576	180351	332112
12	157542	189720	143253	181152	224702	376992	196746	362304
13	170671	205530	155191	196248	243427	408408	213142	392496
14	183799	221340	167129	211344	262152	439824	229537	422688
15	196928	237150	179066	226440	280877	471240	245933	452880
LCC	196928	237150	179066	226440	280877	471240	245933	452880
		PW		***PW***		***PW***		***PW***
IC	27900	-27900	27900	-27900	27900	-27900	27900	-27900
SV	2790	1011	2790	1011	2790	1011	2790	1011
CNP	40222	14577	47374	17168	190363	68988	206947	74998
LTP	15112	5477	22264	8068	165253	59888	181837	65898

As general comments, in this analysis only two values of the solar fractions are used, i.e. 15% and 46%. However, solar fraction is varies greatly depending on the weather or climatic factors, besides system factors. For instance, the minimum and maximum insolation recorded is 5W and 1118W, and a temperature >85°C is reached in the water storage tank.

The solar collector performance is directly affected by the prevailing weather conditions; e.g., the insolation level (clearness of the sky), ambient temperature, wind speed, etc., in addition to system design and components. For example, the solar collector is operated at high temperatures, most of the time. This resulted in low efficiency and considerable amount of energy losses. This situation, in addition to the heat-losses from heat exchangers (which in many cases exceeded the amount of energy supplied to the air), and the losses from the water tank (as the size is only 100litres), contributed highly to the low solar fractions. Consequently, the amount of energy that expected to be saved by installing the solar components is not achieved.

Therefore, by investing extra amount of money, to increase the size of the water tank (500-800*l*), and to improve the heat-exchangers design/configuration, will greatly increase the solar-fraction, and hence the amount of conventional-energy saved. Moreover, the additional investment will be recouped in short time. Increasing the size of the water tank, in particular, will improve the performance of the system, as more energy will be drawn from the tank after the collector has been put-off. With the situation tested the 100 litre tank supply energy (average of 10°C above the ambient) for ≈3-5hr after the collator has been stopped. Thus, increasing the size of the tank would provide energy for over-night drying-process.

The second major site of the energy-consumption, is the silica-gel columns. Each column is regenerated for 12hr, and the process of regeneration and dehumidification is carried out simultaneously. Thus, for regeneration, heater1 (H_1) and the blower (B_1) is put-on 24hr. Therefore, changing the material of the silica gel columns (Acrylic-sheets), by other materials (e.g. stainless steel) that can withstand higher temperature (e.g. 85°C), will reduce the energy and time needed for regeneration, as this process is, mainly, a temperature dependent. Also, increasing the size of the columns, and hence the weight of the silica-gel, will improve the drying-potential of the regenerated silica-gel which represents a mechanism of thermal-storage, as the generated-heat by moisture-adsorption is comparable to the latent-heat of-vaporization, of the moisture-removed.

The system is a promising system and a good alternative to the traditional systems, especially in the situation where the ambient relative-humidity is high around the day as the case of tropical countries. The silica gel reduces water content of drying-air before reaching the drying chamber. Thus, it increases the air-capacity to take more water from drying-material, and reduces the energy required for water evaporation. With very low solar fraction (15%) studied, the system provided a good-profit and recover rate on the investment. Moreover, the system is intended and suitable to dry medical and heat-sensitive products (as the system can be operated at low-temperature and reduced-relative-humidity), where the selling prices of the dried products are very high. Consequently, the expected profit will be high as well.

4. CONCLUSIONS

In this part of the evaluation and thermal-analysis of a solar-assisted drying-system, economic-analysis is carried out. The analysis and the evaluation are based on experimental-data from solar-drying of Roselle under the system. The total initial cost of this solar assisted drying system is RM279000. The average annual operating cost, revenue, and profit are RM15047, 23129, and 8082, respectively. The average annual energy-saving is RM1318 and 2633 with 15% and 46% solar fractions, and RM1976 for the whole tests. Payback period for the solar components, conventional components, and total system cost are 2.94, 2.92, and 5.86 years, respectively. The rates of return are 57.73%, 58.14%, and 28.97% for the solar components, conventional components, and total-system cost, respectively.

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Cite the Article: I.E. Saeed, Zulkhairi Zainol Abidin (2024). Evaluation and Thermal-Analysis of A Solar-Assisted Drying-System: Economic Analysis. *Acta Mechanica Malaysia, 7(2): 175-182.*