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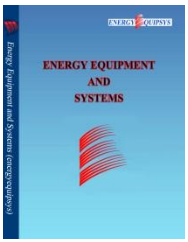

Design and optimization of solar-assisted conveyer-belt dryer for biomass

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ABSTRACT

Biomass, as a renewable source of energy, can be used in many industries to reduce their dependence on fossil fuels. However, due to the significantly high and varied moisture content of biomass, its use has several drawbacks, such as low total efficiency and process instability. Drying biomass before combustion or gasification can eliminate these drawbacks. Besides these benefits, there are several environmental advantages of removing moisture from organic materials before disposal. In this study, a solar-assisted conveyer-belt dryer was designed to remove moisture from biomass. Economic optimization was conducted under different economic conditions to find the optimum performance of the designed dryer. The results indicated that depending on the economic condition, drying biomass with the designed dryer costs between 4 and 7 cents per kilogram of biomass. Under optimum economic operation, the solar fraction is less than 6% in both scenarios. On the other hand, by ignoring economic constraints and reducing the dryer's capacity, solar fraction increases to more than 55%, and in this case, the drying cost will be about 11 cents per kilogram of biomass.

Keywords: Solar Energy, Solar Dryer, Biomass Dryer, Economic Optimization.

1. Introduction

The use of fossil fuel as the main source of energy has caused many environmental problems, like global warming and climate change. So, the development of cleaner and renewable energy sources is needed to reduce dependence on fossil fuels and mitigate global warming by reducing greenhouse gas emission. Biomass, as a clean and renewable source of energy, can be used in many industries. Biomass is generally regarded as a CO_2-neutral fuel. It absorbs the same amount of carbon in growing as it releases when consumed as a fuel. Generally, biomass includes wood and wood waste, municipal solid waste, animal waste, agricultural crops and their waste by-products, and waste from food processing [1]. But, an important difference between biofuels and the conventional fossil fuels is that the former have significantly higher and more varied moisture content. Combustion or gasification of biomass with its high moisture content is associated with several drawbacks, such as operational instability and lowered total efficiency [2]. In case of gasification, the fuel has to be dried to sustain the process. Also, if the heat needed for drying can be reduced, more fuel can be gasified and the efficiency of the process is increased. Furthermore, a biofuel with large fluctuations in the moisture content causes problems in the operation of the gasifier. Therefore, in gasification systems, the fuel is usually dried to a

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moisture content below 15% on the wet basis [3]. In the same way, combustion of biofuels with high moisture content is possible, but it is associated with several drawbacks. First of all, the latent heat that has to be supplied to the combustor to evaporate the water cannot be utilized to generate power. Furthermore, due to lower efficiency, a boiler that operates with high-moisture fuel must have larger dimensions for the same thermal output.

To overcome these drawbacks, moisture should be removed from the biomass. Drying biomass before combustion increases the flame temperature to about 1300°C [4]. This increased flame temperature is beneficial in several ways. It means a larger temperature gradient in the boiler for radiant heat transfer. Thus, the boiler can be smaller because less area is needed for heat transfer. With a higher flame temperature, combustion of the fuel is more complete, which results in lower carbon monoxide levels and less fly ash leaving the boiler [5]. More complete combustion also means more heat released from the fuel. For moist fuels, about 80% excess air is needed, but by drying the fuel, the excess air can be reduced to only 30% [6]. In addition, drying biomass before combustion can improve the overall thermal efficiency of the boiler up to 15% [7].

Besides the benefits for combustion and gasification, moisture removal from organic materials also has several benefits in waste disposal processes. The well-separated organic fraction of municipal solid waste (MSW) is a good source of biomass with moisture content of about 300% on the dry basis (75% on the wet basis) [8]. The moisture content of organic waste causes the generation of leachate that pollutes soil, groundwater, and surface water. Thus, drying the organic waste reduced leachate generation [9]. Moreover, removing moisture from organic waste reduces waste odour by slowing down the deterioration of the waste. It also eliminates the production of landfill gas (LFG) in two ways. LFG is a complex mix of different greenhouse gases (GHG) created by the action of microorganisms within a landfill. Landfill gas is about 45–60% methane, with the remainder being mostly carbon dioxide [9]. Methane, which has a global warming potential (GWP) 21 times greater than carbon dioxide, is the second most common GHG after carbon dioxide [10]. The production rate of LFG varies depending on the moisture content of the waste and the degree of initial compaction. The generation of LFG is retarded if sufficient moisture is not available. Increasing the density of the material placed in the landfill decreases the availability of moisture to some parts of the waste and, thus, reduces the rate of bioconversion and gas production [9]. Therefore, drying of organic waste cripples the LFG production by reducing the moisture content of the waste and the ability to compact it. The benefits of drying biomass are summarized in Table 1.

Drying biomass fuels provides significant benefits, but it must be balanced against increased capital and operating costs. Fuel drying is an energetically and economically expensive pre - treatment process, which

Table 1. Benefits of drying biomass

Process	Benefits
Gasification	Sustain the process Reduce heat demand of the process Increase the efficiency of gasification Increase the fuel production
Combustion	Increase heat value of the fuel Reduce the burner (boiler) size Increase the flame temperature More complete combustion Reduce the CO emissions Reduce the fly ash leaving the boiler Increase the heat released in the combustion Increase required excess air Improve overall thermal efficiency of the burner (boiler)
Organic waste disposal	Reduce the leachate generation Reduce waste odor Reduce LFG production

may not be worth the investment in many cases. Using solar energy to dry biomass is cost-effective due to its availability and reliability, and since it comes for free. Solar dryers proved to be a promising and inexpensive way to preserve food [11]. Lutz et al. designed and built a multi-use solar-tunnel dryer for grapes, vegetables, and medicinal plants in Greece. It was tested by drying 1,000 kg of seedless grapes. The tunnel dryer took only four to seven days to remove moisture up to the safe limit of 9% on the wet basis. This dryer was effectively tested in Greece, Egypt, Yugoslavia, and Saudi Arabia for drying grapes, peppers, dates, and onions. Finally, the economic evaluation of the solar-tunnel dryer yielded a payback period of two to three years [12]. Condori et al. studied a simple, low-cost tunnel greenhouse dryer (13 m long, 7 m wide, and 3.70 m high) to dry red pepper and garlic. Their analysis showed that pepper was dried from 6.5% to 0.2% on the dry basis in 6.5 days and garlic from 1.8% to 0.2% on the dry basis in 7.5 days [13]. Perea-Moreno et al. used a solar greenhouse dryer to dry wood chips in southern Spain. Their experimental study indicated that wood chips can be dried to 10% in 13 days [14]. The studies showed that though solar drying is a cost-effective and suitable way to dry food or biomass, there are some drawbacks in its application for large facilities. The drying process in conventional solar dryers happens in batches. The drying materials are loaded and unloaded in several trays. Also, it takes several days to dry the material in solar dryers and it cannot be used continuously throughout the day. Another disadvantage is low controllability. Many researchers have tried to improve the performance of solar dryers. Hawlader et al. investigated the performance of a solar-assisted heat pump dryer and water heater in tropic meteorological conditions. They found that the dryer's performance depended on the air-flow rate, air temperature, relative humidity, solar radiation, compressor speed, and the load placed in the drying chamber [15]. Sevik experimentally investigated a standalone solar heat pump dryer under different climatic conditions to dry tomato, strawberry, mint, and parsley. Thermal energy requirements were provided by a double-pass solar air collector and the heat pump unit, while the electrical energy requirements were provided by the photovoltaic system [16]. But, using a hybrid solar industrial dryer is a more suitable way to dry biomass on a large scale. In industrial dryers, the drying process is more stable and takes a few hours. These Solar-Assisted Industrial Dryers (SAID) can operate 24/7 with more capacity than solar dryers. Furthermore, in most of the industrial dryers, the drying process is continuous and loading or unloading takes place automatically. For example, Ceylan et al. developed a solar-assisted fluidized bed dryer integrated with a heat pump for mint leaves. The results of the study showed that solar energy systems can be used to pre-heat the air in industrial dryers [17].

As it has been mentioned, biomass includes various materials of different shapes, sizes, and characteristics. It is important to design a SAID that is adaptable to a wide range of organic materials, unlike the conventional solar dryers. Considering all the influential parameters, it has been found that the conveyer-belt dryer is a good choice. Products of different sizes and shapes can be dried in it. Also, the residence time in this kind of dryer is about 0.5 to 3 hours with an evaporation capacity of 5–15 kg/m^{2}h [18]. In this study, a new large-scale Solar-Assisted Conveyer-Belt Dryer (SACBD) was designed to dry biomass in large facilities. The designed system was then simulated by the code implemented in MatLab. Economic optimization was conducted by a genetic algorithm in different economic scenarios. The aim of the optimization was to minimize the total annualized cost (TAC) for the SACBD. Finally, the TAC sensitivity to the design parameters was analysed.

Nomenclature

GHG	Green House Gases
GWP	Global Warming Potential
LFG	Landfill Gas
MSW	Municipal solid waste
SACBD	Solar Assisted Conveyor Belt Dryer
SAID	Solar Assisted Industrial Dryer
TAC	Total Annualized Cost
$\dot{m}_{fa}$	Fresh air flow rate (kg/s)
a_w	Water activity (−)
C_{elec}	Electricity costs ($)
C_{eq}	Equipment costs ($)
C_{fuel}	Fuel costs ($)
C_{op}	Operating costs ($)

C_p	Specific heat capacity (J/kgk)
F'	Solar collector heat removal factor (−)
i_r	Interest rate (%)
l_f	Life time (year)
Q_u	Useful heat in the collector (W)
T_a	Ambient temperature (°C)
t_c	Drying time constant (h)
T_{co}	Preheated air temperature (°C)
T_f	Fluid temperature in the collector (°C)
t_y	Operating time in a year (hr)
U_L	Overall heat loss coefficient of the collector (W/m2k)
X_0	Initial moisture (kg/kg on dry basis)
X_e	Equilibrium moisture content (kg/kg on dry basis)
D	Drying material diameter (m)
E	Electricity demand (W)
E	Recovery Factor (−)
Q	Thermal demand (W)
S	Solar radiation (W/m2)
T	Drying air temperature (°C)
T	Drying time (h)
V	Drying air velocity (m/s)
X	final moisture (kg/kg on dry basis)
Y	Drying air absolute humidity (kg/kg)
A	Area (m^2)
C	Equipment unit cost ($\$/m^2$, $\$/kW$)
n	Equipment size scaling factor (−)

Subscripts

ah	air heater
belt	Conveyor belt
cycl	Cyclone separator
fan	Circulation fan
hex	Heat exchanger
pv	Photovoltaic panel

2.Solar-assisted conveyer-belt dryer

The designed SACBD system consists of a flat-plate solar air heater, photovoltaic (PV) panels, a circulating fan, a heat exchanger with auxiliary fuel, a drying chamber, and a cyclone separator (Fig.1). The wet feed is

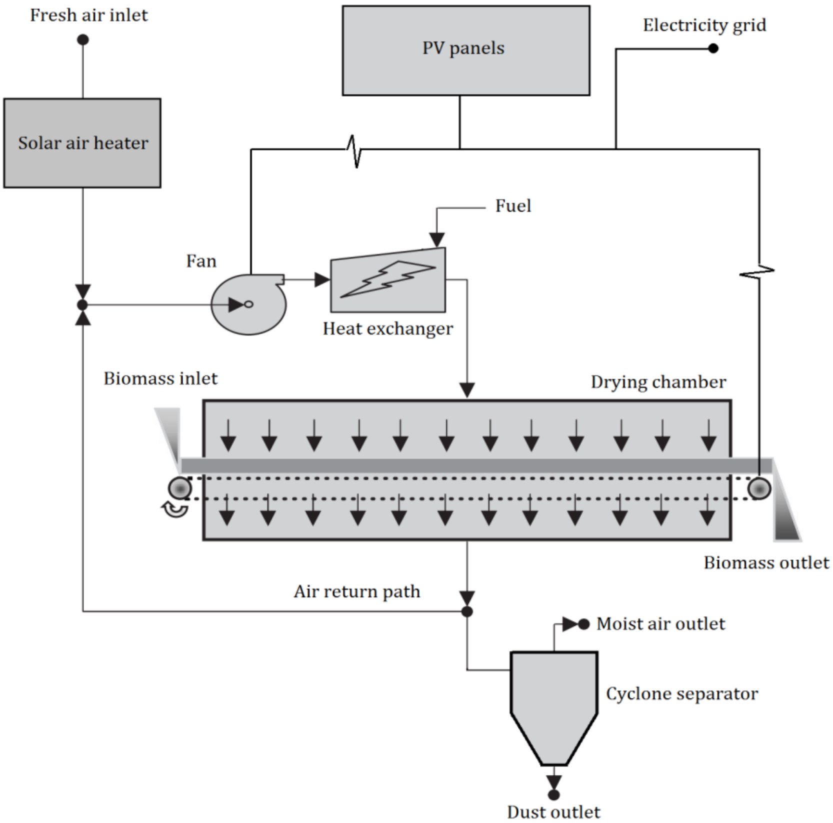

Fig.1. Solar assisted conveyor belt dryer

distributed on the belt as it enters the dryer and the dried product exits the dryer with the same flow rate on the dry basis. The drying air enters the drying chamber from the top and passes through the drying material. This cross-flow of drying air and drying material improves the drying efficiency due to better contact between the material and the drying medium. The drying air temperature is controlled in the heat exchanger, and the drying air humidity is controlled through the flow rate of the fresh air. The solar air collector preheats the fresh air to reduce fuel consumption in the heat exchanger. A part of the moist air leaves the dryer and the rest returns to the drying air loop. This recirculation reduces the energy needed for the process. The moist air leaves the system by passing a cyclone separator to prevent any dust being released into the atmosphere. The SACBD system is also equipped with PV panels to provide electricity to circulate the fan and the belt driver.

The SACBD system is designed to dry 0.1 tonnes of biomass per hour (on the dry basis) in the climatic conditions of Tehran. The operation time of the SACBD is assumed to be 8,000 hours per year for 15 years. The initial moisture content of the biomass is considered to be 3 on the dry basis. Since the drying rate drops as biomass gets drier, most dryers are not designed to completely dry the material [5]. This also reduces the fire risk in the dryer. Therefore, the final moisture of the material is considered to be 0.1 on the dry basis. These main characteristics of the system are summarized in Table 2.The flat-plate air collector that was used as the air heater is illustrated in Fig.2. The collector consists of an absorber plate, a transparent cover, and an insulation layer on the back. The solar energy absorbed by the collector heats up the absorber. Then, a part of the absorbed energy is transferred from the plate to the fresh air entering the air heater. The rest of the energy is lost to the ambient from the cover and the insulator.

2.1.Governing equations

The governing equation of the total system has two major parts—the air heater and the dryer. The useful energy in the solar air heater is calculated with Eq.(1) where F' is the collector heat removal factor and U_L is the overall heat loss coefficient of the collector.

$$Q_u = \dot{m}_{fa} C_p (T_{co} - T_a) = F' A_c [S - U_L (T_f - T_a)] \quad (1)$$

To simulate the dryer, the key parameter is the drying time. The first parameter that has to be calculated for this purpose is the equilibrium

Table 2. The main characteristics of SACBD system

Dryer capacity	0.1 ton/h (dry basis)
Operation time	8000 h/year
Life time	15 years
Ambient average temperature	18°C
Ambient average relative humidity	46%
Material initial moisture content	3 kg/kg (dry basis)
Dried material moisture content	0.1 kg/kg (dry basis)

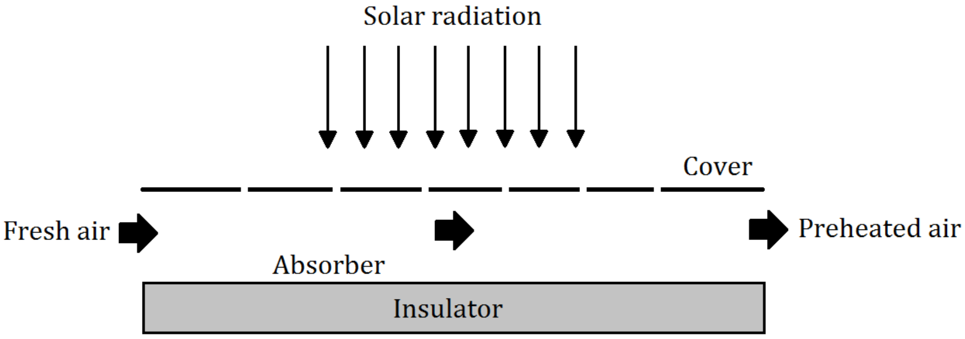

Fig.2. Solar air heater

moisture content of the drying material (X_e), which can be derived from Eq.(2). Based on this equation, the equilibrium moisture content of the material depends on the feed properties (b_1, b_2, b_3), the temperature (T), and the water activity (a_w).

$$X_e = b_1 \exp\left[\frac{b_2}{273 + T}\right]\left[\frac{a_w}{1 - a_w}\right]^{b_3} \quad (2)$$

After that, the drying time constant must be obtained from Eq.(3), in which d is the material diameter, and V, T, and Y are drying air velocity, temperature, and absolute humidity respectively, and c_0, c_1, c_2, c_3, and c_4 are the constant factors of the equation.

$$t_c = c_0 d^{c_1} V^{c_2} T^{c_3} Y^{c_4} \quad (3)$$

with calculating equilibrium moisture content and the drying time constant, the drying time was calculated by Eq.(4) based on the initial and final moisture content of the material.

$$t = -t_c \ln\left[\frac{X - X_e}{X_0 - X_e}\right] \quad (4)$$

Degrees-of-freedom analysis for the proposed SACBD resulted in four design variables that are presented in Table 3.

Table 3. Design variables

Drying air temperature	T
Drying air absolute humidity	Y
Drying air velocity	V
Solar air heater area	A_c

The design parameters directly affect the capital and the operating costs of the system and must be specified by economic optimization. In this way, the capital(equipment) and operating costs of the system are calculated by Eq.(5) and Eq.(6) respectively.

$$\begin{aligned} C_{eq} = c_{hex}A_{hex}{}^{n_{hex}} + c_{belt}A_{belt}{}^{n_{belt}} \\ + c_{fan}E_{fan}{}^{n_{fan}} \\ + c_{ah}A_{ah} + c_{pv}E_{pv} \\ + C_{cycl} \end{aligned} \quad (5)$$

$$\begin{aligned} C_{op} = C_{fuel} + C_{elec} = (c_{fuel}Q \\ + c_{elec}E)t_y \end{aligned} \quad (6)$$

For economic evaluation, the TAC model was used. The TAC of the system was calculated from Eq.(7) where e is the recovery factor for the equipment costs in this equation. This factor depends on the interest rate and the lifetime of the system, and it is obtained by Eq.(8). It should be noted that TAC is considered as the objective function in the optimization process.

$$TAC = eC_{eq} + C_{op} \quad (7)$$

$$e = \frac{i_r(1 + i_r)^{l_f}}{(1 + i_r)^{l_f} - 1} \quad (8)$$

In order to optimize the performance of the SACBD, economic parameters, i.e. electricity cost, fuel cost (in this case natural gas) and interest rate, are needed. For this purpose, 2 different scenarios are considered in economic optimization of the system (Table 4). Finally, it should be mentioned that, since the photovoltaic electricity is more expensive than the one from central grid in both economic scenarios, PV panel area is not considered in the optimization process.

3.Validation

In order to validate the obtained results of the implemented code, the time required to dry gelatin and carrot in conveyor belt dryer presented by Perry et al. [19] and Maroulis et al. [18] is used. Code data was adapted to the conveyor belt dryer characteristics and

Table 4. Economic scenarios for optimization

Scenario I	Electricity price	0.03 \$/kWh
	Natural gas price	0.71 S/ft3
	Interest rate	15%
Scenario II	Electricity price	0.1 \$/kWh
	Natural gas price	5.53 \$/ft3
	Interest rate	2%

meteorological data. Table 5 shows drying time data for these materials and simulation values. The results indicate drying time for both Gelatin and carrot can achieve values showing less than 9% error from the available data in the literature.

4.Results and discussion

The results of economic optimization for both scenarios are available in Table 6. As results indicate, drying temperature in the first scenario is 70% higher than its value in the second scenario, due to the lower fuel price. It’s important to note that 200°C is the upper limit of the optimization interval for drying temperature since there are some safety and environmental considerations for biomass dryers operating above 200°C [5]. Again, due to the large difference in fuel price in these economic scenarios, the fresh air flow rate in the first scenario is higher, compared to the second scenario. In the designed SACBD system, drying air humidity is controlled through the flow rate of the fresh air and more fresh air leads to less drying air humidity. Results also indicate that the optimum drying air velocity in the first scenario is 2.43 m/s (33% percent higher than air speed in the second economic scenario). Lower electricity cost in the first scenario caused the difference between these values.

Generally, cost analysis in economic conditions with low energy prices and higher interest rate leads to low capital costs and high operating costs. Economic optimization of the SACBD shows the same results. The equipment costs in the first scenario are 49000 $ less than the second scenario. Furthermore, the operation costs of the system in the first and second scenario are 8541 and 42726 $ respectively. Although operation costs in the first scenario are much less than the second scenario, the energy consumption of this scenario is more than the second one. As Table 4 shows, electricity and fuel prices in Scenario number two are 3 and 8 times more than the prices in the first scenario. This huge gap in the prices caused the difference in operation costs. Comparing the results for the both scenarios show that although drying air temperature and velocity, and fresh air flow rate is lower in the second scenario compared to the first one, TAC is 83% higher in this case. Finally, drying Cost per kilogram (Cpkg) for biomass in the first scenario is around 4 cents that is 44% less than the Cpkg in scenario number two.

Total heat demand for the first economic scenario is 335 kW that 7 kW of this demand is provided by solar collectors. These values for the second scenario are 262 and 16 kW respectively. The solar fraction (the ratio of solar heat to the total heat demand of the process) is presented in Fig.3. Since the renewable energies are more expensive that the fossil fuels, the solar fraction is less than 6% in both scenarios. More investigation on

Table 5. Validation data for the designed dryer

	Drying time	
	Gelatin	**Carrot**
Drying time	3.20 h [19]	4.94 h [18]
Simulation data	2.92 h	4.73 h
Error	8.75 %	4.25 %

Table 6. Results of economic optimization for both scenarios

Parameter	**Economic scenario**	
	I	**II**
T	200°C	118°C
Y	0.16 kg/kg	0.21 kg/kg
V	2.43 m/s	1.83 m/s
A_c	25.03 m^2	71.89 m^2
Ceq	131458 $	180543 $
Cop	8541 $	42726 $
TAC	31022 $	56777 $
Cpkg	0.039 $/kg	0.071 $/kg

solar fraction indicates that the solar energy fraction in the designed dryer is independent of dryer capacity and product final moisture content.

After investigating optimization results, the sensitivity of TAC to the optimum design parameters is analyzed. In the first economic scenario, TAC is not sensitive to the design parameters change. In this scenario, the parameters that TAC is most sensitive to them are drying air temperature and velocity. As it is illustrated in Fig.4, 10% decrease in drying air temperature leads to only 238$ (0.8%) increase in TAC. Based on Fig.4, increasing the drying air temperature will reduce the TAC and 200°C is not the optimum value for the system. Drying air temperature is limited to a maximum value of 200°C regarding some safety and environmental considerations.

Fig.5 present the sensitivity analysis results for the second economic scenario. As the results indicate, in the second scenario, unlike the first scenario, TAC is most sensitive to drying air moisture and temperature. 10% change in the drying air moisture leads to less than 350$ (0.6%) in the TAC. As it is illustrated in Fig.5, around the optimum values TAC is not sensitive to collector area in the second scenario.

A low solar fraction in both optimization scenarios proves that using solar energy is not a cost-effective way to dry biomass compared to the dryers with fossil fuel. But these results do not mean that solar energy in not capable of drying biomass at all. Table 7 presents the characteristics of a designed SACBD in the

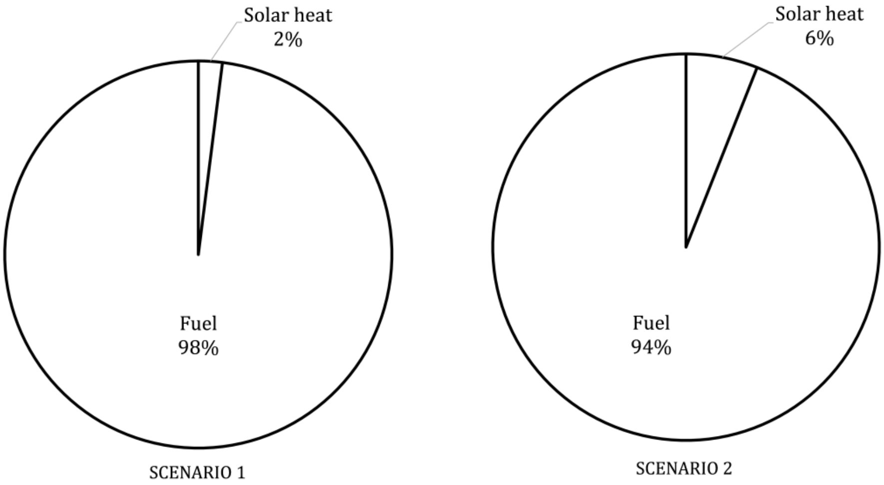

Fig.3. Solar fraction in economic optimization scenarios

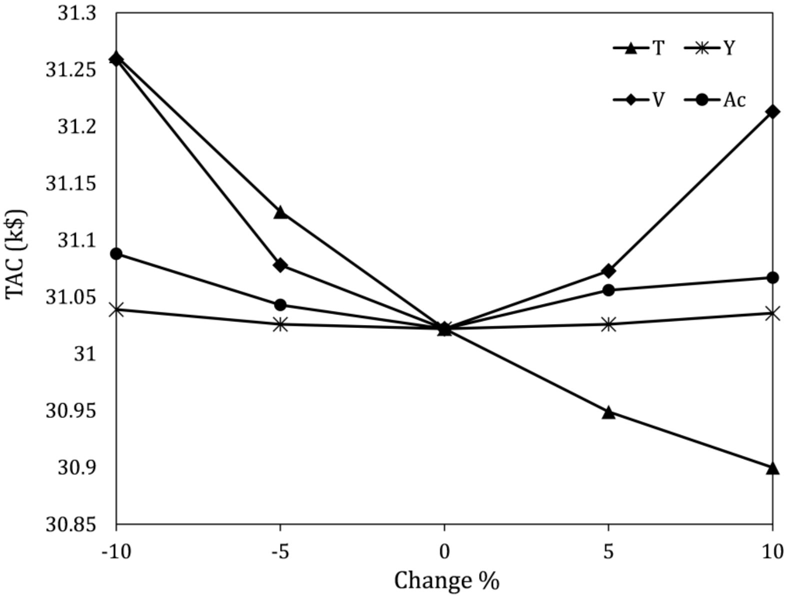

Fig.4. Sensitivity analysis for scenario I

second economic scenario. This system can dry 0.01 ton biomass in an hour and only operates during the daytime. The system is equipped with 100 m^2 solar air heater that preheats the fresh air entering the dryer to 66°C and leads to 55% solar fraction. As the results show, the total cost for the system is less than 5000 $ annually with Cpkg equal to 11.5 cents.

5.Conclusion

In this study, a solar assisted conveyor belt dryer for drying biomass in large facilities was designed. The system operation was then optimized under two different economic conditions and the results were investigated comprehensively. Results indicated that in the first scenario with low energy price and high interest rate, optimum solar collector area was 25 m^2 and dying air temperature was equal to upper limit of the optimization interval for this parameter, i.e. 200°C. In the second scenario which had high energy price and low interest rate, optimum collector area and dying air temperature were 72 m^2 and 118°C respectively. The minimum cost of drying biomass in the designed system was 4 cents per kilogram for the first and 7 cents per kilogram for the second economic scenario. Under optimum economic operation condition, solar fraction for both scenarios was less than 6%. Afterward, sensitivity analysis of the design parameters around the optimum values showed that TAC was not sensitive to these values and in the worst case, i.e. 10% change in the most influential design parameter, TAC variation is less than 1% in both scenarios. Although, based on the low solar fraction, it seems that using solar energy is not a cost-effective way to dry biomass in large scale, it is capable of doing it. Regardless of optimum economic operation, with reducing the capacity and limiting the operation to daytime, designed SACBD equipped with 100 m^2 collector, was capable of drying biomass with 55% solar fraction. In this case cost of drying increased to 12 cents per kilogram.

Table 7. Solar assisted conveyor belt dryer with high solar fraction characteristics

T	90°C	Solar fraction	55%
Y	0.03 kg/kg	C_{eq}	32495 $
V	3 m/s	C_{op}	2068 $
A_c	100 m^2	TAC	4975 $
F	0.01 ton/h	Cpkg	0.115 $/kg
t_y	4000 h		

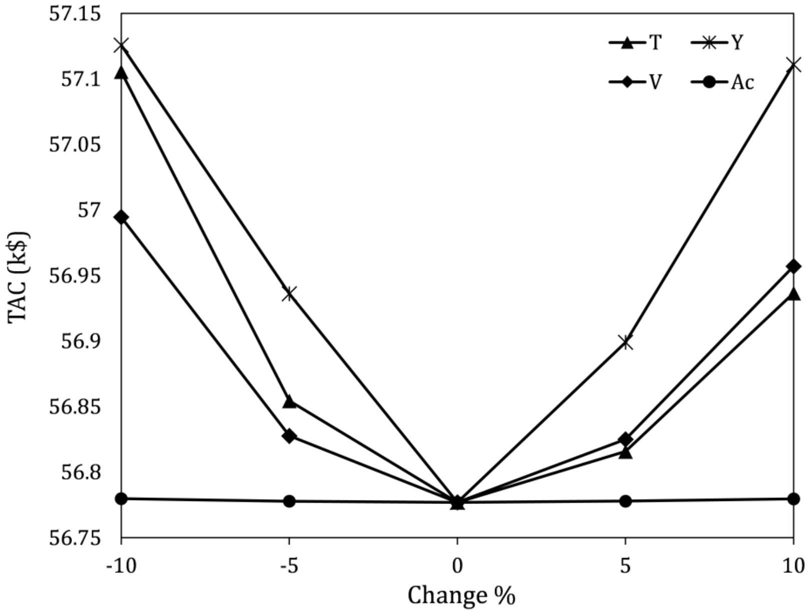

Fig.5. Sensitivity analysis for scenario II

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