Study of Using Solar Thermal Power for the Margarine Melting Heat Process

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The heating process of melting margarine requires a vast amount of thermal energy due to its high melting point and the size of the reservoir it is contained in. Existing methods to heat margarine have a high hourly cost of production and use fossil fuels which have been shown to have a negative impact on the environment. Thus, we perform an analytical feasibility study of using solar thermal power as an alternative energy source for the margarine melting process. In this study, the efficiency and cost effectiveness of a parabolic trough collector (PTC) solar field are compared with that of a steam boiler. Different working fluids (water vapor and Therminol-VP1 heat transfer oil (HTO)) through the solar field are also investigated. The results reveal the total hourly cost ($/h) by the conventional configuration is much greater than the solar applications regardless of the type of working fluid. Moreover, the conventional configuration causes a negative impact to the environment by increasing the amount of CO_2, CO, and NO_2 by 117.4 kg/day, 184 kg/day, and 74.7 kg/day, respectively. Optimized period of melt and tank volume parameters at temperature differences not exceeding 25 °C are found to be 8–10 h and 100 m^3, respectively. The solar PTC operated with water and steam as the working fluid is recommended as a vital alternative for the margarine melting heating process. [DOI: 10.1115/1.4028367]

Keywords: process heat, solar thermal power, photovoltaic, parabolic trough collector

1 Introduction

Margarine as a raw material has a multiple uses in the production of bio-organic materials such as refined oil and butter. It passes through many industrial stages before beginning the process of refining and packaging it to the consumer. One of these important stages is the melting process, which wastes an immense amount of thermal power. The large rate of thermal power consumption occurs due to the huge reservoirs in which the margarine is stored (500 m^3–1500 m^3 Savola International Company-Suez Gulf region-Egypt). With drawing margarine from the reservoirs is a cost and time intensive process due to the solid state of margarine at environmental temperatures. Dry saturated steam is passed through the heat exchanger pipes inside the reservoir to melt the required amount of margarine. In some cases, this process can take up to 8 h in the summer and 12 h in the winter, which can be amplified by the loss of heat energy from the reservoir throughout the day, especially during the night periods. Moreover, steam boilers that use heavy fuel or natural gas can cause serious environmental damage as a result of emissions, such as the carbon oxide and nitrous oxide compounds.

In contrast, solar energy is one of the cleanest and environmentally friendly renewable energies and should be invested as an alternative heat source for the melting process of margarine. As mentioned before, the melting of margarine is considered a heating process that consumes a huge amount of thermal energy. Therefore, solar thermal power can play a vital role in the process of melting margarine. Generally, temperature requirements of solar industrial heat applications range from 60 °C to 260 °C. Cylindrical PTC systems look very promising for delivering industrial heating process applications in the range of 95 °C–350 °C delivery temperature [1]. For solar thermal applications, the operating design conditions of solar collectors should be well above the desired operating conditions of the application to ensure stability of the operation. Therefore, flat plate collectors and evacuated tube collectors are eliminated from this study due to the previous reason and its lower efficiencies compared against the PTC [2]. This is why medium to medium–high temperature solar collectors are used [3,4]. Most of the production processes of the food industry such as milk products, vegetable, meat, fruits, and beer are run at temperatures below or near 100–130 °C. In addition, many cleaning processes such as pasteurizing, sterilizing, drying, hydrolyzing, distillation, washing, polymerization, and cooking processes are conducted under thermal applications [5,6]. Thus, switching to a renewable energy source, such as solar energy, can result in cost savings as well as decrease the negative impacts the production process has on the environment.

The production process of margarine requires a large amount of heat in which solar thermal power is a viable and more cost effective source of energy. The problem originally emerged when Savola's company officials (Savola International Company in Margarine industrial Suez Gulf region-Egypt) decided to optimize the time, energy, and cost of the production process. They summarized their problems into the following points:

- The process of margarine melts takes more than 12 h to obtain 100–200 m^3 of melted margarine per day.
- Which costs the equivalent amount of 476,120 m^3 per day of natural gas (100,000 $/month).
- Reduction of CO_2, NO_2, and CO emissions is a must according to environmental laws.

After reviewing the configuration of their heating process, using solar thermal power as a clean energy alternative seemed to be the most viable solution. Egypt has a great potential for solar energy. It is calculated that an amount of 6–7 kW h/m^2/day of global radiation is in the Suez Gulf region-Egypt [8]. Therefore, it is very promising to utilize this vast amount of untapped solar energy in

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this industrial heating process. The aim of this research is to present a feasibility study, assessing the impact of using solar thermal power as an alternative source of energy in the margarine melting process. In this study, solar PTC is used instead of a conventional steam boiler. Water–steam and/or Therminol-VP1 [7] HTO are utilized through the PTC representing two different configurations. The data results of the conventional configuration (config1) are compared with the PTC–water steam configuration (config2) and PTC–Therminol configuration (config3) according to the hourly cost parameter ($/h). The study plan is organized as follows:

- The process configurations for the proposed systems are performed and the design limits are investigated.
- The mathematical model that represents the proposed systems is constructed.
- Three cases are compared (solar direct vapor generation (two configurations) was conventional configuration).
- Practical and analytical solutions for the process problems are studied and executed.
- solar desalination system (SDS) software package (a part of renewable energy desalination system (REDS) that were developed by the authors) was used to model all the system units [8–11].

2 Margarine Melting Heating Process

2.1 The Process Problems. The problem began when Savola's-Egypt officials decided to evaluate the productive performance of their company. In their current configuration, a steam boiler running on fuels is used in the heating process. The company was faced with several problems identified as below.

- Wasted time, especially in the winter it requires melting about 100–300 m^3 within approximately 12 h. This requires a significant amount of time before the canning process can begin. In addition, the steam boiler has to be operated during night hours to collect the melted margarine early in the morning before the canning process.
- It is noted that the fuel consumption is also very high, especially in the case of heavy fuel operations. As the average daily consumption reached 1 m^3 or more, which is considered to be a high rate of consumption.

The exhaust emissions resulting from the combustion inside the steam boiler today are unacceptable in the light of international regulations which intend to reduce global carbon emissions.

Because of the temperature difference during the night especially in winter a large amount of thermal power gets wasted. This increases the operation time and the rate of fuel consumption.

Thus, Savola's Egyptian officials contacted the authors to investigate and propose solutions to the existing inefficiencies, while at the same time decreasing the negative impact on the environment.

2.2 The Problem Solutions and Configurations. The officials required the study on 100 m^3 capacity tanks connected is series in case more than one tank is required. Figure 1 shows the main sections of the margarine tanks in Savola-Egypt Company. After reviewing the problems and the requirements submitted by the Savola-Egypt company it was decided to try the following solutions using different practical applications and to also find theoretical explanations of the practical results. One of the proposed solutions is to examine the possibility that the upper surface of the margarine tank be exposed to solar radiation and hence provide more thermal energy and reduce the thermal load on the PTC. Removing the metal plate covering on the roof of the tank and replacing it with a glass cover increases the permeability of solar radiation and also stores solar energy in the upper portion of the tank.

The reservoir should be well isolated from the outside using a layer of thermal wool covering the total height of the tank to prevent energy loss.

The study would utilize the parabolic trough solar collector (PTC) to supply the required energy instead of using a steam boiler that runs on natural gas or heavy fuel. The solar field is controlled by the use of direct steam (water steam) and HTO (in case of Therminol-VP1).

During the absence of sun, the steam boiler would run; while during the day time, the solar collector would be the active energy source.

In this study, three proposed configurations are modeled and results are compared. The first configuration represents the original configuration (the conventional) of the factory without any reformation in which the steam boiler is the main source of heat. The second model relies on a glass roof with a thermal insulation and by operating solar collector (water steam). The third model uses HTO through the thermal solar collector. Solar photovolatic panels are used to operate the pumping operation for the second and third configurations. The schematic figures of the proposed configurations are shown in Figs. 2 and 3.

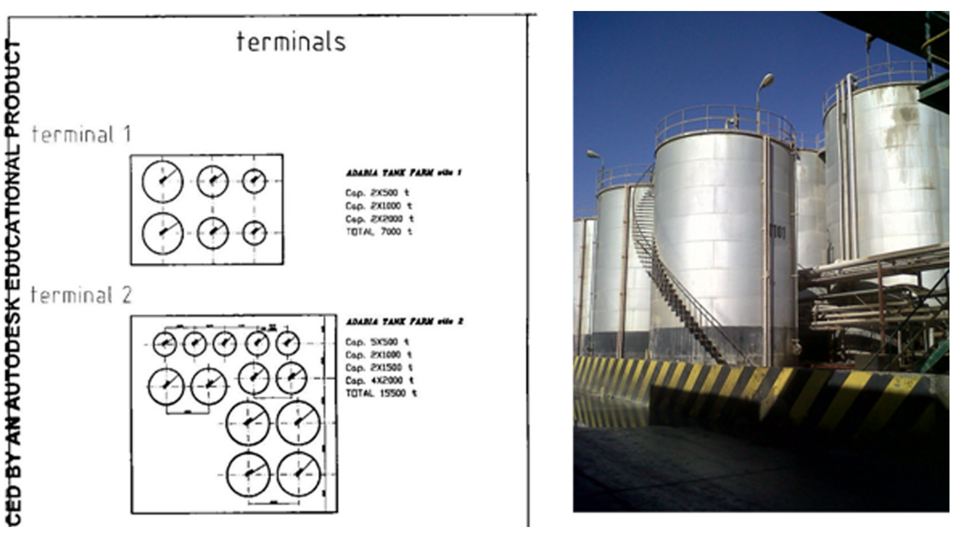


Fig. 1 The Savola-Egypt company terminals and margarine tanks with different capacities

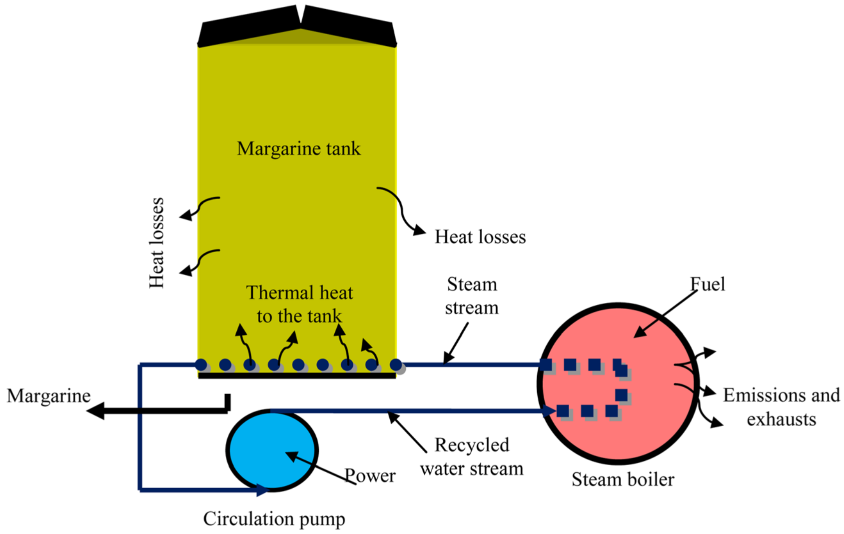


Fig. 2 A schematic diagram of the first configuration

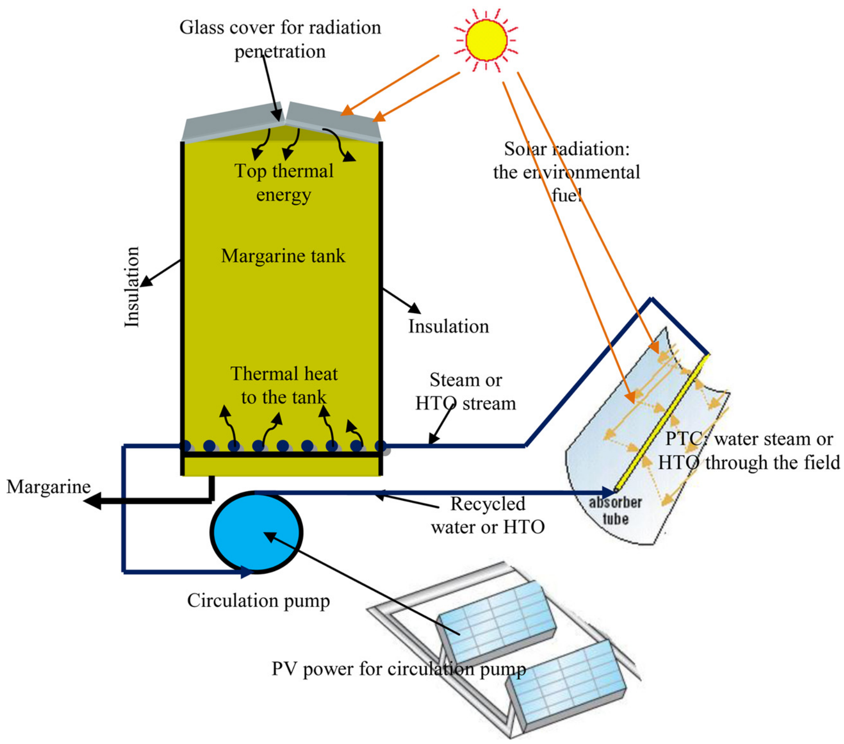


Fig. 3 A schematic diagram of the second and third configurations: PTC with water steam or HTO instead of steam boiler as in the first configuration

3 Modeling the Heating Process

The proposed configurations are modeled and presented in this section. REDS-SDS [9] software package is used to simulate and model the proposed units. REDS is a visual library of general software package to design and simulate renewable desalination systems (Fig. 4) shows a photograph of the proposed library that has been modeled by the use of REDS-SDS library. Generally, the REDS contains three main libraries: (i) SDSs, (ii) wind desalination systems, and (iii) geothermal desalination systems. The main assumptions of the model are listed as follows:

- The scheme is modeled under a steady state condition.
- Time inputs are presented as a transient matrix.
- The margarine tank is the main thermal load which the quantity of the margarine can decide the load for all systems.
- Design technique of modeling (not performance) is considered to calculate the areas, flow rates, emissions, hourly costs, etc.
- The all operating conditions are unified when comparing the proposed configurations.
- Winter operating condition is represented to study the worst case of the proposed schemes.

3.1 Steam Boiler Mathematical Model (First Configuration). The mathematical model is formulated based on design technique of calculation which calculates areas, flow rates, length, etc. Table 1 shows the equations that represent the steam boiler unit.

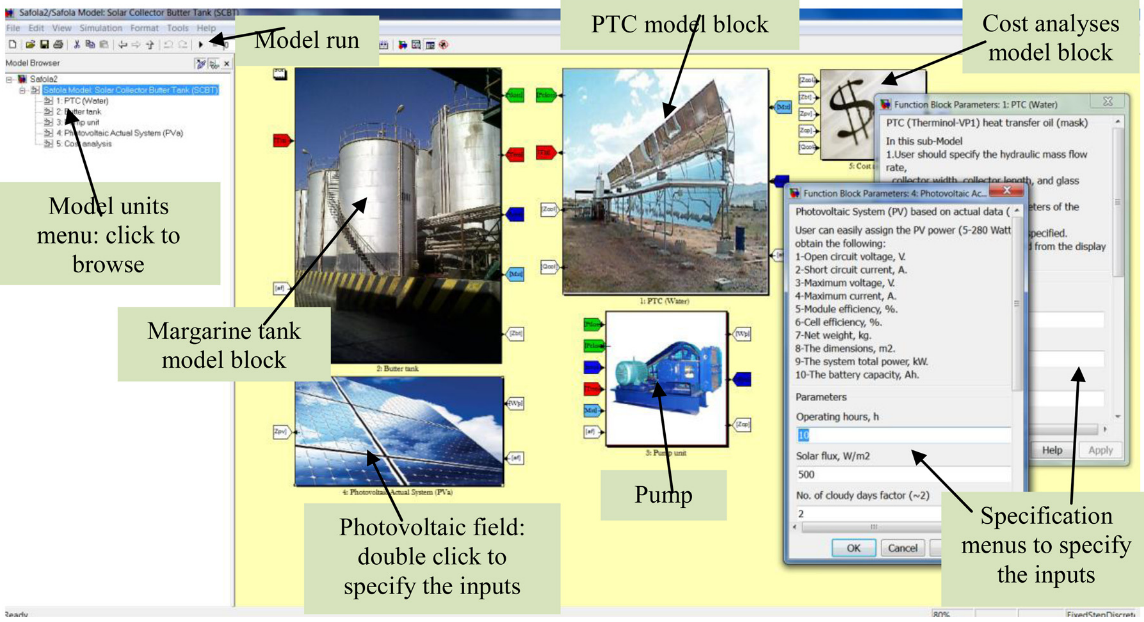


Fig. 4 A photograph of the visual model panel that been developed under the REDS-SDS browser related to the proposed configurations

Table 1 Equations that represent the steam boiler unit based on design technique of modeling

Equation	No.
The fuel mass flow rate kg/s is calculated based on the following equation where C.V, KJ/kg is the calorific value $\dot{M}_{\mathrm{f}} = \dfrac{\dot{M}_{\mathrm{st}} \times (\Delta h)}{C,V \times \eta_{\mathrm{b}}}$, and $\Delta h = f(T)$	1
The fuel power by the boiler is calculated as follows: $Q_{\mathrm{f}} = \dot{M}_{\mathrm{f}} \times C.V \times \eta_{\mathrm{b}}$ where C.V, KJ/kg is the calorific value of the fuel.	2
The specific fuel consumption $SFC = \dfrac{\dot{M}_{\mathrm{f}}}{Q_{\mathrm{b}}}$ (kg/kW h)	3
The mass flow rates of carbon dioxide, carbon monoxide and nitrogen dioxide per day are calculated as follows: $\dot{M}_{\mathrm{co_2}} = 1.375 \times \dot{M}_{\mathrm{f}} \times \mathrm{OH} \times 3600$ (kg/day) $\dot{M}_{\mathrm{co}} = 2.156 \times \dot{M}_{\mathrm{f}} \times \mathrm{OH} \times 3600$ (kg/day) $\dot{M}_{\mathrm{NO_2}} = 0.875 \times \dot{M}_{\mathrm{f}} \times \mathrm{OH} \times 3600$ (kg/day) where $\dot{M}_{\mathrm{f}}$ is the fuel mass flow rate (heavy oil or natural gas).	4
The hourly cost ($/h) is then calculated from the following equation: $Z_{\mathrm{sb}} = \dfrac{(\mathrm{FP} \times \dot{M}_{\mathrm{f}} \times 3600 \times \mathrm{OH})}{\rho_{\mathrm{g}}}$ ($/h) (see the Appendix for more details)	5

Assigned data	Calculated
Operating hours	Fuel mass flow rate (kg/s)
C.V and the density of the fuel = 43000 (kJ/kg) and 0.668 kg/m^3	Flue gas mass flow rates (kg/d)
Steam boiler efficiency = 60%	Steam boiler thermal power (kW$_{\mathrm{th}}$)
Top steam temperature (TST) = 160 °C	Specific fuel consumption (kg/kW h)
Fuel price = 0.1354 $/m^3	Hourly costs ($/h)

3.2 Margarine Tank Model (All Configurations). The margarine tank that used in this study is very important because it determines the thermal load on the thermal power source. The tank is 9 m in diameter and 7.85 m in height. The tank and the steam coil are made of stainless steel with inner tube coil diameter equal to 0.038 m with a length of 12 times of the main tank diameter. Table 2 shows the equations that represent the margarine tank model.

3.3 Pump Model (All Configurations). The mathematical model for the pump is presented in this subsection. The model is formulated in order to calculate the power required for the pump to overcome the pressure losses through the cycle. The user has to assign the pump efficiency and the required operating hours along the operation period. The model calculates the outlet operating conditions of the outlet stream to the steam generator regardless of its type (steam boiler or solar PTC). Table 3 shows the equations that represent the pump model in this study.

3.4 The Photovoltaic (PV) Model (Second and Third Configurations). The PV model is presented to measure a range of 5–280 W per module. Each module-watt type can calculate the module specification based on the data fed in the table.

Table 4 illustrates the inputs and outputs of the developed model block. A 100 V module is chosen in this study. SDS program [9] library is used to model and visualize the PV system program.

Table 2 Equations that represent the margarine tank unit based on design technique of modeling

Equation	No.
Tank top cross sectional area that receiving the top solar radiation, volume, and tube coil area are calculated as follows: $A_{\text{top}} = \frac{\pi}{4} \times D_t^2$ (m^2), and $V_t = A_t \times H_t$ (m^3), $A_{\text{tube}} = \pi \times D_m \times L_{\text{tube}}$ (m^2) ($L_{\text{tube}} = 12$ of D_t)	1
The margarine thermal load is then calculated as follows: $Q_{\text{mar}} = \rho_{\text{mar}} \times V_t \times C_{p_{\text{mar}}} \times \left(\frac{\Delta T}{\text{OH} \times 3600}\right)$ where $\Delta T = T_{\text{mar}} - T_i$ (°C)	2
The thermal resistance between the tank and ambient is calculated as follows: $R_{\text{th}_{\text{tank-air}}} = \left(\left(\frac{Log\left(\frac{r_0}{r_1}\right)}{2 \times \pi \times K_{\text{th}}}\right) + \left(\frac{1}{\pi \times D_t \times H_t \times h_{\text{conv}}}\right)\right)$ where the heat transfer coefficient by convection is presented as $h_{\text{conv}} = f(\text{Nu}, k, D, T_{\text{mar}})$	3
The steam mass flow rate is presented as follows: $\dot{M}_{\text{st}}\left(\frac{Q_{\text{loss}} + Q_{\text{mar}}}{h_{\text{fg}}}\right)$ (kg/s) and is equal to $\dot{M}_{\text{st}}\left(\frac{Q_{\text{loss}} + Q_{\text{mar}} - Q_{\text{solar}}}{h_{\text{fg}}}\right)$ (kg/s) for config2, config3 and h_{fg} is the latent heat of vaporization	4
The overall heat transfer coefficient for the tube coil is calculated as follows: $U_{\text{tube}} = \left(\frac{\dot{M}_{\text{st}} \times h_{\text{fg}}}{\Delta T_{\text{st}} \times A_{\text{tube}}}\right)$ (W/m^2 °C)	5
The indirect and hourly costs are calculated as follows: $\text{ICC} = 0.15 \times \text{IC}_{\text{mar}}$, and $\text{TAC}_{\text{total}} = f(\text{ICC}, \text{IC}_{\text{mar}})$, and $Z_{\text{mar}} = \left(\frac{\text{TAC}_{\text{total}}}{\text{OH} \times 356}\right)$ (\$/h) (see the Appendix for more details)	6
The pressure drop through the tube coil is calculated $\Delta P = f\left(f, \dot{M}_{\text{st}}, L_{\text{tube}}, T_{\text{st}}, dt_i\right)$ (bar) where, f denotes to friction factor T_{st} is the steam temperature	7
All thermophysical properties of the steam are calculated based on the operating temperature such as $\left(h, P, h_{\text{fg}}, s, k, \gamma, \rho, \ldots\text{etc}\right) = f(T_{\text{st}})$	8

Assigned data	Calculated
Operating hours (h)	Tank volume (m^3), and coil area (m^2)
Number of tanks	Pressure profile and loss through the field (bar)
Tank purchase cost (\$)	Top steam temperature profile (°C)
Wind speed (m/s)	Solar power hits the top of the tank (kW)
Solar radiation (W/m^2)	Thermal power losses to the ambient (kW$_{\text{th}}$)
Tank height (m) and coil diameter (m)	Thermal power for the margarine to be melt
Margarine desired temperature difference (°C)	Steam mass flow rate (kg/s)
Outlet steam conditions (°C)	Heat transfer coefficients
	Tank hourly and total annual costs

Table 3 Equations that represent the pump unit based on design technique of modeling

Equation	No.
The pump power to overcome the pressure drop through the system is calculated as follows: $W_p = \left(\frac{100 \times \dot{M}_{\text{st}} \times \Delta P}{\rho \times \eta_r}\right)$ (kW) where ΔP is the total pressure drop through the system in kPa	1
The working fluid properties are defined as a function of temperature $\left(h, P, h_{\text{fg}}, s, k, \gamma, \rho, \ldots\text{etc}\right) = f(T)$	2
The outlet specific enthalpy (kJ/kg) and temperature of saturated liquid conditions are calculated as follows: $h_{\text{po}} = \left(\frac{W_r}{\dot{M}_{\text{st}}}\right) + h_{\text{pi}}$ (kJ/kg), and $T_{\text{po}} = f\left(h_{\text{po}}\right)$ (°C)	3
The initial, total annual, and hourly costs are calculated as follows: $\text{ICC}_p = f\left(W_p\right)$ (\$), $\text{TAC}_{\text{total-pump}} = f\left(\text{IC}_p\right)$ (\$/yr), $Z_p = \left(\frac{\text{TAC}_{\text{total-pump}}}{\text{OH} \times 365}\right)$ (\$/h) (see the appendix for more details)	4

Assigned data	Calculated
Operating hours (h)	Pump power (kWe)
Pump efficiency (%)	Outlet thermophysical properties
	Total annual cost (\$/yr)
	Hourly costs (\$/h)

3.5 The PTC Model (Second and Third Configurations). The PTC is the focus of the system in case of second and third configuration operations. The calculated parameters based on the design modeling technique are: area, number of collectors, mass flow rate through the field, pressure drops, thermophysical parameters, etc. Water steam of Therminol-VP1 are used through the field, however each case is studied individually. Table 5 shows the equation that represents the PTC model. The solar collector instantaneous efficiency can be ascertained from its characteristic curve using the solar irradiance, mean collector, and ambient

Table 4 Equations that represent the PV system based on design technique of modeling

Equation	No.
The number of modules (NOM) could be calculated based on total power and module power $\text{NOM} = \frac{P_t}{P_m}$ where P_t is the total power, and P_m is the module power (W)	1
And the module area in m^2 is then calculated based on module power P_m and efficiency η_m $A_m = 100 \times \frac{P_m}{G_b \times \eta_m}$ (m^2), Then the total area in m^2 can be calculated as $A_t = A_m \times \text{NOM}$ (m^2)	2
The battery storage in Wh based on the operating hours (OH), number of cloudy days = 2 (NOC), the total power (P_t), battery efficiency, and depth of discharge (DOD) $\text{BS} = \frac{\text{OH} \times \text{NOC} \times P_t}{\text{DOD} \times \eta_b}$ (Wh)	3
The required (AH) of the batteries $\text{AH} = \frac{\text{BS}}{V_m}$	4
Number of batteries can be calculated as follows based on the battery bank V_{bb} voltage and the battery voltage V_b $\text{NOB} = \frac{V_{bb}}{V_b}$	5
The system total costs in (C_t, $) are then calculated based on the full over board costs of the modules (FOB_c) and the battery costs (C_b) $C_t = (P_t \times \text{FOB}_c) + (C_b \times \text{NOB})$, where the FOB_c includes the cables, connections, workers' time, inverter unit, and the maintenance costs.	6

Assigned data	Calculated
Operating hours (h)	Open circuit voltage (V_{oc}) (V)
Pump efficiency (%)	Short circuit current (I_{sc}) (A)
Solar flux (G_b) (W/m^2)	Maximum voltage (V_m) (V)
Number of cloudy day's factor	Maximum current (I_m) (A)
System total power (P_t) (kW)	Cell and module efficiencies (%)
Module power (P_m) (5–280 W)	Module area (A_m) (m^2)
Battery depth of discharge (DOD)	Total system area (A_t) (m^2)
Battery voltage (V_b) (V)	Battery storage (Wh)
Battery efficiency (%)	Battery capacity (Ah)
Battery unit price (C_b) ($)	Full over board cost (FOBc) ($)

Table 5 Equations that represent the PTC field based on design technique of modeling

Equation	No.
The collector (PTC) performance equation is arranged as $\eta_{col} = \eta_0 - a_1(T_{co} - T_{amb}) - a_2\left(\frac{T_{co} - T_{amb}}{G_b}\right) - a_3\left(\frac{T_{co} - T_{amb}}{G_b}\right)^2$ where $a_1 = 4.5 \times 10^{-6}$, $a_2 = 0.039$, $a_3 = 3 \times 10^{-4}$, and optical efficiency $\eta_0 = 0.75$.	1
The PTC total area is estimated based on the collector energy balance equation as a function of collector efficiency as $A_{col} = Q_u/\eta_{col}G_b$, where Q_u is the collector useful thermal power and (G_b) is the normal beam solar radiation (W/m^2) hits the collector surface area, and A_{col} is the collector area.	2
The collector useful energy equation may exist according to the following relation: $Q_u = m^*_{col} \times \Delta h$	3
The initial, total annual, and hourly costs are calculated as follows: $\text{ICC}_{col} = f(A_{col})$, $, $\text{TAC}_{total-col} = f(\text{ICC}_{col})$, $/y, $Z_{col} = \left(\frac{\text{TAC}_{total-col}}{\text{OH} \times 365}\right)$, $/h (see the appendix for more details)	4
All thermophysical properties of the inlet and outlet streams are calculated based on the operating temperature such as $(h, P, h_{fg}, s, v, k, \gamma, \rho, \ldots\text{etc}) = f(T_{co})$	5

Assigned data	Calculated
Top PTC temperature (°C)	Useful thermal power (kW_{th})
Ambient temperature (°C)	Collector efficiency (%)
PTC width/module (LS-3 type) (m)	PTC field total area (m^2)
Glass envelop diameter (m)	Pressure drop (bar)
Absorber tube diameter (m)	Field width (m)
	Number of loops
	Field total length (m)
	Total annual costs ($/yr)
	Hourly costs ($/h)

temperatures. The corresponding efficiency equation for the medium–high temperatures PTC is given by Eq. (1) in Table 5 [12].

4 Results and Comments

Results are obtained out from REDS-SDS software package to measure and calculate some indicators which are listed as:

- solar field area (A_{col}), m^2
- steam mass flow rate, kg/s
- thermal power, kW_{th}
- operating hours, cost, $/h
- exhaust analysis in the case of first configuration

Figures 5–9 present the data comparison results for all configurations based on the variation of the number of tanks (NOTs), tank volume (V_t), the margarine temperature difference (ΔT), and period of melt (POM). It is obvious from Fig. 5 that the first configuration is too costly per hour compared to the other

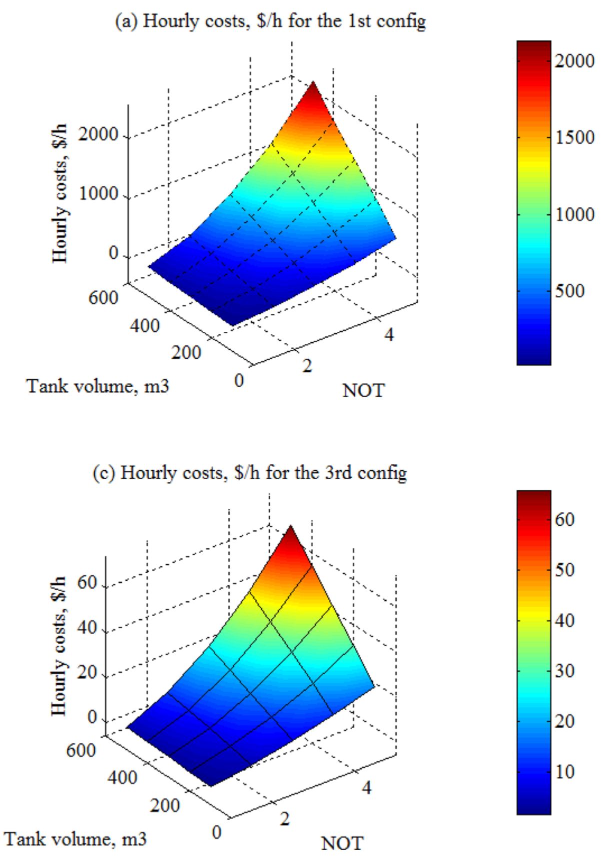


Fig. 5 The result curves for the variation of hourly costs, $/h versus the variation of NOT and tank volume, m^3

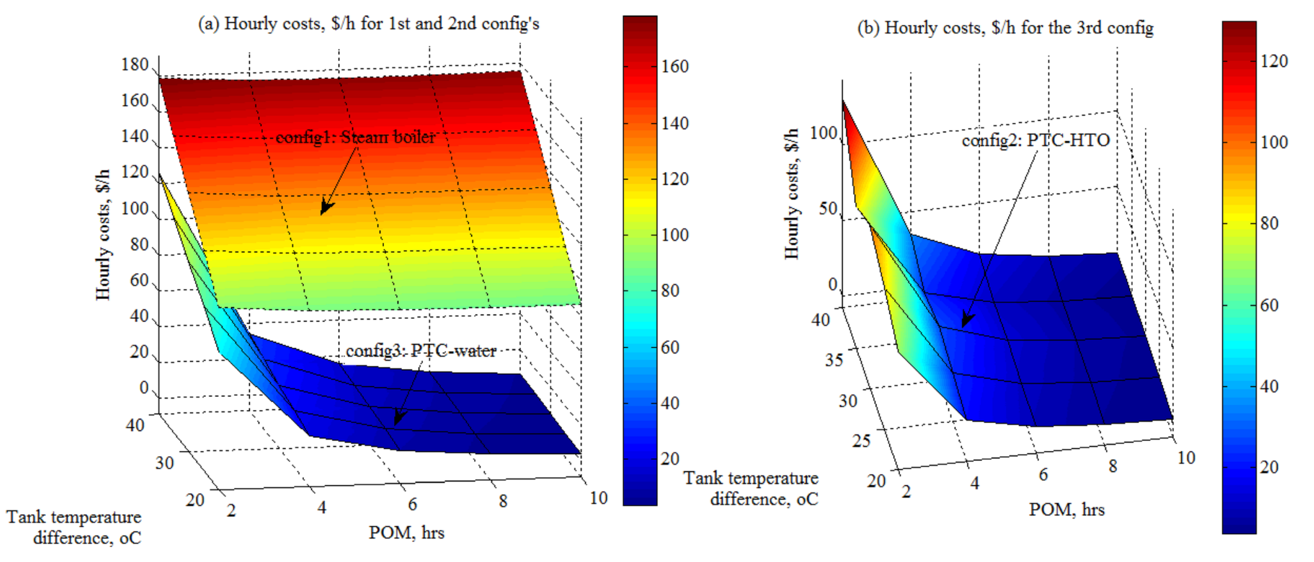


Fig. 6 The variation of hourly costs, $/h versus the variation of butter tank temperature difference, °C and the period of melt (POM), *h* at tank volume equal to 100 m^3

configurations. Regardless the effect of NOT and tank volume variations, the first configuration is not recommended due to the higher values of hourly costs which is varying between 100 and 2000 $/h. However, the remaining configurations (renewable configurations) result in approximately 5 $/h (lowest value) up to 60 $/h regardless the variation itself. Regarding the effect of the tank volume for both figures, increasing the tank volume (the quantity of melting material) would increase the hourly cost. However, the NOT parameter is causing the most significant effect on the whole process even on the renewable configurations (configurations 2 and 3). Figure 5 shows that the 100 m^3 is the best option for the tank volume case against the 500 m^3. Moreover, the NOT = 1 is the best option to lower the hourly costs $/h because the thermal load is decreased by 80%. For renewable configurations, both configurations are identical; however, the second configuration (water, steam) has the advantage against the third one. The third

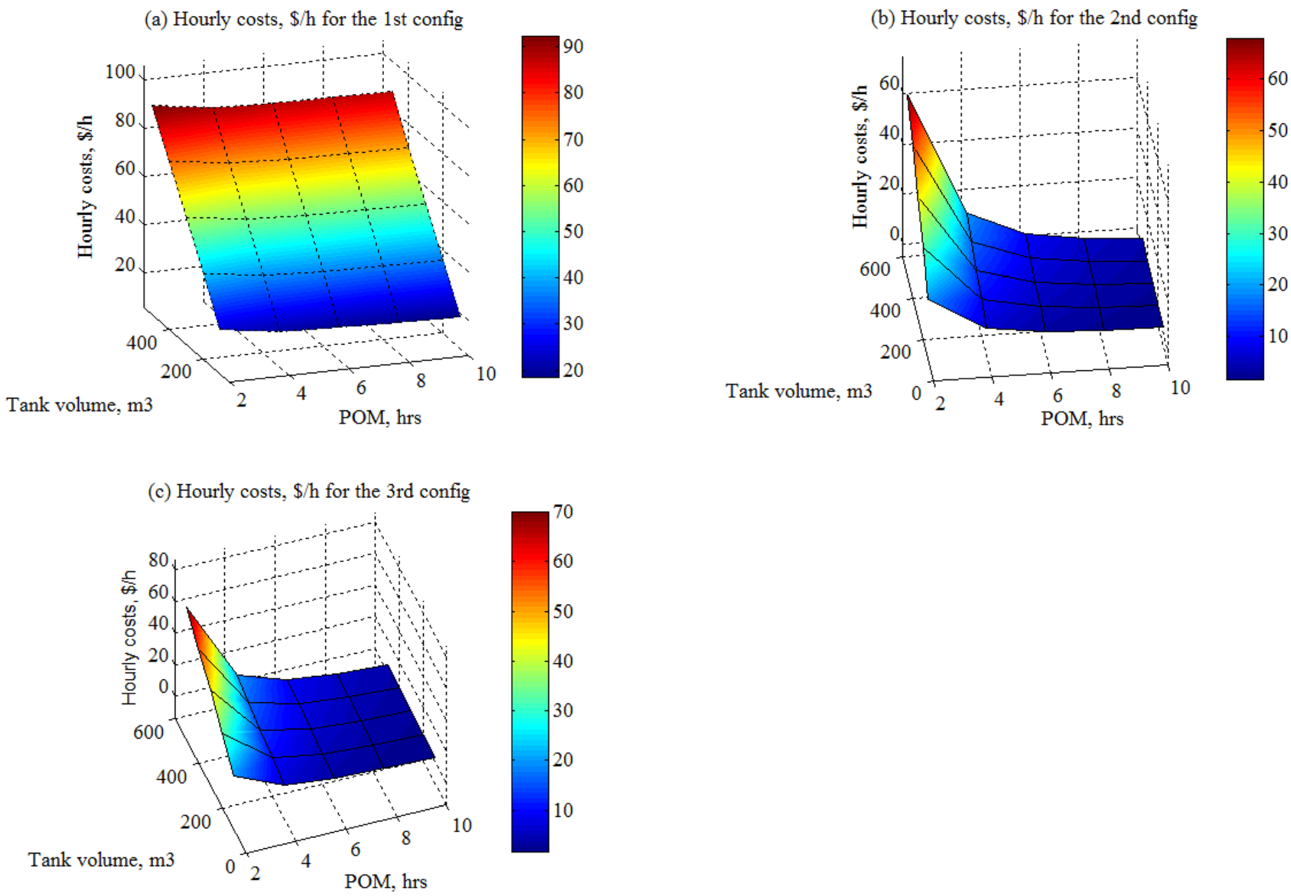


Fig. 7 The variation of hourly costs, \$/h, versus the variation of tank volume, m^3, and the period of melt (POM), *h*, at tank temperature difference = 20 °C

configuration is favorable from the side of operating conditions, i.e., it can operate the solar field up to 400 °C. The main problem with the second configuration that it cannot operate the solar field with a top temperature more than 200 °C due to severe pressure issues. However, the third configuration is considered harmful related to the existence of HTO matter.

Figure 6 shows the variation of the hourly cost term according to the proposed configurations against the effect of POM parameter and the tank temperature difference at 100 m^3 as indicated in the previous figure. The tank temperature difference is the difference between the desired temperature (T_{mar}) specified by the production sector and the initial temperature (T_{i}) of the tank. As indicated earlier in Fig. 5, the first configuration is recorded as the highest value of the hourly costs followed by the second configuration. Generally, the third configuration gives minimum hourly costs compared to the other configurations. It is apparent from the figure that the tank temperature difference ($\Delta T = T_{\mathrm{mar}} - T_i$) has a slight effect on the hourly costs compared against the POM parameter. Although increasing the tank temperature difference would increase the hourly costs, the POM gives significant results, especially in the first configuration. It is also apparent that increasing the POM would decrease the hourly costs from 150 \$/h at POM = 2 h down to 10 \$/h at POM = 10 h. The Savola's officials hoped to run the system at the minimum possible value of the POM. However, it is not recommended to run lower than the value of 10 h. Normally, the POM was in the range of 12–13 h, however, by the use of renewable configurations, the POM is decreased by 2–3 h under the worst case (winter operation) and by 3–4 h in summer periods. It is highlighted from Fig. 6 that the optimal tank temperature difference should be kept in the range of 15–25 °C. This range would decrease the POM and the thermal load on the solar field or even the steam boiler.

Figure 7 displays the effect of tank volume and POM parameters on the hourly cost, \$/h. As seen from Fig. 7, the hourly costs are increased dramatically up 60 \$/h for renewable configurations and as little 100 \$/h for the conventional configuration (first configuration). Increasing the tank volume is followed by the increase of the thermal load depending on the heat capacity of the margarine material (=1.26 kJ/kg °C).

As indicated earlier, the behavior of the renewable configurations is considered the same with little advantage to the second configuration. The results from Figs. 5–7 reveal that the tank volume and the tank temperature difference should be kept at minimum possible values (100 m^3 for the tank volume and 20 °C for the tank temperature difference). However, the POM is recommended to be kept at 10 h in winter and 8 h in summer period regardless the configuration type or the method of process heat. In each case, the effect of POM, tank volume, and tank temperature are influencing the hourly cost of the steam mass flow rate as an intermediary.

The effect of POM and tank volume parameters on the studied variables is very important because these two parameters are the main factor influencing hourly costs. Figure 8(*a*) shows the effect of POM parameter on the mass flow rate of the steam for the three configurations at the same operating conditions ($\Delta T = 20$ °C, $V_{\mathrm{t}} = 100$ m^3, NOT = 1). Increasing the POM parameter would decrease the mass flow rate followed by the decrease of the hourly cost parameter. However, the POM should be minimized as

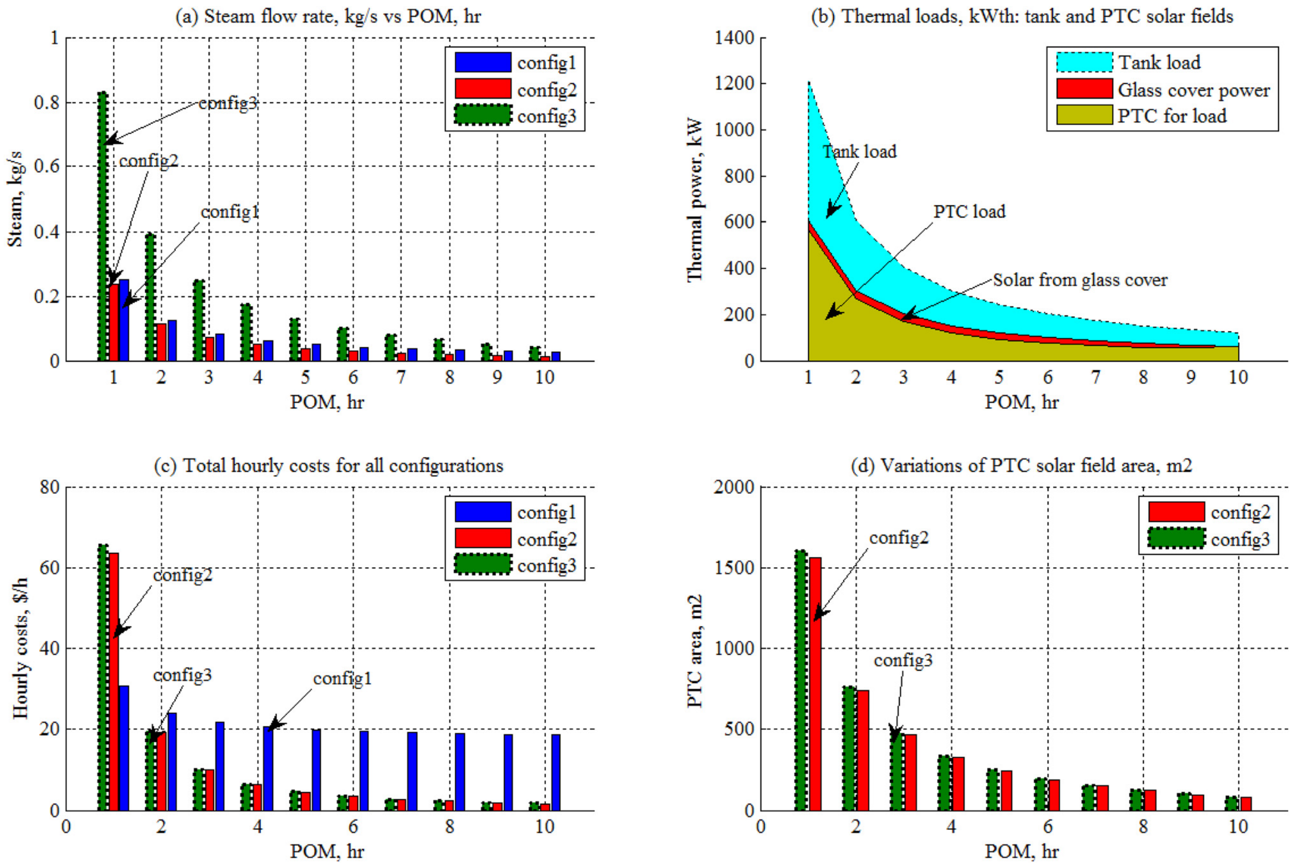


Fig. 8 The effect of period of melt (POM), *h* parameter on: (*a*) steam mass flow rate, kg/s, (*b*) tank and PTC thermal load powers, kW_{th}, (*c*) hourly costs, $/h, and (*d*) PTC field area, m^2

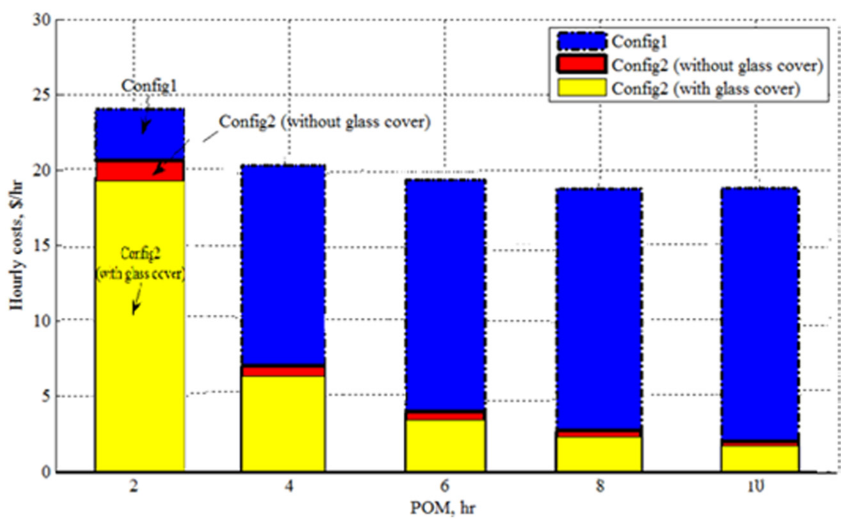


Fig. 9 The effect of top glass covers on the total hourly cost parameter for the conventional and solar configuration

possible, putting into consideration the cost minimization. Therefore, 8–10 h in winter is considered as a vital value for melting the quantity of 100 m^3. The third configuration is considered the highest related to Fig. 8(*a*). For the other configurations, the behavior is the same on the curve related to the operation of the same working fluid (water steam).

The third configuration (Therminol-VP1) is consuming larger value of the mass flow rate based on its specific heat capacity and the density. Figure 8(*b*) shows the thermal power loads for the both margarine tank and the PTC. The figure shows the load distribution based on the energy balance of the tank and the PTC where $Q_{\text{tank}} = Q_{\text{PTC}} + Q_{\text{glass cover}} + Q_{\text{loss}}$. In the case of good insulation, the Q_{loss} is equal to 0.023 kW, i.e., very low compared with PTC and the margarine tank thermal loads. Therefore, it is shown on the figure that the Q_{tank} is almost equal to the $Q_{\text{PTC}} + Q_{\text{glass cover}}$. That explains why the tank load is still a slightly higher than the Q_{PTC}. For example, at POM = 1 h, the $Q_{\text{tank}} = 608$ kW $= Q_{\text{PTC}}$ (577 kW) $+ Q_{\text{glass cover}}$ (31 kW).

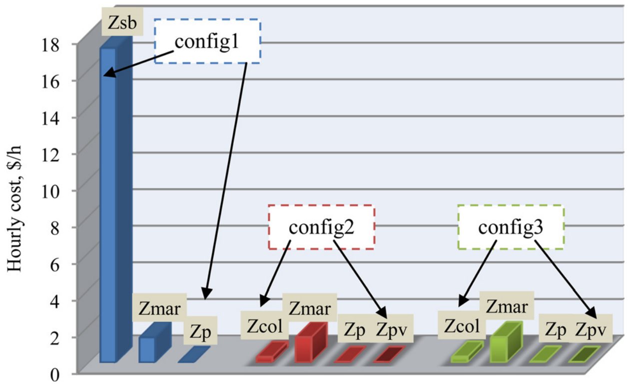


Fig. 10 The hourly costs, $/h for all units based on all proposed configurations at: 10 h, 100 m^3 capacity, and tank temperature difference at 20 °C

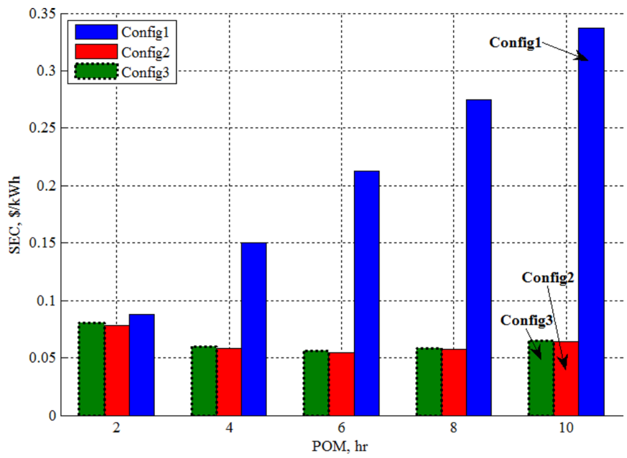


Fig. 11 Specific energy cost (SEC, $/kW h) parameter comparison for all configurations

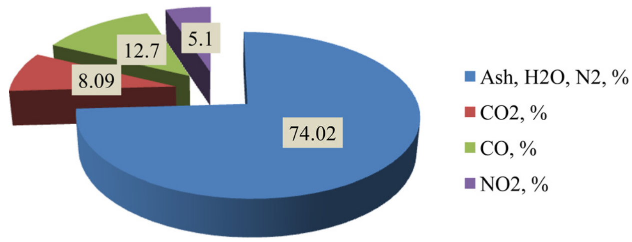


Fig. 12 The natural gas exhaust analysis according to the conventional configuration (config1)

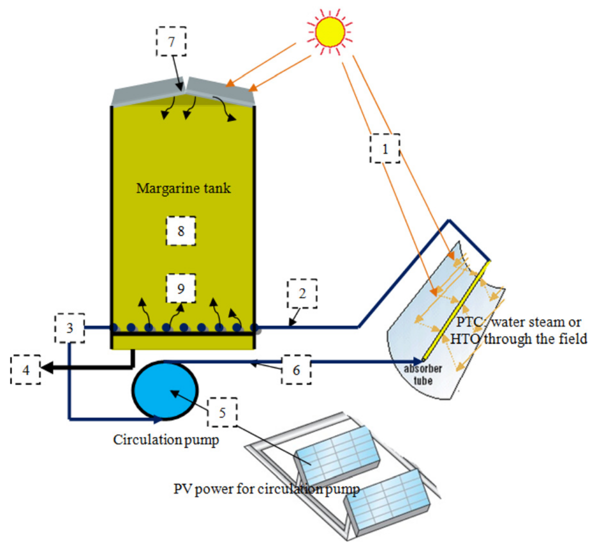
However, without the glass cover, the $Q_{\text{tank}} = 608$ kW $= Q_{\text{PTC}}$ (608 kW). The effect of the insulation on all configurations is not remarkable because that the amount of energy loss per POM would not exceed over 0.5 kW. Such amount of energy loss is considered very low because the temperature difference between the tank and the ambient temperature is too low. Add to this the cylindrical shape of the tank is highly resistant to thermal loss compared to the rectangular version. The insulation would save about 95% of the energy loss which is significant because the amount of the received solar energy is about 31 kW versus 0.5 kW. The effect of solar energy from the top glass cover is equal to 60 times of the effect of the insulation at POM = 10 h. Figure 9 shows the effect of top glass cover on the total hourly cost parameter for the conventional and solar configuration. Figure 8(*c*) shows that by increasing the POM parameter, the hourly cost parameter decreases to a minimum required value. Moreover, the renewable configurations are remarkable compared with the conventional configuration with an advantage for the second configuration (water steam). Figure 8(*d*) shows the comparison between the total solar field areas for the renewable configurations. It is apparent that both configurations achieve the same behavior with an advantage of the second configuration.

Figure 10 shows the data comparison of the hourly cost parameter for all units for all configurations. It is clear that the total hourly costs for the conventional configuration are noticed the highest among all configurations. The hourly costs for the steam boiler is much higher compared the equivalent unit based on the

Table 6 Data streams results for the second configuration (config2) as an alternative option

Config2	Condition/Stream	1	2	3	4	5	6	7	8	9
	T (°C)	15	160	80	45–50	—	82.07	—	$\Delta T = 20$	160–80
	M (kg/s)	—	0.012	0.012	—	—	0.012	—	—	0.012
	Power (kW)	39.43/PTC	33.15	4.03	—	0.1	4.125	31.81	60.9	29.02

- Operating hours = 10
- Solar radiation = 500 W/m^2
- Air temperature = 15 °C
- Average wind speed = 0.2 m/s
- Tank temperature difference = 20 °C
- Number of tanks = 1
- Tank main diameter = 9 m
- Tank height = 7.85 m
- Margarine heat capacity = 1.26 kJ/kg °C
- Margarine melting point = 33 °C
- Margarine melting enthalpy = 45 kJ/kg
- Margarine density = 870 kg/m^3
- Margarine inner coil area = 12.74 m^2
- Top tank area = 64 m^2
- Tank total volume = 500 m^3
- Margarine, melted quantity = 100 m^3
- Total system pressure loss = 7 bar
- PTC area = 80–100 m^2
- PTC efficiency = 73%
- Pump efficiency = 75%
- Thermal tank losses = 0.023 kW
- Tank initial cost = 45,000$



steam generation (PTC). The hourly costs for the steam boiler is 17 \$/h due to the steam consumption and the price of a cubic meter of natural gas. The hourly costs of the margarine tank are seen at the same value according to the fixed initial cost of the tank and the incessant rate of running costs. Therefore, it results in approximately 1.8–2 \$/h. The PTC field costs are a direct function of the total area. Therefore, the hourly costs for the renewable configurations are considered the same because of nearly the same results of the solar field area. For pumps and PV units, the hourly costs are quite low due to the lower demand for power on the pump unit during the operating hour period. In general, the conventional configuration is not favorable as indicated from Fig. 10 due to the largest values of the hourly costs especially in the steam boiler unit. Figure 11 shows the data comparison for all configurations based on a specific energy cost parameter (SEC, \$/kW h). The SEC represents the total system hourly costs over the boiler/collector thermal power $(\mathrm{SEE} = (Z/(\mathrm{LF} \times Q_{\mathrm{th}})))$. Figure 10 indicates that the second configuration recorded the lowest among the remaining configurations. Generally, renewable configurations are observed to be lower by 18% (0.06 versus 0.33 \$/kW h) than the conventional configuration. Figure 12 shows the data analysis of the exhaust of the steam boiler based on the conventional configuration. The result indicates that the CO_2 constitutes approximately 8.09% (117 kg/day) while the remaining analysis for NO_2, CO and the remaining components (sulfate, ashes, H_2O, O_2) are 5.1% (74.7 kg/day), 12.7% (184.04 kg/day), and 74.02% (1075 kg/day), respectively. The results indicate the conventional configuration has a negative impact to the environment. Thus, the second configuration gives more attractive results. The third configuration is quite attractive as well; however, the effect of HTO on the margarine matter is not recorded until now. Moreover, in case of adding an additional intermediate unit such as intermediate heat exchanger would increase hourly costs. The results of the second configuration are illustrated in Table 6.

5 Conclusion

This study examined the benefits of using alternative renewable solar thermal energy systems, such as a PTC over conventional configuration. The initial problem emerged when the Savola's Egypt company for margarine industries decided to lower the power consumption of their heating process. The problem is resolved by reducing the working hour periods especially under winter operating conditions. Three configurations are studied in this work. The first configuration represents the formal process in the Savola's industrial plant which is chiefly dependent on the natural gas steam boiler as a steam thermal generator. The second configuration is viewed as a renewable configuration by replacing the top margarine tank cover and steam boiler by a glass cover and PTC solar field, respectively. Water, steam is also used for the second configuration. The third configuration is similar to the second, however, Therminol-VP1 HTO is used instead of water steam. REDS-SDS software package is used to compare the conventional case versus the other two analytical cases (renewable). Our empirical results reveal the following:

- The conventional configuration is subjected to a considerable amount of energy loss from the margarine tank.
- Increasing the thermal power losses may increase the steam demanded by the steam boiler generator, hence increasing the rate of fuel consumption and extra hourly costs.
- Increasing the number of tanks and tank volume parameters may increase the hourly costs for all configurations. However, renewable energy configurations achieve remarkable results against the conventional one.
- Decreasing the period of melt parameter may cause a massive increase in thermal load on all configurations and hourly costs.
- The optimized operating conditions for the minimization of the hourly cost parameter are: (i) margarine tank temperature difference should not exceed 25 °C, (ii) tank volume should not exceed 100–150 ton, (iii) period of melt should be minimized from 13 h to 10 h.
- For all units, the steam boiler constitutes the largest value of the hourly cost parameter while the margarine tank is responsible for the second highest hourly cost.
- The conventional configuration is considered harmful to the environment by producing a rate of 117 kg/day, 184 kg/day, 74 kg/day of CO_2, CO, and NO_2, respectively. The renewable configurations are considered zero emissions to the environment.
- Generally, the renewable configurations give nearly the same results with regard to hourly cost, solar field area and mass flow rates and a slight advantage of the water steam configuration.

Nomenclature

A = area (m^2)
A_c = cell area (m^2)
A_m = module area (m^2)
AH = battery capacity (Ah)
BS = battery storage (Wh)
BP = barrel price (\$)
C_b = battery cost (\$)
C_p = specific heat capacity (kJ/kg °C)
C_t = total cost (\$)
C.V = calorific value (kJ/kg)
D = diameter (m)
DOD = depth of discharge
F = friction factor
FOB_c = full over board cost (\$)
G_b = solar flux (W/m^2)
H = height (m)
H = specific enthalpy (kJ/kg)
h_{conv} = heat transfer coefficient of convection (W/m^2 °C)
h_{fg} = latent heat of vaporization (kJ/kg)
I = interest rate
IC = initial cost (\$)
ICC = indirect capital costs (\$)
K = thermal conductivity (W/m °C)
L = length (m)
LF = load factor
LT_p = plant life lime (yr)
M = mass flow rate (kg/s)
NOB = number of batteries
NOC = number of cloudy days
NOM = number of modules
NOT = number of tanks
Nu = Nusselt number
OH = operating hours (h)
P = pressure (kPa)
P_m = module power (W)
P_t = total power (W)
P_w = wind power (kW)
POM = period of melt (h)
PTC = parabolic trough collector
PV = photovolatic
Q = thermal power (kW)
Q_u = useful power (kW)
R = radius (m)
R_{th} = thermal resistance
S = entropy (kJ/kg °C)
SEC = specific energy cost (\$/kW h)
SFC = specific fuel consumption (kg/kW h)
T = temperature (°C)
T_{co} = outlet collector temperature (°C)
TAC = total annual costs (\$/y)
U = overall heat transfer coefficient (W/m^2 °C)

V = volume (m^3)
W_p = pump power (kW)
Z = hourly costs (\$/h)

Subscripts

amb = ambient
b = boiler
c = cell
CO = carbon monoxide
CO_2 = carbon dioxide
col = collector
f = fuel
g = gas
i = inner
loss = losses
m = module, or mean
mar = margarine
NO_2 = nitrogen dioxide
o = outer
P = pump
Pi = pump inlet condition
Po = pump outlet condition
sb = steam boiler
solar = solar
st = steam
t = tank
top = top side
tube = tube

Greek Symbols

H = efficiency (%)
P = density (kg/m^3)
μ = dynamic viscosity (Pa · s)

Appendix

A.1 Cost Analysis. Investment and hourly costs analyses are performed for each component, solar field, steam boiler, margarine tank, PV system, condensers, and pump units. The interest rate and set as 5%, LT_p is the plant lifetime and set as 20 yr. Tables 7 and 8 illustrate the indirect capital costs (ICC) and hourly costs for the configuration components.

A.2 Thermophysical Properties
A.2.1 Water. Latent heat of vaporization, kJ/kg

$$L = 2501.897149 - 2.407064037 \times T + 1.192217 \times 10^{-3} \times T^2 - 1.5863 \times 10^{-5} \times T^3$$

Saturation pressure, bar

$$P_{sat} = 872.3 \times \exp^{-(T-585.5/169.5)^2} + 39.07 \times \exp^{-(T-342.4/124.4)^2}$$

Table 8 Cost parameters for margarine tank and steam boiler units

Parameter	Correlation
Interest rate (%)	$i = 5$
Plant life time (yr)	$LT_p = 20$
Amortization factor (1/yr)	$A_f = \dfrac{i \times (1+i)^{LTp}}{(1+i)^{LTp} - 1}$
Margarine tank direct capital costs (\$)	$DCC_{mar} = 45{,}000\$$
Insulation costs (\$/m^3)	30
Margarine tank indirect capital costs (\$)	$ICC_{mar} = 0.15 \times DCC_{mar}$
Margarine tank total annual costs (\$/yr)	$TAC_{mar} = [NOT \times DCC_{mar} + ICC_{mar}] \times A_f$
Margarine tank hourly costs in (\$/h)	$Z_{mar} = \left(\dfrac{TAC_{mar}}{OH \times 365}\right)$
Steam boiler hourly costs (\$/h)	$Z_{sb} = \dfrac{(BP \times M_f \times 3600 \times OH)}{\rho_g}$

Specific enthalpy of dry saturated vapor, kJ/kg

$$h_v = -3.078e - 18 \times T^9 + 4.762e - 15 \times T^8 - 3.076e - 12 \times T^7 + 1.074e - 9 \times T^6 - 2.193e - 7 \times T^5 + 2.646e - 5 \times T^4 - 0.001824 \times T^3 + 0.06417 \times T^2 + 0.894 \times T + 2504$$

Specific enthalpy of saturated liquid, kJ/kg

$$h_l = -0.033635409 + 4.207557011 \times T - 6.200339 \times 10^{-4} \times T^2 + 4.459374 \times 10^{-6} \times T^3$$

A.2.2 Therminol-VP1. Specific heat capacity, kJ/kg °C

$$C_p = -0.6622 \times \exp^{(0.001186 \times T)} + 2.178 \times \exp^{(0.0007637 \times T)}$$

Pressure, bar

$$P = 1.059e - 9 \times T^4 - 3.412e - 7 \times T^3 + 3.867e - 5 \times T^2 - 0.001491 \times T + 0.01249$$

Specific enthalpy, kJ/kg

$$h = 0.00137 \times T^2 + 1.5 \times T - 18.46$$

Specific entropy, kJ/kg °C

$$s = 1.038 \times \exp^{(0.002218 \times T)} - 0.7889 \times \exp(-0.004717 \times T)$$

Table 7 ICC and hourly costs for all units

Parameter	ICC (\$)	O & M (\$)	TAC (\$/yr)	Z (\$/h)	Reference
Solar field	$150 \times (A_{col})^{0.95}$	$15\% \times ICC_{col}$	$A_f \times (ICC + O\&M)_{col}$	$TAC_{col}/OH \times 365$	[8,13]
Condensers	$150 \times (A_{cond})^{0.8}$	$25\% \times ICC_{cond}$	$A_f \times (ICC + O\&M)_{cond}$	$TAC_{cond}/OH \times 365$	
Pump	$3500 \times (W_p)^{0.47}$	$25\% \times ICC_p$	$A_f \times (ICC + O\&M)_p$	$TAC_p/OH \times 365$	

Note: A_{cond} is the condenser area (m^2), W_p is the pump power (kW), and A_{col} is the PTC area (m^2).

A.2.3 Air. Air density, kg/m^3

$$\rho_a = 4.6e-27\times(T^{10}) - 1.5e-23\times(T^9) + 2e-20\times(T^8) - 1.4e-17\times(T^7) + 5.7e-15\times(T^6) - 1.4e-12\times(T^5) + 2.5e-10\times(T^4) - 5.5e-8\times(T^3) + 1.7e-5\times(T^2) - 0.0047\times T + 1.3$$

Thermal conductivity, W/m °C

$$k_a = -2.8e-30\times(T^{10}) + 6e-27\times(T^9) - 2.9e-24\times(T^8) - 2.4e-21\times(T^7) + 3.1e-18\times(T^6) - 9.8e-16\times(T^5) - 2.2e-14\times(T^4) + 4.8e-11\times(T^3) - 3.4e-8\times(T^2) - 8e-5\times T + 0.024$$

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