

## Research Article

# Solar Energy for a Solvent Recovery Stage in a Biodiesel Production Process

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Recent research and development of clean energy have become essential due to the global climate change problem, which is caused largely by fossil fuels burning. Therefore, biodiesel, a renewable and ecofriendly biofuel with less environmental impact than diesel, continues expanding worldwide. The process for biodiesel production involves a significant energy demand, specifically in the methanol recovery stage through a flash separator and a distillation column. Traditionally, the energy required for this process is supplied by fossil fuels. It represents an opportunity for the application of renewable energy. Hence, the current study presents a system of thermal energy storage modeled in TRNSYS® and supported by simulations performed in ASPEN PLUS®. The aim of this research was to supply solar energy for a methanol recovery stage in a biodiesel production process. The results highlighted that it is feasible to meet 91% of the energy demand with an array of 9 parabolic trough collectors. The array obtained from the simulation was 3 in series and 3 in parallel, with a total area of 118.8 m<sup>2</sup>. It represents an energy saving of 70 MWh per year.

## 1. Introduction

The excessive use of fossil fuels for energy supply in the daily life of humanity has had significant environmental consequences. It coupled with an increasing shortage has caused the world to experience a transition from fossil fuels to some renewable energy source [1, 2]. Solar energy has great potential as renewable energy due to its abundance, and its use has been growing more every year, from heating water for households to power generation [3–5].

Solar energy in industry swaps the massive consumption of commercially available electricity. Some industrial processes such as drying, sterilization, cooking, cleaning or degreasing, and pasteurization require heat energy. All the processes temperature required is less than 260°C [6]. Other applications as cleaning, evaporation, distillation, and cooking, among others, as well as applications with

low-temperature heat demand and high consumption rates (domestic hot water, space heating, and swimming pool heating), and heat-driven refrigeration and cooling require temperatures between 85 and 250°C. Recently, one of the aims of solar-thermal engineering is to enhance parabolic trough concentrators for industrial processes. Some research reported in the literature is addressed to the development of new devices, new applications, control methodologies, thermodynamic and technical-economic analysis, and the development of components, support structures, reflective materials, materials for the receiver, and absorber surfaces [7]. One kind of parabolic trough concentrator (PTC) is destined to provide heat to processes that need temperatures between 100 and 250°C. The typical aperture widths are between 1 and 3 m; total lengths vary between 2 and 10 m by row, and geometrical concentrating ratios are between 15 and 20. The PTC of this group are called “medium temperature collectors”

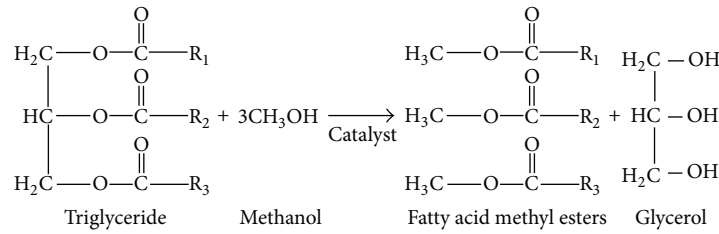


FIGURE 1: Transesterification reaction to obtain biodiesel.

[8]. Some of the applications of PTC face space constraints on the solar field. Factories today are usually located in industrial areas where land is often limited and expensive, so installing the solar field on roofs should be a real possibility [9]. Solar energy is being used for industrial processes in various developing countries. According to International Energy Agency (IEA) currently 120 operating solar-thermal systems for process heat are reported worldwide, with a total capacity of about 88 MW (125,000 m<sup>2</sup>) [6].

Recently, biodiesel has become more attractive because of its environmental benefits and by the fact that it is produced from biomass, a renewable resource [10, 11]. However, the production cost of biodiesel is the main obstacle for the marketing of the product [12, 13]. The biodiesel production process involves a significant energy demand, specifically in the methanol recovery stage through a flash separator and a distillation column. Traditionally, the energy required is supplied by fossil fuels. It represents an opportunity for the application of renewable energy. Hence, the current study presents a system of thermal energy storage modeled in TRNSYS and supported by simulations performed in ASPEN PLUS. The aim of this research was to supply solar energy for a methanol recovery stage in a biodiesel production process in Mexicali, Baja California, Mexico.

Previous work performed simulations using ASPEN PLUS, generating steam and power with solar collectors and photovoltaic panels applied to biodiesel production process [14]. However, important parameters concerning the use of solar collectors, for example, the variation in solar irradiation, the type of solar collector, orientation and inclination, and arrangement of the storage system, were not considered. In the present work, these parameters were included by the utilization of a dynamic simulator called TRNSYS.

ASPEN PLUS is a process modeling software suitable for a variety of steady-state modeling applications. The ASPEN system is based on “blocks” corresponding to unit operations as well as chemical reactors, through which most industrial operations can be simulated [15]. ASPEN PLUS is widely used for simulation processes in different industries, for example, oil and gas, chemical, engineering and construction, pharmaceutical, food, and beverage [16, 17].

TRNSYS is an acronym for a “transient simulation” which is a quasi-steady simulation model. This program was developed by the University of Wisconsin by the members of the Solar Energy Laboratory [18]. It has been used in the evaluation of solar technologies, including their different

design parameters and operating conditions for a specific location in order to obtain reliable results [19–22].

Castor oil was the feedstock used for biodiesel production in the simulation. It consists of triglycerides comprised by 90% of ricinoleic acid [23]. Therefore, the tricinolein was considered as the representative castor oil molecule in the present simulation. Methyl ricinoleate is the corresponding ester of ricinoleic acid and the primary product of the transesterification reaction, which represents the biodiesel. The byproduct of this reaction is glycerol. The transesterification reaction is catalyzed by sodium hydroxide, and the product mixture is neutralized with sulfuric acid. This reaction is shown in Figure 1 [10].

The production process of biodiesel from castor oil in ASPEN PLUS consists of 5 stages: pretreatment, transesterification, separation, neutralization, and alcohol recovery [24, 25].

A biodiesel production plant was simulated in ASPEN PLUS, and it was designed to maintain a biodiesel production of 83.3 kg/h. To achieve it, it is necessary to supply 10.63 kW to the process, where 82.6% of that power is used for the methanol recovery. The flash separator and the reboiler of methanol recovery column consume 2.76 kW and 6.02 kW, respectively. The complete process diagram developed in ASPEN PLUS can be seen in Figure 2.

The solar irradiation in Mexicali, Baja California, was used for heating the heat transfer fluid (HTF) in heat exchangers in the biodiesel production process, specifically, the methanol recovery stage. As a result, the fossil fuels consumption is reduced by the utilization of solar energy. The implementation of solar collector technologies in existing processes represents an opportunity at an industrial level, as it may reduce operation costs associated with heating streams.

## 2. Methodology

**2.1. Study Area.** Mexico is located between 14° and 33°N, a region ideal for the solar energy exploitation. The average daily global irradiation in the country is about 5.5 kWh/m<sup>2</sup> [26]. Mexicali, a northwest city of Mexico, is located on the border with the State of California, USA, and has an average daily normal irradiation (ADNI) on June about 10 kWh/m<sup>2</sup>. Analysis of power generation by the solar irradiation database of the National Renewable Energy Laboratory (NREL) establishes that Mexicali has ADNI levels above 6.5 kW/m<sup>2</sup>/day. According to NREL, a site with an ADNI level greater than

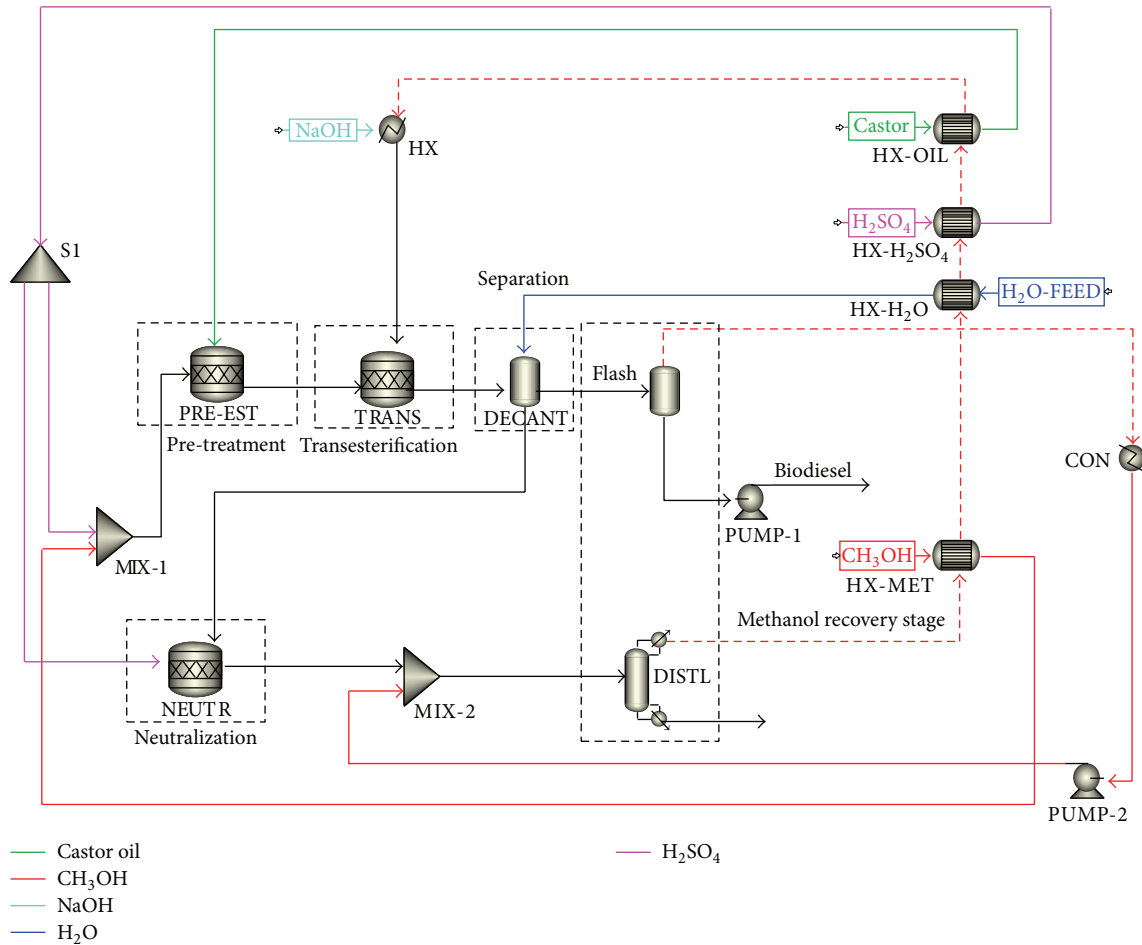


FIGURE 2: Diagram of biodiesel production process in ASPEN PLUS.

6 kWh/m<sup>2</sup>/day, it is considered a profitable area for the exploitation of solar resource [27].

In general, the long-term performance prediction of any solar energy system depends on the long-term climatic features of the location where it is to be used. The need for using a one-year meteorological data file to evaluate the long-term system performance has led to the development of the typical meteorological year (TMY). The TMY is a set of hourly values of solar irradiation and meteorological elements for one year generated from observed long-term data [28].

The TMY file information considered for Mexicali in the simulation was a ten-year average from 2000 to 2009 obtained from the METEONORM® software database [29].

**2.2. General Methodology Description.** Figure 3 displays the methodology scheme applied for the development of this work, where the interaction between the user and the simulation software is highlighted.

First, an HTF able to work over a wide range of temperatures was selected and uploaded to ASPEN PLUS. The transfer of energy from the HTF to the flash and the reboiler was represented through a heat exchanger for each equipment. Based on the simulation, the stream values of the HTF

such as temperature and mass flow suitable to convey the energy required by the process were determined.

Once the HTF stream values and properties required were estimated, the thermal storage system was dimensioned. The info on the sizes of tanks and HTF stream and its properties were provided to TRNSYS.

Through TRNSYS, the final solar collector's array that can provide the energy required for the solvent recovery stage in the biodiesel process, with the lower auxiliary power consumption, was obtained. TRNSYS simulation was dynamic and allowed evaluating the behavior of the system during an average year of continuous operation.

**2.3. Thermal Energy Storage System.** The energy needed for the continuous operation of the biodiesel process was carried out through solar heating of the HTF. The energy storage system includes a tank for the fluid, prior heating (tank 1), and another tank for the heated fluid (tank 2). Also, an array of solar collectors and two heat exchangers are included, which represent the methanol recovery stage where the thermal energy is supplied.

The HTF selected was ethylene glycol, antifreeze used in various applications due to its wide range of working temperatures [30].

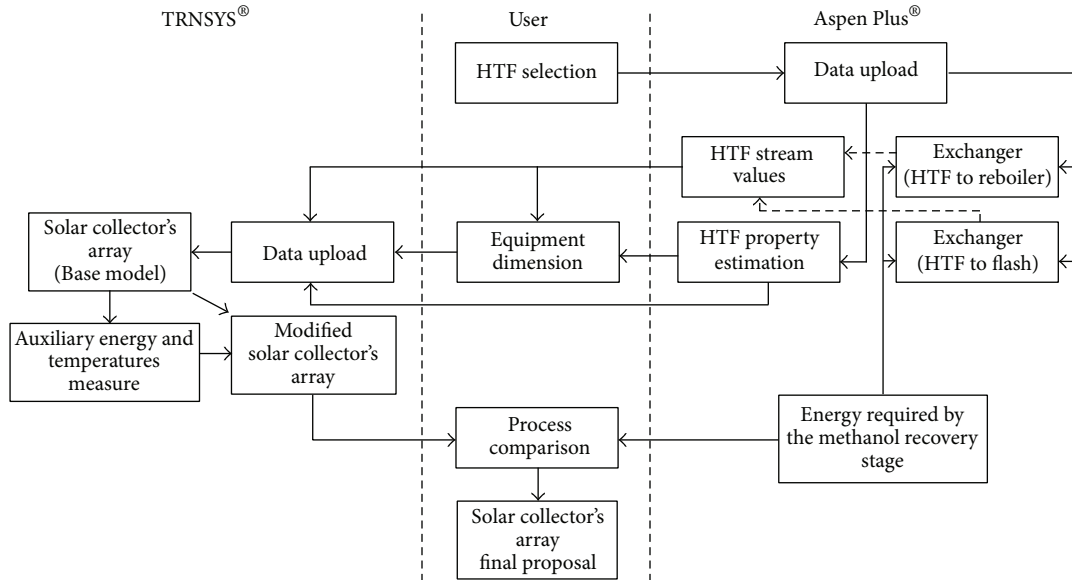


FIGURE 3: Methodology scheme applied.

The working temperature, the heat transfer coefficients, and the mass flows of the HTF were estimated in ASPEN PLUS.

The shortcut method was used for the heat exchangers calculation, specifying the outlet temperature and pressure of the stream that receives energy. The outlet temperature and pressure for the flash separator were 110°C and 10.1 kPa, while being 93°C and 110 kPa for the reboiler. The flow arrangement of the heat exchangers was defined as countercurrent and the correction factor ( $F$ ) method for the logarithmic mean temperature difference (LMTD) was stated constantly. The overall heat transfer coefficients ( $U$ ) were 850 W/m<sup>2</sup> K.

The storage tanks volumes and their inlet and outlet flows were calculated based on the density of the HTF. Two arrays of solar technologies were evaluated: evacuated tube collectors (ETC) and parabolic trough collectors (PTC).

### 3. Results and Discussion

According to the results obtained in ASPEN PLUS, the working temperature of HTF to deliver the heat required was 120°C. The heat transfer coefficient ( $UA$ ) and the area ( $A$ ) of the column reboiler were 482.31 W/K and 0.57 m<sup>2</sup>, while being 394.82 W/K and 0.46 m<sup>2</sup> for the flash separator. The mass flows for the column reboiler and flash separator were 270 kg/h and 93 kg/h, respectively.

The volume required for tank 1 was 9 m<sup>3</sup> while for tank 2 it was 7 m<sup>3</sup>. The HTF mass outflows were 1,452 kg/h for tank 1 and 363 kg/h for tank 2. The difference between outflows is because the HTF must be heated when solar irradiation is available.

With the purpose of heating the HTF and maintaining it at 120°C, ETC were analyzed. The tilt and azimuth angle of the ETC evaluated were 32° and 0°, respectively. The solar collectors array does not have a sun tracking system. The

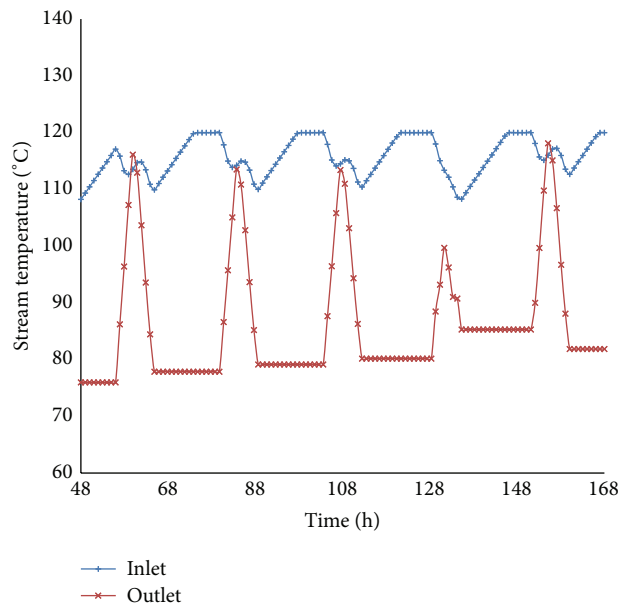


FIGURE 4: Variation of the temperature at the inlet and outlet of the tank 2 for the array with evacuated tube collectors.

array of the collectors was 3 in series and 30 in parallel with an individual area of 2.89 m<sup>2</sup>.

The temperature behavior at the inlet and outlet of the tank 2 is illustrated in Figure 4.

The large variation of the output temperature is observed because the solar collectors hardly reach a temperature of 120°C. With this variation, it is necessary to activate the auxiliary heating in tank 2 frequently, which represents an annual energy consumption of 18.9 MWh.

To achieve an HTF temperature above 120°C, parabolic trough collectors (PTC) were also analyzed. The PTC are

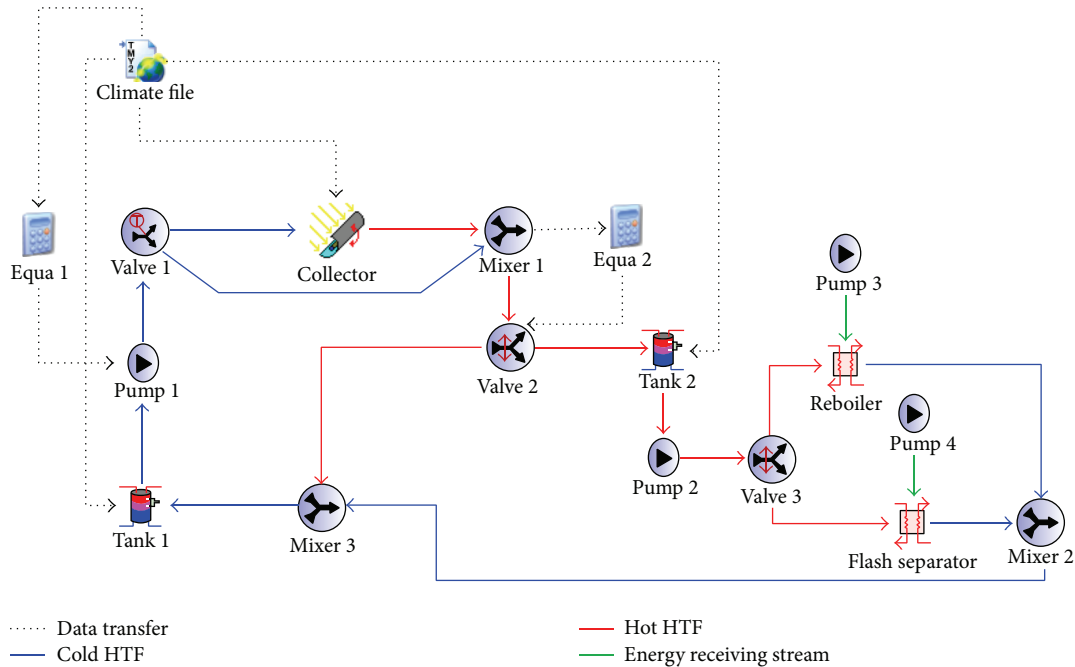


FIGURE 5: TRNSYS simulation diagram for parabolic trough collectors.

more expensive in small scale applications than the ETC, but the PTC efficiency is higher than the ETC [31]. The PTC have been used in power generation due to high temperatures that can be reached [32, 33]. According to the literature, the costs of medium temperature solar collectors range between  $\$195/\text{m}^2$  and  $\$390/\text{m}^2$  [34]. The research and development of this kind of technology will allow a reduction of the cost of the construction of medium temperature solar collectors. Recent investigations have reported experimental PTC prototypes with a manufacturing cost of  $\$170/\text{m}^2$  [35] and even  $\$58.5/\text{m}^2$  [36].

New designs are being studied which reduce the cost of PTC [37].

The arrangement of PTC was comprised by 3 collectors in series and 3 in parallel with an individual area of  $13.2 \text{ m}^2$ . The collectors were enabled with a single axis tracking and fixed azimuth orientation to the south. PTC reach temperatures above  $120^\circ\text{C}$  allowing controlling the outlet temperature of tank 2.

The heating process diagram for PTC developed in TRNSYS is displayed in Figure 5. The following conditions in the simulation to maintain a constant flow of HTF at  $120^\circ\text{C}$  were taken:

- (i) The pump 1 controls the outlet flow of the tank 1. The Equa 1 module receives information about the level of solar irradiation from the climate file and then, it sends a control signal to drive the pump 1. This pump will only be activated when the solar irradiation is above  $270 \text{ W}/\text{m}^2$ . The solar irradiation value was determined in a preliminary analysis.
- (ii) The valve 1 regulates the flow to the solar collectors and the mixer 1, by measuring the temperature at the

outlet of the collectors. When the temperature in the outlet flow of the collectors is greater than  $120^\circ\text{C}$ , the valve 1 divides the HTF flow, to keep the temperature at  $120^\circ\text{C}$  in the outlet flow of the mixer 1.

- (iii) The valve 2 sends the HTF to tank 2 and is controlled by the Equa 2 module. The module Equa 2 measures the temperature at the outlet of the mixer 1. If the temperature equals or exceeds  $120^\circ\text{C}$ , Equa 2 sends the signal to drive the valve 2 and the HTF is sent to the tank 2. Otherwise, all the HTF is directed to the mixer 3. As a result, less variation of temperature occurs in the outlet of tank 2.

The monthly energy required in the process, the energy consumed by the auxiliary heating in tank 2, and the monthly energy savings using PTC are observed in Figure 6.

The utilization of PTC permits a minimal use of auxiliary energy in tank 2, particularly in summer. It represents an annual electrical saving of 70 MWh and a natural gas reduction of  $14,232 \text{ m}^3$ , based on a combined cycle power generation plant in Mexicali with an efficiency of 50%. Environmentally, 27.3 t of  $\text{CO}_2$  emissions could be reduced per year approximately.

#### 4. Conclusions

The biodiesel process presented in this work required a constant supply of thermal energy at temperatures between  $60^\circ\text{C}$  and  $120^\circ\text{C}$ . The medium temperatures solar collectors are one of the best technological options for this application. Even though the solar energy could be applied to the transesterification reactor, the aim of this investigation was to supply energy to the process stage that demands the greater thermal



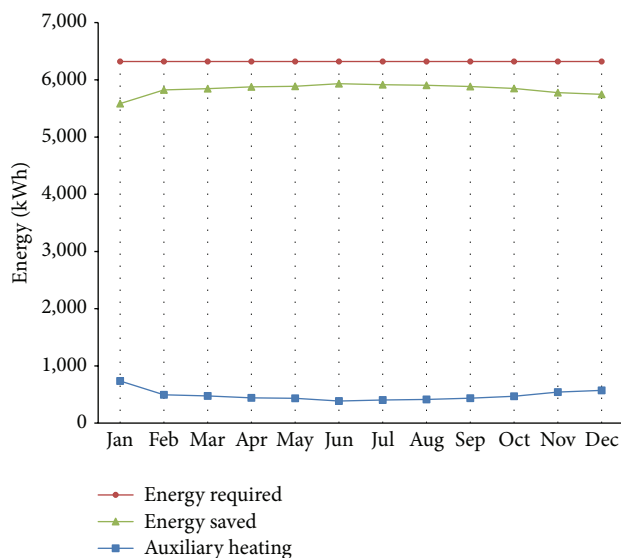


FIGURE 6: Comparison of energy required.

load. Further investigations will be conducted to provide energy to the overall process. The parabolic trough collectors array turned out to be the best option over the evacuated tube collectors to supply the power required for the solvent recovery stage in a biodiesel production process. It is because the PTC efficiency is higher than the ETC. For a constant thermal energy supply, only the PTC can easily increase the HTF temperature above 120°C. The PTC could be more expensive in a small-scale power generation installed capacity. For industrial applications, PTC have smaller dimensions, due to the lowest temperatures required, which imply lower manufacture, installation, and maintenance cost. The final array for supplying the heat required in the methanol recovery stage is comprised of 9 parabolic trough collectors, 3 in series and 3 in parallel with a total collection area of 118.8 m<sup>2</sup>. The collectors were enabled with a single axis tracking and fixed azimuth orientation to the south. This system provides 91% of the energy demanded by the methanol recovery stage in the biodiesel production process. According to the high solar irradiation in the area, Mexicali has great potential for the application of solar energy in industrial processes. The use of solar energy through the thermal energy storage systems allows power savings and reducing greenhouse gasses emissions by avoiding the burning of fossil fuels.

## Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

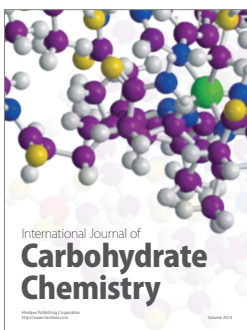
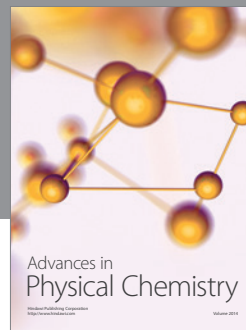
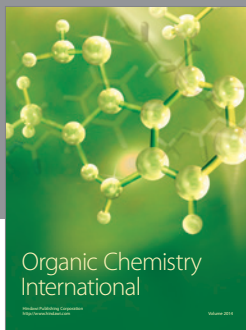
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