energies

Article

Energy, Exergy, Environmental and Economic Analysis (4e) of a Solar Thermal System for Process Heating in Jamshoro, Pakistan

Junaid Ahmed [1], Laveet Kumar [2,*], Abdul Fatah Abbasi [2] and Mamdouh El Haj Assad [3,*]

[1] Directorate of Postgraduate Studies, Mehran University of Engineering and Technology, Jamshoro 76062, Pakistan
[2] Department of Mechanical Engineering, Mehran University of Engineering and Technology, Jamshoro 76062, Pakistan
[3] Department of Sustainable and Renewable Energy Engineering, University of Sharjah, Sharjah P.O. Box 27272, United Arab Emirates
* Correspondence: laveet.kumar@faculty.muet.edu.pk (L.K.); massad@sharjah.ac.ae (M.E.H.A.)

Abstract: With an expected annual increase of 1.2%, the industrial sector already consumes over 54% of all the energy generated globally. The majority of industrial sectors presently relies on fossil fuels to fulfil their needs for heat energy, but renewable sources, especially solar energy, can be substituted for them. For an underdeveloped country such as Pakistan, its industrial sector is important for the country's economic development and long-term growth. The use of solar thermal energy potentially offers a significant and cheap alternative to fossil fuels. The current study focuses on a process heating system based on flat-plate solar collectors, developed to provide low to moderate temperature process heat. The innovative model's thermal efficiency and economic feasibility have undergone a thorough investigation and analysis through TRNSYS simulations. The system portrayed a 79% thermal energy efficiency and 4.31% exergy efficiency during peak hours. The optimized system for three different temperatures of 60 °C, 70 °C, and 80 °C was designed and evaluated. The system presented a total of 82 tons of CO_2 prevention annually. The economic analysis consisting of three parameters, NPV, IRR and PBP, also deemed the FPC-based solar thermal system economically profitable.

Keywords: flat-plate collector; solar thermal system; TRNSYS; process heat; GHG reduction

check for updates

Citation: Ahmed, J.; Kumar, L.; Abbasi, A.F.; El Haj Assad, M. Energy, Exergy, Environmental and Economic Analysis (4e) of a Solar Thermal System for Process Heating in Jamshoro, Pakistan. *Energies* **2022**, *15*, 8617. https://doi.org/10.3390/en15228617

Academic Editor: Antonio Rosato

Received: 22 October 2022
Accepted: 14 November 2022
Published: 17 November 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Around the world, energy demand is increasing every day because of modernization and the development of nature-excavating processes to facilitate human comfort [1]. According to research, worldwide energy consumption is to increase by a significant proportion. Estimations show an increase of 33% for a two-decade forecasting, shown in Figure 1 (i.e., 2010 to 2030) [2]. One of the most immediate issues is the surge in greenhouse gas emissions generated by the consumption of fossil fuels for energy conversion [3]. Many industrially developed countries have pledged to lower their combined greenhouse gas emission levels in comparison to 1990 under the Kyoto Protocol [4,5]. Since a significant portion of energy is utilized in industrial operations, energy is extremely important for the growth of the industrial sector. Over 50% of the world's total energy consumption is caused by industrial processes [6,7]. A review conducted by researchers studying energy use patterns showed that, even though fossil fuel-based industrial processes were deteriorating the environment, due to energy being so closely corelated with their economy, they were showing no any sign of shifting or slowing down their consumption of energy [6]. From 1990 to 2015, global energy-related CO_2 emissions totaled 32.294 gigatons, representing a 57.5% increase. The industrial sector is responsible for roughly 47% of total emissions [8]. A major example of its harm is the catastrophes that struck European countries in 2003, causing USD 10 billion losses in the agriculture industry [9]. According to statistics, the average energy consumption in Pakistan's industrial sector is roughly 35%, and most industries in Pakistan mostly employ natural gas or grid-supplied energy to meet their production goals [10].

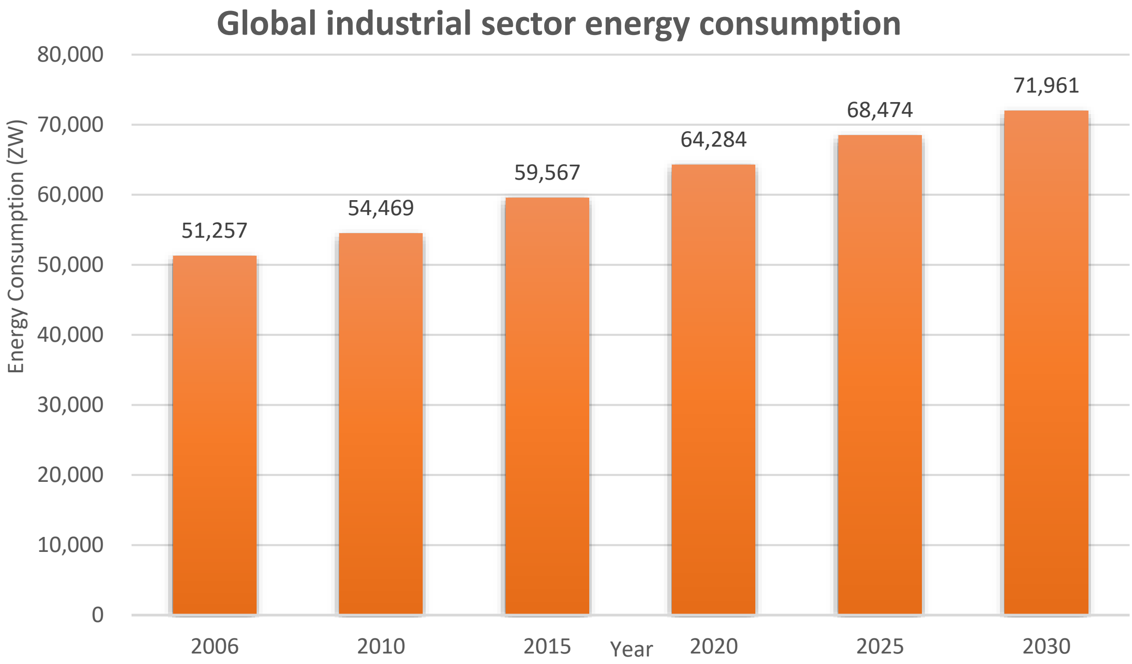

Figure 1. The trend in industrial energy usage until 2030 [6].

Process heating is a very common phenomenon in industrial sectors. Process heating for industries usually utilizes natural gas and electric power to get hot water, which is then incorporated into the system for process heating [11]. This process is so common that it can be found in almost every industry. Due to such characteristics, an environmentally friendly alternative solution to such a process is of critical importance. Solar energy is a green energy resource that offers an appealing range of choices and options for meeting industrial and commercial thermal demand in a manner that is ecologically friendly [12]. Despite this, fossil fuels continue to play a significant role in satisfying the energy demands of many processes. Solar thermal collectors are better for generating process heat since they transform the energy of the sun received on the surface directly into heat, raising the temperature of working fluid with an efficiency of about 3–4 times that of a photovoltaic (PV)-powered electric heater [13]. Several studies conducted around the globe for different industries portray that, for most industries, the operating temperatures for process heating lie below 100 °C [14–26]. This article provides an in-depth examination of many solar thermal-based energy systems and their industrial applications. Additionally, it should be emphasized that natural gas and fossil fuel-based power encompass almost 80% of global energy consumption for industrial processes [27].

Pakistan lags behind in solar thermal research, but there have been major studies conducted in neighboring countries. Researchers [28] examined the uptake of solar thermal technology in China and identified the top 10 prospective industries. They projected that China could cut its CO_2 emissions by at least 39.40 MT of coal in 2020. Researchers [29] looked into the potential for the solar heating of processes in the Indian cement industry. The analysis determined that India's cement plants have a heating potential of 664 PJ. Research [20] evaluated the environmental benefits of using solar energy as a primary fuel for the paper industry of India. A total potential of 25.2 PJ/year of process heating is thought to be available in the Indian paper industry, with a 0.34×10^6-ton reduction in CO_2 emissions annually.

There have been numerous studies carried out for the feasibility of FPC in solar thermal systems and process heating applications. One work [30] carried out a cost analysis for the implementation of solar FPC systems and the SIR ratio was discovered to be most sensitive to shifts in the cost of NG, costs of collector areas, discount rates, and auxiliary heater costs. Research [31] estimated the area of solar collectors required to heat a common house in the northern areas of Pakistan. A flat solar thermal collector with an area of about 12 m^2 is sufficient to maintain a temperature of a typical urban house at or above 26 °C. One work [32] used a combination of solar collectors and PV panels to design a complete system for solar-assisted process heating in a Malaysia-based industry. The resulting systems were able to generate 1420 W of power with a 75% thermal efficiency and 2.72% exergy efficiency. Another work [33] used HTM algorithms to carry out rooftop simulation for the evaluation of flat-plate solar collectors to achieve sustainable energy. A community in southern Spain with 7000 residents was studied. The results indicate that integrating FPC-based thermal systems could reduce CO_2 emissions by 1400 kg per resident. An analysis of flat-plate collector exergy was proposed [34], where the computed maximum useable energy rate was 101.6 W, the ideal fluid inlet temperature was 69 °C, and 5.96% exergy efficiency was reported. On study [35] used orthogonal arrays to create the flat-plate collector's processing settings. The effectiveness with this optimization procedure could successfully accomplish the waste mitigation goal of the research, with a heat dissipation factor of 0.79 and efficiency coefficient of 3.470 W/m^2 °C under ideal circumstances, according to three validation tests conducted through experimentation. These studies showed that the FPC-based system had a great potential to provide thermal heating for processes requiring temperatures up to 100 °C.

Other types of collectors are also widely accepted and used throughout industry to meet temperature requirements above 100 °C. Research [36] investigated the effects of solar irradiation on steam generation. The results show that about 17% to 23% of total yearly steam generation could be possible without the use any thermal storage. One work [37] carried out TRNSYS-based simulation and a parametric analysis of an evacuated-type solar thermal collector water distillation system. The system sustained a required temperature of 110 °C. Another work [38] focused on the developmental study that is being done on solar PTC's efficacy and efficiency to enlarge the application portfolio. Research [39] investigated this, where five different collector types were used, ranging from simple fixed flat-plate collectors to mobile parabolic trough types. According to the data, these systems can produce energy gains of between 550 and 1100 kWh/m^2 per year. Depending on the type of collector used, the costs for the solar thermal range were between 0.015–0.028 CGBP/kWh. One work [40] used TRNSYS software and the simulation of a parabolic trough collector plant spread on a small scale to provide warm air for an industrial factory. According to calculations, the solar facility could prevent up to 57% of CO_2 emissions per year. The applicability of a PTC system in Cyprus on the largest soft drink factory was investigated [41]. The work concluded that the system could efficiently produce 980 L of steam per day and could store 107.3 KWh_{th} energy. These works portray the potential and practicality of solar thermal collectors other than FPCs. Due to the process heating requirements for selected industries being below 100 °C, this research only focuses on the FPC-based system.

There have been numerous studies conducted throughout the globe, as indicated by the reviewed literature, but there have been no such studies carried out for thermal assessment, modelling and simulation of a solar collector-based industrial process heating system for the industrial sector of Jamshoro, Pakistan. The objective of the present study is to demonstrate the energy, exergy, environmental and economic analysis (4E) of FPC technology for heating purposes in Jamshoro, Pakistan. The findings are built on an energy analysis, exergy analysis, and economics to determine how efficiently the model is designed in TRNSYS.

2. Methodology

The objective of this investigation is to evaluate the viability of industrial process heating based on solar collectors in Pakistan. The research is simulation-based, so the objectives are achieved by software simulations using TRNSYS.

2.1. Site Selection and Weather Data

A Jamshoro-based industry was selected as the study area because there have been no such studies carried out for thermal assessment, modelling and simulation of a solar collector-based industrial process heating system. The satellite view of Jamshoro city is shown in Figure 2. The hot water requirements of the selected industry for three different processes and other input parameters for thermal assessment are given in Table 1.

Figure 2. Satellite view of Jamshoro [42].

Table 1. Input parameters.

Parameters	Process A	Process B	Process C
Working fluid	Water	Water	Water
Operating temperature	60 °C	70 °C	80 °C
Fluid inlet temperature	25 °C	25 °C	25 °C
Flow rates of hot water (kg/h)	1000	1000	1000
Duration	8 a.m.–6 p.m.	8 a.m.–6 p.m.	8 a.m.–6 p.m.

2.2. Modelling and Simulation in TRNSYS

A model of a flat-plate collector-based industrial process plant is developed in TRNSYS software to achieve the results through simulations shown in Figure 3. TRNSYS is a simulation tool for passive and active solar design that is largely utilized in the discipline of renewable energy. The model consists of three major pieces of equipment, namely, a water pump, flat-plate solar collector and an auxiliary heater.

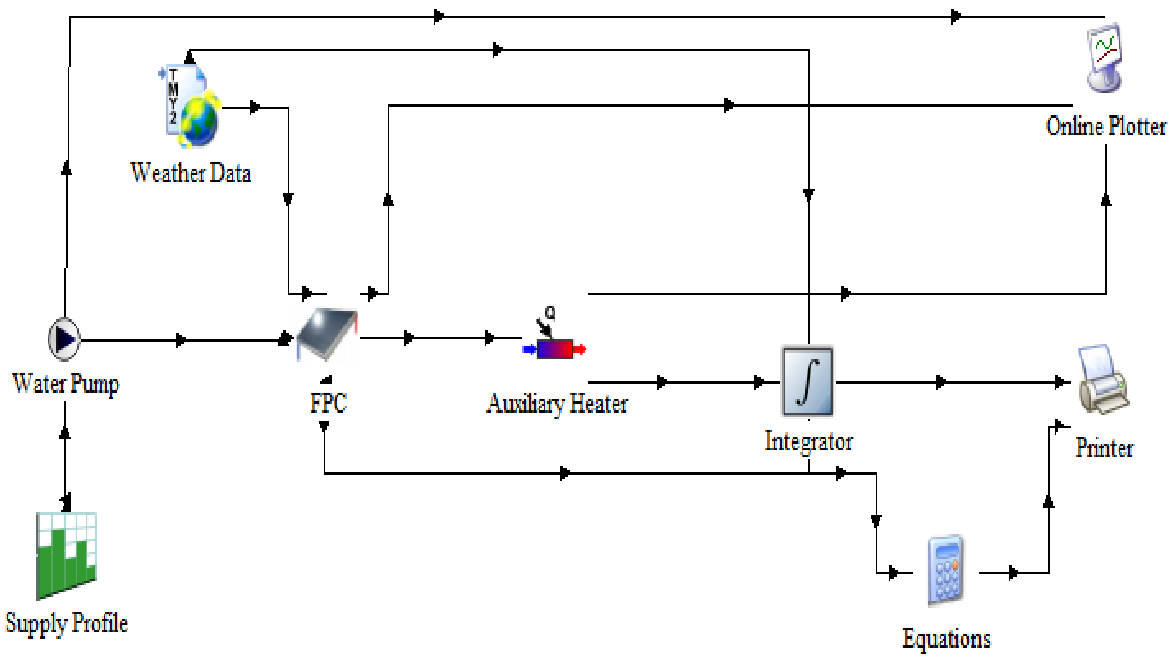

Figure 3. TRNSYS model of FPC-based SIPH plant.

Following assumptions are made about the system:

i. It is assumed that the system is in equilibrium, meaning that the temperature of the pipe and the water are always same.
ii. The annual average ambient temperature of surrounding and inlet cold water are the same (25 °C).
iii. Since there is no pressure relief valve in operation, the mass flow rate is constant throughout the system, and losses are not considered.
iv. The working fluid does not boil or change state.
v. Losses of energy due to piping or valves are neglected.
vi. The materials used maintain their original thermal characteristics and thermal capacity regardless of temperature.
vii. There is no transfer of heat among the components used and the environment.

2.3. Mathematical Framework

2.3.1. Energy Analysis

Energy analysis is the most frequent method for evaluating energy conversion systems [43]. The fundamental law of thermodynamics, which describes how energy is transformed, serves as its foundation. This study generates an energy balance while accounting for the assessment of losses for each energy conversion system and use of the energy source [44]. The first law of thermodynamics serves as the foundation for energy analysis, which consists of calculating the energy balance and assessing energy efficiency [32,45]. The energy balance is expressed as:

$$\sum \dot{Q}_{in} = \sum \dot{Q}_{out} + \sum \dot{Q}_{loss} \quad (1)$$

$$\dot{Q}_{sun} + \dot{Q}_{mass,in} = \dot{Q}_{mass,out} + \dot{Q}_{loss} \quad (2)$$

where $\dot{Q}_{in}$, $\dot{Q}_{out}$ and $\dot{Q}_{out}$ are the energy input, energy output and energy loss, respectively. $\dot{Q}_{sun}$ represents how much energy of solar radiation reaches the solar thermal collector's surface and can be evaluated by the following expression:

$$\dot{Q}_{sun} = \tau\alpha A_{FPC} I_{rad} \quad (3)$$

where τ = Transmittance coefficient, α = Absorptance coefficient, A_{FPC} = Area of flat-plate collector and I_{rad} = Incidence radiations on the solar collector surface.

Thermal Energy Efficiency

Thermal energy efficiency determines the efficiency of the solar collector to collect the solar radiation and transfer it to the working fluid to raise its temperature [46]. The thermal energy efficiency of the system can be expressed as:

$$\eta_{Thermal} = \frac{\dot{Q}_{gain}}{\dot{Q}_{sun}} \quad (4)$$

where $\dot{Q}_{gain}$ is the quantity of heat gained by the working fluid, expressed as:

$$\dot{Q}_{gain} = \dot{m}C_p(T_{water,out} - T_{water,in}) \quad (5)$$

where $T_{water,in}$ = Temperature of the cold working fluid entering the solar thermal collector, and $T_{water,out}$ = Temperature of the hot working fluid leaving the solar thermal collector.

Hence, the final equation for the thermal energy efficiency becomes:

$$\eta_{Thermal} = \frac{\dot{m}C_p(T_{water,out} - T_{water,in})}{\tau\alpha A_{FPC} I_{rad}} \quad (6)$$

2.3.2. Solar Fraction

The solar fraction is the fraction of total required energy provided by the solar collector. It is evaluated by dividing the solar heat gain with the total required energy for process heating, which is expressed as:

$$SF = \frac{\dot{Q}_{gain}}{\dot{Q}_{gain} + \dot{Q}_{aux}} \quad (7)$$

where $\dot{Q}_{aux}$ is the quantity of heat supplied by the auxiliary heater.

2.3.3. Exergy Analysis

The portion of functional energy that may be expended or transformed into useful work is known as exergy [47]. The second law of thermodynamics [48] is the foundation of the basic theory of exergy analysis. The exergy balance is written as:

$$\sum \dot{Q}_{X_{in}} = \sum \dot{Q}_{X_{out}} + \sum \dot{Q}_{X_{Dest}} \quad (8)$$

$$\dot{Q}_{X_{sun}} + \dot{Q}_{X_{mass,in}} = \dot{Q}_{X_{mass,out}} + \dot{Q}_{X_{Dest}} \quad (9)$$

where $\dot{Q}_{X_{in}}$, $\dot{Q}_{X_{out}}$ and $\dot{Q}_{X_{Dest}}$ are the exergy input, exergy output and exergy destruction, respectively. $\dot{Q}_{X_{sun}}$ represents how much exergy of solar radiation reaches the solar thermal collector's surface and can be evaluated by the following equation:

$$\dot{Q}_{X_{sun}} = A_{FPC} I_{rad}\left(1 - \frac{T_{amb}}{T_{sun}}\right) \quad (10)$$

where T_{sun} and T_{amb} are, respectively, the sun's equivalent temperature and the ambient temperature. The value of T_{sun} is 5777 K.

Thermal Exergy Efficiency

The thermal exergy efficiency of the system can be evaluated through the following expression:

$$\varepsilon_{Thermal} = \frac{\dot{Q}_{X_{Thermal}}}{\dot{Q}_{X_{sun}}} \tag{11}$$

$$\dot{Q}_{X_{Thermal}} = \dot{m}C_p\left[\left(T_{water,out} - T_{water,in}\right) - T_{amb}\ \ln\left(\frac{T_{water,out}}{T_{water,in}}\right)\right] \tag{12}$$

$$\dot{Q}_{X_{sun}} = A_{FPC}I_{rad}\left(1 - \frac{T_{amb}}{T_{sun}}\right) \tag{13}$$

Hence, the final equation for the thermal energy efficiency becomes:

$$\varepsilon_{Thermal} = \frac{\dot{m}C_p\left[\left(T_{water,out} - T_{water,in}\right) - T_{amb}\ \ln\left(\frac{T_{water,out}}{T_{water,in}}\right)\right]}{A_{FPC}I_{rad}\left(1 - \frac{T_{amb}}{T_{sun}}\right)} \tag{14}$$

2.4. Economic Analysis

Economic analysis evaluates the advantages and costs of running a project. It is employed to evaluate the suitability and efficiency of resource consumption. This study focuses on the discounted cash flow technique, which adopts net present value (NPV), internal rate of return and payback period (PBP) to evaluate the feasibility of a project. The primary assumptions and variables considered in the economic analysis are shown in Table 2.

Table 2. Parameters selected for economic analysis [49–52].

Parameters	System (FPC)
Capital cost (PKR per m^2)	140,000
Total maintenance and operation cost (PKR per m^2)	8000
Natural gas price (PKR/kg)	225
Discount rate	10%
Interest rate	12%
Plant life (years)	20

2.4.1. Net Present Value (NPV)

NPV measures the return on investment of a project while taking the time value of money into consideration [53]. The projected worth of a financial investment in a project is taken into consideration by NPV. In this procedure, the necessary starting project cost is first subtracted from the overall cash flows after they have been transformed into the equivalent earnings at the project's outset using the proper discount rate [54]. Comparatively, this amount is regarded as an NPV indication, as indicated by Equation (15). A project is deemed acceptable, cost-effective, and productive if its NPV is positive. Conversely, a negative NPV is considered inappropriate and unprofitable.

$$\mathrm{NPV} = -\mathrm{C_o} + \sum_{\mathrm{i=1}}^{\mathrm{i=n}} \frac{\mathrm{C_i}}{(1+\mathrm{r})^{\mathrm{i}}} \tag{15}$$

where $\mathrm{C_o}$ is total cost of initial investment, $\mathrm{C_i}$ is the projected cash flow for i th year, r denotes discount rate, and the plant age number is denoted by i year.

2.4.2. Internal Rate of Return (IRR)

IRR is a benchmark that shows the future returns from a project and the viability of a project [55]. It is obtained by setting the NPV of a project equal to 0, as shown in Equation (16). According to this method of evaluation, if the project's rate of return exceeds the investment's interest rate, the project is deemed financially feasible; if it is less, the project is deemed unprofitable.

$$0 = -C_o + \sum_{i=1}^{i=n} \frac{C_i}{(1 + IRR)^i} \quad (16)$$

2.4.3. Payback Period (PBP)

The term "payback period" refers to the amount of years needed to recoup the investment expenses. It is, in other words, the time frame of a project at which it has generated enough net revenue to pay its investment expenses [56]. The payback period for the project can be evaluated by Equation (17) as:

$$n = \frac{C_o}{CF} \quad (17)$$

where n represents the payback period of the project and CF is the annual cash flow of the system.

3. Results and Discussion

Using the meteorological information for Jamshoro City, the annual results for the basic model and the optimized FPC configuration are obtained and discussed in this section. The thermal performance study, along with an environmental and financial analysis, are covered in the subsequent sections.

3.1. Jamshoro Weather Profile

Jamshoro has a hot and dry climate throughout the year. The fluctuations in annual maximum and minimum ambient temperatures attained from TRNSYS simulation are shown in Figure 4. The solar radiation intensity in Jamshoro varies throughout the year, with a maximum value from April to August of about 3600 kJ/h·m^2, which is equal to 1000 W/m^2. In the remaining months of the year, the radiation intensity falls to an average of about 2600 kJ/h·m^2, which is equivalent to 722 W/m^2. Figure 4 also shows the variation in ambient temperature throughout the year in Jamshoro.

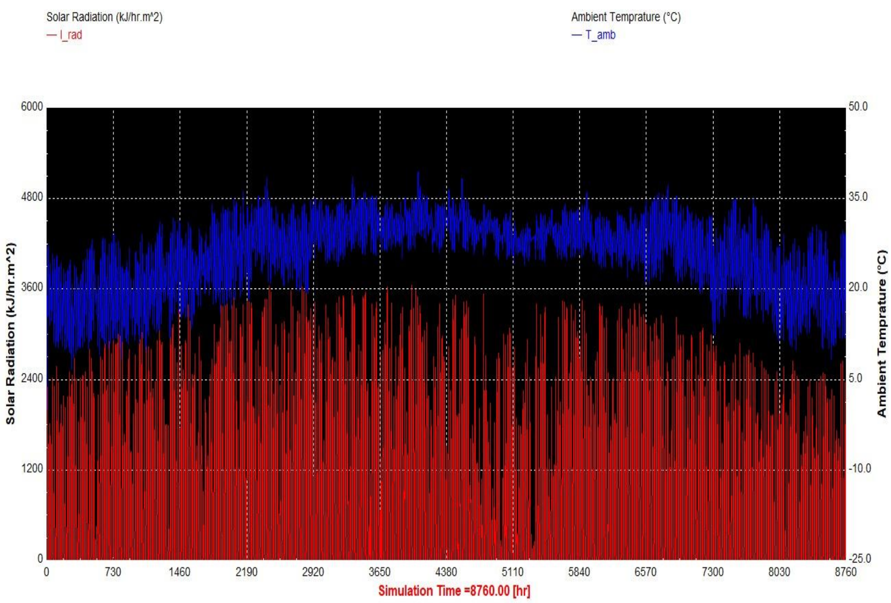

Figure 4. Jamshoro weather profile.

3.2. Optimal Collector Angle

The slope of the flat-plate solar collector must be optimized to achieve the maximum collector efficiency possible for the location of Jamshoro. To optimize the collector angle, simulations were performed in 10° intervals at 0° azimuth and plotted in Figure 5. To obtain the maximum benefit of this system, the slope with the maximum collector efficiency and solar fraction is to be chosen. The results in Figure 5 show that the flat-plate solar collector attained a maximum collector efficiency of 70% and solar fraction of 54% at the angle of 30°.

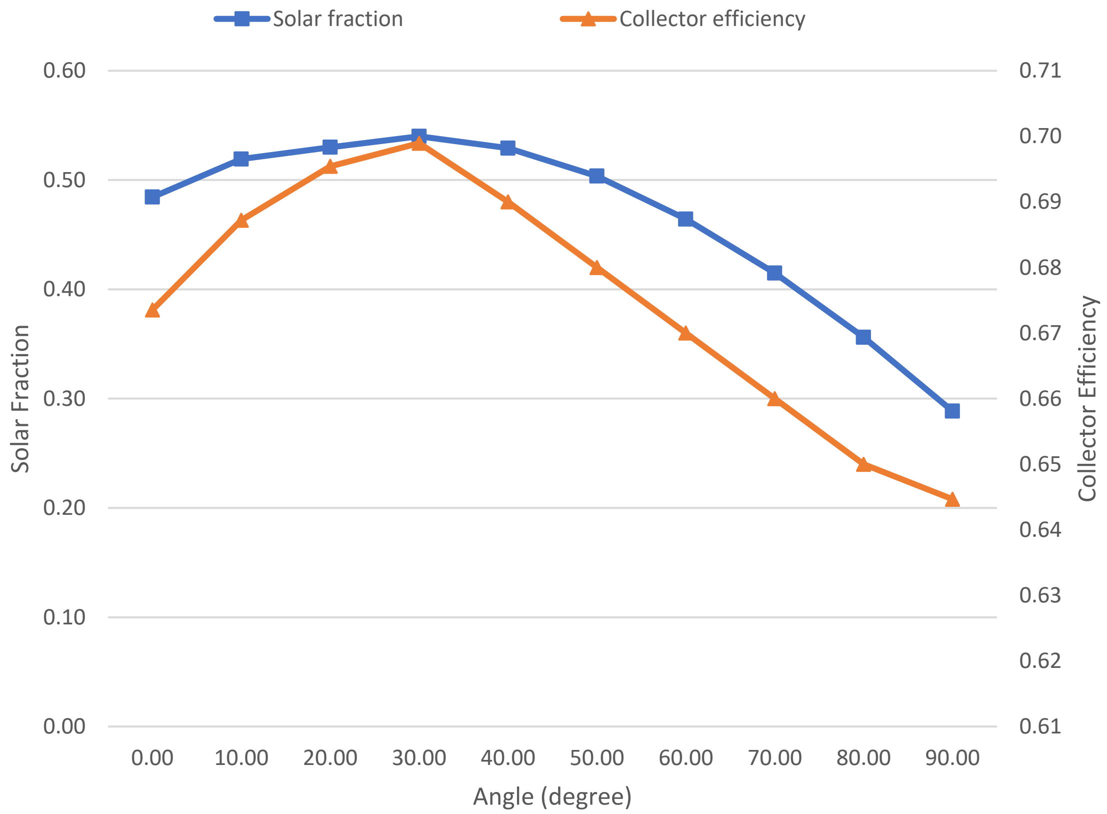

Figure 5. Effect of slope on collector efficiency and solar fraction.

3.3. Energy Analysis

The first law of thermodynamics was applied to analyze the energetic performance of the flat-plate collector system based on the data obtained from TRNSYS simulations. In Jamshoro, radiation levels range from 100 W/m^2 to 1000 W/m^2 throughout the day. At a radiation intensity of 100 W/m^2, the thermal efficiency of the system was negligibly small at 5%. The radiation intensity was then increased by 100 W/m^2 increments. It can be seen in Figure 6 that, as the radiation intensity is further increased, the thermal efficiency curve starts to become steeper and reaches a thermal efficiency of 79.49% as the radiation becomes 1000 W/m^2. It is apparent that the designed system showed a direct relationship between thermal efficiency and increasing radiation levels, which correlates with the literature [57]. The results indicate that the system's efficiency increases gradually from 8 a.m. and then reaches peak efficiency at noon, when the radiation levels are close to 1000 W/m^2. During these peak hours, the fraction of solar energy is significantly higher than the auxiliary heater energy. Further in-depth analysis of Figure 6 also shows the system to be quite responsive. Even at a radiation level of 300 W/m^2, which is significantly lower than the mean radiation in Jamshoro, the thermal energy efficiency of the system remained above 60%. Hence, these results conclude the system to be technically feasible.

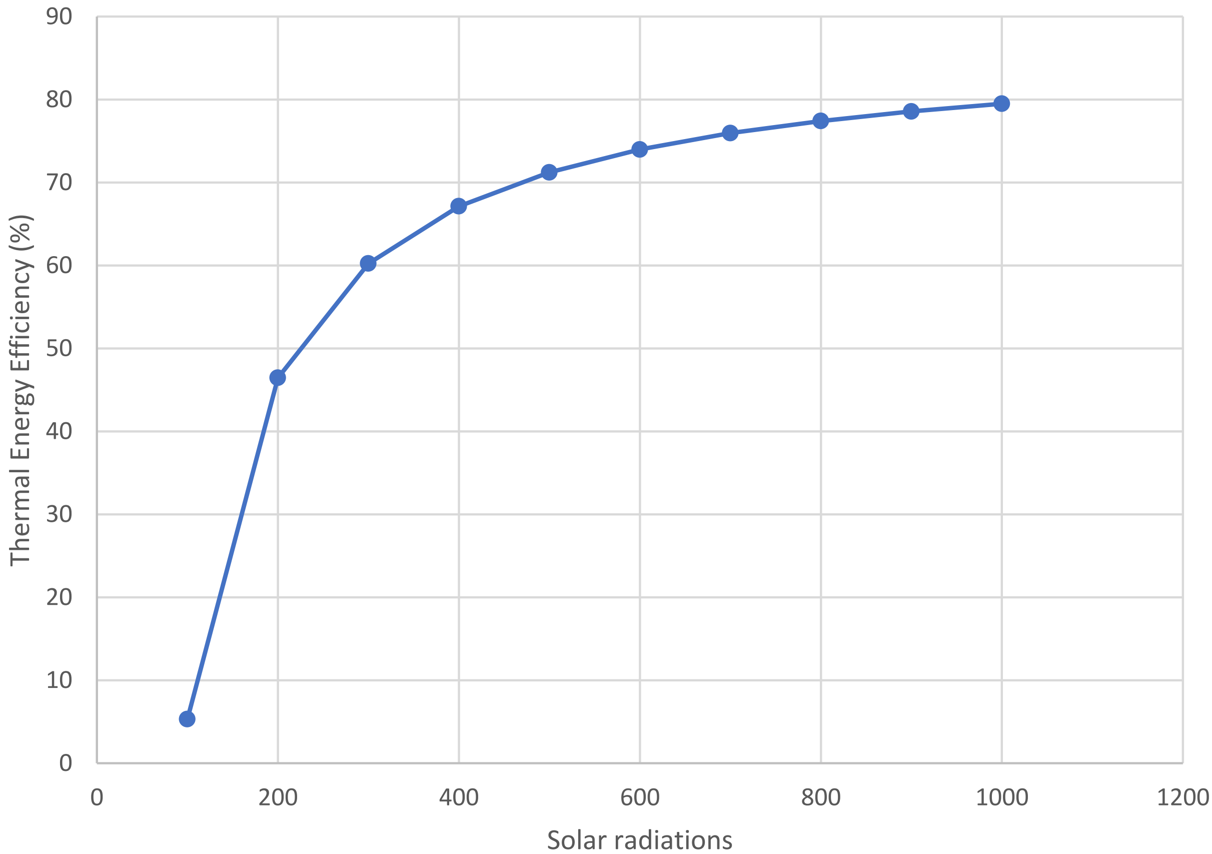

Figure 6. Energy efficiency response of FPC.

3.4. Exergy Analysis

To counterbalance the induced entropy, a certain quantity of energy must be expended, which cannot be obtained for useful purposes. Such behavior of energy systems necessitates the exergy analysis of these systems, in which exergy efficiency is the primary metric used to grade the genuine performance of the considered system. Exergy efficiency is a more crucial metric than energetic efficiency since it provides a more detailed insight into the performance of thermal systems [58,59]. The assessment of the thermal exergy efficiency shown in Figure 3 involved simulating the exergy performance of the STC system at prescribed radiation levels. At a radiation intensity of 100 W/m^2, the system showed a 0% thermal exergy efficiency. The radiation intensity was then increased by 100 W/m^2 increments. The highest exergy efficiency of the system reached 4.31% at an irradiation of 1000 W/m^2. The results are also plotted in Figure 7 to visualize the direct relation between the thermal exergy efficiency of the system and radiation levels, which corresponds to the literature [60]. Even at the highest irradiation level, the energetic performance of the system is quite poor because heat is a low-grade form of energy that cannot be efficiently transformed into useful energy forms [61]. In addition, heat transfer is governed by the temperature difference among two systems [62]. Solar heating systems acquire heat from the temperature gradient between the sun and working fluid, where the temperature contrast is massive. The current study uses the thousands of degrees Celsius of the sun temperature to elevate the water outflow temperature to roughly 80 °C [63]. This significant temperature difference among the two bodies degrades the ability of the thermal process to transform heat into a useable form of energy, and, consequently, the majority of it is dispersed as non-recoverable wasted energy, leading to lower exergy efficiency.

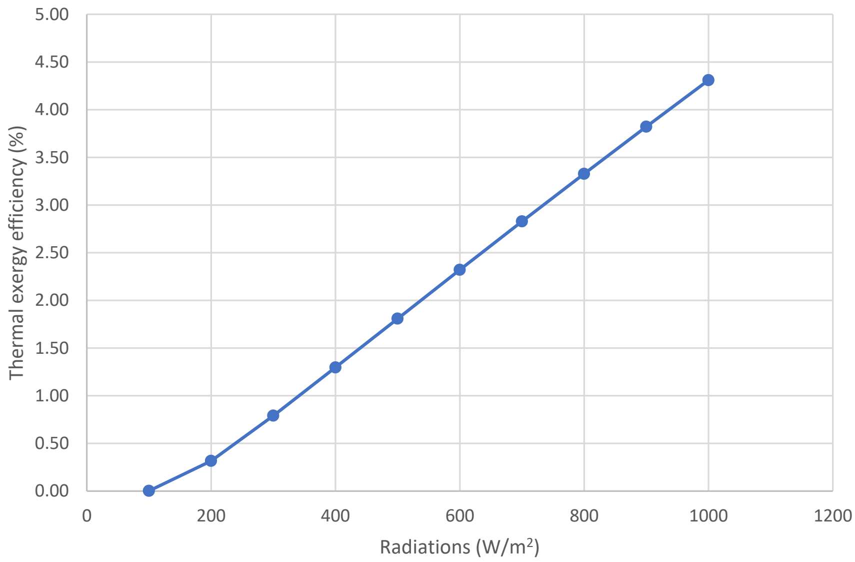

Figure 7. Exergy efficiency response of FPC.

3.5. Optimization of FPC Configuration

The surface area of the collector has a direct impact on how much solar energy a solar thermal system can acquire. Therefore, the area of the solar collector must be optimized according to the process heat requirements. As for this research, the process heating requirements are listed in Table 1. There are three processes, namely, Process A, Process B and Process C, which require process heat at temperatures of 60 °C, 70 °C, and 80 °C, respectively. The simulation results in Figure 8 show that the flat-plate collector efficiency is indirectly proportional to its area. Contrarily, the solar fraction presents a direct relationship with increasing collector area. In addition, as pointed out by [49,64], it is impractical to assume the solar fraction and collector efficiency to be more than 60% due to the limited availability of solar energy. Therefore, area optimization becomes a crucial task in large-scale applications. To achieve this, the data sets of the solar fraction and collector efficiency for processes A, B and C plotted in Figure 8 are utilized. The intersection points of the collector efficiency curve with the solar fraction curves of all three processes yield the area value of the solar collector area. Table 3 contains the summarized results for all three processes.

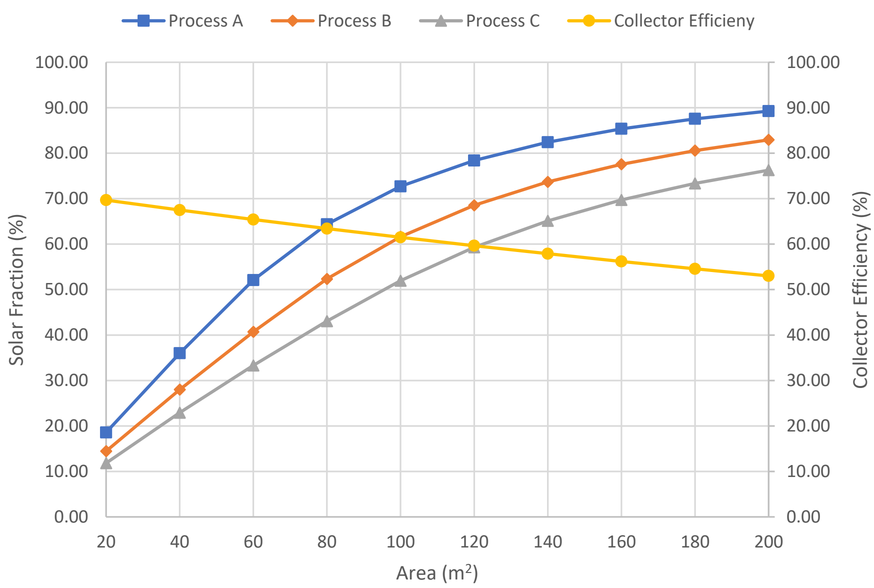

Figure 8. Effect of varying FPC area on collector efficiency and SF.

Table 3. Optimized area of each process.

Process	Area (m^2)	Solar Fraction (%)	Collector Efficiency (%)
Process A	79	63.85	63.51
Process B	100	61.61	61.49
Process C	121	59.62	59.56

3.6. Environmental Analysis

This study involves the analysis of the environmental benefits for the solar thermal system, shown in Figure 3, in terms of the total reduction in CO_2 emissions. The selected industry employs natural gas as the major source of heat for its processes. The average combustion efficiency of natural gas reported by [65] is 83.9%, with an average heating value of 43,900 kJ/kg. The optimized parameters of the STC system are shown in Table 3. These data are used to evaluate the annual CO_2 reduction for all three processes of the given solar thermal system. The results in Figure 9 indicate that deploying this system can prevent around 82 tons of CO_2 emissions yearly.

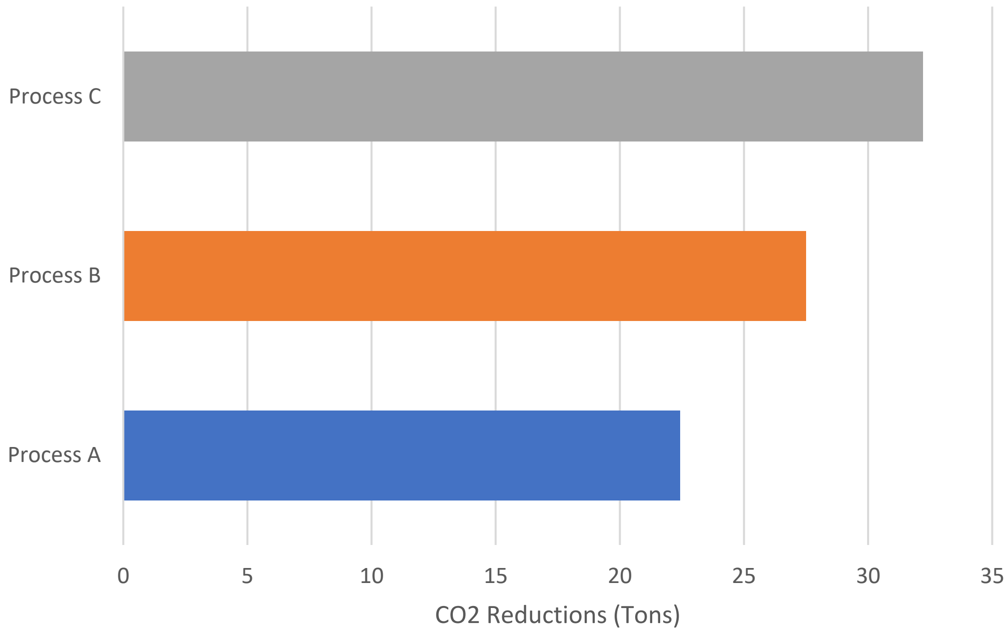

Figure 9. CO_2 reductions per annum.

The designed FPC-based heating configuration shown in Figure 3 can also be used for systems with much higher heating requirements. To validate this statement, the designed system is simulated at 70 and the mass flow rate is gradually increased up to 30,000 kg/h under optimized SF and collector efficiency. Figure 10 contains the response of the system. At a mass flow rate of 1000 kg/h the system showed a reduction in CO_2 emissions of about 28 tons per annum. When the mass flow rate is gradually increased to 30,000 kg/h, the CO_2 emission reductions increased to 830 tons per annum. The extrapolated results conclude the designed configuration to be environmentally feasible and can be opted for other massive installations as well.

3.7. Economic Analysis

Jamshoro weather was used to analyze the economic viability of the solar process heating system. Three distinct processes were examined at temps of 60 °C, 70 °C, and 80 °C. The selected industry utilizes natural gas as the fuel to meet its process heating requirements.

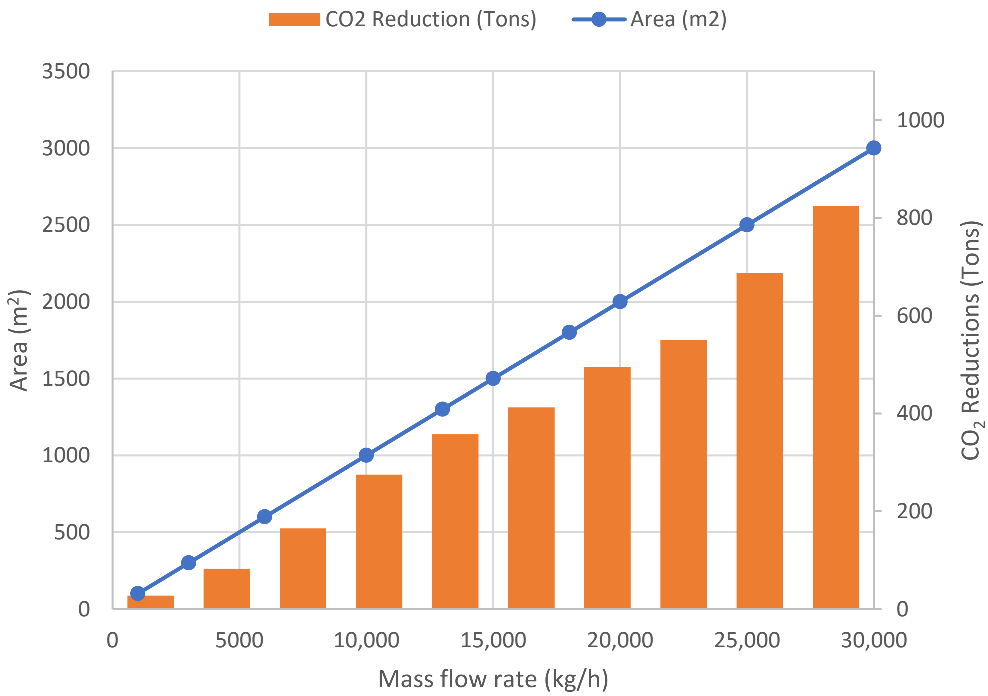

Figure 10. Environmental performance of system at potential higher flow rates.

3.7.1. Net Present Value (NPV)

The net present value of each process is evaluated at a discount rate of 10% and the results are plotted in Figure 11. The net present values or NPVs of Process A, Process B, and Process C are found to be 3,932,172.98 PKR, 4,349,229.14 PKR, and 4,535,139.66 PKR, respectively. The results indicate that the system is profitable since the NPV is positive.

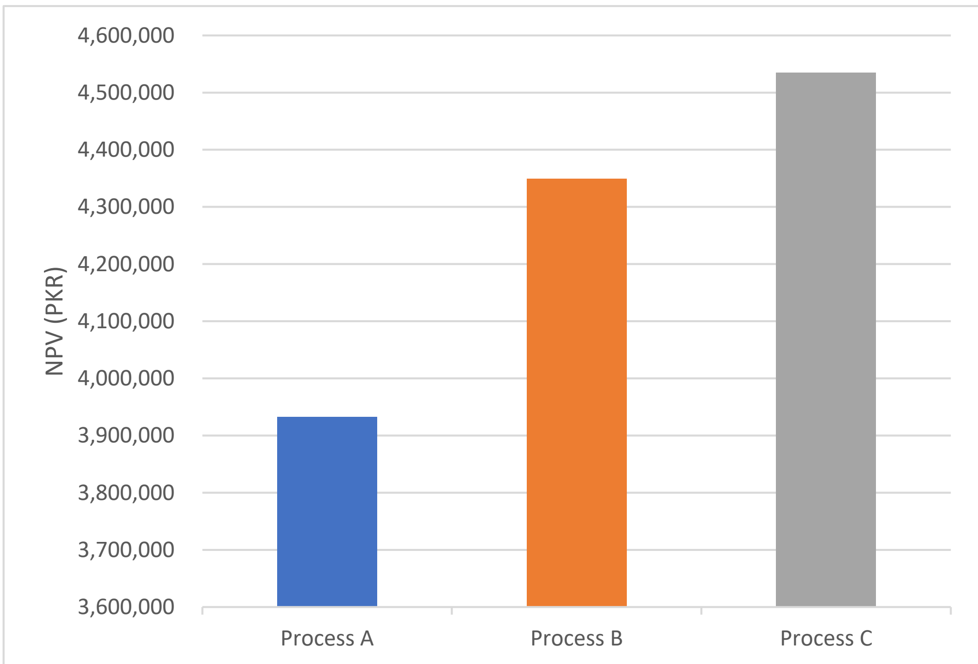

Figure 11. NPV of designed system.

3.7.2. Internal Rate of Return (IRR)

The internal rate of return of the simulated model is evaluated and the results are documented in Figure 12. The IRR of Process A, Process B, and Process C is found to be

14.68%, 14.11%, and 13.56%, respectively. The IRR of each process for the designed system is greater than the interest rate; therefore, the system is economical and profitable.

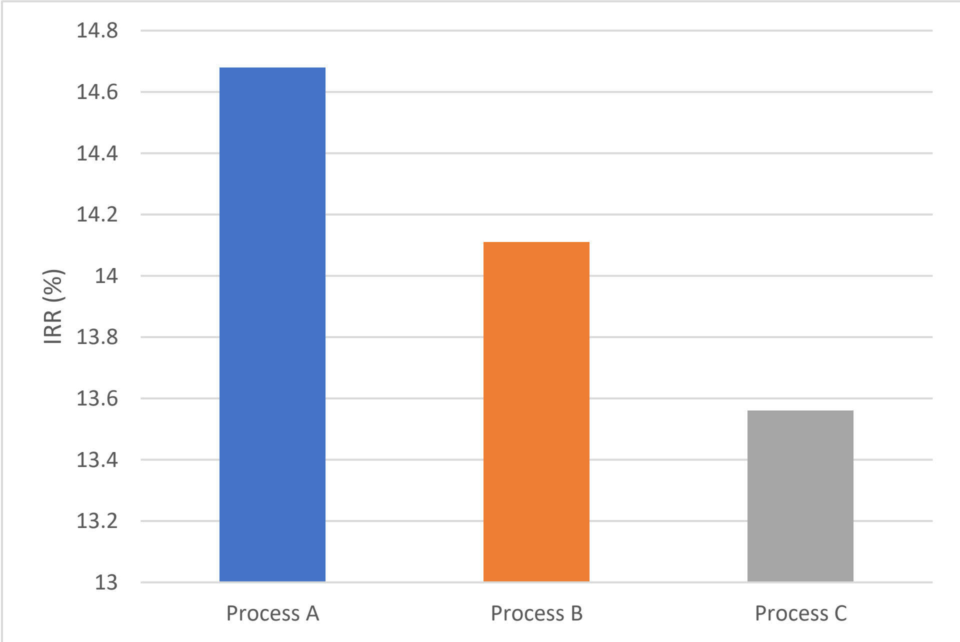

Figure 12. IRR of designed system.

3.7.3. Payback Period (PBP)

The payback period is calculated by considering the cash flows of the project and the results are documented in Figure 13. The payback periods of Process A, Process B, and Process C are calculated to be 6.37 years, 6.58 years, and 6.79 years, respectively. The life of the project is 20 years, and the payback period of the plant is considerably lower, as described above, than the plant life. Therefore, the system is deemed economical.

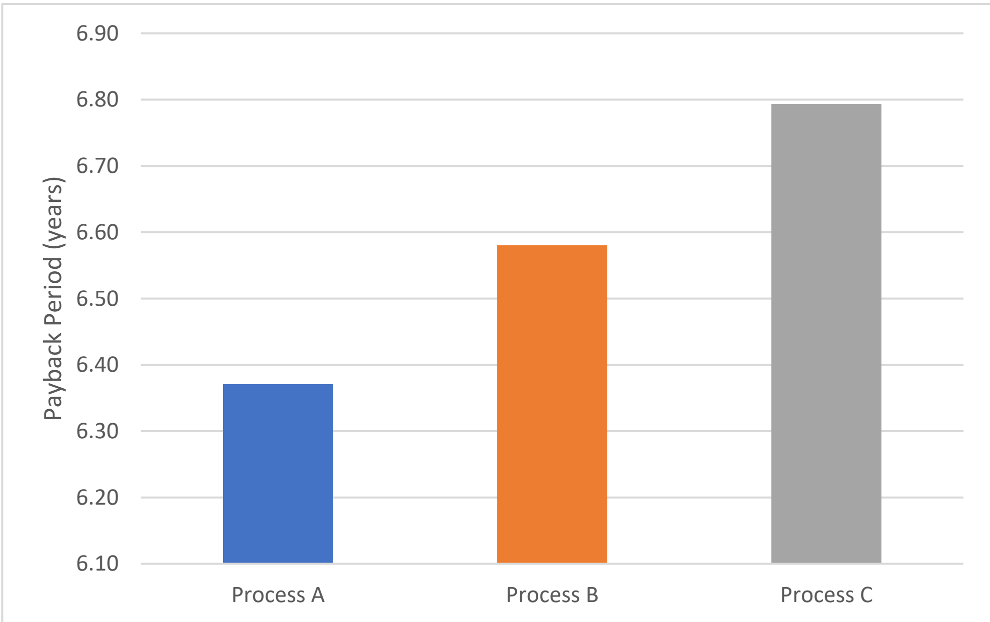

Figure 13. PBP of designed system.

4. Conclusions

To address low to moderate heat demand for industrial operations with the least amount of fossil fuel use, a unique solar FPC process heating system was developed. The following are the key conclusions reached from this research:

1. The optimum FPC angle in terms of maximum solar fraction and collector efficiency is calculated to be 30° at an azimuth of 0°.
2. The energy analysis of the FPC solar thermal system portrayed a maximum thermal energy efficiency of 79% at 1000 W/m^2 solar radiation and a minimum thermal energy efficiency of 5.31% at 100 W/m^2. An in-depth analysis showed the system to be quite responsive. Even at a radiation level of 300 W/m^2, which is significantly lower than the mean radiation in Jamshoro, the thermal energy efficiency of the system remained above 60%.
3. The exergy analysis showed a very low thermal exergy efficiency, peaking at 4.31% at 1000 W/m^2 radiation intensity. Even at the highest irradiation level, the energetic performance of the system is quite poor because heat is a low-grade form of energy that cannot be efficiently transformed into useful energy forms.
4. The solar fraction of the system showed a direct relationship with increasing FPC area. Contrarily, flat-plate collector efficiency showed an indirect relationship with increasing FPC area. Such behavior necessitated the optimization of the solar thermal system. The optimized FPC area for operating temperatures of 60 °C, 70 °C, and 80 °C, at a flow rate of 1000 kg/hour each, is evaluated to be 79 m^2, 100 m^2, and 121 m^2, respectively.
5. The environmental analysis showed that deploying such a system decreases the total amount of CO_2 emissions by 82 tons annually. The designed system was also extrapolated to mass flow rates of up to 30,000 kg/h at 70 °C, and the results show the CO_2 reductions were increased to 830 tons per year compared to 28 tons per year for 1000 kg/h. The extrapolated results conclude the designed configuration to be environmentally advantageous and practical for massive installations as well.
6. The NPV for each process showed a positive valve, concluding the system to be economically profitable.
7. The IRR of each process surpassed the interest rate, concluding the system to be economically profitable.
8. The PBP of the system was comprehensively less than the project life period, concluding the proposed system to be feasible.

Author Contributions: Conceptualization, methodology, software, writing, J.A. and L.K.; Validation, wiring, resources, A.F.A.; Supervision, methodology, validation, writing—review and editing, M.E.H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

A	Area
CF	Cash flow
C_o	Total capital cost
C_p	Heat capacity
C_i	Cash inflow
I_{rad}	Incidence radiations
i^{th}	Year number
$\dot{m}$	Mass flow rate

n	Payback period
$\dot{Q}$	Energy
r	Discount rate
T	Temperature
X	Exergy
Greek letters	
α	Absorptance coefficient
η	Efficiency
ε	Exergy efficiency
τ	Transmittance coefficient
Acronyms	
Dest	Destruction
ETC	Evacuated tube collector
FPC	Flat-plate collector
HTM	Hierarchical temporal memory
IPH	Industrial process heating
IRR	Internal rate of return
NG	Natural gas
NPV	Net present value
OM	Operation and maintenance
PBP	Payback period
PTC	Parabolic trough collector
PV	Photovoltaic
SF	Solar fraction
SIR	Savings-to-investment ratio

References

1. Hosenuzzaman, M.; Rahim, N.A.; Selvaraj, J.; Hasanuzzaman, M.; Malek, A.A.; Nahar, A. Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation. *Renew. Sustain. Energy Rev.* **2015**, *41*, 284–297. [CrossRef]
2. Abdelaziz, E.A.; Saidur, R.; Mekhilef, S. A review on energy saving strategies in industrial sector. *Renew. Sustain. Energy Rev.* **2011**, *15*, 150–168. [CrossRef]
3. Jia, T.; Dai, Y.; Wang, R. Refining energy sources in winemaking industry by using solar energy as alternatives for fossil fuels: A review and perspective. *Renew. Sustain. Energy Rev.* **2018**, *88*, 278–296. [CrossRef]
4. Lamb, W.F.; Wiedmann, T.; Pongratz, J.; Andrew, R.; Crippa, M.; Olivier, J.G.; Wiedenhofer, D.; Mattioli, G.; Al Khourdajie, A.; House, J.; et al. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ. Res. Lett.* **2021**, *16*, 073005. [CrossRef]
5. Huang, W.M.; Lee, G.W.M.; Wu, C.C. GHG emissions, GDP growth and the Kyoto Protocol: A revisit of Environmental Kuznets Curve hypothesis. *Energy Policy* **2008**, *36*, 239–247. [CrossRef]
6. Mekhilef, S.; Saidur, S.R. A review on solar energy use in industries. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1777–1790. [CrossRef]
7. Holappa, L. A general vision for reduction of energy consumption and CO_2 emissions from the steel industry. *Metals* **2020**, *10*, 1117. [CrossRef]
8. IEA. *CO_2 Emissions from Fuel Combustion*; International Energy Agency: Paris, France, 2017.
9. Muneer, T.; Maubleu, S.; Asif, M. Prospects of solar water heating for textile industry in Pakistan. *Renew. Sustain. Energy Rev.* **2006**, *10*, 1–23. [CrossRef]
10. Kumar, L.; Hasanuzzaman, L.M.; Rahim, N. Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: A review. *Energy Convers. Manag.* **2019**, *195*, 885–908. [CrossRef]
11. Kjelstrup, S.; Magnanelli, E. Efficiency in the process industry: Three thermodynamic tools for better resource use. *Trends Food Sci. Technol.* **2020**, *104*, 84–90. [CrossRef]
12. Tiwari, G.N.; Shyam, A.T. *Handbook of Solar Energy*; Springer: Berlin/Heidelberg, Germany, 2016; Volume 498.
13. Sharma, A.K.; Sharma, C.; Mullick, S.C.; Kandpal, T.C. Solar industrial process heating: A review. *Renew. Sustain. Energy Rev.* **2017**, *78*, 124–137. [CrossRef]
14. Lauterbach, C. *Potential, System Analysis and Preliminary Design of Low-Temperature Solar Process Heat Systems*; in Mechanical Engineering; University of Kassel: Kassel, Germany, 2014.
15. Muller, H. Solar Process Heat in the Food Industry–Methodological Analysis and Design of A Sustainable Process Heat Supply System in A Brewery and A Dairy. Ph.D. Thesis, De Montfort University, Leicester, UK, 2016.
16. Benz, N.; Gut, M.; Beikircher, T.; Ruß, W. Solar process heat with non-concentrating collectors for food industry. In Proceedings of the ISES 1999 Solar World Congress, Jerusalem, Israel, 4–9 July 1999.
17. Aladmin. Solar Process Heat for Paintshops. 2013. Available online: https://www.automotivemanufacturingsolutions.com/solar-process-heat-for-paintshops/31633.article (accessed on 15 October 2022).

18. Uppal, A.; Kesari, J.P. Solar industrial process heat in indian automobile industry. *Int. J. Latest Technol. Eng. Manag. Appl. Sci. IJLTEMAS* **2015**, *4*, 117–123.
19. Sharma, A.K.; Sharma, C.; Mullick, S.C.; Kandpal, T.C. Potential of Solar Energy Utilization for Process Heating in Paper Industry in India: A Preliminary Assessment. *Energy Procedia* **2015**, *79*, 284–289. [CrossRef]
20. Sharma, A.K.; Sharma, C.; Mullick, S.C.; Kandpal, T.C. Carbon mitigation potential of solar industrial process heating: Paper industry in India. *J. Clean. Prod.* **2016**, *112*, 1683–1691. [CrossRef]
21. Bullon, J.; González Arrieta, A.; Hernández Encinas, A.; Queiruga Dios, A. Manufacturing processes in the textile industry. Expert Systems for fabrics production. *Adcaij Adv. Distrib. Comput. Artif. Intell. J.* **2017**, *6*, 15. [CrossRef]
22. Kumara, P.; Buddhi, D.; Gupta, M.K.; Sinha, K.K. Process mapping of textile sector for concentrating solar thermal technology intervention. *J. Environ. Sci. Technol.* **2020**, *6*, 10–23.
23. Haagen, M.; Zahler, C.; Zimmermann, E.; Al-Najami, M.M. Solar Process Steam for Pharmaceutical Industry in Jordan. *Energy Procedia* **2015**, *70*, 621–625. [CrossRef]
24. Mehrdadi, N.; Nasrabadi, T.; Hoveydi, H.; Joshi, S. Aplication of solar energy for drying of sludge from pharmaceutical industrial waste water and probable reuse. *Int. J. Environ. Res.* **2007**, *1*, 42–48.
25. Agrawal, R.; Gunopulos, D.; Leymann, F. Mining process models from workflow logs. In *Advances in Database Technology—EDBT'98*; Springer: Berlin/Heidelberg, Germany, 1998.
26. Kumar, K.R.; Chaitanya, N.K.; Kumar, N.S. Solar thermal energy technologies and its applications for process heating and power generation–A review. *J. Clean. Prod.* **2021**, *282*, 125296. [CrossRef]
27. Stryi-Hipp, G. *Renewable Heating and Cooling*; Woodhead Publishing: Sawston, UK, 2016; Volume 1.
28. Jia, T.; Huang, J.; Li, R.; He, P.; Dai, Y. Status and prospect of solar heat for industrial processes in China. *Renew. Sustain. Energy Rev.* **2018**, *90*, 475–489. [CrossRef]
29. Sahoo, N.; Kumar, A. Solar Industrial Process Heating Prospects in Indian Cement Industries. In *Advances in Mechanical and Energy Technology*; Lecture Notes in Mechanical Engineering; Springer: Singapore, 2022; pp. 367–374.
30. Karki, S.; Haapala, K.R.; Fronk, B.M. Technical and economic feasibility of solar flat-plate collector thermal energy systems for small and medium manufacturers. *Appl. Energy* **2019**, *254*, 113649. [CrossRef]
31. Asim, M.; Kanan, S.; Dewsbury, J. TRNSYS simulation of a solar cooling system for the hot climate of Pakistan. *Energy Procedia* **2016**, *91*, 702–706. [CrossRef]
32. Kumar, L.; Hasanuzzaman, M.; Rahim, N.; Islam, M. Modeling, simulation and outdoor experimental performance analysis of a solar-assisted process heating system for industrial process heat. *Renew. Energy* **2021**, *164*, 656–673. [CrossRef]
33. Perea-Moreno, A.-J.; García-Cruz, A.; Novas, N.; Manzano-Agugliaro, F. Rooftop analysis for solar flat plate collector assessment to achieving sustainability energy. *J. Clean. Prod.* **2017**, *148*, 545–554. [CrossRef]
34. Ge, Z.; Wang, H.; Wang, H.; Zhang, S.; Guan, X. Exergy Analysis of Flat Plate Solar Collectors. *Entropy* **2014**, *16*, 2549–2567. [CrossRef]
35. Jeffrey Kuo, C.-F.; Su, T.-L.; Jhang, P.-R.; Huang, C.-Y.; Chiu, C.-H. Using the Taguchi method and grey relational analysis to optimize the flat-plate collector process with multiple quality characteristics in solar energy collector manufacturing. *Energy* **2011**, *36*, 3554–3562. [CrossRef]
36. Holler, S.; Winkelmann, A.; Pelda, J.; Salaymeh, A. Feasibility study on solar thermal process heat in the beverage industry. *Energy* **2021**, *233*, 121153. [CrossRef]
37. Juarez-Trujillo, A.; Martín-Domínguez, I.R.; Alarcón-Herrera, M.T. Using TRNSYS Simulation to Optimize the Design of a Solar Water Distillation System. *Energy Procedia* **2014**, *57*, 2441–2450. [CrossRef]
38. Jebasingh, V.K.; Herbert, G.M.J. A review of solar parabolic trough collector. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1065–1091. [CrossRef]
39. Kalogirou, S. The potential of solar industrial process heat applications. *Appl. Energy* **2003**, *76*, 337–361. [CrossRef]
40. Ghazzani, B.E.; Plaza, D.M.; El Cadi, R.A.; Ihlal, A.; Abnay, B.; Bouabid, K. Thermal plant based on parabolic trough collectors for industrial process heat generation in Morocco. *Renew. Energy* **2017**, *113*, 1261–1275. [CrossRef]
41. Ktistis, P.K.; Agathokleous, R.A.; Kalogirou, S.A. Experimental performance of a parabolic trough collector system for an industrial process heat application. *Energy* **2021**, *215*, 119228. [CrossRef]
42. Maps, G. *Jamshoro Satellite View*; Google: San Francisco, CA, USA, 2022.
43. Sarwar, J.; Khan, M.; Rehan, M.; Asim, M.; Kazim, A.H. Performance analysis of a flat plate collector to achieve a fixed outlet temperature under semi-arid climatic conditions. *Sol. Energy* **2020**, *207*, 503–516. [CrossRef]
44. Erzen, S.; Açıkkalp, E.; Hepbasli, A. Off-grid hybrid systems based on combined conventional and unconventional technologies: Design, analyses, and illustrative examples. In *Hybrid Technologies for Power Generation 2022, Hybrid Energy Systems*; Academic Press: Cambridge, MA, USA, 2022; pp. 189–218.
45. Li, M.; Zhong, D.; Ma, T.; Kazemian, A.; Gu, W. Photovoltaic thermal module and solar thermal collector connected in series: Energy and exergy analysis. *Energy Convers. Manag.* **2020**, *206*, 112479. [CrossRef]
46. Rodríguez-Hidalgo, M.C.; Rodríguez-Aumente, P.; Lecuona, A.; Gutiérrez-Urueta, G.; Ventas, R. Flat plate thermal solar collector efficiency: Transient behavior under working conditions. Part I: Model description and experimental validation. *Appl. Therm. Eng.* **2011**, *31*, 2394–2404. [CrossRef]
47. Dincer, I.; Rosen, M.A. *Exergy: Energy, Environment and Sustainable Development*; Newnes: London, UK, 2012.

48. Schneider, E.D.; Kay, J.J. Life as a manifestation of the second law of thermodynamics. *Math. Comput. Model.* **1994**, *19*, 25–48. [CrossRef]
49. Kumar, L.; Hasanuzzaman, M.; Rahim, P.A. Thermo-Economic Analysis of a Solar-Assisted Industrial Process Heating System. Nasrudin, Thermo-Economic Analysis of a Solar-Assisted Industrial Process Heating System. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4048138 (accessed on 16 October 2022).
50. Nauroz Ali, E.; Liaquat, R.; Ali, M.; Waqas, A.; Shahzad, N. Techno-economic and GHG mitigation analyses based on regional and seasonal variations of non-concentrating solar thermal collectors in textile sector of Pakistan. *Renew. Energy Focus* **2022**, *42*, 165–177. [CrossRef]
51. Pakistan-Key Rates. 2022. Available online: https://countryeconomy.com/key-rates/pakistan (accessed on 16 October 2022).
52. Quiñones, G.; Felbol, C.; Valenzuela, C.; Cardemil, J.M.; Escobar, R.A. Analyzing the potential for solar thermal energy utilization in the Chilean copper mining industry. *Sol. Energy* **2020**, *197*, 292–310. [CrossRef]
53. Espinoza, R.D. Separating project risk from the time value of money: A step toward integration of risk management and valuation of infrastructure investments. *Int. J. Proj. Manag.* **2014**, *32*, 1056–1072. [CrossRef]
54. Abdelhady, S. Performance and cost evaluation of solar dish power plant: Sensitivity analysis of levelized cost of electricity (LCOE) and net present value (NPV). *Renew. Energy* **2021**, *168*, 332–342. [CrossRef]
55. Cetina-Quiñones, A.J.; Xamán, J.; Bassam, A.; Soberanis, M.E.; Perez-Quintana, I. Thermo-economic analysis of a flat solar collector with a phase changing material under tropical climate conditions: Residential and industrial case. *Appl. Therm. Eng.* **2021**, *182*, 116082. [CrossRef]
56. Coker, A.K. CHAPTER 9-Engineering Economics. In *Fortran Programs for Chemical Process Design, Analysis, and Simulation*; Coker, A.K., Ed.; Gulf Professional Publishing: Houston, TX, USA, 1995; pp. 721–776.
57. Kim, S.; Jeong, H.; Park, J.Y.; Baek, S.Y.; Lee, A.; Choi, S.-H. Innovative flat-plate solar collector (FPC) with coloured water flowing through a transparent tube. *RSC Adv.* **2019**, *9*, 24192–24202. [CrossRef]
58. Caliskan, H.; Hepbasli, A.; Dincer, I.; Maisotsenko, V. Thermodynamic performance assessment of a novel air cooling cycle: Maisotsenko cycle. *Int. J. Refrig.* **2011**, *34*, 980–990. [CrossRef]
59. Dincer, I.; Abu-Rayash, A. Chapter 6—Sustainability modeling. In *Energy Sustainability*; Dincer, I., Abu-Rayash, A., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 119–164.
60. Chamoli, S. Exergy analysis of a flat plate solar collector. *J. Energy South. Afr.* **2013**, *24*, 08–13. [CrossRef]
61. Smith, I.K.; Stosic, N.; Kovacevic, A. Introduction: Power from low-grade heat. In *Power Recovery from Low Grade Heat by Means of Screw Expanders*, 2nd ed.; Smith, I.K., Stosic, N., Kovacevic, A., Eds.; Chandos Publishing: Oxford, UK, 2014; pp. xxvii–xxx.
62. Wooldridge, M.; Luebbers, R.H. *Heat Transfer*; McGraw Hill: New York, NY, USA, 2020.
63. Lean, J. The Sun's variable radiation and its relevance for Earth. *Annu. Rev. Astron. Astrophys.* **1997**, *35*, 33–67. [CrossRef]
64. Dincer, I.; Bicer, Y. 4.19 PV-Based Energy Conversion Systems. In *Comprehensive Energy Systems*; Dincer, I., Ed.; Elsevier: Oxford, UK, 2018; pp. 762–793.
65. Najmi, W.; Arhosazani, A.M. Comparison of combustion performance between natural gas and medium fuel oil at different firing settings for industrial boilers. In Proceedings of the International Conference on Energy and Environment (ICEE) 2006, Kajang, Malaysia, 28–30 August 2006; Academia: San Francisco, CA, USA, 2006.