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Article

Solar Thermal Technology Aided Membrane Distillation Process for Wastewater Treatment in Textile Industry—A Technoeconomic Feasibility Assessment

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Abstract: Because textile industries are intensely water-consuming and generate a huge quantity of wastewater, the present study examines the scope of using solar thermal technology to treat wastewater from textile industries. A hybrid technology, comprising a compound parabolic concentrator-based solar thermal system in conjunction with a Membrane Distillation (MD) system, is experimented with for wastewater treatment in textile industries. The MD system requires a water temperature of around 90 °C for efficient functioning. The advanced MD technology using waste heat combined with solar heat to meet the system's thermal load is technologically evaluated for an experimental textile industry in India. Moreover, the present study critically analyses the techno economics of the proposed hybrid technology. A detailed financial analysis has revealed that, besides technological superiority, the recommended technology is also financially rewarding for wastewater treatment in the textile industry. To cope with the delayed payback period, financial incentives are recommended so that the system becomes a lucrative technological option.

Keywords: compound parabolic concentrator; membrane distillation; solar thermal system; wastewater treatment; textile industries; technoeconomic assessment

1. Introduction

An elegant study by Liang et.al. induces the belief that geothermal energy, if harnessed properly, can provide energy solutions in the case of textile industries needing both thermal and electrical energy. Although occasionally of low grade, it bears ample scope to be converted to high-grade green energy with the help of a ground source heat pump (GSHP), comprising a ground heat exchanger, heat pump, and the heating system, for example, a solar heater. This energy-saving technology uses working fluids that are abundantly available on Earth. Water is most suitable for this purpose. The working fluid carries the ground heat via underground tubes. The depth of the tubes is determined by the need for ground temperature, which increases by 250 °C per kilometer depth to 50 °C per kilometer beyond a depth of 3–4 km from the Earth's surface. The tube material must be highly durable, corrosion resistant, strong, and flexible. The transfer takes place through this tube and, hence, it is an important aspect of the GHE system. There should be a good backfill material that separates the tube from the soil; one can use cement or graphite [1].

The textile industries play an important role in a country's economic activities due to the fact that this employment-intensive industrial sector contributes significantly to the GDPs of several countries in terms of increasing the rate of earning by exporting produce to other countries; for example, the amount of such earnings of Indian textile industries exceeds 15% of the country's total earnings from export [1,2].

Due to being highly water-consuming, the textile industry is apt to generate huge quantities of wastewater [3,4]. As the discharged wastewater exhibits a high pH value, contains a high concentration of suspended solids, chlorides, nitrates, metals like manganese, sodium, lead, copper, chromium, and iron with alarmingly high Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) values, it poses several threats, including a risk of endangerment. Therefore, there are calls for the evolution of efficient technological means to treat the wastewater discharged by the textile industries so that the potential environmental pollution can be minimized [4].

To mitigate the potential environmental degradation due to the release of toxic effluents, various wastewater treatment technologies are seen to have been employed by various textile industries. Adsorption technology seems to be an effective option for textile industry wastewater treatment; however, it is cost prohibitive. In fact, Chitosan (CS) may be considered a potential adsorbent material for eliminating toxic pollutants from wastewater discharged by the textile industries [5]. This capability of Chitosan is attributed to its amino and hydroxyl groups, its physico-chemical properties, viz. chemical stability, high reactivity, and its selectivity toward pollutants containing dyes and heavy metal ions. Moreover, Chitosan is non-toxic and biodegradable, and its production cost is low [5]. The other employable methods for the treatment of textile industry wastewater include ion exchange, membrane filtration, (Reverse Osmosis (RO), Ultrafiltration (UF), and nanofiltration (NF); again, ozonation, evaporation (multi-effect evaporation, mechanical vapor compression, and direct contact evaporation), electrochemical oxidation, flocculation phytoremediation, photochemical, and crystallization are other effective technologies being implemented at various places [6–10].

Membrane Distillation (MD), used for treating textile industry wastewater, is essentially a process of thermal effluent treatment; in this process, the effluent is heated to evaporate its water content and, thus, concentrates the remaining fluid. Generally, the separation effect is based on the hydrophobicity of the polymer membrane material, which creates a barrier to the effluent in the liquid phase whilst allowing materials in the vapor phase to pass through the membrane's pores. This non-pressure Membrane Distillation has attracted significant interest in textile wastewater treatment [7,8]; however, the major challenges that hinder the commercial application of MD are the fouling of membranes [9], flux decline [10], and high energy consumption [11,12]. The MD module consists of an Evaporator, Evaporation–Condensation stages, and a Condenser; the alternate evaporation and condensation stages are shown in Figure 1. Each stage recovers the heat used to evaporate vapor from the effluent. Distillate is produced in each evaporation–condensation stage. Seemingly, the repetitive evaporation and condensation stages for yielding water of an acceptable quality necessitates the expenditure of a high amount of thermal energy [13,14]. The high energy requirement affects its process economy. The energy sourced by conventional fuel poses other environmental pollution threats, viz. degradation of air quality by emission of greenhouse gases and solid particulate matter of various sizes. Given such techno-economic constraints in harnessing the accruable benefit from such an efficient wastewater treatment process, it appears prudent to probe into the feasibility of using solar energy to manage the required thermal load for a membrane distillation process.

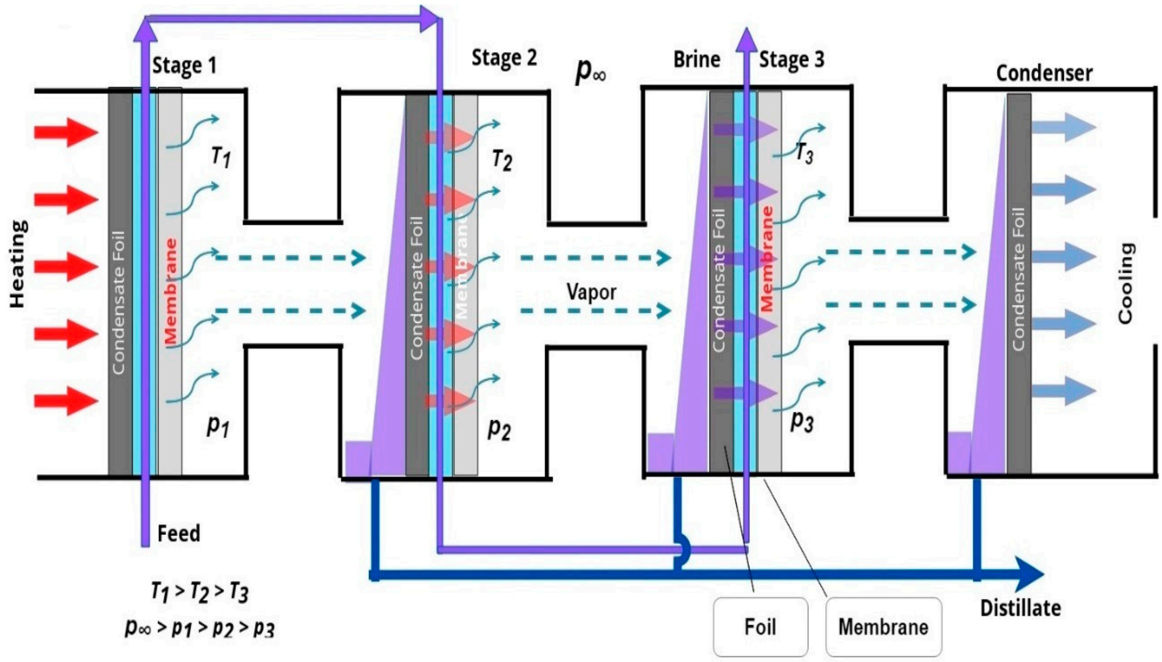

Figure 1. Schematic diagram of MD unit showing evaporation–condensation stages.

While fixing a specific technology option, it is to be kept in mind that apart from the thermal load, there is also a definite demand for electrical load and, quite often, electrical energy is spent to supply the thermal energy due to its direct physical relation with thermal energy. Hence, it appears to be worth taking stock of the present technological scenario amidst the supply need for thermal and electrical energy.

Our proposition is a case of a distributed generation system where hybrid solar thermal energy in association with MD is advocated. Moreover, the textile industries need electric power for many operations. Since electrical and thermal power are intimately linked, an impactful study on the usability of a combined heat power system is reported in the literature [15]. Usually, a compound heat power (CHP) system comprises a gas turbine and a heat recovery boiler. Optimization of the performance of a small-scale CHP is carried out by linear modeling, where a Grasshopper optimization algorithm was used in MATLAB software R2023a [15].

It is known that CO_2 emissions, due to the use of fossil fuels for meeting energy demands in human activities, impair public health in a great way. This directly impacts a state's health expenditure, education expenditure, and gross domestic product (GDP). Therefore, using renewable energy sources as a replacement for fossil fuel has been a global drive. An elegant study on interlinking renewable energy sources for various human activities with health expenditure, education expenditure, emission of greenhouse gases, and GDP is reported elsewhere. Following descriptive statistics using unit root tests and FMLOS and DOL tests demonstrated that renewable energy reduces health expenditure with the concurrent enhancement of GDP in no less than five South Asian countries [16]. Tariffs for electrical and thermal energy often affect a CHP's size and compatibility. The integration of CHP with electrical heat pumps (EHP) is recommended for cases of thermal load exceeding the delivery capacity of a CHP. It is advocated that such a cogeneration system provides an economical solution to the problem of minimizing energy costs [17]. In a recent study, both EHP and CHP were integrated with the understanding that both sources can meet the thermal energy demand in full and that one of higher efficiency would serve as the primary source of thermal energy, with the other remaining a backup [18]. A cost analysis revealed that using standalone EHP as the primary source is an economically cheaper option than CHP, whereas the integrated version is more reliable on account of using two different energy sources, i.e., electricity and natural gas. Suppose the EHP fails to supply the entire thermal energy demand due to an interruption in electric supply or for some other unforeseen reason, the CHP will help supply the needed thermal energy [18].

It may be assumed that the relationship between the heat and electricity in a CHP is nonlinear. The scheduling problem in a proposed microgrid system comprising CHP, renewable energy sources, microturbine, TES facility, and fuel cell unit is taken as a mixed integer nonlinear problem, which is solved by employing the Crow search algorithm, simulated by MATLAB [19]. The provision for energy storage systems envisaged better energy management to meet the thermal and electrical energy requirements [20]. It is known that the availability of solar energy is much less uncertain than other forms of renewable energy. Hence, it can be a better option for microgrid applications in any location. It is important to note that the availability of solar radiation in terms of Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) varies with geographic location, seasons, and climate; however, the data of the average annual GHI or DNI can be obtained from Meteonorm software Version 8.2.0 for all locations across the globe. Although many industries use different systems to cater to the electrical and thermal needs of human activity (domestic/industry), a simultaneous supply of thermal and electrical energy from a single system using a single fuel has become an attractive proposition in recent times. A steam thermal plant where steam caters to thermal energy needs is analog but with certain practical limitations. Considering the benefits of an integrated generation system in cost and efficiency, a novel microgrid system composed of two CHP units, one wind turbine, and a microturbine unit, with a fuel cell, battery storage, and TES, is conceived [19]. It is reported that the novel microgrid with the capacity to exchange power with the main grid is quite profitable. However, the microgrid alone is also a feasible alternative [19].

Therefore, an attempt is made in the present investigation to study the effect of integrating solar thermal technology with a membrane distillation system on the overall energy consumption for the effective treatment of wastewater discharged by textile industries. Although process economy happens to be an important determinant of technology options for industries [14–22], only limited techno-economic reports on solar thermal technology integrated with membrane distillation systems for wastewater treatment in textile industries are available in the literature. Hence, in the present investigation, an attempt is also made to study the techno-economics of wastewater treatment technology in the textile industry, which uses solar thermal energy to meet the thermal load of a typical membrane distillation system.

To invoke the plan for an integrated generation system in industrial wastewater treatment is a new concept. Attempting to obtain an alternative solution against polluting fossil fuel as a traditional process to meet the thermal load of evaporation techniques aimed to be used for industrial wastewater treatment is certainly additive to the existing technological options. Following the emerging trend of using integrated generation systems [15], the proposed wastewater technique of a solar thermal system coupled with an MD system is novel. The novelty of the present research lies in implementing an integrated generation system that can meet the energy load of textile industries. This technology of wastewater treatment in textile industries is new in character. Most textile industries use fossil fuels to meet their energy needs. An attempt is made to study the effect of concentrating solar thermal technology in a combination membrane distillation system for the treatment of wastewater discharged from textile treatments on the overall energy consumption for the effective treatment of wastewater discharged by textile industries. Using the state-of-the-art design of a parabolic concentrator to couple with the MD technique for wastewater treatment in water-intensive textile industries is sure to add new knowledge in the industrial wastewater treatment technology domain. Establishing the techno-economic feasibility and providing the pragmatic recommendation of incentivizing the user industries to promote this hybrid technology is not only eco-conserving but also financially rewarding for any country in terms of reducing its health expenditures and enhancing gross domestic product (GDP). The advocacy of the present paper with the target of insuring socio-economic benefit is highly value additive and, hence, emerges as a completely new solution to the concerned challenges in wastewater treatment in textile industries.

2. Experimental Methods: Methodology Adopted for Techno-Economic Assessment of Solar Thermal Operated Wastewater Treatment System

The research methodology used for the present study comprises a:

- Selection of textile units for the case study
- Design of a solar thermal integrated wastewater treatment system
- Performance evaluation of a solar-MD waste treatment system
- Estimation of techno-economic indicators, such as levelized cost of energy, payback period, internal rate, or return on investment made on solar thermal-operated wastewater treatment system.
- Recommendations

2.1. Selection of Textile Industry

A textile industry specializing in fabric manufacturing is selected for the present investigation. The specificity of this selection is merited by the fact that fabric processing involves a higher thermal load. Fabric processing in cotton-based textile industries requires hot water and steam. The temperature requirement lies between 80 and 180 °C temperature. While the hot water temperature is between 80 and 95 °C, the temperature requirement for steam is as high as 180 °C. Thus, the overall thermal load in a fabric processing unit is quite high. Noting that MD requires a temperature of 90 °C, the flat plate collector is not considered a suitable option. Hence, a parabolic concentrator aiming to serve the dual purpose of supplying steam for fabric processing and hot water for running the integrated wastewater treatment system is considered a far better option. So, this novel approach of coping with the most stringent situation, viz. meeting the requirement of a high thermal load, has formed the basis of the selection of the experimental industry. The selected industry is situated at 22°36′26″ N latitude, 75°55′23″ E longitude, and 565.65 m above mean sea level. Said location falls within the city of Indore in Madhya Pradesh in India. The annual cumulative values of Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), annual average ambient temperature (T_a), and annual average wind speed at the selected location are obtained from the available weather data source and are provided in Table 1 (Meteonorm 8.1.0904-10-2021) software, 2014.

Table 1. Solar Radiation data at the selected industry.

Latitude	Longitude	GHI	DNI	T_a	Wind Speed
(°N)	(°E)	kWh/m^2/Year	kWh/m^2/Year	(°C)	(m/s)
22.71	75.85	1980	2075	25.1	3.8

2.2. Design of Solar Thermal-Based Wastewater Treatment in Textile Industry

A Compound Parabolic Concentrator (CPC)-based Concentrating Solar Thermal (CST) system integrated with the existing MD system is proposed for employment in the selected textile industry.

The design of the proposed solar thermal coupled MD wastewater treatment system is shown schematically in Figure 2. It can be seen that the system is configured with a solar thermal collector field that uses a water–glycol mix as the heat transfer fluid (HTF). Along with the thermal energy storage (TES), said CST is integrated with the membrane distillation unit (Figure 2). Thus, the system is a unique integrated generation system.

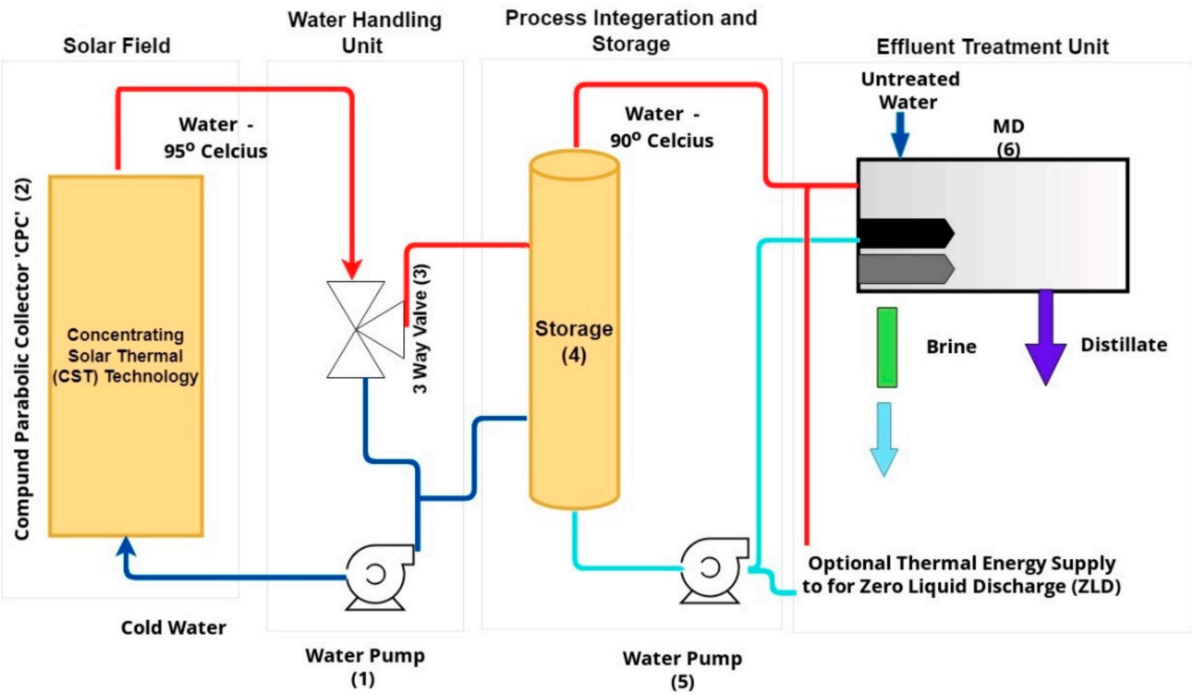

Figure 2. A schematic representation of the design of solar-based waste treatment system at the experimental textile unit.

The Water Pump (1) circulates the water/glycol heat transfer fluid (HTF) through the CPC (2), which uses solar radiation to heat the water up to 90 °C. After being heated, the water passes through a three-way valve (3) that allows the water to enter the thermal storage (4) or to return directly to the water pump. Water is pumped from the thermal storage to the MD unit by a second water pump (5). The heat energy contained in the water is used to meet the thermal energy demand of the installed MD unit (6) such that it becomes capable of ensuring the separation of fresh water and brine from the effluent.

The materials, like membranes and collectors, are procured from the market. The characteristics of membranes like their pore size and size distribution and its other intrinsic property information were provided by the suppliers and were integrated with the MD unit. Although FTIR and XPS and FESEM and AFM studies should have been conducted to unveil the intrinsic material property of the membranes and to assess the separation performance to ensure long-term operation stability, this is opted out in the present investigation as the scope of the present work has been kept limited to the design of the wastewater heating system and assessment of its techno-economic feasibility. However, this will be the subject of a separate study as an extension of the present one.

2.3. Performance Assessment of CST for Wastewater Treatment

The parameters considered for a performance assessment of the CST-based system are the (i) operating temperatures of the process (ii) performance characteristics of the solar collector (iii) availability of solar radiation (i.e., GHI/DNI in case of a CPC collector), and (iv) climatic conditions (e.g., ambient temperature, wind speed).

The performance of the experimental CPC collector technology needs to be assessed in terms of the useful thermal energy it can deliver and the associated solar fraction; these factors aid in quantifying the deliverable process heat that can raise the water temperature of the CST-MD system to the desired level. The specifications of the process' heat requirement of the steam and hot water generation systems, the design parameters of solar-based wastewater treatment systems used for the study (operating temperatures, flow rate of effluents, distillate production), and the TDS of the wastewater are shown in Table 2.

Table 2. Data used for performance evaluation of the proposed system.

Parameter	Unit	Value
Amount of effluent to be treated—10 m^3/day	m^3/day	10
Nominal effluent flow rate	m^3/hour	0.4
The energy required per m^3 distillate	kWh/m^3	150
Input temperature of feed water	°C	90
The outlet temperature of the solar field	°C	100
Distillate production	m^3/day	8.8
Concentrate production	m^3/day	1.2
TDS in feed water	mg/L	30,000
TDS in concentrate	mg/L	220,00~250,000
Concentration factor	-	8 (approx.)

It may be noted that the proposed solar-based wastewater treatment system has been simulated with the aid of the System Advisor Model (SAM). Based on the input parameters as provided in Table 2, the proposed solar-based wastewater system's performance is evaluated utilizing SAM's parametric simulation tool; an estimation of the annual thermal energy delivered at the concerned industrial location has been duly made. The use of appropriate tools by SAM has amply eased the determination of the performance efficiency of the proposed system.

Using the above data in Table 2, the rate at which thermal energy is required to produce 1 m^3 distillate can be estimated in the following manner:

The area of the CPC Collector field (A_{CPC}) to deliver the required energy is calculated by the use of the following expression

$$A_{CPC} = E_{CPC} \times E_S \times GHI_d \quad (1)$$

where E_{CPC} represents the efficiency of a typical CPC; Es, the efficiency of other system components (piping, etc.) and GHI_d, the design value of insolation (GHI in this case). Based on the above, the energy required to produce 1 m^3 distillate = 0.4 m^3/h × 150 kWh/m^3 = 60 KW. In the present calculation, E_{CPC} is taken as 66%. After discovering the collector area, we used the annual GHI in Equation (1) (as available from Meteonorm 8.1 and given in Table 1) to discover the process heat requirement per annum; by reducing it to the value per day (dividing by 365) and assuming the amount of effluent to be treated in a day to be ~10 m^3 per day, one can easily determine the amount of thermal energy required per cubic meter of distillate by applying the calorimetric principle (heat required = mass × specific heat × temperature difference (inlet temperature–outlet temperature). This comes to be 150 kWh/m^3 (vide Table 2). Hence, we obtain the value of the energy required to be ~60 KW.

2.4. Techno-Economic Assessment of Solar Thermal Use for Wastewater Treatment

The measures of the techno-economic assessment used in the analysis are the levelized cost of useful energy (LCUE) delivered, discounted payback period, and internal rate of return. The levelized cost of useful energy (C_l) delivered by the solar process heating system is estimated from the following expression [15]

$$C_l = \left[\sum_j^n \frac{C_j^0}{(1+d)^j}\right]\left[\frac{d(1+d)^n}{(1+d)^n - 1}\right] \quad (2)$$

where C_j^0 represents the unit cost of useful thermal energy delivered by the system in the jth year of its operation, d is the discount rate applicable for the investment, and n is the useful life of the system.

Following Equation (3), the discounted payback period (*DPP*) of the incremental investment in solar thermal system is determined as the period counted from the time of commencement of the project until the cumulative cash flow just becomes zero (i.e., the present value costs are equal to the present value benefits):

$$\sum_{j=1}^{DPP} \frac{B_j - A_j^c}{(+d)^j} = C_0 \quad (3)$$

where C_0 denotes the capital cost of the system, B_j represents the annual benefit accrued by the use of the system as a result of fuel savings in the *j*th year of its operation, and A_j^c denotes the annual cost of operation and maintenance of the solar heating system during the *j*th year.

Annual benefits (B_j), to be accrued in terms of monetary value of the annual amount of fuel replaced by the solar thermal system, can be estimated by Equation (4)

$$B_j = \frac{\left(A_j^u\right)_j (1+\xi)^{j-1}\left(UP_{f,j}\right)}{\left(CV_f\right)\left(\eta_f\right)} \quad (4)$$

where CV_f represents the calorific value of fuel and η_f the efficiency of fuel utilization in the conventional process heating system, $UP_{f,j}$ is the unit price of fuel in the *j*th year, and ξ is rate of annual escalation in the unit price. This is required as the comparison in cost–benefit due to solar energy use over the traditional process is one of the major objectives of the present study.

The internal rate of return (*IRR*) is defined as the annual value of the discount rate at which the Net Present Value (NPV) of the investment is zero, shown in Equation (5).

IRR can be estimated from the following equation:

$$\sum_{j=1}^{n} \left[\frac{B_j - A_j^c}{(1+IRR)^j}\right] + \frac{S}{(1+IRR)^n} - C_0 = 0 \quad (5)$$

In this study, the salvage value of the plant at the end of its useful life is assumed to be negligibly small.

3. Results and Discussion

Using the approach narrated in the preceding section, the performance of a solar thermal-based wastewater treatment is assessed in terms of useful energy delivered and the concerned measures for insurance of economic attractiveness.

In order to determine the performance of the solar operated system, it is required to calculate the area of solar collector field required to meet the energy demand of wastewater treatment in textile units. This has been estimated by using Equation (1) for the design values of insolation ranging from 500 W/m^2 to 900 W/m^2.

Further, the performance of the solar system (in terms of useful thermal energy delivery and solar fraction) corresponding to each value of GHI_d are also estimated. These estimates are made on the basis of the hourly availability of solar radiation at the location of the selected textile unit (obtained by the use of Meteonorm 8.1 software). The results of the above estimation for the CPC-based system are presented in Table 3.

It appears from the results in Table 3 that the performance of the solar-based system is better for the lower regime values of design insolation. This is because a lower design value yields a higher collector area; for a specific GHI value, the higher the collector area is, the higher the magnitude of deliverable energy will be (vide Equation (1)) As such, estimation with a larger solar collector area is also tried within the selected range of GHI_d (500–900 W/m^2); it is needless to say that the use of a larger collector area than is needed to fulfill the requirement of thermal energy to run the system successfully tends to involve a higher investment cost. Based on deliverable annual energy by the solar system and the corresponding values of solar fraction, it may be inferred that in order to achieve the maximum relative benefit in terms of derivable thermal energy from a solar-based system, the design value of insolation ought to be kept in the lower range. However, this assessment is not the only deciding factor for the financial attractiveness of a solar-based system.

Table 3. Energy delivered against the availability of solar insolation at the selected location.

Design Value of Insolation (GHI_d)	Area of CPC Require (A_{CPC})	Energy Delivered Annually	Solar Fraction
W/m^2	m^2	MWh_{th}	
500	267	239	0.46
600	222	199	0.38
700	190	171	0.33
800	167	150	0.28
900	148	133	0.25

In view of the above, a levelized cost of the thermal energy delivered for each value of the design GHI_d has been evaluated and is furnished in Figure 3. For better comprehension, the details for obtaining the levelized cost of the thermal energy are presented in Table 4.

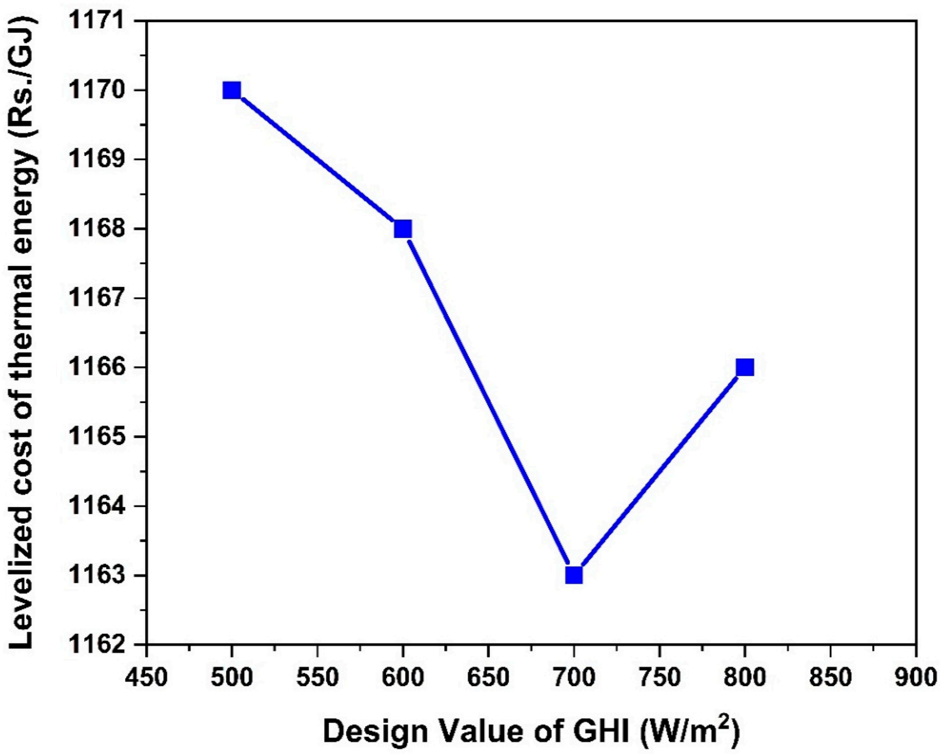

Figure 3. Levelized cost of thermal energy (in Rs/GJ) at Indore in textile unit.

Corroborating the information derivable from Figure 3, the results in Table 4 show that the LCTE attains its lowest value for a design value of GHI as 700 W/m^2. Thus, it is proved from the calculations in the present study that the mere minimization of the GHI_d value, hence securing the highest collector area, does not guarantee the maximization of economic benefit. It appears that there is an optimum value of this parameter ~700 W/m^2 which, when taken into consideration to design the solar-operated wastewater treatment system, means the accrual of maximum economic denomination is inevitable.

Table 4. Levelized cost of energy based on GHI_d.

Design Value of Insolation (GHI_d)	Energy Delivered Annually	Capital Investment	LCTE
W/m^2	MWh_{th}	(Rs in Lakh)	(Rs/GJ)
500	239	80.00	1170
600	199	66.67	1168
700	171	57.14	1163
800	150	50.00	1166
900	133	44.44	1165

It is not out of context to mention that the overall aim of the study has been to analyze the feasibility of using the conceived hybrid technology in the form of a compound parabolic concentrator (CPC)-based concentrating solar thermal (CST) system with an integrated MD system as a meaningful solution to the problem of treating toxic effluent discharged from the textile industries, thereby giving a check to environment degradation. It is to be emphasized that the meaningfulness of a technological solution must be seen as employing technology which is ecologically sustainable and, at the same cost, far more rewarding compared to the contemporary options.

From the foregoing results and discussions, the proposed system is not only technologically competent but also aids in environmental protection at a high economic denomination. On this ground, the authors wish to infer that the present study has successfully found a suitable and cost-effective technology configuration for treating the wastewater discharged by fabric processing textile industries.

The values of other measures of financial performance such as the discounted payback period and internal rate of return for an investment in a solar-operated wastewater system are presented in Table 5. The estimations have been made against each type of fuel that could be saved by installing an operated wastewater treatment system. It is clear from the results of Table 5 that the solar-based system is an economically viable option for all the replaceable fuels except coal, due principally to its lower price in countries like India. This, however, may not be true for every country as there are countries where the cost of coal as a fuel is significantly higher, and, hence, is uncompetitive with renewable energy. It is also important to mention that the use of coal adds to the health expenditure of a country with a concurrent diminution in GDP. Moreover, environmental degradation and the cost of preventing pollution cannot be underrated. In general, fuels like FO, LDO, and natural gas are normally used in the textile sector as attractive means due to the good range of *IRR* (19% to 23.5%). The result of replacing the following fuel by the use of CPC-based CST is also presented in Table 5.

Table 5. Payback period and *IRR* against the use of different types of fuels.

Type of Fuel to Be Replaced by Solar Thermal	Pay Back Period (Years)	*IRR* (%)
Furnace Oil	10	18.87
LDO	7.5	22.05
Coal	Not Possible in country like India	Not Possible in country like India
Natural Gas	7	23.4

4. Conclusions

The present study has demonstrated that the compound parabolic concentrator (CPC)-based concentrating solar thermal (CST) system with an integrated MD system is technologically competent to meet the thermal load for wastewater treatment in a fabric processing textile industry. It is also found that apart from delivering a high amount of useful thermal energy, said technology configuration is environmentally sustainable. It is further noted that the toxic effluent of fabric processing plants needs to implement evaporation technology and, in this respect, the proposed hybrid technology of a solar thermal integrated multiple distillation unit is an attractive technology option. In this way, the proposed technology is superior to the existing technology.

It is further concluded that a maximum solar fraction of about 45% is achievable for insolation design values ranging from 500 to 900 W/m^2 in the case of the experimental industry. Moreover, the present study affirms that the levelized cost of thermal energy (LCTE) varies with the design value of insolation and that the cost is the lowest (Rs 1163/GJ) for the designed GHI value of 700 W/m^2. Thus, LCTE is the determinant of the optimum design value of GHI. The authors further conclude that the solar-operated wastewater system may become financially attractive in industries where fossil fuels, in the form of furnace oil, LDO, natural gas, or petroleum fuel, are used. This advocacy is the first of its kind and is distinct from others. The payback period is much less than the expected useful life of the solar-based system (7–10 years); likewise, the *IRR* values lie within the range of 18.87–23.40%. The measures of financial performance do not seem to be attractive for the industry where coal is used as a major fuel because the payback on the investment of a solar-based system is not realizable within the useful life span of the solar system; this is true only if the price of coal is significantly low, as in India. In view of the extended payback period in certain cases, the authors recommend due incentivization for the sake of making the process techno-economically rewarding to textile industries.

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