Energy, Exergy, Environmental Impact and Economic (4E) Analysis of ET-CPC-Powered Solar Domestic Water Heating System

Dinesh K Sharma (✉ dinesh.sharma@skit.ac.in)
Swami Keshvanand Institute of Technology Management and Gramothan https://orcid.org/0000-0003-3919-1900

Dilip Sharma
Malaviya National Institute of Technology Department of Mechanical Engineering

Ahmed Hamza H. Ali
Assiut University Faculty of Engineering

Research Article

Keywords: Energy, Exergy, Environmental impact, Economic, evacuated tube, compound parabolic concentrator

Posted Date: January 17th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1150649/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Energy, Exergy, Environmental Impact and Economic (4E) Analysis of ET-CPC-powered Solar Domestic Water Heating System

**Author1 (Corresponding Author)**

**Dinesh Kumar Sharma**

1Department of Mechanical Engineering,  
Swami Keshavanand Institute of Technology, Management and Gramothan, Jaipur-302017, India

2Department of Mechanical Engineering,  
Malaviya National Institute of Technology, Jaipur-302017, India

**Email: dinesh.sharma@skit.ac.in**

**Author 2**

**Dilip Sharma**

2Department of Mechanical Engineering,  
Malaviya National Institute of Technology, Jaipur-302017, India

**Email: sharmadmnit@gmail.com**

**Author 3**

**Ahmed Hamza H. Ali**

3Department of Mechanical Engineering, Assiut University, Assiut-71516, Egypt

**Email: drahmedhamza@yahoo.com, ah-hamza@aun.edu.eg**
Energy, Exergy, Environmental Impact and Economic (4E) Analysis of ET-CPC-powered Solar Domestic Water Heating System

Dinesh Kumar Sharma\textsuperscript{1,2*}, Dilip Sharma\textsuperscript{2}, Ahmed Hamza H. Ali\textsuperscript{3}

\textsuperscript{1}Department of Mechanical Engineering, Swami Keshavanand Institute of Technology, Management and Gramothan, Jaipur-302017, India
\textsuperscript{2}Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur-302017, India
\textsuperscript{3}Department of Mechanical Engineering, Faculty of Engineering, Assiut University, Assiut-71516, Egypt

*Corresponding Author: dinesh.sharma@skit.ac.in

Abstract

World energy demand is increasing continuously; consequently, the environmental impact forces towards utilizing renewable energy resources with efficient and optimized cost-performance conversion technologies. Therefore in this study, an analytical model is developed to propose the energy, exergy, environmental impact and economic (4E) analysis of the water heating system at Jaipur (India) with evacuated tube compound parabolic concentrator ET-CPC field of the total area of 81m\textsuperscript{2}. The model results were validated with the experimental data, and a good agreement has prevailed. After that, the model is used to perform parametric studies on the effect of operating and meteorological parameters on the productivity and performance of the system. Moreover, the system’s performance, environmental impact and economic aspects have been investigated and compared under different meteorological conditions at four different locations in Rajasthan (India) using TMY2 weather data files. Results clarified that Jodhpur receives the highest solar radiation intensity from these four locations. Consequently, the results indicate the highest annual energy and exergy with the value of 79.72 MWh and 9.311 MWh followed by Jaisalmer, Barmer, and Jaipur. The economic analysis results clarified that the simple payback
period ranged from 4.5 to 4.75 years and the discounted payback period ranged from 6.6 to 7 years based on a 6% discount rate. At the same time, the Levelized Cost of Heating (LCOH) ranges from 1.62 to 1.72 INR/kWh of heat compared to closest with CNG as fuel ranging from 4.39 to 4.41 INR/kWh for specified locations. The internal rate of return is reported to be 16.76, 16.82, 16.77, and 16.75% for Barmer, Jodhpur, Jaipur, and Jaisalmer respectively, and savings of 74400, 78125, 75371, and 73813 kg of CO₂ emission to the environment.

**Keywords**

Energy; Exergy; Environmental impact; Economic; evacuated tube; compound parabolic concentrator.

**Nomenclature**

| Symbol | Description |
|--------|-------------|
| CC     | construction cost |
| CF     | cash inflows |
| CPC    | compound parabolic concentrator |
| DPBP   | discounted payback period |
| ETC    | evacuated tube collector |
| ET-CPC | evacuated tube with compound parabolic concentrator |
| FPC    | flat plate collector |
| IRR    | internal rate of return |
| LCOH   | Levelized Cost of Heating |
| PCM    | phase change material |
| PTC    | parabolic trough collector |
| RTD    | resistance temperature detector |
| SDWH   | solar domestic water heating |
| SPBP   | simple payback period |
| SPV    | solar photo-voltaic |
| STC    | solar thermal collector |
| TES    | thermal energy storage |
| TLCC   | total life cycle cost |

**Symbols and notations**

| Symbol | Description |
|--------|-------------|
| A      | area (m²) |
| \(C_f\) | specific heat (J/kg.K) |
| D      | tube diameter (m) |
| dt     | time difference (s) |
| Ex     | exergy (W/m²) |
| f      | friction factor |
| \(F_R\) | heat removal factor |
| \(I_T\) | total solar radiation (W/m²) |
| \(L\) | length (m) |
| \(\dot{m}_f\) | mass flow rate (kg/s) |
1. Introduction

Once a luxury afforded to a precious few, energy has become a commodity that the modern world cannot survive without (Shekarchian et al. 2013). Most of the day-to-day needs of modern society are rigorously increasing the energy demand whether it refers to cooling, heating, or power. Presently, conventional sources dominate to produce electricity and are responsible for contributing harmful pollutants to the environment. Renewable energy such as solar energy has been proven to meet the energy demand partially or fully without carbon footprints being a clean fuel. Solar thermal collectors (STCs) and solar photo-voltaic panels (SPVs) are widely accepted for harnessing solar energy and further utilizing it for cooling, heating, and power. Flat plate collectors (FPCs), compound parabolic concentrator (CPC), evacuated tube collectors (ETCs), parabolic trough collectors (PTCs), etc. are some of the popular STC technologies. Recent innovations and technology advancements such as evacuated tube integrated with CPC (termed as ET-CPC), evacuated tube integrated with PTC, and many others are with improved productivity and efficiency by lowering losses to the environment which resulted in achieving higher
working temperature. Out of these, ET-CPCs are the most preferred for medium operational temperature range (up to 150°C) applications being a stationary type of STC. At the same time, these offer better productivity utilizing diffusive and direct radiations with efficiency ranging from 35 to 55%.

Domestic/community water heating is an essential application that is relatively energy-intensive, and the use of conventional resources such as kerosene, natural gas, wood, coal, and electricity is quite expensive and emits harmful emissions. Formerly, FPCs have been primarily promoted but as time progressed, technology advancement in STCs took place as discussed above. Sokhansefat et al. (2018) compared the FPC and ETC solar collectors in cold climatic conditions based on thermoeconomic and environmental impact analysis. It was reported that the performance of the ETC system is 41% better than the FPC system, and the yearly practical heat gain of ETC is 30% more than that of FPC in any climate zone. Hazami et al. (2013) reported a year-round energy performance monitoring results of a new type of domestic solar water heating system (DSWH) based on ETC. It was also reported that ETC generated about 9% more energy than the FPC under the same climatic condition. Kabeel et al. (2020) reported improved thermal performance of modified ETC with the help of hybrid storage materials and low-cost concentrators. Thermal efficiency improvement of modified design for using hybrid storage materials reached 72.1%. They used 0.0, 2, 3, 4, and 5% graphite nanomaterial mass concentration as hybrid storage materials.

Geete et al. (2019) fabricated compound parabolic solar collectors with evacuated tubes and analyzed the thermal performance of the system. Instantaneous energy efficiency was reported to be 69.87% during their experimental work. Jiang et al. (2015) concluded from their studies that CPC integrated ETCs (ET-CPCs) showed 50% efficiency at 200°C using mineral oils. Ma et al. (2010) reported that improving thermal conductance of working fluid from 5 to 40 W/m.K using ET-CPCs helped increase the efficiency by 10% and outlet temperature by 16%. Hence, the use of CPC reflectors at the backside of the ETC tubes is helpful to increase the collector efficiency by improving the overall aperture area. Similarly, Pie et al. (2012) analyzed the evacuated tube CPC and concluded that the concentrator is helpful to improve the
thermal performance of the ETC in high-temperature ranges. Further, Mills et al. (1986) reported a study on the effect of the acceptance angle of CPC on the performance of the evacuated tubes. They concluded that the acceptance angle is less decisive but the aperture area. Performance of ET-CPC is reported to have negligible effect from the selection of orientations from either North-South or East-West. The selection of reflector material was also discussed and suggested that the use of polished stainless steel is better in terms of cost-effectiveness, durability, and maintenance compared to other mirror materials.

Previously, Mishra et al. (2017) compared the performance of ETC and ET-CPC based on energy and exergy analyses. It was reported that 27.28% extra gain was observed in energy by using evacuated tube CPC compared to that of without CPC. Kerme et al. (2017) presented energy and exergy analysis of solar-powered vapor absorption systems. Furthermore, the result also indicated that the main source of the exergy destruction is the solar collector. In the solar collector, 71.9% of the input exergy was destroyed which accounted for 84% of the total exergy loss. Chopra et al. (2021) reported a 4E analysis of a PCM (palmatic acid) embedded ETC-powered solar water heating system. A significant improvement was shown in energy, exergy, and CO$_2$ mitigation with the use of ETC with PCM compared to without PCM. The results claimed a rise of 36-44% in energy efficiency whereas a rise of 28-35% was observed in exergy efficiency with the use PCM filled in annular space between absorber and tube of ETC.

Battisti and Corrado (2005) applied environmental analysis and optimization to the water storage coupled solar thermal collector. Simapro software program was used to obtain environmental indicators. It was found that the reduction of the impacts could be up to 40% and the environmental payback times were 5–19 months. Faizal et al. (2015) applied the energy, exergy, economic, and environmental analysis on a flat-plate solar collector operated with SiO$_2$ nanofluid. It was found that the energy and exergy efficiencies of nanofluids were higher than base fluids. Also, CO$_2$ emissions and payback periods of nanofluids are better. Bellos et al. (2017) reported a 4E analysis for a solar-assisted refrigeration system for various operating scenarios. Evacuated tube collectors fed heat to the generator of the vapour
absorption chiller. The electricity savings were 53.98%, the IRR 6.6%, and the payback period close to 14 years.

Thus, it can be concluded that ET-CPCs are quite efficient at elevated temperatures up to 200°C and have no need for a solar tracking mechanism, which makes them a preferred choice over FPC. Along with this, these utilize diffuse and direct types of solar radiation. The thermodynamic performance of ET-CPCs based solar water heating systems has been measured through energy and exergy analyses. Energy analysis is conservative as per the first law of thermodynamics which typically involves energy efficiency and gain. On the other hand, exergy analysis helps to determine the energy transactions based on quality. Exergy analysis denotes the maximum theoretical work that can be obtained in a given set of environmental conditions. Hence, a thermodynamic system can be better assessed with the help of an exergy method (Caliskan 2017). Also, exergy analysis helps to determine the sustainability of the system (Moran and Shapiro 1993). An overall analysis of the system is incomplete without understanding its monetary transactions and environmental impact during its entire useful life (Dincer and Rosen 2007a)(Meyer et al. 2009)(Tsatsaronis and Morosuk 2012). The first law of thermodynamics is widely used for energy utilization analysis. However, it is limited because it is incapable of quantitatively determining the quality of energy. On the other hand, the second law of thermodynamics supplants this limitation by introducing the exergy analysis that quantifies the potential helpful work for a given amount of energy. Therefore, it is essential that both the quantity and quality of the energy used for practical energy usage be considered (Saidur et al. 2013)(Cengel and Boles 2019). Expressing the true efficiency makes the exergy a powerful tool in sectoral energy analysis and engineering design (Rosen and Dincer 1997). It should be pointed out that economic analysis is indirectly affected by environmental impact and energy analysis results.

In the present work, an analytical model is developed to carry out energy, exergy, environmental impact and economic analysis of an 81 m² ET-CPC powered solar water heating system equipped with thermal energy storage. Along with this, a parametric study is also performed to report the effect of mass flow
rate, solar radiation intensity, and ambient temperature on productivity and efficiency of reported
installation at various fluid inlet temperatures. It was identified that overall analysis of ET-CPC-based
applications are less reported in the literature and thus sufficient data is not available which can be
otherwise helpful to promote its use. Thus, the thermodynamic performance of the SDWH system with its
environmental impact and economic aspects has been investigated and compared under meteorological
conditions of four different locations of Rajasthan (India) using TMY2 weather data files.

2. System Description and Methodology

The system presented in this research is installed at the roof and front lawn of the Department of
Mechanical Engineering, Malaviya National Institute of Technology, Jaipur (26.86° N, 75.81° E). The
schematic and actual photograph is presented in Figure 1. Each ET-CPC module has an effective area of 3
m². As shown in Figure 1, the installed ET-CPC field is arranged as six rows having four ET-CPCs in
series, and one row has three ET-CPCs in-series constituting a total aperture area of 81 m² with 27 ET-
CPC modules. These ET-CPCs are connected with a sensible thermal energy storage tank (containing
soft water as a working medium) with the help of a centrifugal pump. Figure 2 shows the pictorial view of
the ET-CPC solar field. The technical descriptions of the ET-CPC, thermal energy storage tank, and pump
are provided in Table 1. There is no load considered to this system in the specified time. Various
thermocouples, RTDs, and flow meters have been installed as shown in Figure 1 and a 16 channel
Masibus 85xx+ data logger has been used to integrate these data.

This study developed an analytical model for energy, exergy, environmental impact and economic
analysis of this SDWH. Further, experimental validation of the model is carried out using energetic
efficiency and useful heat gain from the system. A parametric study is also made to investigate the effect
of the mass flow rate of working fluid, solar radiation intensity, and ambient temperature on the
productivity and efficiency of the system. Four potential locations have been identified from Rajasthan
(India); Barmer, Jodhpur, Jaisalmer, and Jaipur. Weather data have been taken from the TMY2 file of
these identified locations for ambient temperature and solar radiation intensity around the year. Energy
and exergy gain along with energy efficiency and exergetic efficiency is then estimated and compared for the specified locations. As discussed earlier, no analysis could be decisive without environmental and economic evaluation. Hence, environmental analysis is carried out to show the amount of CO$_2$ emissions saved. In the latter section, economic analysis is done while comparing SDWH with the conventional methods of water heating.

Figure 1 Schematic diagram of ET-CPC solar domestic water heating system
Figure 2 Pictorial view of ET-CPC solar collector field installed on MNIT, Jaipur roof top

Table 1 Technical description of the various components in the system

| Description                                      | Unit | Technical Specification |
|--------------------------------------------------|------|-------------------------|
| Solar Collectors                                 |      |                         |
| No. of evacuated tubes                           | nos. | 18                      |
| $\eta_0$ concerning aperture, EN12975            | %    | 64.2                    |
| Heat transfer Coefficient ($a_1$)                | (W/m$^2$K) | 0.89                |
| Temperature dependent transfer Coefficient ($a_2$) | (W/m$^2$K$^2$) | 0.001             |
| Grid dimensions                                  | m    | 2.08 x 1.64 x 0.10      |
| Aperture area                                    | m$^2$| 3.41                    |
| Max Working overpressure                         | bar  | 10                      |
| Max Stagnation temperature                       | °C   | 250                     |
| Glass Tube Material                              |      | Borosilicate Glass 3.3  |
| Selective Absorber coating material              |      | Aluminum Nitride        |
| Glass Tube (Φ Ext/ Φ Int/ Wall) thickness/Tube length | mm     | 47/37/1.6/1500            |
| Make                                             |      | Linuo-Ritter            |
| Hot Storage Tank                                 |      |                         |
| Tank Diameter                                    | m    | 1                       |
| Tank Length                                      | m    | 3.5                     |
| Volume of Tank                                   | m$^3$| 2.2                     |
| Material of Tank                                 |      | Mild Steel              |
| Insulation Material                              |      | Fiberglass of 50 mm thickness cladded with aluminium sheet |
| Orientation of Tank                              |      | Horizontal              |
| Hot Water Pump                                   |      |                         |
| Hot Water Pump at 25 m head                      | m$^3$/hr | 5.4                 |

Table 2 Design parameters of ET-CPC field

| Parameter | Value       |
|-----------|-------------|
| $R$       | 0.0185 m    |
| $C_f$     | 4186 J/kg.K |
| $L$       | 1500 mm     |
| $A_r$     | 0.1734 m$^2$|
| $A$       | 0.2215 m$^2$|
| $A_{c, total}$ | 81 m$^2$ |
| $n$       | 12          |
| $\tau$   | 0.95        |
3. Energy, Exergy, Environment impact and Economic Analysis

3.1 Energy analysis of ET-CPC

Energy analysis for ET-CPC first involves the rise in fluid inlet temperature upon exit point from the ET-CPC arrays. This temperature gain is achieved from the equations developed by Mishra et al. (2017). It’s essential to understand the flow distribution inside an ET-CPC module so that assessment of flow rate inside a tube could be done perfectly. Figure 3 shows the flow scattering inside a single module of ET-CPC which supports the precise number of evacuated tubes linked in series in the current setup.

Table 3 Energy Analysis of ET-CPC

| Eq. No. | Description |
|---------|-------------|
| 1       | \( T_{out,n} = \frac{(A_L F_R \alpha \tau)^n}{n F_C f} \times \frac{(1 - K_{eff})^n}{(1 - K_{eff})} I_T + \frac{(A_L F_R U_L)^n}{n F_C f} \times \frac{(1 - K_{eff})^n}{(1 - K_{eff})} T_{amb} + K_{eff}^n T_{in} \) |
| 2       | Practical heat gain for the n-tube connected in series is given as: \( Q_{useful,n} = (\alpha \tau)_{eff} I_T - (UA)_{eff} (T_{in} - T_{amb}) \) |
Where,

$$(\alpha \tau)_{\text{eff}} = A_c F_k \alpha \tau \left( \frac{1 - K^n_{\text{eff}}}{1 - K_{\text{eff}}} \right)$$

$$(UA)_{\text{eff}} = A_r F_h U_L \left( \frac{1 - K^n_{\text{eff}}}{1 - K_{\text{eff}}} \right)$$

Instantaneous thermal efficiency ($\eta_{\text{instantaneous}}$) is given as

$$\eta_{\text{instantaneous}} = \frac{Q_{\text{useful}}}{\eta_{\text{opt}} \times A_{c,total} \times I_T}$$

Figure 3 Fluid Flow Diagram inside an ET-CPC module

Table 3 describes reduced equations for desired energy analysis of ET-CPC solar field. In the existing setup, each ET-CPC module involves 18 evacuated tubes and four modules linked in series to create an array and equally 7 rows are arranged parallel. Hence, 12 tubes are linked in series and hence mass flow rate is distributed in 7 rows and 6 subdivisions. Hence, a total mass flow rate is 0.83 kg/s out of centrifugal pump rated discharge 1.5 kg/s because of pressure drop.
due to ET-CPC solar collectors but only 0.0198 kg/s mass flow rate is observed inside any particular evacuated tube for this setup as shown in Figure 3.

Since this system’s thermal energy storage is 2.2 m$^3$ in volume and oriented horizontally, a complete energy mix model is considered inside the TES tank. Further, energy gain is calculated as the successive sum of the energy gains, and subsequent temperature rise at any given time is treated as per equation (3) of Table 3.

### 3.2 Exergy analysis of ET-CPC

As stated in the Introduction section, reported literature mainly considers the physical conditions for exergy analysis and further for exergy gain. These models did not reflect the actual in-sight on the exergy destructions in each phase. Thus presented model is prepared concerning various possible destructions while performing exergy analysis therefore, accurate results could be presented. Figure 4 reports the various exergy destructions from an ET-CPC tube, and table 4 shows the various equations reduced for exergy analysis.

![Figure 4 Representation of various Exergy Destruciions inside a single ET-CPC](image_url)

Table 4 Exergy Analysis of ET-CPC
### Exergy Analysis of ET-CPC

| **Eq. No.** | **Exergy balance equation in the steady-state condition** |
|-------------|----------------------------------------------------------|
| 4           | \( \dot{E}_{\text{net}} = \Delta \dot{E}_{\text{opt}} + \Delta \dot{E}_{\text{abs}} + \Delta \dot{E}_{\text{thermal}} + \Delta \dot{E}_{\text{cond}} + \Delta \dot{E}_{\text{friction}} + \dot{E}_{\text{useful}} \) |

### Exergy inlet (Petela 2003, 2005)

\[
\dot{E}_{\text{in}} = \dot{E}_{\text{sun}} = A_{c,\text{total}} I_T \varphi_{\text{solarrad, max}}
\]

\[
\varphi_{\text{solarrad, max}} = \left[ 1 + \frac{1}{3} \left( \frac{T_{\text{amb}}}{T_{\text{sun}}} \right)^4 - \frac{4}{3} \left( \frac{T_{\text{amb}}}{T_{\text{sun}}} \right) \right]
\]

### Exergy destruction due to optical

\[
\Delta \dot{E}_{\text{opt}} = \dot{E}_{\text{sun}} (1 - \eta_{\text{opt}})
\]

### Exergy destruction due to absorption

\[
\Delta \dot{E}_{\text{abs}} = \eta_{\text{opt}} \left( \dot{E}_{\text{sun}} - I_T \times A_{c,\text{total}} \left( 1 - \frac{T_{\text{amb}}}{T_{\text{receiver}}} \right) \right)
\]

### Exergy destruction due to thermal losses

\[
\Delta \dot{E}_{\text{thermal}} = K_{\text{loss}} \left( T_{\text{surface}} - T_{\text{amb}} \right) \left( 1 - \frac{T_{\text{amb}}}{T_{\text{surface}}} \right)
\]

### Exergy destruction due to conduction

\[
\Delta \dot{E}_{\text{cond}} = T_{\text{amb}} (\Delta S_{\text{cond}})
\]

\[
\Delta S_{\text{cond}} = \int_{T_{\text{in}}}^{T_{\text{out}}} \frac{n \dot{E}_j C_f dT}{T} - \frac{1}{T_{\text{receiver}}} \int_{T_{\text{in}}}^{T_{\text{out}}} n \dot{E}_j C_f dT
\]

\[
\Delta S_{\text{cond}} = n \dot{E}_j C_f \left[ \ln \left( \frac{T_{\text{out}}}{T_{\text{in}}} \right) - \left( \frac{T_{\text{out}} - T_{\text{in}}}{T_{\text{receiver}}} \right) \right]
\]

### Exergy destruction due to pipe friction (Bejan et al. 1981)

\[
\Delta \dot{E}_{\text{friction}} = \frac{n \dot{E}_j T_{\text{amb}} \Delta P}{\rho_f T_{\text{in}}}
\]

\[
\Delta P = f \rho_f L \frac{V^2}{2D}
\]
\[
f = \frac{64}{\text{Re}}, \text{ for } \text{Re} \leq 2200
\]
\[
f = 0.316 \text{Re}^{-0.25}, \text{ for } \text{Re} > 2200
\]
\[
\text{Re} = \frac{\rho_f \text{V} \text{D}}{\mu_f}
\]

**Exergy useful**

\[
\dot{E}_{\text{ex, useful}} = \dot{E}_{\text{ex, in}} - (\Delta \dot{E}_{\text{ex, opt}} + \Delta \dot{E}_{\text{ex, abs}} + \Delta \dot{E}_{\text{ex, thermal}} + \Delta \dot{E}_{\text{ex, cond}} + \Delta \dot{E}_{\text{ex, friction}})
\]

**Total Exergy gain**

\[
E_{\text{x, gain, total}} = \int (\dot{E}_{\text{ex, useful}} \cdot A_{\text{total}}) \text{d}t
\]

**Exergetic efficiency**

\[
\psi_{\text{exergetic}} = \frac{\dot{E}_{\text{ex, useful}}}{\dot{E}_{\text{ex, in}}}
\]

### 3.3 Thermodynamic Analysis of Thermal Energy Storage

Thermodynamic analysis of thermal energy storage has been performed under actual environmental conditions during the charging, storing, and discharging phase. Equations for energy and exergy parameters have been reduced as presented in Table 5, and these are analyzed in conjunction with the performance of ET-CPC.

| Thermodynamic Analysis of Thermal Energy Storage | Eq. No. |
|------------------------------------------------|---------|
| **TES charging stage** (Rezaie et al. 2015) |         |
| **Energy Balance** (Dincer and Rosen 2007)(Rosen and Dincer 2003) |         |
| \[
\dot{Q}_{\text{in, TES}} - \dot{Q}_{\text{loss, TES}} = \Delta U_{\text{charging}}
\] |         |
| \[
\Delta U_{\text{charging}} = m_{\text{total}} C_f \Delta T_m
\] |         |
| \[
m_{\text{charging}} = \frac{\dot{Q}_{\text{m, TES}}}{C_f (T_{e, in} - T_{e, out})}
\] | 14      |
Energy Efficiency

\[ \eta_{\text{charging}} = \frac{\text{Energy accumulated in TES}}{\text{Energy Input}} = \frac{\Delta U_{\text{charging}}}{Q_{\text{in,TES}}} \]  

**Exergy Balance**

\[ Ex_{e,\text{in}} = m_{\text{charging}} \left[ (h_{\text{in}} - h_{\text{out}}) - T_{\text{amb}} (s_{\text{in}} - s_{\text{out}}) \right] \]

\[ Ex_{e,\text{loss}} = Q_{\text{loss,TES}} \left( 1 - \frac{T_{\text{amb}}}{T_m} \right) \]

\[ Ex_{e,\text{accum}} = Ex_{c,f} - Ex_{c,i} = m_{\text{total}} \left[ (u_{c,f} - u_{c,i}) - (s_{c,f} - s_{c,i}) \right] \]  

Exergy Destruction

\[ \Delta Ex_{\text{charging}} = Ex_{e,\text{in}} - Ex_{e,\text{loss}} - Ex_{e,\text{accum}} \]

Exergy Efficiency

\[ \psi_{\text{charging}} = \frac{\text{Exergy accumulated in TES}}{\text{Exergy Input}} = \frac{Ex_{e,\text{accum}}}{Ex_{e,\text{in}}} \]  

**TES Storing Stage**

Energy Efficiency

\[ \eta_{\text{storing}} = \frac{\text{Energy Accumulation in TES during charging and storing}}{\text{Energy Accumulation in TES during charging}} \]  

Exergetic Efficiency

\[ \psi_{\text{storing}} = \frac{\text{Exergy Accumulation in TES during charging and storing}}{\text{Exergy Accumulation in TES during charging}} \]

**TES Discharging Stage**

Energy recovered

\[ Q_{\text{rec}} = - (\Delta U_{\text{discharge}} + Q_{\text{loss,TES}}) \]

\[ \Delta U_{\text{discharge}} = m_{\text{total}} C_f \Delta T_m \]

\[ m_{\text{discharging}} = \frac{Q_{\text{rec}}}{C_f (T_{d,\text{out}} - T_{d,\text{in}})} \]  

Energy Efficiency

\[ \eta_{\text{discharging}} = \frac{\text{Energy recovered by TES}}{\text{Energy released by TES}} = \frac{Q_{\text{rec}}}{Q_{\text{rec}} + Q_{\text{loss,TES}}} \]
Exergy recovered

\[ Ex_{rec} = m_{\text{discharge}} \left( h_{d,\text{out}} - h_{d,\text{in}} \right) - T_{\text{amb}} \left( s_{d,\text{out}} - s_{d,\text{in}} \right) \]

Exergy accumulation

\[ Ex_{d,\text{accum}} = Ex_{d,f} - Ex_{d,i} = m_{\text{total}} \left( u_{d,f} - u_{d,i} \right) - \left( s_{d,f} - s_{d,i} \right) \]

Exergy destruction

\[ \Delta Ex_{\text{discharging}} = Ex_{d,in} - Ex_{d,loss} - Ex_{d,\text{accum}} \]

Exergy efficiency

\[ \psi_{\text{discharging}} = \frac{\text{Exergy recovered by TES}}{\text{Exergy accumulated in TES}} = \frac{Ex_{rec}}{Ex_{d,\text{accum}}} \]

Overall Energy and Exergy efficiency

Energy efficiency

\[ \eta_{O,TES} = \frac{\text{Energy recovered from TES during discharging}}{\text{Energy input to TES during charging}} = \frac{\sum Q_{\text{rec}}}{\sum Q_{\text{in,TES}}} \]

Exergy efficiency

\[ \psi_{O,TES} = \frac{\text{Exergy recovered from TES during discharging}}{\text{Exergy input to TES during charging}} = \frac{\sum Ex_{\text{rec}}}{\sum Ex_{\text{in}}} \]

3.4 Environmental Impact Analysis

With the ever-increasing concern about the environmental impact and specifically global warming due to greenhouse gases, it has become essential to evaluate and analyze the newly designed and developed system environmentally before heading forward. The developed system was weighed on an environmental impact basis which is quantified based on saving on carbon dioxide emissions. The change resulted in significant savings in CO₂ yearly and finally a lesser carbon footprint.

The annual social cost of CO₂ emission varies from one country to another. The cost of penalty for CO₂ emissions is calculated using the relation,

\[ \dot{z}_{\text{env}} = m_{\text{CO}_2} \cdot C_{\text{CO}_2} \]

(29)
In above equation $C_{co2}$ is the cost of unit carbon dioxide production and it varies from 0.022
1.63 INR/kg to 9.62 INR per kg of CO$_2$ emissions. In our study, prices of developing countries
have been chosen which is 3.7 INR/kg. Here $m_{co2}$ is the mass of CO$_2$ emission and has been
calculated using emission conversion factor as follows:

$$m_{co2} = \lambda \cdot Power \ consumption \ in \ kWh$$

Where, $\lambda$ is the emission conversion factor having a value of 0.968 kg/kWh. It is essential to
mention that India’s energy mix has been used to obtain the results. Here it is taken as 1 kWh$e$
leading to 0.968 kg of CO$_2$ production.

### 3.5 Economic Analysis

Whether cooling, heating, or power, every solar-based system has indirect benefits in terms of
environmental protection, lower health costs, and global climate benefits, but never a decision on
investment in renewable systems are made on this basis. Quite a few times, lawmakers provide
incentives that may attract investment when looking to these social benefits. However, any
system must sustain itself until its financial viability or beneficiary.

The fossil-based system is relatively cheaper in terms of initial cost but they have a higher
recurring cost including regular energy billing, maintenance cost, etc. whereas the Solar-based
system is characterized by a high initial cost and negligible operating cost. Therefore it is very
much needed that the life cycle cost approach has to be adopted when comparing the solar-based
systems with the conventional-based systems.

The concept of life cycle cost includes both the initial investment cost and year-to-year operating
cost in making economic decisions. The life cycle cost of any energy system is the total of the
following cost made in its life term:
1. The initial capital cost includes the cost of equipment, installation and land cost (if any).

2. Its running cost throughout its life.

3. Interest cost, if money is invested through borrowing.

4. Periodic maintenance cost of equipment or any miscellaneous cost.

5. Taxes

6. Salvage value, if any at the end of its life span.

The first cost includes all the costs of owning the equipment and normally is one time. It includes the cost of equipment, installation cost, and the cost of land, if applicable. On the other hand, operation and maintenance cost includes the cost incurred during the life cycle of the domestic water heating system year on year for operating the system which includes recurring electricity cost for operating the system. During the economic evaluation of any solar-based system, the initial investment made has to be weighted over the intended benefits in terms of heat, power, or cooling which the system is supposed to provide. Hence the present value of future anticipated benefits needs to be evaluated. Various financial performance parameters are analyzed over here, refer to Table 6.

Table 6 Indicators of Economical Analysis

| Economical Analysis Indicators/Parameters                  | Eq. No. |
|------------------------------------------------------------|---------|
| **Simple payback period (SPBP)**                           |         |
| \( SPBP = \frac{CC}{CF} \)                               | Eq. 31  |
| **Discounted payback period (DPBP)**                       |         |
| \( DPBP = \frac{\ln \left( \frac{1}{1 - \frac{CC}{CF}} \right)}{\ln(1+r)} \) | Eq. 32  |
Internal Rate of Return

\[ 0 = \sum_{n=1}^{N} \frac{CF_n}{(1+IRR)^n} + CI \]

Levelized Cost of Heating (LCOH)

\[ LCOH = \frac{TLCC}{E_n} \left[ \frac{1-(1+i)^{-n}}{l} \right] \]

4. Results and Discussion

4.1 Experimental Validation of Analytical Model

Figure 5 shows the schematic diagram of the setup discussed above. However, only a solar hot charging loop is considered in this present study. Data received from different RTD sensors, mass flow sensors, pyranometer, and ambient temperature thermocouple have been integrated into the data logger and then the performance of ET-CPC coupled with a hot storage tank is discussed by

It is observed from this experimental validation that relative difference is within the range of 3-8%. Hence, there is a good agreement between the values from this analytical model and experimental results.
4.2 Parametric Analysis

This parametric study shows the effect of mass flow rate, solar radiation intensity and ambient temperature on the productivity and efficiency of the ET-CPC. A typical range of mass flow rate is taken from 0.0132 to 0.0357 kg/s through tubes of ET-CPC. The values of solar radiation intensity are considered from 200 to 1000 W/m² varying in the steps of 100 W/m². The ambient temperature values range from 27 to 43°C.

4.2.1 Effect of mass flow rate
Figure 6 Effect of Mass Flow Rate on outlet temperature at a different inlet temperature

Figure 6 shows the variation of the system outlet temperature based on the mass flow rates. The solar radiation intensity has been kept at 1000 W/m² while the ambient temperature is kept at 27°C. Inlet temperatures have been varied from 30 to 90°C within the steps of 10°C. For the different inlet temperatures, the slopes of the curves are declining in nature, which also supports the theoretical knowledge. The slope of the curves decreases with the increase in inlet temperature. The slope of the curve for 30°C is steepest and the slope of the curve for 90°C inlet temperature is flattened.
Figure 7 Effect of Mass Flow Rate on $Q_{useful}$ at different inlet temperatures

Figure 7 shows the effect of mass flow rate over the useful heat gain for various inlet temperatures keeping solar radiation intensity 1000 W/m$^2$ and ambient temperature 27°C. Useful heat gain varies proportionally with the mass flow rate. $Q_{useful}$ is higher for the lower inlet temperatures and vice-versa. At 30°C inlet temperature, the useful heat gain is highest and for 90°C inlet temperature, useful heat gain is lowest. This is since heat loss to the environment increases as the inlet temperature increases and lowers as the mass flow rate increases.

Figure 8 Effect of Mass Flow Rate on instantaneous efficiency with different inlet temperatures
Figure 8 shows the effect of mass flow rate over instantaneous efficiency of ET-CPC for various inlet temperatures at the solar intensity and ambient constant as described earlier. As the mass flow rate increases, the system’s instantaneous efficiency is also increases and vice-versa. Instantaneous efficiency is better for lower inlet temperatures and reduces as temperature increases. The highest instantaneous efficiency is recorded at inlet temperature at 30°C and mass flow rate of 0.0357 kg/s.

![Figure 9 Effect of Mass Flow Rate on Heat Removal Factor](image)

The heat removal factor is an important design parameter as it is a measure of thermal resistance encountered by the absorbed solar radiation is reaching the collector fluid. Figure 9 shows the effect of mass flow rate on the heat removal factor. This can be concluded that there is an increasing trend for heat removal factor, however, this increase in heat removal factor is not significant thus an average value of 0.5635 is taken for further evaluation.

**4.2.2 Effect of solar radiation intensity**

The effect of solar radiation intensity is quite essential to assess as an operating parameter since it is the base for any type of solar energy projects without which proper sizing and economics of
solar energy projects cannot be estimated. The effect of solar radiation intensity on outlet temperature is shown in Figure 10. The solar radiation intensity is ranging from 200 to 1000 m² taking fluid inlet temperature of 27°C and a constant mass flow rate of 0.0357 kg/s. There is an obvious increase in the fluid outlet temperature corresponding to the increase in the solar radiation intensity. However, as the inlet temperature increases, the outlet temperature increases proportionally with the solar radiation intensity.

Figure 10 Variation of the outlet temperature as a function of the solar radiation intensity for various inlet temperatures

Figure 11 Effect of solar radiation intensity on useful heat gain
Figure 11 shows that solar radiation intensity’s effect on useful heat gain for various inlet temperatures ranging from 30°C to 90°C. As mentioned earlier, while showing this mass flow rate is kept as 0.0357 kg/s, and ambient temperature is taken as 27°C. It can be noted from the figure that useful heat gain is directly proportional to the solar radiation intensity. For 30°C inlet temperature, the useful heat gain is highest and lowers as the inlet temperature increases. Useful heat gain is ranges between 40-46 kW for a given system’s solar radiation intensity of 1000 W/m².

Figure 12 Effect of solar radiation intensity on instantaneous efficiency

Figure 12 represents the effect of solar radiation intensity on instantaneous efficiency for various inlet temperatures as discussed earlier. The instantaneous efficiency usually increases with the increase in the solar radiation intensity. The highest instantaneous efficiency was observed at 30°C inlet temperature at solar radiation intensity of 1000 W/m². As the inlet temperature of fluid increases, instantaneous efficiency decreases. This is mainly because of higher heat losses to the environment at higher inlet temperatures. However, these relative differences reduce at the
higher value of solar radiation intensity. Further, it can be observed that instantaneous efficiency
is still in the range of 40-50% which is significantly better than any other stationary STC.

4.2.3 Effect of Ambient Temperature

The effect of ambient temperature on productivity is reported in this section. The solar radiation
intensity is considered as 1000 W/m² along with a constant mass flow rate of 0.0357 kg/s. Figure
13 shows the effect of ambient temperature over fluid outlet temperature for various inlet
temperatures. It is observed that there is no significant variation observed in the fluid outlet
temperatures with ambient temperatures. Hence it can be concluded from this discussion that
ambient is the least dominant factor which affects the productivity of ET-CPC and further, useful
heat gain and instantaneous efficiency.

![Figure 13 Effect of ambient temperature on Outlet temperature with different inlet temperatures](image)

4.3 Evaluation of Useful energy and exergy gain under actual meteorological conditions

As mentioned earlier, four meteorological conditions of Rajasthan (India) have been considered.
Data have been recovered using the TMY2 file for these identified locations. The information
has been used in the model to evaluate the variation of productivity and efficiency for the stated
ET-CPC powered SDWH system with the help of various indicators of energy and exergy analysis such as useful heat gain, instantaneous efficiency, exergy gain, and exergetic efficiency. The results have been shown in stack form altogether to have a better and direct comparison of these identified indicators.

(a)

(b)
Figure 14 Radiation Intensity curves for (a) Barmer (b) Jodhpur (c) Jaisalmer (d) Jaipur

Figure 14 (a), (b), (c) and (d) shows the solar radiation intensity variation for year-round at Barmer, Jodhpur, Jaisalmer, and Jaipur respectively. The highest solar radiation intensity data are recorded between April and June while the lowest is recorded between November and January. The highest solar intensity is observed around 12 PM for nearly every month. The highest value
of solar intensity is recorded as 1075, 1093, 1033 and 985 W/m² for Barmer, Jodhpur, Jaisalmer and Jaipur respectively.
Figure 15 Ambient temperature curves for (a) Barmer (b) Jodhpur (c) Jaisalmer (d) Jaipur

Figure 15 (a), (b), (c), and (d) shows the variation of ambient temperature around the year for Barmer, Jodhpur, Jaisalmer and Jaipur respectively. It is observed that the highest ambient temperature achieved in the month May and lowest ambient temperature in the month January around 2 PM. The highest ambient temperature was recorded as 41.3, 38.5, 40.9 and 39°C for
Barmer, Jodhpur, Jaisalmer and Jaipur respectively while the lowest temperature recorded was 15°C for Jaisalmer for a specified time of the day. The warmest months are May, June and July for all specified locations while the coldest months are December, January and February.

4.3.1 Energy Analysis

Figure 16 (a) shows a comparison analysis between the solar radiation intensity, useful heat gain and instantaneous efficiency under the meteorological condition of Barmer for the different-different months of a typical meteorological year (TMY). Similarly, Figures 16 (b), (c) and (d) are showing useful heat gain, instantaneous efficiency and solar radiation intensity for different months at locations Jodhpur, Jaisalmer and Jaipur respectively. The curve shows that the highest solar radiation intensity 1075 W/m$^2$ measured in May month. Similarly, the useful heat gain curve also has a higher value of 45.03kW during April and May. It is observed from the Figure that the solar radiation intensity and $Q_{useful}$ are greater in the summer season months. But the instantaneous efficiency curve shows the higher values for the winter months. It is mainly because of the higher temperature difference between the inlet and outlet fluid in winter and efficiency is directly proportional to this temperature difference so the instantaneous efficiency is higher in December and January.

The highest value was measured as 67.25% in January. Similarly, the highest solar radiation intensity comes 1093 W/m$^2$ for Jodhpur followed by 1033 and 985 W/m$^2$ for Jaisalmer and Jodhpur locations during April and May. Accordingly, the $Q_{useful}$ is measured higher for April, May and June. The highest value of $Q_{useful}$ is recorded as 46.02 kW for Jodhpur followed by 42.86 and 40.67 kW for Jaisalmer and Jaipur respectively during April and June. However, as discussed earlier, the highest instantaneous efficiency of 66.64% for Jodhpur is recorded during January followed by 67.14 and 66.53% for Jaisalmer and Jodhpur respectively.
Solar Radiation Intensity

Quseful

Efficiency (Instantaneous)
Figure 16 Parameters indicating Energy Analysis under meteorological condition of (a) Barmer (b) Jodhpur (c) Jaisalmer (d) Jaipur
4.3.2 Exergy analysis

Figure 17 (a), (b), (c) and (d) manifests the exergy analysis consisting of three parameters as amount of exergy inlet, amount of useful exergy and exergetic efficiency for various months under the meteorological conditions of Barmer, Jodhpur, Jaisalmer and Jaipur respectively. The first part of the curves elucidates the exergy variation in other months. The maximum exergy in measured as 80.74 kW during May month. This curve also illustrates that the amount of exergy is higher in the summer season and lower in the winter season. It is mainly because of the higher solar radiation intensity in summers as compared to the winters. The second and third parts of these curves illustrate the behavior of exergy gain and exergetic efficiency for different specified locations during different months. The highest value of exergy gain is observed during April and June. It is observed as 7.50 kW for Jodhpur followed by 7.33, 7.17 and 7.09 kW for Barmer, Jaisalmer and Jaipur respectively during May. The exergetic efficiency is observed as 10.57% for Barmer during May. Since the amount of exergy useful is higher and subsequently exergetic efficiency is also higher. The highest exergetic efficiency is again recorded for Jodhpur as 11.05% during June. The highest exergetic efficiency for Jaisalmer and Jaipur is recorded as 10.58 and 10.55% respectively.
Figure 17 Parameters indicating Exergy Analysis under meteorological condition of (a) Barmer
(b) Jodhpur (c) Jaisalmer (d) Jaipur
However, a comparison is essential to discuss site selection to indicate the annual useful heat gain and useful exergy gain for all specified locations. Figure 18 shows the comparison of solar energy received by the ET-CPC solar field, useful heat gain, exergy inlet and exergy gain annual for the specified locations Barmer, Jodhpur, Jaipur and Jaisalmer. As observed Jodhpur is having the most excellent solar radiation 162 MWh/year and thus highest annual useful energy and exergy gain as reported to be 79.72 MWh and 9.311 MWh annually. Jaisalmer receives 157.85 MWh of solar radiation per year which is getting converted to 76.90 MWh/year of useful heat gain. Exergy gain calculated for Jaisalmer is 8.53 MWh concerning inlet Exergy of 146.63 MWh per year. Similarly for useful heat gain is as 75.92 and 75.32 MWh/year for Barmer and Jaipur respectively. Exergy gain for Barmer and Jaipur is calculated as 8.4 and 8.32 MWh/year respectively.

Figure 18 Solar energy-exergy graph comparison for four different meteorological condition

4.4 Environmental Impact Analysis

The use of solar energy is always helpful to overcome CO₂ emission-related environmental impact issues such as global warming, smog, acid rain and rise in mean global ambient
temperature. This analysis reports the massive savings of CO\textsubscript{2} emission compared to the other existing conventional solar water heating systems. Figure 19 represents the CO\textsubscript{2} emission saved in kg of CO\textsubscript{2} for various identified locations.

![Graph showing CO\textsubscript{2} emissions saved for different locations](image)

**Figure 19** Comparison of CO\textsubscript{2} emission saved with the use of solar energy for identified locations

### 4.5 Economic Analysis

As discussed earlier, economic analysis is quite an essential to compare different existing technologies based on profitability. A detailed economic analysis has been reported here to understand the effect of location on cost recovery and other indicators of economic profitability. There are five conventional fuels-based water heating systems for the economic comparison with the existing solar water heating system. Table 7 shows the different fuels used for water heating and their corresponding price, conversion efficiency and calorific value of fuels.

**Table 7** Comparison of price, conversion efficiency and calorific values for various fuels

| Sr. No. | Fuel     | Units   | Price | Conversion Efficiency | CV Fuel (MJ/kg) |
|---------|----------|---------|-------|-----------------------|-----------------|
| 1       | Electricity | per kWh | 9.84  | 0.9                   | 3.6 (MJ/unit)   |
| 2       | LPG      | per kg  | 86.34 | 0.6                   | 55              |
Table 8 shows the installation cost or first cost of the different water heating systems. It can be easily identified that the first cost of a solar water heating system is significantly higher than those of other systems. Table 9 reports the annual operation and maintenance cost of various fuels while Table 10 shows the estimated life expectancy of the selected systems. Economic evaluation is done based on equations reported in Table 6. Table 11 describes the internal rate of return and payback periods. The internal rate of return is 16.82% for Jodhpur followed by 16.77, 16.76 and 16.75 for Jaipur, Barmer and Jaisalmer respectively. Similarly simple payback period is 4.49, 4.65, 4.72 and 4.75 years for Jodhpur, Jaipur, Barmer and Jaisalmer respectively. The discounted payback period is also calculated which is ranging from 6.6 to 7.09 years similarly for identified locations.

Table 8 Comparison of First Cost for various water heating systems

| System                                      | First Cost in INR |
|---------------------------------------------|-------------------|
| ET-CPC Solar Water Heating                  | 947520            |
| Electricity based Water Heater              | 250000            |
| LPG/Kerosene/CNG operated water heaters     | 226762            |
| Firewood operated water heater              | 250000            |

Table 9 O&M cost for various locations for different fuels

| Sr. No. | Fuel      | Units | Price | Conversion Efficiency | CV Fuel (MJ/kg) | Barmer  | O&M Cost (INR) | Jodhpur | Jaipur | Jaisalmer |
|---------|-----------|-------|-------|-----------------------|-----------------|---------|----------------|---------|--------|-----------|
| 1       | Electricity| per   | 9.84  | 0.9                   | 3.6             | 830043  | 871598         | 873202  | 823490 |           |
Table 10 **Life expectancy of equipment**

|                           | Expected Life (Solar System) | 15 years |
|---------------------------|-----------------------------|----------|
|                           | Expected Life (Electricity heating system) | 15 years |
|                           | Expected Life (LPG/CNG/Kerosene fired heating system) | 15 years |
| **Discount Rate**         |                             | 6% annual |

**Table 11 Comparison of IRR and payback periods for identified locations for solar water heating system**

| Location     | IRR(%) | SPBP (Yr) | DPBP (Yr) |
|--------------|--------|-----------|-----------|
| Barmer       | 16.76  | 4.7169    | 7.024     |
| Jodhpur      | 16.82  | 4.492     | 6.615     |
| Jaipur       | 16.77  | 4.656     | 6.912     |
| Jaisalmer    | 16.75  | 4.7543    | 7.093     |

A comparison of operation and maintenance costs has been presented in Figure 20. The kerosene fuel-operated water heating system shows the highest cost of operation and maintenance, followed by Electricity and LPG. This can be seen that solar energy is having significantly less operation and maintenance costs as compared to that of other conventional fuels reported.
Figure 20 Comparison of Annual O&M cost for various fuels used for domestic water heating system

Figure 21 Comparison of Levelized cost of Heating for various fuels for identified locations

Levelized cost of Heating is essentially a significant indicator to compare overall cost per unit kWh of Heating. It can be seen from Figure 21, LCOH is significantly less in the case of ET-CPC solar water heating system ranging from 1.65 INR/kWh to 1.72 INR/kWh followed by Kerosene (13.83 INR/kWh) and Electricity (11.25 INR/kWh). SPBP and DPBP are calculated as
4.5-4.75 year and 6.6-7 year respectively taking a discount rate of 6%. The internal rate of return is reported to be 16.76, 16.82, 16.77 and 16.75% for Barmer, Jodhpur, Jaipur and Jaisalmer respectively which proved that it is a very profitable business model, refer to Table 11.

5. Conclusion

An SDWH powered by an 81 m² ET-CPC solar collector field is reported in presented here. Energy, exergy, environmental and economic analysis is carried out. The following points are drawn as the conclusion of this work.

- The developed model results are validated with the experimental results and relative differences are ranged from 3 to 8%.

- Parametric analysis shows that with the increase in mass flow rate ranging from 0.0132 to 0.0357 kg/s, there is simultaneous improvement in the useful heat gain and instantaneous efficiency of ET-CPCs. However, there is a drop in the useful heat gain and instantaneous efficiency with an increase in the inlet temperature which ranged from 30-90°C.

- Effect of solar radiation intensity ranging from 200 – 1000 W/m² has been reported for various inlet temperatures to evaluate and compare the useful heat gain and instantaneous efficiency of ET-CPC solar field.

- It has also been reported that there is no significant effect of ambient temperature over the useful heat gain and efficiency.

- The analytical model is then implemented under meteorological conditions of four specified locations (Barmer, Jodhpur, Jaisalmer and Jaipur), then annual energy and exergy gain have been evaluated and compared. Jodhpur is receiving the most excellent
solar radiation and thus highest annual useful energy and exergy gain have been reported
to be 79.72 MWh and 9.311 MWh followed by Jaisalmer, Barmer and Jaipur.

- The economic analysis reports the simple payback period ranging from 4.5 to 4.75 years
  and discounted payback period ranging from 6.6 to 7 years based on a 6% discount rate.
- Along with this, based on levelized cost of heating using solar energy as fuel is ranging
  from 1.62 to 1.72 INR/kWh of heat compared to closest with the use of CNG as fuel
  which is ranging from 4.39 to 4.41 INR/kWh.
- The highest LCOH has been reported for electricity for domestic water heating which
  ranged from 11.25 to 11.27 INR/kWh.
- The internal rate of return is reported to be 16.76, 16.82, 16.77 and 16.75% for Barmer,
  Jodhpur, Jaipur and Jaisalmer respectively which proved that it is a very profitable
  business model.
- The environmental analysis also supports the previous trends and report 74400, 78125,
  75371 and 73813 kg of CO$_2$ saved which anyway got added to the environment if the
  electricity was used for the same purpose.

Hence it can be recommended that ET-CPC is a viable, economical and pollution-free alternative
to meet the medium temperature heat demand such as in solar water heating systems for
domestic and community use. ET-CPC operation is not possible during weak sunshine (<200
W/m$^2$) hours and technology advancement is needed in this direction. The use of nanofluids as a
working fluid is reported to be advantageous to improve the productivity and performance of the
ET-CPC further but insufficient data is there and that also reports operational issues. Research
could be made to find the optimal configuration of nanofluids to offer less/no operational issues.
and optimal performance. Further, ET-CPC life cycle cost assessment could be worked out to understand the overall impact on nature.

_Ethical Approval_

We confirm that this work has not been published elsewhere, nor it is currently under consideration for publication elsewhere.

_Consent to Participate_

Authors give their consent to participate.

_Consent to Publish_

We consent it to publish in the Environmental Science and Pollution Research after acceptance.

_Authors Contributions_

Dinesh Kumar Sharma is a corresponding of this manuscript. He has involved in the development of entire manuscript.

Prof. Dilip Sharma has involved in the conceptualization of this research and reviewed the technical details of the manuscript.

Prof. Ahmed Hamza H Ali has involved in the conceptualization and reviewed the language and grammar of the manuscript.

_Funding_

There are no funding disclosures to make.

_Competing Interests_

Authors have no conflict of interest to disclose.

_Availability of data and materials_

Calculations data and other relevant material would be made available to editor/reviewer as and when required.
References

Battisti R, Corrado A (2005) Environmental assessment of solar thermal collectors with integrated water storage. Journal of Cleaner Production 13:1295–1300. doi: 10.1016/j.jclepro.2005.05.007

Bejan A, Kearney DW, Kreith F (1981) Second law analysis and synthesis of solar collector systems. Journal of Solar Energy Engineering Transactions of ASME 103:23-28. doi: 10.1115/1.3266200

Bellos E, Tsivianidis C, Tsifis G (2017) Energetic, Exergetic, Economic and Environmental (4E) analysis of a solar assisted refrigeration system for various operating scenarios. Energy Conversion and Management 148:1055–1069. doi: 10.1016/j.enconman.2017.06.063

Caliskan H (2017) Energy, exergy, environmental, enviroeconomic, exergoenvironmental (EXEN) and exergoenvioeconomic (EXENEC) analyses of solar collectors. Renewable and Sustainable Energy Reviews 69:488–492. doi.org/10.1016/j.rser.2016.11.203

Cengel YA, Boles MA (2019) Thermodynamics: An Engineering Approach 9th Editon (SI Units). McGraw Hill Publication. Newyork

Chopra K, Tyagi V V., Pandey AK, et al (2021) Energy, exergy, enviroeconomic & exergoeconomic (4E) assessment of thermal energy storage assisted solar water heating system: Experimental & theoretical approach. Journal of Energy Storage 35:102232. doi: 10.1016/j.est.2021.102232

Dincer I, Rosen MA (2007) Exergy: Energy, environment and sustainable development. John Wiley and Sons

Faizal M, Saidur R, Mekhilef S, et al (2015) Energy, economic, and environmental analysis of a flat-plate solar collector operated with SiO2nanofluid. Clean Technologies and Environmental Policy 17:1457–1473. doi: 10.1007/s10098-014-0870-0

Geete A, Dubey A, Sharma A, Dubey A (2019) Exergy Analyses of Fabricated Compound Parabolic Solar Collector with Evacuated Tubes at Different Operating Conditions: Indore (India). Journal of the Institution of Engineers (India) Series C 100:455–460. doi: 10.1007/s40032-018-0455-5

Hazami M, Kooli S, Naili N, Farhat A (2013) Long-term performances prediction of an evacuated tube solar water heating system used for single-family households under typical Nord-African climate (Tunisia). Solar Energy 94:283–298. doi: 10.1016/j.solener.2013.05.020

Jiang L, Widyolar B, Winston R (2015) Characterization of Novel Mid-temperature CPC Solar Thermal Collectors. In: Energy Procedia 70: 65-70. doi.org/10.1016/j.egypro.2015.02.098

Kabeel AE, Abdelgaied M, Elrefay MKM (2020) Thermal performance improvement of the modified evacuated U-tube solar collector using hybrid storage materials and low-cost concentrators. Journal of Energy Storage 29:101394. doi: 10.1016/j.est.2020.101394

Kerme ED, Chafidz A, Agboola OP, et al (2017) Energetic and exergetic analysis of solar-powered lithium bromide-water absorption cooling system. Journal of Cleaner Production 151:60–73. doi:10.1016/j.jclepro.2017.03.060

Ma L, Lu Z, Zhang J, Liang R (2010) Thermal performance analysis of the glass evacuated tube solar collector with U-tube. Building and Environment 45: 1959-67. doi: 10.1016/j.buildenv.2010.01.015

Meyer L, Tsatsaronis G, Buchgeister J, Schebek L (2009) Exergoenvironmental analysis for evaluation of the environmental impact of energy conversion systems. Energy 34:75–89. doi: 10.1016/j.energy.2008.07.018

Mills DR, Bassett IM, Derrick GH (1986) Relative cost-effectiveness of CPC reflector designs suitable for evacuated absorber tube solar collectors. Solar Energy 36:199-206. doi: 10.1016/0038-092X(86)90135-0

Mishra RK, Garg V, Tiwari GN (2017) Energy matrices of U-shaped evacuated tubular collector (ETC) integrated with compound parabolic concentrator (CPC). Solar Energy 153:531-539. doi: 10.1016/j.solener.2017.06.004

Mishra RK, Garg V, Tiwari GN (2015) Thermal modeling and development of characteristic equations of evacuated tubular collector (ETC). Solar Energy 116:165-176. doi: 10.1016/j.solener.2015.04.003
