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ORIGINAL PAPER

Enhancing the efficiency of hybrid parabolic and parabolic trough concentrators for dual solar applications

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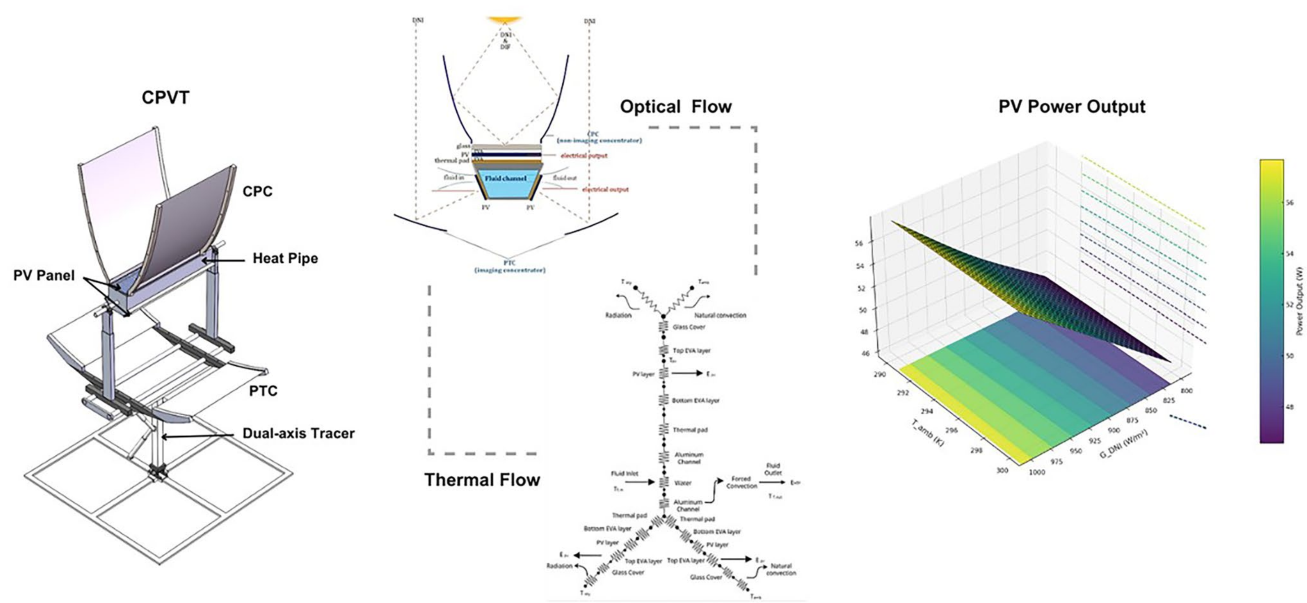
Abstract

This paper proposes and analyzes an improved hybrid system combining a CPC and a PTC. The new system enhances PV module conversion efficiency by shifting the parabolic trough concentrator's focus from a TEG module to a PV module, utilizing PV waste heat for improved overall energy efficiency. The previous system with TEG achieved a PV output of 39.27 W and TEG output of 6.63 W under 998 W/m^2 light intensity, while the improved system achieved a 23.8% efficiency increase, reaching 56.84 W without the TEG. Simulation and modeling results show effective thermal management and energy efficiency optimization under varying light intensity and ambient temperatures. This design provides a practical pathway for optimizing future solar energy systems. The proposed hybrid CPC-PTC system addresses the efficiency limitations of traditional photovoltaic systems by combining the advantages of both concentrators. The motivation for this study is to enhance solar energy utilization by improving the optical and thermal performance of PV modules. This research optimizes concentrator configuration to maximize energy absorption and achieve higher conversion efficiency. The methodology includes geometric modeling with Solidworks, optical simulation using TracePro, and thermodynamic analysis with EES. The results demonstrate significant improvements in PV efficiency and thermal management, highlighting the potential of this hybrid system for renewable energy applications.

Graphical abstract



Keywords Photovoltaic efficiency · Compound parabolic concentrator · Parabolic trough concentrator · Concentrated photovoltaic · Solar energy utilization · Optical simulation · Hybrid solar concentrator · Thermal management in photovoltaic systems · Dual-stage concentration

Extended author information available on the last page of the article

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Abbreviations

PV	Photovoltaic
CPC	Compound parabolic concentrator
PTC	Parabolic trough concentrator
CPV	Concentrated photovoltaic
TEG	Thermoelectric generation module
LCPV	Low-concentration photovoltaic
MCPV	Medium-concentration photovoltaic
BPV/T	Bifacial photovoltaic/thermal
ACPC	Asymmetric composite parabolic concentrator
CR	Concentration ratio
GHI	Global horizontal irradiance
CAD	Computer-aided design
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
EES	Engineering equation solver
STEG	Solar thermal electric generator
DNI	Direct normal irradiance

Introduction

With the increasing energy crisis and environmental problems worldwide, searching for sustainable energy solutions has become a general aim for governments and scientific research institutions. Solar energy is one of the most abundant renewable resources and is thus promising as a potential solution to the energy problem (Ukoba et al. 2024; Chen et al. 2024). Despite its large-scale commercialization, traditional PV technology faces numerous challenges concerning efficiency and cost, primarily due to the limitations and energy losses of single-junction cells (Victoria et al. 2021; Conibeer 2007). This is why thermal management is a critical issue, as the efficiency of PV conversion decreases approximately from 0.45% to 0.5% for every one °C increase in temperature (Jathar et al. 2023).

CPV technology has emerged in response to the problem of thermal effects in PV cells under high light conditions. CPV concentrates sunlight onto high-efficiency PV cells to enhance power output, reduce the need for semiconductor material, and increase energy utilization. CPC and PTC are common concentrators and are most commonly used, as each has pluses and minuses. Due to their ability to collect light over a wide range of angles, CPCs are well suited to low-to-medium concentration systems that don’t require complicated solar tracking. However, high optical losses limit CPC efficiency in high-concentration applications (Paul 2019). While PTCs offer high-concentrating power by focusing parallel sun rays through parabolic reflection, they require precision solar tracking and are more suitable for high-concentration scenarios (Stanek et al. 2022).

Combining CPC and PTC, which possess complementary characteristics, offers the potential to harness the benefits of each while mitigating their weaknesses. In this paper, a novel hybrid system integrating CPC and PTC is proposed to improve overall efficiency. While a typical model in previous studies placed the TEG at the focus point of the PTC by improving the geometry of the heat pipes, the new design focuses the PTC on PV instead of the TEG module, improving power output and thermal management efficiency by maximizing the energy absorption of the PV cells. Combining CPC's wide acceptance angle and PTC's high focusing power, the hybrid system provides a new design for concentrating solar energy utilization.

Previous studies have extensively analyzed the factors influencing PV module performance. For instance, Cuce et al. (Cuce et al. 2018) examined the impact of humidity on solar cell performance, showing that the relative humidity has a negligible effect on the current parameters of monocrystalline and polycrystalline silicon photovoltaic modules and that the linear relationship between short-circuit current and solar irradiance remains unchanged under different humidity conditions. Recent advancements in hybrid systems, particularly those incorporating CPC and PTC, have shown promise in addressing these challenges. According to the study by Pinar Mert et al. (Cuce et al. 2024), it is shown that the integration of TEG into PTC can increase the total system efficiency by up to 70% and the electrical efficiency by about 5%, which provides an effective way to optimize the system performance.

The use of CPC and PTC individually in solar applications has been studied in previous studies (Conibeer 2007; Ganapathiraman, and Manikam 2023; Masood et al. 2021; Mohammadnia and Ziapour 2020; Cai et al. 2024; Wan Roshdan et al. 2022), but the novelty of this study is to combine the two approaches to maximize the optical and thermal performance. This research shows that the proposed hybrid system can significantly increase PV efficiency while efficiently handling waste heat by analyzing simulation results from Solidworks geometric modeling, TracePro optical simulations, and EES thermodynamic modeling. This new approach helps to move the state of the art of solar energy technologies by overcoming the limitations of the traditional CPV systems and making them more suitable for different environmental conditions.

Materials and methods

System components and materials

The Materials and Methods chapter of this study details the specific experimental configurations of the hybrid CPC-PTC system and the simulation tools used. The experimental

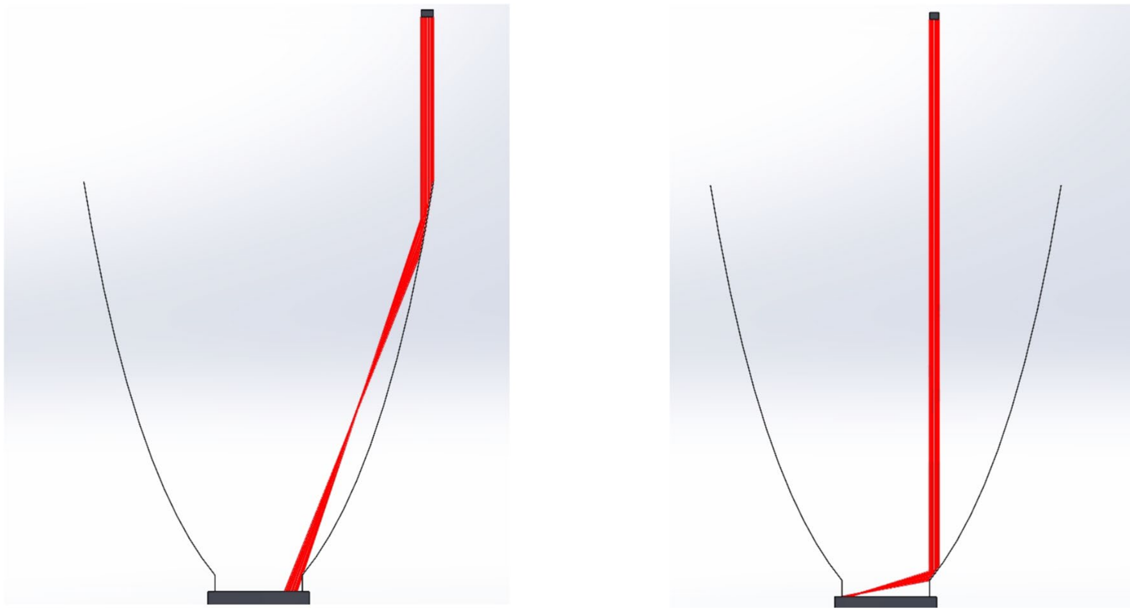


Fig. 1 Reflection of a parallel ray of light directed at the CPC

setup consists of a hybrid CPC-PTC system designed to optimize solar energy harvesting and maximize the efficiency of photovoltaic (PV) modules. The system mainly consists of CPC, PTC, PV modules, and heat pipes. The CPC in this system is made of highly reflective anodized aluminum and is designed to accept a wide angular range of light without the need for solar tracking. The PTC is integrated to concentrate the light further and increase the energy conversion efficiency of the PV module. The entire system is mounted on a tracking frame that can be adjusted in orientation to ensure maximum sunlight reception during testing.

The CPC is a non-imaging optical device for concentrating light; it is optimized explicitly for incident light, focusing on a small target area while maximizing light-gathering efficiency and minimizing optical losses (Shanks et al. 2016). The CPC is composed of two parabolically shaped flanks that converge gradually from the starting point of the light source toward the receiver, as shown in Fig. 1. Typically, a CPC is received by a photovoltaic or thermoelectric module that converts the gathered solar energy into electrical or thermal energy (Masood et al. 2022). Because of the high-concentration ratio, there is usually some impact on the life of the receiver, commonly such as the hot spot effect (Wang et al. 2019). For CPC systems, it is common for the receiver to be combined with a heat sink or waste heat utilization, by which the heat from the PV panels at high-concentration ratios is diverted to increase the system's lifetime.

With the development of photovoltaic technology, a single concentrator structure gradually fails to meet the need to improve system efficiency and the emergence of concentrator photovoltaic systems combining multiple reflector

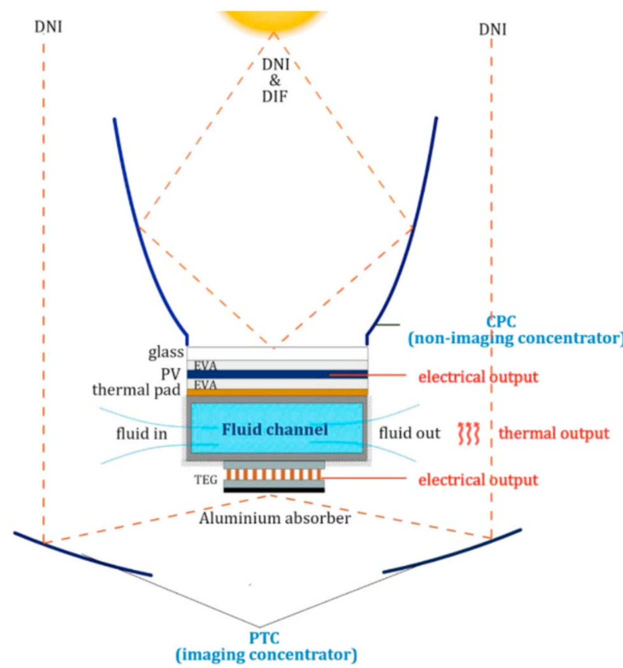


Fig. 2 Schematic diagram of the working principle of hybrid CPVT-STEG prototype (Sripadmanabhan Indira et al. 2022a)

structures (Lokeswaran et al. 2020). In this system, both the CPC and PTC will receive parallel solar rays, and this dual concentrator design improves the capture of light energy while ensuring that the light is concentrated at a high density at the receiver.

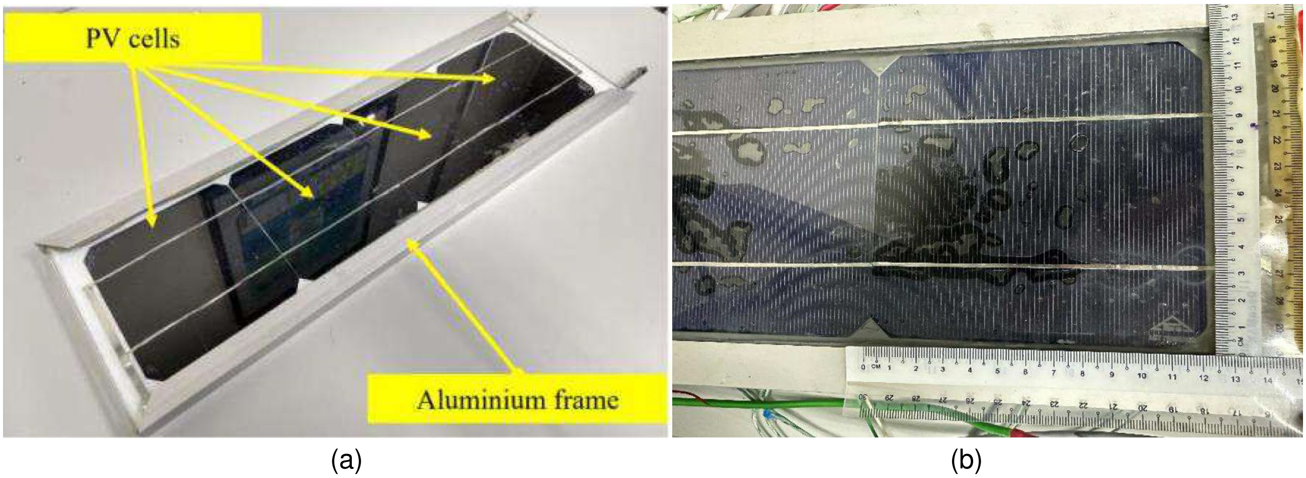


Fig. 3 Fabrication of PV module: **a** PV front side and **b** PV cell dimensions

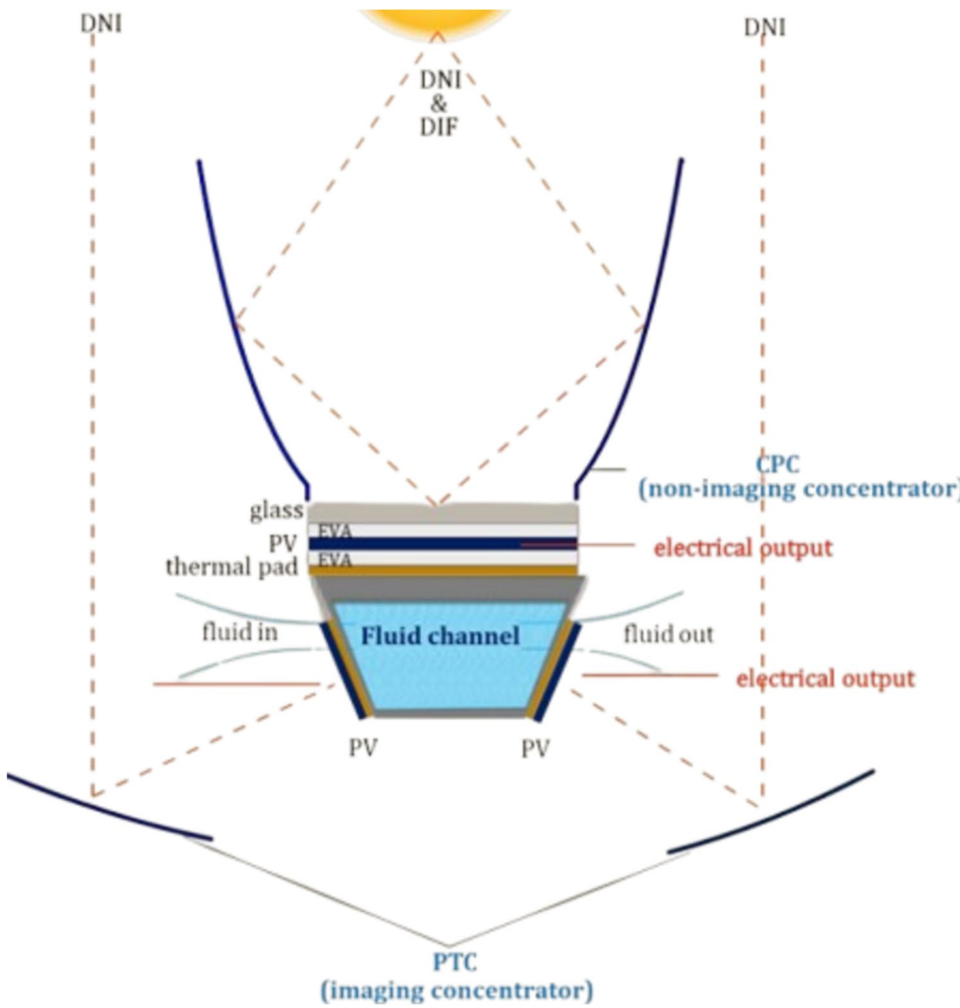


Fig. 4 Modification models proposed

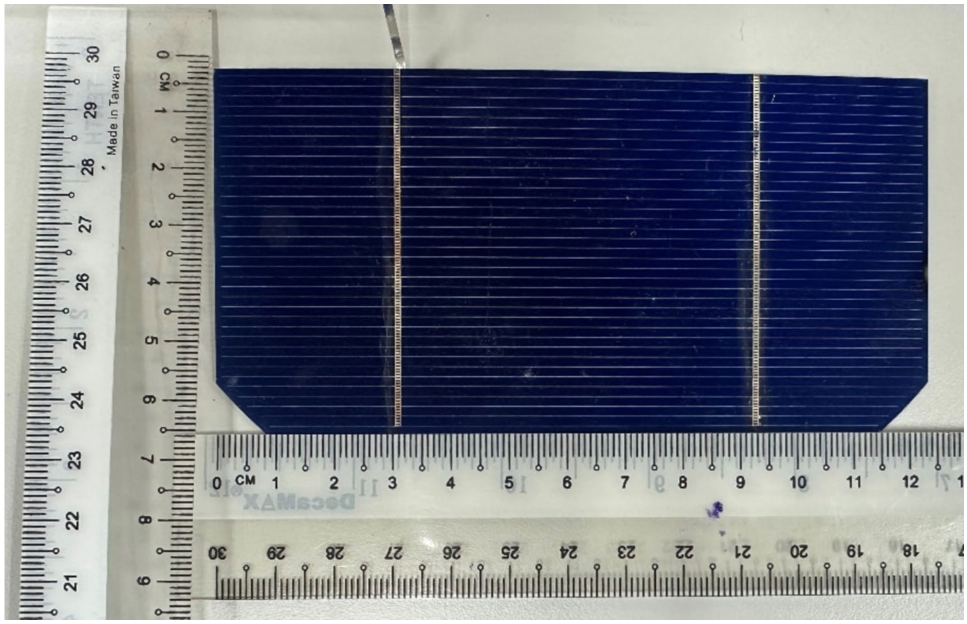


Fig. 5 Half-cell PV cell dimension

Table 1 System setting

Parameter	Value
CPC	
Length	0.54 m
Width	0.5 m
Reflectivity	0.6
PV	
Absorption rate	0.9
Packaging factor	0.89031
Area	0.0702 m^2
Silicon area	0.0625 m^2
Width	0.125 m
Length	0.54 m
Efficiency at STC	18.6%
Temperature coefficient	−0.47%/◦C
PTC	
Length	0.54 m
Width	0.5 m
Efficiency	0.346
Heat pipe	
Length	0.54 m
Width	0.13 m
Materials	Aluminum
Wall	0.003 m
Location	
Taylor's University	3.0626° N 101.6168° E

In the combined CPC-PTC system designed in this paper, a hybrid CPV/TEG system combining a CPC with a PTC is used regarding the study (Sripadmanabhan Indira et al. 2022a) (shown in Fig. 2). The design innovatively combines imaging optics with non-imaging optics to provide a solution that elevates PV efficiency and enhances TEG performance. Based on the results of the mathematical modeling of the system, the electrical output of the hybrid system is improved over the conventional CPV/T-STEG system, and the thermal output is increased by a factor of 1.6. It was also found that the number of TEG modules has a significant effect on the electrical output, and increasing the number of TEGs improves the thermal efficiency but leads to a decrease in the electrical efficiency, so the optimal balance of the number of TEGs needs to be found in practical applications. The PV receiver panel used for CPC is shown in Fig. 3 as four 125*125 mm monocrystalline silicon PV cells wrapped by an aluminum frame.

Regarding the combined CPC-PTC system proposed in Sripadmanabhan Indira et al. 2022a, that mainly improves the focal position of the PTC. In the original design, the PTC concentrates the light on a TEG to generate electricity using the temperature difference. However, due to the relatively low electrical conversion efficiency of the TEG, especially at low-temperature differences, focusing light directly on the TEG fails to utilize the light energy fully. To further improve the overall system efficiency, this study shifts the focus of PTC from TEG to PV module. The new system structure is shown in Fig. 4. The PTC in the improved design directs light directly onto the PV module with parabolic reflection. In doing so, the PV module achieves a higher density of light, which increases electrical output. In the new structure,

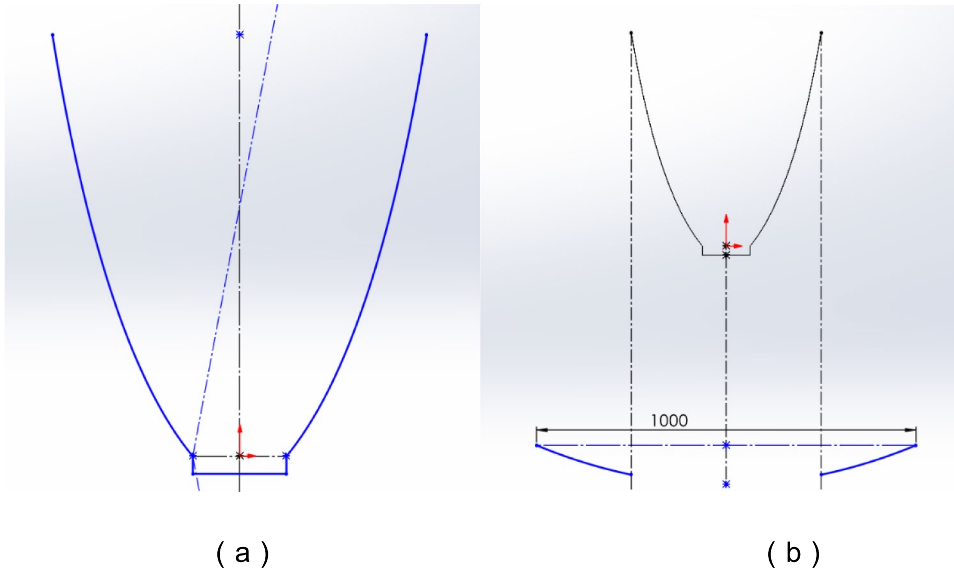


Fig. 6 **a** CPC 2D geometry setup in Solidworks. **b** CPC-PTC 2D geometry setup in Solidworks

the receiver features eight 62.5*125 mm half-cell PV cells, as shown in Fig. 5, and component parameters, as shown in Table 1.

Method

This study combines three software tools, Solidworks, TracePro, and EES, for geometric modeling, optical analysis, and thermodynamic and mathematical modeling of the system. The application of each tool in the modeling and analysis process is described in detail as follows.

Solidworks geometric modeling

Solidworks is a powerful 3D modeling software for system design in mechanical, optical, and energy fields. This study constructs a geometric model of a combined CPC and PTC system using Solidworks. This step is the basis of the system design and provides the basis for optical simulations and thermodynamic analyses on an accurate geometric model.

A 2D section is first drawn in Solidworks and stretched to produce a 3D geometry based on the CPC and PTC design principles. The parabolas of the CPC section collect and reflect light over a wide range of angles, while the PTC focuses the light to a focal point through the paraboloid. These two concentrator geometries are combined to maximize the energy absorption efficiency of both PV and TEG modules.

The position of the focal point, the opening angle of the CPC, and the size of the reflective surface of the PTC were emphasized during the modeling process. These key design parameters are optimized to ensure the system can operate efficiently under varying light conditions. Furthermore, the

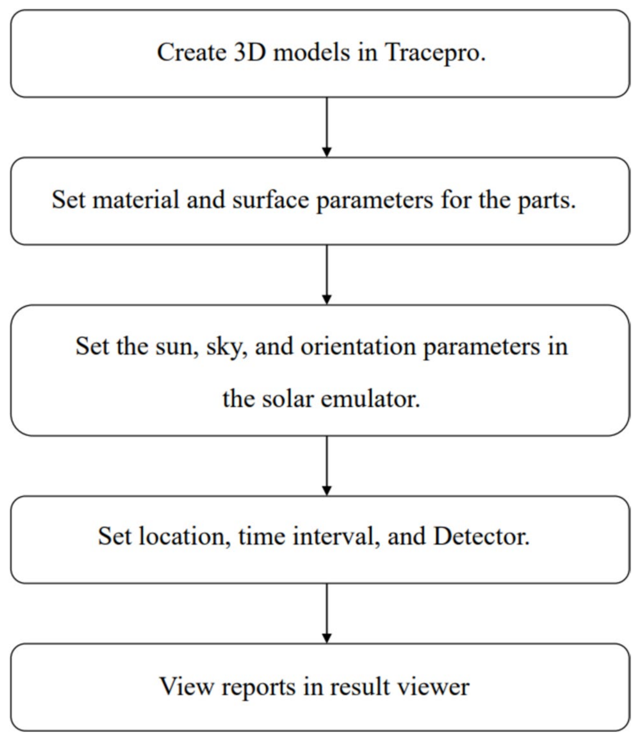
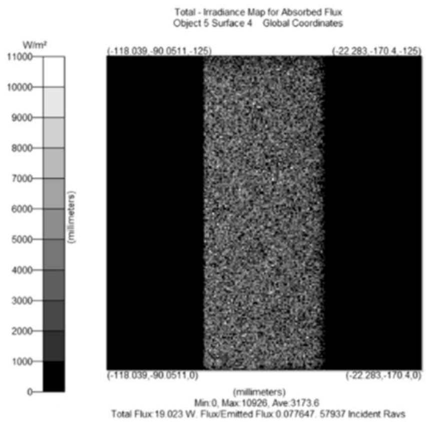


Fig. 7 TracePro optical simulation flow

geometry was optimized considering the system volume and material costs to achieve economy in practical applications. (The 2D structure in CAD is shown in Fig. 6.) Once the geometric modeling is complete, the model in Solidworks is exported to a standard 3D exchange format for subsequent optical simulation analysis in TracePro.



Irradiance map of bottom PV

Distance to upper PV (mm) \ Bottom PV tilt angle (°)	35	37	40	43	45
80	4.0804	4.1199	4.1633	4.1086	4.0725
82	4.0731	4.1332	4.2285	4.1712	4.1484
85	4.0488	4.1699	4.2713	4.2541	4.2124
87	3.9525	4.0963	4.2174	4.2647	4.2054
89	3.8869	4.0027	4.166	4.1962	4.0913

Power at different tilt angles and positions. Unit (watt)

Fig. 8 Irradiance maps of half cells, optimal angle, and position obtained by TracePro

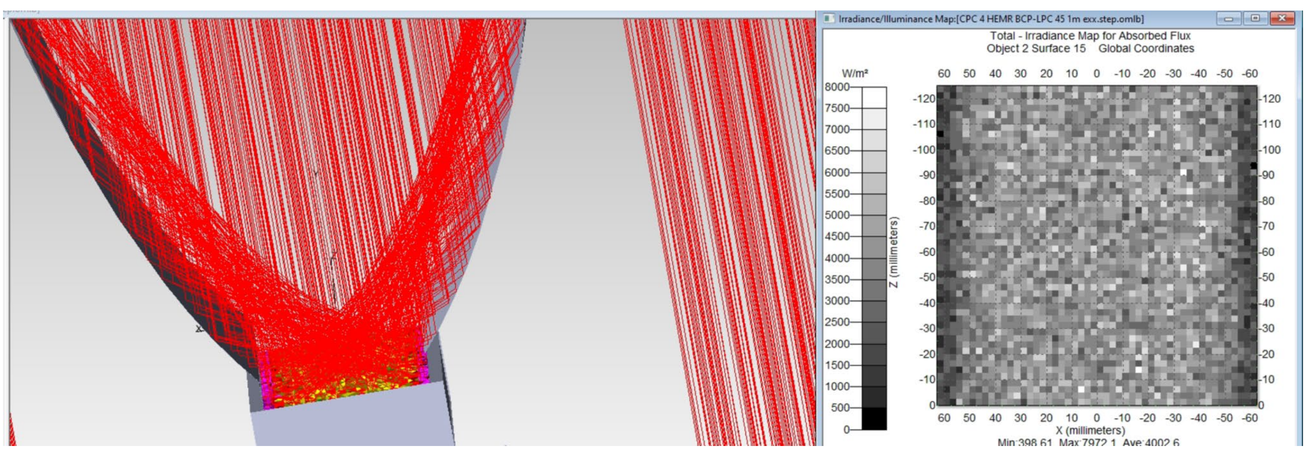


Fig. 9 CPC ray tracing in TracePro

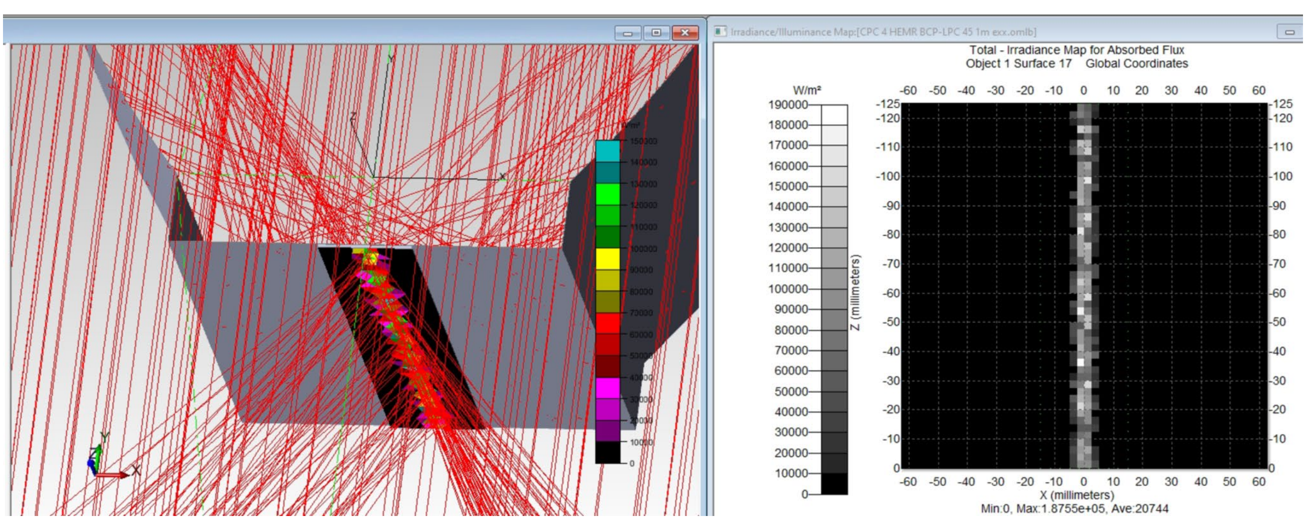


Fig. 10 Ray tracing for model (Sripadmanabhan Indira et al. 2021)

Optical analysis

After completing the geometric modeling, the study turned to the optical analysis part. TracePro is a professional optical design and analysis software for simulating the propagation path and energy distribution of light in a system. After importing the geometric model of the CPC-PTC created through Solidworks in TracePro, ray tracing simulation analysis is performed. The sun rays are simulated as parallel light sources, and the rays are emitted into the CPC and PTC and then enter the receiving surface. The ray tracing function in TracePro is used to analyze the reflective, refractive, and absorptive behavior of the rays and to obtain the optical efficiency of the system, as shown in Fig. 7.

In the simulation, the solar rays are modeled as parallel beams, which are incident on the openings of the CPC and PTC. The reflection, refraction, and absorption behaviors of the light rays in the system are analyzed by TracePro's ray-tracing function to obtain the energy distribution of the light rays on the PV module and the TEG module. By setting the optical parameters of the PV panels and the concentrator (e.g., refractive index, absorptive index, etc.) during the simulation process and by using the solar emulator function, the irradiance in real coordinates can be realized, and the system can be tracked to obtain results close to those of the real world.

The simulation results include the optical efficiency of the CPC and PTC, the energy loss of the incident light, and the optical energy density on the surface of each module. These results can evaluate the system's ability to capture light energy under different light conditions. For example, the simulation results show that the CPC can capture light over a wide range of angles, while the PTC effectively concentrates the light on the receiving surface, thus improving the energy conversion efficiency.

Through simulation (Fig. 8, Fig. 9, and Fig. 10), the optical efficiency and light energy distribution of the system under different incidence angles and light intensities are obtained. In particular, the optical gain of CPC and the light concentration effect of PTC are analyzed in detail to verify the rationality of the optical design of the system. The ray tracing shows that the light perpendicular to the receiving surface is evenly distributed on the receiving surface (PV) with no hot spot effect and high utilization. Optical simulation scenario for PTC is based on Sripadmanabhan Indira et al. 2021. A high-concentration ratio of PTC is used to converge the light onto the TEG module below the heat pipe. Because of the specificity of the hot spot module, a higher temperature difference is needed for better efficiency, so it is necessary to make sure that the focal point of the PTC covers only the thermoelectric module. From the simulation results, the light is well concentrated in a small area, so the system will be in the presence of the Seebeck effect and produce more electrical energy.

In this study, instead of changing the focal point of the PTC, we achieved the effect of separating the refracted light from the PTC by changing the geometry of the heat pipe to a trapezoidal shape so that the two reflective surfaces on both sides reflect the light to different planes of the heat pipe, where the PV is added, thus enabling the system to perform better. It is envisaged that by increasing the contact area between the heat pipe and the PV, the heat dissipation process can be accelerated, thus improving the overall efficiency of the system.

In attempting to change the system, the TracePro plugin in Solidworks, which allows for setting up a light source in

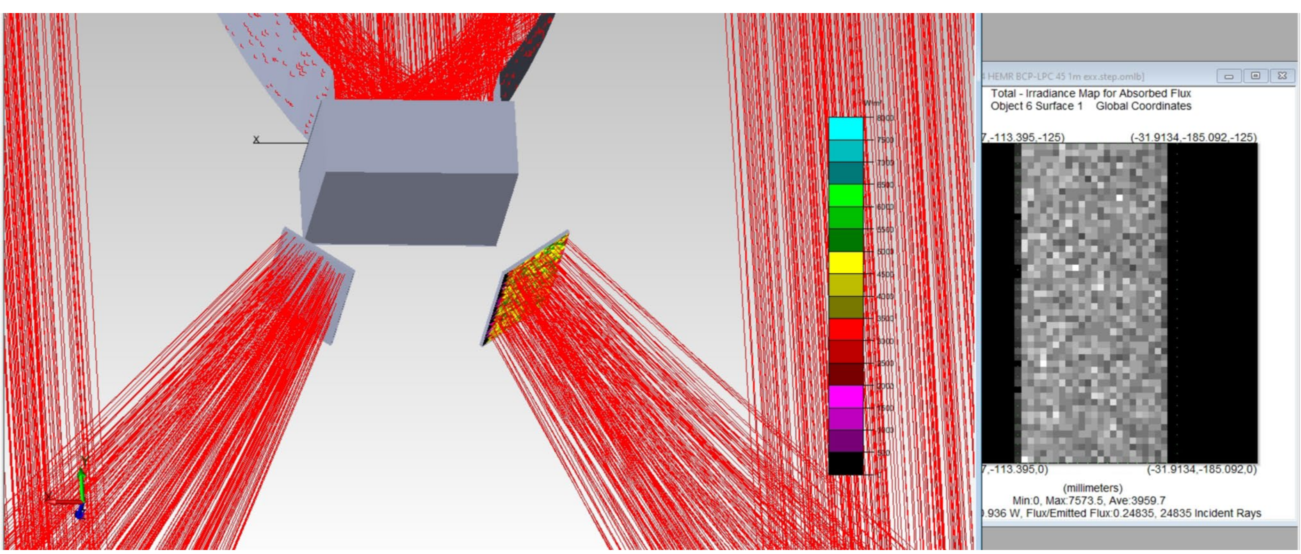


Fig. 11 Ray tracing of the improved model in TracePro

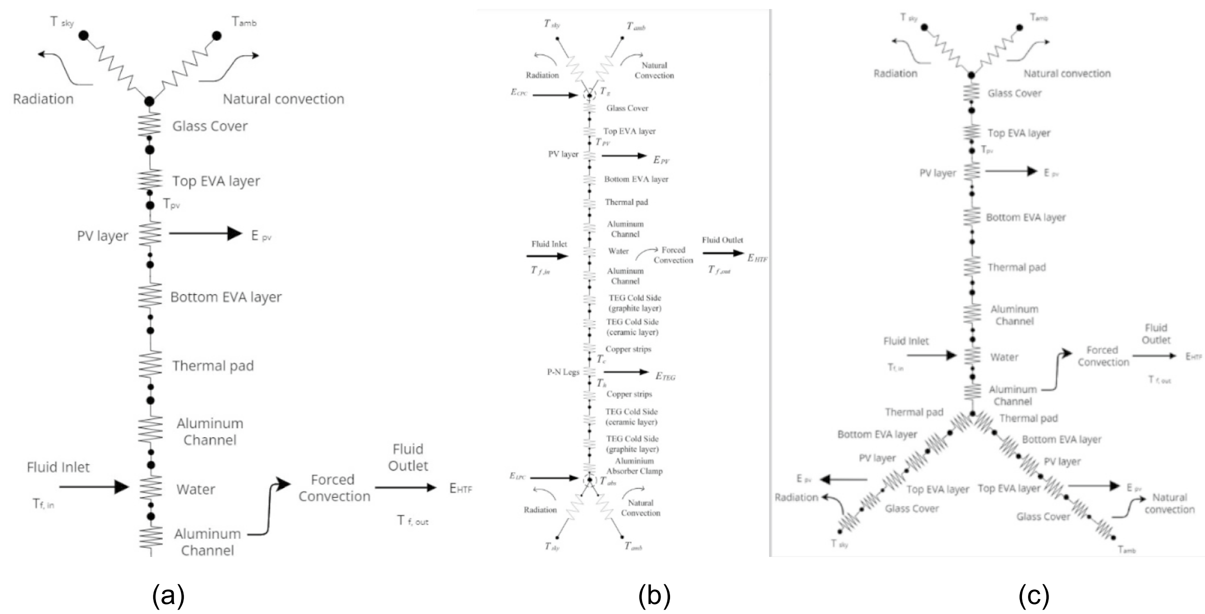


Fig.12 **a** CPC model heat exchange diagram. **b** Sridhar model heat exchange diagram (Sripadmanabhan Indira et al. 2022b). **c** Proposed model heat exchange diagram

Solidworks as well as simple ray tracing, was used to test different tilt angles and spacing, resulting in an optimal tilt angle and distance of 85 mm from the PV plane and a tilt angle of 40 degrees. Optical simulations with TracePro show that in this configuration, the PV is uniformly illuminated from below and achieves maximum efficiency (as shown in Fig. 11).

EES mathematical modeling

After geometric modeling and optical analysis, this study uses EES for thermodynamic analysis and mathematical modeling of the system.

The thermodynamic behavior of the system is further analyzed by inputting the light energy distribution results obtained from TracePro simulation into EES, which is used to calculate parameters such as the temperature distribution of the PV module, the temperature difference of the TEG, and the heat loss. The temperature of the PV module directly affects its photoelectric conversion efficiency, while the temperature difference of the TEG determines its power generation efficiency. Using thermodynamic equations, EES is able to simulate the energy conversion of the system under different temperature conditions.

EES provides a flexible equation-solving function. The study uses EES to solve complex equations related to the system, such as the temperature-corrected efficiency formula for PV modules and the thermoelectric conversion efficiency formula for TEGs. The results of this part of the calculations provide a theoretical basis for further evaluation of the actual performance of the system. The thermodynamic model is shown in Fig. 12**.**

a) Collected solar energy by PV layer For CPC, the concentration ratio is defined as Eq. (1) (Kharaghani et al. 2024):

$$C_{cpc} = \frac{W_{CPC}}{W_{PV}} \tag{1}$$

where W_{CPC} is the opening width of the CPC, and W_{PV} is the width of the PV.

Total solar energy collected by CPC (see Eq. (2)):

$$Q_{cpc} = G_{GHI} \times eta_{CPC} \times A_{CPC} \tag{2}$$

where G_{GHI} represents the global horizontal irradiance (W/m^2), eta_{CPC} represents the optical efficiency of CPC, and A_{CPC} represents the incident area of CPC (m^2).

Conversion efficiency of photovoltaic cells shows in Eq. ((3)Abdo et al. Sep. 2019):

$$\eta_{PV} = \eta_{ref} \times \left(1 - \gamma \times \left(T_{PV} - T_{PV_{ref}}\right)\right) \tag{3}$$

where η_{ref} is the reference efficiency, γ is the temperature coefficient, T_{PV} is the operating temperature of the PV cell, and $T_{\text{PV\_ref}}$ is the reference temperature. This equation describes the effect of temperature on the efficiency of a PV cell.

Total solar energy collected by the PV layer considering transmissivity, absorptivity, and concentration shows as Eq. (4) (Rejeb et al. 2021):

$$Q_{PV} = \tau_g \times \left(\alpha_{PV} \times \beta_{PV} + \alpha_T \times \left(1 - beta_{PV}\right)\right) \times C_{CPC} \times G_{GHI} \times eta_{CPC} \times A_{PV} \tag{4}$$

τ_g: Transmissivity of the glass cover.

α_{PV}: Absorptivity of the PV layer.

β_{PV}: Packaging factor for the PV.

α_T: Absorptivity of the thermal pad.

A_{PV}: Area of the PV layer.

Electrical power generated by the PV panel show as Eq. (5):

$$P_{PV} = \eta_{PV} \times Q_{PV} \tag{5}$$

b) Heat transfer and heat loss Nusselt number for the fluid and hydraulic diameter shows as Eq. (6), Eq. (7) (Lekbir et al. 2018; Fudholi et al. 2013):

$$Nu_1 = 7.54 + \frac{0.03 \times R_e \times P_r \times \left(\frac{D_h}{L_1}\right)}{1 + 0.016 \times \left(R_e \times P_r \times \left(\frac{D_h}{L_1}\right)\right)^{\frac{2}{3}}} \tag{6}$$

R_e: Reynolds number.

P_r: Prandtl number.

D_h: Hydraulic diameter

$$D_h = \frac{4 \times h \times w}{2 \times (h + w)} \tag{7}$$

h: Height of the aluminum channel.

w: Width of the aluminum channel.

L_1: Characteristic length of fluid flow.

In order to calculate the thermal energy transferred from the photovoltaic layer to the fluid, it is first necessary to determine the total heat transfer coefficient C_T, which depends on the thermal conductivity of the multiple layers (see Eq. (1)):

$$C_T = \left(\frac{L_{PV}}{K_{PV} \times A_{Si}} + \frac{L_{EVA}}{K_{EVA} \times A_{PV}} + \frac{L_T}{K_T \times A_{PV}} + \frac{L_{Al}}{K_{Al} \times A_{channel}} + \frac{1}{h_{fluid1} \times A_C}\right) \tag{8}$$

L_{PV},K_{PV},A_{Si} are the thickness of the photovoltaic layer, thermal conductivity, and wafer area, respectively.

L_{EVA}, K_{EVA} are the thickness and thermal conductivity of the EVA layer.

L_T,K_T Thickness and thermal conductivity for thermal pads.

L_{Al},K_{Al},$A_{channel}$ are the thickness, thermal conductivity, and area of the aluminum channel, respectively.

h_{fluid1} is the convective heat transfer coefficient of the fluid, calculated by the Nusselt number $Nu1$:

The convective heat transfer coefficient was calculated by Eq. (9) (Vanaki et al. 2016).

$$h_{fluid1} = \frac{K_{water} \times N_{u1}}{D_h} \tag{9}$$

The heat energy received by the fluid is calculated as Eq. (10) (Vanaki et al. 2016):

$$Q_{Fluid1} = C_T \times \left(T_{PV} - T_{fm}\right) \tag{10}$$

where T_{fm} is the average temperature of the fluid.

The heat dissipated by the photovoltaic layer to the ambient air is transferred through convective and radiative processes, firstly convective losses are calculated by Eq. (11) (Al-Waeli et al. 2019):

$$Q_{con_{conv}} = U_t \times \left(T_{PV} - T_{amb}\right) \times A_{PV} \tag{11}$$

where U_t is the total heat transfer coefficient, calculated from the glass thickness, EVA layer, and air heat transfer.

Overall heat transfer coefficient it represents the efficiency of heat transfer through multiple layers of material or multiple media. It is often used to evaluate how different combinations of materials affect the heat transfer performance of the overall system (see Eq. (12)).

$$U_t = \left(\frac{L_g}{K_g} + \frac{1}{h_{air}} - \frac{L_{EVA}}{K_{EVA}}\right)^{-1} \tag{12}$$

The photovoltaic layer also loses heat to the sky by radiation. According to the Stefan–Boltzmann law, the radiative heat loss is calculated by Eq. (13) (Soltani et al. 2018):

$$Q_{rad1} = E_g \times \sigma \times A_{PV} \times \left(T_{PV}^4 - T_{sky}^4\right) \tag{13}$$

The energy balance of the whole system is expressed by the following Eq. (14):

$$Q_{PV} = P_{PV} + Q_{con_{conv}} + Q_{rad1} + Q_{Fluid1} \tag{14}$$

The above calculations give the system output of a single CPC-PV-aluminum heat pipe.

c) CPVTSTEG mathematical model In the Sridhar model, PTC is used as a second reflector to reflect the solar radiation to the TEG at the back of the heat pipe, which is shared by the PV module with the heat pipe (Sripadmanabhan Indira et al. 2022a). This PTC has a concentrator ratio of 16.6, which will give a better thermoelectric performance with multiple TEG modules, but it will also affect the heat dissipation of the system, so finding a balanced ratio of thermoelectricity and cooling is crucial.

Energy collected by PTC is calculate by Eq. (15) (Sripadmanabhan Indira et al. 2021):

$$Q_{PTC} = G_{DNI} \times \eta_{PTC} \times A_{PTC} \tag{15}$$

where G_{DNI} denotes the direct normal radiation, η_{PTC} is the efficiency of the PTC, and A_{PTC} is the opening area of the PTC. With this formula, we can calculate the energy that the PTC can collect under different radiation conditions.

The thermoelectric module converts the waste heat not utilized by the PV cells into electrical energy by generating electricity through temperature differences. In order to accurately describe the performance of the TEG module, the thermoelectric conversion efficiency of the TEG and the amount of electricity it generates are shown as follows:

The efficiency of TEG is calculated by Eq. (16):

$$\eta_{TEG} = \frac{\Delta T_{TEG}}{T_{hot_{in}}} \tag{16}$$

where ΔT_{TEG} is the temperature difference of the TEG module, and T_{hotin} is the input temperature of the hot side. The calculation of the TEG efficiency is based on the temperature difference in the system, which directly affects its electrical energy output.

Output power of TEG is calculate by Eq. (17) (Shen et al. 2016):

$$P_{TEG} = I_{TEG}^2 \times R_{load} \tag{17}$$

where $I_{TEG}$is the current through the TEG module(see Eq. (18), and R_{load} is the load resistance. The current is generated through the Seebeck effect with the equation:

$$I_{TEG} = \frac{V_{TEG}}{R_{TEG}+R_{load}} \tag{18}$$

The voltage of the TEG module is determined by the Seebeck coefficient α_{TEG} and the temperature differenceΔT_{TEG}:

$$V_{TEG} = \alpha_{TEG} \times \Delta T_{TEG} \tag{19}$$

d) Improved design mathematical model This part introduces the design ideas and related mathematical models of the improved CPC-PTC system. By optimizing the concentrator structure of the CPC and PTC, especially the concentrator's focal point location, the energy absorption efficiency of the PV module is further enhanced, and the overall energy utilization of the system is improved. The improved design shifts the PTC's focal point from the TEG module to the PV module for more efficient light energy conversion.

In the original design, the PTC focuses the light on the TEG to generate electricity using the temperature difference. Still, the direct focus on the TEG fails to fully use the incident light energy due to the TEG's low power generation efficiency, especially under lower temperature difference conditions. Therefore, in this study, the design of the PTC is improved by shifting the focus to the PV module to increase the light intensity received by the PV module and thus enhance its photovoltaic conversion efficiency.

In the improved design, the optical concentrating action of the CPC and PTC is changed. The initial concentrating action of the CPC works in concert with the secondary concentrating action of the PTC to focus light on the surface of the PV module. The following equation can describe the optical model:

Equation (20) calculate the concentration ratio of the LPC:

$$C_{PTC_{NEW}} = \frac{W_{PTC} \div 2}{W_{PV_{NEW}}} \tag{20}$$

where W_{PTC} represents the width of the PTC, and W_{PV_NEW} represents the width of the new PV cell.

The solar energy collected by the new PV layer can be calculated by Eq. (21):

$$Q_{PV_{NEW}} = G_{DNI} \times C_{PTC_{NEW}} \times eta_{LPC} \times A_{PV_{NEW}} \tag{21}$$

G_{DNI}: Global horizontal irradiance.

eta_{LPC}: Optical efficiency of the improved PTC, reflecting its ability to focus light onto the PV module.

A_{PV_NEW}: Effective area of PV modules.

Equation (22) calculates the efficiency of the new PV panel based on its temperature:

$$\eta_{PV_{new}} = \eta_{ref} \times \left(1 - \gamma \times \left(T_{PV_{new}} - T_{PV_{ref}}\right)\right) \tag{22}$$

where η_{ref_new} is the reference efficiency, γ is the temperature coefficient, T_{PV_new} is the operating temperature of the PV cell, and T_{PV_ref} is the reference temperature. Equation (23) describes the effect of temperature on the efficiency of a PV cell.

$$P_{PV} = \eta_{PV_{new}} \times Q_{PV_{new}} \tag{23}$$

Results and discussion

We have selected several key diagrams for detailed discussion to illustrate the system's performance under different environmental conditions and overall efficiency more visually.

Figure 13 illustrates the combined effect of ambient temperature (T_{amb}) and coolant velocity (V_{fluid}) on PV

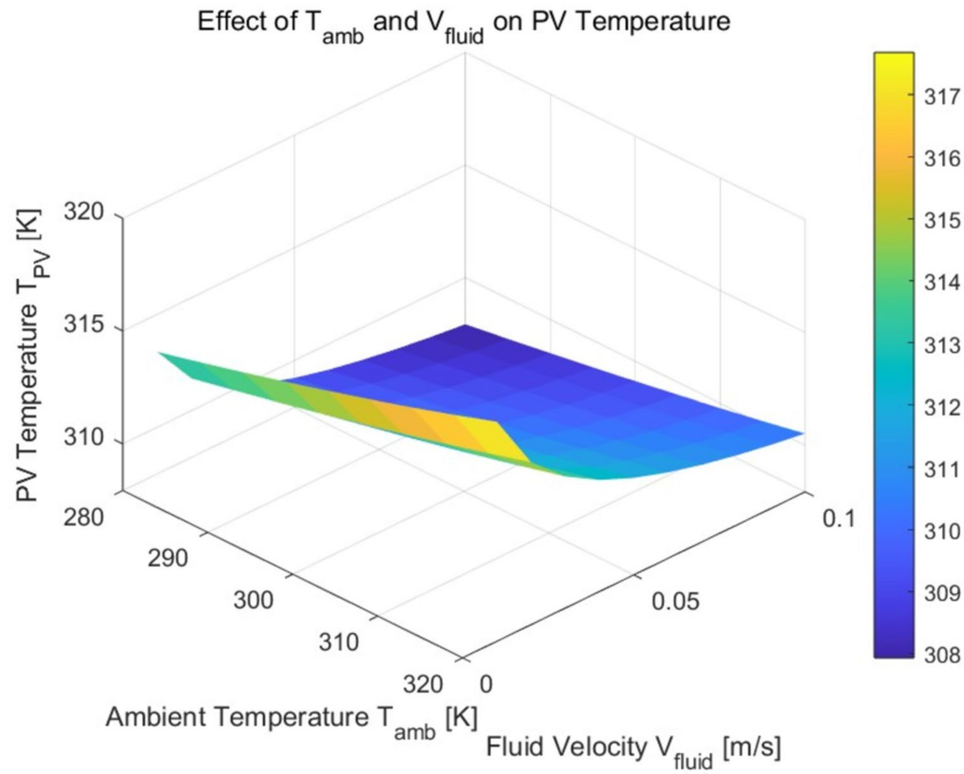


Fig.13 Effect of ambient temperature and cooling fluid velocity on PV temperature

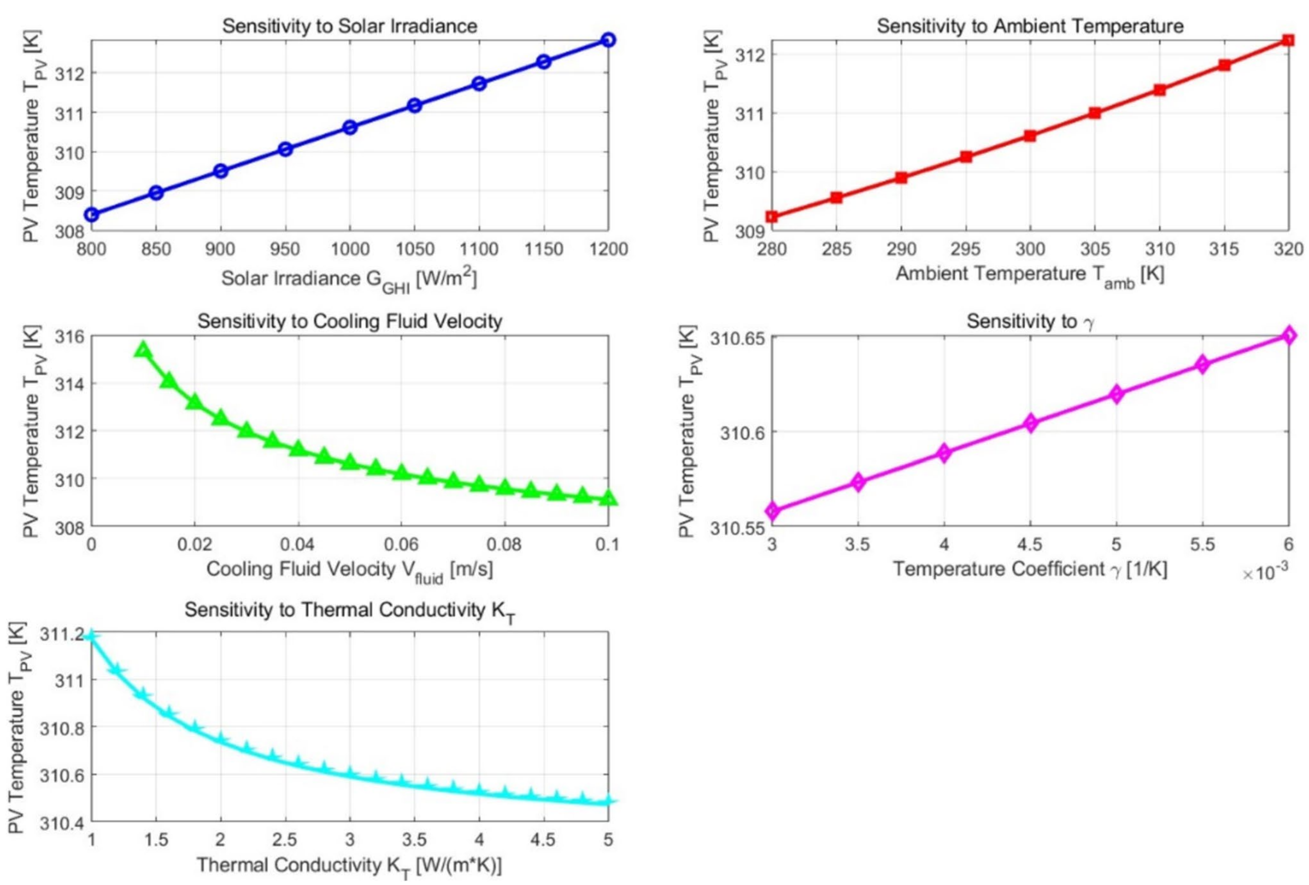


Fig.14 Sensitivity analysis

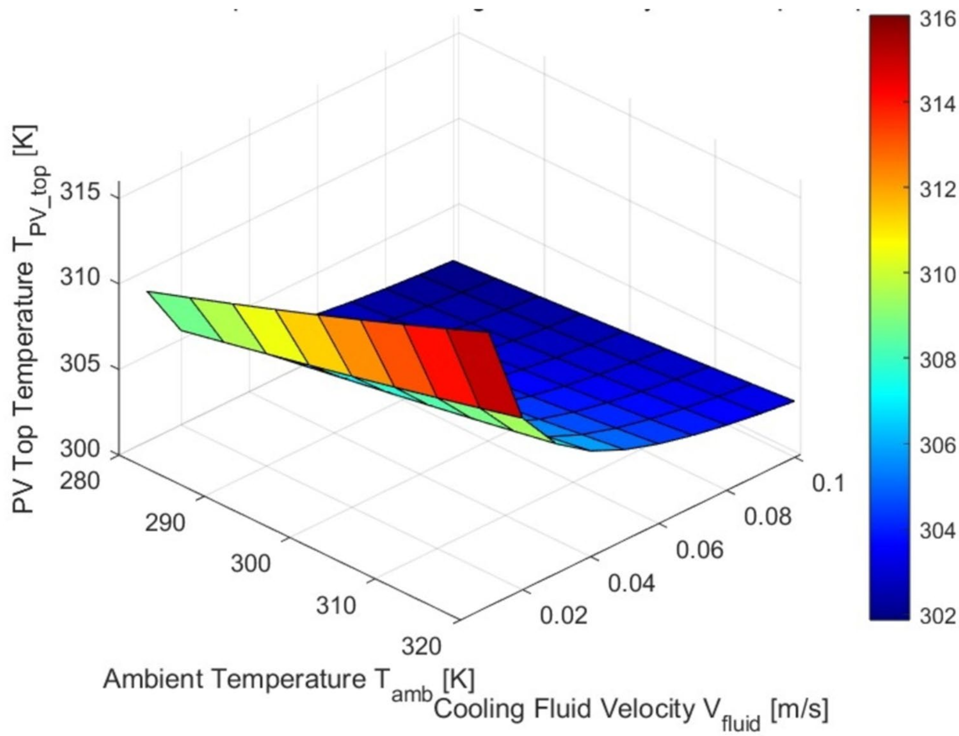


Fig. 15 Effect of ambient temperature and cooling fluid velocity on PV temperature

temperature. It can be seen that both higher coolant flow rates and lower ambient temperatures have a significant effect on reducing the PV temperature. This 3D graph visualizes how the different factors interact to affect the PV temperature and provides theoretical support for the optimization of thermal management systems. Figure 14 shows the sensitivity analysis of the PV temperature (TPV) to several factors, including solar irradiance, ambient temperature, coolant velocity, temperature coefficient, and thermal conductivity. The PV temperature increases with increasing irradiance and ambient temperature while increasing the coolant velocity and thermal conductivity, which helps to reduce the PV temperature. These sensitivity analyses help to understand the responsiveness of the system under different conditions and provide a basis for optimizing the system design.

Compared to the original design, the improved PTC is optically more efficient because it concentrates more light energy directly onto the surface of the PV module rather than focusing on the TEG first, which, in turn, improves the photovoltaic conversion efficiency of the system. The performance of the improved CPC-PTC system was verified by simulation analysis and mathematical modeling, specifically analyzing the system output performance under different light intensity and ambient temperature conditions.

As indicated in Fig. 15, compared to Fig. 13, for the Proposed model, increasing fluid velocity results in a noticeable decrease in PV temperature across the entire range of ambient temperatures. Since the volume of the heat pipe increases, the temperature of the PV panel is better controlled. In the CPC-PTC model, the reduction in temperature gradient is more effective, indicating that the cooling mechanism is well distributed.

The sensitivity analysis can be seen in Fig. 16. Comparing the results of the CPC-PV in Fig. 14, a sensitivity analysis of the Proposed model shows that the PV temperature for the Proposed model is less sensitive to changes in solar irradiance, ambient temperature, and temperature coefficient than the CPC-only model, indicating better performance stability. In addition, the combined system has a greater reduction in PV/T with increasing cooling fluid velocity and thermal conductivity, indicating a more pronounced reduction in PV/T due to enhanced cooling mechanisms.

Table 2 presents the variation of the system output when the input changes, considering the effect of solar irradiance, ambient temperature, and cooling fluid velocity on the PV layer temperature and total output power. The output power of the system increases significantly with increasing solar irradiance, as seen in the table. On the other hand, for the same irradiance and cooling fluid velocity, the increase in ambient temperature causes a slight increase in the temperature of the PV layer but has little effect on the output power. In addition, increasing the cooling fluid flow rate can effectively reduce the temperature of the PV layer and thus enhance system performance. The data in the table form a key basis for optimizing system operation.

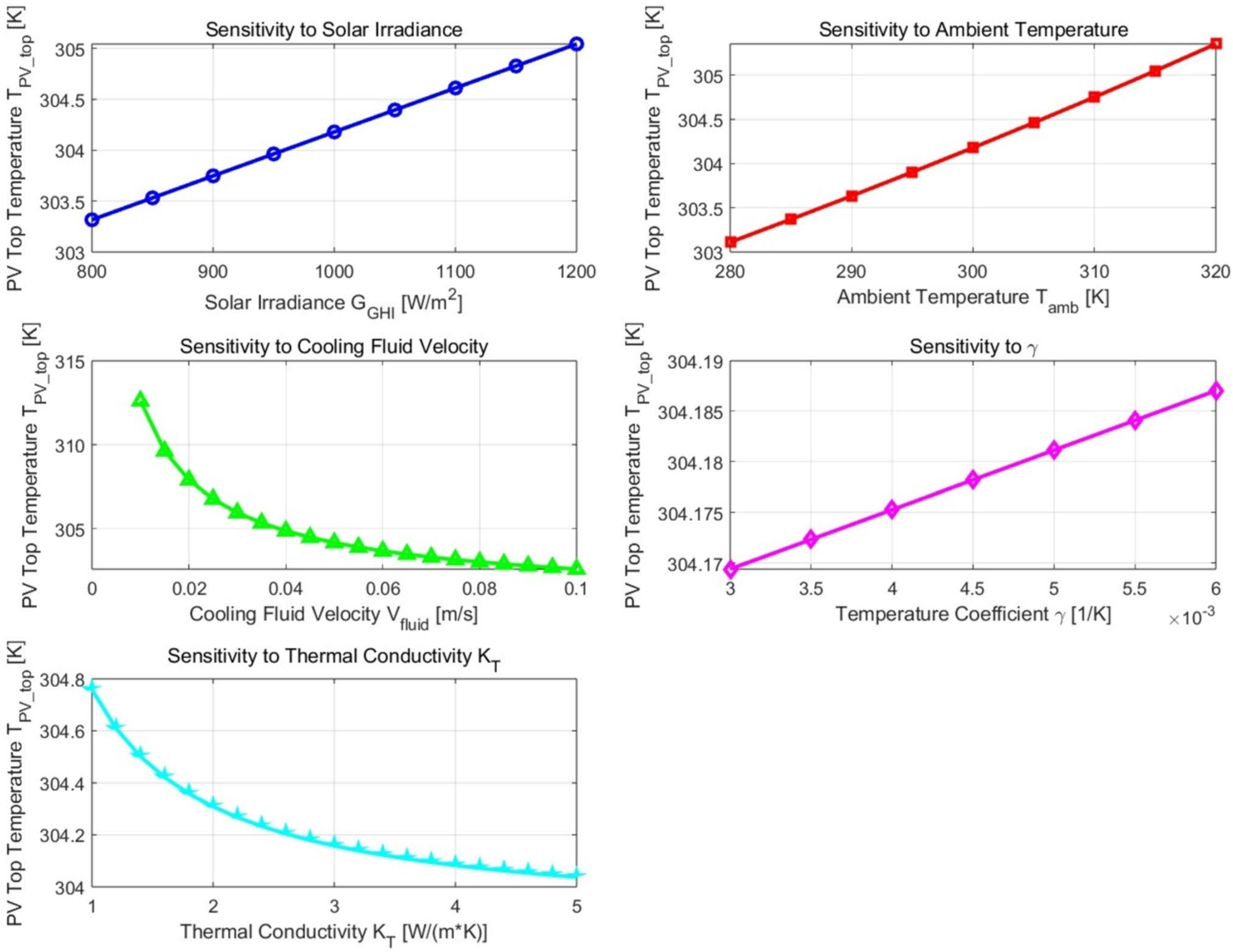


Fig. 16 Sensitivity analysis (proposed model)

Table 2 System output at different input settings

G_{DNI}(w/m^2)	T_{amb}(K)	V_{fluid}(m/s)	T_{PV}(K)	$P_{PV\,\text{total}}$(W)
800	290	0.05	302.69	46.51
800	300	0.05	303.26	46.39
800	300	0.07	302.59	46.54
900	290	0.05	303.12	51.67
900	300	0.05	303.69	52.08
900	300	0.07	302.93	52,27
1000	290	0.05	303.56	57.90
1000	300	0.05	304.12	57.75
1000	300	0.07	303.27	59.98

Table 3 Comparison of Sridhar and Proposed model outputs

Parameters	Reference model (Sripadmanabhan Indira et al. 2022b)	Proposed model
Solar irradiance	998 W/m^2	998 W/m^2
Number of PV cells	8 in series	8 in series
Number of TEGs	4 in series	–
PV output power	39.27 W	56.84W
TEG output power	6.63 W	–
Overall electrical efficiency	4.6%	5.69%

By improving the area of the heat pipes and increasing the heat transfer efficiency, the efficiency of the top PV was increased by 23.8% (shown in Table 3). The photovoltaic output of the system was increased by increasing the focus of the PTC on the PV modules. It was envisioned that TEG could be added to the cooling circuit of the heat pipe, but after preliminary calculations, TEG was not added to the system due to economic considerations, such as the low power of TEG due to the small temperature difference.

By creating the mathematical model and comparing the results, we can draw the following inferences:

- Improving the configuration of the receiver in CPV system can effectively improve the electrical output of the system.
- Through the improvement of the heat transfer efficiency between the heat pipe and the PV, the temperature effect of the PV cell can be effectively reduced, and the development of a more efficient heat pipe can be considered in the subsequent design.

The comparison of CPC alone with CPC and PTC shows significant differences in energy capture and conversion efficiency. CPC is capable of concentrating light over a large range with high efficiency and PTC increases local energy density of the PV module. The overall efficiency of the system is improved by optical justification, particularly the adjustment of the PTC focusing point. The light-absorbing properties of the PV module are enhanced by shifting the focus point of the PTC from the TEG to the PV module, and very high photovoltaic conversion efficiency is achieved.

Conclusions

This study presented a comprehensive analysis of a hybrid CPC-PTC system, both in its original and improved designs. The improved CPC-PTC design was compared in detail to the standard CPC design in terms of optical properties, thermodynamic behavior, and power output performance, and it was found to provide significant enhancements in energy utilization efficiency. Table 3 specifically shows that the power conversion efficiency of the system improved from 4.6% to 5.69%, indicating that the design improvements worked well.

The key advancement in the improved design is the shift of the PTC's emphasis from the TEG to the PV module, resulting in improved photovoltaic conversion efficiency of the system. Mathematical modeling and numerical simulations further validate this enhancement, emphasizing the improved overall energy efficiency of the system.

The optimized concentrating path dramatically increases the light absorption intensity on the PV modules, leading to a dramatic increase in the photovoltaic conversion efficiency. Moreover, the decreased direct exposure of TEGs to high temperatures reduces thermal stress and material degradation, prolonging the system's service life. These innovations highlight the need for thoughtful optical and cooling system design, as they directly impact overall system performance.

The improved CPC-PTC system, moreover, not only overcomes these disadvantages of conventional CPV systems, but also shows the feasibility of such designs in enhancing efficiency and improving thermal management. This study optimizes the optical and thermal performance, establishing a benchmark for adapting hybrid solar energy systems to a range of environmental conditions. Additionally, the integration of advanced configurations with effective thermal management strategies has been shown to enhance system reliability and extend operational lifespan. Future work could focus on experimental validation of the proposed design, innovations in materials, and system performance optimization in response to changing seasonal and geographic conditions in order to develop the next generation of solar technologies further.

Future research directions

Future research should focus on advancing the system's component design to enhance power generation efficiency, cost-effectiveness, and sustainability. This includes improving heat pipe design to optimize heat transfer and reduce PV temperatures, as well as exploring innovative reflector designs to enable multipurpose, adaptable concentrating photovoltaic systems that maximize performance under varying environmental conditions. Additionally, further investigation into thermal management, including the potential integration of thermoelectric generators for waste heat recovery, could open new avenues for system efficiency. Research should also consider testing the CPC-PTC system under diverse climatic conditions, alongside integrating energy storage and other renewable energy sources to achieve greater system synergy and enhanced energy utilization.

Author contributions Xue Wan Chen and Aravind CV conceived of the presented idea. Chen developed the theory and performed the computations. Aravind CV and Suresh Ponnan verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

Data availability No datasets were generated or analyzed during the current study.

Declarations

Competing interest The authors declare no competing interests.

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