

Efficient Energy Generation and Thermal Storage in a Photovoltaic Thermal System Partially Covered by Solar Cells and Integrated with Organic Phase Change Materials

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Abstract

To address the limitations of conventional photovoltaic thermal systems (i.e., low thermal power, thermal exergy, and heat transfer fluid outlet temperature), this study proposes a photovoltaic thermal system with a solar thermal collector enhancer (PVT-STE), incorporating phase change materials for simultaneous electricity and thermal power generation and thermal energy storage. The system consists of a water based solar collector with a partially covered absorber plate utilizing photovoltaic cells, while each component is equipped with a thermal storage enclosure filled with phase change materials. The primary objectives of this research encompass the evaluation of the proposed system's performance and the identification of appropriate phase change materials for each component. To gain comprehensive insight into the effects of employing and selecting appropriate phase change materials, the study investigates various configurations under both hot and cold weather conditions of Shanghai, China. Moreover, the water is used as the heat transfer fluid and the operational conditions are based on real-world conditions. The numerical results indicate that, for the given conditions, optimal phase change material selection entails using higher melting temperatures (e.g., RT42) in the STE component and lower melting temperatures (e.g.,

RT31) in the PVT component. Employing the optimal phase change materials for each component, the system can store 3234 and 1802 kJ/m² of thermal energy during the charging process in July and November, respectively. Moreover, the proposed system generates almost 1.8 and 2 times more thermal energy per square meter in July and November, respectively, compared to a standalone photovoltaic thermal system coupled with a phase change material. These improvements in thermal exergy rate per square meter are notably higher, reaching 2.9 and 5 times in July and November, respectively.

Word count: xxxx

Keywords:

Photovoltaic thermal system; Solar thermal collector; Phase change material; Thermal energy storage; Electricity generation; Renewable energy.

Nomenclature	
A	Area (m ²)
c_p	Specific heat capacity (J.kg ⁻¹ .K ⁻¹)
E	Energy (J)
$\dot{E}$	Power (W)
$\dot{E}_X$	Rate of exergy (W)
$\dot{E}''$	Power per unit area (W.m ⁻²)
$\dot{E}_X''$	Rate of exergy per unit area (W.m ⁻²)
h	Convection heat transfer coefficient (W.m ⁻² .K ⁻¹)
k	Thermal conductivity coefficient (W.m ⁻¹ .K ⁻¹)
$\dot{m}$	Mass flow rate (kg.s ⁻¹)

P	Pressure (Pa)
t	Time (s)
T	Temperature (K)
V	Velocity (m.s ⁻¹)
A_{mush}	Mushy zone constant

Greeks

α	Absorptivity
β	Reference temperature coefficient
ε	Emissivity
η_r	Energy efficiency reference (%)
μ	Dynamic viscosity (kg.m ⁻¹ .s ⁻¹)
ρ	Density (kg.m ⁻³)
σ	Stefan-Boltzmann constant (W.m ⁻² .K ⁻⁴)
τ	Transmissivity
ϕ	Liquid volume fraction

Subscripts

ab	Absorber
amb	Ambient
eff	Effective
el	Electrical
g	Glass cover
HTF	Heat transfer fluid
pV	Photovoltaic unit
ref	Reference
s	Solid components
sun	Sun

th Thermal

w Wind

Abbreviation

EVA Ethylene-vinyl acetate

HTF Heat transfer fluid

PCM Phase change material

PV Photovoltaic unit

PVT Photovoltaic thermal module

PVT-ST Photovoltaic thermal system integrated with solar thermal collector

PVT-STE Photovoltaic thermal system with solar thermal collector enhancer

ST Solar thermal collector

UDF User-defined function

1 Introduction

The continuous growth in demand for energy and global environmental concerns arising from the use of fossil fuels have necessitated an urgent pursuit of alternative technologies that work with sustainable and renewable energy sources. Solar energy has attracted significant interest among various sources because of its abundant availability and increasing affordability. Different systems have been introduced to generate thermal and electrical power from solar radiation. Solar thermal collectors (ST) are particularly attractive options for converting sunlight into heat, offering a wide range of applications spanning from small-scale household heating, cooling, and water heating to large-scale industrial processes and power generation. Another solar conversion technology is photovoltaic cells (PV), which generate only electricity. Most PV panels available in the market have electrical efficiencies between 9 and 20% [1], meaning that around 80-91% of the received solar radiation is either absorbed or reflected. This huge share of solar energy absorbed by PV cells increases their temperature, leading to a decline in cells' electrical efficiency and lifetime [2]. To

resolve these drawbacks and harness thermal power, photovoltaic thermal modules (PVT) are introduced. These systems, which combine the advantages of both PV and ST modules, generate more electrical power than a standalone PV panel and produce thermal power. However, PVTs produce lower levels of thermal power, exergy (thermal exergy efficiency is typically around 1% [3]), and outlet temperature compared to a standalone ST.

The low-temperature output of PVT systems is not directly suitable for many residential and industrial applications, necessitating either improving their thermal performance or using heat pumps or other auxiliary devices. Numerous methods have been proposed in the literature to enhance the electrical and thermal performance of flat plate PVT systems. These methods encompass thermal collector design [4], incorporation of a glass cover [5], utilization of nanofluids [6] and phase change materials (PCM) [7], implementation of spectrum splitting [8], application of jet impingement [9], and adoption of thermoelectric generators [10]. A summary of the impacts and effects of these methods is presented in Table 1.

Table 1. A summary of several different techniques used for improving the thermal and electrical performance of PVT modules.

Ref. (Year)	Improvement technique	Highlights
Abdalla and Shahsavari [6] (2023)	Nanofluid	✓ Experimentally investigating the performance of Water-based GO-TiO₂-Fe₃O₄ ternary nanofluid PVT system. ✓ Evaluating the effects of mass flow rate, nanoparticles volume fraction and mixing ratio. ✓ Achieving best total energy (88.23%) and exergy (15.36%) efficiencies at mixing ratio of 1:1:1, mass flow rate of 80 kg/h, and volume fraction of 1%.
Bhakre et al. [7] (2023)	Phase change material	✓ Numerically addressing high operating temperature of PV and water-based PVT panels with RT42 PCM. ✓ Increasing the electrical efficiency by 14.93% for the PVT system integrated with PCM at 30° orientation.
Praveenkumar et al. [10] (2023)	Thermoelectric generator	✓ Experimentally examining the performance of a PVT system integrating with thermoelectric generator and nanofluid. ✓ Investigating the levelized cost of energy, energy payback time, and the environmental impact of new system ✓ Indicating an improvement in electrical efficiency of PV panel by using water cooling and proposed system by 5.8% and 8.5%, respectively.

Zhang et al. [8] (2022)	Spectral splitting	✓ Numerically investigating the spectral splitting PV/T system with silver nanofluids. ✓ Presenting a flexible control strategy for 45°C outlet temperature. ✓ Calculating the daily mean energy harvesting in Zhengzhou (2.69 MJ), Beijing (5.01 MJ), and Harbin (3.12 MJ) in winter.
Vajedi et al. [4] (2022)	Thermal collector design	✓ Experimentally comparing the performance of an air-based PVT system with converging collector and conventional one. ✓ Presenting a cost-effective enhancement method to achieve uniform temperature distribution on PV cells. ✓ Boosting the convective heat transfer coefficient by 38% and net total efficiency by 12% on average using the proposed ST.
Hissouf et al. [5] (2021)	Glass cover	✓ Numerically comparing the performance of a water-based PVT system with and without glass cover. ✓ Reporting higher thermal efficiency of glazed PVT (21.49% compared to the unglazed PVT) and higher electrical efficiency of unglazed PVT (11.78% compared to the glazed PVT).
Hasan et al. [9] (2017)	Jet impingement	✓ Experimentally evaluating SiC, TiO₂, and SiO₂-water nanofluid PVT system with jet impingement. ✓ Obtaining highest thermal and electrical efficiencies of 12.75% and 85%, respectively, using SiC-water. ✓ Improving the maximum power by 62.5% using SiC-water in comparison with conventional PV module.

According to the findings presented in Table 1, it can be concluded that the employed methods have shown potential in enhancing the performance of PVT modules, both electrical and thermal. Nevertheless, before implementing these improvement techniques, it is crucial to prioritize the design of an efficient PVT module to achieve higher outlet temperatures of the heat transfer fluid (HTF). Over the past decade, two designs have been proposed with the aim of increasing the HTF outlet temperature of PVT systems and rendering them more suitable for real-world applications. Recently, PVT-STs, a combination of flat ST and PVT, have been proposed [11]. PVT-STs are systems in which two separate modules of ST and PVT are connected in series. In these systems, the HTF initially passes through the PVT, and then the preheated HTF enters the ST module to increase the temperature to an acceptable level. A few researchers have explored how well this integrated system performs.

Ma et al. [11] introduced the water-based PVT-ST system and examined its annual performance under the Shanghai weather conditions using a two-dimensional model. The results

showed that the proposed system generated marginally lower electricity for a fixed total area than PV and glazed PVT; however, it showed better thermal and total performance than ST and PVT systems. The module could produce 298.5 and 2096.5 kWh of electricity and thermal energy with a primary energy-saving efficiency of 83.48%. Li et al. [12] evaluated the effects of using a glass cover on the PVT-ST system using a two-dimensional model from energy and exergy standpoints. This work indicated that the maximum total energy (41.51%) and exergy (17.63%) efficiency was obtained once the glass cover was used in both parts of the system. Nevertheless, the highest electricity generation was observed in the unglazed module. Using a two-dimensional simulation, Han et al. [13] compared two systems, including a PV-ST (separate ST and PV) and a PVT-ST. The results recommended using PVT-ST in high ambient temperature and solar radiation conditions, whereas the PV-ST reflected better performance at low ambient temperature and solar radiation. Kazemian et al. [14] compared the performance of ST, PV, PVT, and PVT-ST systems by utilizing a three-dimensional model. Moreover, the impacts of various operating conditions on the performance of the PVT-ST were investigated and optimized using Taguchi-based grey relational analysis. The most influential operating parameter was solar radiation, as the results of that study reported. The performance of the PVT-ST system with/without a glass cover was evaluated by Suresh et al. [15] experimentally and numerically. Using unglazed PVT-ST increased the outlet temperature by 17 °C compared to the unglazed PVT, while for the glazed modules, this increment decreased to 14–15 °C. Although using the glass cover in PVT-ST improved the HTF outlet temperature, the generated electricity dropped by 23% compared to the module without cover.

Although PVT-ST systems effectively improve thermal performance compared to PVTs, this architecture still has some drawbacks. For instance, using an additional pipe to connect two

independent PVT and ST systems increases the pressure and heat losses throughout the pipes, and as a result, it needs higher pumping power. Additionally, there is a greater risk of leakage, and installation in limited spaces can be challenging. Eventually, a compact design called partially covered photovoltaic thermal is used to address these problems by eliminating the connecting pipe and consolidating the PVT-ST system into a single unit [16]. This system, referred to as photovoltaic thermal with ST enhancer (PVT-STE) in this study, utilizes PV cells to partially cover an ST system, where the tubes are positioned beneath the entire absorber plate to capture the heat from both PV cells and absorber plate. Therefore, thanks to the higher thermal efficiency of the ST part (owing to the greater absorptivity of the absorber plate and converting the solar energy to heat only), the HTF outlet temperature from the PVT part could increase to a suitable level by passing under the ST part.

In conclusion, the proposed PVT-STE system, in addition to addressing the mentioned drawbacks of the PVT-ST system, can produce higher thermal energy and exergy than a standalone PVT system. Several studies have examined the PVT-STE system's performance, concentrating especially on the results of linking multiple of them in the shape of flat plate collectors [16] or compound parabolic concentrators [17]. Most of these studies used a number of PVT-STE systems with compound parabolic concentrators, investigating the effects of the number of collectors, mass flow rate, and solar cell materials [18]. Moreover, PVT-STE in the form of a flat plate was studied by Shyam et al. [19] to study the impacts of the number of connected modules, mass flow rate, and PV cells' position on the system efficiency. An additional experimental investigation was conducted by Shyam et al. [20] to evaluate the annual performance of several PVT-STE systems connected in the form of flat plate collectors. The total annual thermal energy and exergy productions were 3561.9 and 376.1 kWh, respectively.

Despite the numerous advantages of using solar energy, it is subject to periodic behavior and mismatches between supply and consumption [21]. To address these challenges, the use of thermal energy storage units filled with PCMs is recommended [22]. PCMs, thanks to their enormous heat storage density, can absorb a vast quantity of thermal energy during the day and release it during periods of low solar radiation or at night. The application of PCMs in ST collectors and PV modules has been investigated by several researchers [23, 24]. For example, in an experimental study, El Khadraoui et al. [25] examined an air-based ST performance and demonstrated that employing PCM increased the outlet air temperature over the night. Moreover, PCM could increase daily energy efficiency from 17% to 33%. Integrating PCMs in PV and PVT modules has demonstrated the potential to enhance electrical efficiency by reducing cell temperature through heat absorption [26]. As an example of using PCM in PV modules, Sheik et al. [27] experimentally evaluated the performance of using polyethylene glycol PCM and nano-enhanced PCMs (adding alumina and silica nanoparticles) on a PV panel. Compare to the PV panel, integrating the system with PCM, silica-PCM, and alumina-PCM could reduce the PV panel temperature by 10.9%, 14.8%, and 17.18%, respectively, resulting in an improvement in electrical efficiency by 4.82%, 7.17%, and 8.1%. By developing 3D numerical modeling, Kazemian et al. [28] studied and optimized a PVT system integrated with PCM using response surface methodology. The obtained results exhibited a reduction in thermal power by increasing the PCM volume while increasing electrical power. Consequently, using PCM in the PVT-STE systems can also improve performance and avoid some of the problems with solar systems that have been previously described. Moreover, PCMs can assist keep HTF from freezing, especially in cold regions [29].

This numerical study proposes a flat plate PVT-STE integrated with PCM capable of simultaneously producing electrical and thermal power. Overall, the main benefits of this system lie in its ability to address the frequent issues of conventional PVT (e.g., low thermal power, thermal exergy, and HTF outlet temperature) and newly introduced PVT-ST modules (e.g., increase in pressure drop, heat loss, leakage possibility, and placement problem). The integration of a thermal energy storage unit filled with PCMs into the system allows for the storage of thermal energy, effectively reducing the temperature of the PV cells, and thereby enhancing the overall energy efficiency of the system. The PVT-STE design exhibits promising potential for improving the applicability of PVT systems in diverse climates, particularly in regions with low solar radiation and ambient temperatures. This design addresses the demand for higher thermal power in addition to electrical power generation. Moreover, the proposed system has the potential to be applied in various sectors, including residential and commercial buildings, where there is a demand for both electrical and thermal energy. Additionally, this system can be used in off-grid locations or areas with limited access to electricity and can contribute to the development of sustainable energy solutions.

Based on the literature review, the following major research gaps still remain: (a) While the advantages of using PCMs in solar systems have been extensively discussed throughout the literature, there is a lack of studies on their application in PVT-STE, and (b) there is no research to address the selection of efficient PCMs for each part of the system (PVT and STE) based on their melting temperature. Therefore, the key research objectives of this study are summarized as follows:

- Proposing an innovative concept of PVT-STE integrated with PCM to address limitations found in conventional PVT, newly introduced PVT-ST, and PVT-STE systems.

- Developing a 3D transient model for PVT-STE integrated with PCM to investigate the module performance regarding energy and exergy under varying weather conditions representative of July (summer) and November (fall).
- Evaluating the energy distribution in different layers, PCM melting fraction, and the quantity of energy stored/released in/from the PCM during the considered operational period.
- Identifying suitable PCMs for each component, PVT and STE, by evaluating the thermal and electrical behavior of the module using different PCMs from RT series.
- Assessing the system's performance under different PCM arrangements, including (a) using the same PCM beneath both components, (b) employing different PCMs in each component, and (c) using PCM in either the PVT or STE component.
- Comparing the performance of the proposed module with standalone PVT and ST systems integrated with PCMs.

2 Methodology

A comprehensive analysis of PCM's effects on PVT-STE performance has been conducted in this study. Fig. 1 summarizes the methodology for this study and illustrates the different steps. Firstly, the PVT-STE system is numerically simulated, as described in Section 2.2. The second step involves validating the model and analyzing the grid and time-dependent data. Considering Shanghai weather in July and November, the analysis is performed. To study the effects of PCMs, firstly, the same PCM is chosen for both components of the PVT-STE module, including RT31, RT35, and RT42 (see Section 3.1). Next, as described in Section 3.2, different combinations of PCMs are applied to each component of the PVT-STE system. The impact of PCM inclusion or exclusion from each component of the PVT-STE is also studied in Section 3.3. Finally, to

investigate the module's applicability, a comparison is made between the proposed system and existing conventional solar systems in the literature, which include a standalone PVT module and ST collector integrated with PCMs.

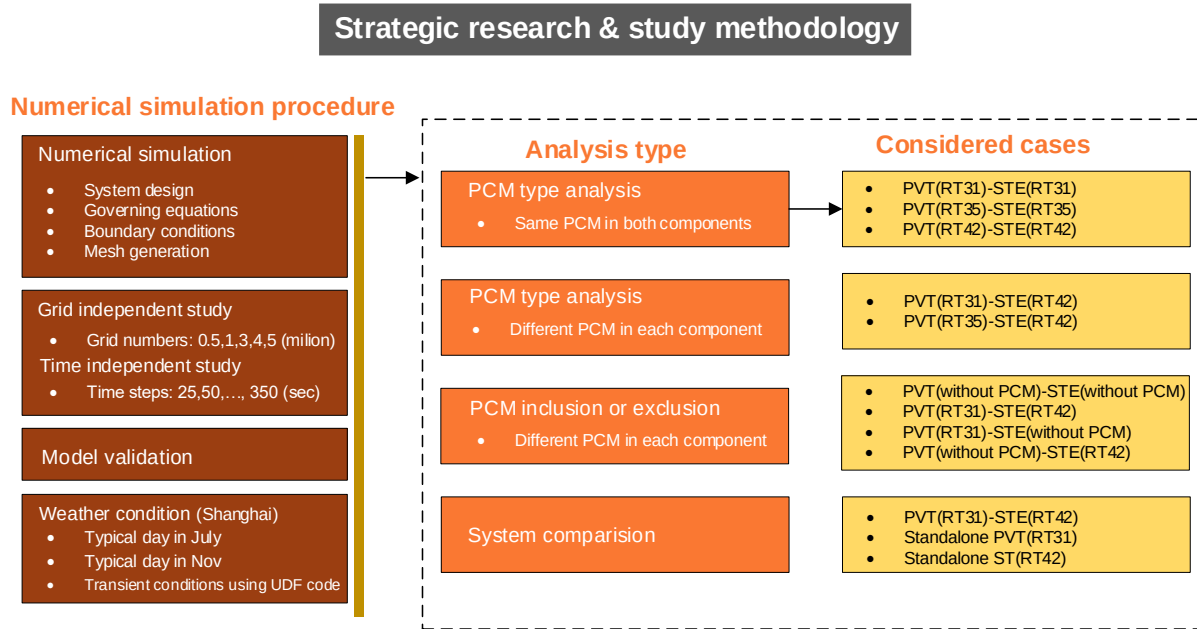


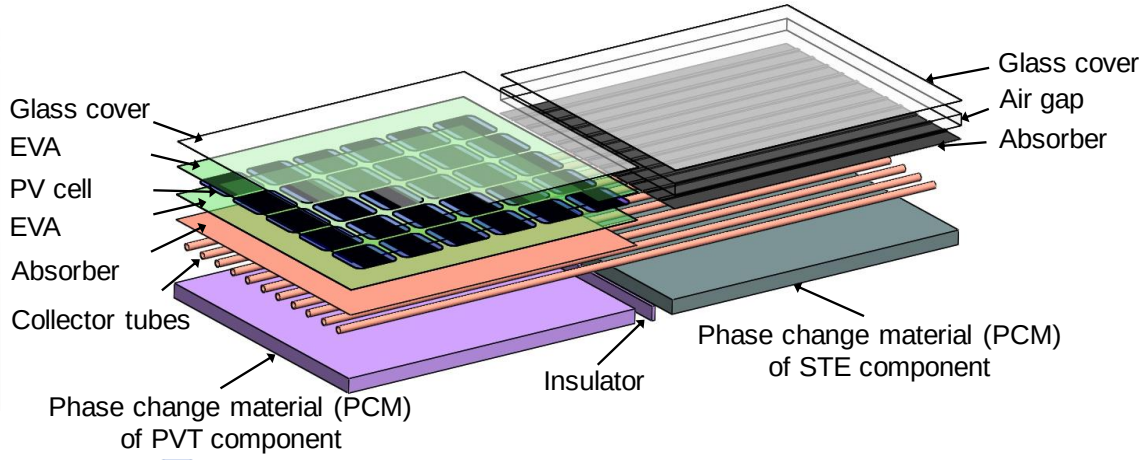
Fig. 1. Overview of the research methodology used to analyze the effects of phase change materials (PCMs) on the performance, visualization, and thermal storage characteristics of a PVT-STE. The methodology includes numerical simulation, analysis of grid and time-dependent data, and validation to select the efficient PCM type for each component of PVT-STE system.

2.1 System description

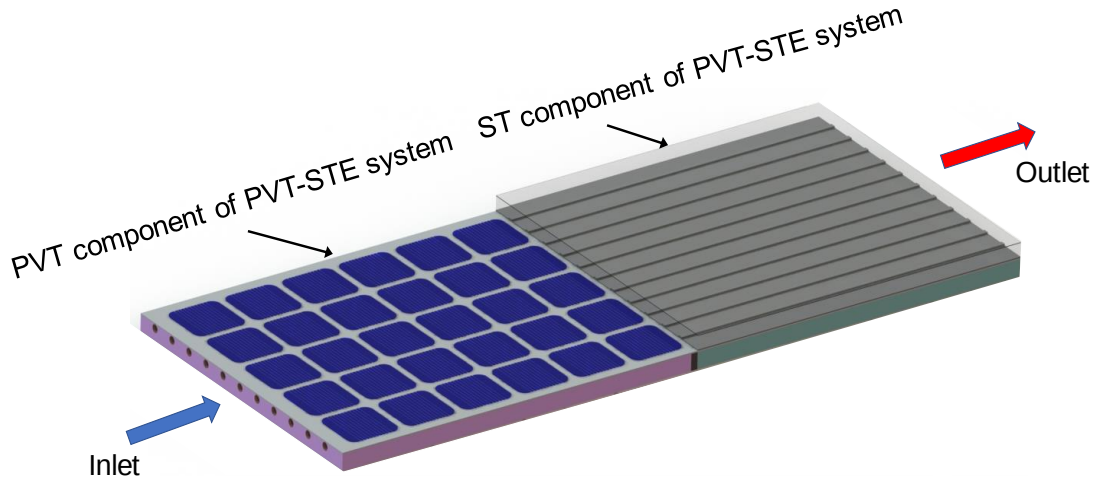
Fig. 2 illustrates the PVT-STE system, featuring a split configuration where half of the system is devoted to the PVT component, and the other half is allocated to the STE component. This design simultaneously provides thermal and electrical energy and ensures a higher outflow temperature than standalone PVT systems. This figure shows that the PVT component consists of PV layers (glass cover, EVA, and PV cells), a copper absorber, and collector tubes that capture

heat. The STE component (the second half of the system in Fig. 2) contains absorber and collector tubes, a glass cover, and an air gap. Unlike the STE component, for the PVT component, the air gap is not considered. Although using the air gap leads to an increase in thermal power, it also enhances the cells' temperature, which in turn negatively impacts electrical performance [30]. A STE component can absorb more solar energy than PV cells due to the air gap between the glass and absorber and the higher absorption of the absorber plate. Therefore, to provide a higher outlet temperature for HTF, the HTF enters the STE part after passing through the PVT component. PCMs can absorb more heat during the day due to their high heat storage density, reducing the system's surface temperature and enabling it to function efficiently. PCM enclosures are also attached to the system to study PCM's impact on system efficiency. In this study, an open-circuit system was selected to enable a comparative analysis between the performance of the novel system proposed and conventional PVT and ST systems. The adoption of an open-circuit system allowed for an assessment of key performance indicators and the subsequent comparison of results. The closed cycle, while potentially offering higher efficiency and outlet temperatures for HTF, is a more complex and expensive system. Overall, the choice between open and closed cycles depends on factors such as cost, efficiency, and the specific application of the system. The dimensions and thermophysical characteristics of various elements are presented in Table 2 and Table 3, respectively. It should be noted that the actual dimensions of the PV panel components are 992 mm $\times$ 1640 mm, readily available in the market [31]. In order to decrease the computational time and leverage model symmetry, this study focuses on simulating a single collector tube (one riser) instead of the entire geometry, following the approach used by Maadi et al. [2]. Therefore, a single collector tube width of 200 mm, with symmetric boundaries is used to simplify the simulation.

Additionally, the nominal power of the adopted PV panel is 590 watts, based on the factory specifications [31].



(a) Exploded view



(b) Assembly model

Fig. 2. Schematic illustration of the proposed PVT-STE system, which combines PVT and ST technologies for simultaneous electricity generation and thermal energy collection. The figure shows the key components of the PVT and STE modules, and the use of phase change materials (PCMs) for thermal storage and efficient operation consisting (a) exploded view and (b) assembly model.

Table 2. Overview of the dimensions of the key elements in the proposed PVT-STE system. The table presents the dimensions of critical components such as the photovoltaic unit, thermal absorber plates and collector tubes, which are essential for simulation of the PVT-STE system.

System elements	Dimensions (mm)
The glass cover of the PVT component	200×1640×3.2
The glass cover of the STE component	200×1640×3.2
Air gap	200×1640×25
EVA	200×1640×0.5
PV unit	200×1640×0.3
Absorber plate of PVT component	200×1640×4.0
Absorber plate of STE component	200×1640×4.0
Tube inner radius	4
Tube's thickness	1
Thickness of PCM in each component	15

Table 3. Overview of the thermophysical characteristics of various components used in the proposed system, including glass cover, PV layers, phase change materials (PCMs), thermal absorber plates, and collector tubes [32, 33].

Components	Density (kg.m ⁻³)	Conductivity (W.m ⁻¹ .K ⁻¹)	Specific heat (J.kg ⁻¹ .K ⁻¹)	Enthalpy of fusion (kJ.kg ⁻¹ .K ⁻¹)	Melting temperature range (°C)
Glass cover	2200	0.76	830	---	---
Ethylene-vinyl acetate	960	0.35	2090	---	---
Photovoltaic cells	2330	148.0	700	---	---
Absorber plate and collector tubes	8960	401.00	385	---	---
PCM (RT31)	760	0.2	2000	165	27-33
PCM (RT35)	770	0.2	2000	160	29-36
PCM (RT42)	760	0.2	2000	165	38-43

2.2 Numerical simulation procedure

A three-dimensional transient numerical simulation for a PVT-STE system is developed using ANSYS Fluent. Using the transient solver, conservation equations are solved because weather data changes over time [34]. A finite volume scheme with a pressure-based approach is used to discretize the conservation equations. Due to Reynolds numbers below 2300, laminar and incompressible flow regimes are considered. The symmetry condition is established with multiple parallel collector tubes; therefore, only one riser is simulated to reduce computational cost [2, 14]. The phase change phenomenon simulation in PCM is conducted using the enthalpy-porosity technique [35]. With ANSYS meshing software, three-dimensional structured grids are generated with a total number of 3290000 cells and a fixed time step of 3 minutes. Several assumptions are made to simulate the system numerically:

- Dust and agents do not accumulate on PVT-STE's glass cover [36].
- There is uniform solar irradiance, which is taken into account as a source term in energy equations for solar cells (in the PVT component) and an absorber plate (in the STE component) [37].
- The inflow temperature is equal to the ambient temperature [28].
- Temperature-independent thermophysical properties are assumed for PCMs and other components [38].
- Contact resistance is negligible between different layers of the system [39].
- Adiabatic condition is assumed for the bottom and side surfaces of the PVT-STE [40].

2.3 Governing equations

The PVT-STE system has different components, including solid and fluid parts. The heat transfer between various solid parts using the conduction mechanism is as follows [14]:

$$\left(\rho c_p\right)_s \frac{\partial T_s}{\partial t} = \nabla \cdot (k \nabla T)_s + \gamma \dot{E}_{eff, sun, PV}'' + \psi \dot{E}_{eff, sun, STE}'' - \xi E_{el}'' \quad (1)$$

where, ρ , c_p and k denote the density, specific heat capacity, and thermal conductivity, respectively, and subscript "s" refers to solid parts. This equation has three source terms, $\dot{E}_{eff, sun, PV}''$, $\dot{E}_{eff, sun, STE}''$ and E_{el}'' , which show the absorbed solar radiation by PV cells, absorbed solar radiation by absorber of the STE component, and electrical energy generated by PV cells, respectively. Electrical power can only be generated by PV cells; thus, $\xi = 1$ is for the PV layer, and for other layers $\xi = 0$. As mentioned in Section 2.2, assuming the absorption of solar radiation by PV cells (in the PVT component) and absorber (in the STE component); $\gamma = 1$ for PV cells, $\psi = 1$ for the absorber plate (in STE component), and for other layers $\gamma = 0$ and $\psi = 0$. These mentioned source terms are applied to the numerical simulation using user-defined functions (UDF) codes, and can be obtained as follows [26, 41]:

$$\dot{E}_{eff, sun, PV}'' = \tau_g \cdot \alpha_{PV} \cdot \dot{E}_{sun}'' \quad (\tau_g = 0.92, \alpha_{PV} = 0.93) \quad (2)$$

$$\dot{E}_{eff, sun, STE}'' = \tau_g \cdot \alpha_{absorber} \cdot \dot{E}_{sun}'' \quad (\tau_g = 0.92, \alpha_{absorber} = 0.95) \quad (3)$$

$$E_{el}'' = E_{eff, sun, pv}'' \cdot \eta_r \cdot [1 - 0.0045 \cdot (T_{cell} - T_{ref})] \quad (4)$$

where τ_g is glass transmissivity, α_{PV} is PV absorptivity, $\alpha_{absorber}$ is absorber absorptivity, and

E_{sun}'' is solar radiation per unit area. $\dot{E}_{eff, sun, PV}''$ and $\dot{E}_{eff, sun, STE}''$ are effective absorbed solar radiation

by PVT and STE components, respectively. Moreover, η_r is the reference cell efficiency (0.173), T_{ref} is the reference cell temperature (25 °C), and T_{cell} is the temperature of PV cells. In addition to solid components, the system has HTF, which passes through the collector tubes. The required conservation equations for working fluid are given as follows [42]:

$$\frac{\partial \rho_{HTF}}{\partial t} + \nabla \cdot (\rho_{HTF} \vec{V}_{HTF}) = 0 \quad (5)$$

$$\rho_{HTF} \left[\frac{\partial \vec{V}_{HTF}}{\partial t} + (\vec{V}_{HTF} \cdot \nabla) \vec{V}_{HTF} \right] = -\nabla P + \nabla \cdot (\mu_{HTF} \nabla \vec{V}_{HTF}) \quad (6)$$

$$\rho_{HTF} C_{p,HTF} \frac{\partial T_{HTF}}{\partial t} + \rho_{HTF} C_{p,HTF} \vec{V}_{HTF} \cdot \nabla T_{HTF} = \nabla \cdot (k_{HTF} \nabla T_{HTF}) \quad (7)$$

where $\vec{V}$, P and μ are fluid velocity, pressure, and viscosity, respectively.

PCM is simulated using the enthalpy-porosity methodology, and detailed information about this method is available elsewhere [43-45]. For PCM simulation, the mass and momentum equations can be given as follows [44]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot \vec{V}) = 0 \quad (8)$$

$$\rho \left[\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla) \vec{V} \right] = -\nabla P + \nabla \cdot (\mu \nabla \vec{V}) + S \quad (9)$$

$$S = \frac{(1-\beta)^2}{(\beta^3 + \phi)} A_{mush} (\vec{V} - \vec{V}_p) \quad (10)$$

where β , A_{mush} , $\vec{V}_p$, S and ϕ are liquid fraction, mushy zone constant, solid phase velocity, energy source, and a small number to prevent division by 0, respectively [44]. Coefficients of A_{mush} and ϕ are equal to 10^5 and 0.001, respectively [44, 45]. Furthermore, the energy equation is given as follows [44]:

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{V} H) = \nabla \cdot (k \nabla T) + S \quad (11)$$

$$H = h + \Delta H \quad (12)$$

$$h = h_{ref} + \int_{T_{ref}}^T C_p dT \quad (13)$$

$$\Delta H = \beta L \quad (14)$$

where H is the enthalpy of material, h is sensible enthalpy, ΔH is latent enthalpy, L is the latent heat of the material, and β is liquid fraction calculated as follows [44]:

$$\beta = \begin{cases} 0 & \text{if } T < T_{solidus} \\ \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & \text{if } T_{solidus} < T < T_{liquidus} \\ 1 & \text{if } T > T_{liquidus} \end{cases} \quad (15)$$

2.4 Boundary conditions

The PVT-STE system cross-section, which includes all layers and boundary conditions, is shown in Fig. 3. For inflow and outflow, “mass flow inlet” and “pressure outlet” conditions are selected. The panel's side surfaces do not transfer heat to the environment, and "adiabatic walls"

are applied to them. An insulation layer is placed between the PVT and STE components for analyzing the impact of different PCMs in each element of the proposed system. In the PVT and STE components, the solar radiation absorbed by PV and absorber plates, respectively, is accounted for as a source term in the energy equation. Radiation and convection heat transfer to the environment occur on the system's top surface. The convection heat transfer coefficient of wind is obtained by $h_w^* = 5.7 + 3.8V_w$ and the sky temperature is calculated by $T_{sky} = 0.0552 \times T_{amb}^{1.5}$ [46].

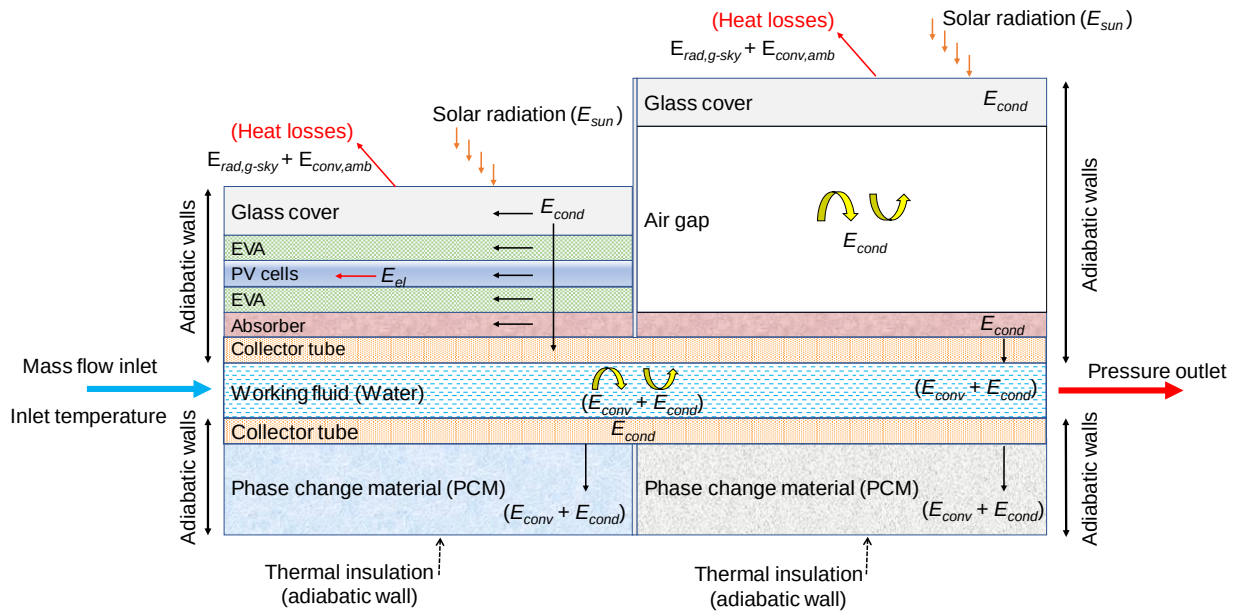


Fig. 3. Boundary conditions and the thermal energy exchange between different parts of the simulated PVT-STE system integrated with PCM. The figure displays the boundary conditions used in the simulation, such as the mass flow inlet, inlet temperature, pressure outlet of the working fluid, and adiabatic walls.

2.5 Performance evaluation method

The thermal power per area of the system is calculated by [14, 47]:

$$\dot{E}_{th}'' = \frac{\dot{m}_{HTF} \cdot C_{p,HTF} \cdot (T_{HTF,out} - T_{HTF,in})}{(A_{PVT} + A_{STE})} \quad (16)$$

where $\dot{m}_{HTF}$, $T_{HTF,in}$, $T_{HTF,out}$, A_{PVT} and A_{STE} are mass flow rate, HTF inflow and outflow temperatures, and area of PVT and STE components, respectively. The electrical exergy ($\dot{E}_{el}''$) is calculated as follows [48]:

$$\dot{E}_{el}'' = \dot{E}_{el}'' \quad (17)$$

The thermal power is obtained as follows [49]:

$$\dot{E}_{th} = \dot{m}_{HTF} \cdot c_{p,HTF} \left[(T_{HTF,outlet} - T_{HTF,inlet}) - T_{amb} \ln\left(\frac{T_{HTF,outlet}}{T_{HTF,inlet}}\right) \right] \quad (18)$$

where, T_{amb} is the ambient temperature.

To analyze the performance of the PVT-STE system based on thermal power, the electrical output power is converted into thermal power using a conversion factor (C_f), as commonly employed in the literature [50, 51]. The net equivalent thermal power of the system can be calculated as shown in [3]:

$$\dot{E}_{net,th}'' = \dot{E}_{th}'' + \frac{\dot{E}_{el}'' - \dot{E}_{pump}''}{C_f} \quad (19)$$

In most PVT systems, a value of 0.35 to 0.40 has been considered for C_f [51]. Accordingly, in the present study, a value of 0.38 has been adopted [52, 53]. $\dot{E}_{pump}''$ is required pump power which can be calculated as follows [3]:

$$\dot{E}_{pump}'' = \frac{\dot{m} \times \Delta P}{A \times \rho \times \eta_{pump}} \quad (20)$$

where $\dot{m}$ is mass flow rate, ρ is density of water and η_{pump} is efficiency of pump. It should be noted that to calculate the pump power per unit area of a system, the total pump power is divided by the system's surface area (A).

2.6 Model validation

The validity of the current research results is confirmed through a comparison with the experimental study conducted by Suresh et al. [15]. The authors used a PV panel with 380 Wp, covered by 70 cells with a fill factor of 0.81. The absorber of the PVT was an aluminum plate (1×2 m²) consisting of 12 tubes, each 8 mm in radius and 1 mm thick. In the ST component, a copper absorber plate (1×2 m²) is used as an absorber connected to nine tubes. Ref. [15] provides information on each layer's thickness and thermophysical properties. The weather conditions for validation are similar to those of their experiments performed in Chennai, India, in February 2020. Fig. 4 compares the numerical and experimental results of the system's power output based on a flow rate of 30 L/h. The maximum error between the results of both studies is estimated to be less than 8%. One possible reason for this discrepancy is that the experimental data was obtained under ideal conditions, while the numerical simulations were conducted using simplified models that may not fully capture all of the real-world complexities of the system. Additionally, there may have been some measurement errors in the experimental setup that could have contributed to the observed differences. Despite these small errors, the numerical results were still found to be in good agreement with the experimental data, supporting the validity of the simulation approach.

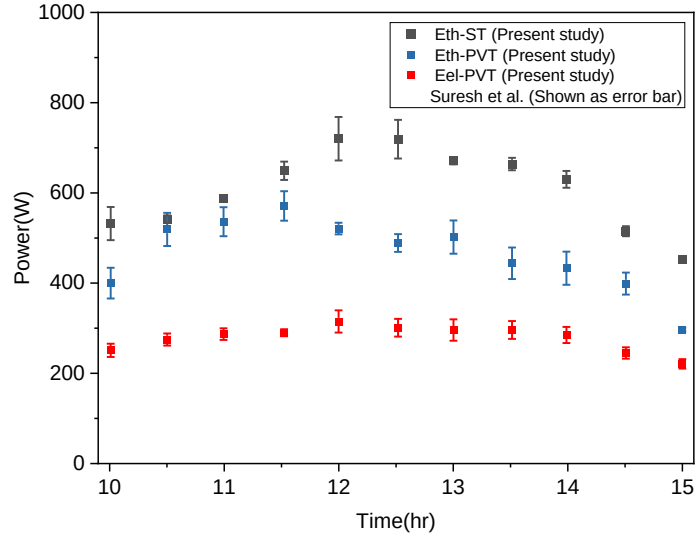


Fig. 4. Comparison of the electrical and thermal powers generated by the proposed PVT-ST system with those generated by the system proposed by Suresh et al. [15]. The figure displays the simulation results of the present study as points and the results presented by Suresh et al. [15] as error bars under varying solar irradiance levels.

3 Results and discussion

For studying the impact of phase change material on the proposed PVT-ST system, first the impact of using the same PCM for both components is evaluated. Then, it is assumed that the PCM type in the two components of the PVT-ST system is different. The effects of PCM existence beneath each component of the hybrid system are then investigated. Finally, a performance comparison is carried out between the PVT-ST system and two conventional solar systems of ST and PVT integrated with PCMs to analyze the proposed system's feasibility. The present work was conducted in Shanghai, China, under the weather conditions of July and November, as presented in Fig. 5. The weather data were collected on the 17th of July and the 14th of November, respectively. The weather data were obtained from the Green Energy Laboratory at Shanghai Jiao Tong University, which is a reputable source for climate data.

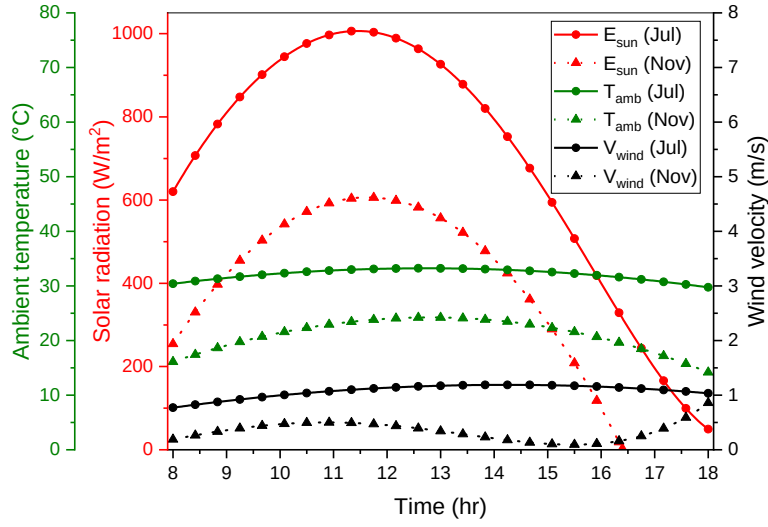


Fig. 5. Hourly variations of solar radiation, ambient temperature, and wind speed for a typical day in July and November in Shanghai, China. The data were collected on the 17th of July and 14th of November.

3.1 Same phase change material in both parts of the PVT-STE

In this section, the PCM of both components of the combined system is assumed to be the same. It is critical to note that a well-selected PCM can effectively reduce the temperature of PV cells and provide a compact thermal storage system at the desired temperature. Based on the literature, organic PCMs (RT type) are frequently utilized in solar systems [54]; thus, various PCMs, including RT31, RT35, and RT42 are selected for analysis in this study. To ensure the system's feasibility throughout the year, it is essential to design it not only for hot seasons but also for colder weather. It is because PCM with high melting temperatures will not melt in November, resulting in insufficient thermal storage capacity. Additionally, if the melting temperature of PCM is so low, melting occurs rapidly, and the stored thermal energy has little value. Therefore, this section aims to explore the possibility of utilizing PCM in the proposed system for both hot and cold weather conditions.

Fig. 6 illustrates the temporal variations of PCM melting fraction, the outlet temperature of HTF, and the PV surface temperature of three modules of PVT(RT31)-STE(RT31), PVT(RT35)-STE(RT35), and PVT(RT42)-STE(RT42) on a typical day in July and November. This figure shows that STE's PCM has a higher melting fraction than PVT's for both months. The first reason is the preheating of the HTF in the PVT system before passing through the STE component and the higher energy absorption of STE than PVT. Another significant reason is that almost entire received solar radiation by the absorber plate of the STE component is converted into heat. In contrast, in the PVT component, a portion of the solar radiation absorbed by the cells is converted into electrical energy, while the remaining energy can be absorbed by PCM and HTF. Furthermore, the air gap shown in Fig. 2 contributes to a higher melting fraction of PCM in the STE component, by reducing the heat transfer to the environment.

As seen in Fig. 6, the maximum melting fraction of RT42 for the PVT component in July is 0.83 and in November is zero. It means that the selection of the RT42 for the PVT component does not provide a suitable energy storage capability for a whole-year design. Due to their higher melting fractions in November, RT31 and RT35 have a better storage capacity than RT42. On the other hand, the STE component is better served by RT42 because a suitable fraction of PCM is melted in July and November.

Fig. 6(a) shows that the PV surface temperature of the PVT component with RT42 is higher than that of the PVT components with RT31 and RT35 from early morning until 10:00 in July. This temperature difference is attributed to the delayed melting of RT42 due to its higher melting temperature. Consequently, a larger portion of RT42 remains in the solid phase during this period, leading to the elevated PV surface temperature. However, the PV surface temperature of the PVT component with RT42 is less than those with RT31 and RT35 between 10:00 and 14:00 in July.

As RT31 and RT35 are completely melted, the liquid phase temperature can increase, leading to a temperature rise in PV cells. However, RT42, with a maximum melting fraction of 0.83, is not melted completely, and solid parts of RT42 still absorb heat for phase change at a constant temperature.

Conversely, starting from 14:00, the discharging process of RT42 initiates, releasing heat and causing a higher PV surface temperature than RT31 and RT35. This phenomenon is also reflected in the outflow temperature in July, as depicted in Fig. 6(b), where each PCM exhibits a distinct trend throughout the day. The behavior of PV surface and outflow temperatures in November, as shown in Fig. 6(c) and (d), differs from that observed in July. During November, there is minimal variation in PV surface temperature among systems with different PCMs due to the slower melting rate caused by lower solar radiation and ambient temperatures in the early morning. As a result of their similar thermal conductivity, density, and heat storage capacity in the solid phase, these PCMs exhibit the same trend in that period. The PV surface temperature of PVT with RT42 in November is higher between 10:00 and 14:00 than that of RT31 and RT35. This is because RT42 is completely solid, while RT31 and RT35 start to melt due to their lower melting temperatures. Moreover, the PVT component with RT42 has a lower surface temperature after 14:00 in November because RT31 and RT35 release stored thermal energy, whereas RT42 remains in the solid phase throughout the month.

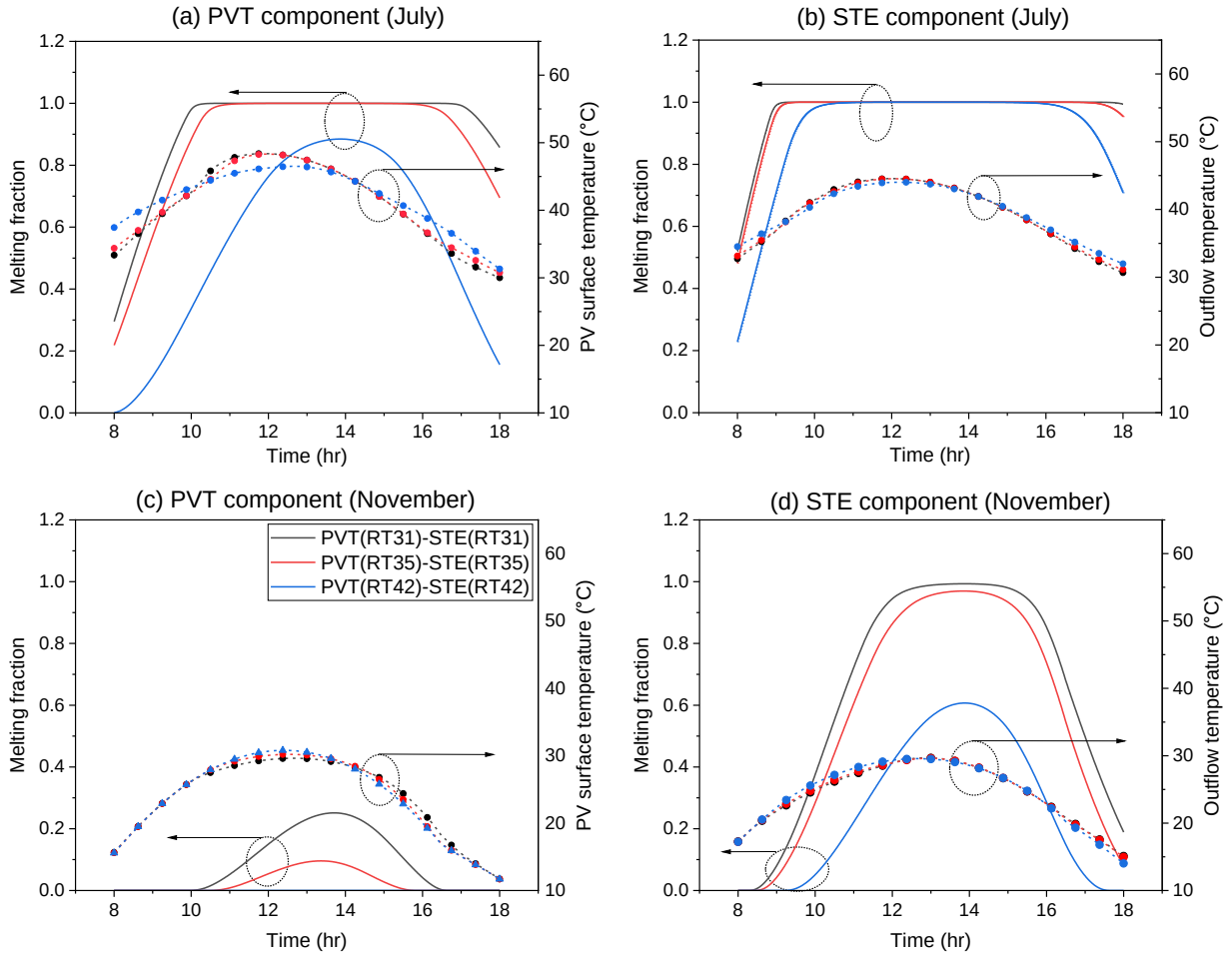


Fig. 6. Hourly variations of the melting fraction of various PCMs in each component of the PVT-STE system as well as the HTF outlet and PV temperature in July and November when both components have the same PCM.

Based on the description in Fig. 6, RT35 can be recommended as a suitable PCM when both components of the combined system have the same PCMs because an appropriate portion of the PCM can be melted during hot and cold seasons. Fig. 7 shows the performance of the PVT(RT35)-STE(RT35) in July and November. Based on Fig. 7(a) and (b) it can be concluded that the thermal power is much greater than the electrical power. It is because the first law of thermodynamics considers only the amount of energy without considering the quality of energy. July's average electrical and thermal powers are 29.77 and 241.31 W, respectively. The corresponding values in

November are 16.76 and 112.87 W, respectively. Fig. 7(c) shows that the thermal exergy, with an average of 3.35 and 0.76 W in July and November, respectively, is much smaller than the electrical exergy because of the higher quality of electricity.

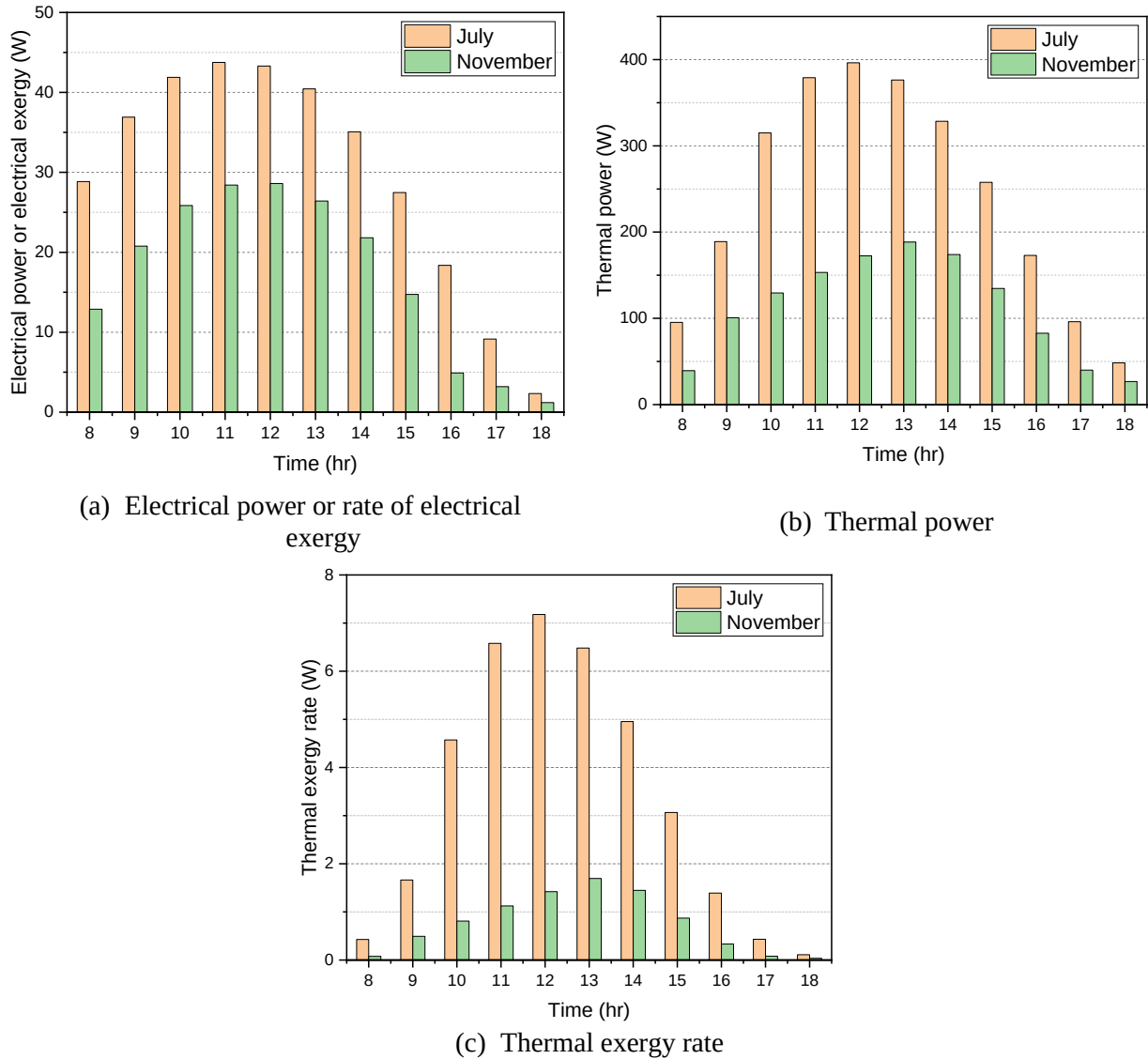


Fig. 7. The average (a) electrical power and electrical exergy rate, (b) thermal power, and (c) thermal exergy rate for PVT(RT35)-STE(RT35) system in July and November.

3.2 Different phase change materials in each component of the PVT-STE system

As mentioned in Section 3.1, selecting the same PCMs for both components of the PVT-STE system is inappropriate. This is because PVT and STE components absorb and convert different amounts of solar radiation into heat. PCMs with higher melting temperatures are more suitable for the STE component than PVT. Therefore, in this section, two different cases of PVT(RT31)-STE(RT42) and PVT(RT35)-STE(RT42) are compared in Fig. 8. Due to the lower melting temperatures of PCM in the PVT component, the PVT(RT31)-STE(RT42) system shows a greater melting fraction as illustrated in Fig. 8(a) and (c). Fig. 8(a) and (b) indicate that in July, the percentage of melted PCM at 18:00 in PVT and STE components of PVT(RT31)-STE(RT42) are 85% and 67%, respectively, whereas for PVT(RT35)-STE(RT42), these percentages are 69% and 34%, respectively.

The melting fraction in STE components of PVT(RT31)-STE(RT42) and PVT(RT35)-STE(RT42) is almost identical, as shown in Fig. 8(b) and (d). This is due to both STE components having the same phase change material with a melting fraction of 42 °C, and the outflow temperature of PVT(RT31)-STE(RT42) and PVT(RT35)-STE(RT42) being relatively similar. In November, a small portion of PCM melts in the PVT components, where maximum melting fractions of 25% and 9.5% are observed for RT31 and RT35, respectively. Moreover, because of the same PCM type in the STE component and the relatively low melting fraction of PCM in the PVT component, the melting fraction in the STE component is nearly the same in both cases. Thermal conductivity, heat capacity, and density of PCM significantly influence the heat transfer, and since these properties are similar for all the PCMs mentioned above, their behavior is alike when the PCMs are in the solid state. Fig. 8(b) and (d) also show that the maximum outflow temperature of this system is 43.85 and 28.85 °C in July and November, respectively. Eventually,

the PVT(RT31)-STE(RT42) system can be recommended because of the higher melting fraction of PCM in both components and, as a result, thermal storage.

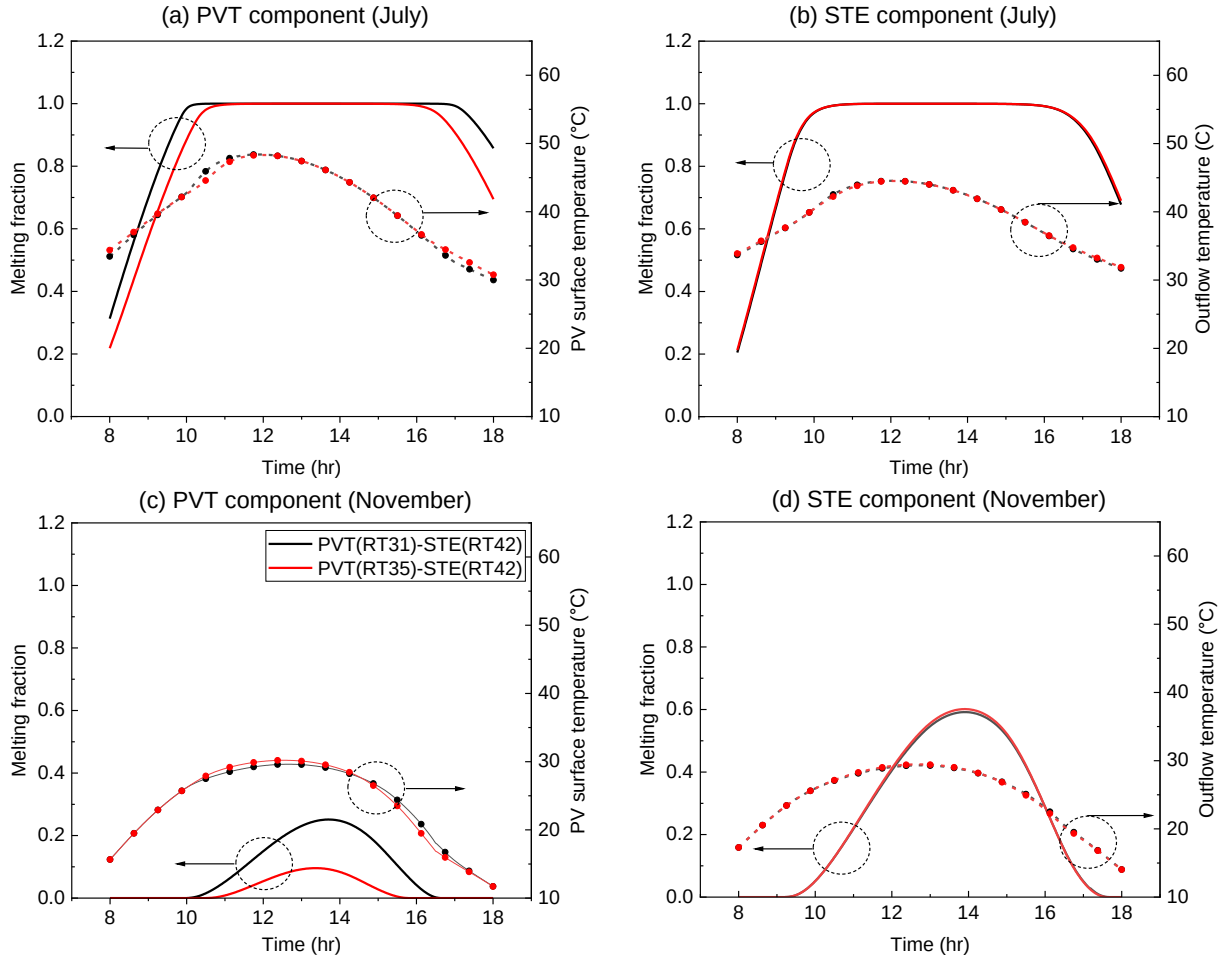
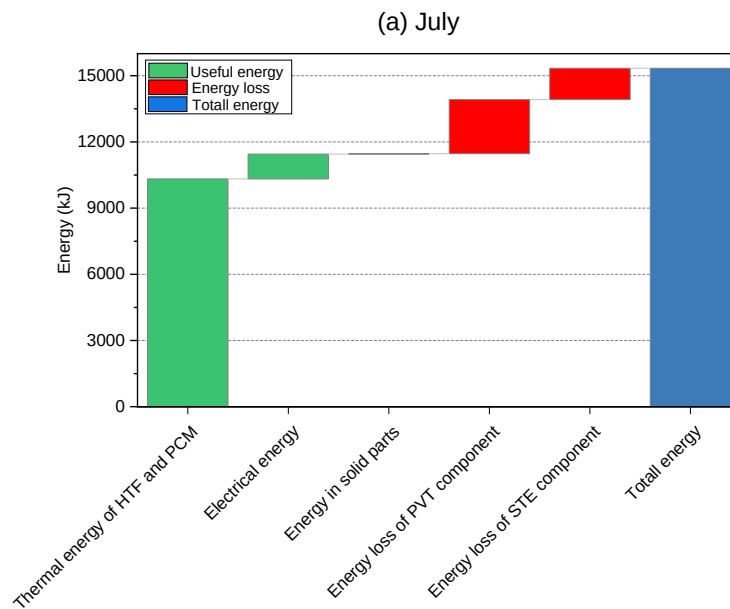


Fig. 8. Hourly variations of the melting fraction of various PCMs in each component of the PVT-STE system as well as the HTF outlet and PV temperature in July and November when different PCMs are used in each component of the system.

Fig. 9 displays the proportion of energy that is effectively utilized (useful energy) and the energy that wasted (energy loss) in each component of the PVT(RT31)-STE(RT42) system in July and November. The input solar energy to the PVT-STE system is distributed across different parts. Excluding the amount that is wasted to the ambient, HTF and PCM absorb most of the energy, while some of the absorbed energy is transformed into electrical power in the PVT component,

and the remnant is consumed to heat up the solid layers. Thermal energy absorbed by HTF and PCM and electricity generated in PV cells can be used and extracted from the system, which is called useful energy, as indicated by the green color in Fig. 9(a) and (b). Moreover, the red color represents the remaining energy that cannot be used and is considered as energy loss. Fig. 9(a) shows that in July, 67.3% of total solar energy is converted to useful thermal power (i.e., summation of thermal energy obtained by working fluid and stored heat in PCM), while based on Fig. 9(b) in November, 62.2% of total solar energy is converted to useful thermal power. Moreover, in July and November, 1125 and 642 kJ of electricity are generated, respectively. The energy loss in the PVT component is approximately three times greater than the energy loss in the STE component. This discrepancy is primarily attributed to the presence of an air gap in the STE component, which effectively reduces heat loss. The total net absorbed heat in solid components is less than 1% of the total energy. This is because the solid parts receive heat in the morning and discharge it in the afternoon, resulting in a small cumulative value for the absorbed heat.



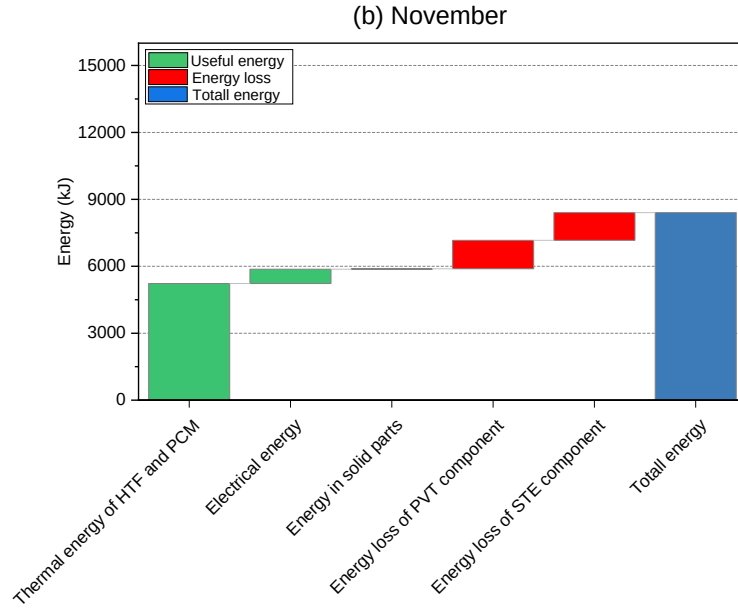


Fig. 9. The share of useful and wasted energy in the proposed PVT(RT31)-STE(RT42) system (a) in July and (b) in November.

3.3 Effects of integrating PCM-based thermal storage units to PVT-STE system

This section examines the effects of adding thermal energy storage unit filled with PCMs beneath each component on the power outputs of the proposed module. Hence, four configurations are considered: (1) PVT(without PCM)-STE(without PCM), where both components are without PCM; (2) PVT(RT31)-STE(without PCM), where only the PVT component has PCM RT31; (3) PVT(without PCM)-STE(RT 42), where only the STE component has PCM RT42; and (4) PVT(RT31)-ST(RT42), where PVT has PCM RT31 and STE has PCM RT42. The power output of four configurations is compared in Fig. 10. As can be seen in Fig. 10 (a) and (b), the PCM has a higher effect on thermal power than electrical power. From early morning to noon in July, PCM-equipped cases have less thermal power than those without because part of the energy is stored in PCM, allowing less energy to be transferred to the HTF. Solidification occurs in the afternoon when PCM releases heat, which can be absorbed by the HTF, thereby increasing the thermal power

of cases with PCM. Fig. 10 (c) and (d) show that the maximum electrical power of these four cases is around 43.7 and 28.7 W in July and November, respectively.

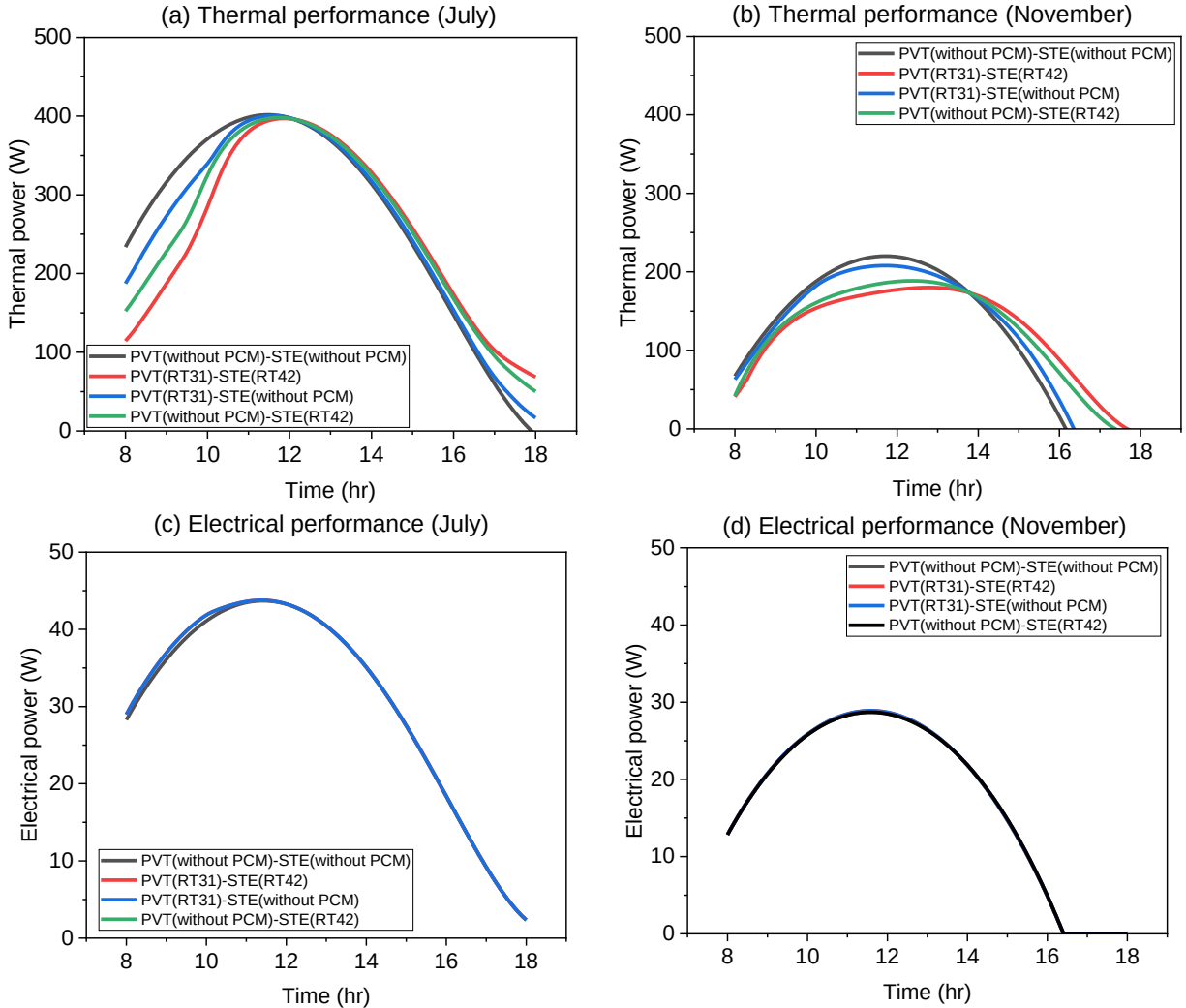


Fig. 10. Power outputs of PVT-STE in the presence and absence of PCM in each component, including thermal power (a) in July and (b) in November and electrical power (c) in July and (d) in November.

The amount of energy in charging and discharging processes in cases with PCM is presented in Fig. 11(a) and (b) for July and November, respectively. Comparing the PVT(without PCM)-STE(RT42) and PVT(RT31)-STE(without PCM) systems, the former can store more thermal energy. The STE part converts most of the absorbed solar energy into heat; on the other hand, the PVT part converts some of the solar energy into electricity and the rest into heat. Moreover, the

PCM placed under the STE component, due to the higher absorptivity coefficient of the absorber plate and the existing air gap in this part, can absorb more thermal energy. Having two thermal storage units, the PVT(RT31)-STE(RT42) system can store more thermal energy than in other cases.

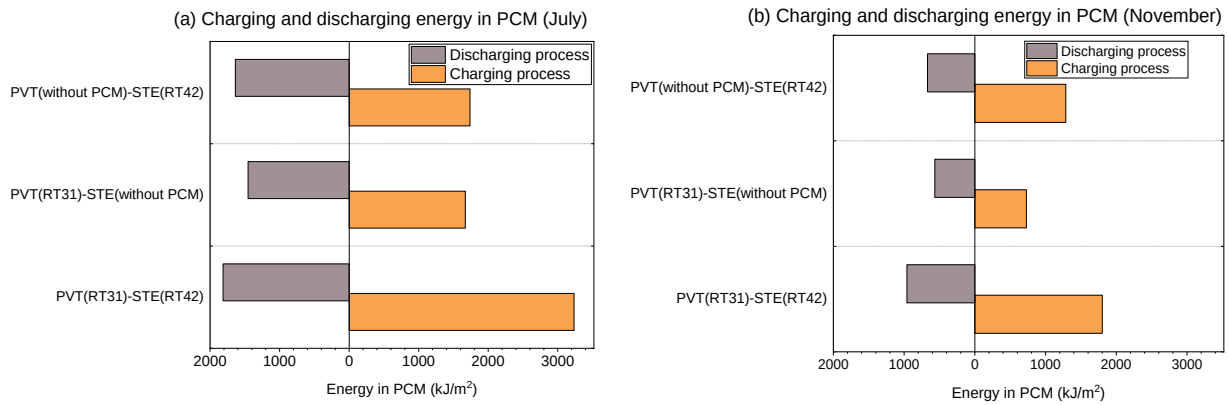
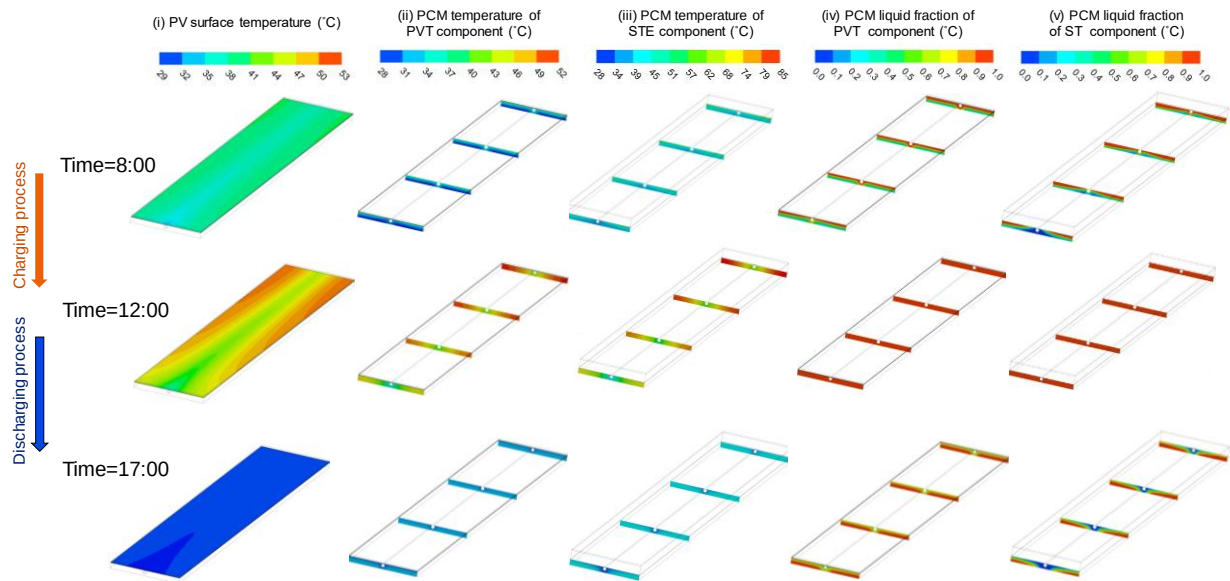


Fig. 11. Amounts of the charging and discharging energy through PCM (a) in July and (b) in November during the working hours for three systems, including PVT(RT31)-STE(RT42), PVT(without PCM)-STE(RT42), and PVT(RT31)-STE(without PCM) systems.

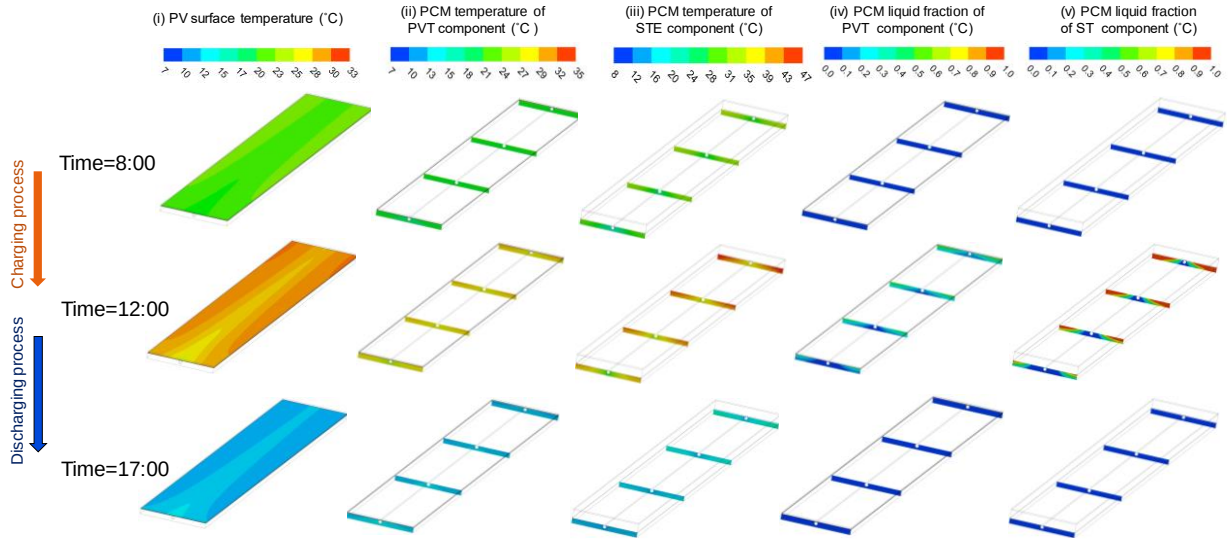
Fig. 12 displays the temperature distribution within the PCM enclosure at various cross-sectional surfaces along the length of both components as well as the PV surface temperature. In July and November, the contours are plotted at three different times, including 8:00, 12:00, and 17:00. As seen in Fig. 12 (a), the temperature distribution along the system length is non-uniform, with lower temperatures observed near the collectors and higher temperatures found away from the collectors. The same trend can also be seen in Fig. 12 (b). Due to heat absorption by the collector, the PCM temperature near the collector decreases. Furthermore, PCM near the collector's outlet exhibits a higher temperature compared to PCM near its inlet. This temperature gradient occurs due to the HTF entering the collector at a lower temperature and absorbing heat as it traverses through the tubes, leading to temperature elevation. A similar temperature distribution is

also observed for the PV surface, i.e., the temperature at the outlet of the system is lower, and areas near the collector have a lower temperature than areas far from the collector.

Fig. 12(a) and (b) also show the melting fraction of the PCM in different sections of the PVT(RT31)-STE(RT42) system. The amount of melted PCM in the inlet section is less than in the outlet section due to the cooler temperature near the collector's inlet. Additionally, the PCM begins to melt from the surface near the PV cells. The areas of PCM near the collector tubes are cooler than other areas due to the heat absorption by the collectors. In November, the lower radiation and ambient temperature cause the PCM to not completely melt during the charging process. The PVT component exhibits a greater melting fraction due to the lower melting temperature of the PCM in this component.



(a) July



(b) November

Fig. 12. Temperature distribution and the melting fraction of PCM in different sections of the PVT(RT31)-STE(RT42) system as well as PV surface temperature.

3.4 Performance comparison

To assess the feasibility of the PVT(RT31)-STE(RT42) system, its performance is compared with that of a standalone solar collector integrated with PCM, ST(RT42), and a standalone photovoltaic thermal module integrated with PCM, PVT(RT31). The PCMs in the standalone PVT and standalone ST systems are RT31 and RT42, respectively, and the operating conditions and total surface area of the three systems are the same. Fig. 13 compares the average electrical and thermal power per unit area as well as the HTF outlet temperature. It is important to note that an open-circuit system is used, resulting in a lower outlet temperature compared to closed-loop systems. However, if the proposed system were used in a closed-loop system, the outlet temperature would significantly increase as the HTF would circulate several times, allowing it to achieve the desired temperature. The required HTF outlet temperature depends on the preferences

of the system designer and end-user, according to the application of the system. Additionally, pump power was calculated, as pumps consume electricity in PVT systems, according to a study by Vajedi et al. [4]. Since the system includes several parallel tubes, a very small pumping power of 0.0058 watt was obtained and can be assumed to be negligible, as previous studies have assumed [39, 55].

As shown in Fig. 13(a) and (b) for July and November, respectively, the PVT(RT31)-STE(RT42) system generates almost 1.8 and 2 times more thermal energy per square meter compared to the standalone PVT(RT31), while producing equal electrical power per unit area. The ST(RT42) module has the highest thermal exergy rate due to its higher absorption coefficient and lower heat loss, but it is unable to generate electricity, which is its main disadvantage. In July and November, respectively, the PVT(RT31)-STE(RT42) system has almost 2.9 and 5 times higher thermal exergy rate per square meter than the standalone PVT(RT31), with an outflow temperature 3.36 and 1.31 °C greater than the standalone PVT system. Therefore, the presented design can improve one of the significant problems associated with PVT systems, namely low thermal exergy.

The net thermal power was calculated using a conversion ratio, as presented in Eq.(19) and shown in Fig. 13, to account for the difference between low-grade thermal energy and high-grade electricity. The results indicate that the PVT(RT31)-STE(RT42) system has a considerably higher net thermal power than the ST(RT42) and PVT(RT31) systems. In terms of module selection, it depends on the designer's or consumer's priorities. If the only requirement is higher thermal power and outflow temperature (without electricity production), the ST system integrated with PCM is recommended. However, if the simultaneous production of electricity and high thermal power is more important, the PVT(RT31)-STE(RT42) system can be utilized.

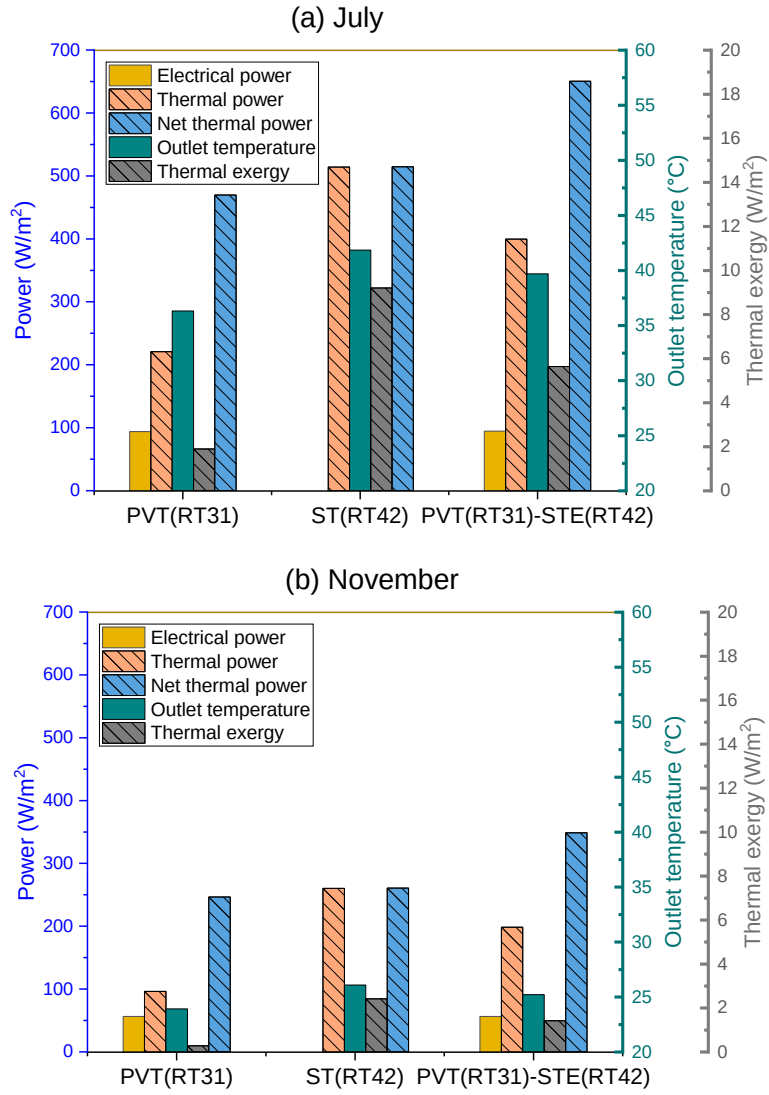


Fig. 13. The average electrical and thermal power per area, thermal exergy rate per area, net thermal power per area, and HTF outlet temperature for standalone PVT(RT31), standalone ST(RT42), and PVT(RT31)-STE(RT42) systems under weather conditions of (a) July and (b) November.

4 Conclusion

Using a three-dimensional numerical model, a PVT-STE system integrated with PCM was studied for the first time. The system's performance in terms of energy and exergy was evaluated, employing different PCMs with various melting points during July and November in Shanghai, China. The amount of stored thermal energy by PCM was calculated, as well as the distribution of

absorbed solar energy across the PVT-STE. In order to evaluate the effects of using and selecting suitable PCM for each component, various configurations were considered, including (a) using the same PCM in both components, (b) employing PCMs with different melting temperatures in two components, and (c) assessing the system without PCM or with only one of the components filled with PCM. Furthermore, the feasibility of the module is then assessed by comparing its performance with conventional solar systems. The main conclusions are summarized below:

- The PVT-STE system benefits from using PCM with higher melting temperatures (e.g., RT42) in the STE component and PCM with lower melting temperatures (e.g., RT31) in the PVT component.
- In July, approximately 67.3% of total solar energy is converted into useful thermal power (i.e., summation of thermal energy obtained by the heat transfer fluid and stored heat in PCM), while in November, this value is 62.2%.
- The PVT(RT31)-ST(RT42) system could store 3234 and 1802 kJ/m² of thermal energy during the day in July and November, respectively.
- The thermal power per area of the PVT(RT31)-STE(RT42) system was approximately 1.8 and 2 times higher than that of the standalone PVT(RT31) system in July and November, respectively.
- The PVT(RT31)-ST(RT42) system generated nearly 2.9 and 5 times more thermal exergy per area than the standalone PVT(RT31) system in July and November, respectively.

This research allows decision-makers to analyze the characteristics of various PCMs in PVT-STE systems to select the best PCM for thermal energy storage. An economic study can be conducted as a next step to assess the feasibility of the PVT-STE with PCM, mainly for residential

applications. The design parameters, including the air gap, PCM properties, and effective surface area of each component, could be optimized to enhance the total efficiency. In addition, further research is necessary to optimize the performance of the proposed system and explore its potential for various design applications, including open and closed loop systems. Such research will provide a more comprehensive understanding of the system's potential and limitations and pave the way for the development of optimized PVT systems for sustainable energy production.

Acknowledgments

This work was supported by the financial support provided by the National Natural Science Foundation of China (NSFC) through Grant 51976124 and the Joint Postdoctoral Scheme with Non-local Institutions of The Hong Kong Polytechnic University.

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