

On the performance of concentrating fluid-based spectral-splitting hybrid PV-thermal (PV-T) solar collectors

Gan Huang^a, Kai Wang^b, Sara Riera Curt^a, Benjamin Franchetti^c, Ioannis Pasmazoglou^c,
Christos N. Markides^{a,*}

^a Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering,
Imperial College London, London SW7 2AZ, UK

^b Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, China

^c Solar Flow Ltd., London SW7 2PG, UK

* Corresponding author: c.markides@imperial.ac.uk

N.B.: This is the ACCEPTED MANUSCRIPT version of this article. The final, published version of the article can be found at: <https://doi.org/10.1016/j.renene.2021.04.070>

Abstract

Concentrating fluid-based spectral-splitting hybrid PV-thermal (SSPVT) collectors are capable of high electrical and thermal efficiencies, as well as high-temperature thermal outputs. However, the optimal optical filter and the maximum potential of such collectors remain unclear. In this study, we develop a comprehensive two-dimensional model of a fluid-based SSPVT collector. The temperature distributions reveal that these designs are effective in thermally decoupling the PV module from the high-temperature filter flow-channel, improving the electrical performance of the module. For a Si solar cell-based SSPVT collector with optical filter #Si400-1100, the filter channel is able to produce high-temperature thermal energy (400 °C) with an efficiency of 19.5%, low-temperature thermal energy (70 °C) with an efficiency of 49.5%, and electricity with an efficiency 17.5%. Of note is that the relative fraction of high-temperature thermal energy, low-temperature thermal energy and electricity generated by such a SSPVT collector can be adjusted by shifting the upper- and lower-bound cut-off wavelengths of the optical filter, which are found to strongly affect the spectral and energy distributions through the collector. The optimal upper-bound cut-off always equals the bandgap wavelength of the solar cell material (*e.g.*, 1100 nm for Si, and 850 nm for CdTe), while the optimal lower-bound cut-off follows more complex selection criteria. The SSPVT collector with the optimal filter has a significantly higher total effective efficiency than an equivalent conventional solar-thermal collector when the relative value of the high-temperature heat to that of electricity is lower than 0.5. Detailed guidance for selecting optimal filters and their role in controlling SSPVT collector performance under different conditions is provided.

Keywords: photovoltaic-thermal; photovoltaics; PV-T; renewables; solar energy; spectral splitting

1. Introduction

Photovoltaic (PV) cells are able to convert directly solar energy to electricity. The record electrical efficiency of common single-junction silicon (Si) PV cells reached 24% in 2019 [1], which is approaching the theoretical efficiency limit of ~30% [2]. The rest of the absorbed solar energy cannot be utilized by the PV cells and is dissipated as waste heat. In hybrid photovoltaic-thermal (PVT) collectors, this heat can be harvested by attaching a thermal absorber to the bottom the cells [3, 4], thus simultaneously producing electricity and useful thermal energy. PVT collectors have been shown to have significantly higher overall solar utilization efficiencies than standalone PV modules [5], and well-designed PVT systems can cover a considerable fraction of the electrical and heating demands of end-users in different applications, *e.g.*, residential homes [6] or sport centres [7].

However, although the thermal absorber of PVT collectors can effectively remove heat from the PV cells, the PV cells still face a problem of overheating when delivering a high-temperature heat output as the PV cells thermally couples with the thermal absorber in PVT collectors. The overheating problem inevitably results in a compromised electrical efficiency and also a reduced lifespan of the PV cells [8]. Therefore, a challenge is to identify PVT collector designs that can generate a high-temperature thermal energy while not sacrificing the PV electrical efficiency.

Spectral splitting is a promising spectrum management approach to this challenge [9-11]. It relies on the fact that a PV cell is only effective within a specific spectral range, *e.g.*, 300-1100 nm for Si solar cells and 300-850 nm for Cadmium telluride (CdTe) solar cells. Spectral splitting design approaches are able to spectrally separate the solar spectrum into different parts, only one of which is directed to the PV cell for electricity generation. The rest of the spectrum, which is not able to be electrically utilized by the cell, is sent to a separate thermal absorber for thermal energy generation, thus avoiding the unnecessary heating of the cell. The thermal absorber is thermally decoupled from the PV cells. Therefore, spectral splitting PVT (SSPVT) collectors are capable of generating high-temperature thermal energy while keeping the PV cell working at a lower temperature.

Current SSPVT collectors typically employ two types of optical filters, *i.e.*, selectively reflective film filters [12-14], and selectively absorptive fluid filters [15-18]. Film-based filters direct part of the solar spectrum to the PV cells, with the rest reflected to a thermal absorber. These collectors usually require optical concentrators [19] and sunlight tracers [20]. Fluid-based filters, on the other hand, only allow a part of the solar spectrum to be transmitted through to the PV cells for electricity generation, while absorbing the rest of the spectrum as thermal energy. Fluid-based filters act as both optical filters, thermal absorbers and heat transfer fluids [15]. Thus, fluid-based SSPVT collectors are usually more compact than film-based SSPVT collectors.

The most crucial requirements of the fluid-based filters are the optical and thermal properties that have direct influence on the electrical and thermal efficiencies of SSPVT collectors. Some common pure fluids, such as water and glycols [21], are good optical filter candidates capable of absorbing photons in the infrared region, while slightly affecting the electrical efficiency of common solar cells. The first concept of a water-based SSPVT collector was proposed in 1970s [22]. Heat transfer oils with higher-temperature boiling points also have been employed to fluid-based SSPVT collectors, such as *Brayco 888 HF*, which was selected as an optical filter for SSPVT collectors by Osborn et al. [23]. *Brayco 888 HF* has a high transmittance (~90%) within the wavelength range of 600-1100 nm, and a high absorptivity (~90%) outside the above wavelength range. Other commercial heat transfer fluids employed as optical filters in SSPVT collectors include *Therminol 66*, *Therminol VP-1*, *Duratherm*, *etc.* [16]. Recently, nanotechnology has been applied to further improve the optical characteristics of such fluids. Taylor et al. [24] have proved that *Therminol VP-1* suspended with low concentrations of nanoparticles (*e.g.*, Ag/SiO₂ and Au/SiO₂) are effective in improving the performance of SSPVT systems. Different nanoparticle suspensions (*e.g.*, Ag [17, 25-27], Au [17, 27], ZnO [28], Ag/TiO₂ [29], Au/SiO₂ [30-32], carbon nanotubes[33], Fe₃O₄ [34], Cu₉S₅ [35], polypyrrole [35]) have been fabricated and tested in order to discover the optimal fluid-based filter for SSPVT collectors. In the experiments performed by Hjerrild et al. [36], Ag/SiO₂ nanoplates and Au/SiO₂ nanorods were suspended in different base fluids (water, heat transfer oils) to fabricate nanofluid filters for different solar cells (Si, GaAs, and Ge). The Ag/SiO₂ nanoplates were used to absorb in the ultraviolet and visible parts of the spectrum, while the Au/SiO₂ nanorods were used to absorb in the infrared. Huang et al. [37] introduced a simple method to fabricate core-shell Ag/SiO₂ nanoparticles for SSPVT collectors, and showed that their employment allowed the collectors to reach an overall efficiency of 63%.

Furthermore, Liang et al. [28] proceeded to investigate the influence of nanoparticle concentration on the performance of a SSPVT collector, and found that the thermal efficiency of their investigated collector increased from 7.4% to 10.9% when the concentration of ZnO nanoparticles

increased from 11 ppm to 89 ppm. The same authors also suggested that ZnO nanofluid was the most cost-effective nanofluid for SSPVT collectors, since the cost of ZnO nanoparticles was much lower (only 0.13%, 0.08% and 0.17%) of those of Au, Ag and polypyrrole nanoparticles. More recently, Walshe et al. [38] employed imidzo-phenanthroline-based luminescent down-shifting (LDS) liquid as the optical filter in order to maximize the solar energy conversion efficiency of a SSPVT collector. The overall efficiency of the LDS-based SSPVT collector was 18-20% points (in absolute terms) higher than that of a standalone PV panel. Detailed modelling methodologies for simulating the performance of fluid-based SSPVT collectors were introduced by Hassani et al. [39, 40], Brekke et al. [30], Ni et al. [41] and Liang et al. [42]. Brekke et al. [30] found that it was essential to decouple the flow between the filter channel and the bottom PV-cooling channel.

Three recent review papers have been published with excellent summaries of the start-of-art of nanofluids research [43] and other nanomaterials [44, 45] in the context of SSPVT collector technology. However, the optimal optical filter for practical fluid-based SSPVT collectors remains unclear, and there is a lack of consensus in the literature concerning the definition of the optimal filter even for the (most common) Si solar cell [44]. Furthermore, there remains a considerable gap between the optical properties of currently-available fluid filters and the desired optical properties of ideal filters as predicted from theoretical approaches. Therefore, the efficiency limits of fluid-based SSPVT collectors, which depend strongly on the spectral-splitting fluid filter, remain unclear.

In this paper, we design a double-channel fluid-based SSPVT collector and develop a comprehensive 2-D model to explore its electrical and thermal performance. Two most common solar cells, *i.e.*, Si and CdTe, are considered in this study. Different ideal fluid filters are assumed and applied to the SSPVT collector, in order to explore the optimal optical filter and the maximum potential of such fluid-based SSPVT collectors under different scenarios. The spectral, thermal and temperature distributions through the collector are simulated and analysed, and the resulting electrical and thermal efficiencies are investigated under different working conditions. Furthermore, we also provide detailed maps for selecting optimal filters for the fluid-based SSPVT collector under different scenarios, which can assist designers in developing high-performance fluid-based SSPVT collectors and can also assist material scientists in developing optical filters for such collectors.

2. Modelling methodology

The fluid-based SSPVT solar collector investigated in this study is illustrated in Fig. 1. The incident sunlight is concentrated by a parabolic trough collector and directed to the SSPVT collector as shown in Fig. 1(a). A detailed structure of the SSPVT collector is shown in Fig. 1(b). A channel filled with a suitable flowing fluid, which acts as the optical filter, is placed above the PV module. Part of the incident solar spectrum is selectively absorbed by the filter fluid and converted to thermal energy (*i.e.*, an increase in enthalpy), with the rest of the spectrum transmitted through the filter to the PV module. The filter channel is surrounded by vacuum gaps to suppress the non-radiative heat losses.

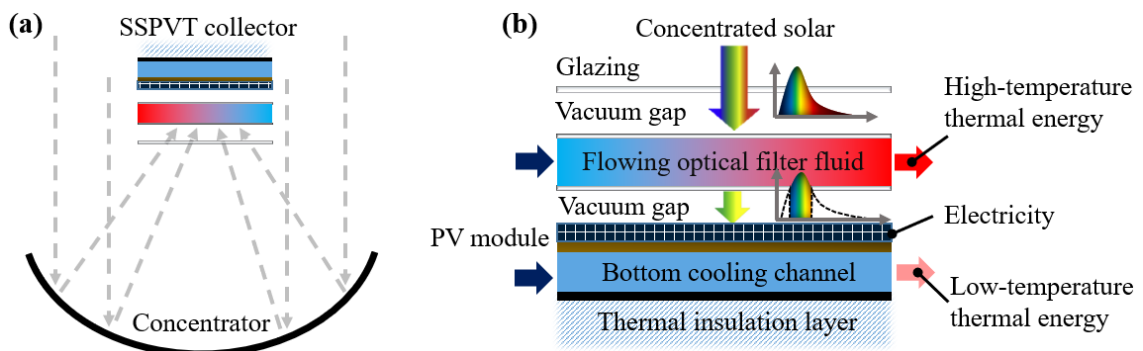


Figure 1. Conceptual concentrating fluid-based SSPVT collector design.

In this design, the flowing fluid in the filter channel acts not only as an optical filter but also a heat transfer fluid to transport the collected thermal energy. Although the filter may be ideal in its ability to absorb a specific region of the solar spectrum that the PV cells are not sensitive to, and therefore to block this from reaching the cells, tremendous heat is still unavoidably generated in the PV module under the high solar concentration ratio. Therefore, a bottom cooling channel is attached to the back of the PV module in order to cool the PV module as shown in Fig. 1(b). The bottom channel produces a low-temperature (60-80 °C) thermal-energy output. The optical filter fluid can be heated to a much higher temperature through the top filter channel, generating a higher-temperature (200-400 °C) thermal-energy output. The collector has a length of 1 m and a depth/height of 0.05 m. The thicknesses of the fluid filter, cooling channel, and of all the gaps are taken as 10 mm.

As shown in Fig. 2, in spectral splitting concepts the solar spectrum is spectrally separated into three parts, signified by the lower- and upper-bound cut-offs wavelengths, λ_L and λ_U . Only the middle part of the spectrum ($\lambda_L < \lambda < \lambda_U$) can pass through the fluid optical filter and arrive at the PV module for electricity generation, while the rest ($\lambda < \lambda_L$ and $\lambda > \lambda_U$) is directly absorbed by the fluid for high-temperature thermal energy generation. In this study, we investigate SSPVT collectors based on two different types of cells, *i.e.*, Si solar cell based SSPVT (Si-SSPVT), and CdTe solar cell based SSPVT (CdTe-SSPVT) collectors. Si and CdTe cells are effective within different specific spectral ranges, *i.e.*, 300-1150 nm for Si cells and 300-850 nm for CdTe cell as shown in Fig. 2. The ideal filter can allow all selected wavelengths to pass through to the PV cells, while the remaining light is all directly absorbed by the filter itself as heat in order to maximize the thermal and electrical efficiencies., *i.e.*:

$$\tau_f = 100\%, \alpha_f = 0\% (\lambda_L < \lambda < \lambda_U) \quad (1)$$

$$\tau_f = 0\%, \alpha_f = 100\% (\lambda < \lambda_L, \lambda > \lambda_U) \quad (2)$$

where τ_f and α_f are the transmittance and absorptivity of the optical filter fluid. The values of λ_L and λ_U should be carefully selected in order to maximize the overall performance of the SSPVT collector. Existing references have already theoretically proved and reached an agreement that the optimal upper-bound cut-off λ_U of the filter should exactly equal to the bandgap wavelength of the solar cell [44], *i.e.*, 1100 nm (corresponding to ~1.12 eV) for Si-SSPVT collector [24, 25] and 850 nm (corresponding to ~1.44 eV) for CdTe-SSPVT collector [44]. However, the optimal lower-bound cut-off λ_L remains unclear and still lacks consensus in existing literature. In this study, we assume six different ideal optical filters for Si- and CdTe- SSPVT collectors as listed in Table. 1. The upper-bound λ_U of the optical filter for Si-SSPVT is set to 1100 nm, while lower-bound λ_L varies from 400 to 800 nm. The upper-bound λ_U for CdTe-SSPVT is set to 850 nm, while lower-bound λ_L varies from 400 to 700 nm. The performance of Si- and CdTe-SSPVT collectors with these different optical filters are simulated and analysed.

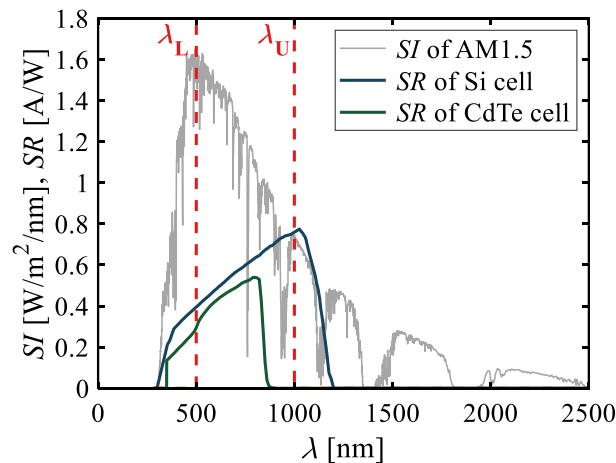


Figure 2. Spectral irradiance (SI) of AM1.5, spectral responses (SR) of Si and CdTe cells, and bounds of the optical filter. λ_L and λ_U are the lower- and upper-bound cut-off wavelengths of the optical filter.

Table 1. Ideal optical filters for Si- and CdTe-based SSPVT collectors.

Solar cell	Filter type	Lower bound, λ_L (nm)	Upper bound, λ_U (nm)
Si	#Si400-1100	400	1100
	#Si600-1100	600	1100
	#Si800-1100	800	1100
CdTe	#CdTe400-850	400	850
	#CdTe500-850	500	850
	#CdTe700-850	700	850

A two-dimensional (2-D) finite volume method (FVM) is applied in the numerical model developed in this work for the modelling of SSPVT collectors, as shown in Fig. 3. The comprehensive numerical model comprises heat transfer, optical and PV sub-models, which are internally linked.

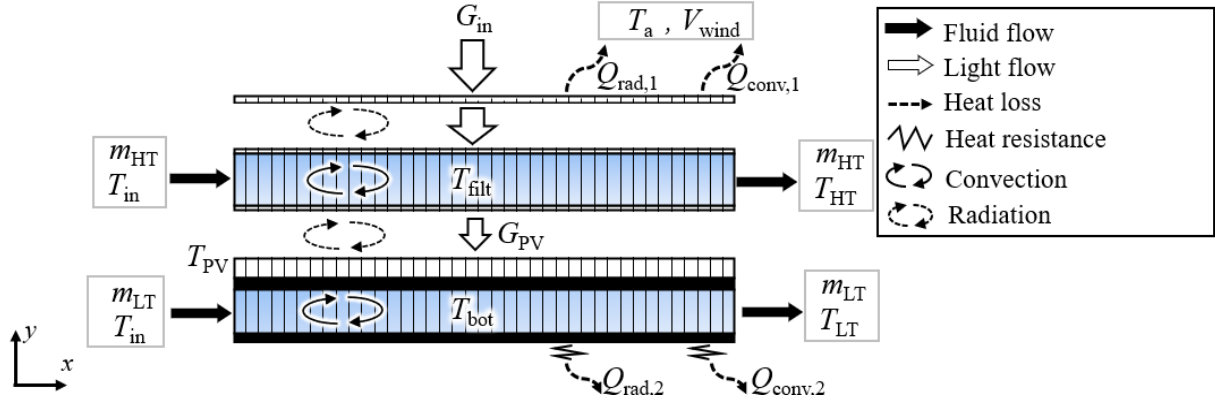


Figure 3. Graphical representation of SSPVT collector numerical model.

2.1. Heat transfer model

The heat transfer model mainly includes two sets of governing equations, *i.e.*, steady-state Fourier heat conduction equation in the solid zones and steady-state fluid flow energy equation in the fluid zones. The solid and fluid zones are conjugated via heat convection and radiation. Boundary conditions for solving the equations include the mass flow rates and inlet temperatures of the two channels, and heat convection/radiation between the outer walls and environment. The detailed governing equations and boundary conditions are enumerated below.

(1) Steady-state Fourier heat conduction equation in the solid zones of glass layers, PV module and thermal insulation layer:

$$k_s \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + Q_s = 0 \quad (3)$$

where k_s is the thermal conductivity of the solid material, T is the temperature of the element. The source term Q_s (unit: W/m^2) of Eq. (3) is the internal heat source of the solid elements, *i.e.*, the absorbed solar energy by glass layers and the heat generated in the PV modules, which are linked with the optical and PV models.

(2) Steady-state fluid flow energy equation in flowing fluid zones in the top and bottom fluid channels:

$$k_f \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - \frac{\partial(\rho c_p u T)}{\partial x} + Q_f = 0 \quad (4)$$

where k_f is the thermal conductivity of the fluid, ρ the density of fluid, c_p the specific heat capacity, u is the velocity of the fluid. The source term Q_f (unit: W/m^2) of Eq. (4) is the internal heat source of the fluid elements. The source term Q_f in the top filter fluid zone is the solar energy absorbed by the filter fluid, which is linked with the optical model. The source term in the bottom fluid zone is zero as no internal heat source in the bottom channel. The thermophysical properties of the fluids are taken

to be the same as those of *Therminol VP-1*, which is a stable heat transfer oil that can be used over a wide workable temperature range up to 400 °C. In addition, *Therminol VP-1* is transparent in the effective wavelength range of common solar cells. For these reasons, *Therminol VP-1* is often selected as a base fluid for spectral splitting filter designs, such as nanofluid filter designs [21, 50]. The thermophysical properties of *Therminol VP-1* refer to the manufacture's datasheet [51].

(3) Boundary equation on the interfaces between solid and fluid zones:

$$-k \frac{\partial T}{\partial y} \big|_{\text{interface}} = h_c \Delta T \quad (5)$$

where ΔT is the temperature difference between the fluid and solid elements, h_c is heat convection coefficient between the fluid and the solid wall. The heat convection coefficient in the filter channel is given in Ref. [3] and [15]. Of note is the fact that heat convection enhancement with, *e.g.*, micro-fins, attached to the bottom cooling channel of concentrated PVT collectors [46-48] are crucial for cooling the PV module effectively to lower temperatures under high concentration solar fluxes. The effective heat convection coefficient in the bottom channel is assumed to be 1000 W/(m²·K) to model the enhanced heat convection effect, which is in a reasonable range of forced oil flow in a channel [49].

(4) Boundary equation on the outer walls of the SSPVT collector, *i.e.*, convection/radiation between and outer walls and surroundings:

$$-k \frac{\partial T}{\partial y} \big|_{\text{wall}} = h_w (T_w - T_a) + \varepsilon \sigma (T_w^4 - T_{sky}^4) \quad (6)$$

where T_w is the outer wall temperature, T_a the ambient temperature, σ is Stefan-Boltzmann constant. The heat convection coefficient h_w is related to the wind speed v_w , *i.e.*, $h_w = 4.5 + 2.9v_w$ [3]. The equivalent sky temperature for radiation is $T_{sky} = 0.0522T_a^{1.5}$ [3, 50].

An in-house code is developed to numerically solve the above set of equations based on FVM method. The grid with 100 elements in the x direction is chosen for the simulation according to the result of grid independence investigation in order to balance calculation accuracy calculation cost. Tridiagonal matrix algorithm (TDMA) is employed to solve the tridiagonal temperature matrixes. The FVM method is detailed in Guarracino et al. [50]. The source term Q_s in Eq. (3) and Q_f in Eq. (4) are inter-linked with the following optical and PV sub-models.

2.2. Optical model

An optical model is applied to calculate the absorbed, reflected and transmitted spectral energy in each layer, in order to provide inputs to the heat transfer model and the PV model. The solar spectrum and solar irradiance arrived at the SSPVT collector are:

$$G_{in}(\lambda) = G_{AM1.5}(\lambda) \cdot C \cdot \eta_{PT} \quad (7)$$

$$I_{in} = \int_0^\infty G_{in}(\lambda) d\lambda \quad (8)$$

where C and η_{PT} are the concentration ratio and the optical efficiency of the parabolic trough. The solar energy absorbed by a certain layer can be calculated by:

$$Q_{abs,i} = \int_0^\infty G_i(\lambda) \alpha_i(\lambda) d\lambda \quad (9)$$

where $G_i(\lambda)$ is the spectral distribution of the incident light onto layer i , and $\alpha_i(\lambda)$ is the absorptivity of layer i . The transmitted spectrum can be calculated by:

$$G_{i+1}(\lambda) = G_i(\lambda) \tau_i(\lambda) \quad (10)$$

where $G_{i+1}(\lambda)$ is the spectral energy distribution that is transmitted through layer i (also the incident

spectrum of layer $i+1$), and $\tau_i(\lambda)$ is the transmittance of layer i .

The absorbed solar energies Q_{abs} of each layer are transferred to the heat transfer model as the source terms. Of note is that the Q_s of the PV module is more complicated as it not only related to the optical module but also related to the following photovoltaic model.

2.3 Photovoltaic model

A model is applied to calculate the electricity and heat generated in the PV module. The spectrum incident onto the module, $G_{\text{PV}}(\lambda)$, is calculated by the optical model above. Based on the spectrum $G_{\text{PV}}(\lambda)$ and spectral response (SR) of the cell, the electrical efficiency can be calculated from:

$$\eta_{\text{el}} = \frac{V_{\text{oc}} \cdot J_{\text{sc}} \cdot FF}{A \cdot I_{\text{in}} / \eta_{\text{PT}}} [1 + \beta(T_{\text{PV}} - T_{\text{ref}})] \quad (11)$$

where V_{oc} , J_{sc} and FF are the open-circuit voltage, short-circuit current and filling factor, β and T_{ref} are the temperature coefficient ($-0.45 \text{ } \%/^{\circ}\text{C}$ for Si cells, and $-0.25 \text{ } \%/^{\circ}\text{C}$ for CdTe cells) and reference temperature ($25 \text{ }^{\circ}\text{C}$) of the solar cells, and A is the area of the collector. The equations for V_{oc} and FF are given in Refs. [15] and [41]. The short-circuit current, J_{sc} , can be calculated from:

$$J_{\text{sc}} = A \int_0^{\infty} SR(\lambda) G_{\text{PV}}(\lambda) d\lambda \quad (12)$$

where $SR(\lambda)$ is the spectral response of the solar cell, which is determined by not only the solar cell material, but also the used manufacturing technique. In this study, the spectral responses of Si and CdTe cells, shown in Fig. 2, were taken the manufacturers' datasheets of *SunPower* (C60 monocrystalline silicon solar cell [52]) and *First Solar* (Series 4 thin film cadmium telluride solar cell [53]). The heat generated in the PV cells is then calculated based on energy balance:

$$Q_{\text{wst,PV}} = Q_{\text{abs,PV}} - \eta_{\text{el}} \cdot C \cdot I_{\text{AM1.5}} \quad (13)$$

where $Q_{\text{abs,PV}}$ is the absorbed solar energy by the PV module (unit: W/m^2), which is calculated from Eq. (8). $I_{\text{AM1.5}}$ is the solar irradiance of AM1.5 spectrum. The heat $Q_{\text{wst,PV}}$ is then transferred to the heat transfer model as the source term of the heat transfer equation of the PV module.

Table 2. Optical and thermal properties, geometric characteristics, and other parameters related to the modelled SSPVT collector.

Layer		Parameter/variable	Value	Unit	Refs.
Glazing glass, filter channel glass walls, PV cover glass	α_{g}	Absorptivity	0.01	-	[50,54]
	ε_{g}	Emissivity	0.90	-	[50, 54, 55]
	τ_{g}	Transmittance	0.95	-	[50, 54]
	k_{g}	Thermal conductivity	1.80	W/m·K	[50, 54]
Top filter fluid and bottom cooling fluid	δ_{g}	Thickness	0.003	m	[50, 54]
	T_{in}	Inlet temperature	300	K	-
	$\delta_{\text{fl}}, \delta_{\text{c}}$	Thickness	0.01	m	-
	α_{PV}	Absorptivity	0.93	-	[54]
PV cell	ε_{PV}	Emissivity	0.90	-	[56]
	δ_{PV}	Thickness	0.00035	m	[55]
	k_{EVA}	Thermal conductivity	0.35	W/m·K	[55]
EVA	δ_{EVA}	Thickness	0.0005	m	[55]
	k_{ad}	Thermal conductivity	0.85	W/m·K	[55]
Adhesive	δ_{ad}	Thickness	0.00005	m	[55]
	k_{ins}	Thermal conductivity	0.035	W/m·K	[3, 55]
Insulation	δ_{ins}	Thickness	0.05	m	-
	η_{PT}	Optical efficiency	0.90	-	[57]
Parabolic trough	C	Concentration ratio	10, 50, 100	-	[58]

The above heat transfer, optical and PV models are strongly conjugated. The outputs of this comprehensive model include the detailed 2-D temperature distributions through the SSPVT collector, spectral distributions on each layers and electrical efficiencies of the solar cells. The thermal efficiencies of the high-temperature outputs of the filter channel, and the low-temperature outputs of the bottom cooling channel can be calculated by:

$$\eta_{th,HT} = \frac{m_{HT}c_p(T_{HT}-T_{in})}{A \cdot C \cdot I_{AM1.5}} \quad (14)$$

$$\eta_{th,LT} = \frac{m_{LT}c_p(T_{LT}-T_{in})}{A \cdot C \cdot I_{AM1.5}} \quad (15)$$

where m_{LT} and m_{HT} are the mass flow rates through the low-temperature bottom channel and high-temperature filter channel, T_{in} the inlet temperature of the bottom and filter channels, T_{LT} and T_{HT} are the output temperatures of the low-temperature bottom channel and the high-temperature filter channel. The reduced temperature of the concentrating SSPVT collector is defined as:

$$T_r = \frac{T_{filt}-T_a}{I_{AM1.5}} \quad (16)$$

where T_{filt} is the average temperature of the high-temperature fluid filter. In order to generate a high-temperature thermal output (200-400 °C) in the filter channel while keeping the PV cells at a lower temperature, the mass flow rate through in the filter channel is set to be much smaller than that of the bottom cooling channel. The mass flow ratio is defined as:

$$MR = \frac{m_{HT}}{m_{LT}} \quad (17)$$

where m_{HT} and m_{LT} are the mass flow rates (unit: kg/s) in the filter and bottom channels. The mass flow rate in the bottom channel m_{LT} needs to be carefully selected according to the sunlight concentration ratio in order to ensure the PV cells can be well cooled to a suitable temperature limit (< 100 °C). The output temperature of the filter channel can be adjusted by changing MR .

2.4 Model validation

Commercial monocrystalline Si cells and thin-film CdTe cells from *SunPower* [52] and *First Solar* [53] are used in this study. Fig. 4 shows their electrical efficiency as a function of temperature in the range of 20-100 °C. The electrical efficiencies of these cells are calculated using the above PV model, and compared to the manufacturers' data to validate the model used here, with average deviations all < 5%.

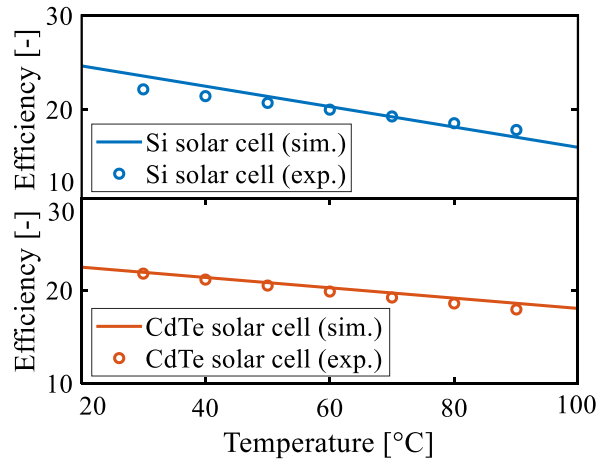


Figure 4. Electrical efficiencies of Si and CdTe solar cells as a function of their operating temperature, validated against the data from manufacturers (*SunPower* [52] and *First Solar* [53]).

The thermal and electrical efficiencies are the most crucial performance indicators of fluid-based SSPVT collectors. The experimental results of these efficiencies from Han et al. [21] are selected here to provide further validation of our model, for which all boundary conditions, optical properties, PV characteristics and geometric parameters of our model are set to be the same as those in the experiments by Han et al. [21]. The performances of the SSPVT collector for 13 different real optical fluids (*e.g.*, water, ethylene, propylene, heat transfer oils, *etc.*) predicted by our model agree well with the experimental results, as shown in Fig. 5, suggesting that our model is capable of accurately simulating both the electrical and thermal performance of fluid-based SSPVT collectors for various optical filters.

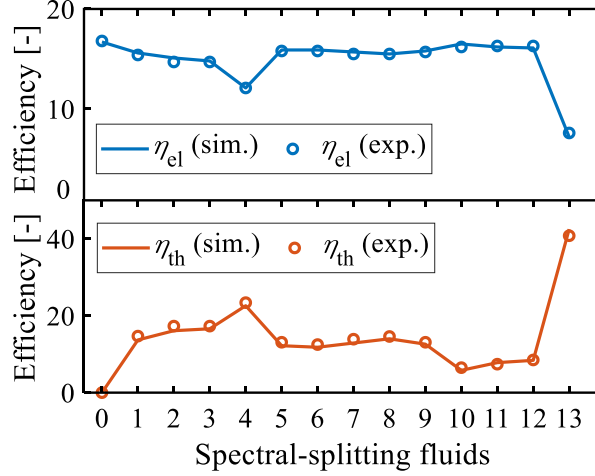


Figure 5. Electrical and thermal efficiencies of a fluid-based SSPVT collector for 13 different real spectral-splitting fluids, validated against the experimental results from Han et al. [21]. (The numbers on the x-axis correspond to different optical fluids: 0- no fluid, 1- water, 2- CoSO₄ solution, 3- Ni₂SO₄ solution, 4- CuSO₄ solution, 5- ethylene, 6- propylene, 7- glycerol, 8- glycerol and water mixture, 9- glycol mixture, 10- silicon oil, 11- VP1 oil, 12- industrial white oil, 13- Valvoline oil).

3. Results and discussion

3.1. Spectral distribution and solar energy allocation

The incident sunlight is reflected and concentrated by the parabolic trough reflector. The concentrated sunlight arrives at the SSPVT collector then passes through the glazing layer and the filter channel (two glass walls sandwich a fluid layer) accordingly before arriving at the PV module. The selectively absorptive fluid filter absorbs a part of the solar spectrum in advance, with the rest of the spectrum being transmitted through the fluid filter to the PV module. The spectral distributions of the original incident light, G_{in} , the filtered light to the PV module, G_{PV} , and solar energy allocations in the Si-SSPVT collector with the #Si400-1100 optical filter is shown in Fig. 6. Most of the solar spectrum that can be electrically utilized by the Si cells is successfully directed to the Si cells for electricity generation as shown in Fig. 6(a), while the rest ($\lambda < 400$ nm and $\lambda > 1100$ nm) is absorbed by the #Si400-1100 optical filter. The allocation of the incident solar energy through the Si-SSPVT collector is shown in Fig. 6(b). Of the total incident solar energy to the parabolic trough, 24.9% is absorbed by the filter channel, and 19.3% is lost optically (via reflection losses at the glass layers and the PV cell surface, and optical loss of the parabolic trough reflector). The rest (55.8%) of the solar energy is absorbed by the Si PV module, such that 19.7% of the total incident solar energy is converted to electricity. Although the filter channel absorbs electrically unusable sunlight in the first instance, a considerable fraction (36.1%) of the total incident solar energy is still unavoidably converted to heat in the cells, which makes the bottom cooling channel essential to the correct operation of this SSPVT collector design.

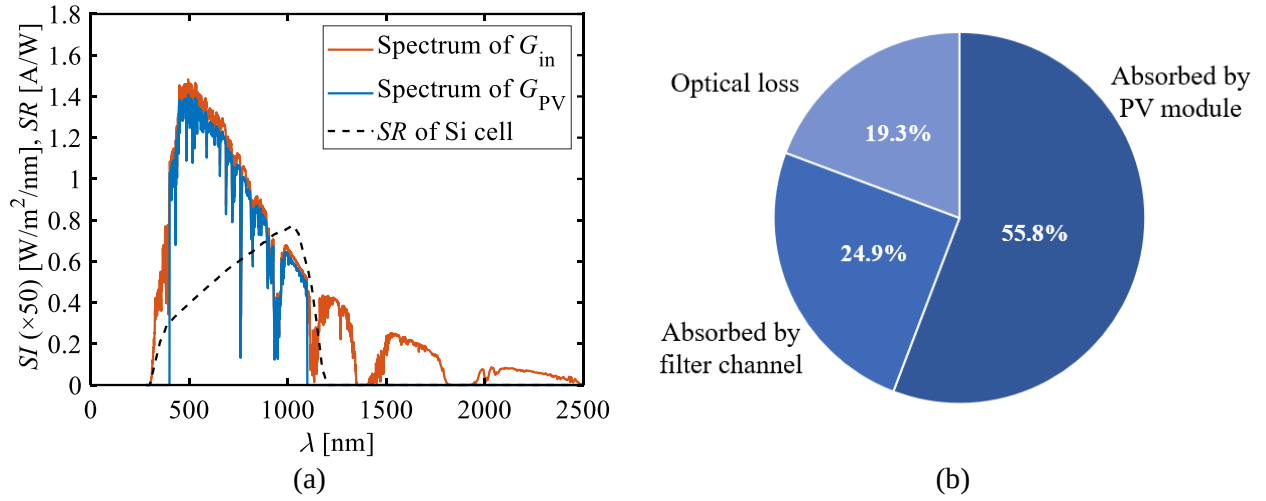


Figure 6. (a) Spectral distributions, and (b) solar energy allocation through Si-SSPVT collector (optical filter: #Si400-1100, $C = 50$).

The spectral distributions and solar energy allocations through the CdTe-SSPVT collector with the #CdTe400-850 optical filter are shown in Fig. 7. The effective wavelength range of CdTe cells is significantly narrower than that of Si cells, due to the higher bandgap energy of CdTe. Thus, the #CdTe400-850 optical filter is able to absorb 38.8% of the incident solar energy, which is significantly larger than that of the #Si400-1100 filter used previously in the Si-based SSPVT collector (27%). The rest (43.6%) of the incident solar energy is absorbed by the CdTe PV module, of which 36.1% of the incident solar energy is converted to heat in the CdTe cells. It is also noted that the electrical efficiency of current commercial CdTe modules (17.2%) is slightly lower than that of the current commercial *SunPower* Si module (19.7%) at the reference temperature of 25 °C. Both the #Si400-1100 and #CdTe400-850 filters are able to generate considerable thermal energy without significantly compromising the electrical efficiencies of Si and CdTe cells, as the #Si400-1100 and #CdTe400-850 filters transmit most of the PV effective spectrum to the solar cells as shown in Figs. 6(a) and 7(a).

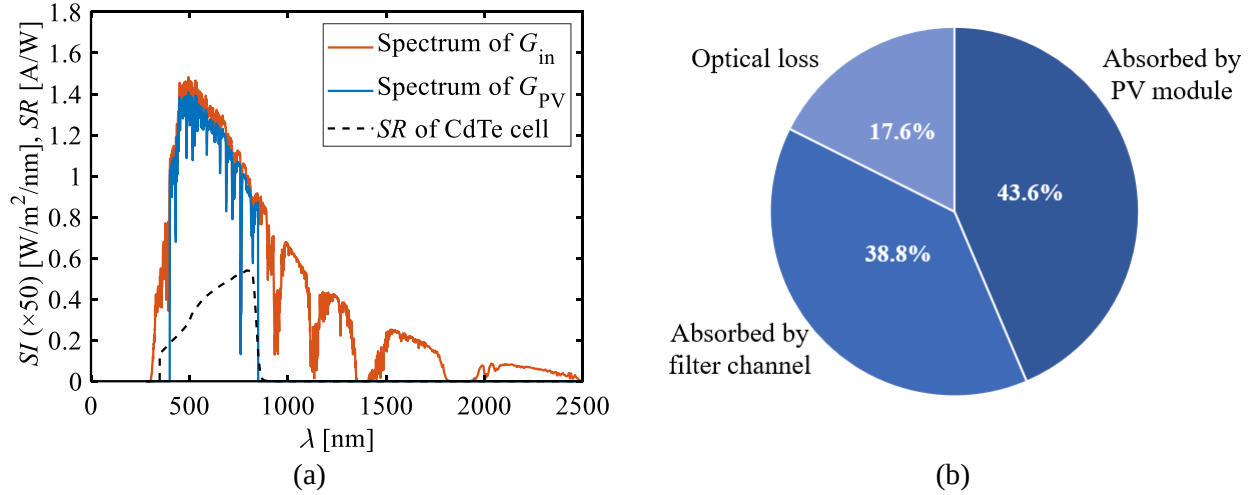


Figure 7. (a) Spectral distributions, and (b) solar energy allocation in CdTe-SSPVT collector (optical filter: #CdTe400-850, $C = 50$).

The solar energy allocations in Si- and CdTe-SSPVT collectors for the different optical filters and concentration ratios are illustrated in Table 3. From this table, it can be observed that the optical filter strongly affects the performance of SSPVT collectors and, specifically, that as the lower-bound cut-off of the optical filter increases (to longer wavelengths), the PV electrical efficiency decreases, while the filter absorption increases and the heat from the PV cell decreases.

Table 3. Solar energy allocations in Si- and CdTe-SSPVT collectors for different optical filters and concentration ratios ($C = 10, 50$ and 100).

SSPVT type	Filter type	Concentration ratio	Absorbed by filter channel	Absorbed by PV module		Optical loss
				Electricity	Heat	
Si-SSPVT	#Si400-1100	10	24.9%	18.5%	37.3%	19.3%
		50	24.9%	19.7%	36.1%	19.3%
		100	24.9%	20.2%	35.6%	19.3%
	#Si600-1100	10	49.1%	13.1%	21.2%	16.6%
		50	49.1%	13.9%	20.4%	16.6%
		100	49.1%	14.2%	20.1%	16.6%
	#Si800-1100	10	70.0%	6.6%	9.2%	14.2%
		50	70.0%	7.0%	8.8%	14.2%
		100	70.0%	7.2%	8.6%	14.2%
CdTe-SSPVT	#CdTe400-850	10	38.8%	16.4%	27.2%	17.6%
		50	38.8%	17.2%	26.4%	17.6%
		100	38.8%	17.5%	26.1%	17.6%
	#CdTe500-850	10	50.4%	14.0%	19.2%	16.4%
		50	50.4%	14.6%	18.6%	16.4%
		100	50.4%	14.8%	18.4%	16.4%
	#CdTe600-850	10	62.9%	10.0%	12.2%	14.9%
		50	62.9%	10.5%	11.7%	14.9%
		100	62.9%	10.6%	11.5%	14.9%

In more detail, in the (50 $\times$) Si-SSPVT collector, the PV efficiency decreases from 19.7% to 7.0%, the PV heat decreases from 36.1% to 8.8%, and the filter absorption increases from 24.9% to 70.0% as the lower-bound cut-off of the optical filter increases from 400 nm to 800 nm. In the (50 $\times$) CdTe-SSPVT collector, the PV efficiency decreases from 17.2% to 10.5%, the PV heat decreases from 36.1% to 8.8%, and the filter absorption increases from 24.9% to 70.0% as the lower-bound cut-off of the optical filter increases from 400 nm to 600 nm. The fraction of high-temperature thermal energy (*i.e.*, the filter absorption), low-temperature thermal energy (*i.e.*, PV heat) and PV electricity generated by the SSPVT collector can be effectively adjusted by shifting the optical bounds of the optical filters, in order to meet different demands and boost the overall effective efficiency in different applications.

The influence of the concentration ratio on the solar energy allocations in the SSPVT collectors is also shown in Table 3. The electrical efficiencies of Si and CdTe solar cells absolutely increase by around 1-2% as the concentration ratio increases from 10 to 100 [59]. The percentage of the PV heat thus slightly decreases as the concentration ratio increases. The concentration ratio has no influence on the filter absorption and optical loss of the SSPVT system.

3.2. Temperature distributions within SSPVT collectors

Both the mass flow rates in the filter channel and bottom cooling channel need to be carefully selected in order to generate a considerably desired high-temperature (200-400 °C) thermal output in the filter channel while keep the PV cells at a lower temperature. The mass flow rate through in the filter channel in this work is set to be much smaller than that of the bottom cooling channel. The temperature distributions through the (50 $\times$) Si- and CdTe-based SSPVT collectors with different optical filters at a typical operation condition are shown in Fig. 8. The mass flow rate through the bottom cooling channel is selected to be $m_{LT} = 0.0163$ kg/s, which is constrained in order to cool the PV module below a temperature limit (<100 °C) and above an imposed low-temperature thermal energy limit (>60 °C). The mass flow rate through the filter channel is 12% of that through the bottom channel. As shown in Fig. 8, the filter channels are able to generate higher-temperature thermal output (200-400 °C), while the bottom channels effectively cool the PV cells to a much lower temperature. The 2-D temperature distributions in Fig. 8 clearly show that the high-temperature thermal absorber (*i.e.*, the filter channel)

is successfully decoupled thermally from the PV module as expected. The output temperature of the filter channel of the Si-SSPVT collector significantly increases from ~ 200 °C to ~ 400 °C as the optical filter changes from #Si400-1100 to #Si800-1100. The output temperature of the filter channel increase as the lower-bound cut-off of the filter increases because the increase of the filter absorption energy.

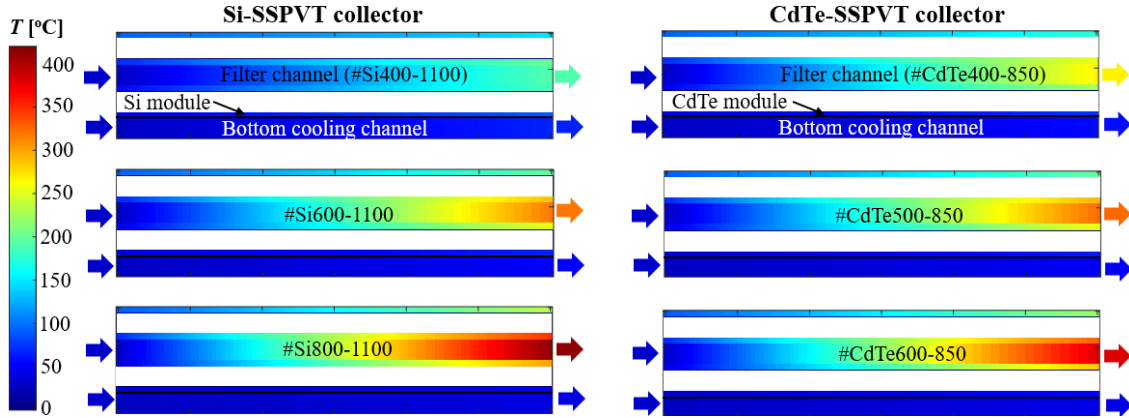


Figure 8. Temperature distributions through Si- and CdTe-SSPVT collectors with different optical filters ($C = 50$, $m_{LT} = 0.0163$ kg/s, $MR = 12\%$).

Detailed temperature distribution curves (profiles) over the length of the bottom channel, filter channel and PV module of the Si-SSPVT collector with the #Si400-1100 filter are shown in Fig. 9(a). The working fluid is heated from 27 °C to 66 °C by the bottom channel and to 192 °C by the filter channel. Although the energy absorbed by the filter ($0.25G_{in}$) is significantly less than that absorbed by the bottom channel ($0.39G_{in}$), the filter is able to heat the fluid to a much higher temperature because the temperature limit of the PV module does not constrain the filter temperature or the flow rate through it. The PV module temperature is about 22 °C higher than the bottom cooling channel due to the thermal resistance. Thus, the aforementioned heat convection enhancement method, *e.g.*, micro-fins, is essential to the bottom channel for reducing the temperature difference between the PV module and the cooling channel when the heat generated in the PV module is tremendous under high concentration ratio situations. The temperature distributions over the length of the Si-SSPVT collector with the #Si800-1100 filter are shown in Fig. 9(b). The working fluid is heated from 27 °C to 412 °C by the filter channel, while the PV cells temperature is only 48 °C. The filter absorption energy increases from $0.25G_{in}$ to $0.70G_{in}$, while the PV heat decreases from $0.36G_{in}$ to $0.09G_{in}$. Therefore, the #Si800-1100 filter can provide a significantly higher-temperature thermal energy and also reduce PV cells temperature comparing to the #Si400-1100 filter.

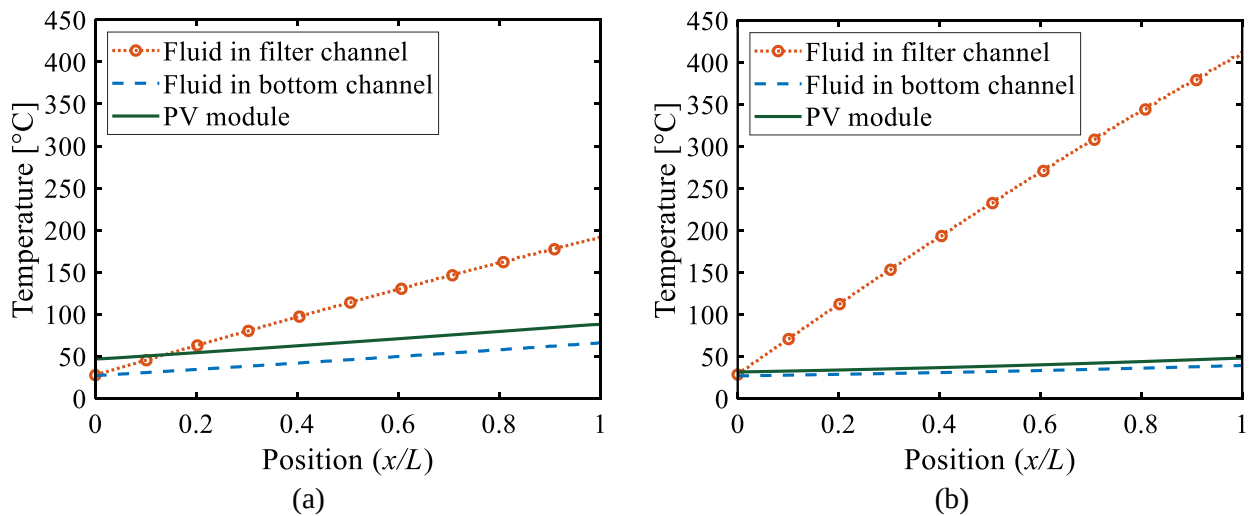


Figure 9. Temperature distributions in the bottom channel, filter channel and PV module of Si-SSPVT collector with optical filters: (a) #Si400-1100, and (b) #Si800-1100 ($C = 50$, $m_{LT} = 0.0163$ kg/s, $MR = 12\%$).

The temperature distributions through the CdTe-SSPVT collector with the #CdTe400-850 filter are shown in Fig. 10(a) at the same operating condition. The working fluid is heated from 27 °C to 55 °C by the bottom channel, and to 266 °C by the filter channel. The high-temperature output of the CdTe-SSPVT collector is 74 °C higher than that of the Si-SSPVT collector with the same lower-bound cut-off of the optical filter, because that the #CdTe400-850 filter absorbs more solar energy ($0.39G_{in}$ vs. $0.25G_{in}$). Increasing the lower-bound of the filter in the CdTe-SSPVT collector results in a higher-temperature output of the filter channel as shown in Fig. 10(b). The temperature distributions in the filter channels are nearly linear with the position in current condition as shown in Figs. 9 and 10 which means the filter does not reach its thermal limit and still has a potential to produce a higher-temperature thermal by further reducing the value of MR or increasing the lower-bound of the filter.

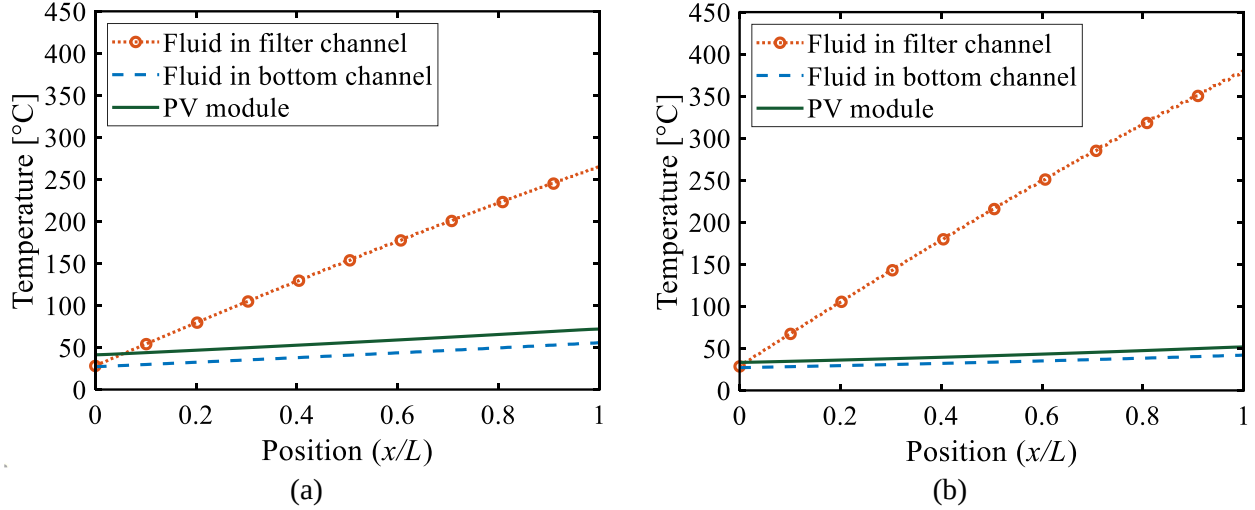


Figure 10. Temperature distributions in the bottom channel, filter channel and PV module of CdTe-SSPVT collector with optical filters: (a) #CdTe400-850, and (b) #CdTe600-850 ($C = 50$, $m_{LT} = 0.0163$ kg/s, $MR = 12\%$).

3.3. Efficiencies of SSPVT collectors

The above sections have shown that both the solar energy allocation and temperature distribution strongly depend on the optical properties of the filter fluid. In this section, the thermal and electrically efficiencies for different optical filters under different operation conditions are investigated and analysed. Fig. 11(a) shows the variations in the temperatures and efficiencies of the (50×) Si-SSPVT collector for different mass flux ratios (MR). The optical filter is set to #Si400-1100. The mass flow rate through of the bottom channel is set to the constant value of $m_{LT} = 0.0163$ kg/s, while the mass flow rate through of the filter, via the value of the ratio MR , is adjustable. The output temperature of the filter channel thus can be adjusted by changing MR . The outlet temperature of the filter T_{HT} , increases significantly from 135 °C to 374 °C as MR decreases from 0.2 to 0.04. The filter channel can produce a high-temperature thermal energy over an extended range of temperatures, and is thus capable of meeting the thermal demands of a wide variety of applications.

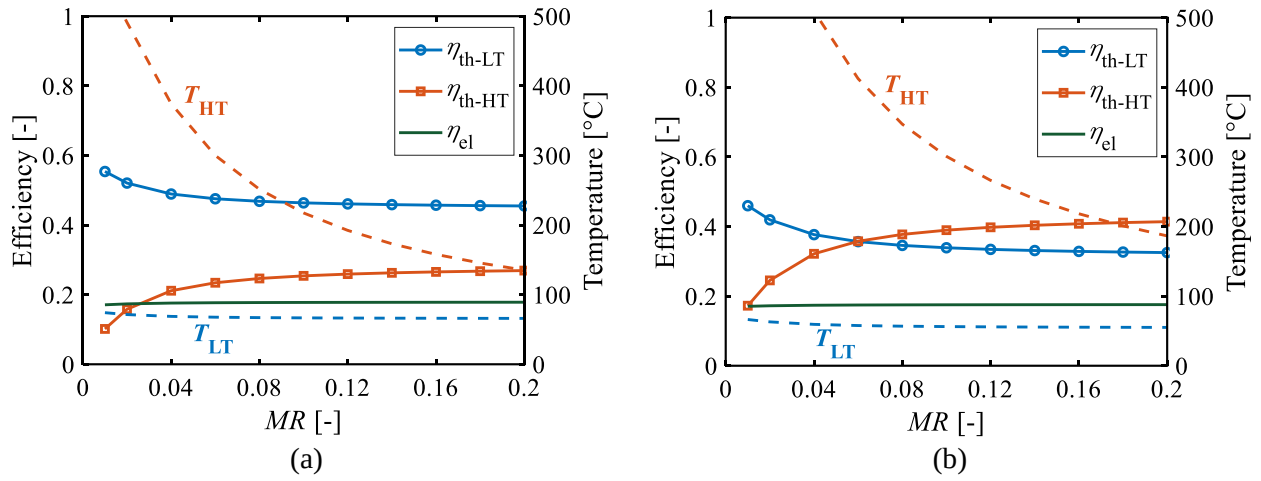
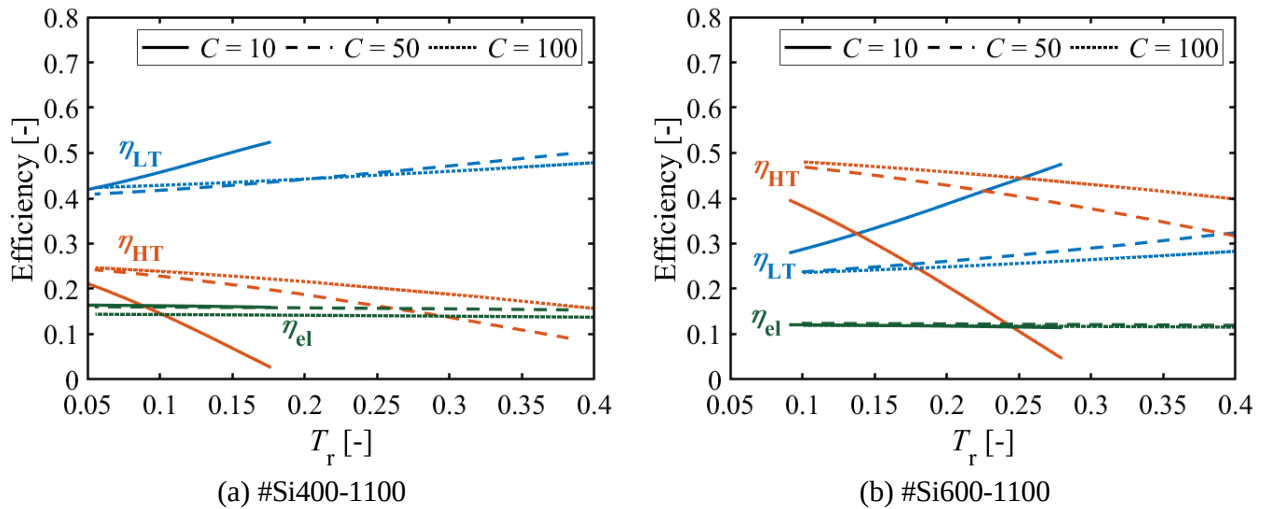
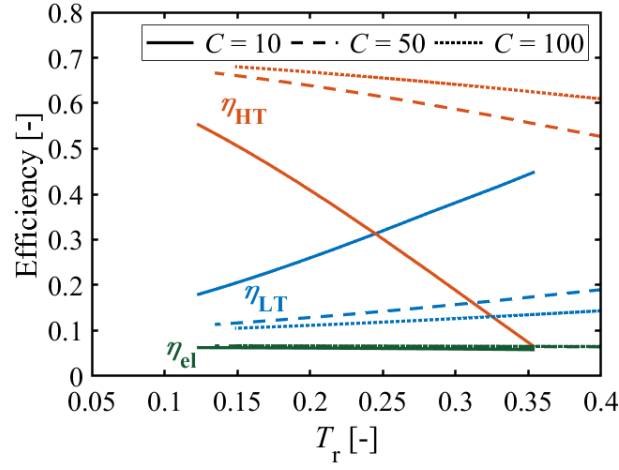


Figure 11. Thermal efficiencies and temperatures for different mass flux ratios: (a) Si-SSPVT collector, and (b) CdTe-SSPVT collector, with $m_{LT} = 0.0163$ kg/s ($C = 50$).

Of note is that a decrease in MR leads to an increase in T_{HT} , but also leads to a decrease in the thermal efficiency with which high-temperature heat is delivered, as shown in Fig. 11(a). The value of MR has slight influence on the outlet temperature of the bottom channel T_{LT} , and on the maximum temperature of the PV panel. The PV module in this SSPVT collector design retains a stable temperature and electrical efficiency over a range of MR values. The Si-SSPVT collector is able to generate simultaneously high-temperature heat ($T_{HT} = 400$ °C, $\eta_{th,HT} = 19.5\%$), low-temperature heat ($T_{LT} = 70$ °C, $\eta_{th,Lt} = 49.5\%$), and electricity ($\eta_{el} = 17.5\%$). Here, $T_{HT} = 400$ °C is chosen as it is typically the limiting operational temperature of common high-temperature heat transfer oils. The temperatures and efficiencies can be adjusted as shown in Fig. 11(a) according to the end-use demand, however, $\eta_{th,HT}$ of the Si-SSPVT collector is limited to the #Si400-1100 filter absorption efficiency of 24.9%. The performance of the (50×) CdTe-SSPVT collector with the #CdTe400-850 filter is shown in Fig. 11(b). The CdTe-SSPVT collector has a considerably better high-temperature thermal performance than the Si-SSPVT collector, with T_{HT} and $\eta_{th,HT}$ of the CdTe-SSPVT collector are both significantly higher than those of the Si-SSPVT collector for the same MR as shown in Fig. 11, owing to the higher absorption efficiency of the #CdTe400-850 filter in the case of the CdTe-SSPVT collector, as discussed earlier. The CdTe-SSPVT collector is able to generate simultaneously high-temperature heat ($T_{HT} = 400$ °C, $\eta_{th,HT} = 35.6\%$), low-temperature heat ($T_{LT} = 57$ °C, $\eta_{th,Lt} = 35.4\%$) and electricity ($\eta_{el} = 17.3\%$). The $\eta_{th,HT}$ of the CdTe-SSPVT collector is limited to the #CdTe400-850 filter absorption efficiency of 38.8%.



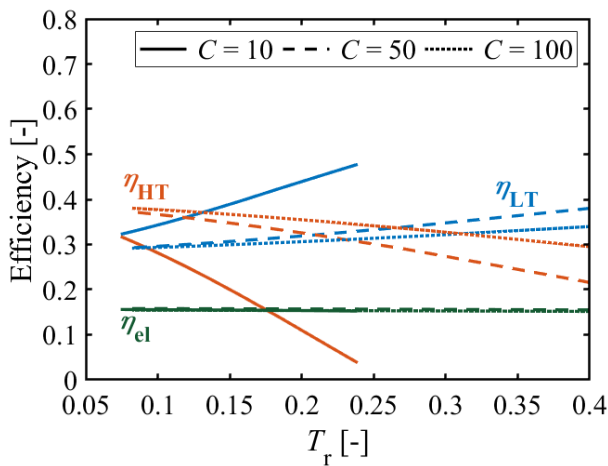


(c) #Si800-1100

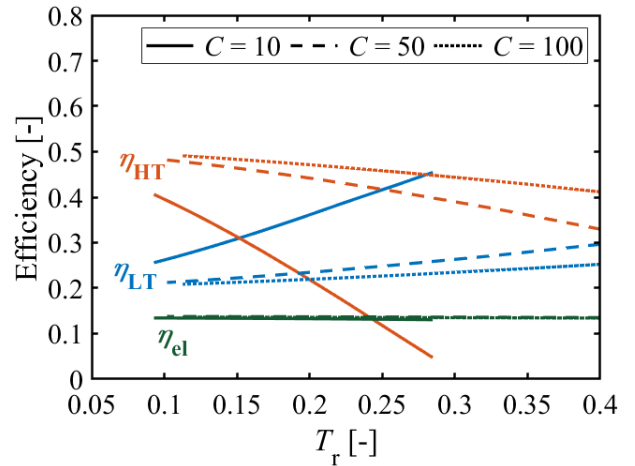
Figure 12. Thermal and electrical efficiencies of Si-SSPVT collectors for different optical filters: (a) #Si400-1100, (b) #Si600-1100, and (c) #Si800-1100; here $T_r = (T_{HT} - T_a)/I_{AM1.5}$.

Figure 12 shows the thermal and electrical efficiencies of the Si-SSPVT collector as a function of reduced temperature T_r for different optical filters and concentration ratios. The concentration ratio has a significant influence on the thermal efficiencies. A higher concentration ratio results in a lower percentage of the heat loss to the total incident solar energy for the same reduced temperature. Therefore, the high-temperature thermal efficiency $\eta_{th,HT}$ significantly increases as the concentration ratio increases from 10 to 100. The reduced temperature T_r has a very slight influence on PV electrical efficiency, since the PV module is thermally decoupled from the high-temperature filter channel, as expected. The high-temperature thermal efficiency $\eta_{th,HT}$ significantly increases, but the low-temperature thermal efficiency $\eta_{th,LT}$ and electrical efficiency η_{el} both decrease as the lower-bound cut-off of the optical filter increases. The increase of $\eta_{th,HT}$ compromises the electrical efficiency. The optical filter is able to adjust the values of $\eta_{th,HT}$, $\eta_{th,LT}$ and η_{el} of the SSPVT collector.

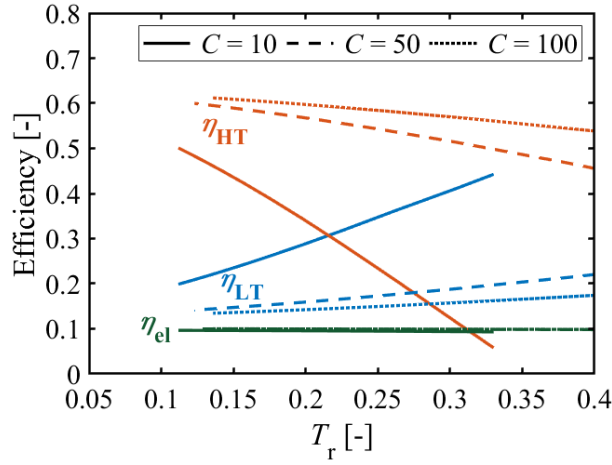
The thermal and electrical efficiencies of the CdTe-based collectors for different optical filters and concentration ratios are shown in Fig. 13. The influence of the concentration ratio and optical filter on the CdTe-SSPVT collectors are similar to those on the Si-SSPVT collectors. The CdTe-SSPVT collector generates its high-temperature thermal energy with a much higher efficiency than the Si-SSPVT collector when the lower-bound cut-offs of the optical filters in both of these collectors are set to 400 nm. The low-temperature thermal efficiency increases as the reduced temperature increases, owing to the more intense radiative heating from the filter channel to the bottom channel.



(a) #CdTe400-850



(b) #CdTe500-850



(c) #CdTe600-850

Figure 13. Thermal and electrical efficiencies of CdTe-SSPVT collectors for different optical filters: (a) #CdTe400-850, (b) #CdTe500-850, and (c) #CdTe600-850; here $T_r = (T_{HT} - T_a)/I_{AM1.5}$.

3.4 Optimal optical filter in different scenarios

According to the results and discussion in the above sections, the optical filter has a significant influence on the spectral distribution, solar energy allocation, high- and low-temperature thermal efficiencies, and PV electrical efficiency of the SSPVT collector. A higher high-temperature thermal efficiency results in a lower electrical efficiency, *vice versa*. Therefore, the optical filter needs to be carefully selected in order to boost the benefit of the SSPVT collector. There are three outputs of the SSPVT collector, *i.e.*, high-temperature heat, low-temperature heat and electricity. Since the values of high-temperature heat, low-temperature heat and electricity are different and depend strongly on the demands for these three energy vectors, a total effective efficiency can be defined as:

$$\eta_{tot} = \eta_{el} + w_{HT} \cdot \eta_{th,HT} + w_{LT} \cdot \eta_{th,LT} \quad (18)$$

where w_{HT} and w_{LT} are weight coefficients that convert the high- and low-temperature thermal energy outputs to equivalent amounts of electricity, and reflect the relative worth of each thermal energy to that of electricity. The coefficients can be based on cost values (*e.g.*, through a price ratio of heat/electricity), or thermodynamic values (*e.g.*, via second-law arguments or heat engine conversion efficiencies), *etc.* Considering the fact that the value of low-temperature heat is always lower than that of high-temperature heat, and further lower than that of electricity, thus w_{HT} is always less than 1, and w_{LT} is always lower than w_{HT} . In this section, the total effective efficiency in Eq. (18) is also treated as the merit function to discover the optimal optical filter. It is difficult to define exact values for w_{HT} and w_{LT} , as they strongly depend on the demands of end-users and specific application scenarios. Therefore, the performance of the SSPVT collector in various application scenarios (*i.e.*, different w_{HT} and w_{LT}) are investigated and analysed in this section, in order to provide a general guidance for designers to select the optimal optical filter for fluid-based SSPVT collectors according to their specified demands.

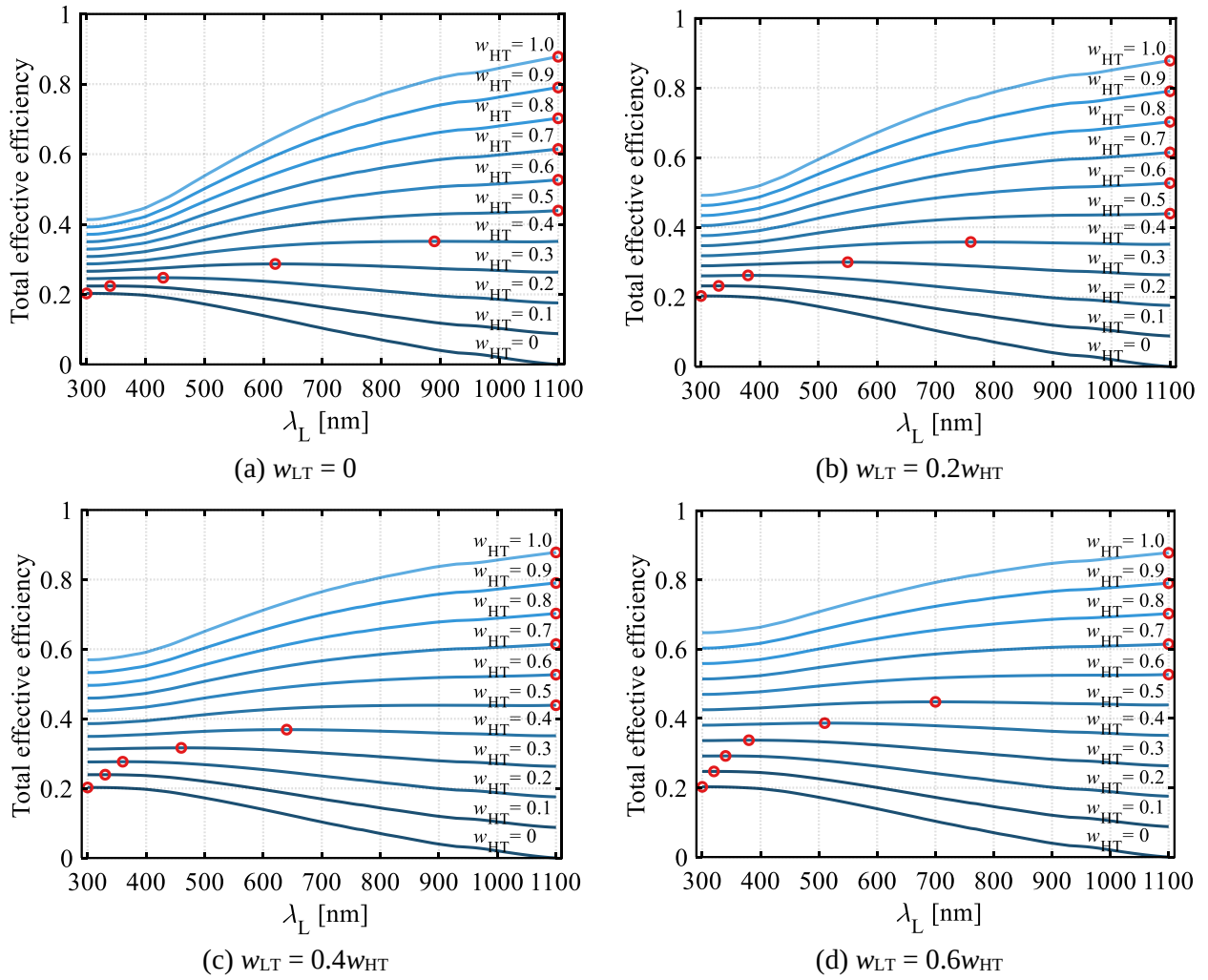


Figure 14. Total effective efficiency of the Si-SSPVT collector for different values of w_{HT} and w_{LT} . The red circle markers are the peak points of the curves ($C = 50$, $\lambda_H = 1100$ nm, $T_r = 0$).

The total effective efficiency of the Si-SSPVT collector for different values of w_{HT} , w_{LT} and λ_L at $C = 50$ and $T_r = 0$ is shown in Fig. 14. The optimal upper-bound cut-off of the optical filter is fixed to $\lambda_U = 1100$ nm. The maximum on each curve is marked by a red circle. Fig. 14(a) shows the total effective efficiency of the Si-SSPVT collector for $w_{LT} = 0$, corresponding to application scenarios in which the low-temperature heat is not recovered and/or has no value. The value of w_{HT} has a significant influence on the total effective efficiency and the optimal filter. The high-temperature thermal output becomes more valuable (relative to electricity) as the weight coefficient w_{HT} increases, leading to a significant increase in the total effective efficiency. The optimal lower-bound cut-off λ_L equals 1100 nm when w_{HT} is larger than 0.5, which means all the solar energy is absorbed by the filter and the collector operates as a pure solar thermal (ST) collector. In this way, the spectral splitting elements and PV cells are no longer necessary, and ST collectors are the best choice when $w_{HT} > 0.5$. The optimal λ_L increases as the weight coefficient w_{HT} increases when $w_{HT} < 0.5$, *i.e.*, more solar energy is absorbed by the filter channel as the value of the high-temperature heat increases. The total effective efficiency at any λ_L in the range of 300-400 nm is very close to that at the optimal λ_L when $w_{HT} < 0.2$, for any w_{LT} . Therefore, the optimal λ_L can be selected anywhere inside the range of 300-400 nm when $w_{HT} < 0.2$. On the other hand, the value of λ_L needs to be more carefully selected when $w_{HT} > 0.2$ and $w_{HT} < 0.5$, as the total effective efficiency is more sensitive to λ_L .

Let's consider a concentrating solar power (CSP) application in which pure ST collectors are used in conjunction with a power block. The cycle efficiency of current second-generation CSP plants varies from 38-44% [60, 61], which corresponds to a relative (thermodynamic) weight value of $w_{HT} \approx 0.4$. The

total effective efficiency of the optimal SSPVT collector with this value of w_{HT} is close to that of a pure ST collector, as shown Fig. 14(a), which is obtained for $\lambda_L = \lambda_H = 1100$ nm. Thus, the advantage of SSPVT technology is not significant in this application. Interestingly, the cycle efficiency of subcritical organic Rankine cycle (ORC) systems is usually less than 20-25% [62, 63], or $w_{HT} \approx 0.2-0.25$. On this basis, optimized SSPVT-driven subcritical ORC systems have higher total effective efficiencies than ST-driven ORC systems operating with lower-temperature ST collectors.

Figure 14(b) shows the total effective efficiency of the Si-SSPVT collector when $w_{LT} = 0.2w_{HT}$, *i.e.*, the value of the low-temperature heat is 20% of that of the high-temperature heat. Figures 12(c) and (d) show the total effective efficiency of the Si-SSPVT collector when w_{LT} further increases to $0.4w_{HT}$ and $0.6w_{HT}$. The optimal lower-bound λ_L always equals 1100 nm (or, the value of λ_U), *i.e.*, the collector operates as a pure ST collector for $w_{HT} > 0.5-0.6$. More solar energy is directed to the PV cells as the value of the lower-temperature heat (recovered from the PV cells) increases, thus the optimal λ_L moves to lower values as w_{LT} increases when $w_{HT} < 0.5-0.6$. The maximum total effective efficiency of the Si-SSPVT collector also significantly increases as the value of w_{LT} increases.

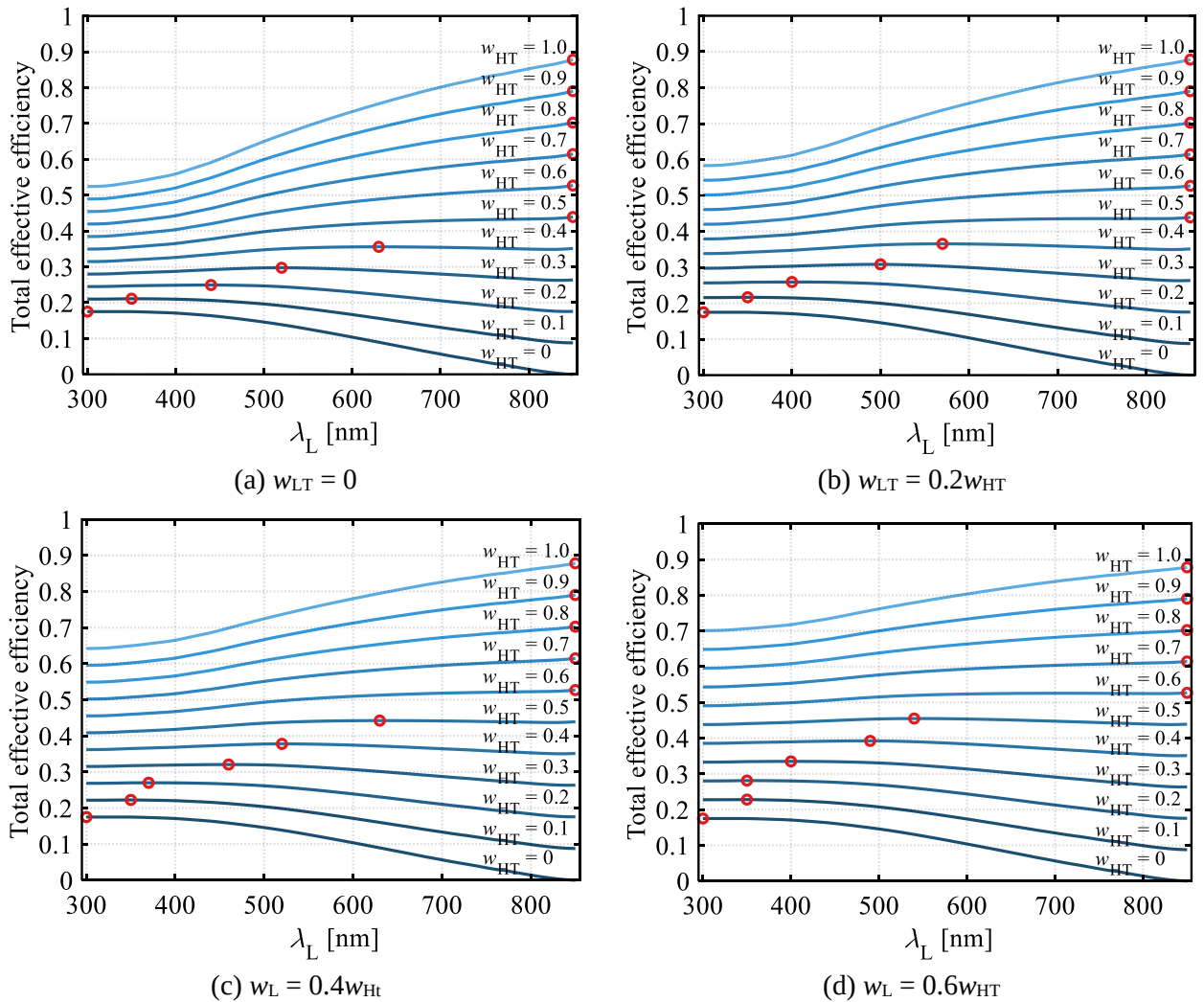


Figure 15. Total effective efficiency of the CdTe-SSPVT collector for different values of w_{HT} and w_{LT} . The red circle markers are the peak points of the curves ($C = 50$, $\lambda_H = 850$ nm, $T_r = 0$).

The total effective efficiency of the CdTe-SSPVT collector for different values of w_{HT} and w_{LT} is shown in Fig. 15. The optimal upper-bound cut-off of the optical filter is fixed to $\lambda_U = 850$ nm. The influence of w_{HT} and w_{LT} on the performance of the Cd-SSPVT collector are similar to those of the Si-SSPVT collector. The spectral splitting and PV cells are both not necessary when $w_{HT} > 0.5$, and the collector operates as a ST collector. The optimal lower-bound λ_L can be selected as any values in

the range of 300-400 nm when $0 < w_{HT} < 0.2$. The lower-bound cut-off of the optical filter needs to be carefully selected when $0.2 < w_{HT} < 0.4$, of which the detailed selection can refer to Figs. 14 and 15.

The influence of the concentration ratio on the performance, *i.e.*, in terms of the total effective efficiency, of Si- and CdTe-SSPVT collectors for $w_{LT} = 0$ and $T_r = 0$ is shown in Fig. 16. The concentration ratio has a slight influence on the total effective efficiency and the optimal optical filter when this is in the range $C = 10$ -100. The PV electrical efficiency only increases by 1-2% as the concentration ratio increases from 10 to 100 as had shown in Table 3. Therefore, the concentration ratio has a slight influence on the total effective efficiency and the optimal filter for $T_r = 0$.

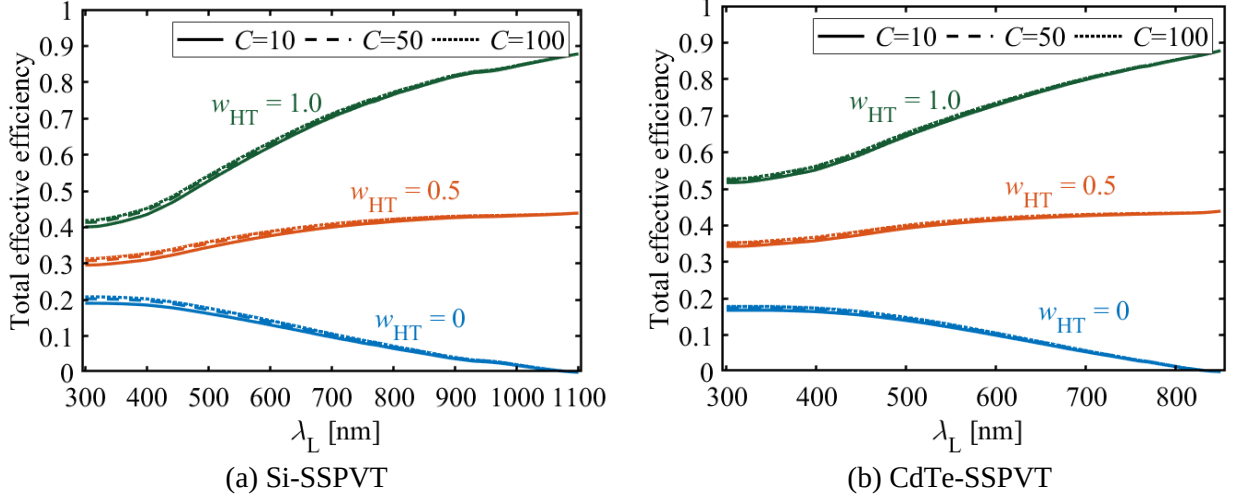


Figure 16. Influence of concentration ratio on total effective efficiency and optimal optical filter ($w_{LT} = 0$, $T_r = 0$).

Figures 12 to 14 show the optimal filter and total effective efficiency of SSPVT collectors when $T_r = 0$. The heat loss from the high-temperature filter channel needs to be considered as T_r increases. It is necessary to analyse the optimal filter of these collectors for different values of T_r , which is of great practical significance. As T_r increases, $\eta_{th,HT}$ decreases and $\eta_{th,LT}$ increases as shown in Figs. 12 and 13. The decrease in $\eta_{th,HT}$ and increase in $\eta_{th,LT}$ when T_r increases from zero to a certain value can be found from:

$$\Delta\eta_{th,HT} = \frac{-\Delta Q_{HT}}{A \cdot C \cdot I_{AM1.5}} \quad (19)$$

$$\Delta\eta_{th,LT} = \frac{+\Delta Q_{LT}}{A \cdot C \cdot I_{AM1.5}} \quad (20)$$

where ΔQ_{HT} is the heat loss of the filter channel, and ΔQ_{LT} is the heat gain of the bottom channel when T_r increases from zero to a certain value. The absolute values of ΔQ_{HT} and ΔQ_{LT} are functions of the temperatures of filter channel, bottom channel and ambient temperature for a given collector. For a given ambient temperature and a bottom channel temperature within a narrow variation range, ΔQ_{HT} and ΔQ_{LT} mainly depend on the filter channel temperature of the SSPVT collector. Therefore, the value of $\Delta\eta_{th,HT}$ and $\Delta\eta_{th,LT}$ are functions of reduced temperature T_r and concentration ratio C .

The total effective efficiency of the SSPVT collector at T_r can be calculated as:

$$\eta_{tot} = \eta_{tot,T_r=0} + \Delta\eta_{tot} \quad (21)$$

$$\Delta\eta_{tot} = w_{HT}\Delta\eta_{th,HT} + w_{LT}\Delta\eta_{th,LT} \quad (22)$$

where $\Delta\eta_{tot}$ is the change of total effective efficiency when the T_r increases from zero to the certain value. The $\Delta\eta_{tot}$ is mainly a function of T_r and C , but not a function of the λ_L and λ_H of the optical

filter. The value of $\Delta\eta_{\text{tot}}$ is constant when the values of T_r and C are specified. Therefore, the optimal filters at any values of T_r are the same as the optimal filters at $T_r = 0$, as indicated in Figs. 14 and 15.

4. Conclusion

Spectral splitting is a design methodology capable of improving the performance of hybrid PVT collector technology. In this study, we develop a comprehensive 2-D model of fluid-based SSPVT collectors, and employ this to investigate the performance of SSPVT collectors, providing detailed guidance for selecting the optimal filter in different application scenarios.

The SSPVT collector design investigated in the present work can produce high-temperature heat, low-temperature heat and electricity from a filter flow-channel, a bottom cooling channel and PV module, respectively. The temperature distribution through the collector shows that the PV module is effectively decoupled thermally from the high-temperature filter channel. The filter channel is able to produce high temperature (200-400 °C) heat, while the PV module is at a relatively lower working temperature (<100 °C). The output temperature of the filter channel can be adjusted over a wide temperature range by changing the flow rate through this channel or changing the optical filter, in order to meet different temperature demands as required by different applications.

It is found that a Si-SSPVT collector variant, with an optical filter designated #Si400-1100 (*i.e.*, the lower- and upper-bound cut-off wavelengths of the filter are 400 and 1100 nm), is able to generate simultaneously: high-temperature heat ($T_{\text{HT}} = 400$ °C) with an efficiency of 19.5%, low-temperature heat ($T_{\text{LT}} = 70$ °C) with an efficiency of $\eta_{\text{th,LT}} = 49.5\%$, and electricity with an efficiency of $\eta_{\text{el}} = 17.5\%$, whereas a CdTe-SSPVT collector with a filter designated #CdTe400-850 is able to generate high-temperature heat ($T_{\text{HT}} = 400$ °C) with an efficiency of 35.6%, low-temperature heat ($T_{\text{LT}} = 64$ °C) with an efficiency of 35.4%, and electricity with an efficiency of 17.3%.

The optical lower-bound cut-off of the fluid filter is found to have a significant influence on the solar energy allocation through these collectors. More solar energy is absorbed by the filter channel and less is absorbed by the PV module when the lower-bound cut-off of the filter moves to longer wavelengths. Hence, the thermal efficiencies associated with the high- and low-temperature thermal outputs, as well as the electrical efficiency strongly depend on the optical filter. The fraction of solar energy absorbed by the filter channel increases from 25% to 70%, and the PV efficiency decreases from 19% to 7%, as the lower-bound of the filter increases from 400 to 800 nm in the Si-SSPVT collector.

Two important weighting coefficients, w_{HT} and w_{LT} , which consider the relative values (thermodynamic, economic, or otherwise) of the high- and low-temperature thermal outputs to that of electricity, have significant influence on the total effective efficiency and optimal optical filter of SSPVT collectors. Specifically, the total effective efficiency increases as w_{HT} , w_{LT} , but also as the concentration ratio increases. The optimal upper-bound cut-off of the optical filter equals the bandgap wavelength of the solar cell material (*i.e.*, 1100 nm for Si, and 850 nm for CdTe), while the optimal filter lower-bound cut-off follows more complex selection criteria. The optimal filter lower-bound wavelength can be any value within the range 300-400 nm when $w_{\text{HT}} < 0.2-0.3$, but needs to be more carefully selected when w_{HT} is between 0.2-0.3 and 0.5-0.6 in order to attain the highest total effective efficiency. The optimal filter is independent of the reduced temperature T_r . Interestingly, the optimization results show that spectral splitting is no longer necessary, and that ST collectors are the best choice when $w_{\text{HT}} > 0.5-0.6$, however, in all other cases and scenarios, SSPVT collectors with optimal filters have considerably higher total effective efficiencies than standalone PV or ST collectors.

In recent years, nanofluid-based optical filters have attracted particular attention, appearing as a promising solution for SSPVT collector technology. Both the nanoparticles and the base fluid can be effective as optical filters based on selective absorption. Synergy between the nanoparticles and base fluid enables excellent absorption at both short and long solar wavelengths, outside the electrically-sensitive spectral regions of PV cells. Although there remains a gap between the performance of

current nanofluid filters and the requirements of ideal filters, nanofluid filters are under fast development and have already shown significant improvement in recent years. In addition to nanofluid filters, some common fluids are also good optical filter candidates for SSPVT collectors, *e.g.*, water is an excellent filter capable of absorbing in infrared spectral region (>1100 nm). Based on the fixed optical properties of water, we can select optimal application scenarios and an optimal PV material for water-based SSPVT collectors according to the detailed maps provided in this study.

In summary, detailed maps and results provide insights and a more complete understanding of fluid-based SSPVT collectors, which can assist designers in selecting optimal filters for achieving optimal overall performance. The maps can also assist designers in judging whether it is worth to employ SSPVT technology, relative to conventional PV and ST options, in specified application scenarios. Although this study is mainly based on assumed ideal working fluids as filters, it suggests a significant potential for these fluid-based SSPVT collector designs. A significant gap remains between real fluids (*e.g.*, high-temperature oils, nanofluids, *etc.*) and optimal ideal filter. This study also provides a guidance for material scientists when developing optical filters for SSPVT collectors.

Acknowledgments

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) [grant numbers EP/M025012/1, and EP/R045518/1]. The work was also supported by an Imperial College London EPSRC Impact Acceleration Account [grant number EP/R511547/1]. The authors would like to thank UK company Solar Flow Ltd. (www.solar-flow.co.uk). Data supporting this publication can be obtained on request from cep-lab@imperial.ac.uk.

References

- [1] Green M. A., Dunlop E. D., Levi D. H., Hohl-Ebinger J., Yoshita M., Ho-Baillie A. W., Solar cell efficiency tables (Version 54). *Prog Photovoltaics* 2019; 27(7):565-575.
- [2] Shockley W., Queisser H. J., Detailed balance limit of efficiency of p-n junction solar cells. *J Appl Phys* 1961; 32(3):510-519.
- [3] Herrando M., Markides C. N., Hellgardt K., A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance. *Appl Energy* 2014; 122: 288-309.
- [4] Herrando M., Pantaleo A. M., Wang K., Markides C. N., Solar combined cooling, heating and power systems based on hybrid PVT, PV or solar-thermal collectors for building applications. *Renew Energy* 2019; 143:637-647.
- [5] Li G., Xuan Q., Akram M. W., Akhlaghi Y. G., Liu H., Shittu S., Building integrated solar concentrating systems: A review. *Appl Energy* 2020; 260:114288.
- [6] Herrando M., Ramos A., Freeman J., Zabalza I., Markides C. N., Technoeconomic modelling and optimisation of solar combined heat and power systems based on flat-box PVT collectors for domestic applications. *Energy convers manag* 2018; 175:67-85.
- [7] Wang K., Herrando M., Pantaleo A. M., Markides C. N., Technoeconomic assessments of hybrid photovoltaic-thermal vs. conventional solar-energy systems: Case studies in heat and power provision to sports centres. *Appl Energy* 2019; 254:113657.
- [8] Hasanuzzaman M., Malek A., Islam M. M., Pandey A. K., Rahim N. A., Global advancement of cooling technologies for PV systems: A review. *Sol Energy* 2016; 137:25-45.
- [9] Mojiri A., Taylor R. A., Thomsen E., Rosengarten G., Spectral beam splitting for efficient conversion of solar energy—A review. *Renew Sust Energy Rev* 2013; 28: 654-663.

- [10] Ju X., Xu C., Han X., Du X., Wei G., Yang Y., A review of the concentrated photovoltaic/thermal (CPVT) hybrid solar systems based on the spectral beam splitting technology. *Appl energy* 2017; 187:534-563.
- [11] Huang G., Wang K., Markides C. N., Efficiency limits of concentrating spectral-splitting hybrid photovoltaic-thermal (PV-T) solar collectors and systems. *Light Sci Appl* 2021; 10(1): 1-14.
- [12] Widyolar B., Jiang L., Ferry J., Winston R., Kirk A., Osowski M., Abbasi H., Theoretical and experimental performance of a two-stage (50×) hybrid spectrum splitting solar collector tested to 600 °C. *Appl Energy* 2019; 239:514-525.
- [13] Jiang S., Hu P., Mo S. and Chen Z., Optical modelling for a two-stage parabolic trough concentrating photovoltaic/thermal system using spectral beam splitting technology. *Sol Energy Mater Sol Cells* 2010; 94(10):1686-1696.
- [14] Weinstein L. A., McEnaney K., Strobach E., Yang S., Bhatia B., Zhao L., ... & Ren Z., A hybrid electric and thermal solar receiver. *Joule* 2018; 2(5):962-975.
- [15] Hassani S., Taylor R.A., Mekhilef S., Saidur, R., A cascade nanofluid-based PV/T system with optimized optical and thermal properties. *Energy* 2016; 112: 963-975.
- [16] Looser R., Vivar M., Everett V., Spectral characterisation and long-term performance analysis of various commercial heat transfer fluids (HTF) as direct-absorption filters for CPV-T beam-splitting applications. *Appl energy* 2014; 113:1496-1511.
- [17] An W., Chen L., Liu T., Qin Y., Enhanced solar distillation by nanofluid-based spectral splitting PV/T technique: Preliminary experiment. *Sol Energy* 2018; 176:146-156.
- [18] Huang G., Wang K., Riera Curt S., Franchetti B., Pasmazoglou I., Markides C. N., Performance analysis of fluid-based spectral-splitting hybrid photovoltaic-thermal solar collectors. *Proceedings of the 33th International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems (ECOS)*; June 2020; Osaka, Japan.
- [19] Crisostomo F., Taylor R. A., Zhang T., Perez-Wurfl I., Rosengarten G., Everett V., Hawkes E.R., Experimental testing of SiN_x/SiO₂ thin film filters for a concentrating solar hybrid PV/T collector. *Renew Energy* 2014; 72:79-87.
- [20] Liang H., Han H., Wang F., Cheng Z., Lin B., Pan Y., Tan, J., Experimental investigation on spectral splitting of photovoltaic/thermal hybrid system with two-axis sun tracking based on SiO₂/TiO₂ interference thin film. *Energy Convers Manag* 2019; 188:230-240.
- [21] Han X., Xue D., Zheng J., Alelyani S. M., Chen X., Spectral characterization of spectrally selective liquid absorption filters and exploring their effects on concentrator solar cells. *Renew Energy* 2019; 131:938-945.
- [22] Chappell T.I. and White R.M., Characteristics of a water absorber in front of a silicon solar cell. *Appl Physics Letters* 1976; 28: 422-423.
- [23] Osborn D. E., Chendo M. A. C., Hamdy M. A., Luttmann F., Jacobson M. R., Macleod H. A., Swenson R., Spectral selectivity applied to hybrid concentration systems. *Sol Energy Mater* 1986; 14: 299-325.
- [24] Taylor R. A., Otanicar T., Rosengarten G., Nanofluid-Based optical filter optimization for PV/T systems. *Light Sci Appl* 2012; 1:e34.
- [25] Tang S., Hong H., Jin H., & Xuan Y., A cascading solar hybrid system for co-producing electricity and solar syngas with nanofluid spectrum selector. *Appl Energy* 2019; 248: 231-240.
- [26] Han X., Chen X., Wang Q., Alelyani S. M., Qu J., Investigation of CoSO₄-based Ag nanofluids as spectral beam splitters for hybrid PV/T applications. *Sol Energy* 2019; 177:387-394.

- [27] Saroha S., Mittal T., Modi P. J., Bhalla V., Khullar V., Tyagi H., Taylor R. A., Otanicar T. P., Theoretical analysis and testing of nanofluids-based solar photovoltaic/thermal hybrid collector. *J Heat Trans* 2015; 137: 091015.
- [28] Liang H., Wang F., Dong Z., Cheng Z., Zhang C., Lin B., & Xu X., Experimental investigation of cost-effective ZnO nanofluid based spectral splitting CPV/T system. *Energy* 2020; 194: 116913.
- [29] Li H., He Y., Wang C., Wang X., Hu Y., Tunable thermal and electricity generation enabled by spectrally selective absorption nanoparticles for photovoltaic/thermal applications. *Appl Energy* 2019; 236: 117-126.
- [30] Brekke N., Dale J., DeJarnette D., Hari P., Orosz M., Roberts K., Tunkara E., Otanicar T., Detailed performance model of a hybrid photovoltaic/thermal system utilizing selective spectral nanofluid absorption. *Renew Energy* 2018; 123: 683-693.
- [31] Otanicar T., Dale J., Orosz M., Brekke N., DeJarnette D., Tunkara E., Roberts K., Harikumar P., Experimental evaluation of a prototype hybrid CPV/T system utilizing a nanoparticle fluid absorber at elevated temperatures. *Appl Energy* 2018; 228: 1531-1539.
- [32] Hjerrild N. E., Mesgari S., Crisostomo F., Scott J. A., Amal R., Taylor R. A., Hybrid PV/T enhancement using selectively absorbing Ag-SiO₂/carbon nanofluids. *Sol Energy Mater Sol Cells* 2016; 147:281-287.
- [33] Crisostomo F., Hjerrild N., Mesgari S., Li Q., Taylor R. A., A hybrid PV/T collector using spectrally selective absorbing nanofluids. *Appl energy* 2017; 193:1-14.
- [34] Xiao L., Gan L. N., Wu S. Y., Chen Z. L., Temperature uniformity and performance of PV/T system featured by a nanofluid-based spectrum-splitting top channel and an S-shaped bottom channel. *Renew Energy* 2021; 167: 929-941.
- [35] An W., Zhang J., Zhu T., Gao N., Investigation on a spectral splitting photovoltaic/thermal hybrid system based on polypyrrole nanofluid: preliminary test. *Renew energy* 2016; 86: 633-642.
- [36] Hjerrild N. E., Crisostomo F., Chin R. L., Scott J. A., Amal R., Taylor R. A., Experimental results for tailored spectrum splitting metallic nanofluids for c-Si, GaAs, and Ge solar cells. *IEEE J Photovoltaics* 2018; 9(2): 385-390.
- [37] Huang J., Han X., Zhao X., Meng C., Facile preparation of core-shell Ag@ SiO₂ nanoparticles and their application in spectrally splitting PV/T systems. *Energy* 2021; 215: 119111.
- [38] Walshe J., McCarron P., McCormack S., Doran J., Amarandei G., Organic luminescent down-shifting liquid beam splitters for hybrid photovoltaic-thermal (PVT) applications. *Sol Energy Mater Sol Cells*, 2021; 219: 110818.
- [39] Hassani S., Saidur R., Mekhilef S., Taylor R. A., Environmental and exergy benefit of nanofluid-based hybrid PV/T systems. *Energy Convers Manag* 2016; 123: 431-444.
- [40] Hassani S., Taylor R. A., Mekhilef S., Saidur R., A cascade nanofluid-based PV/T system with optimized optical and thermal properties. *Energy* 2016; 112: 963-975.
- [41] Ni J., Li J., An W., Zhu, T., Performance analysis of nanofluid-based spectral splitting PV/T system in combined heating and power application. *Appl Therm Eng* 2018; 129: 1160-1170.
- [42] Liang H., Wang F., Li D., Zhu J., Tan J., Optical properties and transmittances of ZnO-containing nanofluids in spectral splitting photovoltaic/thermal systems. *Int J Heat Mass Tran* 2019;128: 668-678.

- [43] Goel N., Taylor R. A., Otanicar T., A review of nanofluid-based direct absorption solar collectors: Design considerations and experiments with hybrid PV/Thermal and direct steam generation collectors. *Renew Energy* 2020; 145:903-913.
- [44] Huang G., Riera Curt S., Wang K., Markides C. N., Challenges and opportunities for nanomaterials in spectral splitting for high-performance hybrid solar photovoltaic-thermal applications: A review. *Nano Mater Sci* 2020; 2(3):183-203.
- [45] Liang H., Wang F., Yang L., Cheng Z., Shuai Y., Tan H. Progress in full spectrum solar energy utilization by spectral beam splitting hybrid PV/T system. *Renew Sust Energy Rev* 2021; 141: 110785.
- [46] Elsafi A. M., Gandhidasan P., Comparative study of double-pass flat and compound parabolic concentrated photovoltaic-thermal systems with and without fins. *Energy Convers Manag* 2015; 98:59-68.
- [47] Hader M., Al-Kouz W., Performance of a hybrid photovoltaic/thermal system utilizing water-Al₂O₃ nanofluid and fins. *Int J Energy Res* 2019; 43(1):219-230.
- [48] Alfegi M. E. A., Sopian K., Othman M. Y. H., Yatim B. B., Experimental investigation of single pass, double duct photovoltaic thermal (PV/T) air collector with CPC and fins. *Am J Appl Sci* 2008; 5(7):866-871.
- [49] Incropera F. P., Lavine A. S., Bergman T. L., DeWitt D. P, Fundamentals of heat and mass transfer. Wiley; 2007.
- [50] Guarracino I., Mellor A., Ekins-Daukes N. J., Markides C. N., Dynamic coupled thermal-and-electrical modelling of sheet-and-tube hybrid photovoltaic/thermal (PVT) collectors. *Appl Therm Eng* 2016; 101:778-795.
- [51] Therminol VP-1 Heat Transfer Fluid – Available at:
<https://www.therminol.com/sites/therminol/files/documents/TF09A_Therminol_VP1.pdf>[accessed 9.9.2020].
- [52] SunPower Ltd., C60 monocrystalline silicon solar cell – Available at:
<http://eshop.terms.eu/data/s_3386/files/1379942540-sunpower_c60_bin_ghi.pdf>[accessed 9.9.2020].
- [53] First Solar Inc., Series 4 thin film cadmium telluride solar cell – Available at:
<<https://docplayer.net/56102249-spectral-response-of-fs-series-pv-modules.html>>[accessed 9.9.2020].
- [54] Hoang P., Bourdin V., Liu Q., Caruso G., Archambault V. Coupling optical and thermal models to accurately predict PV panel electricity production. *Sol Energy Mater Sol Cells* 2014; 125: 325-338.
- [55] Zondag H. A., De Vries D. W., Van Helden W. G. J., Van Zolingen R. J. C., Van Steenhoven A. A., The yield of different combined PV-thermal collector designs. *Sol Energy* 2003; 74: 253-269.
- [56] Sandnes B., Rekstad J., A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Experimental study and analytical model. *Sol Energy* 2002; 72: 63-73.
- [57] Manikandan G. K., Iniyan S., Goic R., Enhancing the optical and thermal efficiency of a parabolic trough collector–A review. *Appl energy* 2019; 235: 1524-1540.
- [58] Wang F., Cheng Z., Tan J., Yuan Y., Shuai Y., Liu L., Progress in concentrated solar power technology with parabolic trough collector system: A comprehensive review. *Renew Sustain Energy Rev* 2014; 79: 1314-1328.
- [59] Paternoster G., Silicon concentrator solar cells: fabrication, characterization and development of innovative designs (2013, Doctoral dissertation, University of Trento).
- [60] He Y. L., Qiu Y., Wang K., Yuan F., Wang W. Q., Li M. J., Guo J. Q., Perspective of concentrating solar power. *Energy* 2020; 117373.

- [61] Qiu Y., Zhang Y., Li Q., Xu Y., Wen Z. X., A novel parabolic trough receiver enhanced by integrating a transparent aerogel and wing-like mirrors. *Appl Energy* 2020; 279: 115810.
- [62] Markides C. N., Low-concentration solar-power systems based on organic Rankine cycles for distributed-scale applications: Overview and further developments. *Front Energy Res* 2015; 3: 47.
- [63] Gangar N., Macchietto S., Markides C. N., Recovery and utilization of low-grade waste heat in the oil-refining industry using heat engines and heat pumps: An international technoeconomic comparison. *Energies* 2020; 13(10): 2560.