

RADIANT ENERGY SPECTRUM CONVERTERS FOR SOLAR ENERGY HARVESTING

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A DISSERTATION SUBMITTED TO
THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

GRADUATE PROGRAM IN MECHANICAL ENGINEERING

York University

Toronto, Ontario

October 2021

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Abstract

Solar energy is a particularly attractive form of renewable energy because it is widely available and the amount of solar energy received on Earth each year is $\sim 3.5 \times 10^6$ EJ, which is more than 7000 times greater than the annual global energy consumption. However, solar energy remains largely untapped because it is a broadband, intermittent and sparse resource, making it difficult to harness. Herein, the implementation of newly designed optical cavities, referred to as Radiant Energy Spectrum Convertors (RESC), in the form of ellipsoids, spheroids and/or paraboloids is presented for broadband solar energy harvesting and conversion applications. In this thesis RESC structures are designed and their application in four broadband solar energy harvesting applications is numerically analyzed: 1) photobioreactors, 2) agri-voltaics, 3) hybrid solar lighting, and 4) Solar Thermophotovoltaics (STPV). 1) The RESC structure in the photobioreactor is a luminescent solar spectrum splitter that partitions the solar irradiance into photosynthetically active radiation (PAR) and photosynthetically inactive radiation (non-PAR) to simultaneously power algae cultivation systems and PV cells, respectively. Results show that a RESC structure enables 0.25 MJ of electric power generation in a photobioreactor with a projected area of and volume of 0.2 m^2 and 0.2 m^3 , respectively. 2) The RESC structure implemented in agri-voltaics is an elliptic array luminescent solar concentrator for combined power generation and microalgae growth with the similar concept of partitioning solar irradiance into its PAR and non-PAR components. Considering the combined effects of emission, transmission and surface scattering losses, numerical results show the optical efficiency of the elliptic array luminescent solar concentrator (LSC) is 63%, whereas in comparison the optical efficiency for a conventional planar LSC of the same size is 47.2%. 3) The RESC structures used in hybrid solar lighting applications are based on luminescent solar spectrum splitters that partition the incoming solar irradiance into its visible and non-visible components to simultaneously power fibre optic lighting system and PV cells, respectively. Numerical analysis

shows that the non-visible portion of the solar irradiance can be converted to electricity with an efficiency of 13.4% using a double-junction PV cell within a RESC structure. 4) RESC structures implemented into STPV systems are based on highly specular IR reflective optical cavities in the form of oblate and prolate spheroid structures to enhance the power density and photoconversion efficiency of the STPV systems. The optical cavity partially encloses a solar receiver that is located at the focal point of an ellipsoid/paraboloid. Concentrated solar radiation is absorbed by the receiver, which functions as both an absorber and an emitter. Radiation is emitted from the emitter, and the internal surface of the cavity is able to reflect a large portion of this emitted radiation either back to the emitter or to a PV cell. Emitted radiation that is returned to the emitter is referred to as "photon recycling". A high degree of photon recycling can be used to achieve high emitter temperatures, which enhances the performance of STPV systems. The results presented in this thesis show that optical structures in the form of spheroids and paraboloids can be used to partition, control and harness broadband solar energy to simultaneously provide for multiple applications, which ultimately increases overall solar energy conversion efficiencies.

Acknowledgements

First of all, from the bottom of my heart I would like to say big thank you to my supervisor, professor Paul O'Brien for his endless support, thoughtful comments, recommendations and guidance in my PhD program. Dr. O'Brien continuously provided encouragement and was always willing and enthusiastic to assist and support me in any way he could, not only throughout the research projects, also other sides of my life. I learnt from him how to be gentle, kind, supportive, helpful and also a dedicated and hardworking researcher. Thank you, professor!

I would like to express my thanks to my committee members, professor Zheng Hong (Georg) Zhu and Siu Ning (Sunny) Leung for their constructive and informative feedback in committee meetings.

I would also like to express my very great appreciation to professor Rodolphe Vaillon for accepting to be the external referee of my oral examination. I am sure it is going to be a great opportunity for me to learn a lot from his insightful feedback and comments. I'm extremely grateful to the chair of my defence session, professor Simone Pisana for his invaluable suggestions and advice.

I am thankful to all the Mechanical Engineering faculty members for letting me be part of this wonderful department.

I am also thankful to all my colleagues and friends at York University for their wonderful friendship and support. These people made my life and PhD studies enjoyable.

Finally, special thanks to my special friends and family members who endured this long process with me, always offering support and love.

Sep. 1st, 2021

Nima Talebzadeh

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List of abbreviations

AM0	Air mass outside the atmosphere
AM1.5	Air mass at solar zenith angle of 48.2°
AMTEC	Alkali metal thermal-to-electric converters
AVT	Average visible transparency
BB	Blackbody
BSR	Back surface reflector
BIPV	Building integrated PV systems
CA	Critical angle
CNT	Carbone nanotube
CRI	Color rendering index
d-EPSSS	dual-elliptical paraboloid solar spectrum splitter
DBR	Distributed Bragg reflectors
EASSS	Elliptic array solar spectrum splitter
ECE	External combustion engines
ECLSS	Environmental control and life support systems
EQE	External quantum efficiency
EPSSS	Elliptic paraboloid-based solar spectrum splitters
FF	Fill factor
FOL	Fiber optical lighting
HSL	Hybrid solar lighting
ICE	Internal combustion engines
IQE	Internal quantum efficiency
IR	Infrared
LED	Light emitting diode
LSC	Luminescent solar concentrators
MSR	Molten salt reactors
NIR	Near infrared
non-PAR	Photosynthetically inactive radiation

OD	Optical density
PAR	Photosynthetically active radiation
PBR	Photobioreactor
PCE	Power conversion efficiency
PDMA	Polydimethylsiloxane
PLQY	Photoluminescent quantum yield
PMMA	Poly(methyl methacrylate)
PV	Photovoltaic
RESC	Radiant energy spectrum converter
RTPV	Radioisotope thermophotovoltaic
SSS	Solar spectrum splitter
STPV	Solar thermophotovoltaic
TEG	Thermoelectric generator
TIR	Total internal reflection
TIS	Total integrated scattering
TPV	Thermophotovoltaic
UV	Ultraviolet

Author Contributions

- Patent:

Nima Talebzadeh, Paul O'Brien. "RADIANT ENERGY SPECTRUM CONVERTER" U.S. Provisional Patent Application No. 63/050513, 2021

- Journal Papers:

1. **Talebzadeh, N.**, Rostami, M., & O'Brien, P. G. (2021). Elliptic paraboloid-based solar spectrum splitters for self-powered photobioreactors. *Renewable Energy*, 163, 1773-1785.
2. **Talebzadeh, N.**, & O'Brien, P. G. (2021). Elliptic array luminescent solar concentrators for combined power generation and microalgae growth. *Energies*, 14(17), 5229.
3. **Talebzadeh, N.**, Pirvaram, A., O'Brien, P. G., Ellipsoidal optical cavities for enhanced thermophotovoltaics. *IEEE Journal of Photovoltaics*, 2021 Oct 27.
4. **Talebzadeh, N.**, O'Brien, P. G., Spheroid-based optical cavities for tunable photon recycling and emitter temperature control in solar thermophotovoltaic systems (submitted for publication)
5. **Talebzadeh, N.**, O'Brien, P. G. Selectively harvesting near-infrared photons in fiber optic-based hybrid solar lighting systems for power generation in buildings (submitted in Dec. 2021).
6. **Talebzadeh, N.**, O'Brien, P. G., Photon fate analysis for thermophotovoltaic systems (submitted in Dec. 2021).
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1. **Talebzadeh, N.**, & O'Brien, P. G. (2017, August). Selective solar concentrators for biofuel production and photovoltaic applications. In *Proceedings of the International Conference of Energy Harvesting, Storage, and Transfer (EHST'17)*, Toronto, ON, Canada (pp. 21-23).
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1. **Talebzadeh, N.**, O'Brien, P. G., (2021). Novel optical cavity designs for enhanced radiation control in thermophotovoltaic systems. *Spring Meeting of the European Materials Research Society (E-MRS), Energy materials B: Advances in thermophotovoltaics: materials, devices and systems, virtual conference, May 31 – Jun 3, 2021.*
2. O'Brien, P. G., **Talebzadeh, N.**, (2020) Novel spectrally selective mirrors and optical cavities for thermophotovoltaic systems, *IEEE 20th international Conference on Nanotechnology (IEEE-NANO), virtual conference, July 29-31, 2020.*
3. Daigle, Q., **Talebzadeh, N.**, Rauf, I. A., O'Brien, P. G. (2019) Spectral splitting luminescent solar concentrator panels for agrivoltaic applications, *Proceedings of the 3rd International Conference of Energy Harvesting, Storage and Transfer (EHST' 19) Ottawa, Canada – June 16-18, 2019.*
4. **Talebzadeh, N.**, Rostami, M., O'Brien, P. G., The design of solar spectrum splitters for biofuel and concentrated PV electricity cogeneration systems” *Energy and Sustainability Symposium and Industry Summit, University of Windsor, Canada, June 21-22, 2018.*

- **Conference Poster Presentations:**

1. **Talebzadeh, N.**, Paul G. O'Brien, P. G., (2019). Elliptic-based selective solar spectrum splitter for self-powered photobioreactors. 10th Annual Nano Ontario Conference. Toronto, Ontario, Nov 2019.

- **Grant Writing:**

1. Co-wrote the successful **Lab-2-Market/Mitacs Accelerate Grant** titled “Radiant Energy Spectrum Converter for Enhanced Thermophotovoltaic Systems” (**\$15,000** to work on the project co-sponsored by Mitacs and the L2M program – 4 to 6 months starting Oct 2020).
2. Co-wrote the successful **Elevate Industrial Postdoc/Mitacs Elevate Grant** titled “Thermophotovoltaics for waste-heat to electric power conversion on spacecrafts” (**\$60,000** to work on the project co-sponsored by Mitacs and Columbiad Launch Services company – 1 to 2 years starting January 2022)

1 Introduction

Energy derived from fossil fuel sources significantly increases atmospheric CO₂ concentrations and contributes to global warming. Nevertheless, recent advances and technological developments have made renewable energy sources a promising alternative that are increasingly being used. The primary renewable energy sources are categorized as: Hydro, geothermal, wind, bioenergy and solar [1]. Of these sources solar energy is particularly attractive because it is widely available and the amount of solar energy received on Earth each year is $\sim 3.5 \times 10^6$ EJ, which is more than 7000 times greater than the annual global energy consumption. However, solar energy remains largely untapped because it is a broadband, intermittent and sparse resource, making it difficult to harness. Furthermore, certain technological limitations have prevented it from becoming the primary source of renewable energy.

As shown in Fig. 1-1, the solar spectrum is divided mainly into three regions. The UV section ($\Delta\lambda_{UVsolar}$) which ranges from ~ 280 to 380 nm and makes up 6% (81 W/m^2) of the AM0 spectrum, and 3.2% (32.4 W/m^2) of the AM1.5 spectrum (the AM0 solar spectrum is the solar spectrum just outside the Earth's atmosphere and the AM1.5 spectrum is the solar radiation incident from the solar-zenith angle of 48.2°). A large portion of solar irradiance is in the visible spectrum ($\Delta\lambda_{vis}$), which ranges from 380 to 740 nm and makes up 46% (607 W/m^2) of the AM0 spectrum, and 49.2% (492 W/m^2) of the AM1.5 spectrum. The IR region ($\Delta\lambda_{IRsolar}$) of the solar irradiance spans from 740 nm to ~ 2500 nm. The IR region of the solar spectrum accounts for 48% (630 W/m^2) of the AM0 spectrum, and 47.6% (476 W/m^2) of the AM1.5 spectrum. In some studies, the solar spectrum is considered to extend up to 4000 nm. For the AM0 solar irradiance, the total power over the spectral region from 280 to 2500 nm is $\sim 1320 \text{ W/m}^2$ and the power over the spectral region from 280 to 4000 nm is 1355 W/m^2 . For the AM1.5 solar irradiance, the total power over the spectral region from 280 to 2500 nm is $\sim 1002 \text{ W/m}^2$ and the power over the spectral region from 280 to 4000 nm is 1010 W/m^2 .

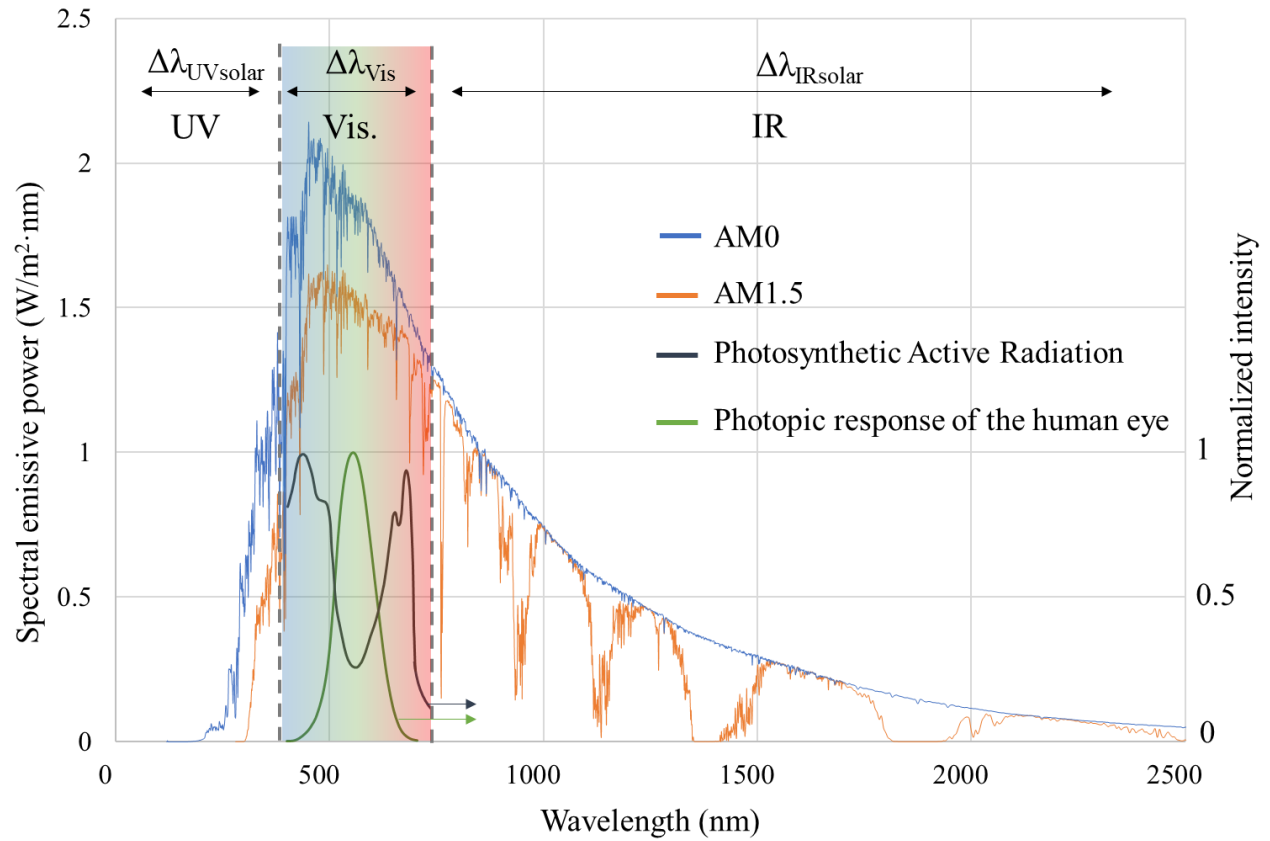


Figure 1-1 The spectral emissive power of the AM0 and AM1.5 solar irradiance with three main spectral regions of UV ($\Delta\lambda_{UVsolar} < 380$ nm), visible ($380 \text{ nm} < \Delta\lambda_{Vis} < 740$ nm), and IR ($\Delta\lambda_{IRsolar} > 740$ nm). The normalized photosynthesis active radiation for most green plants and the photopic response of the human eye as a function of wavelength is also shown.

Each range of the solar spectrum (e.g. $\Delta\lambda_{UVsolar}$, $\Delta\lambda_{Vis}$, and $\Delta\lambda_{IRsolar}$) can be useful for a wide variety of applications. The UV portion of the solar spectrum has been used for water and surface sterilization and medical therapy [2]. This spectral range also helps to create and stimulate vitamin D in the human body. UV light is also able to deactivate bacteria and viruses to sterilize surfaces and drinking water. Furthermore, recent research performed by Sensor Electronic Technology, Inc. (SETi) showed 99.9% effectiveness of the UV light against Corona viruses when exposed for 30 seconds. They showed that the UV light source can be more effective for deactivating the Corona virus when the UV light source is very close to the virus, which provides a very high intensity of UV light on the virus [3]. In this regard, an air channel with close exposure to UV light (5mm) was developed to effectively sterilize the incoming air. The visible portion of

the solar spectrum is vastly used for applications including lighting, photosynthesis and electric power generation by photovoltaic (PV) cells. Fig. 1-1 shows the photopic response of the human eye (the relative sensitivity of the human eye) as a function of wavelength. The average sighted human eye has the highest sensitivity at the wavelength of 555 nm, and green light can produce higher brightness in comparison to other wavelengths. The visible light region is also important for photosynthetic processes. photosynthesis is a light-to-chemical energy conversion process in plants, in which the light energy is captured by the plant and used to convert water and carbon dioxide to chemical energy (sugar) and oxygen. Photosynthetically Active Radiation (PAR) is the portion of the solar spectrum used for photosynthesis and growth. The PAR spectrum for most green plants is plotted as a function of wavelength in Fig. 1-1. As can be seen, for most green plants blue and red light are used extensively whereas green light is used to a lesser extent. It should be mentioned that the plentiful amount of light for photosynthesis provided by the sun has inspired researchers to create artificial photosynthesis machines [4, 5].

One of the most important solar energy conversion processes, especially for the visible and near IR portions of the solar spectrum, is to directly convert solar energy into electricity using PV cells. PV cells are the most commonly used optoelectronic device and are able to directly convert incident photons into electricity by generating electrons and holes. Furthermore, the IR region of the solar spectrum is useful for heating applications. This range of solar energy has also been used for water desalination/purification, medical treatments, and hydrogen generation [6- 8].

1.1 Solar-to-electricity energy conversion

The conversion of solar energy into electricity is an exceptionally important energy conversion process because electricity is a high-grade energy resource which has high potential and prospects to power the majority of devices for both terrestrial and also space applications [9]. PV cells have been widely used for many applications including satellites, space crafts, building integrated PV systems (BIPV), water pumping, street lighting, telecommunications, water desalination, and weather monitoring [10]. Currently, crystalline

silicon single-junction PV cells dominate the market of sunlight-to-electricity energy conversion as they are relatively inexpensive, environmentally friendly, and exhibit long-term stability. However, as discussed in the next section, the maximum efficiency of these PV cells is bound to about 30% by the Shockley-Queisser limit due to the broad spectral nature of sunlight.

1.1.1 Limitations of solar-to-electric energy conversion using PV cells

According to the Shockley–Queisser limit, single junction PV cells suffer from two dominant loss mechanisms [11]: 1) Unabsorption losses (η_{unabs}): the photons with energy lower than the bandgap (E_g) of a PV cell (sub-bandgap photons) do not have enough energy to generate electron-hole pairs and they are mostly transmitted through the PV cell. 2) Carrier thermalization losses (η_{therm}): photons with energy in excess of the bandgap of a PV cell generate one electron–hole pair in most cases, and the excess energy is converted to heat and thermal losses rather than contributing to the electric power output from the cell. The transmission and thermalization loss fractions are formalized as follows [12].

$$\eta_{unabs} = \frac{q}{P_{in}} \int_0^{E_g} E \Phi(E) dE \quad (1.1)$$

$$\eta_{therm} = \frac{q}{P_{in}} \int_{E_g}^{\infty} (E - \gamma(E)E_g) \Phi(E) dE \quad (1.2)$$

$$P_{in} = q \int_0^{\infty} E \Phi(E) dE \quad (1.3)$$

where q is the electron charge, E is the photon energy in eV, $\Phi(E)$ is the radiation photon flux, which is often assumed to be the AM1.5 standard, $\gamma(E)$ is the multiplication factor (in most cases $\gamma(E) = 1$) and P_{in} is the input power which is calculated using Eq. 1.3. Fig. 1-2a shows the unabsorption and thermalization losses as a function of the PV cell band gap. The minimum amount of total thermalization and unabsorption

losses is $\eta_{Si-therm} + \eta_{Si-unabs} = 51\%$, which occurs when $E_g \sim 1.1$ eV. For comparison Ge and amorphous Si-based PV cells have $\eta_{Ge-therm} + \eta_{Ge-unabs} = 61\%$ and $\eta_{a-Si-therm} + \eta_{a-Si-unabs} = 64\%$, respectively.

Furthermore, the Shockley–Queisser analysis reveals that if broadband sunlight energy can be converted into incident photons with energy slightly above the bandgap of the PV semiconductor, a single-junction-based PV cell can achieve an efficiency of 85%, which is the highest amount allowed by the second law of thermodynamics [13].

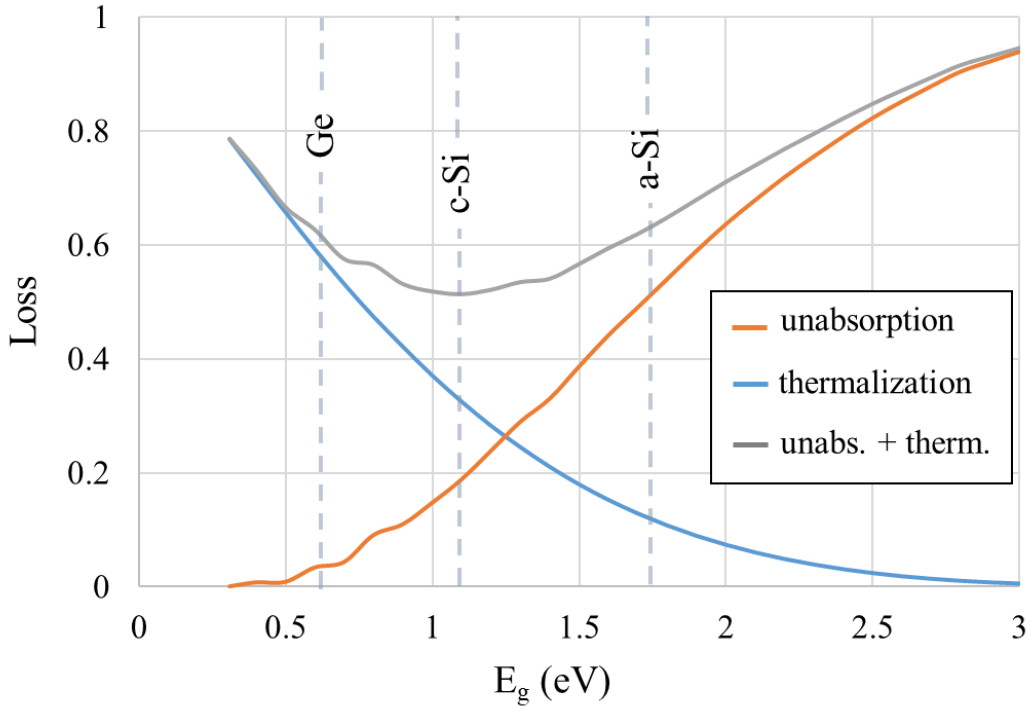


Figure 1-2 Unabsorption, thermalization losses, and the summation of these losses as a function of the bandgap of PV cells under the AM1.5 solar irradiance.

To convert the vast amount of clean energy provided by the sun into electricity, a wide variety of solar-to-electric energy conversion technologies have been developed including different types of PV cells [14], concentrated solar technologies [15], solar thermoelectric [16], and solar thermophotovoltaics [17]. Furthermore, novel strategies and materials have been implemented to enhance the performance of solar-to-electricity energy conversion technologies. One strategy to surpass the conversion limits of PV cells is to

tune the incoming photon spectrum, either directionally or spectrally. Methods to achieve this have been reported in the literature, including using spectral up-converters, down-converters, solar spectrum splitters, spectrally selective filters, and optical cavities [18, 19].

1.1.2 Solar thermophotovoltaics

Solar thermophotovoltaic (STPV) systems have emerged as one of the promising technologies to surpass the Shockly-Queisser limit of the solar-to-electricity conversion efficiency. STPV is a solid-state optical heat engine capable of converting concentrated solar irradiance into electricity. In this technology, the broadband solar spectrum is absorbed by a selective absorber surface and emitted with a tailored spectrum from an emitter surface. This spectral selectivity of the emitter surface allows the PV cell to exceed the conversion efficiency of the Shockley-Queisser limit. Optimum directional and spectral selectivity of the absorber/emitter surfaces are one of the key factors in a STPV system. For example, Sakakibara et al. [20] provided a comprehensive review on the practical emitters for TPV/STPV systems. They categorized the emitters to naturally selective emitters (e. g. rare earth materials), multilayer stacks, meta-materials, and photonic crystal structures. They further subcategorized the emitters based on their optical performance, size scalability, long-term thermal durability, ease of integration to TPV systems, and costs.

To further increase the conversion efficiency of a STPV system, using optical filters between the emitter and PV cell to transmit the high energy photons and reflect the low energy photons to the emitter, and rear mirror on the backside of the PV cell to reflect unabsorbed photons in the PV cell to the emitter, have been extensively investigated. For example, Ganapati et al. [21] coated an IR band-edge filter on the rear side of a $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ PV cell ($E_g = 0.8$ eV) and showed an efficiency record of 28.8%. They provided an estimation that for an emitter at 1200 °C if all photons above the band gap ($E_g = 0.8$ eV) are used and 99% of the below-bandgap photons would be reflected and recycled by the emitter, the TPV system can reach to > 50% system efficiency. However, still several loss mechanisms hinder the STPVs to reach their theoretical limits, which will be discussed in more detail in Chapters 5-7 of this thesis. [22]

1.2 Cogeneration, multi-function, and hybrid solar energy systems

The use of solar powered technologies is still not widespread due to their relative costs, limited performance, and energy density in comparison to existing non-renewable energy resources. Electricity generation in PV cells is presently the most important and widespread solar energy conversion technology due the high quality of electric power which can be used to power most devices and applications. However, as discussed in Section 1.1.1 the most cost-effective PV cells are relatively inefficient towards the direct conversion of sunlight into electricity. As mentioned in Section 1.1.2, one potential method of improving the energy conversion efficiency of PV cells is through solar thermophotovoltaics. Another method of improving PV solar energy harvesting systems, described in this section, is through the design and development of cogeneration, multi-functional, or hybrid systems.

By utilizing the different parts of the solar spectrum simultaneously for multiple applications, the total energy conversion efficiency can be improved. To facilitate the simultaneous operation of multiple solar energy conversion processes, sunlight can be partitioned and separated by wavelengths, energy levels, and propagation directions. The ability to separate or convert the broadband solar irradiance into multiple spectra in a controlled manner offers several advantages. For example, PV cells can harvest solar energy within an optimized spectral band with energy just above its bandgap [23, 24]. This helps the PV cell maintain low temperatures and have higher efficiency and less thermalization losses. Secondly, the part of the solar irradiance not absorbed in PV cells can be used for other applications such as heating or photochemical and photothermal applications in hybrid systems [25]. A wide variety of approaches including the use of solar spectrum splitters, waveguides and cavities have been investigated to directionally and spectrally split and control the solar irradiance to facilitate energy conversion in multifunctional and hybrid solar applications [26, 27].

1.2.1 Using solar spectrum splitters for solar energy harvesting

Due to broadband nature of the solar irradiance, splitting and controlling the distribution of solar energy in different wavelength bands can significantly enhance overall solar-to-energy conversion efficiencies. Various techniques have been proposed and developed to partition and control the solar spectrum. For example dispersive optical elements such as grating, meta-surfaces and photonic crystal structures have been comprehensively investigated. Yuhan et al. [28] designed a multilayer meta-film to partition the light into different wavelengths with different angles. The meta-surface was composed of several two-dimensional grating layers stacked vertically. The implementation of the designed structure was shown in solar concentrators. The concentrated solar beam hits the dispersive element and is directionally and spectrally partitioned to reach appropriate PV cells. Elikkottil et al. [29] designed a silicon nitride-based diffraction grating structure on a glass substrate to diffract the portion of the solar spectrum from wavelengths of 700 to 1400 nm. The diffracted spectrum is propagated in the glass sheet waveguide to the edges where the PV cells are located. They reported an NIR guiding efficiency of 18% and power conversion efficiency of 11%. Elsarrag et al. [30] used a photonic crystal optical filter as a beam splitter to partition the solar spectrum into regions wherein the wavelength is below-800 nm and above-800 nm. The higher and lower energy regions of the solar spectrum were transferred to PV cells and thermoelectric generators (TEG), respectively. The overall performance of the proposed hybrid PV-TEG solar harvesting system achieved ~20% efficiency which was ~10% higher in comparison to the PV-only setup. Ellikottil et al. [31] designed and fabricated a novel dielectric grating structure on a window glass as a planar concentrator to be used in net zero energy buildings. The solar spectral splitter transmitted the visible light and guided the IR light to the edges of the window to be captured by the PV cell. The grating was polarization independent and able to achieve 0.72% guiding efficiency for wavelength range of 700 to 1000 nm. Guiding and coupling losses were attributed to be the major loss mechanisms in the system.

1.2.2 Using waveguides for solar energy harvesting

Waveguides, which confine and direct the propagation of electromagnetic waves with minimal losses, can be used in the design of broadband solar energy harvesting systems. For example, Luminescent Solar Concentrators (LSCs) comprise photoluminescent materials embedded within a transparent planar host matrix [32]. The photoluminescent materials absorb solar radiation and subsequently emit radiation at a longer wavelength. A large portion of emitted radiation will undergo total internal reflection (TIR) at the upper and lower surfaces of the host matrix. The transparent host matrix functions as a waveguide, directing light towards its edges where PV cells can be located. Also, Chou et. al. made flexible waveguide solar concentrators composed of polydimethylsiloxane (PDMS) and TiO_2 particles [33]. The TiO_2 particles scatter incident solar radiation and the PDMS guide a significant portion of scattered light to PV cells located at its sidewalls. These flexible-waveguide PV structures demonstrated an optical efficiency of greater than 42% and a power conversion efficiency of 5.57%. Michel et. al. proposed a solar concentrator that functions as both a spectrum splitter and a waveguide. [34] This concentrator is made of two main optical elements: a lens with a grating structure and a waveguide. The graded lens partitions the solar irradiance into different spectral regions, which are directed to different PV cells and opposite ends of the waveguide. PV cells with band gap positions that minimize unabsorption and thermalization losses for the portioned spectral regions are used at the edges of the waveguide. Vu et. al. designed and numerically evaluated a spectral splitting concentrator PV system based on a Fresnel lens array and double waveguides [35]. Dichroic mirrors within the double stacked waveguide structure partition the solar irradiance into different spectral regions, which are guided to PV cells that well-matched to these spectral regions. Numerical analysis showed an overall conversion efficiency of 46.1%.

1.2.3 Using optical cavities for solar energy harvesting

Another type of structure that can be used to facilitate solar energy conversion is optical cavities. An optical cavity comprises an arrangement of mirrors or reflective surfaces which confine light to a certain spatial

region. Pastorelli et. al. used an optical metal cavity configuration to trap near infrared light in an organic solar cell. By using this optical cavity configuration a PV cell that transmitted more than 20% of the incident light over the visible spectral region was demonstrated to have an efficiency equal to 90% of the efficiency of an opaque cell [36]. Moreover, cavity receivers are used to minimize losses in concentrated solar power systems [37]. Tian et. al. have performed numerical analysis and reported that blackbody-cavities can be used to design spectrally selective absorbers that enable temperatures of 880 °C to be achieved under solar radiation with a concentration factor of 10. This work emphasized the robustness and durability of using a cavity to make a selective solar absorber rather than alternative methods such as photonic crystals, metamaterials, and other structures that are built using nanofabrication methods [38]. Weinstein et. al. used optical cavities to design directionally selective solar receivers wherein radiation losses from the receiver are suppressed by the cavity in all directions other than those for which there is incident sunlight. By using a hemispherical cavity, a 75% reduction in radiative losses from a blackbody absorber surface was demonstrated [39].

Optical cavities are relatively inexpensive and can be made to withstand high temperatures cyclic temperature cycles. When used in conjunction with other materials and structures, such as solar spectrum splitters and waveguides, optical cavities can manipulate the directional and spectral properties of the solar irradiance. Despite these advantages, very little work has been reported on the use of optical cavities for controlling the directional and spectral properties of light to facilitate the conversion of the solar irradiance into useful forms of energy.

1.3 Goals and objectives

This thesis addresses the underexplored area of using optical cavities, combined with spectral splitters and waveguides, to harness the broadband solar energy resource. Emphasis is placed on the design of structures that function as waveguides and cavities that manipulate light in relatively simple, yet very useful, ways. For example, elliptical structures have the inherent property that they refocus rays emitted from one of their

focal points to their second focal point. Also, parabolic surfaces can collimate rays emitted from their focal point. These geometrical properties are well-known, but have not yet been sufficiently applied to enhance cavities and waveguides in the design of broadband solar energy harvesting structures.

This thesis addresses this technological gap by investigating the scientific questions as to what extent optical cavities can be used to directionally and spectrally modify the incoming solar radiation, and to what extent this can be used to enhance solar energy harvesting. In this thesis, the geometrical properties of paraboloid and spheroid-based optical cavities are investigated to directionally and spectrally manipulate and control solar energy. These optical cavities are used in the design of solar energy harvesting applications. In some instances, they are used to drastically reduce the effective emissivity of emitters in solar thermophotovoltaic devices. In other applications these optical cavities are used to partition the solar irradiance into its PAR and non-PAR components. The non-PAR is directed towards PV cells with negligible emission losses, while the PAR is transmitted to be used in underlying photobioreactors. The goals and objectives of this thesis are as follows:

- To explore the area of optical cavity and waveguide design for broadband solar energy harvesting applications, and design novel optical structures to address the gap wherein this technology has been underexplored for solar applications. As this objective is the main goal in this thesis, this objective is addressed throughout the Chapters Two through Seven. In Chapters Two and Three elliptic-based solar spectrum splitters are used in the design of self-powered photobioreactors and microalgae cultivation systems. In Chapter Four, elliptic and paraboloid-based solar spectrum splitters are used to design hybrid solar lighting systems for power generation in buildings. In Chapters Five through Seven ellipsoidal-based optical cavities are used in the design of thermophotovoltaic systems.
- To determine the extent and efficiency with which the newly designed optical cavities and structures (from the previous step) can partition, control and utilize the solar irradiance for multiple purposes simultaneously (such as electric power generation, photosynthesis, and indoor lighting). This objective is addressed throughout the Chapters Two, Three and Four. In first implementation of the optical cavity, elliptic

paraboloid-based solar spectrum splitters for self-powered photobioreactors are defined. The results show that the system can partition the solar irradiance into PAR and non-PAR spectra in order to power algae cultivation system and PV cells, respectively. The self-powered photobioreactor has optical efficiency and emission losses of 73% and 6%, respectively with capability of producing 0.2 kg algae and 0.25 MJ electric power daily for 0.2 m² projected area of solar radiation. In the next application, the optical cavity is implemented into elliptic array luminescent solar concentrators for combined power generation and microalgae growth. In this application the system has an optical efficiency of 63%, whereas in similar conditions, the optical efficiency for a conventional planar LSC is 47.2%. The electrical conversion efficiency for the elliptic array LSC is ~17%. In the third implementation of the optical cavity, a fiber optic-based hybrid solar lighting system is designed to selectively harvest near-infrared photons for electric power generation in buildings. The results show a non-visible-light-to-electricity conversion efficiency of ~ 13.4%.

- To determine the extent to which the newly designed optical cavities can enhance the performance of solar thermophotovoltaic systems. This objective is vastly addressed throughout the Chapters Five to Seven. One of the key findings is that there is always an optimum trade-off value between photon recycling and view factor for the system efficiency of a TPV system for a blackbody emitter. Further, by implementing the optical cavity proposed in this study in an STPV system, a system efficiency of up to ~ 42.5% can be achieved using a black body emitter.

1.4 Thesis overview

The contents of this thesis are as follows: In Chapter Two, an optical structure in the form of an elliptic paraboloid-based solar spectrum splitters (EPSSS) is designed and numerically investigated for the application of a self-powered photobioreactor. In this application the EPSSS is shaped in the form of two oppositely facing semi-elliptic paraboloids, that partition the solar irradiance into PAR and non-PAR to simultaneously power algae-based biofuel cultivation systems and PV cells, respectively. In Chapter Three, a novel waveguide in the form of an elliptic array LSC is numerically evaluated for combined power and

microalgae growth. Chapter Four presents a new optical structure, referred to as a double-stack semi-elliptic/parabolic solar spectrum splitter, used for hybrid solar lighting (HSL) systems for both indoor lighting and electric power generation. In Chapter Five, thermophotovoltaic systems (TPV) are introduced and the effect and importance of optical cavities for TPV systems are discussed. In this chapter parametric analysis of the effects of the probable fate of emitted photons on the output of TPV systems are presented. In Chapters Six and Seven, as optical structure in form of oblate/prolate spheroid is proposed to significantly enhance the performance of TPV systems. In this section of the study, the main focus is on the implementation of the optical structure on Solar Thermophotovoltaic (STPV) systems. In the last chapter future works are discusses.

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2 Elliptic paraboloid-based solar spectrum splitters for self-powered photobioreactors¹

Nomenclature			
<i>Roman symbols</i>			
A	area	P_{max}	maximum output power
A_{LED}	installed area of red LEDs	q	charge of an electron
$A(\lambda)$	luminophore absorption spectrum	T	temperature
a	self-absorption coefficient	V_{extra}	additional volume of biofuel
C	concentration factor	V_{OC}	open circuit voltage
C_{algae}	algae concentration	W	width of the elliptic paraboloid
D	probability of a photon to scatter		
$F(\lambda)$	luminophore emission spectrum	<i>Greek symbol</i>	
FF	fill factor	α	material absorption coefficient
G	geometric gain factor	ΔW_1	spectral region from 280 ~ 400 nm
h	heat transfer coefficient	ΔW_2	spectral region from 500 ~ 600 nm
$\bar{I}$	mean light intensity	ΔW_3	spectral region from 740 ~ 900 nm
I_0	dark saturation current	$\eta_{Emission}$	emission efficiency
I_i	initial light intensity	$\eta_{Fresnel}$	incident light coupling efficiency
I_n	normalized intensity	$\eta_{non-PAR-Abs}$	non-PAR absorption efficiency
I_{SC}	short circuit current	$\eta_{non-PAR-opt}$	non-PAR optical efficiency
k	Boltzmann's constant	η_{PLQY}	photoluminescence quantum yield
L	length of the elliptic paraboloid	$\eta_{Roughness}$	surface roughness efficiency
l	optical pathlength	$\eta_{self-abs}$	self-absorption efficiency
N	the number of photon collisions with the surface	η_{Stokes}	Stokes shift efficiency
n_1	refractive index of the external medium	$\eta_{Transmission}$	transmission efficiency
n_2	refractive index of the internal medium	θ_p	solar half-angle
O	radius of the entrance port on the elliptic paraboloid	λ	wavelength
P	focal distance	σ_{SA}	self-absorption cross section
		Φ_1	light intensity incident onto the nonimaging solar concentrator
		Φ_2	light intensity incident onto the annular PV cells
		$\Phi_{\Delta W_1}$	photon flux of ΔW_1
		$\Phi_{\Delta W_2}$	photon flux of ΔW_2
		$\Phi_{\Delta W_3}$	photon flux of ΔW_3

¹ This chapter is based on references [91, 92]

2.1 Abstract

Microalgae has potential for large-scale biofuel production and CO₂ remediation, however its growth is easily hindered by contamination, unsuitable environmental conditions, and photosaturation. To mitigate these problems the solar irradiance can be partitioned into photosynthetically active radiation (PAR) and photosynthetically inactive radiation (non-PAR). The PAR can be used for algae growth in a photobioreactor under controlled conditions. The non-PAR can be used to generate electricity in photovoltaic (PV) cells which could provide for agitation, thermoregulation, CO₂ replenishment, and enhanced illumination in a photobioreactor. This chapter presents numerical analysis of a luminescent solar spectrum splitter (SSS) shaped in the form of two oppositely facing elliptic paraboloids, that partitions the solar irradiance into PAR and non-PAR to simultaneously power algae-based biofuel cultivation systems and PV cells, respectively. The SSS enables 0.25 MJ of electric power generation in a photobioreactor with a projected area and volume of 0.2 m² and 0.2 m³, respectively, which produces 0.2 kg of algae daily. The SSS directs non-PAR to PV cells with emission losses of 6%, and an optical efficiency of 73%. In comparison if a planar luminescent panel was to split the solar spectrum emission losses would be 26% and the non-PAR optical efficiency would be 39%. Furthermore, the Shockley-Queisser efficiency limit for non-PAR is calculated to be 24% and the SSS enables a conversion efficiency of 15.8% for direct solar irradiance. This is enough electric power to provide for the cultivation and harvesting processes in the photobioreactor and to operate the two-axis solar tracking system required by the SSS. This extra generated power can also be used to increase biomass volume productivity by 9.3%, which represents an additional ~ 0.17 kg/m²·day of CO₂ fixation. The luminescent SSS enables self-powered photobioreactors with increased utilization of space and solar radiation, and higher net energy gain ratios.

2.2 Introduction

Energy derived from fossil fuel sources increases atmospheric CO₂ concentrations and contributes to global warming. Biofuels from microalgae are an interesting alternative energy source considering their ability to

tolerate various habitats including salt and water environments, biomass production rates of 30-100 times faster than land plants, and because each ton of algal biomass produced fixes 1.83 tonnes of CO₂ [1, 2]. However, innovative research efforts are required to optimize growth parameters and develop competitive algae cultivation systems. To date, algae production has not been efficient enough to provide a commercially competitive biofuel product. The "open pool" style of algae production suffers from a number of disadvantages including extreme land area demand, high evaporation rates, high contamination risk, and low volumetric productivity. More recent advancements have focused on the design of enhanced photobioreactors. However, a major problem with these reactors is their high operating cost, weak stability and sub-optimal cultivation processes [3].

One fundamental method of improving photobioreactors is to utilize the entire solar spectrum. In this context, spectral photon management strategies have been employed [4-6]. For example, it has been shown that microalgae growth or crop production in greenhouses can be improved by using acrylic fluorescent sheets to modify the spectral distribution of the incident solar irradiance [7, 8]. Moreover, Ooms et al. [9] demonstrated a growth rate increase of 6.5% in photosynthetic organisms by tuning the resonant wavelength of gold plasmonic nanodisk arrays to match their absorption peak. Another spectral photon management strategy is to integrate solar spectrum splitters (SSS) to direct the portion of the AM1.5 spectrum not fully utilized for photosynthesis onto PV cells to generate electricity. Detweiler et. al. [10] showed that luminescent solar concentrator (LSC) panels comprising Lumogen Red 305 fluorescent dye can be utilized to transmit blue and red wavelengths used for photosynthesis while using the energy from absorbing green photons to emit red photons. The fluorescently emitted red light could be used to boost algal growth or be converted to electric power in PV cells. Barbera et. al. [6] placed semi-transparent dye-sensitized solar cell modules overtop of a biomass reactor to improve the overall photoconversion efficiency by producing electricity while transmitting light used for photosynthesis. They showed that for low light intensities, the presence of the semi-transparent modules decreases the biomass productivity. However, for high light intensity conditions, photo-inhibition effects were mitigated and biomass productivity was enhanced. In

addition, A. Brodu et. al. [11] combined a semi-transparent amorphous silicon PV panel with a photobioreactor. In this study the semi-transparency of the PV cell was tailored to match the spectral response of microalgae in order to enhance the overall sunlight photoconversion efficiency while providing power to a photobioreactor.

SSSs have been made using selectively transmitting fluids, chromatic mirrors, Bragg reflectors, diffractive structures, and luminescent materials [12-16]. Utilizing spectral-splitting LSCs to enhance photobioreactors are particularly attractive because they are relatively inexpensive, lightweight and amenable to large scale production. LSCs also offer design flexibility in shape, size and spectral transparency [17-19]. However, due to their intrinsic loss mechanisms and modest efficiency, LSCs have yet to be extensively commercialized. The main loss mechanism in LSCs is emission losses, which occur when light is emitted within the escape cone by luminophores within the LSC. Light emitted within the escape cone propagates in a direction less than the critical angle for total internal reflection (TIR) to occur and is refracted outside the waveguide. To date, research directed towards reducing emission losses in LSCs has investigated the effects of coating wavelength-selective mirrors on the surface of LSC panels, or aligning the luminophores within the LSC [20-23]. The purpose and novelty of the work reported herein is to investigate the possibility of mitigating emission losses by shaping the matrix that hosts the luminophores to drastically reduce the size of the escape cone such that it is almost eliminated. The design of a novel dual-Elliptical Paraboloid Solar Spectrum Splitter (d-EPSSS) is considered that is shaped to reduce emission losses from its focal point. As described in the subsequent section, the d-EPSSS uses the spectral-splitting properties of LSCs to partition the solar irradiance into its PAR and non-PAR spectral components to simultaneously power photobioreactors and PV cells, respectively.

2.3 Description of the self-powered photobioreactor

To enhance the performance of algae photobioreactors, PV cells can be used to convert non-PAR to electricity to provide power to operate the photobioreactor. For example, electric power generated from

non-PAR could be used to power equipment that provides blue and red lighting, temperature regulation, CO₂ enrichment, or agitation within the photobioreactor. The PAR spectrum for chlorophyll, the main pigment in algae, is shown overlaying the AM1.5 solar spectrum in Fig. 2-1a [24]. The PAR spectrum extends from 400 nm to 740 nm and exhibits maxima in the spectral vicinities near 450 nm and 700 nm. Furthermore, the solar irradiance in the spectral region from approximately 500 nm to 600 nm is not fully utilized for photosynthesis. Herein we refer to the portion of the solar irradiance that is inactive towards photosynthesis, or barely used for photosynthesis (e.g. ~500 nm to ~600 nm for chlorophyll) as non-PAR. Moreover, as shown in Fig. 2-1b, the Shockley-Queisser efficiency limit [25] for the non-PAR spectra formed by subtracting the chlorophyll PAR spectrum from the AM1.5 solar spectrum shown in Fig. 2-1a, is 24% for a single junction PV cell with a band-gap of 1.1 eV. A theoretical maximum of 17% of the AM1.5 spectrum can be converted to power because 24% of the non-PAR spectrum represents 170 W/m² out of a possible 1000 W/m² available from the solar irradiance. This result is technologically significant because silicon-based PV cells, which dominate the PV market and have a band gap of 1.1 eV, can be optimally utilized in biofuel/ PV energy co-generation systems. Furthermore, using the AM0 solar spectrum for electricity production and bioregenerative life support systems (BLSS) that provide food production and air revitalization is of interest for future planetary outposts, especially lunar and martian greenhouse systems [26-28]. The solar-to-electric power conversion efficiencies for the total and non-PAR components of the AM0 spectra are plotted in Fig. 2-1b as a function of the band-gap energy of the PV cell used in the system. The maximum solar-to-electric conversion efficiency for the non-PAR component of the AM0 spectra is 22% at a band-gap energy of 1.07eV.

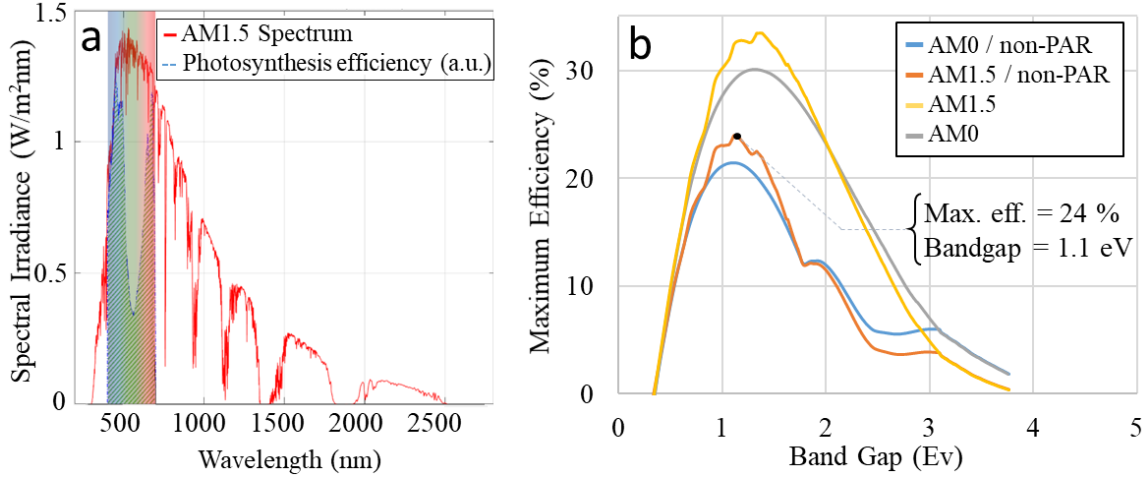


Figure 2-1 a) The normalized chlorophyll PAR spectrum, in arbitrary units, overlaying the AM1.5 solar spectrum. b) The Shockley-Queisser efficiency limit for the AM0, AM1.5 spectra and the non-PAR portions of the AM0 and AM1.5 spectra.

2.3.1 Description of the dual-elliptical paraboloid solar spectrum splitter

A dual-Elliptical Paraboloid Solar Spectrum Splitter (d-EPSSS), made of a solid transparent material, such as glass or PMMA, with the shape of two oppositely facing solid elliptic paraboloids that share the same focal point is shown in Fig. 2-2a. The d-EPSSS accepts a collimated beam of concentrated solar radiation through an entrance port located at the center of its upper surface. In this work it is assumed that solar radiation with an intensity of 1000 W/m^2 received over an area of 0.2 m^2 is concentrated and collimated prior to being directed into the entrance port at the top of the d-EPSSS. It has been reported that solar energy can be concentrated and collimated with efficiencies as high as 71% with a divergent angle of 0.15° using the combination of a parabolic mirror and a convex lens [29]. A high numerical aperture-fibre optic collimator attached to a two-stage non-imaging solar concentrator can be utilized to create a highly concentrated-collimated beam with a projected area of 0.2 m^2 in the X-Y plane [29-31]. In this work our numerical analysis focuses on the efficiency with which the d-EPSSS absorbs and converts non-PAR from this incident collimated beam into electric power.

The collimated beam of light propagates along the axis of the paraboloids to their shared focal point, where a region concentrated with luminescent dye absorbs non-PAR and re-emits radiation at equal intensity in all

directions. As described subsequently with reference to Fig. 2-2b, light radiated from the luminescent dye is ultimately directed towards PV cells. For the case shown in Fig. 2-1a, dye that absorbs in the spectral regions from 280-400nm, 500-600 nm and ~740-1100 nm should be used to absorb non-PAR from the collimated beam of solar radiation and re-emit radiation that will be directed towards silicon-based PV cells. The portion of the collimated beam not absorbed by the fluorescent dye exits a port at the bottom of the SSS and can be efficiently distributed in a photobioreactor [32-38]. In a LSC the primary function of the dye is to absorb incident radiation and then isotropically emit radiation such that a large portion of it becomes trapped due to TIR in the medium hosting the dye. The work presented herein considers the benefits of shaping the medium hosting the dye in a parabolic-based, rather than planar-based, configuration. As shown in Figs. 2-2a and 2-2b, the radiation emitted from the focal point of the d-EPSSS is directed towards annular PV cells located at its top and bottom surfaces. Annular shaped PV cells can be attained using laser processing methods described in the literature [39, 40]. Moreover, the majority of light (over 90%) emitted from the focal point of the d-EPSSS impinges onto the PV cells from the normal direction, which minimizes reflection from the surface of the PV cell. This is achieved by designing the curvature and degree of overlap of the two elliptic paraboloids such that radiation emitted at their shared focal point undergoes TIR at their curved sidewalls. The design for the curvature and overlap of the elliptical paraboloids for the two-dimensional case can be described with reference to Fig. 2-2b. The general equation for the parabola shown on the left side of Fig. 2-2b is given as Equation 2.1:

$$(z - z_0) = \frac{(x - x_0)^2}{4P} \quad (2.1)$$

Where z_0 and x_0 are the x and z intercepts, respectively, and P is the distance from the vertex to the focal point. By setting the vertex at the origin, h and k are set equal to zero. If the index of refraction of the medium internal and external to the parabola is n_2 and n_1 , respectively, then based on Snell's law radiation emitted from the focal point of the parabola will undergo TIR when Equation 2.2 is satisfied:

$$\left| \frac{dz}{dx} \right| = \left| \frac{x - x_0}{2P} \right| > \tan(\sin^{-1}(\frac{n_1}{n_2})) \quad (2.2)$$

For light emitted from the focal point ($z = P$) Equation 2.2 is simplified to $\frac{n_1}{n_2} < \frac{\sqrt{2}}{2}$, and the ratio of the refractive indices, $n_1:n_2$, should be less than 0.707. For example, if the external medium is air ($n_1 = 1$) and the internal medium has an index of refraction of $n_2 = 1.49$, which is a good approximation for PMMA, then TIR will occur at points along the parabola for which $x > 1.81P$ and $z > 0.82P$. As shown on the right side of Fig. 2-2b, two parabolas with an internal index of refraction of $n_2 = 1.49$, sharing the same focal point but facing opposite directions, can be overlapped such that they intercept at $x = \pm 2P$, and all radiation emitted from the focal point will undergo TIR at the parabolic surfaces.

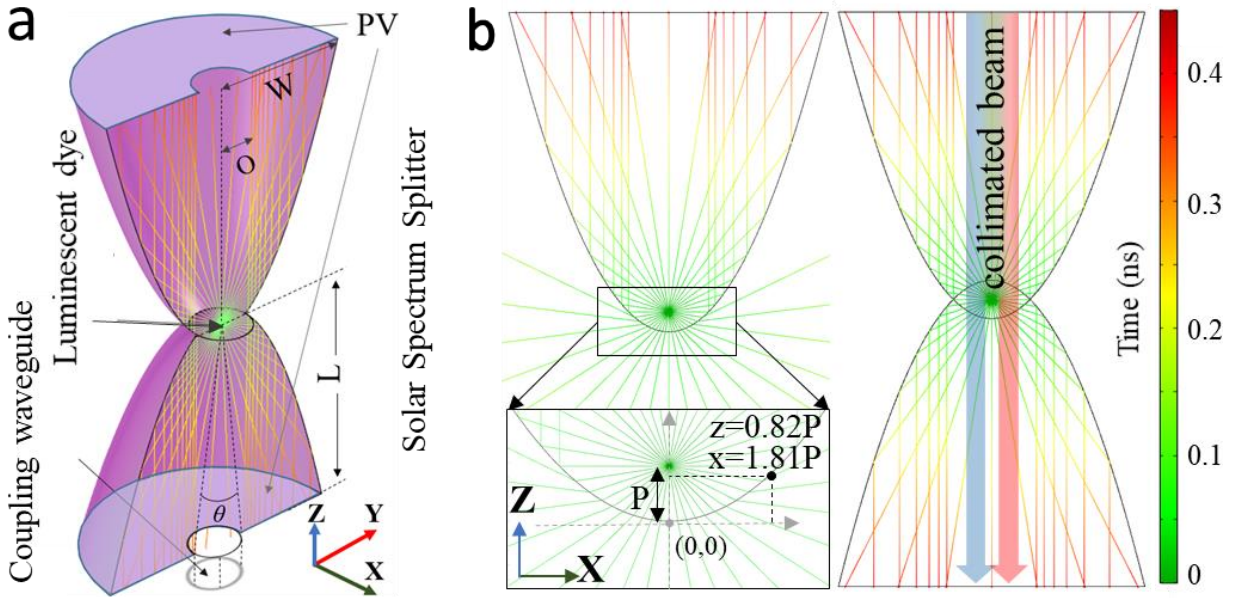


Figure 2-2 a) A cross-sectional diagram of the dual-Elliptical Paraboloid Solar Spectrum Splitter (d-EPSSS). b) A two-dimensional cross-sectional diagram showing the elliptical paraboloids within the solar spectrum splitter can be designed such that radiation emitted from their shared focal point undergoes total internal reflection at their sidewalls.

2.4 Geometric gain factor and emission losses for the dual-elliptical paraboloid solar spectrum splitter

2.4.1 Methods used to calculate the geometric gain factor and emission losses.

The geometric gain factor, G , is defined as the planar area of the solar receiver with normal incident to the solar irradiance divided by the area of the PV cells. Thus, the geometric gain factor depends on the d-EPSSS and the solar receiver used to provide it with a collimated beam of light. For the numerical analysis performed in this work it is assumed that a solar receiver with a planar area of 0.2 m^2 concentrates and focuses a direct beam of solar irradiance onto the d-EPSSS along its vertical z -axis. The radius of the collimated beam is assumed to be equal to or less than O shown in Fig. 2-2a. The area of the PV cells is assumed to be equivalent to the areas of the upper and lower annular surfaces of the d-EPSSS.

The primary loss mechanism for radiation emitted from the focal point of the d-EPSSS is radiation that propagates through the ports at the center of the annular PV cells on its upper and lower surfaces. The percentage of radiation lost through these ports as a function of the geometrical parameters, L , W , and O , of the d-EPSSS, is determined using Equations 2.3 and 2.4.

$$\text{Emission Losses (\%)} = \left(1 - \frac{L}{\sqrt{O^2 + L^2}}\right) \times 100 \quad (2.3)$$

$$(L+P) = \frac{W^2}{4P} \quad (2.4)$$

2.4.2 Results and discussion for calculating the gain factor and emission losses.

As shown in Fig. 2-3a, the geometric gain factor (G) decreases as W increases for constant values of O . The percentage of radiation lost through the entrance and exit ports at the upper and lower surfaces of the d-EPSSS is shown as a surface plot as a function of L , and O in Fig. 2-3b. G is plotted as a function of the percentage of radiation lost through the center ports for values of L and O ranging from 1 to 10 cm in Fig. 2-3c. As the length, L , of the elliptic paraboloids increases, the width, W , and area, A , of the PV cells also

increase, and G decreases. As the opening, O (and focal distance, P), decrease, G increases. A maximum value of G of 159 is achieved when the length of the d-EPSSS is 1 cm and the emission loss in this case is 29.3%. G is 130 when the losses are the same as that of a planar LSC, which is ~25%. Moreover, when the emission losses are 5% $G = 52$. Furthermore, it is noteworthy that the geometric concentration factor can be significantly increased by further decreasing the opening. For example, for a d-EPSSS with $O = 0.1$ cm, a maximum value of $G = 5231$ can be achieved while the emission losses are just 5%.

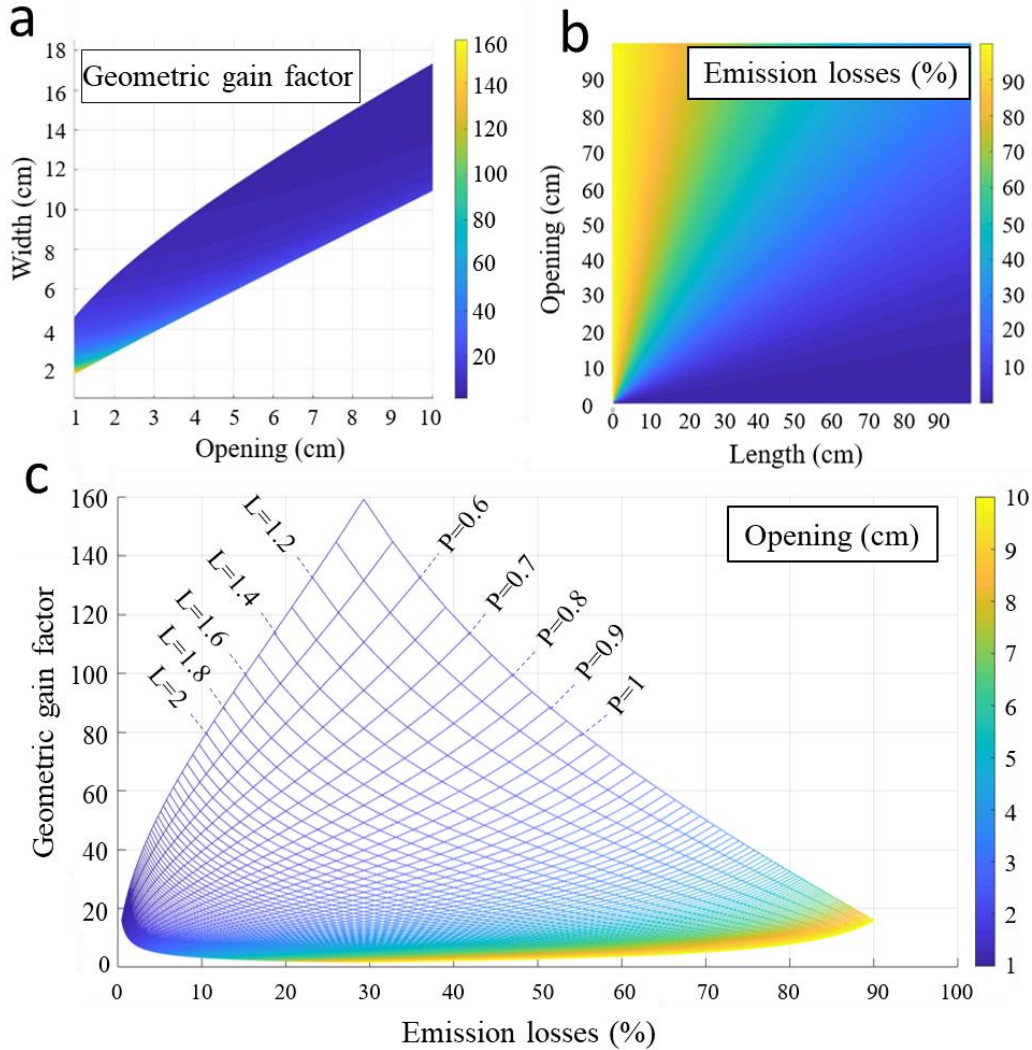


Figure 2-3 a) A surface plot of the geometric gain factor (G) as a function of the dimensions of the d-EPSSS: the opening, O , and width, W , as indicated in Fig. 2a. b) A surface plot of the percentage of light emitted from the focal point of the d-EPSSS that is lost through its entrance and exit ports as a function of O , and L . c) The geometric gain factor plotted as a function of the percentage of

light lost through the opening and exit ports; increasing and decreasing curves are plotted for constant values of P and L , respectively, as indicated in the figure.

The geometric gain factors plotted in Fig. 2-3c are calculated assuming annular PV cells were situated at both the upper and lower surfaces of the d-EPSSS. In practice, the geometric gain factor could be increased by replacing the PV cell at the upper surface of the d-EPSSS with a mirror. If the annular PV cell located at the top surface of the d-EPSSS is replaced with a mirror, light emitted from the dye that is normally incident onto the mirror is reflected and refocused at the focal point and is ultimately directed onto the PV cell located at the bottom side of the d-EPSSS. Thus, replacing the PV cell at the top surface of the d-EPSSS with a mirror increases the geometric gain factor (G) by a factor of ~ 2 (G is slightly less than 2 because $\sim 10\%$ of the light rays impinging onto the mirror are incident from the off-normal direction and have a chance to escape the d-EPSSS before they are incident onto the PV cell at the bottom surface). The geometric gain factor and emission losses for a d-EPSSS with differing values of L and O , and with either two PV cells or a single PV cell (and mirror at its upper surface) are provided in Table 2-1. The optical efficiency, $\eta_{non-PAR-opt}$, and concentration factor, C , are also included for each configuration in Table 2-1 for completeness. The methods used to attain these parameters are provided in Section 2.6.

Table 2-1 Gain factor, emission losses, optical efficiency, and concentration factor for d-EPSSS with different lengths and opening port size for the cases where a mirror or PV cell is located at their upper surface.

d-EPSSS number	Opening (mm)	Length (cm)	Width (cm)	Geometrical gain factor (G)	Emission loss (%) (no-mirror)	Emission loss (%) (mirror)	Optical efficiency ($\eta_{non-PAR-opt}$) (%)	Concentration factor (C)
A1	1	7.94	1.26	200	0.01%	-	82.3	164.6
A2	1	7.94	1.26	400	-	0.68%	78.6	314
A3	2	3.98	1.28	200	0.13%	-	83.9	167.8

A4	2	3.98	1.28	400	-	1.29%	80.7	323
A5	3	2.64	1.29	200	0.64%	-	84	168
A6	3	2.64	1.29	400	-	5 %	79.1	316
A7	4	2	1.33	200	1.9%	-	83.2	166.4
A8	4	2	1.33	400	-	8.5%	76.6	306
A9	5	1.6	1.36	200	4.45%	-	81	162
A10	5	1.6	1.36	400	-	12.35%	73.5	294
B1	1	15.9	1.79	100	0.00%	-	79.1	79.1
B2	1	15.9	1.79	200	-	0.5%	73.2	146.4
B3	2	7.69	1.765	100	0.03%	-	82.3	82.3
B4	2	7.69	1.765	200	-	1.2%	78.2	156.4
B5	3	5.3	1.81	100	0.16%	-	83.1	83.1
B6	3	5.3	1.81	200	-	2.5%	79	158
B7	4	3.98	1.83	100	0.50%	-	83.4	83.4
B8	4	3.98	1.83	200	-	4.33%	78.5	157
B9	5	3.18	1.85	100	1.20%	-	83	83
B10	5	3.18	1.85	200	-	7.24%	76.4	153
C1	2	39.8	4	20	0.00%	-	70	14
C2	2	39.8	4	40	-	0.25%	58.4	23.4
C3	4	19.9	4.01	20	0.02%	-	77.5	15.5
C4	4	19.9	4.01	40	-	1%	70	28

C5	9	8.84	4.09	20	0.51%	-	81	16.2
C6	9	8.84	4.09	40	-	4.48%	73	29.2

The results presented in Figs. 2-2, 2-3 and Table 2-1 are calculated assuming the fluorescent dye is located precisely at the focal point of the elliptical paraboloids. In practice, the luminescent dye molecules will occupy a finite volume, the size of which depends on the amount of dye required to absorb the incident non-PAR solar photon flux. The effects of distributing the dye over a finite volume are discussed in the subsequent section.

2.5 Effects of spatial distribution of the luminescent dye on the efficiency of the dual-elliptical paraboloid solar spectrum splitter

To further investigate the effects of the finite dye volume we consider the specific case wherein the projected area of the two-stage non-imaging concentrator that receives the incident solar radiation is 0.2 m^2 and the d-EPSSS has a length, opening, and width of 8.84 cm, 0.9 cm, and 4.09 cm, respectively. Furthermore, it is assumed that a mirror resides at the upper surface of the d-EPSSS and the geometrical concentration factor in this case is 40 (this is listed as configuration d-EPSSS_{C6} in Table 2-1).

2.5.1 Methods for estimating the volume occupied by the luminescent dye and related optimal efficiency.

To estimate the volume occupied by dyes within the d-EPSSS_{C6} we considered LR 305 luminescent dye, which absorbs green light (with a peak wavelength of 575 nm) and emits red light (with a peak wavelength of 620 nm) [5, 41- 44]. Furthermore, it is assumed that the dye radius is $\sim 10 \text{ nm}$, the fluorescence lifetime is $\sim 6 \text{ ns}$, and the solar photon flux of green light in the vicinity of 575 nm that the dye is required to absorb is $\sim 4 \times 10^{20} / \text{s} \cdot \text{m}^2$ [44, 45]. It is also assumed that the density of the luminescent dye solution is equal to that

of its host matrix (e.g. glass or PMMA) and that the dye is 0.1 wt% of the volume it occupies, such that self-quenching or agglomeration effects are negligible [46].

To investigate the effects of the spatial distribution of the luminescent dye on the optical emission losses, we calculate the losses for luminescent point sources located in a three-dimensional grid array. The position of the point sources (x,y,z) in the grid array, with the focal point situated at the origin, is given as a combination of x , y , and z points that have the following values:

$$x = \pm n_x \cdot 0.4 \text{ mm}; \quad y = \pm n_y \cdot 0.4 \text{ mm}; \quad z = \pm n_z \cdot 0.1 \text{ mm}; \quad n_x, n_y, \text{ and } n_z = 0, 1, 2, 3, \dots$$

where z represents the direction along the axis of the d-EPSSS_{C6}.

To determine the emission losses as a function of the volume occupied by the dye we rank the points (at position x,y,z) in increasing order of the amount of light lost when emitted from a dye located at that point.

In previous work LSCs have been modeled using Monte Carlo ray-tracing methods [47-50]. Herein we model the optical path, emission losses and optical efficiency for light emitted within the d-EPSSS using COMSOL Multiphysics software (version 5.4) ray optics and heat transfer modules supplemented with MATLAB for analytical analysis. The number of rays emitted from each point source is 10^6 , the maximum mesh size is kept to one-thousandth of the focal distance, and maximum relative tolerance for convergence is 10^{-5} .

2.5.2 Results and discussion for estimating the volume occupied by the luminescent dye and related optimal efficiency.

Based on the assumptions reported in Section 2.5.1 it is estimated that the volume required to host a sufficient amount of LR 305 Luminescent dye in d-EPSSS_{C6} is $\sim 2 \text{ mm}^3$. The optimal spatial distribution of dye is shown in Fig. 2-4a, where dye molecules are situated at the corners of the grey cubes. As shown in Fig. 2-4b, the emission losses when the luminescent dye is optimally distributed over a 2 mm^3 volume is

6%. The effects of optimally distributing the dye over a 2 mm^3 volume (as opposed to assuming all the dye is situated at the shared focal point of the d-EPSSS) on the emission losses is discussed subsequently.

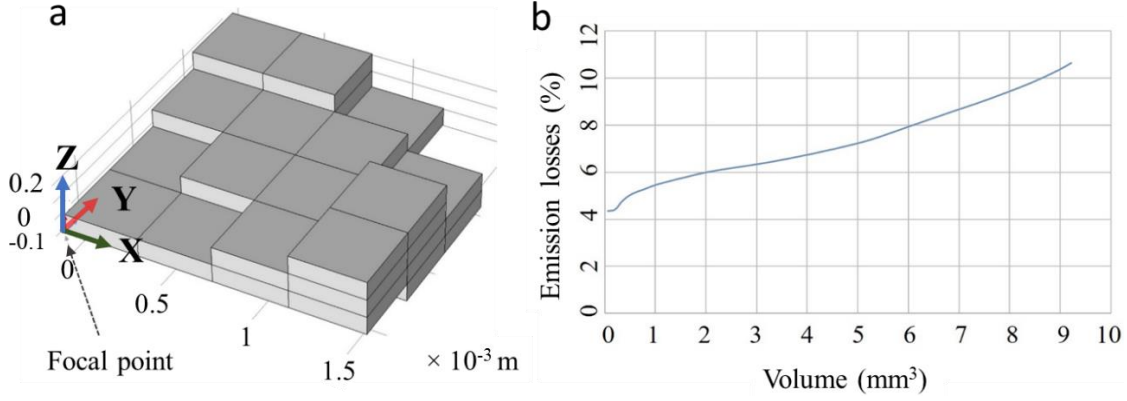


Figure 2-4 a) Optimum distribution of luminescent dye for the case in which a volume of 2 mm^3 is required to host a sufficient amount of dye. Each cube in the array occupies a volume of 0.016 mm^3 . The volume, which has rotational symmetry about the z-axis, is shown for the $x > 0, y > 0$ quadrant; b) Emission losses as a function of the volume optimally occupied by the luminescent dye in the vicinity of the d-EPSSS_{C6} focal point.

The percentage of radiation emitted from the dye that is lost through the exit and entrance ports as a function of the displacement of the dye from the focal point of the d-EPSSS_{C6} with $L = 8.84 \text{ cm}$, $O = 9 \text{ mm}$ and $W = 4.09 \text{ cm}$ is shown in Fig. 2-5. The emission losses and spatial intensity distribution of radiation incident onto the annular PV cell from dye molecules that are offset from the focal point in the X-Y plane are shown in Figs. 2-5a and 2-5b I-III, respectively; the emission losses for a dye-offset by $r = 1, 2$, and 3 mm is 5.81, 12.4 and 21%, respectively. The emission losses and intensity distribution of radiation incident onto the annular PV cell as a function of dye displacement in the X-Y and Y-Z planes are shown in Figs. 2-5c and 2-5b IV-IX, respectively. Notably, while displacing the dye from the focal point in the x-y plane increases emission losses, light emitted from these displaced dye molecules is more evenly distributed on the surface of the annular PV cells, which is beneficial for achieving high conversion efficiencies [51, 52].

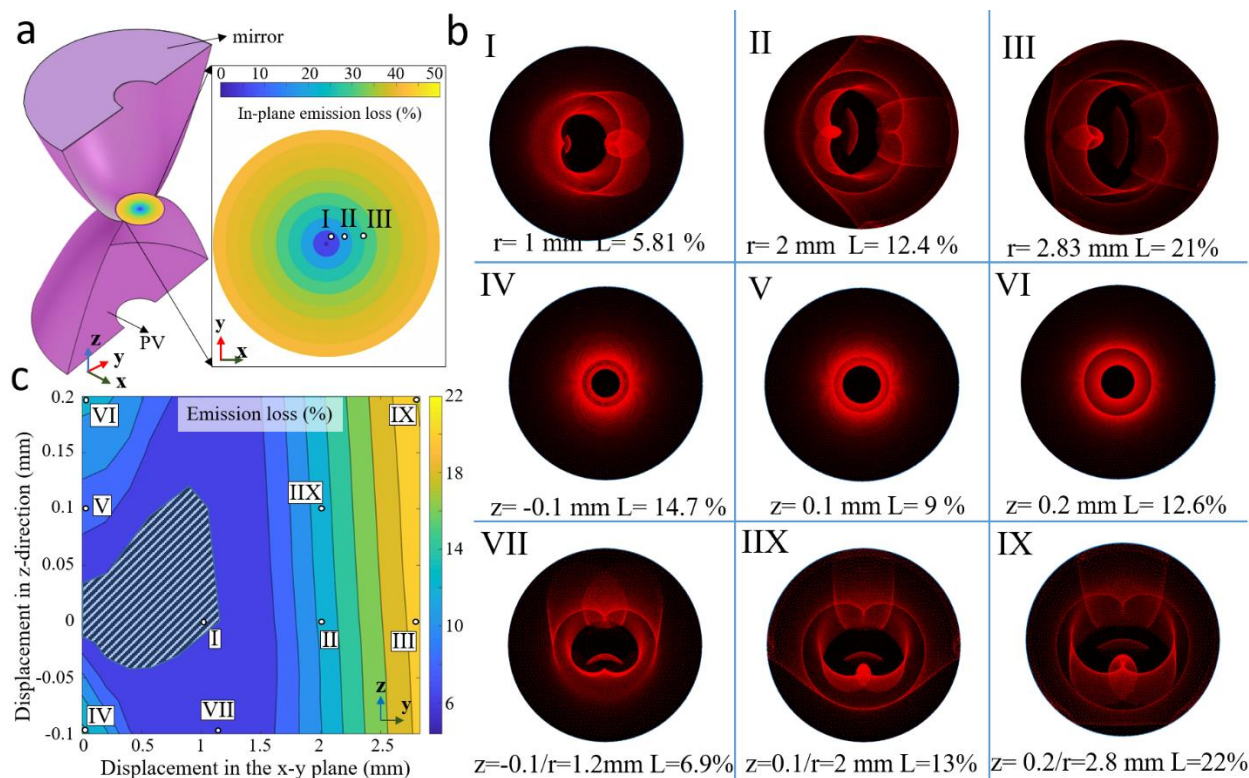


Figure 2-5 a) A cross-sectional diagram of the spectral-splitting solar concentrator with an inset showing the radiation loss percentage as a function of the in-plane displacement of the luminescent dye from the focal point. b) The intensity distribution of radiation incident onto the annular PV cell from dye molecules that are displaced in the radial and vertical directions by a distance of r , and z , respectively. The percentage of light emitted from dye molecules located at (r, z) that is lost, L , is also provided. c) The percentage of radiation lost as a function of the displacement of the dye molecule from the focal point in both the vertical and in-plane directions.

The 2 mm^3 volume required to host the dye in d-EPSSS_{C6} is indicated as the region shaded with blue stripes in Fig. 2-5c and, considering the luminescent dye occupies this volume, the geometric concentration factor and optical emission losses are 40 and 6%, respectively. In comparison, the emission losses for a planar LSC with an index of refraction of 1.49 are ~25%, however, as described in the following section, to estimate the overall efficiency of the d-EPSSS_{C6} a complete set of loss mechanisms must be considered.

2.6 Evaluating the optical efficiency of the dual-elliptic paraboloid solar spectrum splitter using the concentration factor

2.6.1 Methods for estimating the optical efficiency of the dual-elliptical paraboloid solar spectrum splitter

The overall efficiency of the d-EPSSS_{C6} is evaluated using the concentration factor (C), which is defined as the light intensity incident onto the annular PV cells (Φ_2) divided by the light intensity incident onto the non-imaging solar concentrator (Φ_1): $C = \Phi_2/\Phi_1$. The concentration factor can be rewritten as $C = G \cdot \eta_{non-PAR-opt}$, where G is the geometrical gain factor and $\eta_{non-PAR-opt}$ is the optical efficiency of the d-EPSSS_{C6} for the incident non-PAR spectrum which is given as [53]:

$$\eta_{non-PAR-opt} = \eta_{Fresnel} \cdot \eta_{non-PAR-Abs} \cdot \eta_{PLQY} \cdot \eta_{Stokes} \cdot \eta_{Emission} \cdot \eta_{Roughness} \cdot \eta_{Transmission} \cdot \eta_{self-abs}. \quad (2.5)$$

where $\eta_{Fresnel}$ is the efficiency with which incident light is coupled into the d-EPSSS_{C6}, rather than being reflected from the surface. If the d-EPSSS_{C6} is made from a material with an index of refraction of $n = 1.49$ then $\eta_{Fresnel} \sim 96\%$. $\eta_{non-PAR-Abs}$ is the efficiency with which the incident non-PAR is absorbed by the luminophores. We assumed a sufficient amount of Lumogen Red 305 resides in the d-EPSSS_{C6} (~ 100 ppm) such that 100% of the non-PAR in the spectral region of ~ 500 to ~ 600 nm is absorbed. η_{PLQY} is the photoluminescence quantum yield defined as the ratio between the number of photons emitted and absorbed by the luminescent dye. In this study, for LR 305 luminescent dye, it is assumed that $\eta_{PLQY} = 0.95$ [53]. η_{Stokes} is the energy lost through molecular vibrations and heat generation during the absorption and emission event which is assumed to be $\eta_{Stokes} = 95\%$ for Lumogen Red 305 [53]. However, in this analysis we set $\eta_{Stokes} = 1$ because as long as the photons incident onto the c-Si PV cell have energy greater than its band-gap, which is 1.1 eV, the amount of energy these photons contribute to the output current is independent of the Stokes shift. $\eta_{Emission}$ is the efficiency with which the LSC “traps” the light re-emitted from the luminophores. As discussed previously with reference to Figs. 2-4 and 2-5, emission losses for the d-EPSSS_{C6} are 6%, and thus $\eta_{Emission} = 94\%$. In comparison the emission losses and $\eta_{Emission}$ for a planar LSC

with an index of refraction of 1.49 are ~26% and ~74%, respectively. $\eta_{\text{Roughness}}$ represents the efficiency with which TIR occurs. That is, a fraction of light that undergoes TIR at a smooth surface may be emitted from the LSC if the surface is not perfectly smooth. These emission losses increase with increasing surface roughness. In practice, emission losses in a LSC due to surface scattering can be described using the expression $(1-D)^N$, where D is the probability that a photon is scattered out of the LSC host matrix for a single collision and N is the number of collisions with the LSC surface [54]. In this study, for the specific case of d-EPSSSC₆, D and $\eta_{\text{Roughness}}$ are assumed to be 0.03 and 94%, respectively. $\eta_{\text{Transmission}}$ is the efficiency with which photons emitted from the luminescent dye are transported through the LSC without being absorbed by the host material. The transmission efficiency is governed by the Lambert-Beer law:

$$\frac{I_{\text{out}}}{I_{\text{in}}} = e^{-\alpha l} \quad (2.6)$$

where α is the material absorption coefficient of the medium hosting the luminophore and l is the optical pathlength from the dye molecules to the PV cells. Assuming the hosting matrix in the d-EPSSSC₆ is PMMA, $\alpha = 5 \times 10^{-3} \text{ cm}^{-1}$ for $\lambda = 620 \text{ nm}$ [55], which is the emission peak wavelength of the luminescent dye, the transmission efficiency for d-EPSSSC₆ is $\eta_{\text{Transmission}} = 90.8\%$. $\eta_{\text{self-abs}}$ is the efficiency with which reemitted light can be transported through the d-EPSSSC without being absorbed by other luminophores. Self-absorption is a consequence of the spectral overlap between the emission and absorption spectra of the luminescent dye. Denoting the emission spectrum by $F(\lambda)$ and the absorbed spectrum by $A(\lambda)$, the self-absorption cross section, σ_{SA} , for an optical path length of 1 cm is quantified as [56]:

$$\sigma_{\text{SA}} = \frac{1}{b} \int_0^\infty F(\lambda) A(\lambda) d\lambda \quad (2.7)$$

$$\text{where } b = \int_0^\infty F(\lambda) d\lambda \quad \text{and} \quad [\sigma_{\text{SA}}] = \frac{1}{\text{cm}} \quad (2.8)$$

As can be seen from Equation 2.7, self-absorption losses decrease significantly as the Stokes shift increases. Considering self-absorption losses, the corrected Photoluminescent Quantum Yield (PLQY_{corr}) can be calculated from the observed PLQY using Equation 2.9 [46]:

$$PLQY_{\text{corr}} = \frac{PLQY_{\text{obs}}}{1 - a + aPLQY_{\text{obs}}} \quad (2.9)$$

Where a is the self-absorption coefficient. As can be seen from Equation 2.9, if the quantum yield of luminescent dye is close to 1 (~ 0.95 for Lumogen Red 305), then self-absorption can be neglected for the d-EPSSS_{C6}.

2.6.2 Results and discussion of estimating the optical efficiency and concentration factor of the dual-elliptical paraboloid solar spectrum splitter.

Considering all loss mechanisms and efficiencies as described by Equation 2.5, the non-PAR optical efficiency and concentration factor for d-EPSSS_{C6} are $\eta_{\text{non-PAR-opt}} = 73\%$ and $C = 29.2$, respectively. In comparison, a conventional planar LSC with a thickness of 1 cm under the same area of solar irradiance (0.2 m^2) has an optical efficiency and concentration factor of $\eta_{\text{non-PAR-opt}} = 39\%$ and $C = 4.9$, respectively. Before estimating the amount of electric power that can be generated using the d-EPSSS_{C6} in Section 2.7 we perform a thermal analysis in the next section to consider the effects of elevated operating temperatures on the performance of d-EPSSS_{C6}.

2.7 Thermal analysis

2.7.1 Methods used to perform the thermal analysis.

Solar irradiance absorbed in PMMA-based d-EPSSS generates thermal energy that causes its temperature to rise. Thus, another important point to consider is the performance of the d-EPSSS_{C6} at elevated operating temperatures, as the absorption and emission efficiency of luminescent dyes are known to degrade as temperatures increase [57]. To evaluate any potential deleterious thermal effects on the performance of the luminescent dye we use COMSOL Multiphysics software to simulate the temperature distribution throughout the d-EPSSS_{C6}. In this simulation optical power transmission, governed by the Lambert-Beer law (Equation 2.6), is coupled with heat transfer equations. Solar radiation with an intensity of 1000 W/m^2 received over an area of 0.2 m^2 is concentrated and collimated prior to being directed into the entrance port

at the top of the d-EPSSS. We considered d-EPSSS_{C6} with a length, width and opening of 8.84 cm, 4.09 cm and 0.9 cm, respectively, and assumed it is made of partially fluorinated/perfluorinated PMMA or N-BK7 glass with an effective attenuation of $\alpha = 2 \times 10^{-3} \text{ cm}^{-1}$ over the incoming solar spectrum. The heat generated due to the Stokes shift between the light absorbed and emitted by Lumogen Red 305 is determined to be 0.137 W/m^2 . This is modeled by putting a thermal source within the d-EPSSS_{C6} with the material properties similar to that of PMMA and the given volume of 2 mm^3 as stated in section 2.5.2. The heat is generated uniformly throughout this volume. The heat generated from these two sources is modeled and simulated separately, and then based on superposition principle the results are summed. It should be noted that the refractive index is also a function of temperature. However, the changes in index of refraction caused by temperature changes are assumed to be negligible and have not been taken into consideration. The validation for this assumption is given in the next section.

2.7.2 Results and discussion for the thermal analysis

The temperature distribution throughout the d-EPSSS_{C6} under operating conditions is shown in Fig. 2-6. The temperature of d-EPSSS_{C6} increases from room temperature to a maximum temperature of $\sim 330 \text{ K}$ at the region where the luminescent dye resides. The initial consequence of this temperature increase is that the absorption efficiency of the luminescent dye is expected to decrease by $\sim 20\%$. However, over time the absorption efficiency of the dye will partially recover [57], and the long-term effects of elevating temperatures to $\sim 330 \text{ K}$ are expected to be insignificant. Furthermore, different techniques can be used to significantly decrease the attenuation coefficient of the host matrix to mitigate the thermal effects associated with high absorption levels. These techniques include fluorination and perfluorination [58, 59], and modifying the host medium by adding copolymers or fluoroacrylate [60]. Alternatively, different types of transparent solid host materials such as N-BK7 glass and low-OH fused silica optical fibers can be used to decrease the attenuation coefficient [61, 55].

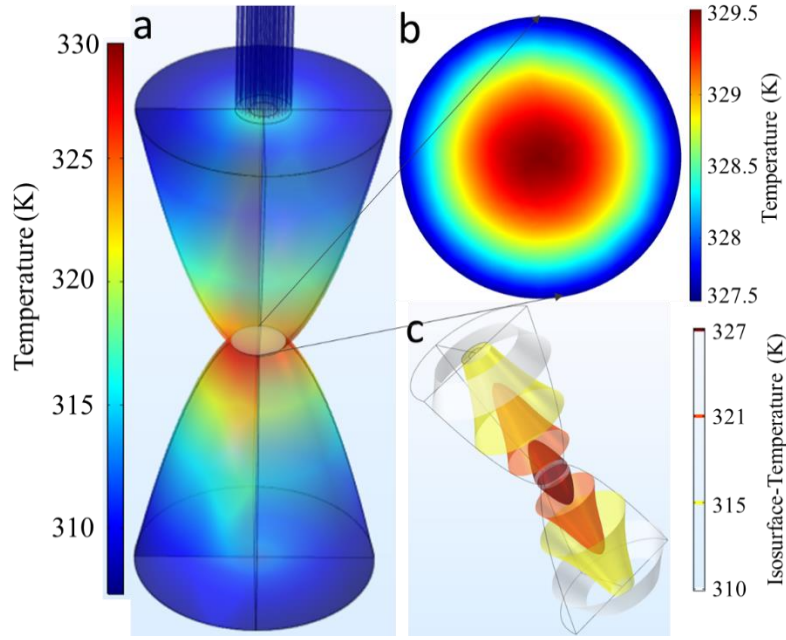


Figure 2-6 a) temperature distribution on the surface of d-EPSSSc₆ under operating conditions; b) temperature distribution on the planar cross-section through the focal point and (c) four isothermal surfaces within d-EPSSSc₆ under operating conditions. (The heat transfer coefficient from the surface of d-EPSSSc₆ to the surrounding region is assumed to be $h = 10 \text{ W/m}^2\cdot\text{K}$).

It can also be noted that the upper and lower surface of the d-EPSSSc₆ shown in Fig. 2-6 reach a temperature of $\sim 310 \text{ K}$, while the ambient temperature is assumed to be 300 K . The efficiency of Si PV cells generally decreases with increasing temperature. The affect of this increase in temperature by 10 K is expected to reduce the efficiency of Si PV cells by less than 1% [62] and this has not been taken into consideration in this work. Moreover, the temperature of the PV cells is expected to be lower than that of the upper and lower surface temperatures of the d-EPSSSc₆ due to thermal contact resistances and insulation provided by glass that would cover the PV cells.

The increase in temperature can also cause a change in the refractive index of the host matrix. For PMMA the following equation is used for the refractive index as a function of temperature ranging from 0 to 140°C [63, 64]:

$$n(T) = n_0 + a \cdot T + b \cdot T^2 \quad (2.10)$$

$$n_0 = 1.49538, \quad a = -0.000115, \quad b = -5.17358 \times 10^{-7}$$

When the temperature of a PMMA-based optical cavity reaches from ambient temperature (25 °C) to maximum of 55 °C (Fig. 2-6), the refractive index decreases from 1.492 to 1.488. This verifies the assumption that the small change in refractive index can be neglected.

2.8 Estimating the electric power generated by the dual-elliptical paraboloid solar spectrum splitter

2.8.1 Methods for estimating the electric power generated by the dual-elliptical paraboloid solar spectrum splitter.

To estimate the amount of electric power generated during operation we consider d-EPSSSC₆. As mentioned before, the structure has $L = 8.84$ cm, $O = 9$ mm and $W = 4.09$ cm. It is assumed that the power provided by the non-PAR spectral regions from ~ 280 - 400 nm ($\Delta W_1 = 45$ W/m²), ~ 500 - 600 nm ($\Delta W_2 = 152$ W/m²) and ~ 740 - 900 nm ($\Delta W_3 = 161$ W/m²) can be absorbed in d-EPSSSC₆ and converted to electricity. In order to calculate the optical efficiencies for ΔW_1 and ΔW_3 , a similar approach that was used for ΔW_2 is implemented. To harvest the UV region (ΔW_1), highly efficient rare earth complexes such as Eu(TTA)₃(TPPO)₂ and Eu(AP)₃, or an acene compound and a benzothiadiazole compound, or nanocluster phosphors can be used [65-70]. In the optimal scenario, the non-PAR optical efficiency over the spectral region from ~ 280 - 400 nm, $\eta_{\Delta W_1\text{-non-PAR-opt}}$, is 30%. To harvest the IR region (ΔW_3), ytterbium chelates, cyanine and cyanine-like dyes, and near-infrared fluorescein dyes containing a tricoordinate boron atom can be used [71-73]. For the best-case scenario the non-PAR optical efficiency in the spectral region from ~ 740 - 900 nm, $\eta_{\Delta W_3\text{-non-PAR-opt}}$, is 65%.

Here we assume the non-imaging solar concentrator has a projected area of $A = 0.2$ m² and the photobioreactor is cylindrical with a top surface area of 0.2 m² and a height of 1 m. It is also assumed that

the photon flux incident onto the c-Si PV cell at the bottom side of d-EPSSSc₆ for these spectral regions are $\Phi_{\Delta W1} = 8.5 \times 10^{15} \text{ cm}^{-2} \cdot \text{s}^{-1}$, $\Phi_{\Delta W2} = 4.15 \times 10^{16} \text{ cm}^{-2} \cdot \text{s}^{-1}$ $\Phi_{\Delta W3} = 6.55 \times 10^{16} \text{ cm}^{-2} \cdot \text{s}^{-1}$.

Moreover, we assume the PV cells have an External Quantum Efficiency (EQE) of $EQE^*_{\Delta W^*1} \cong 95\%$, $EQE^*_{\Delta W^*2} \cong 85\%$ and $EQE^*_{\Delta W^*3} \cong 80\%$, for light that is absorbed by the dye in spectral regions ΔW_1 , ΔW_2 and ΔW_3 , and reemitted in spectral regions ΔW^*_1 , ΔW^*_2 and ΔW^*_3 , respectively [74-76]. Under these assumptions, the short circuit current (I_{sc}), open circuit voltage (V_{oc}) and the maximum output power (P_{max}) generated by the PV cell are calculated using Equations 2.11, 2.12 and 2.13, respectively [77]:

$$I_{sc} = A \cdot q \cdot \left(\int_{\Delta W1} \eta_{\Delta W1_non_PAR_opt} \cdot \Phi_{\Delta W1}(\lambda) \cdot EQE^*_{\Delta W^*1}(\lambda) \cdot d\lambda + \right. \\ \left. \int_{\Delta W2} \eta_{\Delta W2_non_PAR_opt} \cdot \Phi_{\Delta W2}(\lambda) \cdot EQE^*_{\Delta W^*2}(\lambda) \cdot d\lambda + \right. \\ \left. \int_{\Delta W3} \eta_{\Delta W3_non_PAR_opt} \cdot \Phi_{\Delta W3}(\lambda) \cdot EQE^*_{\Delta W^*3}(\lambda) \cdot d\lambda \right) \quad (2.11)$$

$$V_{oc} = \frac{nkT_{PV}}{q} \ln \left(\frac{I_{sc}}{I_0} + 1 \right) \quad (2.12)$$

$$P_{max} = I_{sc} \cdot V_{oc} \cdot FF \quad (2.13)$$

Where $n = 1$ is the ideality factor, k is Boltzmann's constant, $T_{PV} = 300 \text{ K}$ is the cell temperature, $I_0 = 10^{-10}$ A is the dark saturation current, q is the charge of an electron, and FF is the fill factor which can be expressed as a function of open-circuit voltage (V_{oc}) [77]:

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \quad (2.14)$$

where

$$v_{oc} = V_{oc} \frac{q}{k_B T} \quad (2.15)$$

is a normalised voltage. Equation 2.14 is assumed as an appropriate approximation of the FF when $v_{oc} > 10$.

2.8.2 Results and discussion for estimating the electric power generated by the dual-elliptical paraboloid solar spectrum splitter

Based on Equation 2.13, out of a total of 71.6 W of non-PAR incident in the ΔW_1 , ΔW_2 and ΔW_3 solar spectral regions, 11.32 W can be converted to electric power, representing a total non-PAR to electric power conversion efficiency of 15.81% (where $I_{sc} = 20.02$ A, $V_{oc} = 0.673$ V, and $FF = 0.84$). This 11.32 W of electric power can be used to provide the energy required to power the cultivation and harvesting steps which includes agitation, heating/cooling, aeration, and CO₂ replenishment [78]. For example, given an algae biodiesel volumetric productivity rate of 1 kg/day·m³ in a tubular photobioreactor [79], the photobioreactor shown in Fig. 2-7 would produce 0.2 kg of algae per day. Further, assuming an operation time of 6 hours per day, 340 Wh would be generated for each kilogram of algae produced in the reactor. Thus, the photobioreactor shown in Fig. 2-7 can generate much more energy than the 120 Wh/kg that is consumed for algae cultivation and harvesting in a typical photobioreactor. The power surplus can be used to operate a two-axis solar tracking system (estimated to be ~ 9 Wh) [80] required for operation of the d-EPSSS, and to provide extra PAR to further accelerate algae production. Alternatively, the electricity surplus could be used to power Radio Frequency (RF) techniques for rapid lipid quantification [81], or drive Pulsed Electric Field (PEF) instruments (~ 6 kJ) to directly convert algae to biofuel by bypassing the conventional drying and solvent-based extraction processes [82].

As an example of producing extra algae-based biofuel, this extra power (11.32 W) can be used to operate red LEDs at an intensity of 310 $\mu\text{mol}/\text{m}^2\cdot\text{s}$ over an area of 0.2 m² to illuminate the photobioreactor. Assuming a light absorption coefficient of $\alpha_c = 200$ m²/Kg in the algal solution and a constant algae concentration of $C = 1$ Kg/m³, an optimal productivity (where all the photons emitted are absorbed by microalgae) of 100 $\mu\text{mol}/\text{m}^2\cdot\text{s}$ can be achieved. The additional volume of algae biofuel produced can be calculated from Equations 2.16 and 2.17 [83]:

$$V_{extra} = A_{LED} \cdot l \quad (2.16)$$

$$\bar{I} = \frac{\int_0^l I_i e^{-\alpha_c C l} dl}{l} \quad (2.17)$$

where, $A_{LED} = 0.2 \text{ m}^2$ is the installed area of red LEDs, l is the optical depth from the illumination surface to the depth with the mean light intensity of $\bar{I} = 100 \text{ } \mu\text{mol/m}^2 \cdot \text{s}$ and $I_i = 310 \text{ } \mu\text{mol/m}^2 \cdot \text{s}$ is the initial light intensity. Solving Equations 2.16 and 2.17 shows that an extra 18.6 litres/day algae-based biofuel solution with algae concentration of $C_{algae} = 1 \text{ Kg/m}^3$ can be produced (representing a 9.3% increase in biomass volume productivity) and an additional $\sim 34 \text{ g/day}$ of CO_2 can be bio-fixated (1g of biomass requires 1.804 g of CO_2).

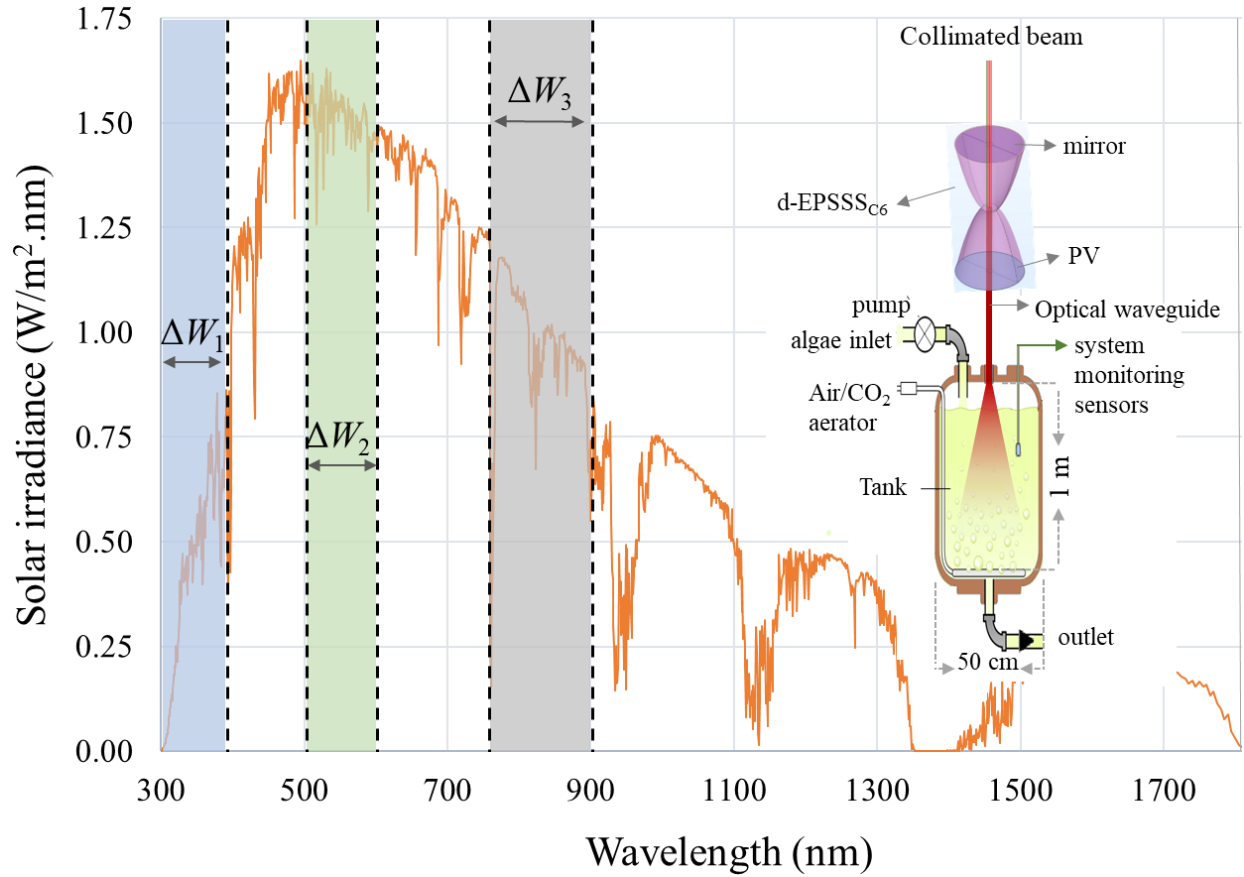


Figure 2-7 non-PAR spectrum utilized by d-EPSSSC₆ to power different components of a tubular photobioreactor shown in faded color bands: $\Delta W_1 = 280\sim 400 \text{ nm}$, $\Delta W_2 = 500\sim 600 \text{ nm}$ and $\Delta W_3 = 740\sim 900 \text{ nm}$.

It can be noted that in determining the extra power provided from using the d-EPSSS (11.32 W) it was assumed that the mirror used at its upper surface reflected 100% of the light incident onto its surface. If it was assumed that a Silver mirror is coated on the top side of the d-EPSSS, which has a reflectivity of 97% from 400 to 900 nm (the range of emission wavelengths related to ΔW_1 , ΔW_2 , ΔW_3) [84], the emission losses would decrease by only ~1%.

2.9 Discussion

In this chapter a luminescent solar spectrum splitter shaped in the form of two oppositely facing elliptic paraboloids (referred to as d-EPSSS) with reduced emission losses as compared to a conventional planar LSC is presented. That is, the d-EPSSS exhibits minimal emission losses, on the order of ~6% in a practical design, as compared to emission losses of ~25% in a conventional flat-panel LSC. Furthermore, in comparison to a conventional planar LSC, optical surface scattering and absorption losses are smaller in the d-EPSSS because radiation emitted at its focal point is internally reflected from its surface only once (minimizing scattering losses) and directed towards PV cells, thereby minimizing its path-length (and related absorption losses).

The ability to use the d-EPSSS to partition the solar irradiance into its PAR and non-PAR spectral components to simultaneously power algae-based biofuel cultivation systems and PV cells, respectively, was investigated. Numerical analysis shows that when operating in conjunction with a high numerical aperture fibre optical collimator and a two-stage non-imaging solar concentrator such as a Cassegrain structure that receives solar radiation over a projected planar area of 0.2 m², the d-EPSSS can be designed to achieve a geometrical gain factor, concentration factor, and optical efficiency of 40, 29.2, and 73%, respectively, while the emission losses are less than 6%.

Using LSCs to separate non-PAR from PAR has been reported in the literature [10, 85]. For comparison, we performed numerical analysis showing that a conventional LSC has a geometrical gain factor of 12.6, a concentration factor of 4.9, and an optical efficiency of 39% under similar solar irradiance conditions. The

caveat for this comparison is that the LSC provides both the spectral-splitting and solar concentration functions, whereas the d-EPSSS only functions as a solar spectrum splitter, and must work in conjunction with a collimator. Nevertheless, assuming a collimator with an efficiency of 71% [29] the optical efficiency of a system comprised of both the d-EPSSS and the collimator is 52%, which is still a significant improvement over the LSC. The collimator increases system complexity and cost, but provides additional benefits. Algae growth is often limited by photoinhibition, but collimated light can be efficiently distributed in a photobioreactor through light guides to alleviate the affects of photoinhibition [86-88]. Furthermore, the collimated beam allows for ‘light-piping’; a thin light guide can bring light into a building to run algae-based indoor oxygen production and air purification systems [89] or into a spacecraft for bioregenerative life support systems [90]. Future work requires experiments to validate the results and optimization of a complete system, including light distribution in a photobioreactor.

2.10 Conclusions

Microalgae has potential for large-scale biofuel production, CO₂ remediation, and oxygen production. However, its growth is energy intensive and easily hindered by contamination, unsuitable environmental conditions, and photosaturation. To mitigate these problems the solar irradiance can be partitioned into PAR and non-PAR. The PAR can be used for algae growth in a photobioreactor under controlled conditions. The non-PAR can be used to generate electricity in photovoltaic (PV) cells which could provide for agitation, thermoregulation, CO₂ replenishment, and enhanced illumination in a photobioreactor. In designing systems that use sunlight for simultaneous algae and electric power production it is worth noting the upper limit on the amount of electricity that can be generated from the non-PAR portion of the solar spectrum. In this work the Shockley-Queisser efficiency limit for the non-PAR from the AM1.5 solar spectrum is determined to be 24% for a single junction PV cell. For the non-PAR portion of the AM0 spectra, which is relevant for space exploration applications, the Shockley-Queisser limit is 22%. In this work numerical analysis of a luminescent solar spectrum splitter in the form of two oppositely facing elliptical paraboloids shows that collimated light can be partitioned into PAR and non-PAR with minimal emission losses. The solar spectrum

splitter enables conversion of non-PAR to electric power at a conversion efficiency of 15.8% and provides efficient utilization of space and available solar radiation, and high net energy gain ratios. They can potentially be utilized as a key component in self-powered photobioreactors with applications for air purification highly-populated urban areas and bioregenerative life-support systems for space exploration applications.

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3 Elliptic array luminescent solar concentrators for combined power generation and microalgae growth¹

Nomenclature		T	temperature
<i>Roman symbols</i>		T_{m1}	mean traveling time for photons in a conventional LSC
		T_{m2}	mean traveling time for photons
		V_{OC}	open circuit voltage
		<i>Greek symbol</i>	
A	area	α	material absorption coefficient
$A(\lambda)$	luminophore absorption spectrum	θ	Light propagation angle
a	semi-major axis of an ellipse	ΔW_1	spectral region from 500 ~ 600 nm
a_s	self-absorption coefficient	ΔW_2	spectral region from 740 ~ 1100 nm
b	semi-minor axis of an ellipse		
c	distance between the focal point and centre of an ellipse	$\eta_{Emission}$	emission efficiency
C	concentration factor	$\eta_{Fresnel}$	incident light coupling efficiency
D	probability of a photon to scatter	$\eta_{non-PAR-Abs}$	non-PAR absorption efficiency
E_g	bandgap energy	$\eta_{non-PAR-opt}$	non-PAR optical efficiency
$F(\lambda)$	luminophore emission spectrum	η_{PLQY}	photoluminescence quantum yield
FF	fill factor	$\eta_{Roughness}$	surface roughness efficiency
G	geometric gain factor	$\eta_{self-abs}$	self-absorption efficiency
h	height	η_{Stokes}	Stokes shift efficiency
I_0	dark saturation current	$\eta_{Transmission}$	transmission efficiency
I_{in}	input light intensity	θ_p	solar half-angle
I_n	normalized intensity	λ	wavelength
I_{out}	output light intensity	σ_{SA}	self-absorption cross section
I_{SC}	short circuit current	Φ_1	light intensity incident onto the nonimaging solar concentrator
k	Boltzmann's constant	Φ_2	light intensity incident onto the annular PV cells
l	optical pathlength	$\Phi_{\Delta W1}$	photon flux of ΔW_1
N	the number of photon collisions with surface	$\Phi_{\Delta W2}$	photon flux of ΔW_2
n_1	refractive index of the external medium	Φ_{out}	output energy flux
n_2	refractive index of the internal medium	Φ_{in}	input energy flux
O	width of the optical receiver port		
OD_{EASSS}	optical density for the EASSS		
OD_{LSC}	optical density for planar LSC		
q	charge of an electron		

¹ This chapter is based on references [56, 57]

3.1 Abstract

Full utilization of the broadband solar irradiance is becoming increasingly useful for applications such as long-term space missions, wherein power generation from external sources and regenerative life support systems are essential. Luminescent solar concentrators (LSC) can be designed to separate sunlight into photosynthetically active radiation (PAR) and non-PAR to simultaneously provide for algae cultivation and electric power generation. However, the efficiency of LSCs suffers from high emission losses. This chapter shows that by shaping the LSC in the form of an elliptic array, rather than the conventional planar configuration, emission losses can be drastically reduced to the point that they are almost eliminated. Numerical results, considering the combined effects of emission, transmission and surface scattering losses show the optical efficiency of the elliptic array LSC is 63%, whereas in comparison the optical efficiency for conventional planar LSCs is 47.2%. Further, results from numerical simulations show that elliptic array luminescent solar concentrators can convert non-PAR to electric power with a conversion efficiency of ~17% while transmitting PAR to an underlying photobioreactor to support algae cultivation.

3.2 Introduction

Human space exploration endeavours include returning to the moon, extended duration crew missions, and occupying mars [1-3]. These ambitious missions will require re-generative environmental control and life support systems (ECLSS). Further, it will not be possible to bring an energy source that can supply the power required for the duration of the mission and onboard energy conversion systems that utilize energy sources available in space will be needed. Regarding ECLSS for long-term space missions, microalgae cultivation has been investigated as a promising solution owing to its potential to regenerate O_2 from CO_2 , high growth-rates, and ability to close the carbon loop by providing a source of food [4-6]. Indeed, in the Photobioreactor at the Life Support Rack (PBR@LSR) experiment an advanced microalgae photobioreactor (PBR) utilizes concentrated CO_2 from a life support rack onboard the International Space Station [7]. Onboard power generation for spacecrafts operating in the inner solar system is often achieved using

photovoltaic (PV) solar panels to convert sunlight into electricity. In this work we are interested in the potential use of luminescent solar concentrators (LSCs) that focus sunlight onto PV cells located at their sidewalls for space applications. LSCs are particularly interesting because in addition to concentrating sunlight they can also function as a solar spectrum splitter that separates PAR from non-PAR. Our objective is to design a LSC that splits the solar radiation to simultaneously provide for electric power generation and microalgae cultivation using non-PAR and PAR, respectively. The ability to provide multiple functions is highly valuable for mass and volume conservation on spacecrafts. Further, using LSCs for PV operation in space can offer additional benefits. For example, small PV cells are located at the edges of the LSC where they can be shielded from harmful radiation [8], and it has been predicted that specific power values greater than 1 kW/kg can be achieved by using LSCs in space [9]. However, the efficiency of LSCs suffers from emission losses, whereby a large fraction of light emitted from the dye within the LSC panel exits the structure rather than being directed towards the edges of the LSC via total internal reflection (TIR). LSCs have a planar configuration, although in this work we investigate the ability of using other structures to achieve TIR over a broad range of angles to minimize emission losses. We show that emission losses can be drastically reduced by structuring the LSC in the form of an elliptic array rather than a planar configuration. In this chapter we design and numerically evaluate the performance of elliptic-array LSCs that can operate in tandem with a PBR and use solar energy to simultaneously generate electric power and provide for microalgae cultivation.

3.3 Background

Significant research efforts have been undertaken to explore innovative spectral photon management strategies that optimize algae growth conditions and biofuel cultivation systems [10-15]. For example, Sun et al [16], enhanced microalgae production by embedding hollow light guides in a flat plate PBR made of PMMA. The hollow light guides also induced turbulent flow, promoting microalgae suspension mixing, and the photosynthetic efficiency of microalgae growth in the PBR was increased by 12.52%. Ooms et al [17] demonstrated wavelength specific scattering from plasmonic nano-patterned surfaces as a means of

addressing the challenge of photon management in PBRs. Modular PBRs were constructed with different reflective substrates including arrays of plasmonic nanodisks, and broadband reflectors, and untreated glass and a power efficiency enhancement of 52% was achieved with the plasmonic nanodisk arrays as compared to the case wherein the broadband reflector was used. Furthermore, a 6.5% cyanobacterium growth rate increase was achieved by using a plasmonic substrate in comparison to using a photobioreactor equipped with untreated glass.

As another spectral photon management strategy for optimizing algae-based biofuel cultivation systems, LSCs are one of the most economical and practical options to harvest solar energy because they have the dual-advantage of: (1) concentrating light onto a smaller area (resulting in greater geometrical gain), and (2) splitting the solar irradiance into different spectral regions such that it can be used to simultaneously provide power for multiple applications. A LSC is typically comprised of a transparent panel that hosts luminophore molecules. These luminophores, such as quantum dots or organic dyes, absorb incident solar radiation and use this energy to isotropically emit radiation with a longer wavelength. If the photons are emitted within the critical angle, they will be directed, via TIR, towards PV cells located at the edges of the transparent panel. Incident solar radiation outside the spectral region absorbed by the fluorophores may pass through the panel. This technology can be used in a vast range of applications including green house panels, semi-transparent windows that generate electricity or heat [18], and skylights because the transparency, shape, size and color of the panel are easily controlled [19].

The luminophore embedded within the LSCs can be designed to split the solar spectrum into its PAR and non-PAR components and concentrate the non-PAR onto PV cells located at the LSC sidewalls. Over the course of millions of years, photosynthetic organisms have adopted photo-protection mechanisms to naturally regulate energy flow and minimize energy fluctuations within their photocells [20]. Most photosynthetic organisms reflect green light (non-PAR), which has the maximum photon flux in the solar radiation spectrum, to avoid overheating. Instead, light harvesting antennas within photosynthetic organisms often absorb in the spectral vicinity of blue and red light (PAR) [21]. However, due to several deficiencies

and considerable loss mechanisms, the power conversion efficiency of LSCs is still less than 10%. The main operating mechanisms and loss phenomena in LSC devices are described subsequently with reference to Fig. 3.1 [22].

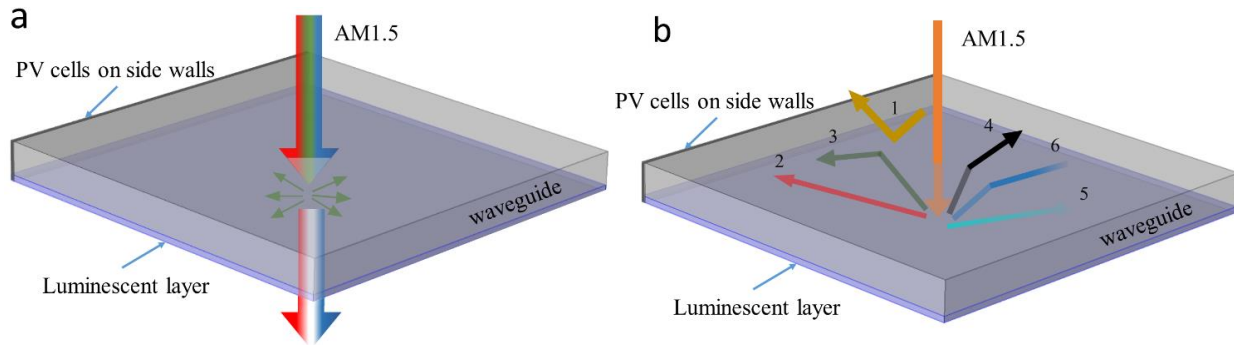


Figure 3-1 a) Mechanism of a LSC as a solar spectrum splitter and solar concentrator and, b) Operation and loss mechanisms in an LSC: 1) Fresnel reflection loss, 2&3) Light guiding of photons emitted outside the escape cone via TIR to PV cells at the sidewalls of the planar waveguide 4) Emission losses of photons emitted within the escape cone, 5) Internal absorption losses, 6) Surface scattering losses at the waveguide/air boundary.

A main reason for low efficiencies in LSCs is transmission losses because a large amount of incident sunlight passes through the panel. Transmission losses occur because luminophore dyes absorb over a small spectral region compared to the spectrally broad solar irradiance. However, this feature makes it possible to use LSCs as semitransparent windows for numerous applications including greenhouses and building facades. Other loss mechanisms include surface reflection loss (which is $\sim 4\%$ for normally incident light), emission losses due to light being emitted at angles less than the critical angle for which TIR occurs, and emission losses due to surface roughness, which increases photon scattering out of the LSC, and internal absorption losses, which includes absorption of light by the host matrix waveguide material and the re-absorption of emitted photons by other dye molecules. Many efforts have been applied to reduce the aforementioned losses in LSCs. Methods of reducing surface losses include fabricating selective mirrors, Bragg reflectors, or plasmonic structures at the LSC surfaces, and aligning the luminophores within the LSC to control the path of the emitted light.

Efforts to reduce internal losses caused by reabsorption include studies on novel organic fluorescent dyes, quantum dots and inorganic phosphors [23]. Correia et al. [24] provided a comprehensive overview about the potentials of lanthanide-based organic-inorganic luminescent dyes in order to increase the performance of LSCs. Meinardi et al. [25] designed and fabricated CdSe/CdS quantum dots that utilize a large Stokes shift to eliminate reabsorption losses in large area LSCs and optical efficiencies exceeding 10% with a concentration factor of 4.4 were achieved. Buffa et al. [26] developed dye-doped polysiloxane rubber waveguides for LSC systems and evaluated the potential of enhancing fluorophore fluorescence efficiency in the presence of different concentrations of Au nanoparticles. Unlike the more common waveguide hosts (e.g. PMMA), polysiloxane rubber is flexible which enables applications in tents, fabrics, sleeping bags, or other such devices that can be rolled up, folded, or otherwise deformed. The first transparent near-infrared (NIR)-absorbing LSC with high transparency was demonstrated by Zhao et al. [27]. In this study they developed luminophore blends of cyanine and cyanine salts and synthesized cyanine salt-host blends with quantum efficiencies greater than 20% accompanied with spectrally selective NIR harvesting. Debije et al. [28] increased the energy output of LSC waveguides by adding white scattering layers to the bottom side of LSCs separated from the waveguide by an air gap. Cambié et al. [29] developed a Monte Carlo ray tracing algorithm to simulate photon paths within LSC-based photomicroreactors and experimentally validated their results. Chou et al. [30] fabricated a flexible waveguiding LSC that exhibits high optical efficiencies and great mechanical flexibility. In this research, a certified power conversion efficiency (PCE) of 5.57%, with a projected PCE as high as approximately 18% was reported. A significant amount of research has also been performed to investigate the performance of LSCs for agrivoltaics, algae cultivation, and greenhouse applications [11, 31-33]. For example, Detweiler et al. [11] fabricated a wavelength selective LSC panel that harnesses the green light portion of the solar irradiance, most of which is not used for algae growth. The LSC panel contains Lumogen Red 305 dye which absorbs and emits green and red light, respectively. The fluorescently emitted red light was either used to enhance algal growth, or waveguided and captured by PV cells to be converted into electricity. The results revealed that microalgae growth rates under the LSC panels were equivalent to growth rates under the full solar radiation spectrum.

Based on Snell's law, all photons emitted from luminescent dyes within a LSC that impinge on the surface of the LSC panel at an angle smaller than the critical angle will be emitted to the surrounding medium, (loss 4 in Fig. 3-1b) which is one of the main loss mechanisms in LSCs. Measurements reveal that the accumulated emission losses, considering secondary absorption and emission events and scattering due to surface rough-ness can reach 50-70% [34]. In this context, all strategies for reducing surface losses are based on two main processes: integrating selective mirrors, and aligning the luminophores to directionally control the emission of light [35, 36]. However, topology-based strategies wherein the shape of the host medium is altered and optimized to reduce emission losses have yet to be explored. In this context, the work presented herein considers the benefits of shaping the medium hosting the dye in an elliptic-based, rather than planar-based, configuration to minimize the absorption and surface (including scattering and cone zone) losses for LSCs. The performance of these novel elliptic-based LSCs is investigated and compared to conventional LSCs for the dual application of simultaneously providing power for algae and PV electricity production systems.

In this study, we present a novel spectral splitting solar concentrator (SSS) with an elliptical configuration that partitions the solar irradiance into its PAR and photosynthetically inactive radiation (non-PAR) spectra to be utilized in microalgae cultivators and PV cells, respectively.

An ellipse can be defined as a curved line that forms a closed loop around two focal points, f_1 and f_2 , with the property that for any point S on the curve, the sum of the distances from f_1 to S and f_2 to S is constant. Moreover, the normal to the curve at any point S on the ellipse bisects the angle between the lines connecting f_1 to S and f_2 to S . As shown in Figure 2a, from a ray-optics perspective, this implies that all light emitted from f_1 (f_2) that is specularly reflected from the internal surface of the ellipse will be directed towards f_2 (f_1) because the angle of incidence θ_1 (θ_2) is equal to the angle of reflection θ_2 (θ_1). In this work we utilize this internal refocusing property of an ellipse to design a LSC panel with minimal optical losses.

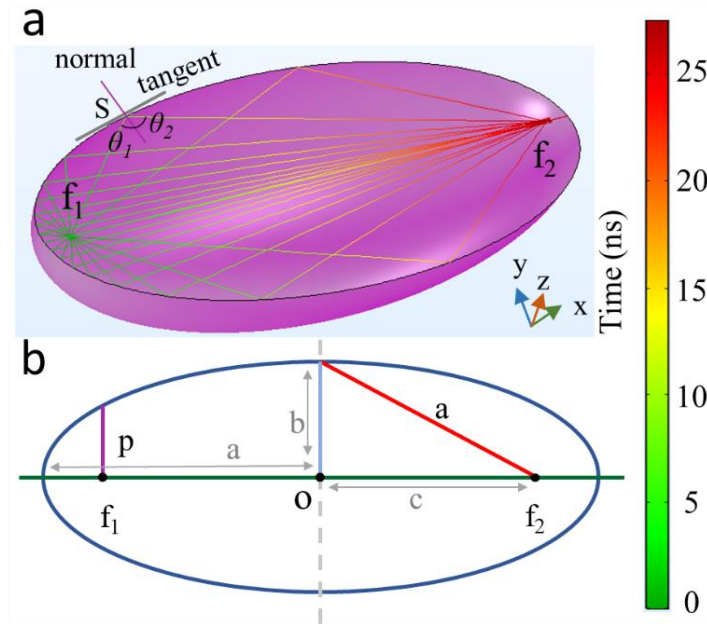


Figure 3-2 a) Cross-section of an ellipsoid as a closed loop curve and, b) the geometrical parameters for an ellipse.

The equation defining an ellipse using Cartesian coordinates is provided in Equation 3.1. Where the center of the ellipse is at the origin, O , and the x -axis is the major axis.

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \quad (3.1)$$

With reference to Figure 2b, the values of p and b are given in Equation 3.2:

$$p = \frac{b^2}{a} \text{ and } b^2 = a^2 - c^2 \quad (3.2)$$

The shape parameters a and b are the semi-major axis and semi-minor axis, respectively. The proposed SSS is composed of an array of unit-cells wherein each unit cell has the shape of two overlapping half-ellipses that share the same focal point as shown in Fig. 3-3. The shared focal point is occupied with concentrated luminescent dye that absorbs non-PAR and re-emits radiation at equal intensity in all directions. Light radiated from the luminescent dye is directed towards the focal points of the adjacent unit cells.

This phenomenon, whereby light emitted from one focal point is refocused at the focal points of adjacent unit cells, is achieved by designing the curvature of the ellipses such that radiation emitted at their shared focal point undergoes TIR at their curved sidewalls. If the medium internal to the SSS, has an index of refraction equal to n_1 and the medium external to the structure is air ($n_{air}=1$) then, according to Snell's law, radiation emitted from the focal point of the overlapped ellipses will undergo TIR at the surface when Equation 3.3 is satisfied:

$$\frac{c}{a} > \tan \left(\sin^{-1} \left(\frac{1}{n_1} \right) \right) \quad (3.3)$$

The minimum value of c/a for which radiation emitted from the focal point of the ellipse will undergo TIR at the ellipse surface is plotted as a function of n_1 (the medium internal to the ellipse) in Fig. 3-3b for the case in which the external medium is air. For example, if the ellipse was made from glass ($n_{glass} = 1.49$), polymer ($n_{high\ refractive\ index\ polymers} = 1.7$) or titanium dioxide ($n_{TiO_2} = 2.5$) the minimum values of c/a that would satisfy the TIR condition defined by Equation 3.3 would be 0.905, 0.727 or 0.436, respectively. Based on the definition of an ellipse $c/a < 1$, which implies that the index of refraction of the medium internal to the ellipse must be 1.41 or greater, as indicated by the red line in Fig. 3-3b, to satisfy the TIR condition if the medium external to the ellipse is air. The inset at the top right in Fig. 3-3b shows five different shapes of ellipses over the range of $0.905 < c/a < 1$. The TIR condition defined by Equation 3.3 for the case in which the internal medium is glass is illustrated in Fig. 3-3c, which shows that radiation emitted from the shared focal point of two overlapping ellipses escapes the SSS structure for values of $c/a < 0.905$; conversely, all rays emitted from the focal point undergo TIR at the surfaces of the glass-based ellipse for the case in which $c/a \geq 0.905$.

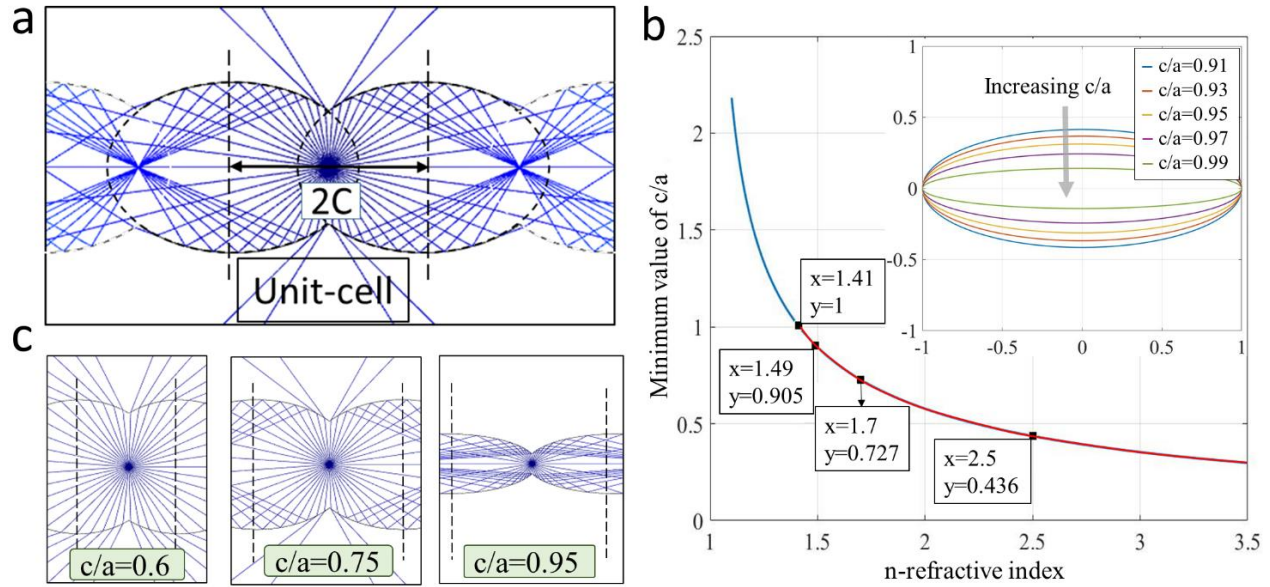


Figure 3-3 a) A unit cell which hosts concentrated luminescent dye at the shared focal point of two ellipses. The width of the unit cell is $2C$. b) The minimum value of c/a for which TIR will occur for radiation emitted from the focal point plotted as a function of the refractive index of the medium internal to the ellipse (assuming the medium external to the ellipse is air), and c) propagation behaviour of radiation emitted from a point source located at the shared focal point of overlapping ellipses for the cases in which the index of refraction of the internal medium is $n = 1.49$ and the ellipse parameters are $c/a = 0.6$, $c/a = 0.75$ and $c/a = 0.95$.

Herein the ellipse-based unit cell shown in Fig. 3-3 is used in the design of a spectral splitting solar concentrating panel that transmits PAR radiation such that it can be used for algae cultivation while absorbing non-PAR incident from the solar irradiance to generate electric power. A cross-section of this panel, in the “X-Y” plane, is shown in Fig. 3-4a, and the shape of this panel is realized in three-dimensions by translating this cross-section in the “Z” direction as shown in Fig. 3-4b. For conciseness, we refer to this panel as an elliptic array solar spectrum splitter (EASSS). Also shown in Fig. 3-4b is an array of Petzval lenses which focuses the incident solar irradiance onto the focal lines within the EASSS. The concentrated light beams coming from the Petzval lens array are incident onto an array of linear receivers (negative lenses) residing on the upper surface of the EASSS which facilitate coupling the incident light onto the focal lines. The incident non-PAR is absorbed by luminophores concentrated along the focal lines within the EASSS while PAR is transmitted and leaves the EASSS through a linear exit port located beneath the focal

line. Radiation from the luminophores, emitted with equal intensity in all directions, is confined within the EASSS via TIR and is directed towards PV cells embedded at the side walls of the EASSS. In this case, luminescent dye absorbs the spectral region from $\sim 500\text{-}600\text{ nm}$ and from $\sim 740\text{-}1100\text{ nm}$ and re-emits photons at wavelengths matched to the single junction PVs at the EASSS side walls. For example, Lumogen Red 305, one of the most commonly used dyes in LSCs, which has an absorption peak of $\sim 580\text{ nm}$ and an emission peak of $\sim 613\text{ nm}$, and CY (a cyanine derivative) with absorption spectra peaks at 742 nm and NIR emission peaks at 772 nm can be utilized. InGaP ($E_g = 1.82\text{ eV}$), single junction Si ($E_g = 1.1\text{ eV}$) and GaSb ($E_g = 0.67\text{ eV}$) solar cells can be used as PV cells at the panel sidewalls to harvest different ranges of the non-PAR spectrum. The portion of the incoming beam not absorbed by the luminescent dye can be used for algae cultivation in a photobioreactor located beneath the EASSS [37-44].

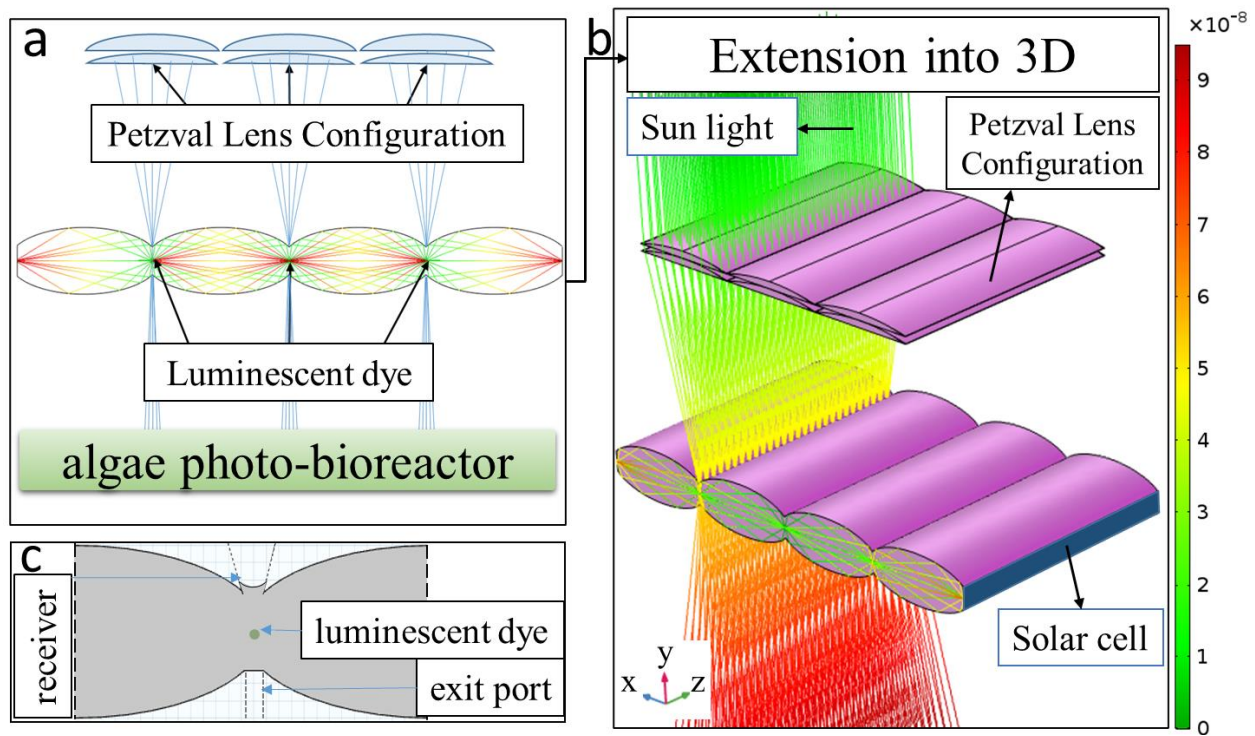


Figure 3-4 a) The proposed configuration of Elliptic Array Solar Spectrum Splitter (EASSS) in 2D; b) extension of the EASSS into 3D and; c) The concept of receiver to couple the incoming concentrated light from Petzvel lens to the luminescent dye area and send out through the exit port.

The EASSS exhibits significant advantages in comparison with conventional LSCs including: (1) minimal emission losses, (2) minimal surface scattering losses and (3) minimal internal absorption losses.

In conventional flat-panel LSCs light emitted within a broad cone does not undergo TIR at the panel surface and emission losses are ~25%. In the EASSS TIR occurs for all light emitted from the focal line with the exception of the light which is emitted onto the receiver or the exit port. As discussed subsequently with reference to Figure 4, the expected emission losses from the EASSS are just a few percent. Surface scattering losses can be estimated using the equation $(1-D)^N$ where D is the surface scattering coefficient and N is the number of ray collisions with the surface of the EASSS. Moreover, the internal absorption losses can be determined using the expression $e^{-\alpha L}$ where α is the absorption coefficient of the internal medium the EASSS is comprised of, and L is trajectory path length of the rays through this internal medium.

In the literature, LSCs are often modeled using Monte Carlo ray-tracing methods [43-45]. Herein we numerically modeled the optical path, emission losses and optical efficiency for light emitted within the EASSS using COMSOL Multiphysics software (version 5.4) ray optics and heat transfer modules supplemented with MATLAB for analytical analysis. The number of rays emitted from each point source was at least 10^6 , the maximum mesh size was kept to one-thousandth of the focal distance, and maximum relative tolerance for convergence was 10^{-5} .

The analysis is performed as follows: Firstly, the EASSS structure without entrance ports (receivers) or exit ports is considered. Specifically, surface scattering losses, in terms of the number of surface scattering events, N , within the EASSS is modeled and analyzed in 2D and compared with that of the conventional flat panel LSC. Then, the absorption losses, in terms of the mean light ray path length, are determined for the EASSS and flat-panel LSC. Subsequently, the effect of structure thickness on the absorption and surface scattering losses are investigated. Afterward, the receivers and exit ports are introduced on the upper and lower sides of the EASSS, respectively. The effect of altering the structure of the receiver on the performance of the EASSS is considered and discussed thereafter. In practice, all the luminescent dye required to absorb the incident non-PAR spectra would occupy a finite volume and could not lie precisely

on the focal lines within the EASSS. In this regards the effects of the finite volume occupied by the dye and the sensitivity of the performance of the EASSS with respect to the displacement of the dye from the focal line is investigated. Furthermore, considering the highly concentrated solar irradiation on the narrow receivers, thermal analysis of the EASSS is carried out. Finally, the optical and power conversion efficiency for a sample case of an EASSS working in conjunction with a photo-bioreactor is analyzed and discussed.

3.4 Results

3.4.1 Surface scattering losses in the elliptic array solar spectrum splitter

The number of scattering events per meter width in the x-direction is plotted as a function of the height ($2b = h$) and c/a ratio of the EASSS in Fig. 3-5. For a constant height of the EASSS structure, as c/a increases the number of unit cells (focal lines) per meter within the EASSS panel decreases and therefore the number of surface collisions decreases, which lowers surface scattering losses. In general, as c/a and h increase surface scattering losses decrease.

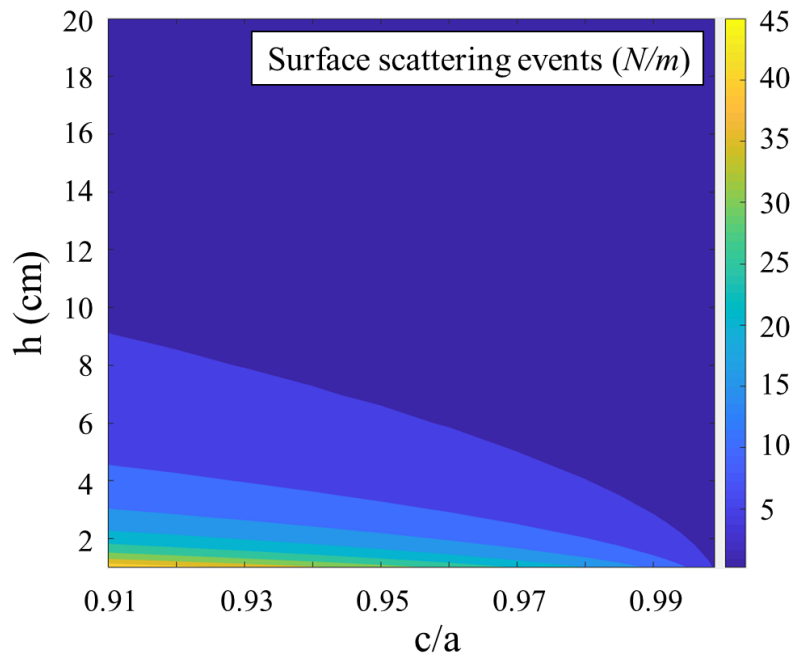


Figure 3-5 Number of surface scattering events per meter, N/m , within an EASSS panel plotted as a function of h and c/a .

The number of surface scattering events per meter in the x-direction is plotted as a function of LSC height for an EASSS with $c/a = 0.91$ and a conventional flat-panel LSC in Fig. 3-6a. Fig. 3-6b shows comparisons of the trajectory of light emitted from a point source located at the center of the EASSS to the trajectory of light emitted from the center of a conventional LSC panel. When the panel height is 2 cm, the number of surface scattering events in the EASSS and conventional LSC panels are $N = 22/\text{m}$ and $N = 55/\text{m}$, respectively. When the panel height is increased to 10 cm, the number of surface scattering events in the EASSS and conventional LSC panels is $N = 4/\text{m}$ and $N = 11/\text{m}$, respectively. Thus, the number of surface scattering events in the EASSS is typically less than half that in the conventional LSC, which helps to minimize surface scattering losses.

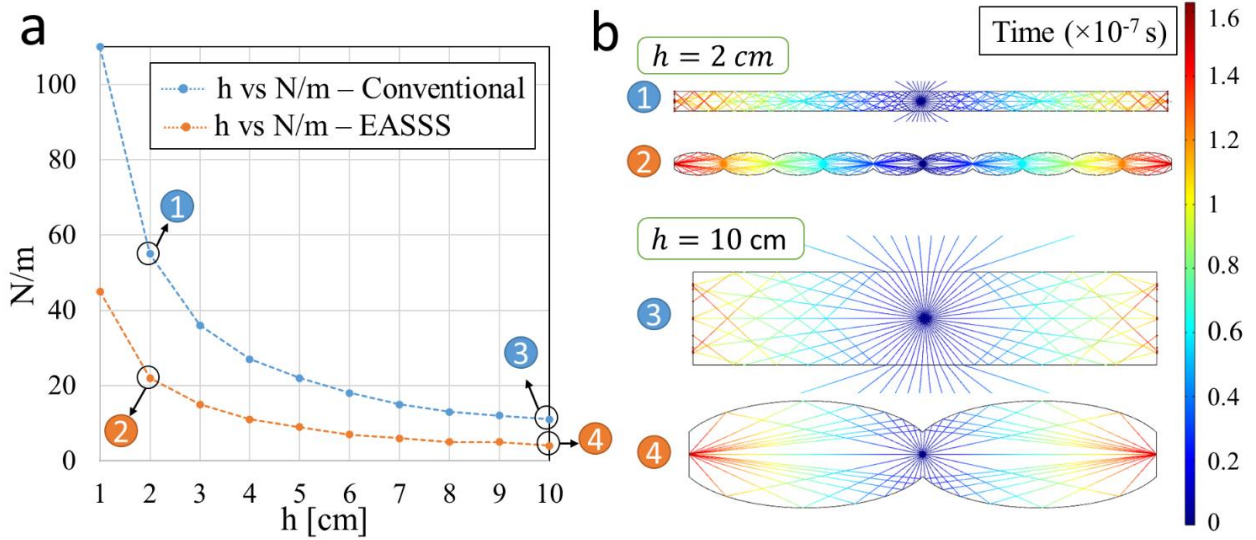


Figure 3-6 a) A comparison of surface scattering loss events on a per-meter basis for light propagating along the planar direction (the x-direction) of an EASSS and a conventional flat-panel LSC for a constant value of $c/a = 0.91$ and; b) The trajectory of light emitted from the center of a conventional LSC panel and EASSS for two cases wherein the height of the panels is $h = 2$ and $h = 10$ cm.

3.4.2 Absorption losses in the elliptic array solar spectrum splitter

The optical pathlength traversed by light emitted from the luminophores within an EASSS in the x-direction are plotted as a function of c/a and h in Fig. 3-7. The absorption losses are independent of structure height,

h , because, for a constant value of c/a , as h increases the optical path length remains invariable. On the other hand, as c/a increases the curvature of the EASSS surfaces increase and light emitted from the focal lines is more strongly directed towards the EASSS sidewalls, resulting in a decrease in the optical path length.

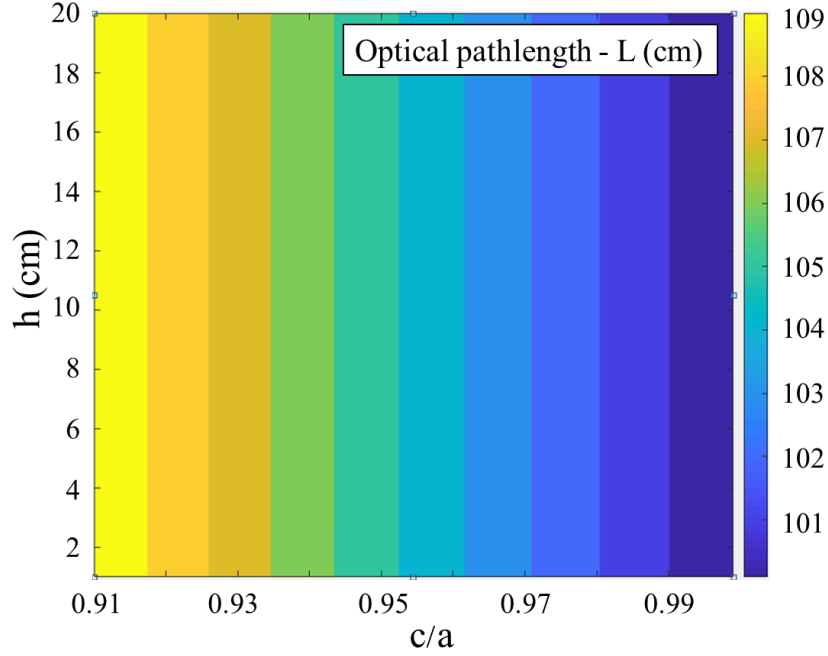


Figure 3-7 The optical pathlength of light emitted from the focal lines within the EASSS as a function of c/a and h .

The optical pathlength of radiation emitted from the center of a panel to its sidewalls is shown in Fig. 3-8a for the EASSS and the conventional LSC panels for a height of $h = 2$ cm and a width of 2 m. For a point source located in the middle of a conventional LSC, emission at the critical angle (C.A) ($\sim 42^\circ$ when the index of refraction of the LSC is 1.41) and $C.A/2$ results in optical path-lengths of 150 cm and 110 cm, respectively. For the EASSS however, the optical pathlength is independent of the emission angle. Furthermore, the optical pathlength ranges from 110 cm (for $c/a = 0.905$) to 100 cm (for $c/a = 0.999$). As can be seen in Fig. 3-8b, the number of unit cells (focal lines) in the EASSS increases as c/a decreases, resulting in a longer optical pathlength for an EASSS with a fixed height and width of 2 cm and 2 m, respectively.

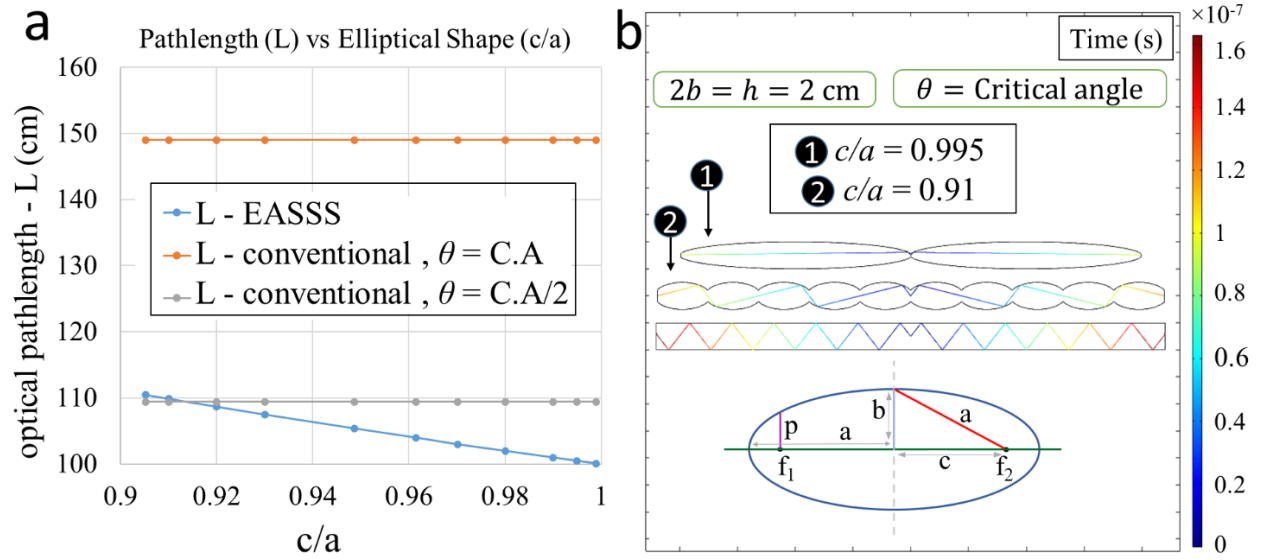


Figure 3-8 a) Optical path-lengths of radiation emitted from the center of the EASSS and conventional LSC panels for a structure with a width of 2 m. For the conventional LSC, the pathlengths for emission at the critical angle for which TIR occurs ($\theta = C.A.$) and for emission at half the critical angle are considered; and b) Geometrical illustration of the ray propagation in conventional LSC and EASSS with $c/a = 0.91$ and 0.995 for $h = 2$ cm.

The optical path length and number of surface scattering events are plotted as a function of the height of the EASSS panel, h , in Fig. 3-9. As h decreases the number of surface scattering events increases thereby increasing the expected surface losses ($c/a=0.91$).

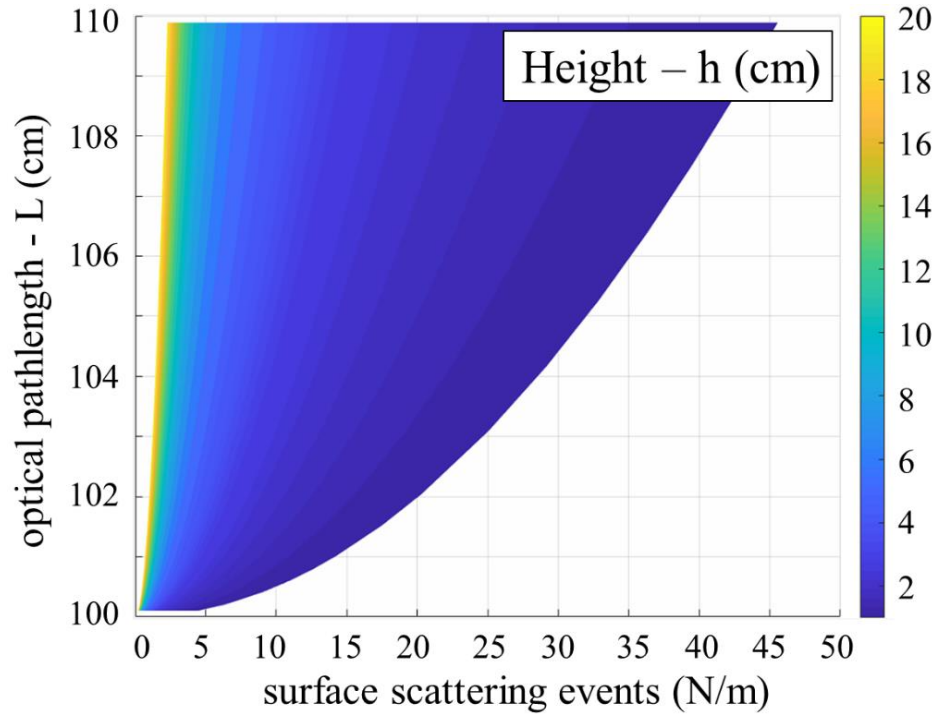


Figure 3-9 The relationship between the EASSS thickness (h) and the optical pathlength and the number of surface scattering events for light emitted from the focal lines within the EASSS.

3.4.3 Transmission losses in the elliptic array solar spectrum splitter

Fig. 3-10 shows the fraction of radiation emitted from luminophores at the center of the EASSS and conventional LSC panels that are incident onto PV cells located at the panel sidewalls as a function of time. In this figure two EASSS with $c/a = 0.995$, and $c/a = 0.91$ and a conventional LSC are considered, each having a height of $h = 2$ cm. The distance between the luminophore at the center of the panels and the PV cells at the panel sidewalls is assumed to be one meter. As can be seen in Fig. 3-10, for the EASSS the emitted photons from luminescent dyes reach the solar cells sooner in comparison to the conventional LSC. This improved time profile is consistent with a reduction of transmission ($\eta_{Transmission}$), self-absorption ($\eta_{Self-abs}$), surface roughness ($\eta_{Roughness}$) and emission ($\eta_{Emission}$) losses, which will be discussed subsequently.

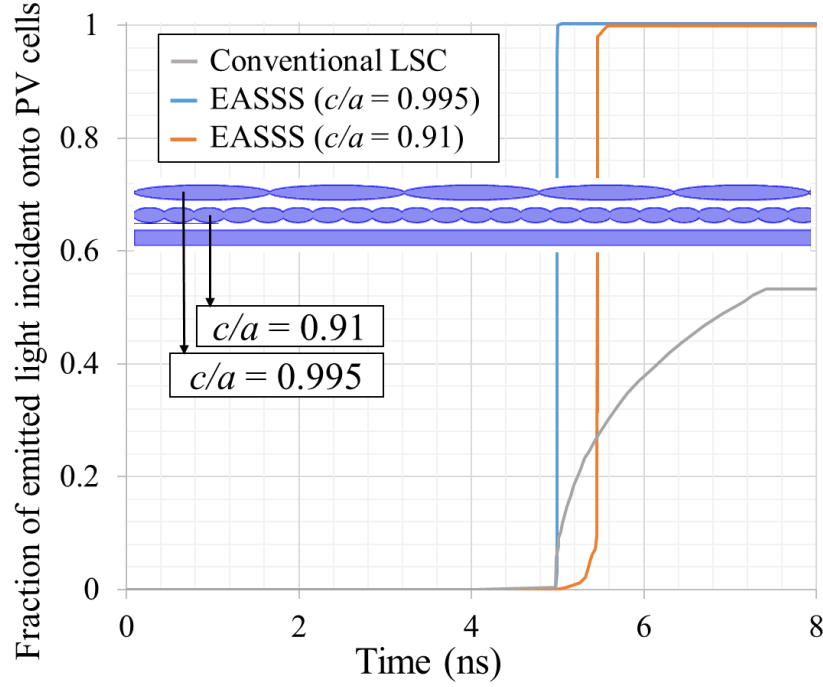


Figure 3-10 Radiation emitted from the center of the EASSS and conventional LSC panels incident onto the PV cells at the panel sidewalls plotted as a function of ray travelling time for $h = 2$ cm.

3.4.4 Optical receiver design

As mentioned previously, a linear array of Petzval lenses is used to collimate the solar irradiation into the EASSS along the focal lines where the luminescent dyes are concentrated. The Petzval lens configuration is composed of two positive lens groups separated by an air gap. To enable the incoming concentrated PAR to efficiently exit the underside of the EASSS, a negative lens element is placed on top of the entrance port on the upper side of the EASSS as shown in Fig. 3-4c. The entrance port introduces emission losses, which are discussed subsequently.

3.4.4.1 Emission losses as a function of the optical receiver design

It is clear that increasing the width of the optical receiver port (O), as shown in Fig. 3-11c, results in higher emission losses. For constant values of O and h , as c/a increases, $p = b^2/a$ decreases and emission losses increase. From the perspective of structure thickness (h), for constant values of O and c/a , as h increases p

increases and emission losses decrease. The emission losses are shown as a function of O and c/a for three different values of $h = 2, 5$, and 10 cm in Figs. 3-11a, b and c, respectively.

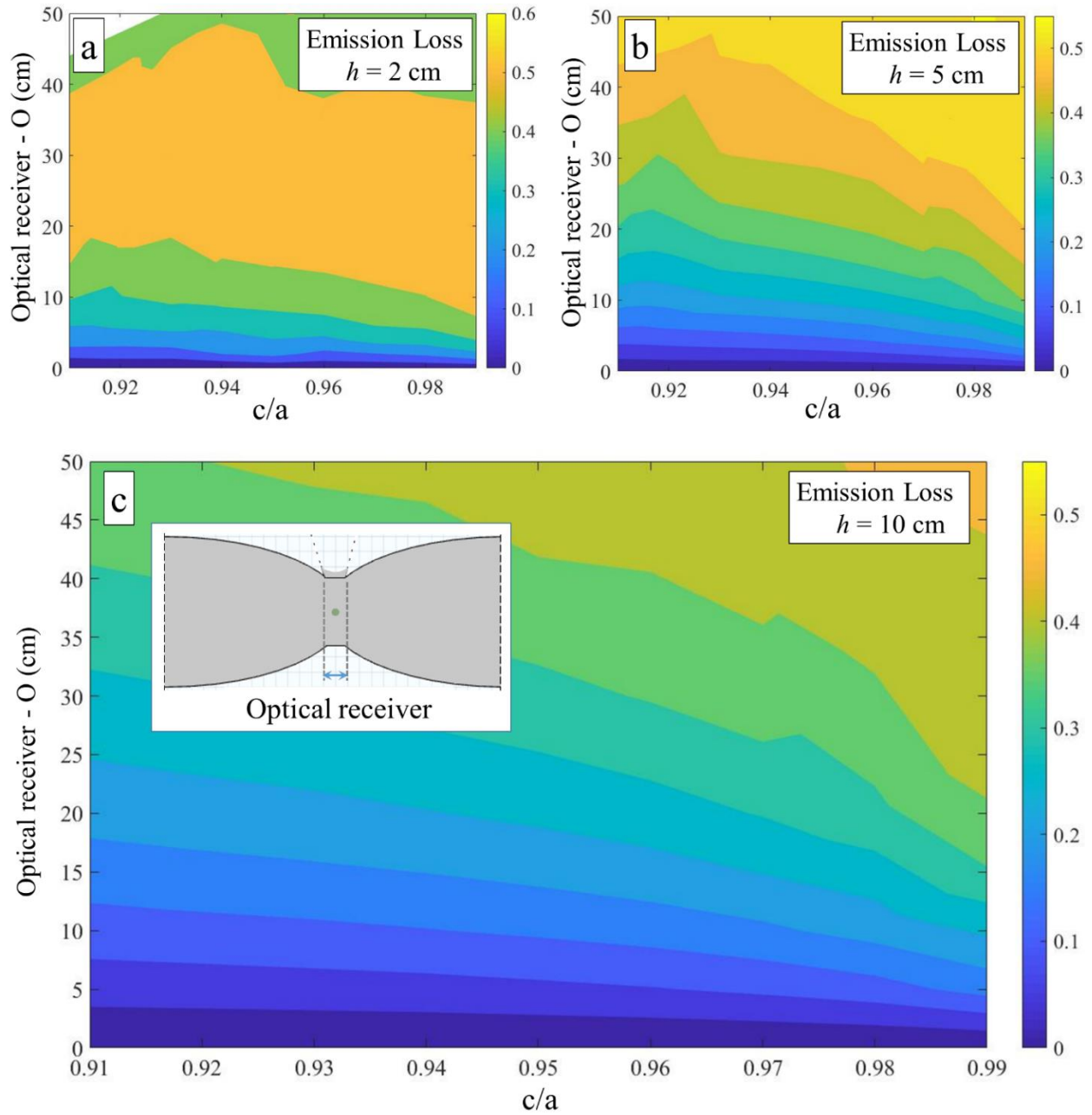


Figure 3-11 Emission losses as a function of c/a and the width of the optical receiver port (O) for a) $h = 2$ cm b) $h = 5$ cm, and c) $h = 10$ cm.

3.4.4.2 Emission losses as a function of the volume occupied by the luminescent dye in the vicinity of the elliptic array solar spectrum splitter focal line

The results presented in all previous sections were calculated in 2D assuming the luminescent dye is located precisely at the focal point of the overlapped ellipses. In practice, the luminescent dye molecules will occupy a limited volume, the size of which depends on the amount of dye required to absorb the incident non-PAR solar photon flux. Figs. 3-12a and b, show the percentage of radiation emitted from the focal line that is lost through the upper and bottom entrance and exit ports as a function of the in-plane (X-Y plane shown in Fig. 3-3b) and out-of-plane (Y-Z plane shown in Fig. 3-3a) displacement of the luminescent dye from the focal line for two sample EASSS configurations with $c = 5$ cm and $h = 2$ and $h = 4$ cm, respectively.

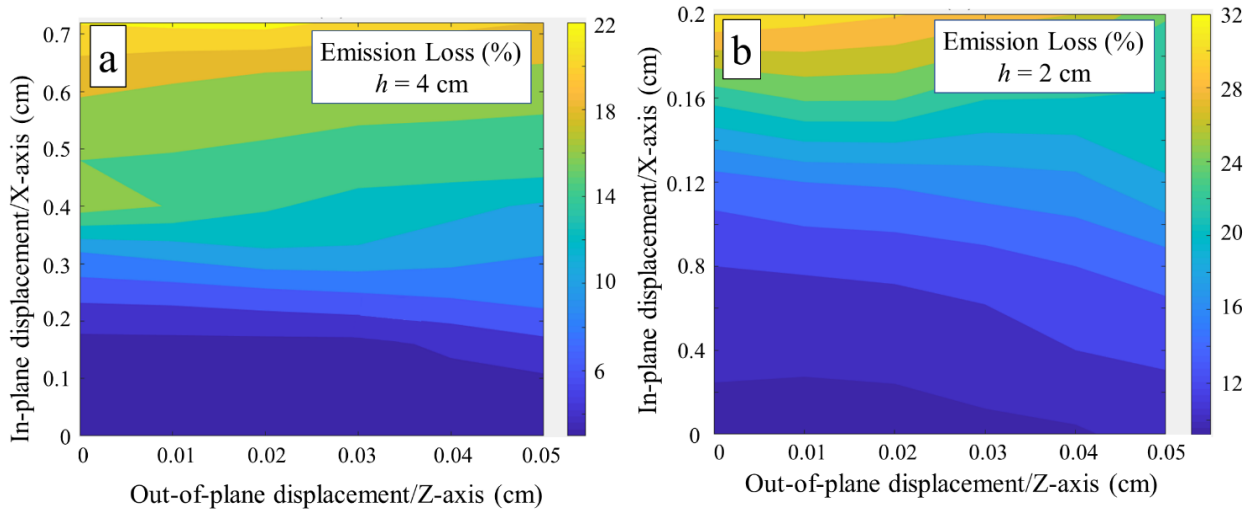


Figure 3-12 The percentage of emission loss as a function of in-plane and out-of-plane displacement due to the volume distribution of luminescent dye along the focal line for a) $h = 4$ and; b) 2 cm ($c = 5$ cm, $O = 1$ mm).

As an example, based on assumptions and analysis regarding dye concentration and absorption that we reported in previous work [46], it was concluded that the required volume of Lumogen R305 dye in EASSS with parameter values of $c/a = 0.91$, $c = 1.25$ cm, $O = 0.1$ cm and area of 10×10 cm² to absorb all incident light over the spectral range of 575~620 nm, requires $\sim 1.57 \times 10^{-3}$ mm³ for each unit cell. This required volume creates negligible focal line-offset losses (less than $\sim 1\%$).

3.4.5 Performance comparison: elliptic array solar spectrum splitter vs. conventional luminescent solar concentrator panels

In this section we compare a conventional LSC and a EASSS panel with parameter values of $c/a = 0.91$, $c = 1.25$ cm and $O = 0.1$ cm. The area of both panels is assumed to be $10 \text{ cm} \times 10 \text{ cm}$, and the height ($h = 2b$) of both panels is assumed to be identical.

The fraction of radiation emitted from a point source located at the center of the panel that is incident onto PV cells located at the panel sidewalls is plotted as a function of time in Fig. 3-13 for the conventional LSC and EASSS panels. At steady state the emission losses for the EASSS and conventional LSC panels are 7.4% and 25.8%, respectively, resulting in 24.8% improvement in emission efficiency. The mean traveling time for photons to propagate from the center of the EASSS and conventional LSC panels to the sidewalls is $T_{m1} = 0.66$ ns and $T_{m2} = 1.45$ ns, respectively. The difference between the mean propagation time for the two panels is related to the differences in transmission efficiency, $\eta_{Transmission}$ (here transmission efficiency refers to losses that occur for light propagating within the host of the LSC towards its sidewalls). For example, assuming the same intensity of incident light on the EASSS and conventional LSC panels, and that the host material has an index of refraction and mean absorption coefficient of $n = 1.49$ and $\alpha_{mean} = 3 \times 10^{-3} \text{ 1/cm}$, respectively, [45] the Optical Density (OD) can be determined for a light emitted from the center of the EASSS or a planar LSC using the following equation:

$$OD = \log_{10}\left(\frac{I_{in}}{I_{out}}\right) \quad (3.4)$$

where, I_{in} = the intensity of light at the center of the LSC and I_{out} = the intensity after the light has propagated to the sidewalls of the LSC. The ratio of the optical density for the EASSS and planar LSCs is $OD_{EASSS}/OD_{LSC} = 0.45$, which implies that the transmission losses through the EASSS panel are significantly less than that for the conventional LSC panel.

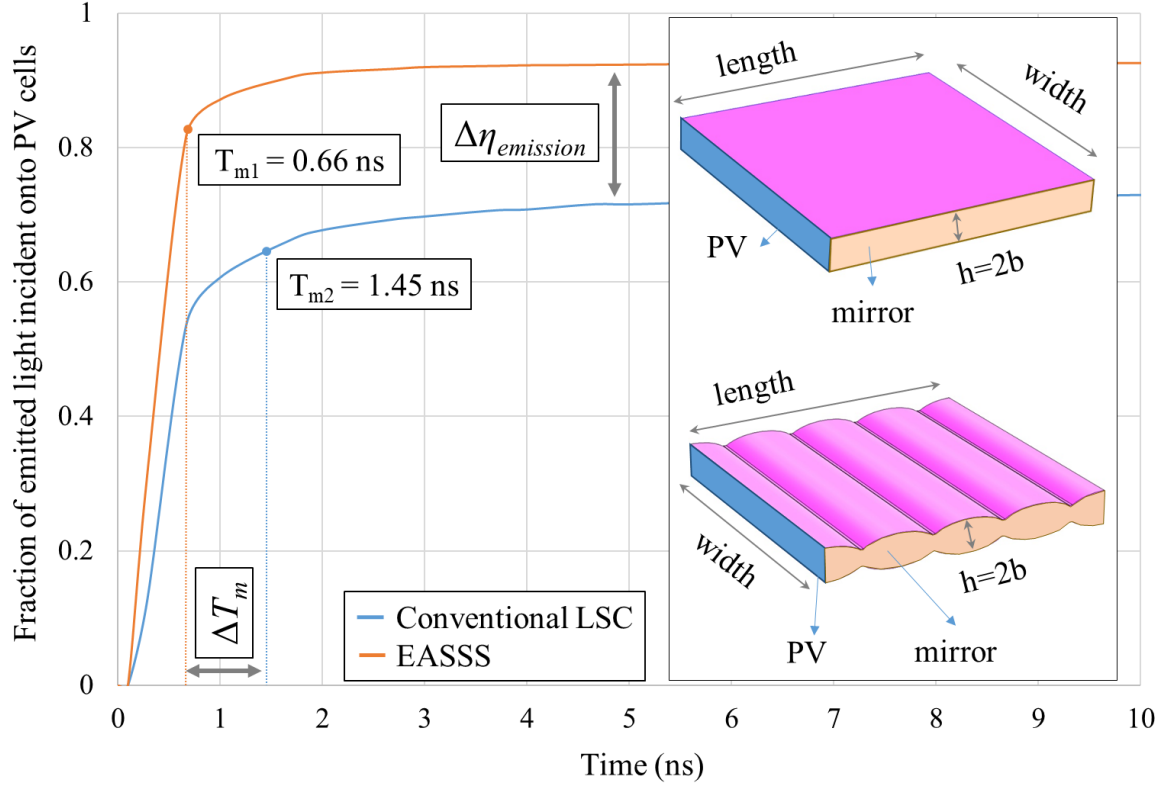


Figure 3-13 Fraction of photons emitted within the EASSS and conventional LSC panels incident onto PV cells located at the panel sidewalls as a function of time.

The total efficiency of the EASSS can be calculated using the concentration factor, C , which is the light intensity incident onto the rectangular PV cells embedded on two sidewalls, Φ_2 , divided by the light intensity incident onto the Petzvel lens concentrator, Φ_1 : $C = \Phi_2/\Phi_1$. In other words, the concentration factor can be re-written as $C = G \cdot \eta_{non-PAR-opt}$, where G is the geometrical gain factor and $\eta_{non-PAR-opt}$ is the optical efficiency of the EASSS for the incident non-PAR spectrum which is given as:

$$\eta_{non-PAR-opt} = \eta_{Fresnel} \cdot \eta_{non-PAR-Abs} \cdot \eta_{PLQY} \cdot \eta_{Stokes} \cdot \eta_{Emission} \cdot \eta_{Roughness} \cdot \eta_{Transmission} \cdot \eta_{self-abs} \quad (3.5)$$

where $\eta_{Fresnel}$ depicts the Fresnel law-based efficiency with which incident light is coupled into the EASSS, rather than being reflected from the boundary surfaces. If the EASSS and two negative Petzvel lenses are made from PMMA ($n = 1.49$) then $\eta_{Fresnel} \sim 82\%$. $\eta_{non-PAR-Abs}$ is the efficiency with which the luminophores absorbs the emitted non-PAR. Here, we assume that sufficient amount of luminescent material such as

Lumogen Red 305 are embedded in the EASSS (~30 ppm) such that 100% of the non-PAR in the spectral region from ~500 to ~600 nm is absorbed. η_{PLQY} represents the photoluminescence quantum yield (PLQY) efficiency described as the ratio between the number of photons emitted and absorbed by the luminescent dye in non-PAR range. It is assumed that $\eta_{PLQY} = 0.95$ for LR 305 luminescent dye [47]. η_{Stokes} shows energy lost through molecular vibrations and heat generation during the absorption (~580 nm peak) and emission (~620 nm peak) event which is assumed to be $\eta_{Stokes} = 95\%$ for Lumogen Red 305 [47]. However, in this study we set $\eta_{Stokes} = 1$ because we are investigating the fraction of incident non-PAR photons in the spectral region in the vicinity of 500-600 nm that are absorbed by Lumogen Red 305 and eventually directed towards the rectangular PV cells located at the two sidewalls of the EASSS. That is, all the photons incident onto the c-Si PV cell with energy greater than its bandgap, which is ~1.1 eV ($\lambda_g \sim 1.1 \mu m$), independent of the Stokes shift contribute to the output current. $\eta_{Emission}$ is the efficiency with which the LSC panels “trap” the light, thus preventing photons emitted from the luminophores from escaping the panel. As discussed previously with reference to Fig. 3-13, emission losses for an EASSS with parameters $c/a = 0.91$, $c = 1.25$ and $O = 0.1$, are 7.4%, and in this case $\eta_{Emission} = 92.6\%$. In comparison, the $\eta_{Emission}$ for a planar LSC with an index of refraction of 1.49 is ~74%, which is only valid for a perfectly smooth interface. Surface roughness creates parasitic surface losses and reduces the efficiency of total internal reflection and therefore an additional factor, $\eta_{Roughness}$, is introduced in Equation 3.5. These surface scattering losses increase with increasing surface roughness. In practice, surface scattering losses are highly dependent on the quality of fabrication and in a LSC panel can be described using the expression $(1-D)^N$, where D is the probability that a photon is scattered out of the LSC due to surface roughness each time it is incident onto the LSC surface and N is the number of collisions with the LSC surface [48]. In this study, for the specific case wherein $c/a = 0.91$, $c = 1.25$ cm and $O = 0.1$ cm of EASSS, it is further assumed that $D = 0.03$, which results in $\eta_{Roughness} = 93\%$. $\eta_{Transmission}$ is the efficiency with which photons generated from the luminescent dye are transported through the LSC without being absorbed by the host material due to the concentrations of attenuating species in the material sample. The transmission efficiency is governed by the Lambert-Beer law:

$$\frac{I_{out}}{I_{in}} = e^{-\alpha l} \quad (3.6)$$

where α is the absorption coefficient of the material the panel is comprised of (PMMA in this study). The absorption coefficient is assumed to be $\alpha = 5 \times 10^{-3} \text{ cm}^{-1}$ for $\lambda = 620 \text{ nm}$ [45] and therefore, the transmission efficiency is $\eta_{Transmission} = 93.6\%$. $\eta_{self-abs}$ is the efficiency with which re-emitted light can be transported through the EASSS panel without being absorbed by other luminophores. Self-absorption is a consequence of the spectral overlap between the emission and absorption spectra of the luminescent dye. Denoting the emission spectrum as $F(\lambda)$ and the absorbed spectrum as $A(\lambda)$, the self-absorption cross section, σ_{SA} , for an optical path length of 1 cm is quantified as [49]:

$$\sigma_{SA} = \frac{1}{k} \int_0^\infty F(\lambda) A(\lambda) d\lambda \quad (3.7)$$

$$\text{where } k = \int_0^\infty F(\lambda) d\lambda \quad \text{and} \quad [\sigma_{SA}] = \frac{1}{\text{cm}} \quad (3.8)$$

As can be seen from Equation 3.7 and 3.8, self-absorption losses decrease significantly as the Stokes shift increases. Considering self-absorption losses, the corrected Photoluminescent Quantum Yield ($PLQY_{corr}$) can be calculated from the observed PLQY using Equation 3.9 [50]:

$$PLQY_{corr} = \frac{PLQY_{obs}}{1 - a_s + a_s PLQY_{obs}} \quad (3.9)$$

Where a_s is the self-absorption coefficient. As can be seen from Equation 3.9, if the quantum yield and the self-absorption coefficient of luminescent dye are ~ 1 and 0.7 , respectively ($PLQY_{obs} = 0.95$ and $a_s = 0.7$ for Lumogen Red 305 [50]), then self-absorption can be assumed $\eta_{self-abs} = 98\%$. Considering all loss mechanisms and efficiencies as described by Equation 3.5, the non-PAR optical efficiency and concentration factor for the EASSS panel considered in this section is $\eta_{non-PAR-opt} = 61.5\%$ and $C = 2.77$, respectively.

It should be mentioned that self-absorption losses can be the dominant loss mechanism in most cases when luminescent dyes have lower quantum yield and/or a smaller Stokes shift. For every re-absorption event the

photon energy can be dissipated again through one of the above-mentioned loss channels. Consequently, for an irradiance input energy flux of Φ_{in} , the output flux Φ_{out} decreases after an average re-absorption number of $N-1$ per photon to [49]:

$$\Phi_{out} = \Phi_{in} \cdot \eta_{Fresnel} \cdot \eta_{non-PAR-Abs} \cdot (\eta_{PLQY} \cdot \eta_{Stokes} \cdot \eta_{Emission} \cdot \eta_{Roughness} \cdot \eta_{Transmission})^N \quad (3.10)$$

This equation shows that losses increase exponentially as the number of re-absorption events increases. As an example, Fig. 3-14 shows $\eta_{non-PAR-opt}$ for both a conventional LSC and the EASSS panel with $c/a = 0.91$, $c = 1.25$ cm and $O = 0.1$ cm, and their efficiency ratio ($\eta_{EASSS} / \eta_{LSC}$), as a function of self-absorption events, N . As can be seen, as the number of self-absorption events increases, optical efficiencies exponentially decrease, and these decreases occur to a much greater extent for the conventional LSC panel as compared to the EASSS panel.

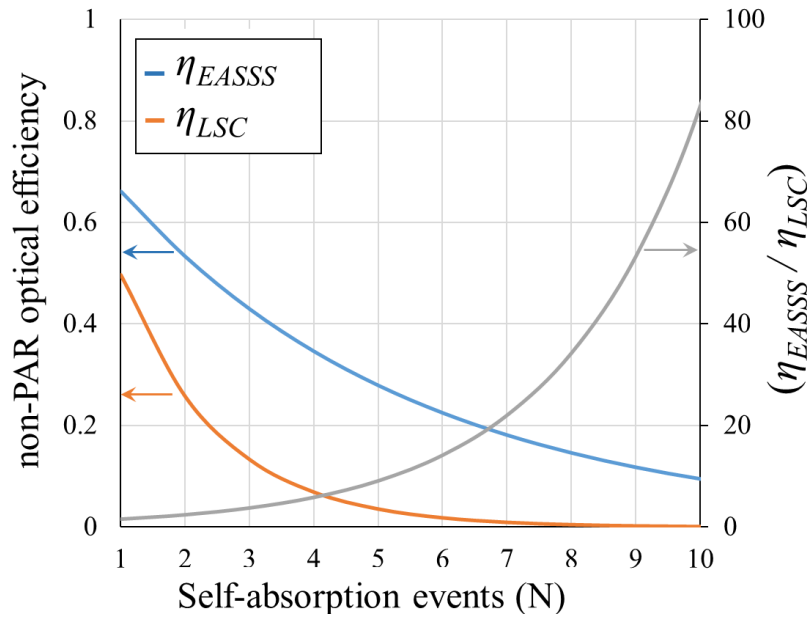


Figure 3-14 Optical efficiencies for both a conventional LSC and the EASSS panel with $c/a = 0.91$, $c = 1.25$ cm and $O = 0.1$ cm, and their efficiency ratio ($\eta_{u-AESSS} / \eta_{LSC}$) as a function of self-absorption events (N).

The mean travelling time, distance, and surface scattering events for photons emitted from the luminophores within the conventional LSC and EASSS panels are provided in Table 3-1 along with the various efficiency factors and concentration factor for the two LSC panels.

Table 3-1 Performance parameters for the EASSS and conventional planar LSC panels

	Mean photon traveling time (ns)	Average traveling distance (cm)	Scattering quantity (times/photon)	$\eta_{Emission}$ (%)	$\eta_{Transmission}$ (%)	$\eta_{Roughness}$ (%)	$\eta_{non-PAR-opt}$ (%)	Concentration factor
EASSS	0.66	13.29	2.38	92.6	93.6	93	63	2.77
LSC	1.45	29.11	6.92	74	86.45	81	47.2	2.07

3.4.6 Thermal analysis

It is well-known that the quantum efficiency of luminescent dyes degrades as the operating temperature increases [51]. In this study, COMSOL Multiphysics software was utilized to evaluate any potential deleterious thermal effects on the performance of the luminescent dyes throughout the EASSS under the same illumination conditions as mentioned in the previous sections. In this thermal analysis the attenuation coefficient and heat transfer coefficient are assumed to be $\alpha_{mean} = 3 \times 10^{-3} \text{ 1/cm}$ and $h = 10 \text{ W/m}^2\cdot\text{K}$, respectively.

The EASSS considered in the previous section, with $c/a = 0.91$, $c = 1.25 \text{ cm}$ and $O = 0.1 \text{ cm}$, is comprised of a Petzval lens array concentrating solar radiation from a planar area of 100 cm^2 onto four receiver ports that have a width of $O = 1 \text{ mm}$. The results (not shown) reveal that the temperature increases by less than 2 degrees throughout the EASSS and the effects of increased temperature on the performance of the EASSS during operation are assumed to be negligible.

3.4.7 Tandem elliptic array luminescent solar concentrator-photobioreactor for combined power and algae production

The inset in Fig. 3-15 illustrates the concept of an EASSS operating in tandem with a PBR. In this example sunlight is incident onto the topside of a Petzval lens array which directs light to the focal lines of the EASSS. Dye located along these focal lines can absorb the non-PAR in the spectral regions from 500 ~ 600 nm ($\Delta W_1 = 152 \text{ W/m}^2$) and 740 ~ 1100 nm ($\Delta W_2 = 282 \text{ W/m}^2$) as shown as the shaded regions in Fig. 3-15. Light emitted from the dye undergoes TIR and is directed towards crystalline silicon PV cells located at the sidewalls of the EASSS. Light emitted from the dye undergoes TIR and is directed towards crystalline silicon PV cells located at the sidewalls of the EASSS.

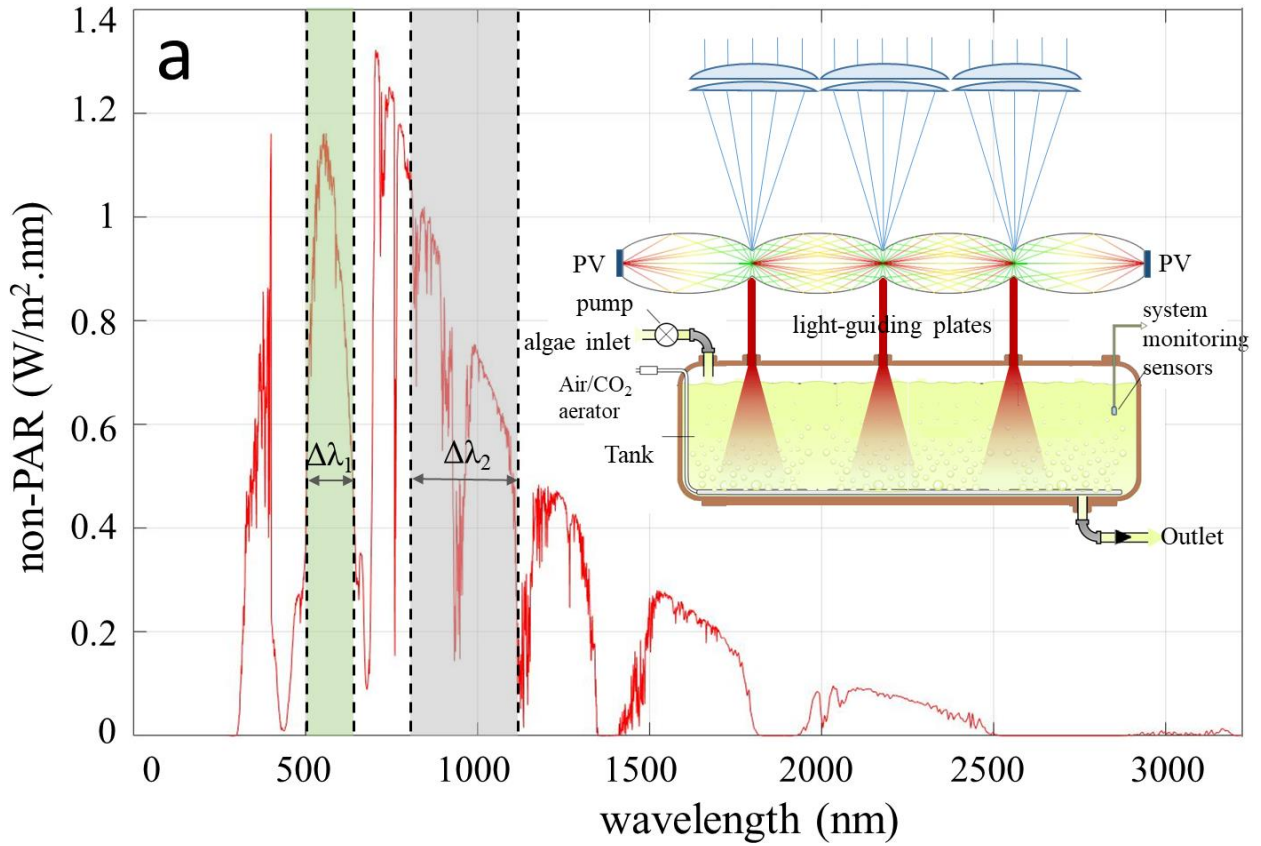


Figure 3-15 non-PAR from sunlight ($\Delta W_1=500\sim600 \text{ nm}$ and $\Delta W_2= 740\sim1100 \text{ nm}$) can be absorbed in a EASSS in a tandem configuration with a PBR (inset). PAR is transmitted through the EASSS and used to support algae cultivation in the PBR.

In this example it is considered that the non-PAR spectral regions from 500 ~ 600 nm ($\Delta W_1 = 152 \text{ W/m}^2$) and 740 ~ 1100 nm ($\Delta W_2 = 282 \text{ W/m}^2$) can be absorbed in an EASSS and converted to electricity in c-Si based PV cells at the edges of the EASSS. The Petzval lens array and upper surface area of the PBR shown in Fig. 15 are assumed to have an area of $A = 10 \times 10 \text{ cm}^2$. It is also assumed that the optical efficiency of the EASSS is $\eta_{non-PAR-opt} = 61.5\%$ for both the ΔW_1 and ΔW_2 spectral regions, and the photon flux incident onto the c-Si PV cell at the top side of EASSS for these spectral regions are $\Phi_{\Delta W_1} = 4.163 \times 10^{16} \text{ cm}^{-2} \cdot \text{s}^{-1}$ and $\Phi_{\Delta W_2} = 1.263 \times 10^{17} \text{ cm}^{-2} \cdot \text{s}^{-1}$, respectively, which is consistent with receiving solar radiation at an intensity of 1000 W/m^2 (e.g. one sun).

It is assumed the PV cells have an External Quantum Efficiency (EQE) of $EQE^*_{\Delta W^*_1} \cong 100\%$ and $EQE^*_{\Delta W^*_2} \cong 85\%$, for light that was absorbed by the dye in spectral regions ΔW_1 and ΔW_2 , and reemitted in spectral regions ΔW^*_1 and ΔW^*_2 , respectively [52-54]. Under these assumptions, the short circuit current (I_{sc}), open circuit voltage (V_{oc}) and the maximum output power (P_{max}) generated by the PV cell are calculated using Equations 3.11, 3.12 and 3.13, respectively [55]:

$$I_{sc} = A \cdot q \cdot \eta_{non-PAR-opt} \cdot \left(\int_{\Delta W_1} \Phi_{\Delta W_1}(\lambda) \cdot EQE^*_{\Delta W^*_1}(\lambda) \cdot d\lambda + \int_{\Delta W_2} \Phi_{\Delta W_2}(\lambda) \cdot EQE^*_{\Delta W^*_2}(\lambda) \cdot d\lambda \right) \quad (3.11)$$

$$V_{oc} = \frac{nkT}{q} \ln \left(\frac{I_{sc}}{I_0} + 1 \right) \quad (3.12)$$

$$P_{max} = I_{sc} \cdot V_{oc} \cdot FF \quad (3.13)$$

where $n = 1$ is the ideality factor, k is Boltzmann's constant, $T = 300 \text{ K}$ is the cell temperature, $I_0 = 10^{-10} \text{ A}$ is the dark saturation current, q is the charge of an electron, and FF is the fill factor which can be expressed as a function of open-circuit voltage (V_{oc}) [55]:

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \quad (3.14)$$

where

$$v_{oc} = V_{oc} \frac{q}{k_B T} \quad (3.15)$$

Is a normalized voltage. Equation 3.14 is assumed as an appropriate approximation of the FF when $v_{oc} > 10$. Based on Equation 3.13, out of a total of 4.34 W of non-PAR incident in the ΔW_1 and ΔW_2 solar spectral regions, 0.735 W can be converted to electric power, representing a total non-PAR to electric power conversion efficiency of 16.94% (where $I_{sc} = 1.466$ A, $V_{oc} = 0.605$ V, and $FF = 0.8285$).

Notably, this analysis was done for the AM1.5 spectrum, whereas in space applications sunlight has an AM0 spectrum. Nevertheless, using the AM0 spectrum in the previous calculation would not result in any significant difference from the $\sim 17\%$ value determined for the efficiency. On the other hand, the amount of electric power generated (and amount of PAR available for algae cultivation) strongly depends on the distance from the sun. For example, the maximum solar irradiance on Mars is ~ 590 W/m², compared to a maximum of ~ 1050 W/m² on Earth's surface, and thus it is expected that the total power (and light available for algae cultivation) that could be generated in the vicinity of Mars would be about half of that generated on Earth.

It should also be noted that the lenses within the Petzval lens array must track the sun, which will require a tracking system. Furthermore, the fabrication methods and stability of the materials used in the EASSS would have to be tested for duration, temperature, vacuum conditions and radiation exposure. In this context the Petzval lens array could provide shielding for the EASSS.

3.5 Conclusion

In this work a new LSC in the form of an elliptic array solar spectrum splitter (EASSS) is presented. Numerical simulations were carried out to compare the performance of the elliptic array LSC to that of a conventional planar LSC. A distinct advantage of the elliptic array LSC is that it can be designed to achieve TIR over a broad range of emission angles, which drastically reduces emission losses. Furthermore, in comparison to a planar LSC the number of surface scattering events for photons propagating within the EASSS LSC is significantly less than that of a planar LSC, thereby reducing scattering losses. Also, the pathlength traversed by light travelling from the center to the edge of an EASSS is substantially less than

the pathlength for light moving from the center of a planar LSC to its edge. The shorter pathlength for light in the EASSS reduces absorption losses wherein a portion of light emitted from the dye is absorbed in the LSC host material as it travels towards PV cells located at the edges. Moreover, considering the combined effects of emission, transmission and surface scattering losses numerical results show the optical efficiency of the elliptic array LSC is 63%, whereas in comparison the optical efficiency for conventional planar LSC of the same size is 47.2%. It should be noted that an array of Petzval lenses that track the sun to focus light onto focal lines within the EASSS is required, which increases system cost and complexity. Nevertheless, the EASSS can provide the dual function of partitioning solar irradiance into PAR and non-PAR components to simultaneously provide for algae growth and power generation. The ability to optimally use the broadband solar irradiance for these purposes has potential applications for extended duration space missions wherein power generation and regenerative environmental control and life support systems that include algae growth are of high value. In this context, results from numerical simulations show that elliptic array luminescent solar concentrators can convert non-PAR to electric power with a conversion efficiency of ~17% while transmitting PAR to an underlying photobioreactor to support algae cultivation.

3.6 References

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4 Selectively harvesting near-infrared photons in fiber optic-based hybrid solar lighting systems for power generation in buildings¹

Nomenclature			
<i>Roman symbols</i>		q	charge of an electron
A	area	T	temperature
$A(\lambda)$	luminophore absorption spectrum	V_{OC}	open circuit voltage
a	semi-major axis of an ellipse	W	radius of the top surface
a_s	self-absorption coefficient	<i>Greek symbol</i>	
b	semi-minor axis of an ellipse	α	material absorption coefficient
c	distance between the focal point and centre of an ellipse	ΔW_1	spectral region from 280 ~ 435 nm
D	probability of a photon to scatter	ΔW_2	spectral region from 675 ~ 900 nm
$F(\lambda)$	luminophore emission spectrum	$\eta_{Emission}$	emission efficiency
FF	fill factor	$\eta_{Fresnel}$	incident light coupling efficiency
G	geometric gain factor	η_{IR-opt}	optical efficiency for the wavelength ranges from 675 to 900 nm
I_0	dark saturation current	$\eta_{non-Vis-Abs}$	non-visible absorption efficiency
I_i	initial light intensity	$\eta_{non-Vis-opt}$	non-visible optical efficiency
I_n	normalized intensity	η_{PLQY}	photoluminescence quantum yield
I_{SC}	short circuit current	$\eta_{Roughness}$	surface roughness efficiency
K	distance from the vertex to the focal point	$\eta_{self-abs}$	self-absorption efficiency
k	Boltzmann's constant	η_{Stokes}	Stokes shift efficiency
L	distance of the focal point to PV cell	$\eta_{Transmission}$	transmission efficiency
l	optical pathlength	η_{UV-opt}	optical efficiency for the wavelength ranges from 280 to 435 nm
N	the number of photon collisions with surface	λ	wavelength
N	the number of photon collisions with surface	σ_{SA}	self-absorption cross section
n_1	refractive index of the external medium	Φ_1	light intensity incident onto the nonimaging solar concentrator
n_2	refractive index of the internal medium	Φ_2	light intensity incident onto the annular PV cells
O	radius of the entrance port on the elliptic paraboloid	$\Phi_{\Delta W_1}$	photon flux of ΔW_1
P_{max}	maximum output power	$\Phi_{\Delta W_2}$	photon flux of ΔW_2

¹ This chapter is based on references [5, 45, 46]

4.1 Abstract

Hybrid Solar Lighting (HSL) systems have recently been expanded in order to fully utilize the broadband solar spectrum to bring the natural light into an indoor space, and make use of the non-visible spectrum in other forms of energy and applications. In this chapter a parabolic/elliptic shaped solar spectral splitter (SSS) is presented to partition the concentrated collimated solar radiation into its visible and non-visible parts. In the proposed SSS, phosphorescent emitter materials and a bifacial PV cell are appropriately placed in the structure to capture the spectral ranges of 280 to 435 nm, and 675 to 900 nm and convert them into electricity. The visible light is coupled to a waveguide to be used in indoor lighting systems. The proposed SSS is analysed for 0.2 m² projected area of solar radiation and the results show that the system can reach up to ~ 13.4% non-visible-to-electricity conversion efficiency. The power generated in the system can be used to power the electrical components of the system.

4.2 Introduction

Most factories, manufacturing centres and residential buildings with finite natural lighting input are mainly lit using fuel-based electricity which vastly contributes to the rapidly increasing atmospheric CO₂ concentration and global warming. Currently, powering fuel-based electrical lighting systems causes approximately 244 million tons of CO₂ emissions per year [1]. Estimations from the U.S. energy information administration reveal that in 2015 approximately 404 billion kWh of electricity were consumed just for lighting applications by the commercial and residential sectors in the United States. This amount was about 10% of the total electricity consumption in the U.S. Solar energy, as a renewable and eco-friendly resource is a promising alternative to electrical lighting systems as it can be directly used for illumination by bypassing the conversion and storage phases that results in low efficiencies and high-loss events in the form of heat generation. Evaluations show that, efficient utilization of sunlight in buildings can decrease the consumption of electric lighting energy by 50% to 80% [2]. In this regard, solar-based indoor lighting systems have a prominent economic value, especially due to the fact that in filtered sunlight there are more

lumens per Watt (200 lm/W) in comparison to incandescent (~ 15 lm/W), fluorescent (~ 65 lm/W) or LED (~ 90 lm/W) lighting. In other words, at least 2 W of electricity can be displaced with 1 W of visible sunlight [3]. Indeed, considering the health and wellness of building occupants, recent research reveals that natural light improves the level of well-being, human health and productivity [4]. In this context, one of the most promising strategies for transporting sunlight deep inside a building is utilizing a solar fiber optical lighting (FOL) system. This system is comprised of three main sub-systems: 1) a concentrator, (which concentrates and couples solar irradiation in an optical waveguide), 2) a plastic optical fiber (which functions as a light pipe to deliver sunlight throughout the interior of a building) and, 3) a diffuser (sunlight traveling through the optical fibre is guided into the diffuser to be uniformly distributed). This type of system is referred to as a “Hybrid Solar Lighting (HSL)” system when it includes both solar-based and artificial lighting to adjust and control the indoor light intensity when sunlight is unavailable. Furthermore, there is significant growth potential for HSL systems in applications such as photocatalytic reactors, chemical reactors and photobioreactors, especially to improve algae productivity for biofuel production and for the food industry [5].

However, FOL systems face a number of technical challenges including high manufacturing costs, the low acceptance angle inherent to fiber optic waveguides, spectral loss mechanisms due to the incomplete use of the solar irradiance, and light pipe absorption losses and the accompanying heat generation throughout the waveguide. Significant research efforts have been put forth to address these technical challenges. Obianuju and Chong [6] developed a novel dual-axis solar tracker coupled with a two-stage reflective non-imaging dish concentrator to transfer the solar irradiance into high acceptance angle fibre optics. The proposed daylighting system with a reflective area of 0.2 m^2 was capable of illuminating an office with an area of 6.3 m^2 with an average illuminance of 647.94 lux. Chen Wang et al. [7] developed a new concept for remote indoor daylighting systems based on a fluorescent fiber-solar concentrator. This system consists of a PMMA plate and 150 pieces of three-color 1 m long, 2 mm diameter fluorescent fibers. The system was tested over a 6-month monitoring and evaluation period and achieved a radiation-to-radiation efficiency of 0.057 and a

lighting effect of up to 110 lm. Ullah et al. [8] designed a large scale, highly concentrated and uniform optical fiber-based daylighting system by integrating a collimator segment and a trough compound parabolic concentrator upstream of the optical fibers. They also performed a comparative analysis between using a linear Fresnel lens or a parabolic trough as the first stage of the solar concentrator. They showed that using the parabolic trough provides more illuminance than that of the linear Fresnel lens. A combination of a biconcave lens and a concavo-convex lens was also designed to make a uniform distribution of light in the building. Nilsson et al. [9] investigated the color distribution of light transmitted through light pipes by using spectrophotometric measurement approaches for the assessment of the qualitative perception of the delivered illumination. Their results showed a great color shift for different illuminants, which were used to represent daylight of different correlated color temperatures.

To enhance the lighting efficiency and reduce the payback period for HSL systems, a significant amount of research has been directed towards using optical filters and spectrum splitters to partition the solar irradiance for co-generation applications. For example, Schlegel et al. [10] presented a full-spectrum hybrid lighting system in which the secondary “cold” mirror located at the focal point of a parabolic concentrator reflects the visible spectrum into the optical fibers for lighting and transmits the IR region of the concentrated solar irradiance to a low band-gap photovoltaic array. The annual impact on lighting, heating, and cooling loads in six locations within the United States were estimated and analyzed. Honolulu, HI and Tucson, AZ performed the best over a 10-year analysis period. Kandilli et al. [11] presented a lighting-power generation system that used cold mirrors to split the solar irradiance into its visible and IR spectral components (a cold mirror reflects visible light while efficiently transmitting light in the infrared spectral region). The visible light was coupled into a fiber optic bundle for indoor lighting while light in the IR spectral region was used to power a Stirling engine. The energy and exergy efficiencies of the combined lighting-power system were calculated as 0.15 and 0.09, respectively, and an average luminous efficacy of 347 Lm/W was achieved.

According to estimations performed under a contract with the US Department of Energy it was predicted that by 2020 full-spectrum solar energy systems in the US will enable more than 30 billion kWh in energy savings, surpass \$5 billion in economic benefits, and reduce carbon emissions by more than 5 MtC. [2]

In maximizing the power generation and evaluating the efficiency limits of full spectrum-based HSL systems, it is first essential to define the spectral range of the visible and non-visible portions of the solar radiation. For example, the photopic response of the human eye (relative sensitivity of human eye) and the AM1.5 solar spectrum is illustrated in Fig. 4-1a. The Color Rendering Index (CRI) and Average Visible Transparency (AVT) are common parameters used to measure visible light, the level of transparency, and light quality. Herein, it is assumed that solar light within the visible spectral range from 435-675 nm is transported to the indoor environment via the HSL system. This implies $\text{CRI} > 95$ and $\text{AVT} > 99.5\%$ [12]. Although the human eye can slightly sense the outer ranges of the visible spectral region (380 to 435 nm and 675 to 740 nm) light in these ranges has an insignificant contribution towards our general perception of light. In this regard, a vast amount of research has been conducted to develop transparent photovoltaics and Luminescent Solar Concentrators (LSC) to be utilized for both lighting applications and energy harvesting resources, simultaneously. For example, electric power generated from the non-visible spectrum could be utilized to run different components in an HSL system such as a solar tracker, powering visible LED lights for higher luminescence/intensity, and running sensors and control systems to manage indoor lighting.

It is clear that the power generated by PV cells depends on their efficiency. The maximum theoretical efficiency of a single-junction PV cell can be determined by the Shockley–Queisser (SQ) efficiency limit [13]. In this study, numerical analysis is carried out and the maximum efficiency for a single junction PV cell for the full solar irradiance and the non-visible portion of the solar irradiance (from 280 nm to 435 nm and 675 to 4000 nm) at three concentration values of 1, 100 and 500 are shown in Fig. 4-1b. This figure shows a maximum efficiency of 20.5, 23.4 and 24.5% occurs when the PV cell band gap is ~ 0.95 eV for the non-visible portion of the solar spectrum at concentrations of 1, 100 and 500, respectively. A theoretical maximum of 132 W/m^2 for a single-junction PV cell is achieved for the non-visible portion of the AM1.5

spectrum under a concentration of one sun. These results are technologically very important due to the domination of silicon-based photovoltaic cells in the PV market which have a bandgap of 1.1 eV, which is close to the optimal band gap of 0.95 eV. A single-junction silicon-based PV cell (bandgap energy of 1.1 eV) has a theoretical efficiency of 20.1% for the non-visible portion of the AM1.5 solar irradiance, which generate 129 W/m^2 power under a concentration of one sun. Thus, silicon-based PVs are well-suited to be used in fibre optic lighting energy co-generation systems. Figs. 4-1c and 4-1d illustrate the Shockley–Queisser efficiency limit for double junction PV cells as a function of the band gap energy of the top and bottom junctions for the AM1.5 solar spectrum and the non-visible portion of the AM1.5 solar spectrum, respectively. For double junction PV cells under the AM1.5G solar irradiance, a best efficiency of 45.2% is achieved when the bandgap of the top and bottom side junctions are 1.65 and 0.95 eV, respectively. For the non-visible portion of the AM1.5 spectrum, the maximum efficiency attained using double-junction PV cells decreases to 27.5% for the case when the top and bottom PV cells have bandgaps of 1.4 and 0.95 eV, respectively.

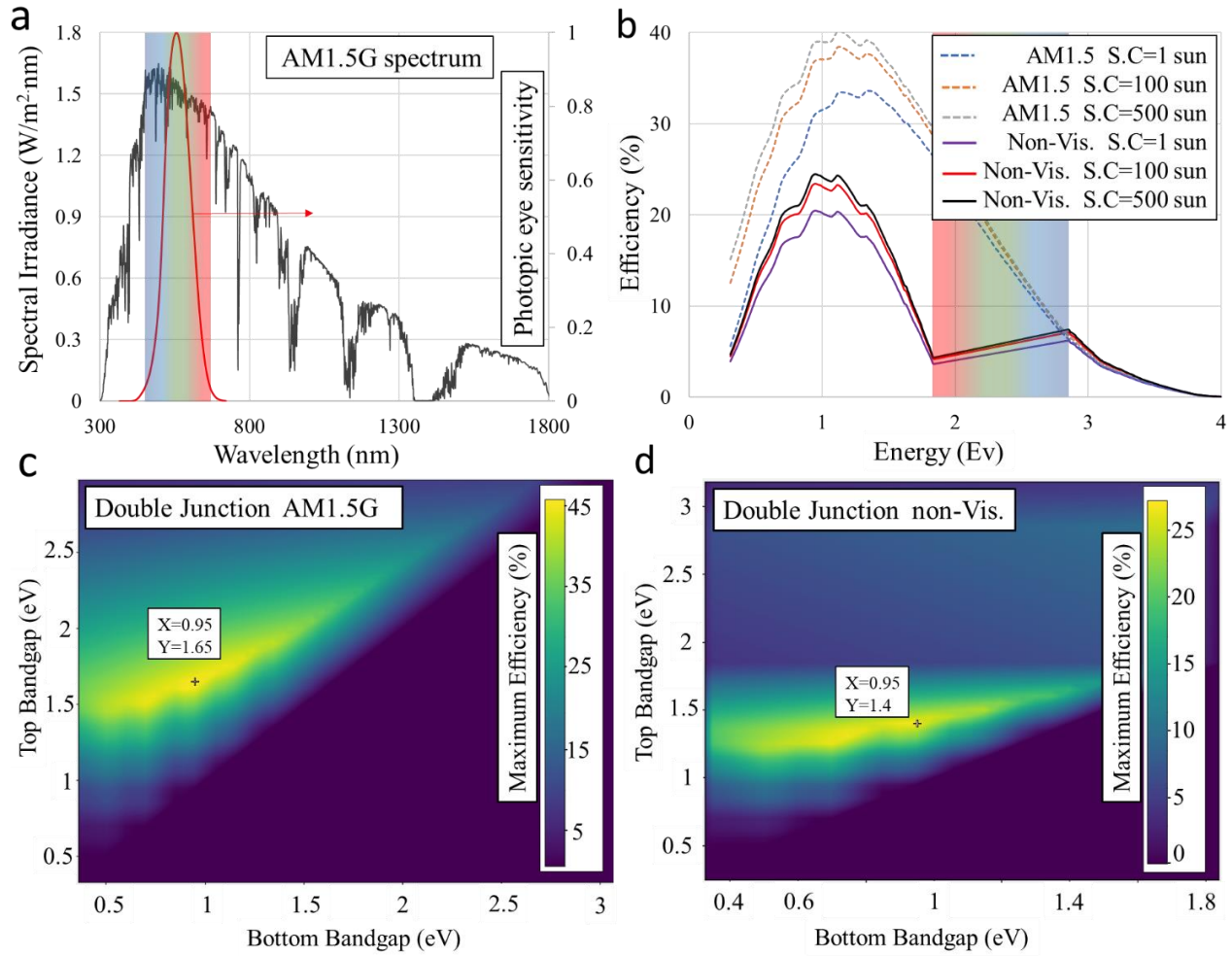


Figure 4-1 a) The AM1.5 solar spectrum and the relative human eye sensitivity plotted as a function of wavelength b) The SQ efficiency limit for the AM1.5G solar spectrum and the non-visible portion of the AM1.5 at concentrations of 1, 100 and 500. c) The efficiency of a double-junction PV cell under the AM1.5 solar spectrum. d) The efficiency of a double junction PV cell under the non-visible portion of the AM1.5 solar spectrum

SSSs reported in the literature that partition the solar spectrum into its visible and non-visible parts are based on chromatic mirrors, spectrally selective absorber fluids, diffractive structures, Distributed Bragg Reflectors (DBR), and phosphorescent materials [14- 17]. As a promising spectral photon management strategy, LSCs are remarkably desirable as they have several advantages: comparatively inexpensive fabrication costs, lightness and amenability to large scale production, supplemented with design flexibility in size, shape, formation, configuration and spectral transparency. However, this type of SSS includes

several intrinsic loss mechanisms and has yet to reach widescale commercialization. The primary loss mechanisms in LSCs are emission losses, which occurs for the photons emitted from luminescent dyes with angles less than the critical angle ($\sim 42^\circ$ for a PMMA waveguide panel). These photons with small propagation angles do not undergo total internal reflection (TIR) at the surface of the PMMA matrix and are refracted outside the panel and lost rather than being directed towards PV cells situated at the sheet edges of the PMMA matrix. To date, research has focused on aligning the luminophores embedded in LSCs or using Bragg reflectors on the surface of LSCs to reduce emission losses [18- 21]. In this study, the design of a host matrix for luminescent dyes that significantly reduces emission losses is presented. More specifically, an HSL system that combines the focusing capabilities of a collimator with the spectral splitting properties of LSCs with a unique geometry that is designed to drastically reduce and nearly eliminate emission losses. This study combines these two specifications to design a spectral solar concentrator to partition the sun irradiance into visible and non-visible spectrum to simultaneously power the fibre optic lighting system and PV cells, respectively.

4.3 Description of the double-stack semi-elliptic/parabolic solar spectrum splitter

Fig. 4-2a shows two configurations of double-stack semi-elliptic/parabolic solar spectrum splitter comprised of a two-stage SSS connected in series and attached to the underside of a concentrator. The concentrator is comprised of a first primary upward-facing parabolic mirror with a projected area of 0.2 m^2 in the X-Y plane and a smaller secondary downward-facing parabolic mirror located near the focal point of the primary mirror. The incoming solar irradiance is concentrated onto the focal point of the main parabolic dish and then reflected and collimated by the secondary mirror along the axis of the Cassegrain structure and coupled into a waveguide port at the center of the primary parabolic mirror. After passing through the port the collimated beam enters the double stack SSS as shown in Figs. 4-2b or 4-2c.

The SSS, which would be made of a solid transparent material such as PMMA or glass, has two stages stacked in series to sequentially absorb selected spectral regions of the collimated solar irradiance, and subsequently emit light in appropriate spectral regions to power a PV cell.

Each stage within the SSS in Fig. 4-2b is comprised of two oppositely facing semi-ellipsoids that share the same focal point. The shared focal point of the first stage is occupied with luminescent dyes that absorb incident light in the spectral region from ~280 to 435 nm and emit light with a longer wavelength (in the visible or IR spectral region). The portion of the collimated light beam not absorbed by the dye at the focal point of the first stage of the SSS continues to propagate along the central axis (along the z-direction) of the SSS. Similarly, dyes that absorb and emit light in the NIR spectral region are located at the shared focal point of the semi-ellipsoids in the second stage of the SSS. A double-junction PV cell with an annular shape (to allow the collimated beam to pass through its center) is located along the plane that separates the upper and lower stages of the SSS. The top junction in the PV cell absorbs light emitted from the dye situated at the shared focal point of the semi-ellipsoids in the first stage of the SSS, while the bottom junction in the PV cell absorbs light emitted from the dye at the shared focal point of the semi-ellipsoids comprising the lower stage of the SSS. Planar annular mirrors (assumed to be ideal in that they reflect 100% of the light incident onto their surface) are located at the top and bottom surfaces of the SSS. These mirrors specularly reflect light emitted by the dye at the focal points of the semi-ellipsoids and, due to the symmetry of each stage in the SSS, reflected light is directed back to the focal point and towards the PV cell. The SSS shown in Fig. 4-2c is similar to that shown in Fig. 4-2b, however the lower semi-ellipsoid in the first stage and the upper semi-ellipsoid in the second stage are replaced with paraboloids. Notably, light that is emitted from the shared focal points in Fig. 4-2c and reflected from the internal walls of the paraboloids are normally incident onto the PV cell, which can be beneficial for reducing reflection losses from the PV cell.

Fig. 4-2d shows the first stages of the SSSs shown in Figs. 4-2b and 4-2c. The trajectories of radiation emitted by the dye at the shared focal point at time $t = 0$, shown as the green lines, change colour to yellow and then red as time proceeds according to the colour bar shown in the right side of the figure. Light emitted

from the shared focal point is reflected from the internal surface of the first stage of the SSS either in the downwards direction towards the PV cell (if reflected from the surface of the lower semi-ellipsoid) or in the upper direction towards the planar mirror located at the top surface of the SSS (if reflected from the surface of the upper semi-ellipsoid). As shown in Fig. 4-2dI, emitted light reflected from the internal surface of the semi-paraboloid is incident onto the PV cell from the normal direction.

The SSS is designed to reflect all light emitted from its shared focal point that is incident onto its internal surface. This is achieved by designing the curvature and degree of overlap of the two semi-ellipsoids (or the semi-ellipsoid and parabola for the structure shown in Fig. 4-2c) such that radiation emitted from the focal points undergo total internal reflection (TIR) at the internal surfaces of the SSS. Referring to Figs. 4-1b and c, The PV cell located on the plane between the two stages of the SSS can be a double-junction or bifacial solar cell designed to optimally harvest the photons emitted from the focal points within the top and bottom stages of the SSS. The portion of the collimated sunlight beam that is not absorbed by the dyes at the focal point within the SSS (e.g. the visible portion) is coupled into a waveguide at the bottom of the SSS to be used for indoor lighting. The proposed SSS can be expanded into multiple stacks and stages to optimally split, tune, concentrate and harvest the different ranges of solar spectrum by using appropriate luminescent dyes for each stage. Fig. 4-2e shows the propagation of a point source light located on the focal point of an elliptic/parabolic structure constructed of a solid PMMA polymer. The wave propagation in these structures will be explained in the following section.

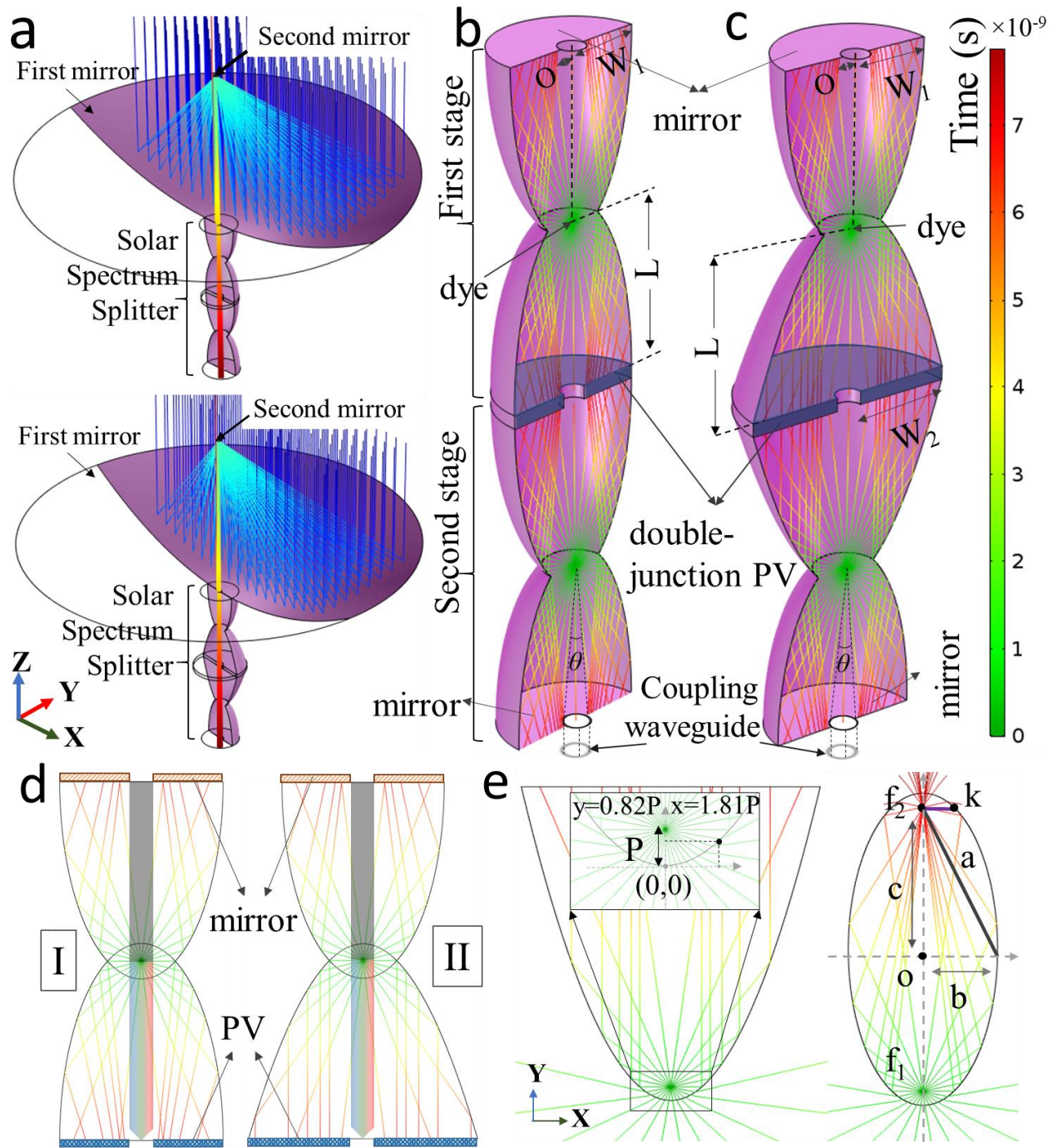


Figure 4-2 a) A Cassegrain-based collimator and a two-stage SSS. b) The Z-Y planar cross-section of the SSS composed of semi-ellipsoids and c) semi-ellipsoids and paraboloids. d) Two-dimensional cross-sectional diagram of the first stages of the SSSs showing light emitted from the focal point undergoing total internal reflection at the internal surfaces of the SSSs. e) The propagation behaviour of a light-point source located on the focal points of an ellipse and parabola made of PMMA ($n = 1.49$). their shared focal point undergoes total internal reflection at their curved sidewalls.

The function of the dye at the focal points in the SSS is to absorb light within a certain spectral range and subsequently isotopically emit light at a longer wavelength. As mentioned, the geometry of the SSS can be designed such that the majority of light isotopically emitted from its focal points is trapped via TIR and ultimately directed towards the PV cell at its midplane.

Designing the curvature and the extent to which the semi-ellipsoids (or the semi-ellipsoid and paraboloid for the SSS shown in Fig. 4-2c) overlap can be described with reference to Fig. 4-2e. The general equations describing the surfaces of a parabola and an ellipse are given in Equations 4.1 and 4.2, respectively:

$$(y - u) = \frac{(x-h)^2}{4P} \quad (4.1)$$

$$\frac{x^2}{b^2} + \frac{y^2}{a^2} = 1 \quad \text{where,} \quad k = \frac{b^2}{a} \quad \text{and} \quad b^2 = a^2 - c^2 \quad (4.2)$$

In the equation for the parabola, u and h represent the x and y intercepts, respectively, which are set equal to zero in this study. K represents the distance from the vertex to the focal point. In Equation 4.2, the shape parameters a and b represent the semi-major and semi-minor axis of the ellipse, respectively.

The internal medium of the SSS is assumed to have an index of refraction equal to n_l and the medium external to the structure is assumed to be air ($n_{air} = 1$). Under these conditions, according to Snell's law, photons emitted from the shared focal points of the overlapped semi-ellipsoids or semi-ellipsoid/paraboloid will undergo TIR at their surfaces when Equations 4.3 and 4.4 are satisfied for the elliptic and parabolic curves, respectively:

$$\left| \frac{dy}{dx} \right| = \left| \frac{x}{2P} \right| > \tan(\sin^{-1}(\frac{n_1}{n_2})) \quad (4.3)$$

$$\left| \frac{dy}{dx} \right| = \left| \frac{x a^2}{y b^2} \right| = \left| \frac{c}{a} \right| > \tan(\sin^{-1}(\frac{n_1}{n_2})) \quad (4.4)$$

$\Big|_{y=c, x=k}$

For example, for a refractive index of $n_2 = 1.49$, which is a good approximation for a PMMA-based SSS, as shown in Fig 4-2e TIR will occur at points on the surface of a parabola for which $x > 1.81P$ and $y > 0.82P$. Likewise, when $n_2 = 1.49$, TIR will occur on the surface of an ellipsoid when $c/a \geq 0.905$. Fig. 4-2d(I) shows two overlapped semi-ellipsoids with $c/a = 0.91$, and Fig 4-2d(II) shows a semi-ellipsoid/paraboloid with $k = 1.32$ cm.

Monte Carlo ray-tracing methods are vastly applied for the numerical modeling and analysis of LSCs [22-25]. Herein, ray tracing and heat transfer modules from COMSOL Multiphysics software (version 5.4) are used to model the light propagation through the double-stack SSSs shown in Fig. 4-2. Analytical analysis performed by MATLAB, are also supplemented to calculate the optical efficiency, emission losses and optical density. The normalized intensity distributions for light emitted from the focal point of the SSS shown in Fig. 4-2b (comprised of double-stacked ellipsoids) at four horizontal cross-sections (labeled I-IV) are shown in Figs. 4-3a and b.

The geometric parameters of the ellipsoids shown in Fig 4-3a are $K = 1$ cm, $c/a = 0.94$, and $L = 0.25, 0.5, 0.75$ and 1 cm for cross-sections I, II, III, and IV, respectively. The annular PV cell within the SSS is to be located at a plane that is at a distance L from the focal point and is parallel to cross-sections I-IV. As L increases the area of the PV cells increases, and the intensity distribution of the radiation broadens in the radial direction. As shown in Fig. 4-3b, the normalized intensity distribution profile has two symmetric peaks due to the emitted light that is specularly reflected from the mirror at the upper surface of the top ellipsoid. As L increases the intensity peaks from light emitted from the focal point in the downwards and upwards (reflected from the mirror) directions approach each other and merge into one peak when the upper and lower semi-ellipsoids have the same length ($L = 1$ cm for the case shown in Fig 4-3a).

Figs. 4-3c and 4-3d illustrate the intensity distribution of light emitted from the shared focal point of a semi-ellipsoid that overlaps with a paraboloid. Three ellipsoid/paraboloid structures are considered wherein $c/a = 0.91$ and I) $P = 0.25$, II) $P = 0.5$, and III) $P = 1$ cm. W is the radius of the top surface of the semi-ellipsoid. As P and W increase the distribution of the radiation intensity broadens in the radial direction, W . For all

cases, due to reflected radiation from the top surface, the radiation intensity has two peaks at the edge of the opening and decreases exponentially in the radial direction.

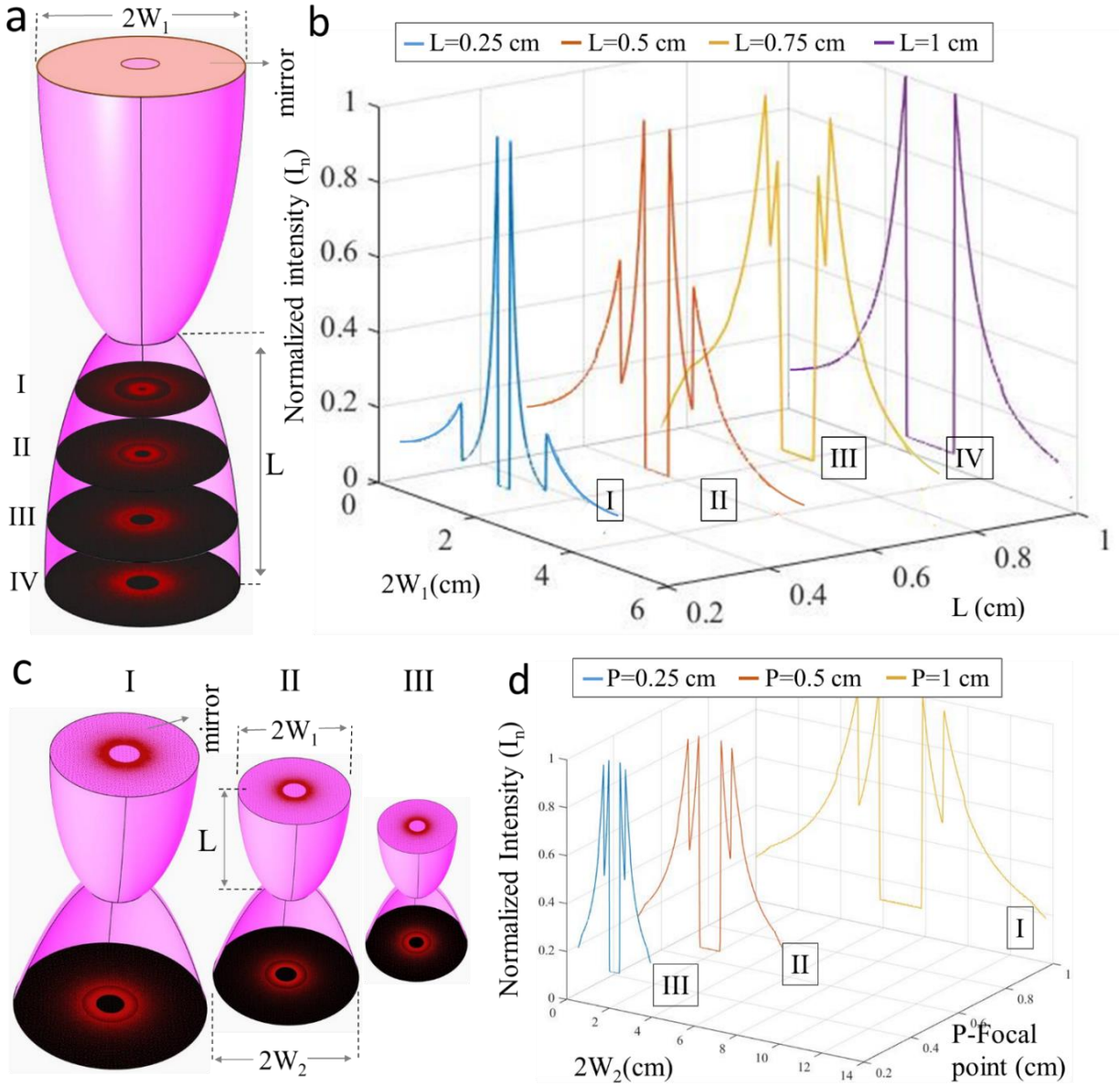


Figure 4-3 a) Four horizontal cross-sections, denoted as I, II, III, and IV, along the length of two overlapped semi-ellipsoids. b) The incident light intensity distribution profile along the width of four horizontal cross-sections: I, II, III, and IV. c) Three different semi ellipsoid-paraboloid configurations denoted as I, II, and III with $c/a = 0.91$ cm for the ellipsoid and focal points of $P = 0.25, 0.5$, and 1 cm, respectively. d) The incident light intensity distribution along the width of the bottom surface of I, II, and III. For all structures considered the top surfaces are assumed to be specular annular mirrors with ideal (100%) reflectivity.

4.4 Types of luminescent dyes required to absorb the non-visible spectrum.

The SSSs shown in Fig. 4-2 sequentially harvests UV and IR light from a collimated sunlight beam. UV light is absorbed at the shared focal point in the first stage of the SSS while IR light is absorbed at the focal point in the second stage of the SSS. A wide variety of phosphorescent materials can be used to absorb UV and IR light at the focal points within the SSS. Organic dyes have an excitonic nature due to their π -conjugated molecular structure which brings tenability and selectivity in harvesting several ranges of the solar spectrum. This potential can be a key factor for non-visible spectrum harvesting. However, two common challenges in organic dyes are: small Stokes shift (<100 nm) and low quantum yields for emitters in the NIR range ($<50\%$) [26].

Quantum dots are another class of phosphorescent materials that can be used to absorb and emit light within the SSS. By varying the reaction conditions and particle size for quantum dots, the absorption and emission spectra can be manipulated. Doping quantum dot semiconductors can significantly decrease their reabsorption losses. The reason is that by adding small amounts of luminescent activator ions throughout the quantum dots, new localized excited states are created within the bandgap of the quantum dots. This causes a significant downshift of the emission spectrum of the quantum dot in comparison to its absorption spectrum [27]. In this regard, a novel class of quantum dots has been introduced based on 0D nanocluster nanocrystals. For an example, a $(\text{TBA})_2\text{Mo}_6\text{Cl}_{14}$ nanocluster showed a considerable Stokes shift of ~ 400 nm with absorption and emission peaks in UV and NIR, respectively, which can result in significant reduction of reabsorption losses in the luminescent dye [28].

Another class of emitters are rare-earth materials. It is shown that rare-earth ions can be directly embedded into inorganic hosts to make them suitable options to harvest the UV spectrum with large Stokes shift (> 200 nm) and sharp emission peaks (< 20 nm) [29-30]. Single-walled carbon nanotubes are another type of photoluminescent material which are comprised of 1D rolled graphene sheets with different tube diameters. This material exhibits a wide photoluminescence tenability in the NIR spectral range with a peak emission ranging from 1000 to 1600 nm. On the other hand, Carbon nanotubes (CNTs) have remarkably small

Stokes shift [31-32]. Table 4-1 provides a summary of the absorption and emission peaks as well as the quantum yield for various emitter materials that can be used to harvest non-visible photons within the proposed SSS.

Table 4-1 Some examples of phosphorescent materials to harvest non-visible spectrum.

Luminophore	Absorption $\lambda_{\max}$ (nm)	Emission $\lambda_{\max}$ (nm)	Quantum Yield (%)	Reference
Cyanine Salt	742	772	20–30	[33]
CdSe/CdS QDs	< 450	650	65	[34]
Mn ²⁺ :ZnSe/ZnS NCs	400	600	37	[35]
CuInSe _x S _{2-x} /ZnS QDs	500	960	40	[36]
CdSe/Cd _x Pb _{1-x} S QDs	460	625	40	[37]
(TBA) ₂ Mo ₆ Cl ₁₄ NCs	325	750	75	[28]
R-phycoerythrin (R-PE)	425	625	39	[38]

4.5 Geometric gain factor and emission losses for the double-stack semi-elliptic/parabolic solar spectrum splitter

The geometric gain factor (G) is defined as the planar area of the solar receiver that has its normal direction pointing towards the sun divided by the area of the PV cells. Referring to Fig. 3, G decreases as W increases. The primary loss mechanism for radiation emitted from the focal point of the SSS is the emission that propagates through the ports at the center of the specular mirror and annular PV cell on its upper and lower surfaces, respectively (emission losses). As expected, losses increase as the radius of the port, O , increases. For a constant value of O , the losses decrease as L increases.

4.6 Effects of special distribution of the luminescent dye on the efficiency of the double-stack semi-elliptic/parabolic solar spectrum splitter

In Figs. 4-2, and 4-3 it is assumed that the emitter material is located precisely at the focal points within each stage of stacked SSS. In practice, the fluorescent dye will occupy a finite volume. The volume occupied by the emitting dye in the first stage (or second stage) of the SSS depends on the amount of dye required to absorb the UV light (or IR light) in the collimated sunbeam. The offset for the location of phosphorescent dyes from the shared focal point (due to the finite volume of the dye region not all dyes will be precisely at the focal point) can increase emission losses and the traveling distance within the host material (resulting in transmission losses). These loss mechanisms will be discussed in Section 1.7. In the following, a sample calculation for the volume of the dye region and the effects of the spatial distribution of the luminescent dye on the optical emission losses is presented.

First, it is assumed that the area of the Cassegrain reflector is 0.2 m^2 and each semi-ellipsoid or paraboloid of the SSS has a length of 7 cm, and $c/a = 0.95$, such that the total length of the two-stage SSS (as shown in Fig. 4-2b or 4-2c) would be 28 cm (the thickness of the PV cell is neglected). These assumptions result in a concentration factor of 120 and 60 for double-semi-ellipsoid and a semi-ellipsoid-paraboloid SSS structures, respectively. To estimate the volume occupied by dye at the focal point within the first stage, CdSe/CdS quantum dots are considered which is a UV absorption-based phosphorescent material [34]. This quantum dot can absorb light up to wavelength of 435 nm and emits photons with an emission peak of $\sim 650 \text{ nm}$. Furthermore, it is assumed that the radius of the quantum dots is $\sim 5 \text{ nm}$, the radiative lifetime is $\sim 5 \text{ ns}$ [39], and the solar photon flux in the spectral region from $280 \sim 435 \text{ nm}$ is $1.7 \times 10^{20} / \text{s} \cdot \text{m}^2$. It is also assumed that the density of the region comprising the luminescent dye solution is equal to that of its host matrix (e.g. glass or PMMA) and that the dye is 0.1 wt% of the volume it occupies, which results in negligible effects of self-quenching or agglomeration. Based on these assumptions it is estimated that the volume required to host a sufficient amount of quantum dot luminophore in the first stage of the SSS is $\sim 0.1 \text{ mm}^3$. By assuming similar conditions for the second stage of the SSS and using near-IR polymethine dye to harvest the IR and

NIR spectrum in range from 675 to 900 nm and a photon flux of $9.43 \times 10^{20} / \text{s} \cdot \text{m}^2$, the volume required to host a sufficient amount of luminescent dye for second stage will be $\sim 0.6 \text{ mm}^3$.

To investigate the effects of the spatial distribution of the luminescent dye on the optical emission losses, the losses for luminescent point sources located in a three-dimensional grid array were calculated. The approach used to calculate the emission losses is similar to that presented in Section 2.5. The optical losses due to emission through the entrance and exit ports when the luminescent dye/quantum dot is optimally distributed over a 0.1 mm^3 volume is determined to be $\sim 0.5\%$ for both the double semi-ellipsoid and semi-ellipsoid-paraboloid SSSs. Furthermore, for the second stage as supposed to be occupied by $\sim 0.6 \text{ mm}^3$ luminescent dye, the optical loss through the ports for optimally distributed dye will be 1.5% for a semi-ellipsoid-paraboloid structure and 4% for double-semi-ellipsoid configuration.

The percentage of radiation emitted from the dye/quantum dot that is lost through the exit and entrance ports is shown in Fig. 4-4 for displacements of the emitting material from the focal point for both structures with $L = 7 \text{ cm}$, $O = 0.35 \text{ cm}$ and $c/a = 0.95 \text{ cm}$. The emission losses and intensity distribution of radiation incident onto the annular PV cell from dye molecules that are offset from the focal point in the X-Y plane are shown in Figs. 4-4a I-II and 4-4b I-II. Similarly, Figs. 4-4a III-IV and 4-4b III-IV shows the emission losses and intensity distribution for out-of-plane (z-axis) displacements of dye. Finally, the effects of dye offsets where both in-plane and out-of-plane displacements occur, are illustrated in Figs. 4-4a V-VI and 4-4b V-VI. As an example, for the semi ellipsoid-paraboloid structure, the emission losses for an in-plane dye offset by $r = 1$, and $r = 1.5 \text{ mm}$ is 3.6, and 3.14%, respectively.

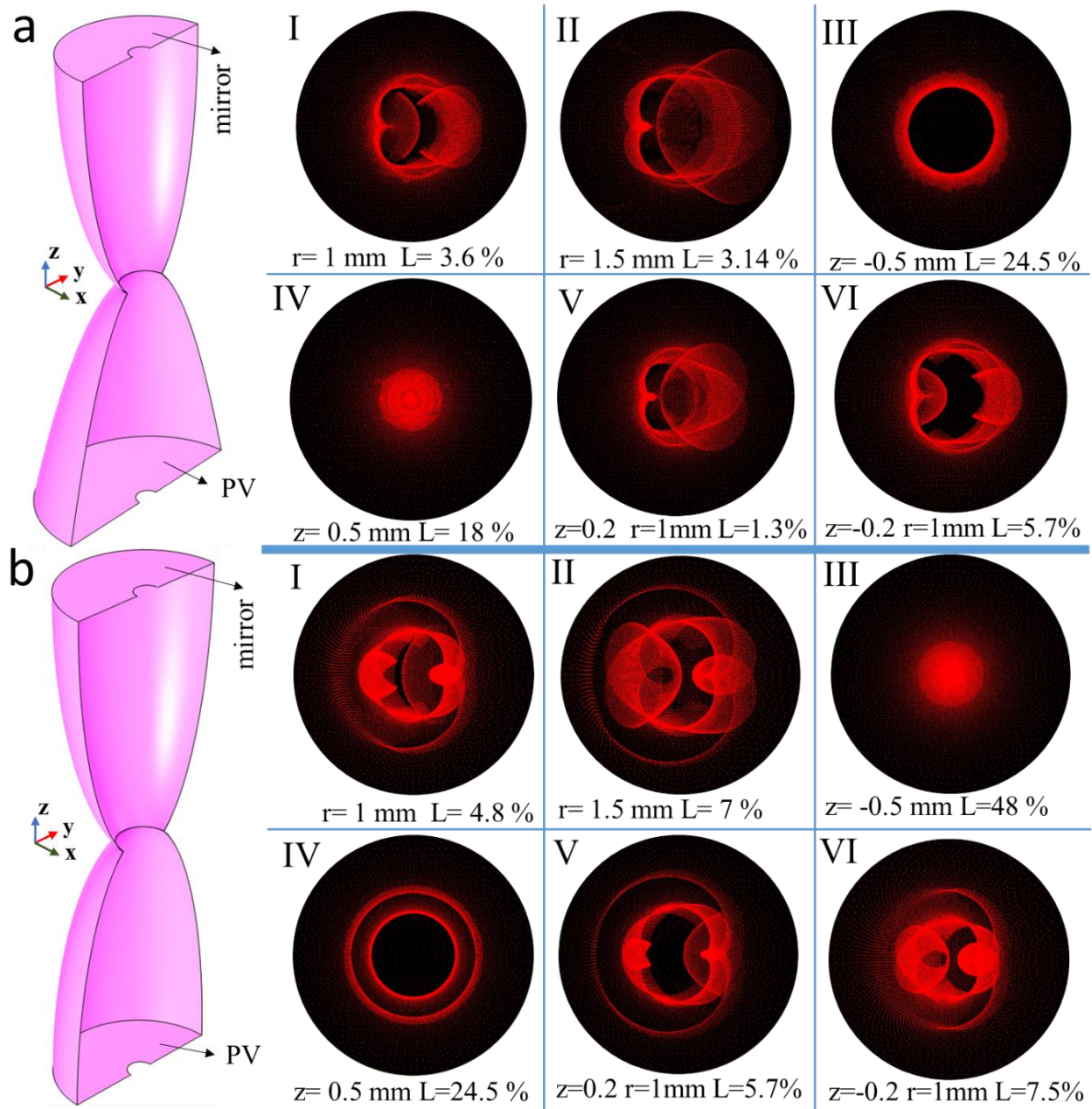


Figure 4-4 The spectral intensity distribution of radiation incident onto the annular PV cell from dye molecules that are displaced in the radial and vertical directions by a distance of r , and z , respectively for a) a semi-ellipsoid/paraboloid SSS and b) a double semi-ellipsoid SSS. The corresponding loss ratio for the dye molecules located at (r, z) are also provided.

4.7 Evaluating the optical efficiency of the double-stack semi-elliptic/parabolic solar spectrum splitter

The overall efficiency of the proposed SSS can be evaluated using the concentration factor (C), which is defined as the light intensity incident onto the annular PV cells (Φ_2) divided by the light intensity incident onto the Cassegrain solar concentrator (Φ_1): $C = \Phi_2/\Phi_1$. The concentration factor can be rewritten as $C=G\cdot\eta_{non-Vis-opt}$, where G is the geometrical gain factor and $\eta_{non-Vis-opt}$ is the optical efficiency of the SSS for the incident non-visible spectrum which is given by:

$$\eta_{non-Vis-opt} = \eta_{Fresnel} \cdot \eta_{non-Vis-Abs} \cdot \eta_{PLQY} \cdot \eta_{Stokes} \cdot \eta_{Emission} \cdot \eta_{Roughness} \cdot \eta_{Transmission} \cdot \eta_{self-abs}. \quad (4.5)$$

This equation can be considered for each stage separately to calculate the optical efficiency for the wavelength range from 280 to 435 nm (η_{UV-opt}), and 675 to 900 nm (η_{IR-opt}). Each of the efficiencies shown in Equation 4.5 are explained in Section 2.6. Based on the assumptions and analysis regarding the optical efficiency we reported in Section 2.6, it was concluded that for η_{UV-opt} , $\eta_{Fresnel} = 0.96$, $\eta_{non-Vis-Abs} = 100\%$, $\eta_{PLQY} = 65\%$, $\eta_{Stokes} = 100\%$, $\eta_{Emission} = 99.5\%$, $\eta_{Roughness} = 90\%$, $\eta_{Transmission} = 94\%$, and $\eta_{self-abs} = 50\%$. Likewise, for η_{IR-opt} , $\eta_{Fresnel} = 0.96$, $\eta_{non-Vis-Abs} = 100\%$, $\eta_{PLQY} = 75\%$, $\eta_{Stokes} = 100\%$, $\eta_{Emission} = 98.5\%$, $\eta_{Roughness} = 90\%$, $\eta_{Transmission} = 94\%$, and $\eta_{self-abs} = 90\%$. The resulting total efficiencies are $\eta_{UV-opt} = 27\%$ and $\eta_{IR-opt} = 55\%$ for the semi-ellipsoid-paraboloid structure.

4.8 Estimating the electric power generated by the double-Stack semi-elliptic/parabolic solar spectrum splitter

Here we calculate the electrical energy generated from the SSS. In this regard, the spectral regions from 280 ~ 435 nm ($\Delta W_1 = 86.85 \text{ W/m}^2$) and 675 ~ 900 nm ($\Delta W_2 = 240.2 \text{ W/m}^2$) can be absorbed in the SSS and converted to electricity in bifacial c-Si PV cells to power an HSL system. Here we assume the Cassegrain concentrator has a projected area of $A = 0.2 \text{ m}^2$ and the photon flux incident onto the bifacial c-Si PV cell at

the middle part of SSS for these spectral regions are $\Phi_{\Delta W1} = 1.7 \times 10^{20} / \text{s} \cdot \text{m}^2$ and $\Phi_{\Delta W2} = 9.43 \times 10^{20} / \text{s} \cdot \text{m}^2$, respectively.

Moreover, we assume the PV cells have an External Quantum Efficiency (EQE) of $EQE_{\Delta W1}^* \cong 100\%$ and $EQE_{\Delta W2}^* \cong 85\%$, for light that was absorbed by the dye in spectral regions $\Delta W1$ and $\Delta W2$, and emitted in spectral regions $\Delta W1^*$ and $\Delta W2^*$, respectively [40-42]. Under these assumptions, the short circuit current (I_{sc}), open circuit voltage (V_{oc}) and the maximum output power (P_{max}) generated by the PV cell are calculated using Equations 4.6, 4.7 and 4.8, respectively [43]:

$$I_{sc} = A \cdot q \cdot \left(\int_{\Delta W1} \eta_{UV-opt} \cdot \Phi_{\Delta W1}(\lambda) \cdot EQE_{\Delta W1}^*(\lambda) \cdot d\lambda + \int_{\Delta W2} \eta_{IR-opt} \cdot \Phi_{\Delta W2}(\lambda) \cdot EQE_{\Delta W2}^*(\lambda) \cdot d\lambda \right) \quad (4.6)$$

$$V_{oc} = \frac{nkT}{q} \ln \left(\frac{I_{sc}}{I_0} + 1 \right) \quad (4.7)$$

$$P_{max} = I_{sc} \cdot V_{oc} \cdot FF \quad (4.8)$$

Where $n = 1$ is the ideality factor, k is Boltzmann's constant, $T = 300$ K is the cell temperature, $I_0 = 10^{-10}$ A is the dark saturation current, q is the charge of an electron, and FF is the fill factor which can be expressed as a function of open-circuit voltage (V_{oc}) [43]:

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \quad (4.9)$$

where

$$v_{oc} = V_{oc} \frac{q}{k_B T} \quad (4.10)$$

is a normalised voltage. Equation 4.9 is assumed as an appropriate approximation of the FF when $v_{oc} > 10$. Based on Equation 4.8, out of a total of 65.4 W of non-visible light incident in the $\Delta W1$ and $\Delta W2$ spectral regions, 8.76 W can be converted to electric power, representing a total non-visible to electric power conversion efficiency of 13.4% (where $I_{sc} = 15.55$ A, $V_{oc} = 0.67$ V, and $FF = 0.841$). This power can be used

to operate the two-axis solar tracking system (estimated to be ~ 0.36 W) [44], light sensors and control the systems to regulate the indoor lighting.

4.9 Effect of surface roughness

It should be noted that, with regards to the optical configurations that use TIR, surface roughness and imperfections affect the performance of the device and create scattering losses. Loss mechanisms and scattering losses due to the surface roughness in optical waveguides have been vastly investigated in the literature. The Total Integrated Scattering (TIS) has been defined to consider the effect of the root mean square of surface roughness in an optical waveguide [47- 49]:

$$\text{TIS} = R_0 \left[1 - \exp \left[- \left(\frac{4\pi\sigma \cos\theta_i}{\lambda} \right)^2 \right] \right] \quad (4.11)$$

Where, R_0 , σ , θ , and λ represent the surface reflection, root mean square of the surface roughness, incident angle and the wavelength of the incident light. TIS is defined as the ratio of the incident wave and the scattered light. One condition should be considered in this equation: the root mean square value of the surface roughness should be small in comparison to the wavelength of light [50]. As can be seen, as the wavelength of the incident light decreases, the amount of scattering due to surface roughness increases. For greater values of surface roughness, in comparison to the wavelength of light, the incident light can either be refracted to outside or guided in the waveguide due to TIR. For the applications considered in this thesis the wavelength range of interest is ~ 380 nm to ~ 1000 nm. It should be noted that, current technology can provide optical elements 3D printed with nanometer (~ 5 nm) scale surface roughness [51, 52].

4.10 Conclusion

In this chapter, an HSL system is presented to fully utilize the broadband solar spectrum for indoor lighting and electric power generation. The HSL is composed of a paraboloid/ellipsoidal structure constructed of PMMA polymer, phosphorescent dyes and a bifacial PV cell to partition the collimated concentrated solar spectrum into visible light for indoor lighting and non-visible light to be converted to electricity. The

analysis shows a system efficiency of 13.4% for non-visible-to-electricity energy conversion. The visible light can be coupled to waveguides to offset the need for indoor lighting, and the electric power generated in the system can be used to run and control the HSL system.

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5 The effect of optical cavities on thermophotovoltaic (TPV) systems¹

Nomenclature			
<i>Roman symbols</i>		P_{emission}	emission power
A_{abs}	absorber area	P_{input}	input power
A_{emt}	emitter area	P_{inband}	in-band power
BB	blackbody	P_{loss}	loss power
C	solar concentration	$P_{\text{PV-in}}$	power received by the PV cell
c	light speed	R_{inband}	in-band power ratio for cavity and non-cavity emitter
$E_{b\lambda}$	blackbody spectral emissive power	T_0	emitter temperature without cavity
E_λ	spectral emissive power	T^*	emitter temperature within a cavity
E_g	bandgap energy	<i>Greek symbol</i>	
F_{PV}	view factor	η_{inband}	in-band power over total emissive power
F_{loss}	loss factor	$\eta_{\text{conv-eff}}$	conversion efficiency
F_{rec}	recycling factor	λ	wavelength (nm)
G	direct solar irradiance	λ_g	bandgap wavelength (nm)
h	Planck constant	σ	Stefan-Boltzmann constant
k_0	Boltzmann constant	ϵ_{emt}	emissivity of the emitter
$P_{\text{conversion}}$	conversion power	ϵ^*	effective emissivity
		α_{abs}	total absorption

5.1 Introduction

Thermo-photovoltaic (TPV) systems are optical heat engines that directly convert radiant heat to electricity using a photovoltaic (PV) cell. TPV is a highly promising technology because it can potentially be used to generate electric power from any high-temperature heat source including concentrated solar irradiance, industrial waste heat, heat from radioisotope decay, and fuel combustion systems. The only necessity is that the temperature should be high enough for the photon-to-electron conversion to occur. This makes TPV a flexible and versatile/multi-purpose technology with many applications: portable generators, uninterruptible power supplies, remote renewable hybrid systems, auxiliary power supplies in vehicles, micro-combined

¹ This chapter is based on references [73, 74]

heat and power systems, solar energy conversion, self-powered heating devices and industrial waste heat recovery [1].

TPV systems are composed of two main components: 1) an emitter that is heated to provide radiant energy, and 2) a PV cell that absorbs radiation from the emitter and generates electric power. It should be noted that most TPV systems have additional components such as optical filters to reflect photons with energy less than the bandgap of the PV cell back to the emitter. Also, the PV cell often has a rear-side reflector to return incident light not absorbed by the PV cell back towards the emitter. Furthermore, solar thermophotovoltaic (STPV) systems, which use concentrated solar energy as a heat source, are equipped with an absorber, which converts incident sunlight into heat and transfers it to the emitter.

To provide further explanation about TPV systems, the operating principles of STPVs, which are one of the promising TPV technologies and a main subject of study in this thesis, is provided here. In typical solar panels comprised of single-junction PV cells, electricity is generated by directly absorbing the solar irradiance in a semiconductor layer with a fixed electronic bandgap. However, the solar spectrum is very broad and PV cells suffer absorption and thermalization losses. That is, PV cells are not able to absorb solar photons with energy less than their bandgap, and energy in excess of the bandgap generates heat and thermal losses rather than contributing to the electric power output from the cell. In fact, as defined by the Shockley–Queisser limit [2], at least 60% of the solar irradiance is lost due to the inability of single junction PV cells to effectively convert light energy over a broad spectral region into electric power. Further, the Shockley–Queisser analysis reveals that if broadband sunlight energy can be converted into incident photons with energy slightly above the bandgap of the PV semiconductor, a single-junction-based PV cell can achieve an efficiency of 85.4% [3].

STPV systems utilize an intermediate element, situated between the sun and the PV cell, to convert the solar irradiance into light energy with a more favorable spectrum for which PV cells work with higher efficiency (Fig. 5-1). The intermediate element shown in Fig. 5-1b, is comprised of a broadband absorber that is highly

absorbing over the entire solar spectrum and an emitter that provides radiant energy with an optimized spectrum to be harvested by a PV cell (a spectrally selective emitter).

It is important for emitters within TPV systems to generate radiant energy with optimal spectral, angular and spatial distributions to maximize the harvestable radiation energy that is incident onto the PV cell. In STPV systems the intermediate element should be able to provide broadband absorption of light over the solar spectrum and adjust the emission spectrum to match the absorption characteristics of the PV cell. Fig. 5-1c shows the solar spectrum incident onto a broadband absorber and the emission spectrum from a thermal emitter within a TPV system. Ideally, the absorber absorbs the solar irradiation and the emitter radiates thermal emission slightly above the bandgap of the PV cell. As the operating temperature of the emitter increases its emission spectra shifts towards higher energies and begins to overlap the solar spectrum. In this case it is desirable for the absorber to have a low emissivity over the long-wavelength portion of the solar spectrum to prevent radiative losses over this spectral region. Considering Kirchhoff's law of thermal radiation, if the emissivity is low then the absorption must also be low over this spectral region, as is shown in Fig. 5-1c.

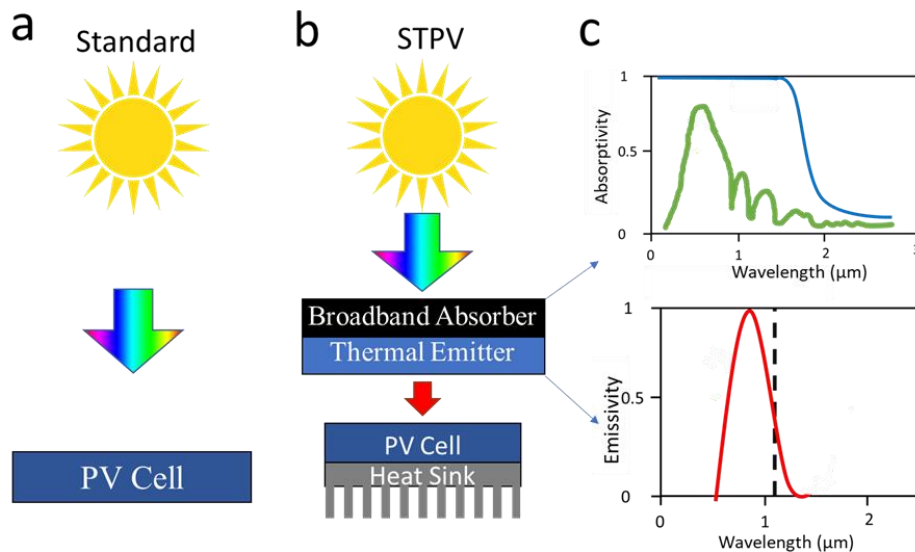


Figure 5-1 Solar energy flow for a) standard PV cell and b) STPV system. c) Top: The incident solar spectrum (green line) and favorable absorptivity (blue line) for a solar absorber are shown in the top graph. Bottom: A favorable emission spectra (red line) with peak emission energy just above the PV band-gap energy (dashed line) is shown in the bottom graph.

Many different STPV system designs have been reported in the literature. For example, Rana et al. [4] presented a Tantalum (Ta) based meta-material structure as an ultra-broadband absorber and selective emitter for an SPTV system. Tantalum can be an appropriate candidate for STPVs due to its thermal stability at high temperatures. They used cross-shaped Ta structures due to its highly spectral sensitivity and polarization insensitivity behaviour. Their analytical and numerical calculations showed the structure can absorb 92% of the direct AM1.5 solar spectrum and had a PV cell efficiency of 41.8% for an InGaAsSb PV cell with a 0.55 eV bandgap. Kohiyama et al. [5] used a confined cuboid emitter to significantly increase the photon recycling factor in an STPV in order to decrease the emission losses and increase the system efficiency. They showed that the photon recycling in the proposed system can increase the temperature of the emitter which results in a 1.5% increase in the PV conversion efficiency when solar radiation is incident at an intensity of 200 W/cm². They described that the efficiency of the system could be increased to more than 20% by further improving the back surface reflector. Pirvaram et al. [6] designed a one-dimensional multi-stack photonic crystal optical filter in order to reflect low energy photons and transmit high energy photons in a TPV system. The optical filter is comprised of alternating layers (bilayers) of dense zirconia and zirconia aerogel. They showed that for an ideal case composed of two parallel infinite plates as an emitter and a GaSb PV cell, system efficiency and spectral efficiency can reach to 33% and 46%, respectively. Kelsall [7] demonstrated a cylindrical hollow core-based graphite absorber for STPV systems. They showed that the optimized system design parameters can lead to a 9% system efficiency at 3600X solar concentration.

The absorber/emitter structure in TPV and STPV systems can be categorized as naturally selective materials and metals, composite materials, multilayered stacks, 1D, 2D and 3D photonic crystals, meta-materials and meta-surfaces [8]. Other key factors in STPV systems are the solar concentration factor and the maximum achievable operating temperature for the absorber, and the ratio between the area of the emitter and the area of the absorber [13, 18]. A summary of STPV systems reported in the literature, along with their system design details and efficiencies is provided in Table 5-1.

Table 5-1 A summary of different STPV systems

Config.	Absorber	Emitter	Sun conc.	PV type	Efficiency	Comment	Year	Ref.
cylindrical	hollow core	Bare tungsten	4000	GaSb	~ 10%	- Experimental	2005	[9]
planar	multiwalled carbon nanotubes (MWCNTs)	1-D Si/SiO ₂ photonic crystal	750X (T=1285 K)	InGaAsSb	3.2%	- Experimental - The absorber–emitter areas optimized to tune the energy balance of the device=> $A_e/A_a=7$	2014	[10]
planar	2D PhC on Ta	2D PhC on Ta	130 (130 kW/m ²)	InGaAsSb (E _g = 2.3 um)	3.74%	- Experimental - Both the absorber and the emitter side are based on the 2D PhC however with different geometrical parameters.	2014	[11]
planar	1D PC (YSZ and W stack)	1D PC (YSZ and W stack)	45 W/cm ² (T _{emit} = 1640 K)	GaSb	8% (Exp.) 16% (Theory)	- Experimental - Multilayer coating consists of thin-film tungsten sandwiched by yttria-stabilized zirconia. - View factor is assumed to be 1	2015	[12]
planar	Multilayer sandwiched	Multilayer sandwiched	102 W/cm ² (1640 K)	GaSb	5.1%	- Experimental - Area ratio of $A_{em}/A_{abs} = 2.3$ - Multilayer structure based on hafnium oxide (HfO ₂) and molybdenum	2016	[13]
planar	multiwalled carbon nanotube (MWCNT) forest	1D PC Si/SiO ₂	800X (1273 K)	InGaAsSb	6.8%	- Experimental - Tandem plasma–interference optical filter is placed on the PV - Two area ratios are considered: 7 & 12	2016	[14]
Cage type	HfO ₂ /Mo/HfO ₂ films on a metallic surface	HfO ₂ /Mo/HfO ₂ films on a metallic surface	-	-	15% increase in comparison to ideal case	- Theoretical - A bifunctional hybrid absorber–emitter - Sequentially depositing HfO ₂ /Mo/HfO ₂ films on a metallic surface - Simultaneous broadband solar absorption and narrowband infrared emission are enabled by the same surface of the structure - It is theoretically shown that the HAE-based cage-type STPV can enable a maximal system efficiency increment of >15% compared to the double-side planar systems	2018	[15]
planar	Titanium nitride nanopatterns/dielectric/TiN stack metamaterial	Titanium nitride nanopatterns/dielectric/TiN stack metamaterial	1900 K	E _g =0.5 eV	36%	- Theory - Metamaterial structure based on TiN-nanopatterns/AlN/TiN stack - Angle-insensitive absorption/emission,	2015	[16]
cylindrical	Hollow core (graphite)	tungsten coated with HfO ₂	3,200X (T=1700 K)	Ge (E _g =0.66)	0.8%	- Experimental & theoretical - Concentrator efficiency of 65–70% - Efficiency of 2.5% is predicted by T _{cell} = 300 K and FF=0.65	2013	[17]
planar	selective metamaterial	selective metamaterial	200X	InGaAsSb	12.6%	- Theoretical - $A_{em}/A_{absratio} = 4$ - if $A_{em}/A_{absratio} = 1$, efficiency=10%	2016	[18]
planar	tungsten with an anti-reflectio	tungsten with single-layer dielectri	2,500X (T=1777 K)	GaSb	6.2%	- Experimental study - Simulated solar energy. - Simulations show that this efficiency would rise to 7.5% if the PV cell was kept at room temperature during the measurement	2015	[19]

	n layer (Si ₃ N ₄) and laser-microtextured	c coated (Si ₃ N ₄)						
planar	Ta PhC	Ta PhC	130 kW/m ² (T=1400 K)	InGaAsSb	10%	- Analytical - Tandem filter on PV	2014	[20]
planar	Meta material	Meta material	500X	InGaAsSb (E _g =2.3 um)	14.8%	- Theory - Optimized area ratio of 32 for this efficiency (14.8%)	2017	[21]
cylindrical	Hollow core	Graphite or Tungsten	3,600 (T=1800 K)	GaSb	9%	- Emitter is fabricated but the total efficiency is calculated/estimated from the real data from emitter - Emitter is either Tungsten or Graphite	2018	[22]
-	Tungsten cavity	Thin W film	T=2000 K	GaSb	1%	- Experimental	2007	[23]
-	Pyramid W nano-structure	Si/SiO ₂ stack	T=6000 K	GaSb	49%	- Theoretical only	2009	[24]
-	Periodic hole array on W	Pseudo-random cones on W	T=1700 K	GaSb	14.4%	- Theoretical only	2015	[25]
-	Selective absorber	W surface grating with Si/SiO ₂ filter	T=1920 K	GaSb	23.4%	- Theoretical only	2011	[26]
-	Blackbody absorber	Monochromatic emitter	T=2872 K	Ideal cell	45.3%	- Theoretical only	2013	[27]

5.2 Market potentials

Market potentials for TPV systems can be categorized based on user needs, power demand, market value and market size [1]. As an example, Ref. [28] presented potential examples of TPV-based portable power generators arranged by their power range: watt to kW (home electronics and soldier equipment), kW to 10 kW (recreational vehicles), 10 to 100 kW (small-scale cars and vehicles), and larger than 100 kW (spacecraft and electric bus). Ref. [29, 30] assessed the market in the area of TPV systems for the commercial market of Japan. Based on their investigation, portable power generator and micro-CHP were the most favourable applications.

5.2.1 Market potentials for Canada

Canada is a well-developed country with lots of demands and opportunities in energy sectors. In addition to the above-mentioned applications, the nuclear technology of Canada is another promising and highly potential example: According to the Canadian nuclear FACTBOOK released in 2020, Canada has been one of the world's strongest nuclear energy ecosystems in the world. It is also positioned to be a leader in the next generation of nuclear technology. This technology is the second most utilized source of energy to provide Canada's electricity. The cost of nuclear power in Ontario in 2018 has been the second cheapest source of energy (7.7¢ / kWh which is six times cheaper than solar energy and twice as cheap as gas and wind energy sources) [31]. Using Molten Salt Reactors (MSR) and integral-core MSR (iMSR) has been the most interesting prospect for Canada in the short to medium term as well as one of the most remarkable/fascinating recycling scenarios for the future of nuclear power in the province of Ontario. In these types of reactors, molten salt is as a carrier for nuclear fuel in liquid form. The outlet temperature of this carrier can vary from 460 °C to 1430 °C. This heat source can be a significant source of high-energy thermal photons to be converted to electricity by using of the invented TPV system [31, 32].

Another important sector that Canada has a great potential to use TPV systems in is the space sector. The Canadian Space Sector generated \$5.7 billion, contributed \$2.5 billion to the GDP, and supported ~21,000 jobs in 2018 [33]. Furthermore, it is estimated that the space sector provides revenues of ~300 billion USD globally [34].

There is a strong need for generating more power in space applications. The reason is, space missions are very costly, limited and often short-lived. The capabilities and overall value of a space mission depends on the energy and power available on a space craft. For many space missions it is not possible to bring an energy source that can supply the required power throughout the entire duration of the mission. Energy can be harvested from the sun using PV cells, or from the orbital energy of a spacecraft using electrodynamic tethers [35]. However, these sources of energy are not always available and require additional components, increasing the size and weight of a spacecraft. It is recognized that TPV technology has a significant and

influential role in space applications due to its inherent advantages over other thermal-to-electric conversion systems [39- 39]. According to recent research and articles, the following three approaches can bring a significant advancement in space technology/applications and increase the duration of space missions:

- a) Radioisotope TPV (RTPV) as the main power generator: RTPV, especially for deep space applications, can bring a higher system efficiency and specific power in comparison to radioisotope thermoelectric generators and Stirling radioisotope generators which have been previously used for deep space applications [36].
- b) Waste heat recovery: Presently, excess heat on spacecrafts is largely unused, and is most often concentrated and transported to a radiator and emitted to space to prevent the spacecraft from overheating. Nevertheless, unwanted heat on spacecrafts has great potential to generate electrical power independently of solar panels [40]. TPV technology with a very high power density can be a great match for this applications.

IR power beaming: Previously, space power beaming was based on microwave transmission [41]. This method is very costly and has many disadvantages. Recently, IR power beaming using GaSb PV cells has emerged which can provide 24 hour per day power with 40% efficiency [41, 42].

5.3 Competitors, alternatives, and advantages

Competing technologies can be compared based on different parameters such as power densities (W/kg and W/m^3) and conversion efficiencies. Five classes of competing technologies that convert the same types of heat sources that TPV systems use (chemical and nuclear energy, waste heat, and sun radiation) are: External heat engine generator, internal heat engine generator, electrochemical cells, direct heat-to-electricity converters, and solar photovoltaics. Examples for each of the five classes of competing technologies are provided subsequently [43, 44].

- a) **Heat engine generators** can convert thermal energy from any of the four heat sources explained above into work and subsequently into electricity if desired. Examples of heat engine generators include internal combustion engines (ICEs), external combustion engines (ECE) including steam turbines (Rankine cycle) and Stirling engine generators. ICEs are noisy, exhibit limited performance at low power ranges and have high-maintenance costs. ECEs are costly and still in a field test phase.
- b) **Electro-chemical cells** use stored chemical energy to provide electric power on demand. Examples of electro-chemical cells include different types of tertiary cells (fuel cells) and batteries. By using a combustor powered by any fuel such as H_2 , propane, or methanol in a TPV system, the TPV system can convert stored chemical energy into electrical energy. Thus, the TPV system, when combined with stored fuel, can provide functions similar to that of batteries. In electrical power generation mechanisms two important parameters should be considered to evaluate the system: power and energy density. The energy density of fuels is much greater than that of batteries and even at low photoconversion efficiencies (<5%) the TPV system, when powered by stored fuel, has a much higher energy density than state-of-the-art lithium-ion rechargeable batteries. In fact, it is estimated that a fuel-powered TPV system can easily reach energy densities of ~ 1000 Wh/kg, which is 5 times more than that of rechargeable lithium-ion battery technology [45]. Furthermore, the proposed fuel-powered TPV system is expected to exhibit higher reliability and safety as compared to lithium-ion battery technology.
- c) **Direct heat-to-electricity conversion devices** includes TEGs, alkali metal thermal-to-electric converters (AMTEC), and thermionic converters. TEGs have lower efficiencies and electric power density, and also higher costs in comparison to developed TPV systems. AMTECs deteriorates over time. The components in a thermionic technology, especially the emitter, is complex.
- d) **Solar photovoltaics** includes single junction, multijunction, thin-film, dye-sensitized, perovskite, organic and quantum dot cells. Currently the market is dominated by crystalline single-junction silicon PV cells. The conventional PV panels available in the market have maximum efficiencies of

about 22% [46]. However, by optimizing an STPV system, the thermal radiation-to-electricity conversion efficiency can reach as high as 85.4% in theory [47].

TPV systems have several advantages including: No moving parts and vibrations, no direct contact with a heat source, low or no noise, low maintenance, high reliability, versatile fuel usage, continuous combustion, low or no pollution, long operation time, good scalability, potential for use in hybrid systems, combined heat and power applications, and very high electrical power density. It should be noted that, recently TPV systems have reached a world-record system efficiency of ~30% which is the highest among the static-based heat-to-electricity converters [48]. It should be mentioned that STPV systems require a solar tracker system which can increase the system complexity and cost.

5.4 Thermophotovoltaic systems and optical cavities

The radiative heat transfer power for a surface is calculated by the Stefan–Boltzmann law:

$$P_{\text{emission}} = \int_0^{\infty} E_{\lambda}(\lambda, T_0) d\lambda \quad \& \quad E_{\lambda}(\lambda, T_0) = \varepsilon_{\text{emt}}(\lambda) \cdot E_{b\lambda}(\lambda, T_0) \quad (5.1)$$

where, $\varepsilon_{\text{emt}}(\lambda)$ is the emissivity factor, T_0 is the temperature of the emitter, and $E_{\lambda}(\lambda, T_0)$ and $E_{b\lambda}(\lambda, T_0)$ are the spectral emissive power of the emitter and blackbody spectral emissive power, respectively. According to Planks law:

$$E_{b\lambda}(\lambda, T_0) = \frac{2\pi hc^2}{\lambda^5 \left[\exp\left(\frac{hc}{\lambda k_0 T_0}\right) - 1 \right]} \quad (5.2)$$

Equation 5.1 can be simplified to Equation 5.3 for a graybody surface:

$$P_{\text{emission}} = \varepsilon_{\text{emt}} \cdot \sigma \cdot T_0^4 \quad (5.3)$$

where, $\sigma = 5.67 \text{ W/m}^2 \text{ K}^4$ is the Stefan-Boltzmann constant. The thermal radiation-to-electricity convertible power for a TPV system, and conversion efficiency can be calculated by Equation 5.4 and 5.5, respectively:

$$P_{conversion} = F_{pv} \cdot \int_0^{\infty} E_{\lambda}(\lambda, T_0) \cdot EQE(\lambda) d\lambda \quad (5.4)$$

$$\eta_{conv-eff} = \frac{P_{conversion}}{P_{input}} \times 100\% \quad (5.5)$$

where, F_{pv} is the emitter-to-PV cell view factor and $EQE(\lambda)$ is the external quantum efficiency of the PV cell which determines the ratio of the number of electric charge carriers generated in the PV cell to the number of photons incident onto the surface of the PV cell. Achieving high efficiencies in TPV systems depends on matching key parameters in Equation 5.1 to 5.4: 1) the emissivity of the emitter ($\varepsilon_{emt}(\lambda)$) should ideally be one for the spectral region just above the bandgap of the PV cell, and zero over other spectral ranges to achieve the maximum photoconversion efficiency, 2) the higher the temperature of the emitter (T_0) the higher the amount of spectral emissive power above the bandgap energy of the PV cell (in-band photons) that can be converted to electricity, 3) the higher the emitter-to-PV cell view factor (F_{pv}) the higher the fraction of emitted radiant power captured by the PV cell. and 4) different types of PV cells have different bandgaps and $EQE(\lambda)$, which determines how the radiation spectrum incident onto the PV cell is converted to electric power. As an example, Fig. 5-2 shows the $EQE(\lambda)$ for a GaSb PV cell, and the spectral emissive power for a blackbody at a temperature of 1920 K. The convertible power ($P_{conversion}$), which is the product of the EQE and the spectral emissive power integrated over the region for which the EQE is non-zero, is shown as the patterned area in red color in Fig. 5-2. In this figure it is assumed that $F_{pv} = 1$.

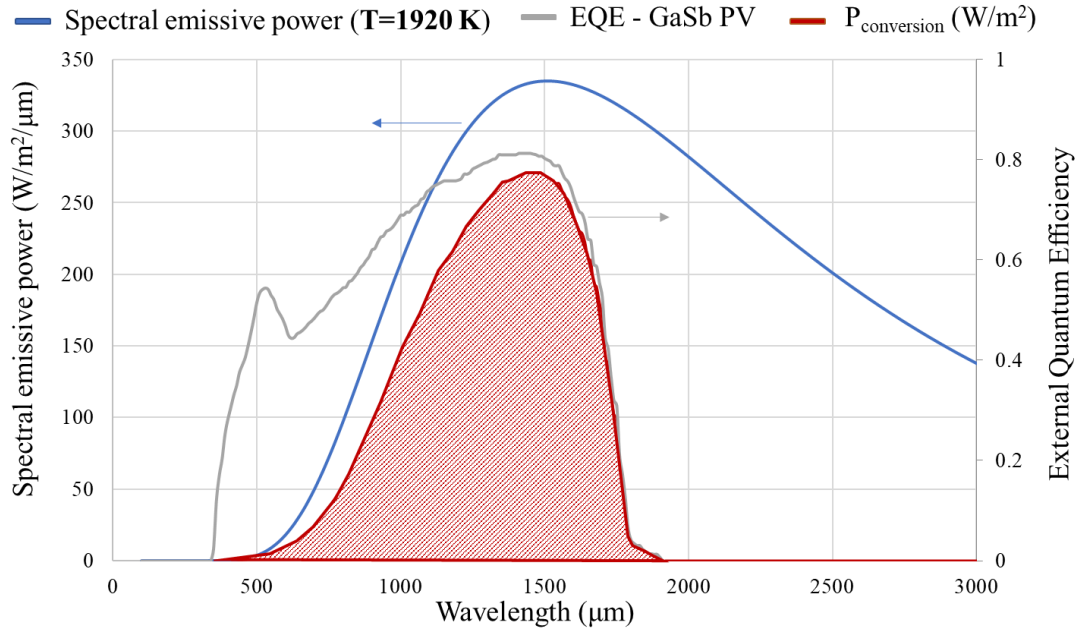


Figure 5-2 The convertible power ($P_{conversion}$) for a TPV system is shown as the red-colored area for a blackbody emitter with $T_0 = 1920$ K and a GaSb PV cell. It is assumed $F_{pv} = 1$.

Recently, the efficiency of TPV systems has reached 30%, which is higher than that of other static thermal-to-electric energy conversion systems [48]. In this world-record system a highly reflective rear mirror was coated beneath the PV cell to reflect the low-energy photons transmitted through the PV cell to the emitter to be recycled. Moreover, intense research and development is presently being directed towards further improving their efficiencies and the present target is to achieve efficiencies of 50% in practical TPV systems [49]. The vision of TPV systems operating with 50% efficiencies is justified by the extensive capacity for further improvements, as TPV systems do not currently operate close to their theoretical efficiency limits of ~85% [50, 51]. The efficiency of TPV systems can be improved by addressing their two major loss mechanisms. 1) Spectral losses due to the miss-match between the emission spectrum of the emitting surface and the bandgap of the PV cell. In most TPV applications, the majority of photons from the emitter have energy less than that of the bandgap of the PV cell and are not able to generate current in the PV cell. In other words, only the photons with an energy greater the bandgap of the PV cell (0.73 eV for a GaSb PV cell) are able to generate current in the PV cell. 2) Directional losses due to the non-unity view factor

between the emitter and the PV cell. To date, most research on TPV systems has focused on PV cells [52-54], absorbers/emitters [55-57], and optical filters to reflect low-energy photons that cannot generate current back to the emitter [58,59]. An alternative technique for improving TPV systems is to design optical cavity structures. An optical cavity is an enclosure that confines the direction of photons emitted from the emitter. It can decrease the directional losses by increasing the effective view factor between the emitter and the PV cell. An optical cavity can also reduce spectral losses by photon recycling and therefore, increasing the temperature of the emitter. When the temperature of the emitter is increased, a greater number of photons that have a high enough energy to generate electricity in a PV cell are produced. A TPV system can achieve a high level of tunability for increasing either photon recycling or the view factor by using a well-designed optical cavity. However, the design of optical cavities for TPV systems has rarely been studied, despite the fact that optical cavities can be used to increase the system efficiency, photon recycling, power density, emitter-to-cell effective view factor and provide a number of advantages that other components in TPV systems cannot [60,61]. Further, optical cavities can be made using durable and relatively inexpensive mirror-polished metallic surfaces that direct the radiation from the emitter toward either the PV cell or emitter itself [62]. Fig. 5-3 shows several structures of TPV systems integrated with optical cavities in 2D and 3D. Fig 5-3a shows a cubical/rectangular optical cavity for a TPV system. The side reflectors can be either specular or diffusive reflective surfaces to increase the effective view factor between the PV cell and emitter [62]. Fig. 5-3b shows a hemi-circular/spherical optical cavity. In this configuration the emitter is placed along the centre of the hemi-circle. Upward thermal emissions are redirected to the emitter and recycled by the optical cavity [63, 64]. Fig. 5-3c is a circular/spherical optical cavity in which the emitter is placed at the centre and the PV cell is on a small sector of the optical cavity [65]. Fig. 5-3d shows a parabolic optical cavity and the emitter is placed on its focal point. Emitted radiation reflected from the parabolic cavity is normally incident onto the surface of the PV cell [66]. Fig. 5-3e shows a conical optical cavity for STPV applications [67]. The emitter is located along the y-axis centre line of the cavity and a PV cell is placed on the base surface of the structure. Concentrated solar irradiance enters the cavity through the top opening. Fig. 5-3f and 5-3g show two configurations for cylindrical optical cavities. PV cell arrays are

placed on the side walls and concentrated light enters the system through the top opening [68, 69]. The emitters are spherical and cylindrical structures in Fig. 5-3f and 5-3g, respectively.

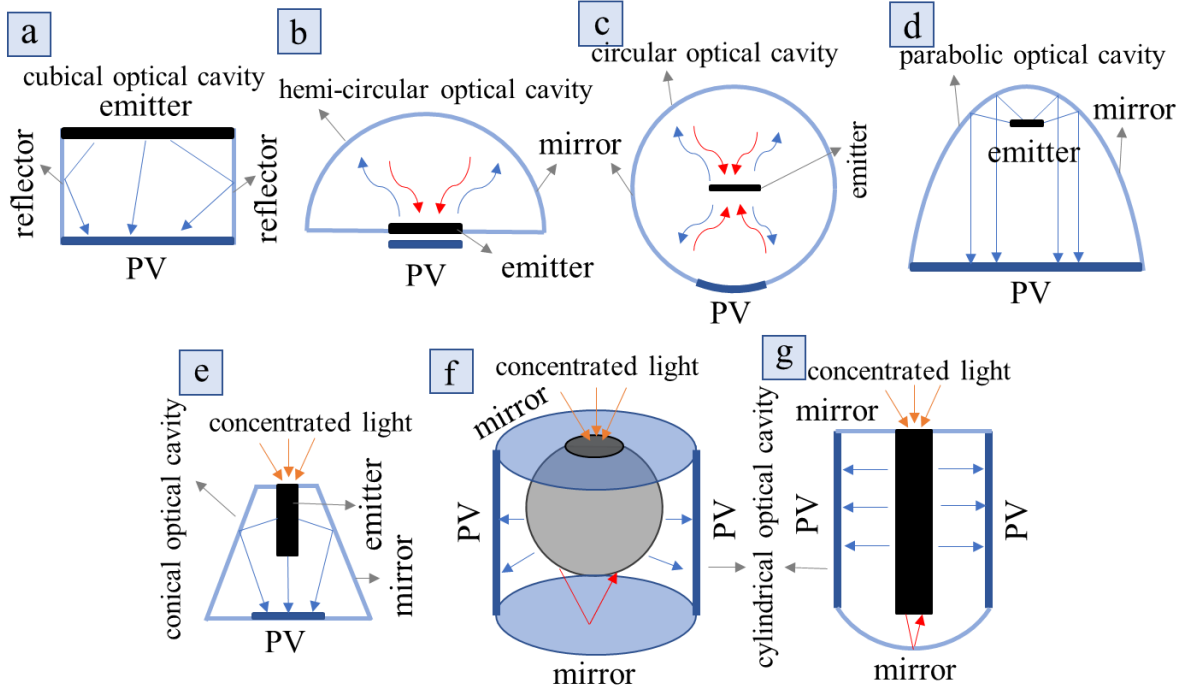


Figure 5-3 Examples of optical cavities integrated in TPV systems. a) A cubical/rectangular optical cavity [62], b) A Hemispherical/circular optical cavity [63, 64], c) A spherical/circular optical cavity [65], d) A parabolic/paraboloid optical cavity [66], e) A conical optical cavity [67], f) A cylindrical optical cavity with a spherically-shaped emitter [68] and g) A cylindrical optical cavity with a cylindrically-shaped emitter [69].

The geometrical parameters of an optical cavity-based TPV system can be tailored to control the probable fate of photons emitted from the emitter, such as the fraction of photons that are reflected by the cavity walls, returned to the emitter and recycled, and the portion of photons that are incident onto the PV cell. The portion of emitted photons incident onto the PV cell is referred to as the effective view factor (F_{pv}). The portion of photons returned to the emitter determines the recycling factor (F_{rec}). The emitted photons could also be absorbed by the cavity walls or lost to the surroundings through any openings or leakage in the cavity, and these photons contribute to the loss factor (F_{loss}). The summation of the photon fate is unity ($F_{pv} + F_{rec} + F_{loss} = 1$).

5.4.1 Effective emissivity and its effect on temperature

The effective emissivity (ε^*), extracted from the recycling factor, is a key parameter to evaluate and measure the efficiency of an optical cavity in thermal radiation systems. The effective emissivity is the emittance an emitter would have in the absence of a cavity that results in equivalent radiative losses as compared to the case when the cavity is present. In other words, increasing the photon recycling factor (F_{rec}) results in a decrease in the effective emissivity (ε^*). Also, for a constant input power, P_{in} , and according to Planck's radiation laws, decreasing ε^* causes an increase in the temperature of the emitter. Increasing the temperature of the emitter shifts the peak of its radiation spectrum to shorter wavelengths (higher energy) which increases the usable photon flux density for PV cells. For a gray/blackbody emitter, the effective emissivity and equilibrium temperature (T^*) can be calculated by Equation 5.6 and 5.7:

$$\varepsilon^* = \varepsilon_{emt} (1 - F_{rec}) \quad (5.6)$$

$$T^* = \sqrt[4]{\frac{\varepsilon_{emt}}{\varepsilon^*}} T_0 \quad (5.7)$$

where, T^* gives the temperature of a gray/blackbody emitter when it is within an optical cavity. ε_{emt} is the emissivity of the emitter, ε^* is the effective emissivity, and T_0 is the temperature the emitter would be at if the optical cavity was not present. Fig. 5-4a shows the temperature of the emitter (T^*) as a function of the ratio between the emissivity and effective emissivity of the emitter ($\varepsilon/\varepsilon^*$), and the temperature of the emitter in the absence of the optical cavity (T_0). Fig. 5-4b shows T^* for three samples of $T_0 = 600, 1000$ and 1400 K as a function of $\varepsilon/\varepsilon^*$ and photon recycling factor (F_{rec}). In Fig. 5-4c, the blackbody spectral emissive power of an emitter with an initial temperature of $T_0 = 1000$ K is shown for four emissivity ratios of $\varepsilon/\varepsilon^* = 1, 4, 7$, and 10 . The power from the emitter increases substantially as the emissivity ratio increases from 1 to 4 to 7 to 10. In this figure the bandgap of a GaSb PV cell is also plotted as a vertical dashed line. Only the photons with wavelengths to the left of this vertical line can be converted to electricity within the GaSb PV cell. These photons are referred to in-band photons. The photons with energy less than the bandgap of the PV cell (and wavelength to the right side of the dashed line in Fig. 5-4c) are referred as out-of-band

photons. As can be seen in Fig. 5-4c, as the emissivity ratio increases the number of photons from the emitter that can be converted to electricity drastically increases.

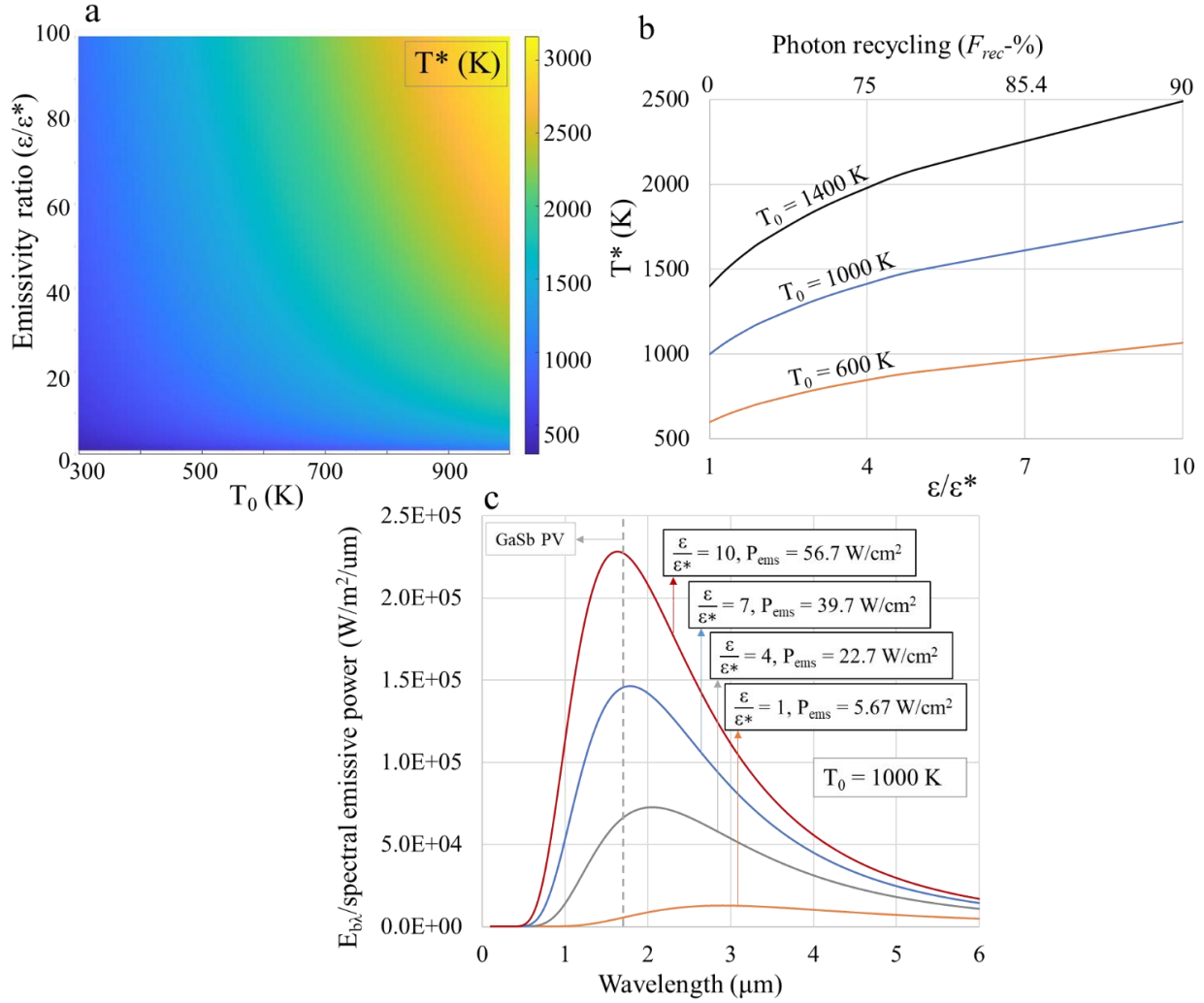


Figure 5-4 a) The temperature of a gray/blackbody emitter (T^*) as a function of the emissivity ratio (ϵ/ϵ^*) and its initial temperature when there is no photon recycling (T_0), b) T^* as a function of ϵ/ϵ^* and photon recycling (F_{rec}) for three values of $T_0 = 600, 1000, 1400$ K, and c) Blackbody spectral emissive power for four cases of $\epsilon/\epsilon^* = 1, 4, 7$ and 10 for $T_0 = 1000$ K. The bandgap of a GaSb PV cell is shown as the dashed vertical grey line.

As an example, for an STPV system within an optical cavity, the temperature of an emitter (T^*) can be determined by performing an energy balance using the probable fate of the emitted photons:

$$C \cdot G \cdot A_{abs} \cdot \alpha_{abs} = P_{PV} + P_{loss} = A_{emt} \cdot \int_0^{\infty} \varepsilon^*(\lambda) \cdot E_{b\lambda}(\lambda, T^*) d\lambda = A_{emt} \cdot \int_0^{\infty} \varepsilon(\lambda) \cdot E_{b\lambda}(\lambda, T_0) d\lambda \quad (5.8)$$

where, C is the solar concentration, G is the direct solar irradiance ($G = 800 \text{ W/m}^2$), A_{abs} is the area of the absorber surface, α_{abs} is the total absorption of the absorber surface, P_{PV} is the power received by the PV cell, P_{loss} is the loss factor in which the radiant power is absorbed by the optical cavity or escapes the cavity, and A_{emt} is the area of the emitter. For a gray/blackbody emitter, Equation 5.8 is simplified to:

$$C \cdot G \cdot A_{abs} \cdot \alpha_{abs} = A_{emt} \cdot \varepsilon^* \cdot \sigma \cdot T^{*4} = A_{emt} \cdot \varepsilon \cdot \sigma \cdot T_0^4 \quad (5.9)$$

It should be noted that, $T_0 = T^*$ if $\varepsilon/\varepsilon^* = 1$ or $F_{rec} = 0$. According to Kirchhoff's law it can be assumed that $\alpha_{abs} = \varepsilon_{abs}$. Fig. 5-5 shows the temperature of a gray/blackbody emitter as a function of solar concentration from $C = 10$ to $C = 100$ and the emissivity ratio from $\varepsilon/\varepsilon^* = 1$ to $\varepsilon/\varepsilon^* = 100$. In these ranges the effect of the surrounding temperature, $T_s = 300$, on T_0 and T^* can be neglected. Also, the area of the absorber and emitter are assumed to be equal ($A_{abs}/A_{emt} = 1$). As can be seen in Fig 5-5, increasing the solar concentration and emissivity ratios have a similar effect towards increasing the temperature of the emitter in an STPV system. For example, for a constant solar concentration of $C = 50$, increasing the emissivity ratio (decreasing the effective emissivity, ε^*) increases the temperature of the emitter from $T^* = 916 \text{ K}$ for $\varepsilon/\varepsilon^* = 1$, to $T^* = 2145 \text{ K}$ for $\varepsilon/\varepsilon^* = 30$ and to $T^* = 2550 \text{ K}$ for $\varepsilon/\varepsilon^* = 60$ (indicated by black dots in Fig 5.5). Furthermore, for a blackbody absorber/emitter increasing the emissivity ratio from $\varepsilon/\varepsilon^* = 1$ to $\varepsilon/\varepsilon^* = 30$ and $\varepsilon/\varepsilon^* = 60$, increases the total emissive power from 4 W/cm^2 to 120 W/cm^2 and 240 W/cm^2 , respectively. Similarly, for a constant emissivity ratio of $\varepsilon/\varepsilon^* = 50$, increasing the solar concentration increases the temperature of the emitter from $T^* = 916 \text{ K}$ for $C = 1$, to $T^* = 2145 \text{ K}$ for $C = 30$ and to $T^* = 2550 \text{ K}$ for $C = 60$ (indicated by the red dots for $C = 30$ and 60 in Fig 5-5).

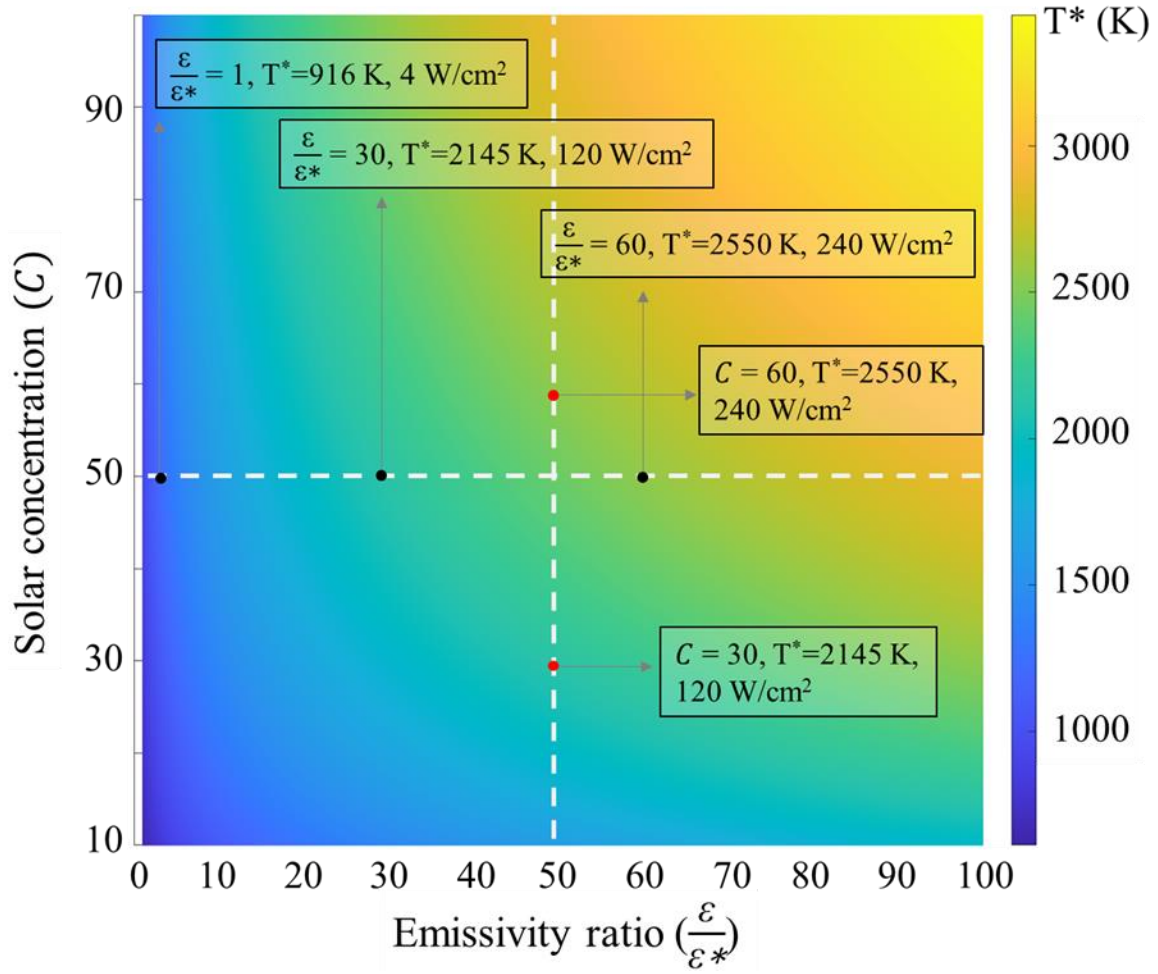


Figure 5-5 The temperature of an emitter as a function of solar concentration (C) and emissivity ratio (ϵ/ϵ^*). Three examples of emissivity ratios ($\epsilon/\epsilon^* = 1, 30, 60$) and two examples of solar concentration ($C = 30, 60$) with corresponding temperatures, blackbody emissive powers and power densities are shown.

5.4.2 Parametric study on the effect of the photon fates in a thermophotovoltaic system

As mentioned before, a photon emitted from an emitter in an optical cavity can have three probable fates. It is either recycled (F_{rec}), incident onto the PV cell (F_{pv}), or lost (F_{loss}). By controlling the probable fate of photons emitted from the emitter it is possible to increase the temperature of the emitter, the conversion efficiency, and other important parameters/output results in a TPV system. The total and spectral emissive power for a TPV in an optical cavity can be re-written as Equation 5.10 and 5.11, respectively.

$$P_{\text{emission}} = \int_0^{\infty} E_{\lambda}(\lambda, T^*) d\lambda \quad \& \quad E_{\lambda}(\lambda, T^*) = \varepsilon_{\text{emt}}(\lambda) \cdot E_{b\lambda}(\lambda, T^*) \quad (5.10)$$

$$E_{b\lambda}(\lambda, T^*) = \frac{2\pi hc^2}{\lambda^5 \left[\exp\left(\frac{hc}{\lambda k_0 T^*}\right) - 1 \right]} \quad (5.11)$$

For a black/graybody emitter, emission power (P_{emission}) can be re-written as:

$$P_{\text{emission}} = \varepsilon_{\text{emt}} \cdot \sigma \cdot T^{*4} \quad (5.12)$$

The fraction of energy incident on the PV cell ($P_{\text{pv-in}}$) is given by Equation 5.13. The in-band power (P_{inband}), which is the radiant power of emitted photons with energy above the bandgap of the PV cell, is provided by Equation 5.14. Equation 5.15 gives the in-band efficiency (η_{inband}) which is the ratio of the in-band power over the total emissive power. The in-band ratio (R_{inband}) which is the ratio of in-band power due to the presence of the optical cavity over the in-band power when the cavity is absent is determined using Equation 5.16. The output power density from the PV cell is given by Equation 5.17:

$$P_{\text{pv-in}} = F_{\text{PV}} \cdot P_{\text{emission}} \quad (5.13)$$

$$P_{\text{inband}} = \int_0^{\lambda_g} E_{\lambda}(\lambda, T^*) d\lambda \quad (5.14)$$

$$\eta_{\text{inband}} = \frac{\int_0^{\lambda_g} E_{\lambda}(\lambda, T^*) d\lambda}{\int_0^{\infty} E_{\lambda}(\lambda, T^*) d\lambda = P_{\text{emission}}} \times 100\% \quad (5.15)$$

$$R_{\text{inband}} = \frac{\int_0^{\lambda_g} E_{\lambda}(\lambda, T^*) d\lambda}{\int_0^{\lambda_g} E_{\lambda}(\lambda, T_0) d\lambda} \quad (5.16)$$

$$\text{Power Density} \left(\frac{W}{cm^2} \right) = P_{\text{PV-out}} \cdot \frac{A_{\text{emt}}}{A_{\text{PV}}} \quad (5.17)$$

The system efficiency (η_{TPV}) and output electric power for TPV systems (P_{PV-out}) are calculated using Equations 5.18 through 5.23 [70, 71]:

$$\eta_{TPV} = \frac{P_{PV-out}}{P_{in}} \times 100\% \quad (5.18)$$

$$P_{PV-out} = V_{OC} \times J_{SC} \times FF \quad (5.19)$$

$$J_{SC} = F_{PV} \times q \times \int_0^{\infty} \frac{\lambda}{hc} \times E_{by}(\lambda, T^*) \times IQE(\lambda) d\lambda \quad (5.20)$$

$$V_{OC} = \frac{k_0 T_0}{q} \ln \left(\frac{J_{SC}}{J_s} + 1 \right) \quad (5.21)$$

$$J_s = (1.84 \times 10^{-3}) \times T_0^3 \times \exp \left(\frac{-E_g}{k_0 \times T_0} \right) \quad (5.22)$$

$$FF = \left(1 - \frac{1}{\ln \left(\frac{J_{SC}}{J_s} \right)} \right) \times \left(1 - \frac{\ln \left(\ln \frac{J_{SC}}{J_s} \right)}{\ln \left(\frac{J_{SC}}{J_s} \right)} \right) \quad (5.23)$$

where, V_{OC} is the open-circuit voltage of the PV cell, J_{SC} is the short-circuit current density of the PV cell, FF is the fill factor for the PV cell, q is the elementary charge, $IQE(\lambda)$ is the Internal quantum efficiency of a GaSb PV cell [72], h is Planck's constant, c is the speed of light, k_0 is the Boltzmann constant, T^* is the equilibrium temperature of the BB, T_0 is the temperature of the PV cell, J_s is the saturation current density and E_g is the energy bandgap of PV cells.

It should be noted that the input power can be $P_{input} = C \cdot G \cdot A_{abs} \cdot \alpha_{abs}$ for an STPV system, and $P_{input} = A_{emt} \cdot \varepsilon \cdot \sigma \cdot T_0^4$ for any black/graybody emitter with known initial temperature when the optical cavity is absent (T_0). Based on the equations defined above, the analysis and calculations for a TPV system in an optical cavity are performed and the effect of a combination of different values for the loss factor (F_{loss}), view factor

(F_{pv}), and recycling factor (F_{rec}) on TPV systems are considered. The emitter is assumed to be a blackbody or a graybody in this parametric analysis. Fig. 5-6 shows the temperature of a gray/blackbody emitter as a function of the recycling factor (F_{rec}), view factor (F_{pv}), and the initial temperature of the emitter when the optical cavity is absent (T_0) for four values of the loss factor: $F_{loss} = 1, 5, 10$ and 20% . When the loss factor is 1% (Fig. 5-6a) the view factor and recycling factor can vary between 0 to 99% ($F_{pv} + F_{rec} = 99\%$). For example, when $F_{rec} = 90\%$, the view factor will be $F_{pv} = 9\%$, as $F_{loss} = 1\%$. In this case the maximum temperature of the emitter is achieved when the recycling factor is maximum ($F_{rec} = 99\%$). However, for this value of the recycling factor, the power delivered to the PV cell is $F_{pv} = 0$ and the system does not generate electricity. As an example, when $T_0 = 1000$ K and $F_{rec} = 0.99$, the temperature of the emitter reaches to $T^* = 3160$ K. In a similar way, Fig 5-6b shows the temperature of the emitter when the loss factor is $F_{loss} = 5\%$. In this case a maximum temperature of $T^* = 2115$ K is achieved when $F_{rec} = 95\%$ and $F_{pv} = 0\%$. In Figs 5-6c and 5-6d it is assumed that the loss factor is $F_{loss} = 10\%$ and $F_{loss} = 20\%$, respectively. The maximum temperature of the emitter reaches to $T^* = 1780$ when $F_{rec} = 90\%$ ($F_{pv} = 0\%$) for $F_{loss} = 10\%$; and $T^* = 1496$ when $F_{rec} = 80\%$ ($F_{pv} = 0\%$) for $F_{loss} = 20\%$.

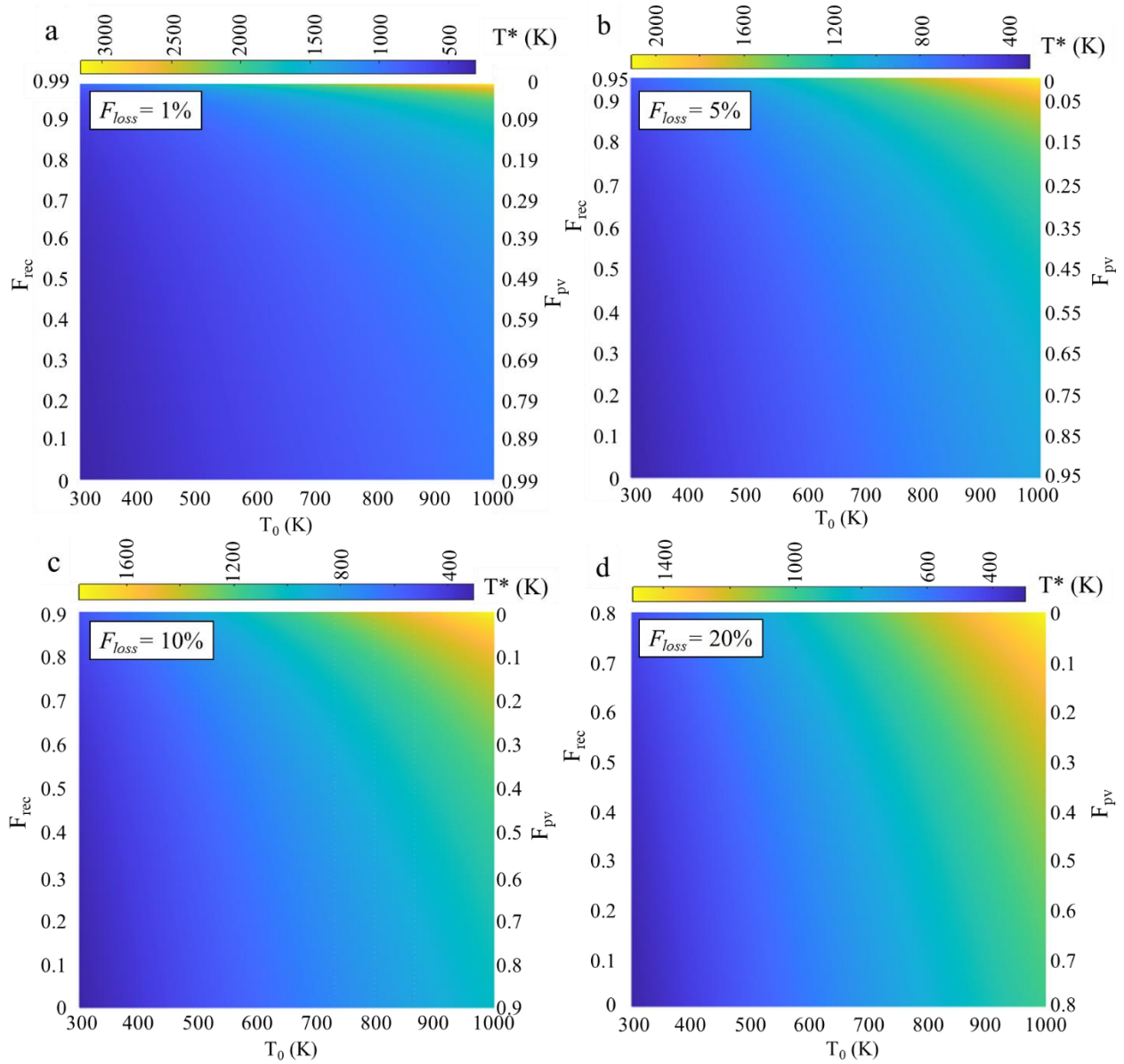


Figure 5-6 The temperature of the emitter as a function of recycling factor (F_{rec}), view factor (F_{pv}) and the temperature of the emitter in absence of the optical cavity (T_0) for four cases of a) $F_{loss} = 1\%$, b) $F_{loss} = 5\%$, c) $F_{loss} = 10\%$, and d) $F_{loss} = 20\%$.

Fig. 5-7 shows the total emissive power of the emitter ($P_{emission}$ -W/cm²) as a function of the recycling factor (F_{rec}), view factor (F_{pv}) and the temperature of the emitter in absence of the optical cavity (T_0). In this case, emission power is calculated for three cases of $F_{loss} = 1, 5$ and 10% . It should be noted that, when it is considered the TPV system does not have an optical cavity, the recycling factor is $F_{rec} = 0$. In calculations for the emission power, the emitter is assumed to be blackbody ($\epsilon_{emt} = 1$). For a graybody emitter the total

emissive power should be multiplied by the emissivity of the graybody ($\epsilon_{emt} < 1$). Fig. 5-7a shows the total emissive power of a blackbody emitter as a function of recycling factor (F_{rec}), view factor (F_{pv}) and initial temperature of the emitter (T_0) when the loss factor is $F_{loss} = 1\%$. In this case, F_{rec} and F_{pv} varies between zero and 0.99 and the total emissive power can reach to 567 W/cm^2 when $T_0 = 1000 \text{ K}$, $F_{rec} = 0.99$ and $F_{pv} = 0$. Likewise, Fig. 5-7b shows the total emissive power when the loss factor is $F_{loss} = 5\%$. In this case the maximum emission power is $P_{emission} = 113.4 \text{ W/cm}^2$ when $T_0 = 1000 \text{ K}$, $F_{rec} = 0.95$ and $F_{pv} = 0$. Fig. 5-7c shows the total emissive power when the loss factor is $F_{loss} = 10\%$. The maximum emission power is $P_{emission} = 56.7 \text{ W/cm}^2$ when $T_0 = 1000 \text{ K}$, $F_{rec} = 0.9$ and $F_{pv} = 0$. Fig. 5-7d shows the emission power as a function of F_{pv} and F_{rec} for four cases of $T_0 = 600, 1000, 1400$, and 1800 K when the loss factor is $F_{loss} = 5\%$. As can be seen, as the recycling factor increases the total emissive power increases rapidly. For example, when $T_0 = 1000 \text{ K}$, the total emissive power starts from $P_{emission} = 5.67 \text{ W/cm}^2$ when $F_{rec} = 0\%$, to $P_{emission} = 28.35 \text{ W/cm}^2$ when $F_{rec} = 80\%$. Then it reaches to $P_{emission} = 113.4 \text{ W/cm}^2$ when $F_{rec} = 95\%$.

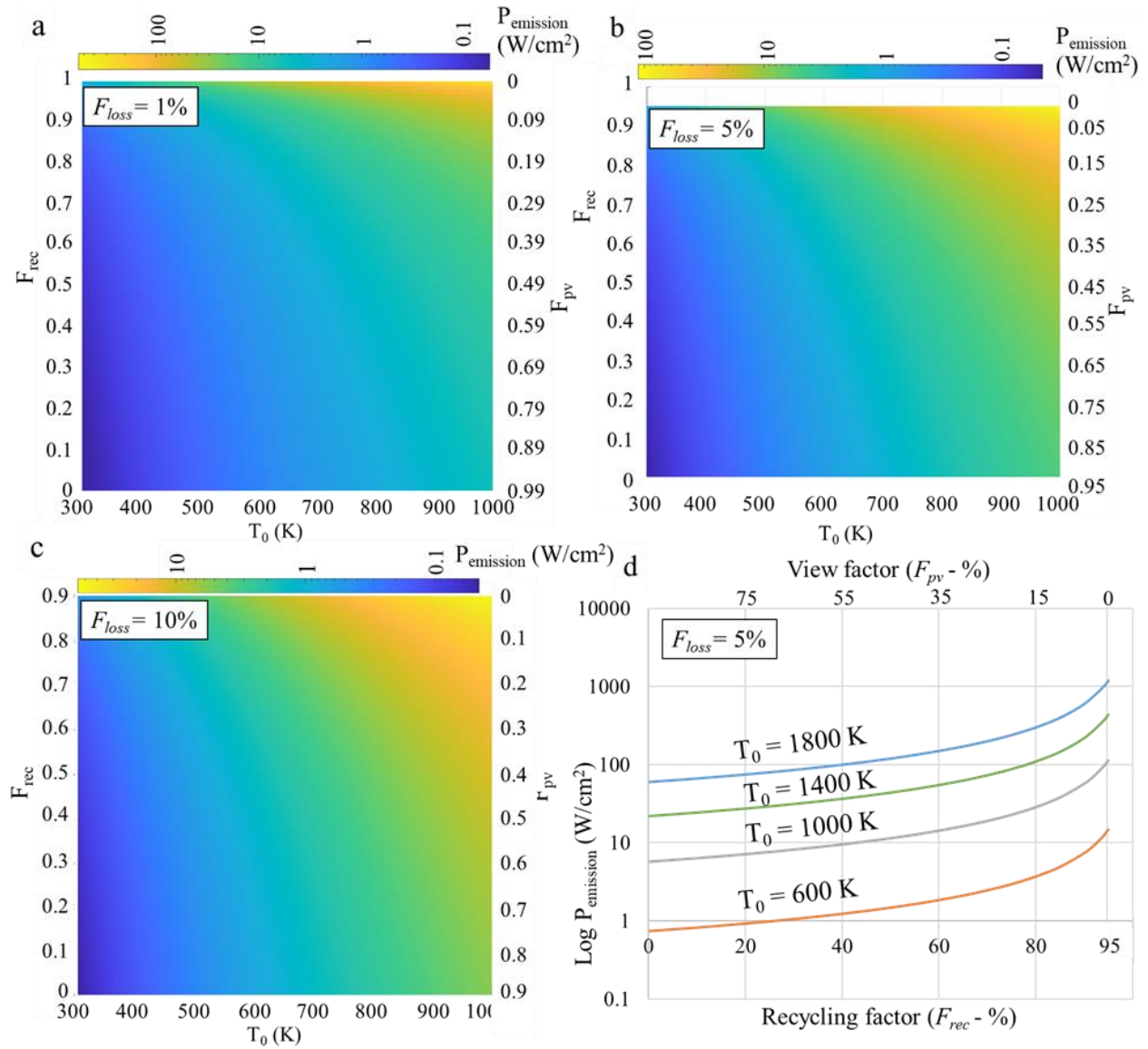


Figure 5-7 Total emissive power (P_{emission}) per surface area of a blackbody emitter in an optical cavity as a function of recycling factor (F_{rec}), view factor (F_{pv}) and the temperature of the emitter in the absence of the optical cavity (T_0) for three cases of a) $F_{\text{loss}} = 1\%$, b) $F_{\text{loss}} = 5\%$, and c) $F_{\text{loss}} = 10\%$. d) Total emissive power (P_{emission}) as a function of recycling factor (F_{rec}) and view factor (F_{pv}) for four values of $T_0 = 600, 1000, 1400$ and 1800 K when $F_{\text{loss}} = 5\%$. Note that P_{emission} is plotted on a logarithmic scale for all sub-figures.

Fig. 5-8 shows the portion of power incident onto the PV cell ($P_{\text{pv-in}}$ -W/cm²) as a function of the recycling factor (F_{rec}), view factor (F_{pv}) and the temperature of the emitter in the absence of the optical cavity (T_0). In this case, the emission power is calculated for three cases of $F_{\text{loss}} = 1, 5$ and 10% . For the results shown in

Fig. 5-8, it is assumed that the emitter has a blackbody surface ($\epsilon_{emt} = 1$) and all the photons incident on the PV cell are absorbed ($\epsilon_{pv} = 1$). In this case, P_{pv-in} can be calculated by:

$$P_{pv-in} = \frac{F_{pv}}{1 - F_{rec}} \cdot \epsilon_{emt} \cdot \sigma \cdot T_0^4 = F_{pv} \cdot \epsilon_{emt} \cdot \sigma \cdot T^*{}^4 \quad (5.19)$$

where the emissivity of the emitter is assumed to be $\epsilon_{emt} = 1$. According to this equation, the maximum power is delivered to the PV cell when the recycling factor is minimum, and the view factor is maximum. However, when the recycling factor is small, the emitter has a lower temperature (T^*) and the fraction of in-band energy incident onto the PV cell is low. This will be discussed further with references to Figs. 5-12 and 5-14. Fig. 5-8a shows the net amount of emitted power that is incident onto the PV cell (P_{pv-in}) for a loss factor of $F_{loss} = 1\%$ as a function of F_{pv} , F_{rec} and the temperature of the emitter (T_0). In this case, F_{pv} and F_{rec} can vary between 0 to 0.99. Similarly, Fig. 5-8b shows the power incident on the PV cell as a function of F_{pv} , F_{rec} and the temperature of the emitter (T_0) when $F_{loss} = 5\%$. In this case, $0 < F_{pv} + F_{rec} < 0.95\%$. Fig-5.8c shows the incident power onto the PV cell when $F_{loss} = 10\%$. In this case, $0 < F_{pv} + F_{rec} < 0.90\%$. Fig-5.8 d plots P_{pv-in} as a function of F_{pv} and F_{rec} for four values of $T_0 = 600, 1000, 1400$ and 1800 K when $F_{loss} = 5\%$. As can be seen, when the recycling factor (F_{rec}) increases and view factor decreases (F_{pv}), the power incident on the PV cell decreases and finally reaches to $P_{pv-in} = 0$ when $F_{rec} = 0.95$ and $F_{pv} = 0$.

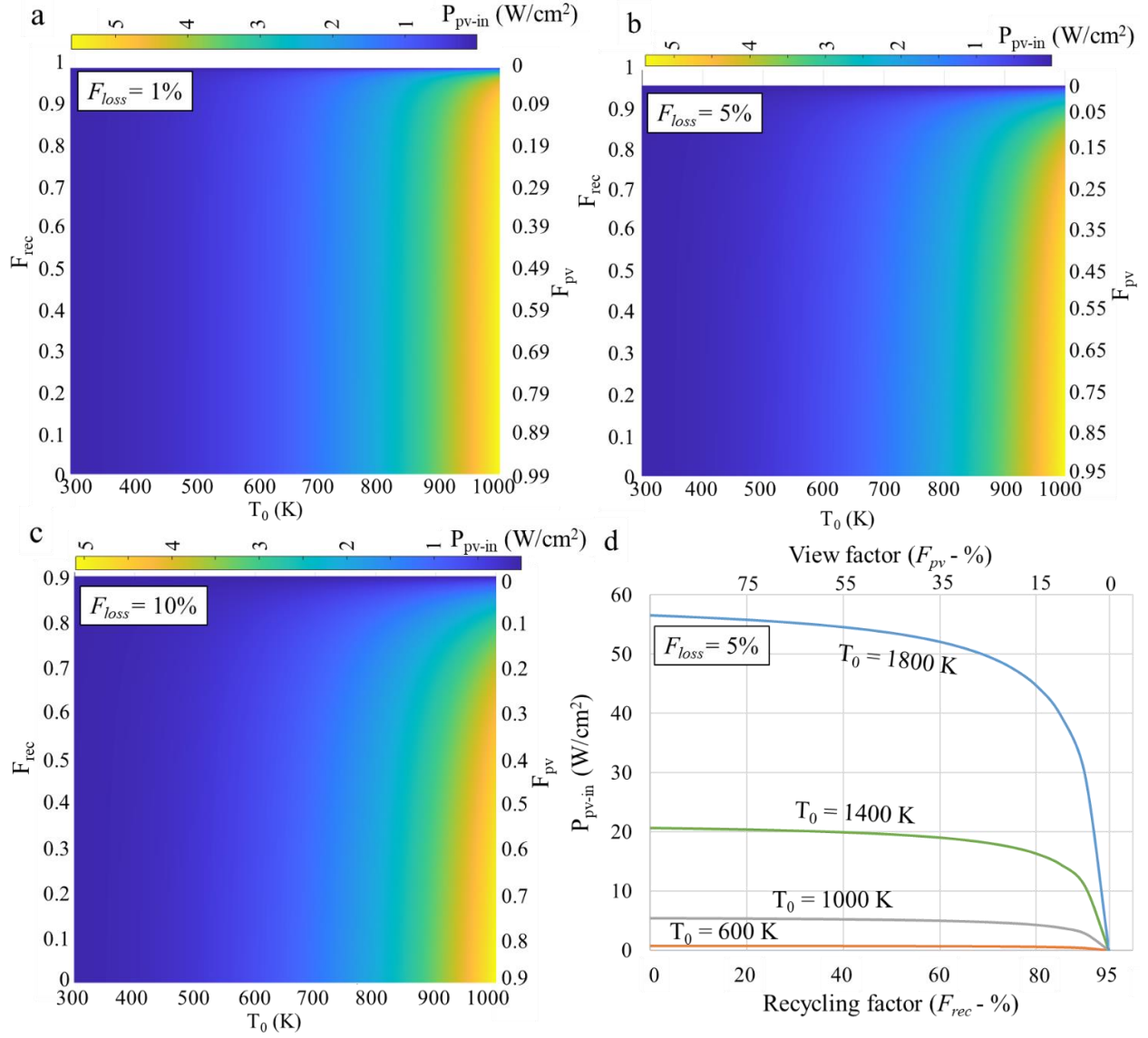


Figure 5-8 Incident power on the PV cell (P_{pv-in}) from a blackbody emitter in an optical cavity as a function of the recycling factor (F_{rec}), view factor (F_{pv}) and the temperature of the emitter in the absence of the optical cavity (T_0) for the three cases of a) $F_{loss} = 1\%$, b) $F_{loss} = 5\%$, and c) $F_{loss} = 10\%$. d) Incident power on the PV cell (P_{pv-in}) as a function of the recycling factor (F_{rec}) and view factor (F_{pv}) for four values of $T_0 = 600, 1000, 1400$ and 1800 K when $F_{loss} = 5\%$.

Fig. 5-9 shows the in-band efficiency (η_{inband}) as a function of recycling factor (F_{rec}) and view factor (F_{pv}) for four values of the temperature of the emitter in absence of the optical cavity ($T_0 = 600, 1000, 1400$ and 1800 K). In this case, the in-band efficiency is calculated for three cases of $F_{loss} = 1, 5$ and 10% . In this series of study, it is assumed that the emitter has a blackbody surface ($\epsilon_{emt} = 1$). As shown in Fig. 5-9a, 5-9b

and 5-9c, increasing the recycling factor increases the temperature of the emitter and then the amount of in-band power emitted from the blackbody emitter increases. For higher values of the recycling factor, in-band efficiency increases rapidly.

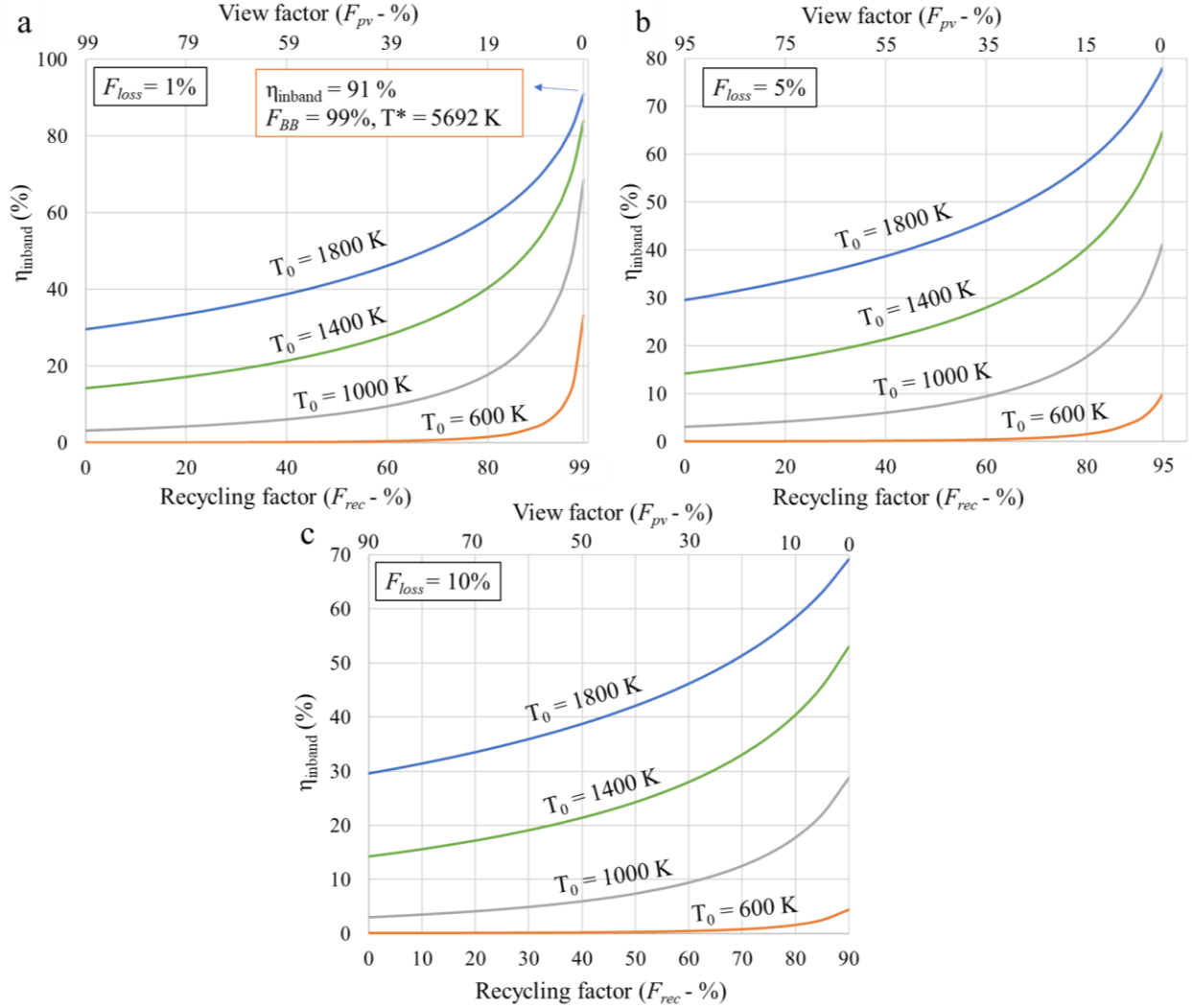


Figure 5-9 In-band efficiency (η_{inband}) for the power emitted from a blackbody emitter in an optical cavity as a function of the recycling factor (F_{rec}) and view factor (F_{pv}) for four values of the temperature of the emitter in the absence of the optical cavity ($T_0 = 600, 1000, 1400$ and 1800 K) for three cases of a) $F_{loss} = 1\%$, b) $F_{loss} = 5\%$, and c) $F_{loss} = 10\%$.

Fig. 5-10 shows the in-band power (P_{inband}) emitted from the emitter as a function of the recycling factor (F_{rec}) and the view factor (F_{pv}) for four values of the initial temperature of the emitter in the absence of the optical cavity ($T_0 = 600, 1000, 1400$ and 1800 K). In this case, in-band power is calculated for three cases

of $F_{loss} = 1, 5$ and 10% and shown on a logarithmic scale as well as a linear scale. For the results shown in Fig. 5-10, it is assumed that the emitter has a blackbody surface ($\epsilon_{emt} = 1$). As shown in Fig. 5-10a, 5-10b and 5-10c, increasing the recycling factor increases the temperature of the emitter and then the amount of in-band power emitted from the blackbody emitter increases. At higher values of the recycling factor, the in-band power increases rapidly as the recycling factor increases. It should be noted that when $F_{loss} = 1\%$, the sum of F_{rec} and F_{pv} varies between 0 and 99%, when $F_{loss} = 5\%$, the sum of F_{rec} and F_{pv} varies between 0 and 95%, and when $F_{loss} = 10\%$, the sum of F_{rec} and F_{pv} varies between 0 and 90%.

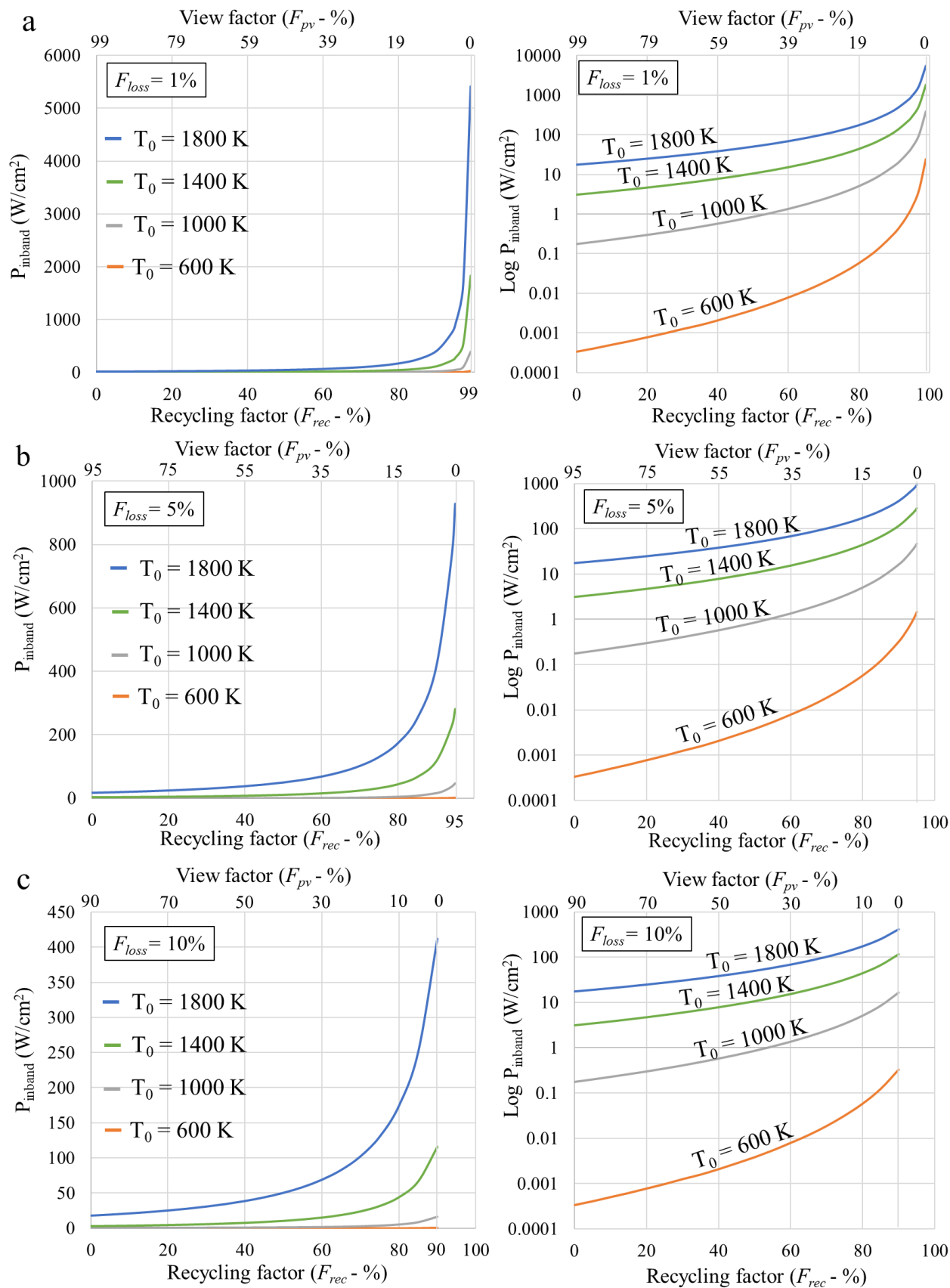


Figure 5-10 In-band power (P_{inband}) emitted from a blackbody emitter in an optical cavity as a function of the recycling factor (F_{rec}) and view factor (F_{pv}) for four values of the temperature of the emitter in the absence of the optical cavity ($T_0 = 600, 1000, 1400$ and 1800 K) for three cases of a) $F_{loss} = 1\%$, b) $F_{loss} = 5\%$, and c) $F_{loss} = 10\%$. The results are plotted on both linear (left) and logarithmic (right) scales.

Fig. 5-11 shows the in-band ratio (R_{inband}) as a function of the recycling factor (F_{rec}) for four values of $T_0 = 600, 1000, 1400$ and 1800 K. In this figure the blue patterned area shows the region of R_{inband} where $F_{loss} = 10\%$. In this region, F_{rec} and F_{pv} both can vary between 0 to 90%. By decreasing the loss factor to 5%, the green pattern area is added to the in-band ratio (R_{inband}) and therefore, the total F_{rec} and F_{pv} can vary between 0% to 95% (in only the green region F_{rec} can vary between 90% and 95% and therefor F_{pv} varies between 0 to 5%). By further decreasing the loss factor to 1%, the orange patterned region is added to the in-band ratio (R_{inband}) and therefore the total F_{rec} and F_{pv} can vary between 0% to 99% (in the only orange region F_{rec} can vary between 95% and 99% and therefor F_{pv} varies between 0 to 4%).

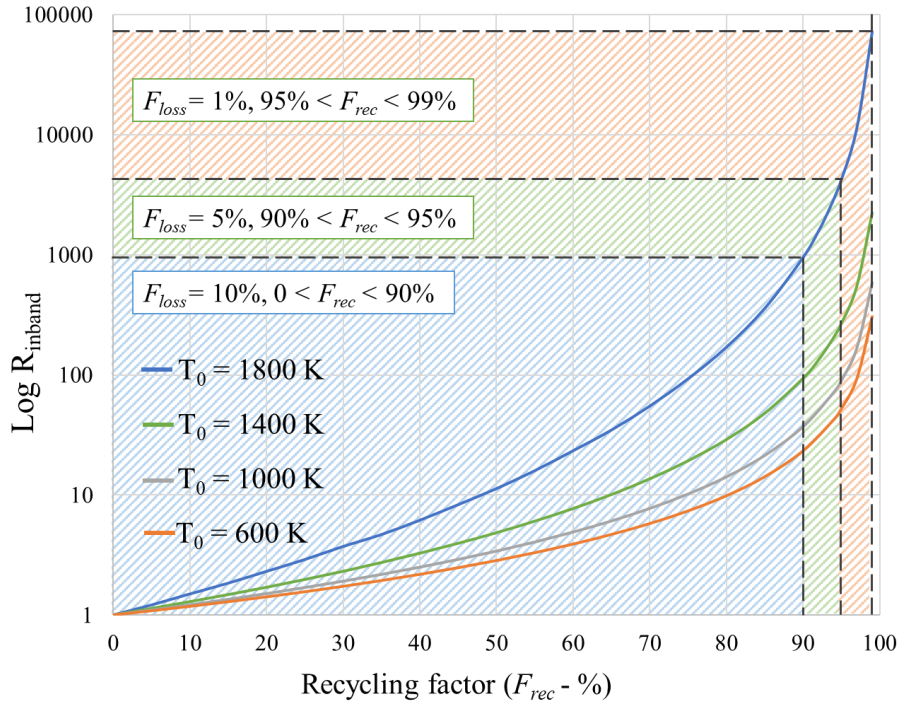


Figure 5-11 In-band ratio (R_{inband}) as a function of the recycling factor (F_{rec}) for four values of $T_0 = 600, 1000, 1400$ and 1800 K. The blue region is the in-band ratio when $F_{loss} = 10\%$. The green region is added when $F_{loss} = 5\%$, and the orange region is added when $F_{loss} = 1\%$.

Fig. 5-12 shows the output electric power from the PV cell for TPV systems (P_{PV-out}) as a function of the recycling factor (F_{rec}) and view factor (F_{pv}) for four values of the initial temperature of the emitter in the absence of the optical cavity ($T_0 = 600, 1000, 1400$ and 1800 K). In these cases, the effect of the IQE of the PV cell comes into the picture. In this series of calculations the emissivity of the PV cell and emitter is equal to one. As can be seen, increasing the recycling factor increases the temperature of the emitter and therefore, more in-band power is delivered to the PV cell. However, the view factor between the emitter and PV cell decreases as the recycling factor increases and finally reaches to zero when the recycling factor is at its maximum. Furthermore, as the PV cell has the maximum IQE close to its bandgap, when the temperature of the emitter is very high, the photons incident onto the PV cell have excessive energy which decreases the efficiency and causes thermalization within the PV cell. Therefore, there will be an optimum value for the convertible power for a TPV system inside an optical cavity. As can be seen in Fig. 5-12a, which is for $F_{loss} = 1\%$, the maximum output electric power of $P_{PV-out} = 17.6 \text{ W/cm}^2$ (17.6 W per cm^2 of the emitter surface area) is achieved when $F_{rec} = 90\%$ and $F_{pv} = 9\%$ for $T_0 = 1800$ K. Similarly, the maximum output electric power of $P_{PV-out} = 14.1 \text{ W/cm}^2$ is achieved when $F_{rec} = 75\%$ and $F_{pv} = 20\%$ for $T_0 = 1800$ K when $F_{loss} = 5\%$ (Fig. 5.12b), and $P_{PV-out} = 11.6 \text{ W/cm}^2$ is achieved when $F_{rec} = 60\%$ and $F_{pv} = 30\%$ for $T_0 = 1800$ K when $F_{loss} = 10\%$ (Fig. 5-12c).

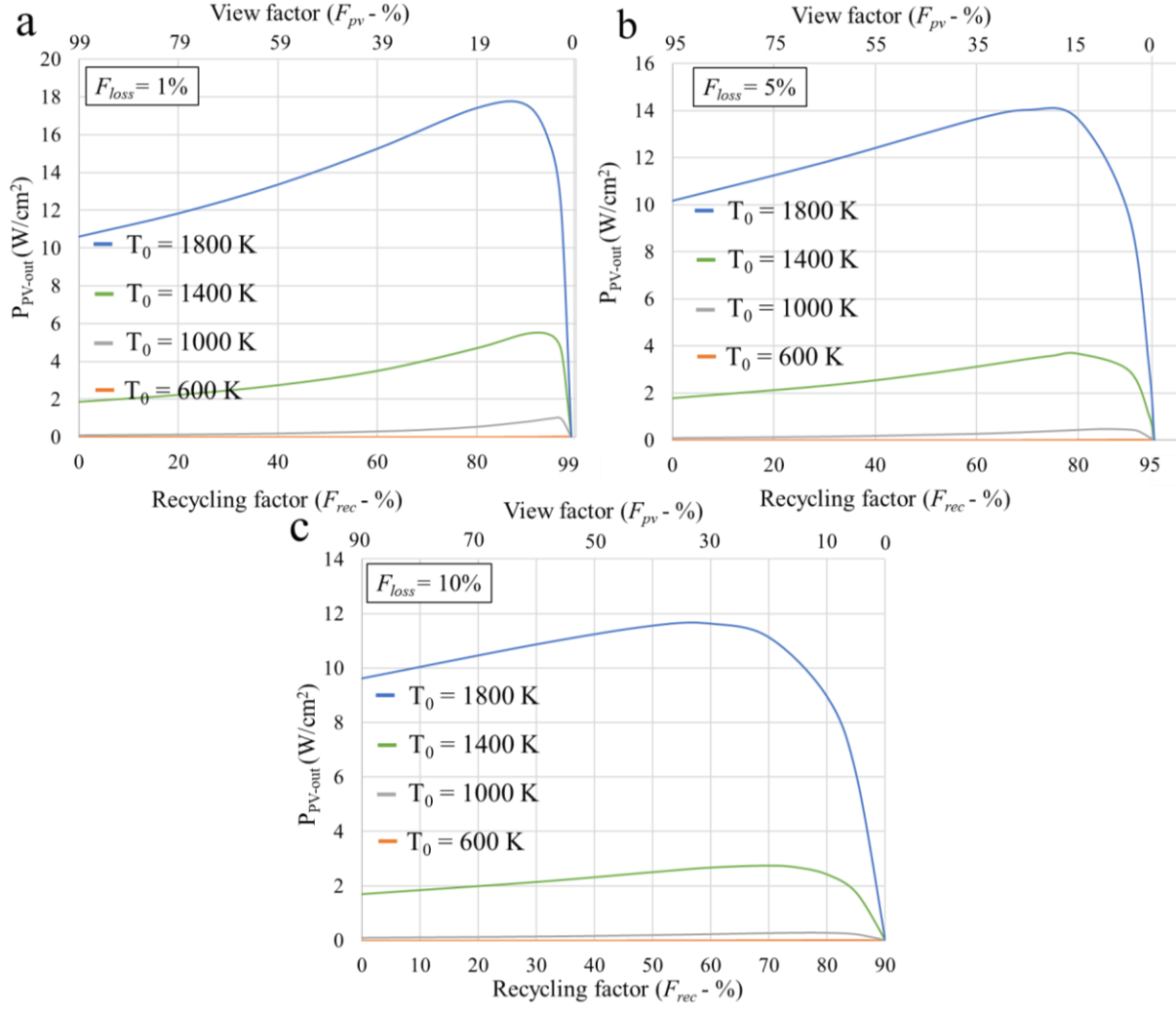


Figure 5-12 The output electric power of PV cell (P_{PV-out}) as a function of the recycling factor (F_{rec}) and the view factor (F_{pv}) for four values of the initial temperature of the emitter in the absence of the optical cavity ($T_0 = 600, 1000, 1400$ and 1800 K) for three cases of a) $F_{loss} = 1\%$, b) $F_{loss} = 5\%$, and c) $F_{loss} = 10\%$.

Fig. 5-13 shows the system efficiency (η_{TPV}) as a function of the recycling factor (F_{rec}) and view factor (F_{pv}) for four values of the initial temperature of the emitter in the absence of the optical cavity ($T_0 = 600, 1000, 1400$ and 1800 K). As can be seen in Fig. 5-13a which is for $F_{loss} = 1\%$, the maximum system efficiency of $\eta_{TPV} = 29.54\%$ is achieved when $F_{rec} = 90\%$ and $F_{pv} = 9\%$ for $T_0 = 1800$ K. Similarly, the maximum system efficiency of $\eta_{TPV} = 23.1\%$ is achieved when $F_{rec} = 75\%$ and $F_{pv} = 20\%$ for $T_0 = 1800$ K when $F_{loss} = 5\%$

(Fig. 5-13b), and $\eta_{TPV} = 19.54\%$ is achieved when $F_{rec} = 60\%$ and $F_{pv} = 30\%$ for $T_0 = 1800$ K when $F_{loss} = 10\%$ (Fig. 5-13c).

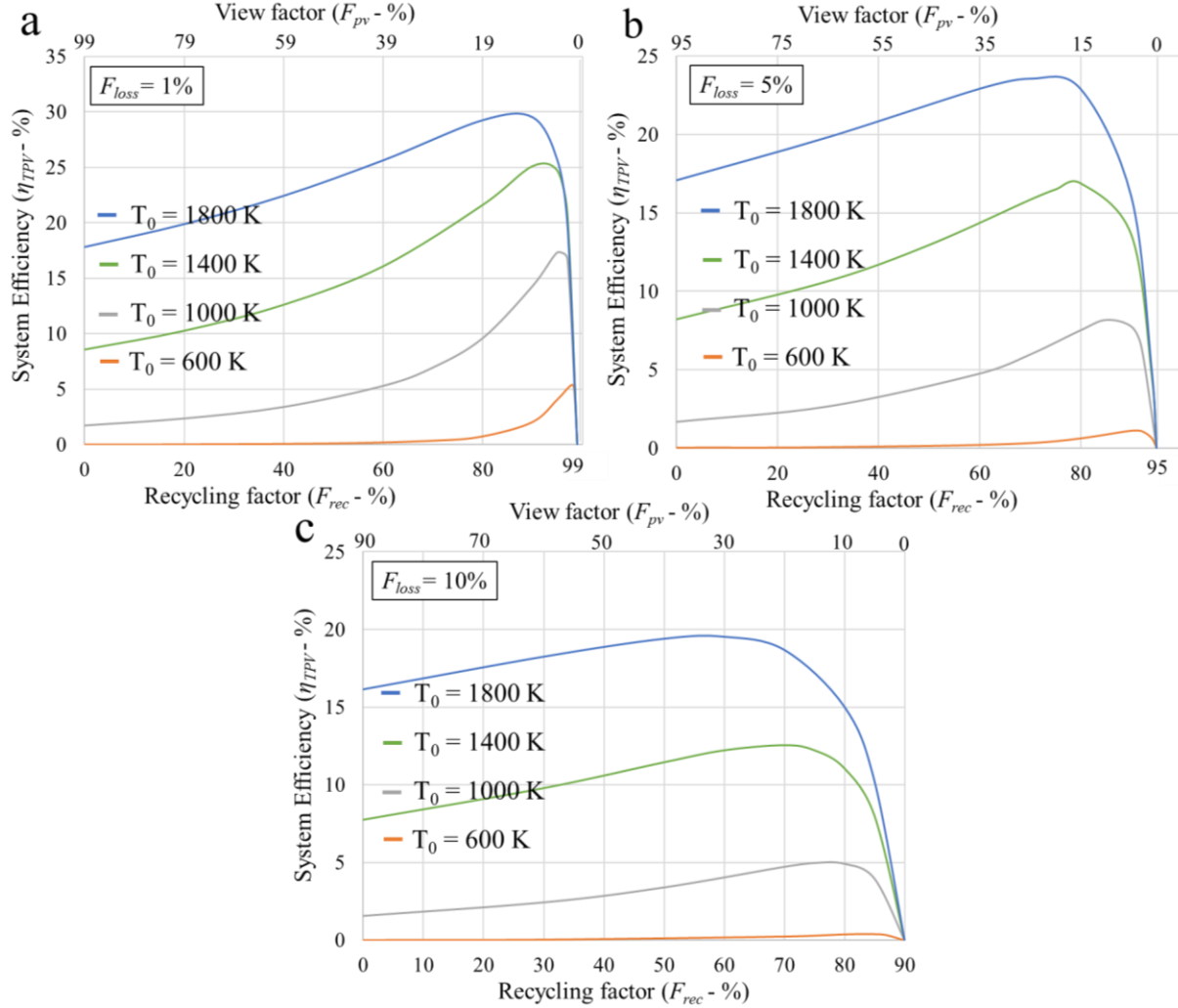


Figure 5-13 System efficiency (η_{TPV}) as a function of the recycling factor (F_{rec}) and view factor (F_{pv}) for four values of the initial temperature of the emitter in absence of the optical cavity ($T_0 = 600, 1000, 1400$ and 1800 K) for three cases of a) $F_{loss} = 1\%$, b) $F_{loss} = 5\%$, and c) $F_{loss} = 10\%$.

5.5 Conclusion

In this chapter TPV systems are introduced, and their market potentials and competing technologies are explained. Then, the loss mechanisms in TPV systems are discussed and the importance of using optical

cavities in a TPV system are provided. The probable fate of photons emitted from an emitter inside an optical cavity is explained and subsequently, a parametric analysis for the effect of an optical cavity in a TPV system was discussed for different output and evaluation parameters of a TPV system. It was shown that an optical cavity has a significant role in increasing the performance of a TPV system, especially when the loss factor is low and the recycling factor is high. The analysis shows there are optimum values of the recycling and view factors for a TPV system to reach the maximum conversion power and system efficiency for a blackbody emitter in different temperatures and loss factors. For example, for $T_0 = 1800$ K and $F_{loss} = 1\%$, the maximum output electric power of $P_{PV-out} = 17.6$ W/cm² and system efficiency of $\eta_{TPV} = 29.54\%$ are achieved when $F_{rec} = 90\%$ and $F_{pv} = 9\%$. In the next chapters a highly efficient optical cavity invented by the author will be introduced to be used in STPV systems.

5.6 References

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6 Radiant energy spectrum converter (RESC) for thermophotovoltaic applications¹

Nomenclature			
<i>Roman symbols</i>			
A_{abs}	absorber area	P_{input}	input power
A_{emt}	emitter area	P_{inband}	in-band power
a	minor semi-axis of an ellipsoid	P_{cav}	power absorbed by the cavity
BB	blackbody	P_{esc}	power escaped through the entrance
C	solar concentration	P_{PV-in}	power received by the PV cell
c	light speed	P_{PV-out}	output power
$E_{b\lambda}$	blackbody spectral emissive power	$P_{heat-BB}$	convective and conductive heat from the emitter
E_{λ}	spectral emissive power	$P_{heat-cav}$	conductive and radiative heat from cavity
F_{BB}	recycling factor	$P_{heat-load}$	heat load on the PV cell
F_{esc}	escape factor	q	elementary charge
F_{PV}	view factor	R_{inband}	In-band power ratio for cavity and non-cavity emitter
E_g	bandgap energy	r_{BB}	radius of the blackbody
F_{cav}	cavity absorption factor	r_{pv}	radius of the PV cell
FF	fill factor	T_0	emitter temperature without cavity
G	direct solar irradiance	T^*	emitter temperature within a cavity
h	Planck constant	T_{avg}	average temperature between the emitter and PV cell
h_c	convective heat transfer coefficient	V_{oc}	open circuit voltage
J_s	saturation current density	w	width of the annular aperture
J_{sc}	short circuit current density	<i>Greek symbol</i>	
k	distance between the center of the ellipsoid and the PV cell	η_{inband}	in-band power over total emissive power
k_0	Boltzmann constant	α_{abs}	total absorption
k_e	thermal conductivity of air at reduced pressures	η_{PV}	PV cell efficiency
k_c	thermal conductivity of air at atmospheric pressure	η_{TPV}	system efficiency
N_{abs}	total number of rays re-absorbed	θ	cavity acceptance angle
N_{tot}	total number of rays emitted	ϕ	polar angle
p	semi-latus rectum	λ	wavelength (nm)
$P_{conversion}$	conversion power	λ_g	bandgap wavelength (nm)
$P_{emission}$	emission power (W/m ²)	σ	Stefan-Boltzmann constant
		ε^*	effective emissivity
		ε_{emt}	emissivity of the emitter

¹ This chapter is based on references [54, 55]

6.1 Abstract

Herein this chapter presents an optical cavity in the form of a prolate ellipsoid that can greatly enhance the performance of solar thermophotovoltaic (STPV) systems. The geometrical parameters of the cavity can be designed to control the degree of photon recycling, the temperature of the emitter within the STPV system, gap distance and effective view factor between the PV cell and the emitter, and to minimize the emission losses. Numerical analysis shows the ellipsoidal optical cavity can be designed to achieve an effective view factor of 88.7% between the emitter and PV cell within a STPV system. Results show an efficiency of 5.62% in a STPV system with a GaSb PV cell and a black-body emitter under solar radiation at a concentration factor of 350X. Further, assuming the surface of the ellipsoidal optical cavity is capable of reflecting 99% of the radiation incident onto its surface, efficiencies of 15.54% can be attained when the solar concentration factor is 1400X. These results are attained for STPV systems without using selective absorbers, emitters or filters. The ellipsoidal optical cavity can be integrated into the design of advanced TPV systems and bring them closer to the high theoretical efficiencies TPV systems are capable of.

6.2 Introduction

Thermophotovoltaic (TPV) is a versatile technology with many applications including uninterruptible power supplies, self-powered heating devices and industrial waste heat recovery [1, 2]. The primary components in a TPV system are the emitter and the photovoltaic (PV) cell. The emitter operates at a temperature of ~ 600 K to ~ 2000 K, and radiates photons that are incident onto a low-bandgap PV cell, such as InGaAs, Ge or GaSb cells. Photons from the emitter with energy above the bandgap of the semiconductor in the PV cell, referred to as in-band photons, can be converted to electric power. However, the PV cell is unable to convert photons with energy below the bandgap, which are referred to as out-of-band photons. While research interest in TPV systems has increased considerably over the last few years [3, 4], there is extensive capacity for further improvements, as TPV systems do not currently operate close to their theoretical efficiency limits [5, 6].

Advancements in TPV system performance will promote clean energy in the form of waste-heat recovery, combined heat and power systems, and solar thermophotovoltaics (STPV). STPV in particular has potential to improve the performance of solar energy harvesting by converting the broadband solar irradiance to a spectrum that is more favorably matched to the PV cell band gap. From a theoretical perspective, STPV can achieve an efficiency of 85.4% [5- 7]. From an experimental perspective, the advantages of integrating STPVs with energy storage systems have been investigated [8- 10]. For example, Datas et al. [11] used silicon as a latent heat storage material in a highly-compact concentrated solar power (CSP) system which was capable of both thermal energy storage and electric power generation. Further, Datas et al. [12] reported on the practical implementation of a STPV system comprised of a cylindrical cup-shaped absorber/emitter. Conversion efficiencies of $\sim 0.8\%$ were measured under outdoor conditions. The low system efficiency was attributed to overheating of the PV cells and high optical concentration losses.

In contrast to 3-dimensional cylindrical structures, STPV systems with planar architectures show better performance due to their smaller emission surface area which enables higher emitter operating temperatures. Ungaro et al. [13] experimentally demonstrated a planar STPV system with an overall power conversion efficiency of 6.2% under solar-simulated radiation at a concentration factor of 2500X. The STPV system was operated at a vacuum pressure of 10 mTorr, and the temperature of the PV cell reached a maximum of 72 °C. The main losses were attributed to the low efficiency of the PV cell ($\sim 45\%$ loss), thermal emission that does not reach the PV cell (11% loss), and emittance from the absorbing surface (23.6% loss). Kohiyama et al. [14] used a confined cuboid emitter/absorber surrounded by PV cells to increase the photon recycling in STPV systems. Their analysis predicted a 4.1% higher system efficiency than that attained using a planar absorber/emitter configuration. Experimental results showed system efficiencies of 7% when the input power density was 81 W/cm². Numerical analysis predicted the system efficiency could reach 20% by improving the back surface reflector and the enclosed space. Wang et al. [15] used selective meta-materials as absorber and emitter for a planar STPV system with an InGaAsSb PV cell and optimized the emitter to absorber area ratio. Their theoretical analysis revealed 12.6% efficiency at a solar concentration

of 200X, and $A_{emitter}/A_{absorber} = 4$. Wang et al. [16] proposed a cage-type STPV in which the absorber and emitter are surrounded by PV cells. In their theoretical analysis, they used a bifunctional hybrid absorber–emitter sequentially deposited by $\text{HfO}_2/\text{Mo}/\text{HfO}_2$ films on a metallic surface. They reached to the conclusion that the cage-type STPV system can increase the system efficiency by 15% in comparison to that of ideal planar STPV system with emitter/absorber area ratio of 10. Kelsall [17] designed, fabricated and characterized a graphite-based cylindrical absorber for an STPV system with a GaSb PV cell. The STPV system was theoretically evaluated under 3600X Sun concentration and the analysis estimated 9% system efficiency.

To date, most research on TPV/STPV systems has focused on PV cells [18- 25], absorbers/emitters [26- 34], and optical filters to reflect out-of-band photons back to the emitter [31- 36]. However, the design of optical cavities for STPV systems has rarely been studied, despite the fact that optical cavities can be used to increase the system efficiency, photon recycling (also known as photon recuperation or regenerative TPV [35]), and emitter-to-cell effective view factor [37, 38]. Optical cavities can be made using durable and relatively inexpensive mirror-polished metallic surfaces that direct the radiation from the emitter toward the TPV cell [39]. Sansoni et al. [40] evaluated a combustion-based TPV system in a tubular optical cavity with an elliptical cross-section. The burner was situated along one focal line within the tube and TPV cells were located along the second focal line, such that radiation emitted from the burner was specularly reflected from the inner surface of the tube toward the PV cells. Several cavity configurations were analyzed using ray tracing configurations and simulations predicted a maximum thermal emission collection efficiency of 62% when the reflectance of the cavity walls is 90%. Moreover, Lindberg et al. [41] designed a wood powder-fueled TPV system consisting of an egg-shaped cone with an emitter at one end, an edge filter at the wide center, and a PV-cell array at the other end. The function of the edge filter is to reflect low-energy thermal photons back to the emitter while transmitting photons with energy greater than the band-gap energy to the PV cell. The inner surface of the cone specularly reflects radiation from the emitter to limit the angular

distribution of radiation incident on the filter. This is desirable because the cut-off frequency of edge filters is sensitive to the incident angle of incoming photons.

Herein we numerically investigate the potential for using ellipsoidal optical cavities to enhance the performance of STPV systems. We investigate ellipsoidal-shaped cavities because they have two focal points, and rays emitted from one of these focal points that are specularly reflected from the internal surface of the cavity will converge onto the second focal point. Thus, the objective of this study is to numerically evaluate STPV system configurations wherein the absorber/emitter resides at one focal point and the PV cell is located at the second focal point within an ellipsoidal cavity. We determine how the ellipsoidal cavity configuration can increase the emitter-to-cell effective view factor, output power density, photon recycling capability, and decrease the emission loss and heat load on the PV cell (thereby decreasing the cooling power demand). In practice the walls of the ellipsoidal cavity can be fabricated from mirror-polished metallic surfaces. In this work we are interested in determining the extent to which the ellipsoidal cavity configuration can improve these STPV performance parameters without the use of selective absorbers, emitters, filters, or other components that are less stable at high operating temperatures. Our results show the ellipsoid-based cavity can achieve an emitter-to-cell effective view factor of 88.7%. In comparison, the maximum emitter-to-cell effective view factor for an emitter and PV cell in a planar (parallel plate) configuration is 50%. We also show that the number of photons reflected back to the emitter (recycled) can be controlled by either changing the ratio of the area of the PV cell to that of the absorber/emitter or by adding an annular reflector at the mid-plane of the ellipsoidal optical cavity. Increasing the degree of photon recycling is beneficial for increasing the emitter temperature and amount of high energy photons that can be converted to power in the PV cell. Results show the optical cavity can be designed to achieve an efficiency of 5.62% in a STPV system with a GaSb PV cell, black-body absorber/emitter and 350X solar concentration (incoming power of 28 W/cm^2) when the specular reflectivity of the ellipsoidal cavity is 95%. The system efficiency increases to 15.5% by increasing the incoming solar concentration ratio and specular reflectivity of the ellipsoidal cavity to 1400X and 99%, respectively. We also investigate the heat transfer

to the cell within the STPV system at different operating pressures from 0.01 to 1 Pa. Results show the cooling power requirement (reported in Watts) to keep the PV cell at a temperature of $T_0 = 300$ K is dominated by radiative heat transfer. The effects of conductive heat transfer for the range of operating pressures considered in this work are negligible. Further, results show the ratio between the heat load (cooling requirement to keep the PV at 300K) and power output from the PV cell can be reduced from 19.9 for a reference STPV system (comprised of an emitter and PV cell configured as two parallel plates) to 9.36 for STPV systems comprising the ellipsoid optical cavity investigated in this work.

The structure of this chapter is as follows: In Section Two, the system design and geometrical parameters of the ellipsoidal cavity are provided. In Section Three the methods used to determine the probable fates of photons radiated from the emitter, and to evaluate the performance of STPV systems, are presented. Specifically, numerical methods used to determine the output power, system efficiency, effective emissivity, and heat load on the PV cell for STPV systems are described in detail. In Section Four, firstly the photon fate for different STPV system configurations is presented and interpreted. Subsequently, the performance of selected ellipsoidal-based STPV systems is explained. In the final part of Section Four the heat load and cooling requirements for keeping the PV cell at room temperature are discussed. Finally, conclusions and future works are provided.

6.3 Description of the optical cavity

An example of the ellipsoidal optical cavity investigated in this work, referred to as a Radiant Energy Spectrum Converter (RESC), is shown in Fig. 6-1. An innovative aspect of this optical cavity is its ellipsoidal structure, with principal semi-axis a , b , and c and two focal points (shown as f_1 and f_2 in Fig. 6-1a). All thermal radiation emitted from f_1 that is specularly reflected from the internal surface of the ellipsoid converges onto f_2 . As shown in Fig. 6-1b, a disc-shaped blackbody (BB) emitter (i.e. graphite could be used, which has emissive properties close to that of a blackbody) can be placed at f_1 to receive incident radiation that enters a port at the top of the RESC. The internal surface of the ellipsoid is coated with an IR mirror

(such as Aluminum which has a reflectivity of $\sim 95\%$ over a broad spectral range), and thermal radiation emitted from f_1 is reflected to f_2 . A small bifacial PV cell situated at f_2 can absorb a large portion of thermal radiation emitted from f_1 (high effective view factor). The geometrical parameters of the RESC structure shown in Fig. 6-1b can be tailored to control the acceptance angle of concentrated solar radiation entering the cavity, the temperature of the emitter, effective view factor between the emitter and PV cell, photon recycling and the distance between the emitter and the PV cell. For example, the radius of the disc-shaped absorber/emitter, r_{BB} , in Fig. 6-1b and the acceptance angle, θ , can be designed to optimize the trade-off between the incoming solar irradiance absorbed by the absorber/emitter and the emission losses exiting the opening at the top of the RESC. Also, the semi-latus rectum (the radius of the ellipse at its vertices), p , and the distance between the center of the ellipsoid and the PV cell, k , determine the number of emitted photons that are recycled back to the emitter, the emitter-PV cell separation distance, and the power delivered to the PV cell (effective view factor). Further, an annular reflector (Fig. 6-1c and 6-1d) can be added at the mid-plane of the ellipsoidal cavity to increase the photon recycling, thereby increasing the temperature of the emitter and the number of in-band photons it radiates.

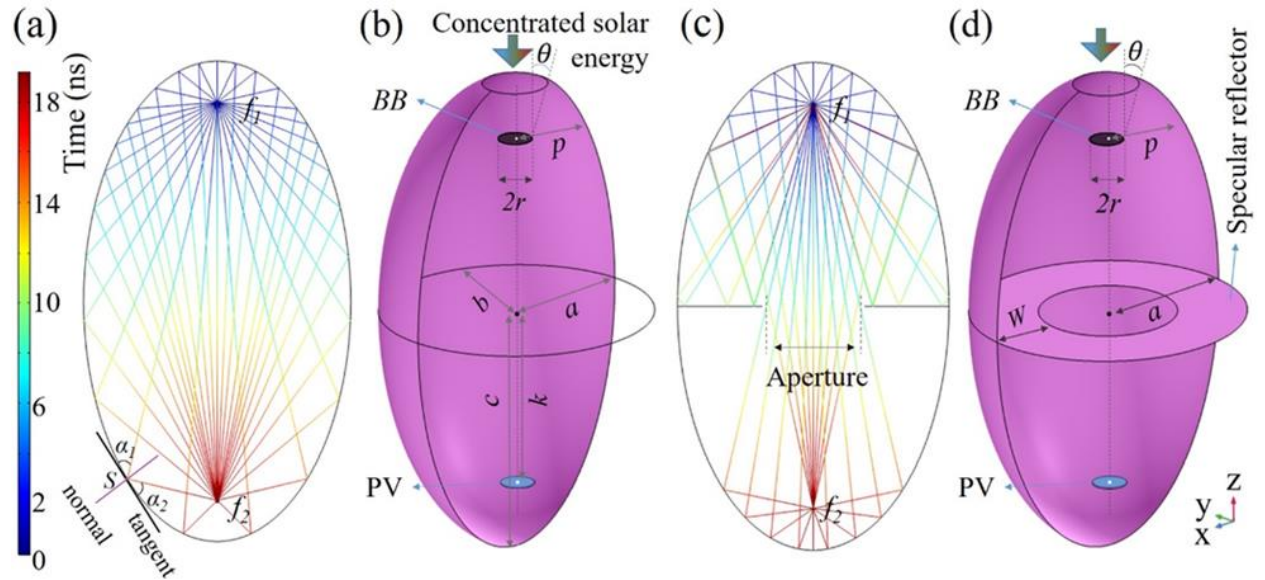


Figure 6-1 a) Schematic of an ellipse showing the optical refocusing of light emitted from f_1 onto f_2 . b) Prolate spheroid used as an optical cavity to convert concentrated solar radiation for STPV applications. c) The addition of an annular specular reflector can be

used to recycle photons back to the emitter at f_1 . d) The fraction of emitted photons that are recycled or incident onto the PV cell is also determined by the width of the annular reflector, w , and the radius of the aperture, $a - w$, respectively.

The proposed RESC structure shown in Fig. 6-1 offers a unique combination of advantages, including a high effective spherical view factor between the emitter and the PV cell, tunable photon recycling, and a large PV cell-emitter separation distance. The high effective view factor enables large system efficiencies by low emission and reradiation losses, and using PV cells with small areas (thermal lens effect), which reduces system costs and increases output power density. The tunable photon recycling can be used to control the temperature and spectrum of the emitter and increase system efficiencies. The large PV cell-emitter separation distance allows for the design of efficient cooling systems for the PV cell. Furthermore, the STPV design presented in this work is expected to be less expensive and more durable than competing STPV systems because it comprises simple robust components that can withstand high temperatures. All of these advantages are achieved without using selective emitters, optical fibers or composite, structured or multilayer materials which increase system costs and can decrease durability at high operating temperatures. Also, low-bandgap PV cells are the most expensive component in STPV systems, and the ellipsoidal cavities proposed in this study enable cost reductions because high conversion efficiencies can be achieved using small PV cell areas. Moreover, a sealed glass window can be placed at the entrance port of the RESC structures, which can then be operated under vacuum conditions to minimize convective and conductive heat losses. Another important advantage of the RESC structure is that it enables a low emitter-to-absorber area ratio of $A_{emt}/A_{abs} = 2$. In comparison, for planar STPV systems a large emitter-to-absorber area ratio (~5 to 30 times) is typically used to achieve reasonable efficiencies.

6.4 Method

Comsol Multiphysics and MATLAB software are used for ray optics analysis and numerical computation, respectively, to determine the probable fate of photons emitted from the BB shown in Fig. 6-1. Four different fates are considered; photons are either absorbed by the PV cell (F_{PV} - effective view factor), returned to and

absorbed by the BB emitter (i.e. photon recycling, F_{BB}), lost through the top entrance port (F_{esc}), or absorbed by the cavity walls (F_{cav}). The photon fate probabilities are used to calculate the effective emissivity, ε^* , for the emitter within the RESC structures shown in Fig. 6-1. The effective emissivity is the emittance an emitter would have in the absence of a cavity that results in equivalent radiative losses as compared to the case when the cavity is present [42,43]. The higher the photon recycling, the lower the effective emissivity. Once the photon fate probabilities and ε^* are known, the power density and efficiency of the RESC-based TPV systems can be calculated. Ray tracing methods are performed to determine the dependency of the emitted photon fate and ε^* on the geometrical parameters of the RESC structures. The following assumptions are made: a) All thermal emission from the BB is assumed to be diffusive and Lambertian. A total number of one million rays are emitted with a Lambertian profile, distributed in a hexapolar grid. b) Unless stated otherwise, 95% of the light incident onto the internal surface of the RESC structures is reflected and 5% is absorbed (similar to the reflectivity of Aluminum in the IR spectrum). c) All light rays reflected back to the BB emitter are absorbed. d) Unless stated otherwise, the acceptance angle, θ , is constant at 5° , which allows for a maximum solar concentration of $\sim 350X$. e) The cavity is at a pressure of 10 mTorr (~ 1.3 Pa) or less [44]. f) The PV cell is assumed to be sufficiently cooled such that its temperature is maintained at 300 K (the heat load and cooling power required to keep the PV at 300K are calculated). g) All radiation incident onto the PV cell is absorbed ($\varepsilon_{cell} = 1$), and the External Quantum Efficiency of a GaSb PV cell (EQE_{GaSb}) is used to calculate the electrical power generated [45]. The mesh sizes are normalized to the radius of the emitter. The non-dimensional mesh size does not exceed 0.01, and the maximum relative tolerance for convergence is 10^{-5} . According to the design parameters considered in this study, all photons absorbed by the PV cell come from the emitter, and photons from the sun are not directly incident onto the PV cell.

It should be noted that the thermal conductivity of the graphite is high, the surface area ratio between the emitter and absorber is low, and the emitter disc is very thin in this study. Under these circumstances a constant temperature distribution on the emitter surface can be assumed [46]. Furthermore, the effects of

non-uniform illumination due to small temperature differences across the emitter surface on the performance of GaSb PV cells is insignificant [17].

The directional emittance, ε' , is integrated across the surface of the emitter to determine the effective emissivity as shown in Equation 6.1 [43]:

$$\varepsilon^* = \frac{2}{A_{emt}} \int_{A_{emt}} \int_0^{\pi/2} \varepsilon'(\phi, x, y) \cos \phi \sin \phi d\phi dA \quad (6.1)$$

where, A_{emt} is the area of the emitter surface and ϕ is the polar angle. When using ray tracing methods, it is convenient to express the effective emissivity using Equation 6.2 [42]:

$$\varepsilon^* = \varepsilon_{emt} \left(1 - \frac{N_{abs}}{N_{tot}}\right) \quad (6.2)$$

where, N_{tot} and N_{abs} are the total number of rays emitted and re-absorbed by the BB, respectively and ε_{emt} is the emissivity of the BB absorber/emitter ($\varepsilon_{emt} = 1$). The temperature of the emitter located in an optical cavity, T^* , can be expressed as a function of ε^* as shown in Equation 3:

$$T^{*4} = \frac{A_{abs} \cdot G \cdot C}{A_{emt} \cdot \sigma \cdot \varepsilon^*} + T_0^4 \quad (6.3)$$

where, $T_0 = 300$ K is the initial temperature of the optical cavity and PV cell, σ is the Stefan–Boltzmann constant, G is the direct solar irradiance, C is the solar concentration factor, A_{abs} is the BB absorber area, and A_{emt} is the BB emission area. In this study $A_{emt} = 2 A_{abs}$ because only the top side of the BB shown in Fig. 1b functions as an absorber while both sides of the BB emit thermal radiation. Herein it is assumed that $G = 800$ W/m². Furthermore, the contribution from the T_0 term in Equation 6.3 is less than 0.05% of T^* , and is omitted from the calculations in this work. The power and efficiency of the RESC-based TPV systems shown in Fig. 6-1 are determined by performing an energy balance using the probable fate of emitted photons as shown in Equation 6.4 and 6.5:

$$G \cdot C \cdot A_{abs} = P_{PV-in} + P_{cav.} + P_{esc.} = A_{emt} \cdot \varepsilon^* \cdot \sigma \cdot T^{*4} \quad (6.4)$$

$$F_{PV} + F_{cav.} + F_{esc.} + F_{BB} = 1 \quad (6.5)$$

where, P_{PV-in} is the power received by the PV cell, P_{cav} is the radiant power absorbed by the optical cavity, and P_{esc} is the radiant power that escapes the cavity through the entrance port. The efficiency (η_{TPV}) and output electric power for the STPV systems (P_{PV-out}) are calculated using Equation 6.6 through Equation 6.12 [47, 48]:

$$\eta_{TPV} = \frac{P_{PV-out}}{P_{in}} \times 100\% \quad (6.6)$$

$$P_{PV-out} = V_{OC} \times J_{SC} \times FF \quad (6.7)$$

$$J_{SC} = F_{PV} \times q \times \int_0^{\infty} \frac{\lambda}{hc} \times E(\lambda, T^*) \times EQE(\lambda) d\lambda \quad (6.8)$$

$$E(\lambda, T^*) = \frac{2\pi hc^2}{\lambda^5 \left[\exp\left(\frac{hc}{\lambda k_0 T^*}\right) - 1 \right]} \quad (6.9)$$

$$V_{OC} = \frac{k_0 T_0}{q} \ln\left(\frac{J_{SC}}{J_s} + 1\right) \quad (6.10)$$

$$J_s = (1.84 \times 10^{-3}) \times T_0^3 \times \exp\left(\frac{-E_g}{k_0 \times T_0}\right) \quad (\text{amps/cm}^2) \quad (6.11)$$

$$FF = \left(1 - \frac{1}{\ln\left(\frac{J_{SC}}{J_s}\right)}\right) \times \left(1 - \frac{\ln\left(\ln\left(\frac{J_{SC}}{J_s}\right)\right)}{\ln\left(\frac{J_{SC}}{J_s}\right)}\right) \quad (6.12)$$

where, V_{OC} is the open-circuit voltage of the PV cell, J_{SC} is the short-circuit current density of the PV cell, FF is the fill factor for the PV cell, q is the elementary charge, $E(\lambda, T^*)$ is the spectral emissive power of the BB, $EQE(\lambda)$ is the external quantum efficiency of a GaSb PV cell, h is Planck's constant, c is the speed of light, k_0 is the Boltzmann constant, T^* is the equilibrium temperature of the BB, T_0 is the temperature of the PV cell, J_s is the saturation current density and E_g is the energy bandgap of PV cells. As the spectral emissive power of the BB is changed for different levels of photon recycling, Equation 6.13 is used to calculate the

PV cell efficiency in different system design parameters and structures. Equation 6.14 is used to calculate the fraction of in-band photons according to the energy bandgap of the GaSb PV cell. The bandgap of the GaSb PV cell is assumed to be $\lambda_g = 1.72$ nm.

$$\eta_{PV} = \frac{P_{PV-out}}{P_{PV-in}} \times 100\% \quad (6.13)$$

$$\eta_{inband} = \frac{\int_0^{\lambda_g} E(\lambda, T^*) d\lambda}{\int_0^{\infty} E(\lambda, T^*) d\lambda} \times 100\% \quad (6.14)$$

The maximum heat load on the PV cell ($P_{heat-load}$) including all heat transfer mechanisms in the system is calculated by Equation 6.15:

$$P_{heat-load} = P_{PV-in} - P_{PV-out} + P_{heat-cav} + P_{heat-BB} \quad (6.15)$$

where, the first two terms ($P_{PV-in} - P_{PV-out}$) represents the heat generated from radiation absorbed in the PV cell, $P_{heat-cav}$ is the conductive and radiative heat transferred from the optical cavity to the PV cell (it is assumed the cavity absorbs 5% of the radiation incident onto its surface which elevates its temperature), and $P_{heat-BB}$ is the convective and conductive heat transferred from the BB emitter to the PV cell. The cooling power required to keep the PV cell at 300 K is assumed to be equal to $P_{heat-load}$ as given in Equation 6.15 (for simplicity it is assumed the cooling process is 100% efficient). In this study the operating pressure of the STPV system is assumed to vary from 0.01 to 1 Pa. The thermal conductivity of air at reduced pressures, k_e , used to determine $P_{heat-BB}$ is given by Equation 6.16 [49]:

$$k_e = \frac{k_c}{1 + 7.657 \times 10^{-5} \times \left(\frac{T_{avg}}{p \cdot d} \right)} \quad (6.16)$$

where, k_c is the thermal conductivity of air at atmospheric pressure, T_{avg} is the average temperature between the emitter and PV cell, p is the reduced pressure in units of Pascals, and d is the distance between the emitter and PV cell. It is assumed convective heat transfer is suppressed at the low operating pressures

considered and its effects are neglected [49, 50]. Moreover, the convective heat transfer coefficient between the outer shell of the ellipsoidal cavity and the surrounding environment is set to $h_c = 10 \text{ W/m}^2\cdot\text{K}$. Simulations are carried out for different separation distances between the emitter and the PV cell (e.g. different values of k with reference to Fig. 6-1). Further, simulations are carried out for the cases wherein the cavity is present and absent, and the results are compared.

It should be noted that the simulation conditions considered in this chapter and Chapter 7 have been validated with the theoretical and experimental results reported in Reference [43]. In this reference a comprehensive study about the effect of a spheroid optical cavity on the effective emissivity of an emitter located at its focal point has been performed. The validations are further explained in Appendix A.

6.5 Results and discussion

6.5.1 Photon fate determination and optical cavity characterization

Fig. 6.2 shows the probable fate of photons emitted from the BB located at the focal point of a prolate spheroid (Fig. 6-1a and b) as a function of the ratio between the emitter radius and the semi-latus rectum (r/p) for $k/p = 1, 2$, and 4 . For the results in Fig. 6-2 it is assumed the radius of the BB emitter is equal to the radius of the PV cell ($r_{BB} = r_{pv} = r$). If the BB emitter and PV cell were point sources, photon recycling, wherein emitted photons are returned to the BB, would not occur. However, due to the finite size of the BB, there is some degree of photon recycling for all cases shown in Fig. 6-2. As the radius of the BB emitter increases the entrance port increases, causing the escape losses to increase, and the fraction of photons incident onto the PV cell generally decreases. The cavity losses decrease as r/p increases because a larger number of photons emitted from the BB are directly incident onto the PV cell or escaped through the opening, and less photons are reflected from cavity walls. When r/p is small the escape losses, F_{esc} , is small and the number of rays available to be recycled or delivered to the PV cell is high, and it is probable to have maximum values for either F_{pv} or F_{BB} . As shown in Fig. 6-2, when $k/p = 1$ and $k/p = 4$, F_{pv} has a maximum value at $r/p = 0.2$. When $k/p = 2$, F_{BB} has a maximum value at $r/p = 0.2$.

In progressing from Fig. 6-2a to 6-2c, as k/p increases from 1 to 4 (for a constant value of r/p), F_{cav} increases because the fraction of photons emitted from the BB that are directly incident onto the PV cell (without being reflected from the cavity walls) decreases. For example, when $r/p = 0.2$, F_{cav} increases from 10.2% at $k/p = 1$ to 11.2% at $k/p = 2$, and to 13.4% at $k/p = 4$. Further, as k/p increases the distance between the BB emitter and the entrance port decreases, which causes F_{esc} to increase. For example, when $r/p = 0.2$, F_{esc} increases from 8.7% at $k/p = 1$ to 9.3% at $k/p = 2$, and to 9.4% at $k/p = 4$. Therefore, when k/p increases, total losses ($F_{cav} + F_{esc}$) increase as well, and it is expected to have lower system efficiencies at higher values of k/p .

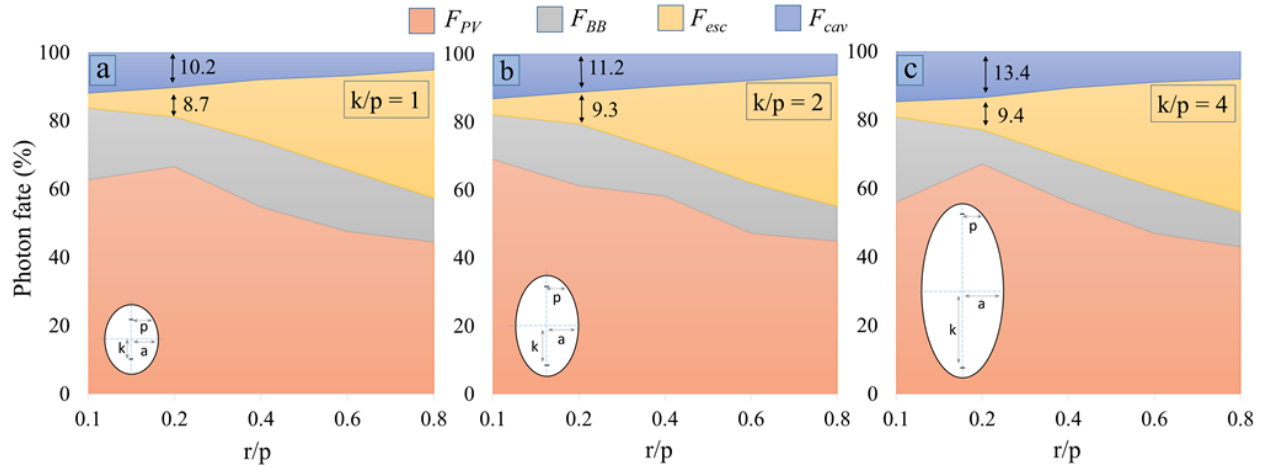


Figure 6-2 The photon fate for the disc-shaped absorber/emitter within the RESC structure shown in Fig. 1b as a function of r/p , plotted for the case when a) $k/p = 1$, b) $k/p = 2$, and c) $k/p = 4$. The relative lengths of k and p are shown in the inset for each sub-figure.

The photon fate probabilities for the cases when $r_{pv}/r_{BB} = 1$, $r_{pv}/r_{BB} = 0.5$ and $r_{pv}/r_{BB} = 2$ are shown in Fig. 6-3. Results are shown for $k/p = 1$, $k/p = 2$, and $k/p = 4$, and $r_{BB}/p = 0.1$ for all cases. As r_{pv}/r_{BB} increases the fraction of photons incident onto the PV cell (effective view factor) increases. This will increase the output power from the PV cell if these are in-band photons. However, if the BB temperature is low, and it emits a high percentage of out-of-band photons, the output power from the TPV system can be increased by increasing the degree of photon recycling and therefore the temperature of the BB (T^*). As shown in the top

row of Fig. 6-3, more than 50% of the photons emitted from the BB can be recycled when $r_{pv}/r_{BB} = 0.5$. A lower number of photons are incident onto the PV cell when $r_{pv}/r_{BB} = 0.5$, however, a greater fraction of these photons are in-band photons due to the increased temperature of the BB (T^*) and decreased effective emissivity. The net result can be an increase in electric power output. The optimal amount of photon recycling and effective view factor depends on the temperature of the BB and the EQE of the type of PV cell used.

In this figure, when k/p increases (for a constant value of r_{pv}/r_{BB}), emission losses through the opening (F_{esc}) and cavity losses (F_{cav}) are increased. The reason is, when k/p increases, the distance between the emitter and top opening decreases and this results in higher emission losses (F_{esc}). Also, when k/p increases, the distance between the emitter and PV cell ($2 \cdot k$) increases and the number of photons directly arrive the PV cell (without being reflected by the cavity walls) are decreased, resulting in higher values of F_{cav} .

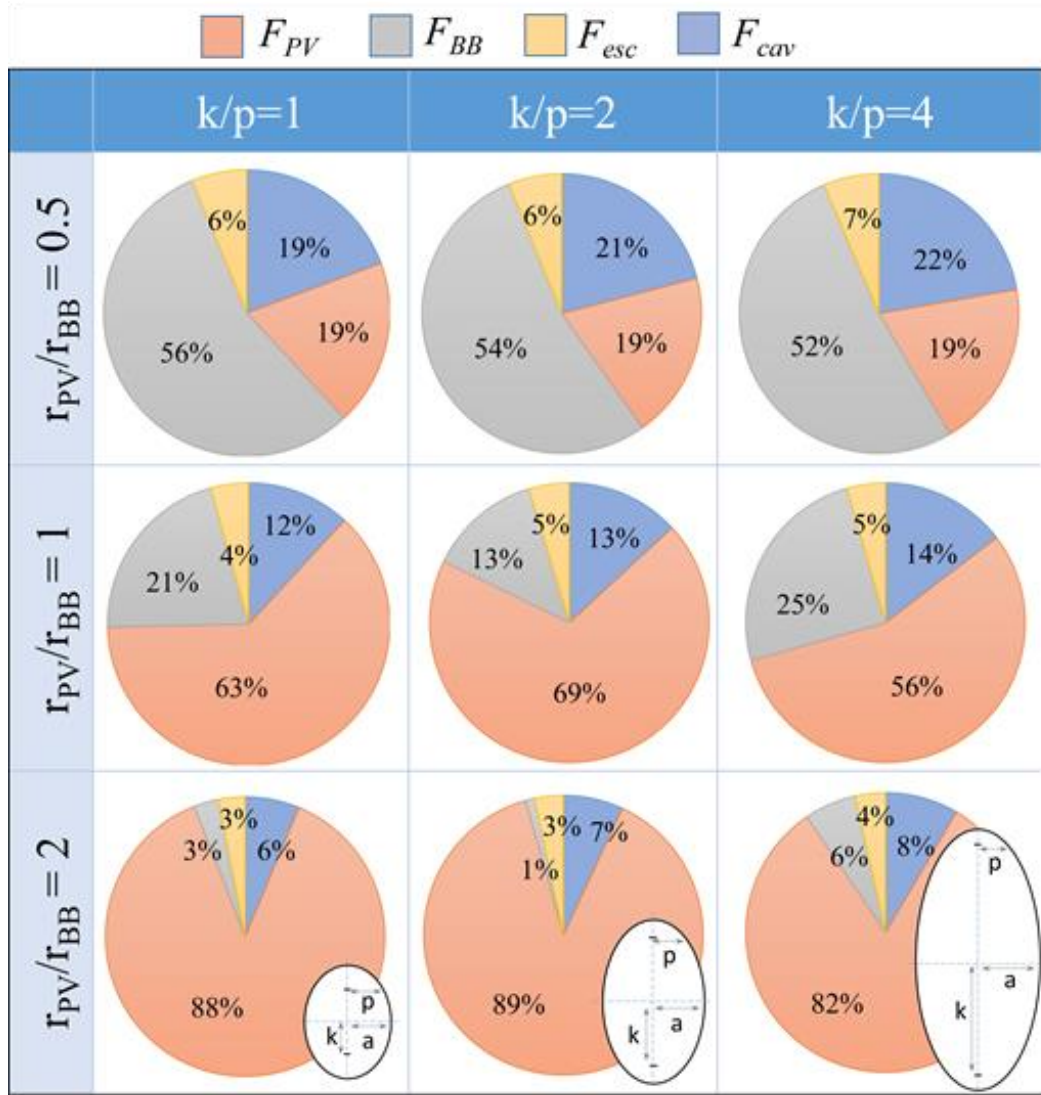


Figure 6-3 The photon fate for the disc-shaped emitter within the RESC structure shown in Fig. 1b for three different values of $r_{PV}/r_{BB} = 0.5, 1$ and 2 , plotted for the cases when $k/p = 1, 2$, and 4 . The relative lengths of k and p are shown in the insets.

In some situations, such as partial overcast conditions, the temperature of the emitter within the RESC structure may be low, and a higher degree of photon recycling can be used to boost its temperature. To achieve a high degree of photon recycling an annular specular reflector can be placed at the midplane of the RESC structure. As shown in Fig. 6-1c, due to the symmetry of the ellipsoidal cavity, rays emitted from the focal point at f_1 that are incident onto the annular reflector will be returned to f_1 . The relative width of the annular specular reflector, w/a , can be designed to control the degree of photon recycling (Fig. 6-1d).

The probable fate of photons emitted from the BB within the RESC structure shown in Fig. 6-1d are plotted in Fig. 6-4 as a function of w/a for the cases wherein $k/p = 1$, $k/p = 2$, and $k/p = 4$, and r/p is kept constant at 0.1 ($r_{pv} = r_{BB} = r$). The specular reflectivity and absorptivity of the annular reflector are assumed to be 95% and 5%, respectively. Losses due to absorption by the annular reflector are included in the cavity losses, which increase slightly as w/a increases.

As shown in Fig. 6-4, as w/a increases the degree of photon recycling increases while the fraction of emitted photons incident onto the PV cell (effective view factor) decreases. These trends illustrate the trade-off between F_{BB} and F_{PV} . Increasing the degree of photon recycling (by increasing F_{BB}) increases the temperature of the emitter and the number of in-band photons it emits. However, increasing the degree of photon recycling also decreases the fraction of photons incident onto the PV cell. The value of w/a can be tuned to optimize the number of in-band photons incident onto the PV cell. For the cases considered in Fig. 6.4, a maximum photon recycling value of 68.8% ($\varepsilon^* = 0.312$) is achieved when $k/p = 1$ and $w/a = 0.9$.

Similar to the explanations for Figs. 6-2 and 3, in progressing from Fig 6-4a to 6-4c, as k/p increases from 1 to 4 (for a constant value of w/a), F_{cav} increases because the distance between the emitter and PV cell increases and the amount of reflection events by the cavity wall increases. For example, when $w/a = 0.4$, F_{cav} increases from 13.5% at $k/p = 1$ to 14.6% at $k/p = 2$, and to 16.3% at $k/p = 4$. Further, as k/p increases the distance between the BB emitter and the entrance port decreases, which causes F_{esc} to increase. For example, when $w/a = 0.4$, F_{esc} increases from 3.9% at $k/p = 1$ to 5.8% at $k/p = 4$. Therefore, when k/p increases, total losses ($F_{cav} + F_{esc}$) increase, and it is expected to have lower system efficiencies at higher values of k/p for this case.

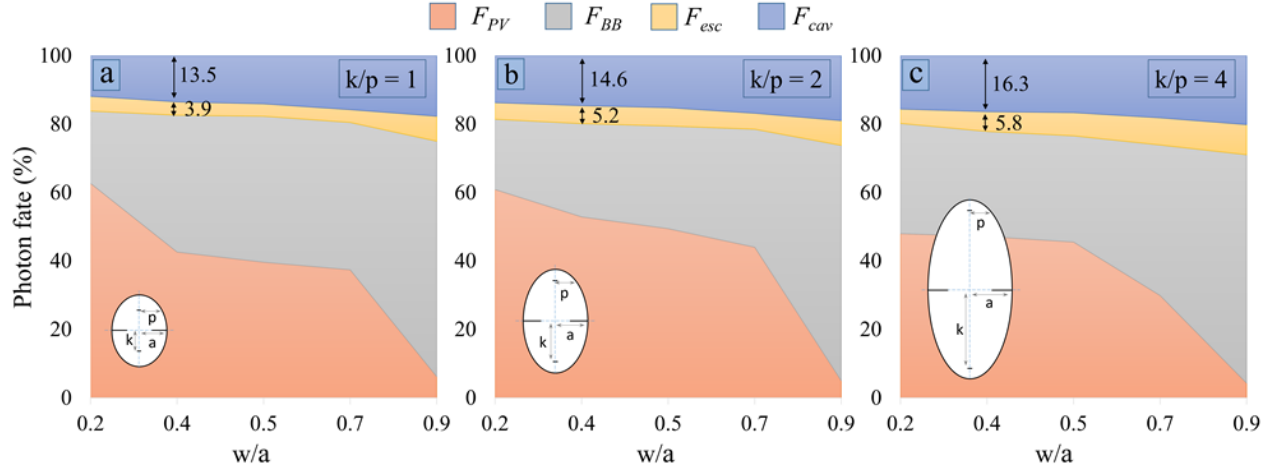


Figure 6-4 The photon fate for the disc-shaped emitter within the RESC structure shown in Fig. 1d as a function of w/a , plotted for the case when a) $k/p = 1$, b) $k/p = 2$, and c) $k/p = 4$. The relative lengths of k and p are shown in the inset for each sub-figure.

The performance of selected RESC-based STPV systems is compared to that of a hypothetical reference case comprised of a BB emitter and a GaSb PV cell configured as two infinite parallel plates in Table 6-1. The hypothetical reference case is referred to “non-cavity” in the first row of Table 1. For all cases in Table 6-1 the solar intensity incident onto the BB emitter is 28 W/cm^2 ($G \cdot C = 800 \text{ W/m}^2 \cdot 350 = 28 \text{ W/cm}^2$). For the reference STPV system (non-cavity case), the temperature of the emitter reaches 1253.5 K and 50% of the solar energy concentrated onto the STPV system is ultimately radiated from the emitter onto the PV cell and the other half is lost through the top surface of the BB. However, only 9.33% of the photons emitted are in-band (η_{inband}) and the system efficiency for this reference case is 2.38%. The efficiency of the PV cell in this case is 4.76%. In this case as there is no cavity, the photon fates considered for the calculation of system efficiency are: $F_{PV} = 50\%$, $F_{BB} = 0\%$, $F_{esc} = 50\%$, and $F_{cav} = 0\%$. The performance of the STPV system can be improved by using the prolate-spheroid cavity shown in Fig. 6-1b. As shown in Table 6-1, the effective emissivity of the BB can be reduced to 0.442 for the case when $r_{pv}/r_{BB} = 0.5$, $k/p = 1$, and $r_{BB}/p = 0.1$; the BB temperature increases to 1537.37 K , 19.4% of the emitted photons are in-band, and the system efficiency, output power density and PV cell efficiency are 4.05%, 2.3 W/cm^2 and 9.5%, respectively. The efficiency increases to 4.42% for the case when $r_{pv}/r_{BB} = 2$, $k/p = 2$, and $r_{BB}/p = 0.1$ because although the in-band photons are 11%, the percentage of photons emitted from the BB that are incident onto the PV cells

(effective view factor) increases to 88.7%. The highest efficiency of 4.85% for the RESC-based TPV system shown in Fig. 6-1b occurs when $r_{pv}/r_{BB} = 1$, $k/p = 1$, and $r_{BB}/p = 0.1$; this is due to the combination of a relatively high BB temperature (1329.6 K), low effective emissivity (or a high degree of photon recycling), and a high effective view factor between the emitter and the PV cell (62.77%).

Table 6-1 Comparison of the performance of selected RESC-based STPV systems at a solar concentration factor of $C = 350X$.

TPV system		ϵ^*	Temp. (K)	Effective view factor ($F_{PV}\%$)	In-band photon ($\eta_{inband}\%$)	PV output power density (W/cm^2)	PV cell efficiency ($\eta_{PV}\%$)	System efficiency ($\eta_{TPV}\%$)
Non-cavity case (two parallel infinite plates)		1	1253.5	50	9.33	0.67	4.76	2.38
Prolate spheroid	PS ₁ $r_{pv}/r_{BB} = 0.5$, $k/p=1$, $r_{BB}/p=0.1$	0.442	1537.4	18.8	19.4	2.3	9.5	4.05
	PS ₂ $r_{pv}/r_{BB} = 2$, $k/p=2$, $r_{BB}/p=0.1$	0.99	1256.7	88.7	9.43	0.155	4.9	4.42
	PS ₃ $r_{pv}/r_{BB} = 1$, $k/p=1$, $r_{BB}/p=0.1$	0.79	1329.6	62.77	11.8	0.68	6.1	4.85
Prolate spheroid with annular specular reflector	PSA ₁ $r_{pv}/r_{BB} = 1$, $k/p = 1$, $r_{BB}/p=0.1$, $w/a = 0.5$	0.573	1440.8	39.6	15.7	0.775	8	5.53
	PSA ₂ $r_{pv}/r_{BB} = 2$, $k/p = 1$, $r_{BB}/p=0.1$, $w/a = 0.7$	0.67	1385	53.43	13.72	0.197	7.1	5.62
	PSA ₃ $r_{pv}/r_{BB} = 2$, $k/p = 2$, $r_{BB}/p=0.1$, $w/a = 0.9$	0.306	1685.4	5.5	25.1	0.074	11.7	2.1

The performance of the STPV system can be further improved by including an annular specular reflector at its midplane (Fig. 6-1d) as shown in the bottom half of Table 6-1. Fig. 6-5 shows the efficiency for various RESC-based STPV configurations with different combinations of values for w/a (0, 0.2, 0.5, 0.7, 0.9), r_{pv}/r_{bb} and k/p , for the cases wherein the solar concentration factor is 350X (Fig. 6-5a), 700X (Fig. 6-5b), and 1400X (Fig. 6-5c), where $\theta = 5^\circ$, 7.1° and 10.1° for $C = 350X$, 700X and 1400X, respectively. The results presented in Figs. 6-5a through 6-5c were attained assuming the specular reflectivity of the optical cavity is 95%. As shown in Figs. 6-5a through 6-5c, for most configurations the system efficiency increases as w/a increases due to enhanced photon recycling which raises the emitter temperature. However, there is an optimal value of w/a because the emitter-to-cell effective view factor decreases as the width of the annular reflector increases.

At a solar concentration factor of 350X the efficiency of a hypothetical STPV system that does not have a cavity (non-cavity case) wherein the emitter and PV cell are two parallel infinite plates is 2.38% (shown as the dashed blue line in Fig 6-5a). As shown in Fig. 6-5a, for the RESC-based STPV structure operating at a solar concentration factor of 350X the highest efficiency of 5.62% is achieved when $r_{pv}/r_{BB} = 2$, $k/p = 1$, $r_{BB}/p = 0.1$, and $w/a = 0.7$; for this case the effective emissivity, temperature of the BB and PV cell efficiency is 0.67, 1385 K, and 7.1%, respectively. Notably, the lowest effective emissivity, highest BB temperature, in-band photons and PV cell efficiency are 0.306, 1685.4 K, 25% and 11.7%, respectively, for the case when $r_{pv}/r_{BB} = 2$, $k/p = 2$, $r_{BB}/p = 0.1$, and $w/a = 0.9$. However, the efficiency for this case is only 2.1% because only 5.5% of the photons emitted from the BB are incident onto the PV cell. A comprehensive system evaluation of RESC-based STPVs for different design parameters is provided in Table A in Appendix B for the incoming solar concentration ratio of 350X and the specular reflectivity of the optical cavity of 95%.

At solar concentration factors of 700X and 1400X the efficiency of a hypothetical STPV system (non-cavity case) wherein the emitter and PV cell are two parallel infinite plates is 4.5% and 7.22%, respectively (shown as the dashed blue lines in Fig 6-5b and 6-5c). As shown in Figs. 6-5b and 6-5c, the highest efficiencies of 9.4% and 13.9% are predicted for RESC-based STPV structures when operating at solar concentration factors of 700X and 1400X, respectively. Referring to Fig. 6-5, overall, the RESC structures with $k/p = 1$ have higher system efficiencies in comparison to RESC structures with $k/p = 2$. The reason is, total losses ($F_{esc} + F_{cav}$) for RESC structures with $k/p = 1$ is smaller than that of with $k/p = 2$ as shown in Figs. 6-2 to 6-4.

For the best case shown in Figs. 6-5a through 6-5c, further improvements are considered by increasing the reflectivity of the optical cavity from 95% to 99% (Gold and Silver coatings can achieve 99% reflectivity in the IR region). As shown in Fig. 6-5d, for the best configuration at $C = 350X$ (PSA₂ in Table 6-1), when the reflectivity of the optical cavity increases from 95% to 99%, the system efficiency increases from 5.62 to 6.7%. When the solar concentration factor is $C = 700X$, the efficiency of the selected STPV system ($r_{pv}/r_{BB} = 2$, $k/p = 1$, and $w/a = 0.5$) increases from 9.4 to 11.1% as the reflectivity of the optical cavity

increases from 95% to 99%. By further increasing the solar concentration to $C = 1400X$, the efficiency of the selected STPV system ($r_{pv}/r_{BB} = 2$, $k/p = 1$, and $w/a = 0.5$) increases from 13.9% at 95% reflectivity of the optical cavity to 15.4% at 99% reflectivity of the optical cavity.

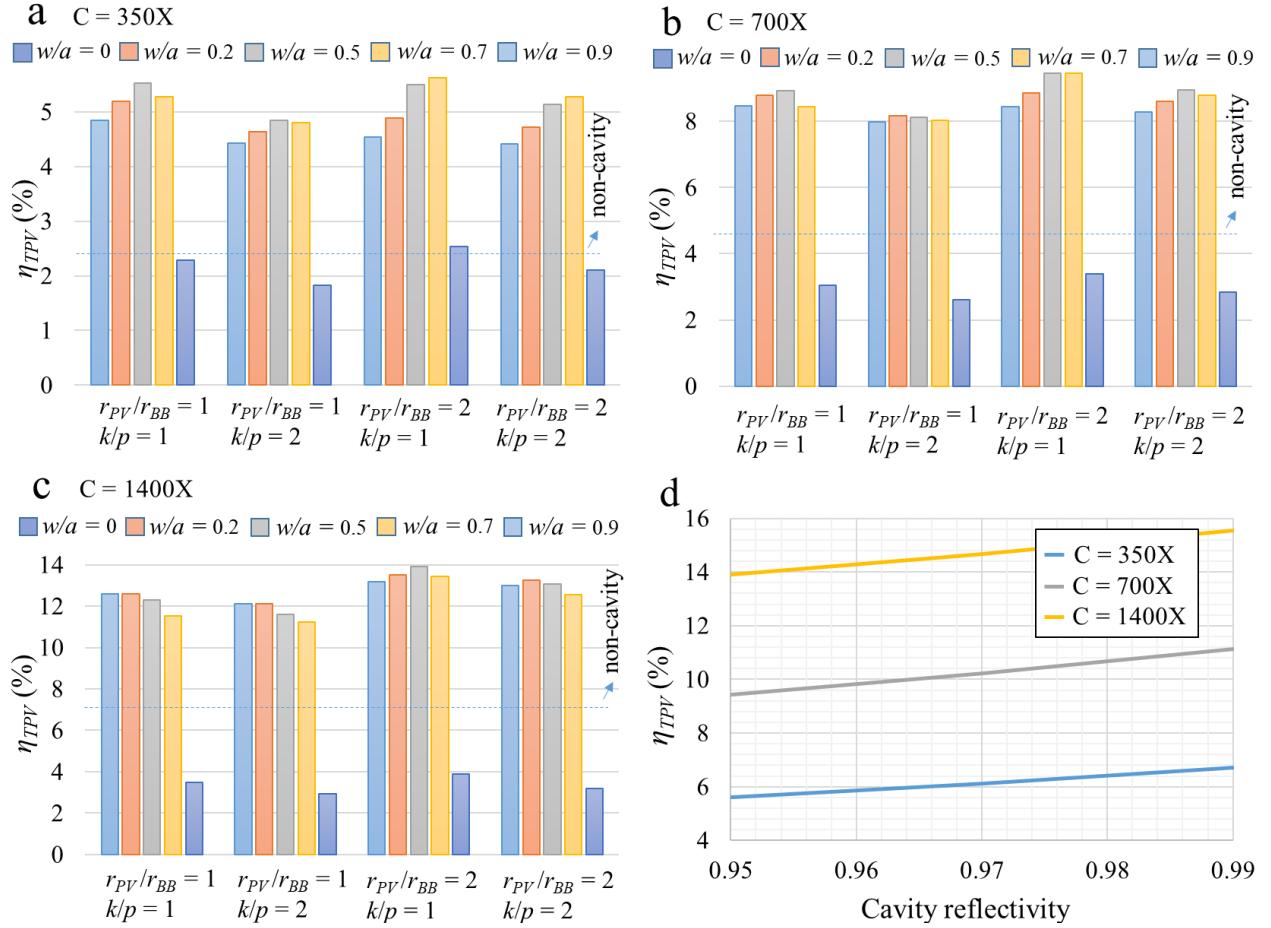


Figure 6-5 System efficiency for various RESC-based STPV configurations with different combinations of values for w/a (0, 0.2, 0.5, 0.7, 0.9), r_{pv}/r_{bb} and k/p , for the cases wherein the solar concentration factor is a) 350X, b) 700X, c) 1400X, and d) System efficiency for the best cases shown in Figs. 5a through 5c for solar concentration factors of 350X, 700X, and 1400X plotted as a function of the specular reflectivity of the ellipsoidal optical cavity for values ranging from 95% to 99%.

Fig. 6-6a shows a comparison of efficiencies for the highest performing TPV systems shown in Fig. 6-5d with an ideal planar TPV system wherein the emitter to absorber ratio is allowed to vary. Fig. 6.6b shows an example of the ideal case when $A_{eml}/A_{abs} = 4$. The concentrated solar irradiation is focused onto the central portion of a receiver that functions as both an absorber and an emitter. The absorber at the middle of the

receiver's upper surface is a blackbody and emits radiation. The sides at the upper surface of the receiver do not emit radiation. The under side of the receiver is assumed to be a black-body and emits radiation. As shown, when $C = 1400$, the ideal planar case has a system efficiency of $\eta_{TPV} = 7.54\%$ at $A_{emt}/A_{abs} = 3$. The system efficiency of the ideal planar case for $C = 700$ and $C = 350$ are $\eta_{TPV} = 4.5\%$ ($A_{emt}/A_{abs} = 2$) and $\eta_{TPV} = 2.38\%$ ($A_{emt}/A_{abs} = 2$), respectively. In comparison, the system efficiencies of the RESC-based TPV cases for $C = 350$, $C = 700$, and $C = 1400$ are $\eta_{TPV} = 6.7\%$ ($r_{pv}/r_{BB} = 2$, $k/p = 1$, $w/a = 0.7$, and $R = 99\%$), $\eta_{TPV} = 11.1\%$ ($r_{pv}/r_{BB} = 2$, $k/p = 1$, $w/a = 0.5$, and $R = 99\%$), and $\eta_{TPV} = 15.4\%$ ($r_{pv}/r_{BB} = 2$, $k/p = 1$, $w/a = 0.5$, and $R = 99\%$), respectively.

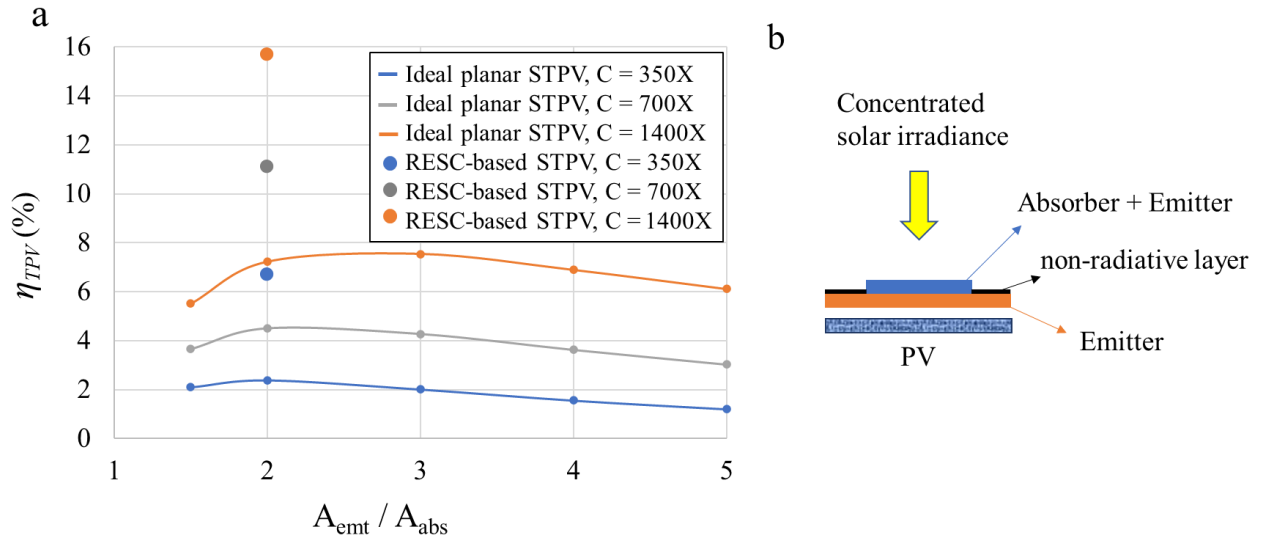


Figure 6-6 a) The comparison of the best RESC -based STPV systems shown in Fig. 6-5d with ideal planar cases for different area ratios of $1 < A_{emt}/A_{abs} < 5$, and b) the schematic of the ideal case when $A_{emt}/A_{abs} = 4$.

It should be noted that, the IQE relates to the efficiency with which absorbed photons are converted to electrons that contribute to the output current of the PV cell. On the other hand, the EQE relates to the efficiency with which photons incident onto the PV cell are converted to electrons that contribute to the output current:

$$(1 - R(\lambda) - T(\lambda)) \times IQE(\lambda) = EQE(\lambda) \quad (6-17)$$

In this chapter, it is assumed that all the photons impinging the GaSb solar cell are absorbed ($T(\lambda) = R(\lambda) = 0$) and therefore, to be consistent with the definitions, IQE (λ) could be used in the calculation of photogenerated current. However, to have a more conservative estimate the EQE (λ) can be used for the calculations of photogenerated current. Also, in practice, the transmission of in-band photons through the PV cell would be negligible, and the assumption that $T(\lambda) = 0$ is reasonable. On the other hand, in the STPV system some of the photons incident onto the PV cell would be reflected. However, we assume that $R(\lambda) = 0$ to make the ray tracing simulations tractable. By assuming that $R(\lambda) = 0$ we neglect some losses. However, by using the EQE rather than the IQE these losses are accounted for to some degree. For comparative purposes it was calculated what the results would be if the IQE were to be used for the STPV system with the best performance reported in this chapter. The best-performance case is for the RESC structure with a system efficiency of 15.54% (using the EQE), $r_{pv}/r_{bb} = 2$, $k/p = 1$, $w/a = 0.5$, and surface reflectivity of $R = 99$, when $C = 1400X$. If the IQE of the GaSb PV cell [56] was used instead of the EQE the system efficiency increases from $\eta_{TPV} = 15.5\%$ to $\eta_{TPV} = 18\%$.

6.5.2 Heat load and cooling power

Conductive heat losses within a TPV system can be decreased by reducing the operating pressure. In this study, the operating pressure is varied from 0.01 to 1 Pa to investigate the effect of conductive heat transfer in the proposed TPV systems on the cooling power required to keep the PV cell at 300 K. Considering Equation 6.15, the heat-load on the PV cell comes from two main sources: 1) $P_{Con-heat}$: conductive heat transferred from the ellipsoidal cavity and BB emitter, and 2) $P_{Radiation-heat}$: radiative heat transferred from the BB emitter and the surface-to-surface radiation transferred from the optical cavity to PV cell (P_{cav-PV}). These two heat load sources can be derived from Equation 6.15 as follow:

$$P_{Con-heat} = P_{heat-cav} + P_{heat-BB} \quad (6.18)$$

$$P_{Radiation-heat} = P_{PV-in} - P_{PV-out} + P_{Cav-PV} \quad (6.19)$$

However, the heat load induced by the cavity is negligible as the temperature of the cavity increases by a maximum of 3 K for all cases considered, and the $P_{heat-cav}$ and P_{cav-PV} terms in Equation 6.18 and Equation 6.19 are neglected.

Herein the heat load on the PV cell is investigated for six different TPV systems at operating pressures ranging from 0.01 to 1 Pa. The first two STPV systems, PS₁ and PS₃, have the prolate spheroid configuration as shown in Fig. 6-1b. The next two STPV systems, PSA₁ and PSA₂, have a prolate spheroid configuration with the addition of an annular ring, as shown in Fig. 6-1d. The geometrical parameters for the PS₁, PS₃, PSA₁ and PSA₂ TPV configurations are available in Table 6-1. Further, for the PS₁, PS₃, PSA₁ and PSA₂ configurations it is assumed the walls of the optical cavity are 0.5 cm thick and are made from aluminum. The convective heat transfer coefficient between the outer surface of the cavity and the surrounding environment is $h_c = 10 \text{ W/m}^2\cdot\text{K}$. For these four cases, r_{BB} is set to 1 cm, which sets $k = 10 \text{ cm}$. The final two STPV configurations considered comprise an emitter and PV cell without the presence of an optical cavity (referred to as “non-Cavity”). For these two reference configurations $r_{BB} = r_{PV} = 1 \text{ cm}$. Furthermore, the separation distance between the BB emitter and PV cell for these two cases is selected to be $2\cdot k = 0.5 \text{ mm}$ and $2\cdot k = 1 \text{ mm}$, such that the efficiency of these systems is comparable to the efficiency of the PS₁, PS₃, PSA₁ and PSA₂ STPV systems. If the separation distance between the emitter and PV cell were set to be the same as that of the PS₁, PS₃, PSA₁ and PSA₂ configurations ($2\cdot k = 20 \text{ cm}$) then the system efficiency for these reference cases would be less than 0.005%. To model the heat transfer for the reference cases it is assumed the PV cell is located on an Aluminium substrate with a thickness of 0.5 cm. The convection heat transfer coefficient between this substrate and the surrounding environment is $h = 10 \text{ W/m}^2\cdot\text{K}$.

Fig. 6-7 shows the ratio of the heat load on the PV cell to the output power due to conductive heat transfer within the STPV system for the six aforementioned case studies. For all six cases considered the conductive heat load on the PV cell is small in comparison to the output power from the PV cell up to an operating pressure of 10^{-1} Pa . However, as the operating pressure approaches 1 Pa the heat load on the PV cell due to conductive heat transfer within the reference cases (non-cavity with $2\cdot k = 0.5 \text{ mm}$ and $2\cdot k = 1 \text{ mm}$) becomes

comparable to the output power from the PV cell. In fact, at 1 Pa the conductive heat transferred to the PV cell is 16 and 18% of the output power for the $2 \cdot k = 0.5$ mm and $2 \cdot k = 1$ mm reference cases, respectively. On the other hand, the conductive heat load transferred to the PV cell for the cases wherein the ellipsoidal optical cavity is present (PS_1 , PS_3 , PSA_1 and PSA_2) is less than 1% of the output power from the PV cell for operating pressures up to 1 Pa. Notably, achieving vacuum levels of 1 Pa is relatively inexpensive, whereas higher vacuum levels require more complex equipment such as multistage rotary vane, diffusion or turbomolecular pumps.

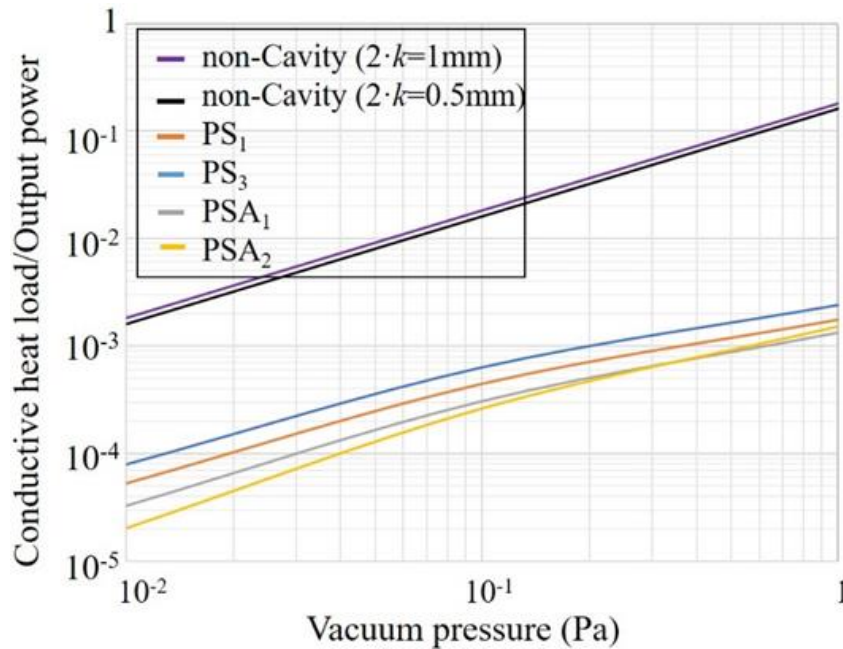


Figure 6-7 The ratio of the conductive heat load on the PV cell to the generated power for six case studies plotted over the pressure range from 0.01 to 1 Pa.

Fig. 6-8 shows the radiative heat load and output power for PV cells within the six aforementioned STPV configurations. Of the six STPV configurations considered, the radiative heat load on the PV cell for the PS_1 configuration is the smallest and, due to its relatively high output power (3.6 W), the ratio of the radiative heat load to the output power is the smallest (9.5). For the non-cavity structures, the radiation cooling power required to keep the PV cell at 300 K is close to 40 W, the power output generated by the PV cell is ~ 2 W,

and the radiative cooling power to output power ratio is ~ 20 . Thus, the non-cavity STPV systems require 20 times the output power generated to be removed as heat to keep the PV cell at 300 K. In comparison, this ratio is 9.5, 15.4, 11.5, and 13.1 for PS_1 , PS_3 , PSA_1 and PSA_3 , respectively. This heat load can be dissipated by different passive and active techniques.

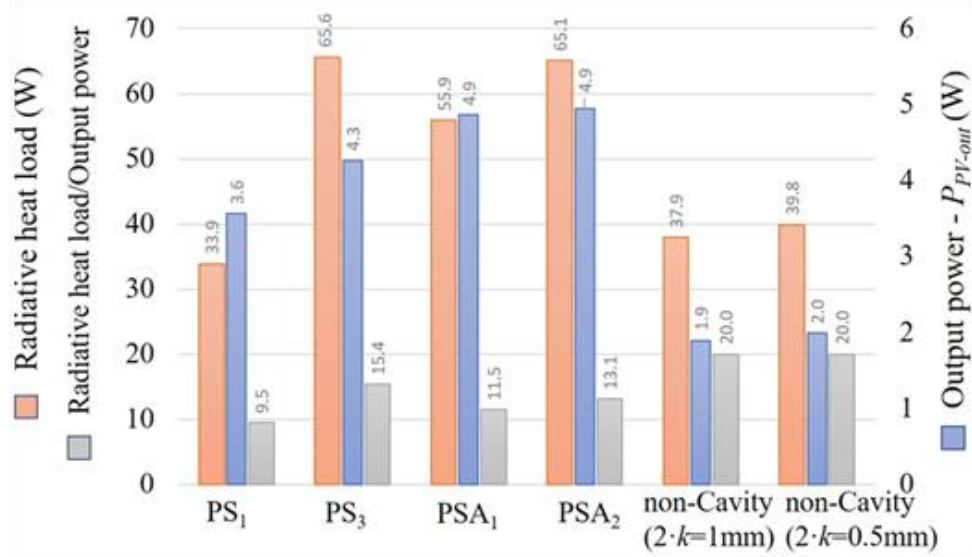


Figure 6-8 The results of the radiative heat load/power required to keep the temperature of the PV cell at 300K for six case studies.

As shown from Figs. 6-7 and 6-8 the dominant heat transfer mechanism to the PV cell is radiative heat transfer. The radiative heat transferred from the emitter to the PV cell depends on the effective view factor and the degree of photon recycling. A high effective view factor is required to achieve high system efficiency, but increases the radiative heat load to the PV cell. A high degree of photon recycling can reduce the radiative heat load on the PV cell by increasing the emitter temperature and reducing the number of incident out-of-band photons (which are assumed to contribute to the heat load on the PV cell in this work). On the other hand, high emitter temperatures also increase the average energy of in-band photons incident onto the PV cell which results in higher thermalization losses, thereby increasing the heat load on the PV cell. It should be noted that using the RESC structure to increase the separation distance between the PV cell and emitter allows for the PV cell to be brought out of the vacuum enclosure where superior cooling

systems that make use of conductive and convective heat transfer can be implemented. Considering future work, selective emitters and filters can be integrated into the design of the RESC-based STPV systems to reduce the amount of out-of-band photons incident onto the PV cell, increase the degree of photon recycling and emitter temperature, and ultimately increase system efficiency. For example, filters that selectively reflect out-of-band photons while transmitting in-band photons can be integrated at the mid-plane of the ellipsoidal optical cavity or at the upper surface of the PV cell. Further, selective filters that transmit solar radiation while reflecting thermal radiation from the emitter can be placed at the opening at the top of the ellipsoidal optical cavity to further decrease the emission losses through the top opening (F_{esc}) [51- 53]. As mentioned previously, the performance of selective emitters and filters can degrade due to extended exposure to high temperatures. However, the performance of RESC-based STPV systems proposed in this work can be more tolerant to degradation of these components because the optical cavity may be made from durable materials that can continue to provide high emitter-to-cell effective view factors and a high degree of photon recycling despite prolonged exposure to radiant energy from emitters operation at high temperatures.

6.6 Conclusion

In this work an STPV system design wherein the emitter and PV cell reside at the focal points of an ellipsoidal optical cavity is proposed. Results from numerical analysis demonstrate the ellipsoidal optical cavity greatly enhances the system efficiency by boosting the effective view factor, emitter temperature and photon recycling, whereby photons are returned to the emitter to increase its temperature. Furthermore, an annular reflector can be inserted at the mid-plane of the ellipsoidal optical cavity to tune the degree of photon recycling. Results show the efficiency of a STPV system can be increased from 2.38% for a hypothetical STPV system comprised of a GaSb PV cell and an absorber/emitter in a parallel plate configuration to 5.62% by using the ellipsoidal optical cavity. Furthermore, assuming the surface of the ellipsoidal optical cavity reflects 99% of the radiation incident onto its surface, efficiencies of 11.1% and 15.4% can be attained when the solar concentration factor is 700X and 1400X, respectively. These results are attained for STPV systems

without using selective emitters or filters. The proposed optical cavity reduces the PV cell area required to achieve high radiation-to-power conversion efficiencies, which is important for reducing the cost of TPV systems. Furthermore, the ellipsoidal optical cavity proposed in this study has the capability to reduce the conduction and radiation heat load on the PV cell, which should be kept at low operating temperatures. The ellipsoidal optical cavity can be integrated into the design of advanced TPV systems and bring them closer to the high theoretical efficiencies TPV systems are capable of.

6.7 References

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6.8 Appendix A

To validate the simulation analysis and conditions for TPV systems considered in this thesis, a spherical optical cavity presented in Reference [43] is modeled and the results are compared. Fig. 6-8Aa shows the effective emissivity (ε^*) as a function of the ratio between the size of the cavity and the size of the emitter (the radius of the cavity (r_{cav}) divided by the radius of the emitter (r_{emt})). The emissivity of the cavity is $\varepsilon_{cav} = 0.05$ and the emitter is assumed to be a blackbody. Fig. 6-8Ab shows the solar-thermal system embedded in a spherical optical cavity studied in Reference [43]. As shown, the ray tracing analysis are highly matched with the simulation approaches performed by Comsol in this work.

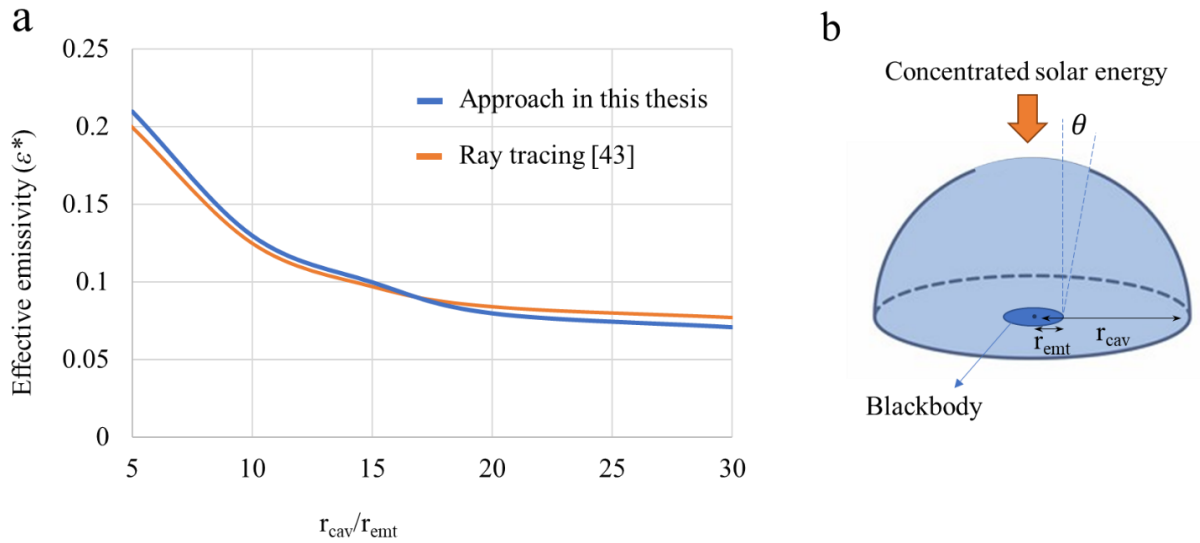


Figure 6-8A a) Comparing the results from Ref. [43] and the approach in this thesis for validation, and b) the solar-thermal system.

6.9 Appendix B

Table 6.9B System evaluation of RESC-based STPVs for different design parameters and $C = 350X$.

Structure name	ε^*	Temp. (K)	Effective view factor (F_{PV} %)	In-band photon (η_{inband} %)	PV output power den. (W/cm ²)	PV cell efficiency (η_{PV} %)	System efficiency (η_{TPV} %)
Non-cavity case (two parallel infinite plates)	1	1253.5	50	9.33	0.67	4.76	2.38

Prolate Spheroid	$r_{PV} / r_{BB} = 1$	k/p=1	r/p=0.1	0.79	1329.6	62.77	11.8	0.68	6.1	4.85
			r/p=0.2	0.855	1303.6	66.6	10.93	0.62	5.7	4.41
		k/p=2	r/p=0.1	0.867	1298.3	69.06	10.76	0.62	5.6	4.43
			r/p=0.2	0.82	1317.8	61.28	11.4	0.62	5.9	4.41
		k/p=4	r/p=0.1	0.75	1346.6	56	12.37	0.665	6.4	4.75
	$r_{PV} / r_{BB} = 2$ $r_{BB}/p = 0.1$	k/p=4		0.94	1273.1	82	9.95	0.16	5.2	4.524
		k/p=2		0.99	1256.7	88.7	9.43	0.155	4.9	4.42
		k/p=1		0.97	1262.6	87.74	9.62	0.16	5	4.54
	$r_{PV} / r_{BB} = 0.5$	k/p=1, $r_{BB}/p=0.1$		0.44	1537.4	18.8	19.4	2.27	9.5	4.05
Middle-aperture Prolate Spheroid	$r_{PV} / r_{BB} = 1$	k/p=1	w/b=0.2	0.69	1374.2	52.45	13.34	0.727	6.85	5.19
			w/b=0.5	0.573	1440.8	39.6	15.7	0.775	8	5.53
			w/b=0.7	0.57	1443.3	37.4	15.8	0.74	8	5.27
			w/b=0.9	0.31	1677.2	6.18	24.8	0.32	11.6	2.29
		k/p=2	w/b=0.2	0.795	1327.5	60.9	11.73	0.65	6.1	4.64
			w/b=0.5	0.7	1370.4	49.44	13.2	0.68	6.85	4.84
			w/b=0.7	0.655	1393.4	44	14	0.67	7.1	4.8
			w/b=0.9	0.31	1677	4.98	24.8	0.26	11.5	1.83
	$r_{PV} / r_{BB} = 2$	k/p=1	w/b=0.2	0.8836	1292.9	78.38	10.58	0.17	5.5	4.89
			w/b=0.5	0.74	1352.4	62.3	12.57	0.19	6.5	5.5
			w/b=0.7	0.67	1385	53.43	13.72	0.2	7.1	5.62
			w/b=0.9	0.315	1673	6.9	24.6	0.09	11.55	2.53
		k/p=2	w/b=0.2	0.91	1283.8	79.94	10.3	0.16	5.4	4.72
			w/b=0.5	0.764	1340.8	62.37	12.2	0.18	6.3	5.14
			w/b=0.7	0.68	1381.9	51.2	13.6	0.18	7	5.28
			w/b=0.9	0.306	1685.4	5.5	25.1	0.074	11.7	2.1

7 Spheroid-based optical cavities for tunable photon recycling and emitter temperature control in solar thermophotovoltaic systems¹

Nomenclature			
<i>Roman symbols</i>			
A_{abs}	absorber area	P_{cav}	power absorbed by the cavity
A_{emt}	emitter area	P_{esc}	power escaped through the entrance
a	minor semi-axis of an ellipsoid	P_{PV-in}	power received by the PV cell
BB	blackbody	P_{PV-out}	output power
C	solar concentration	$P_{heat-BB}$	convective and conductive heat from the emitter
c	light speed	R	cavity reflectivity
$E_{b\lambda}$	blackbody spectral emissive power	r_{BB}	radius of the blackbody
E_{λ}	spectral emissive power (W/m ² . nm)	r_{pv}	radius of the PV cell
F_{BB}	recycling factor	T_0	emitter temperature without cavity
F_{esc}	escape factor	T^*	emitter temperature within a cavity
F_{PV}	view factor	T_{inband}	in-band transmission
E_g	bandgap energy	$T_{outband}$	out-band transmission
F_{cav}	cavity absorption factor	w	width of the annular aperture
G	direct solar irradiance	<i>Greek symbol</i>	
h	Planck constant	α_{abs}	total absorption
k	distance between the center of the ellipsoid and the PV cell	η_{inband}	In-band power over total emissive power
k_0	Boltzmann constant	$\eta_{conv-eff}$	conversion efficiency
N_{abs}	total number of rays re-absorbed	θ	cavity acceptance angle
N_{tot}	total number of rays emitted	ω	recycling angle
p	semi-latus rectum	λ	wavelength (nm)
$P_{conversion}$	conversion power	λ_g	bandgap wavelength (nm)
$P_{emission}$	emission power	σ	Stefan-Boltzmann constant
P_{input}	input power	ϵ^*	effective emissivity
P_{inband}	In-band power	ϵ^*_{inband}	in-band effective emissivity
		$\epsilon^*_{outband}$	out-band effective emissivity
		ϵ_{emt}	emissivity of the emitter

¹ This chapter is based on references [57, 58]

7.1 Abstract

Solar thermophotovoltaic systems have a high theoretical efficiency of 85.4%, although their efficiencies are much lower in practice. This chapter presents spheroid-based optical cavities with reflective optical elements that can significantly enhance the performance of solar thermophotovoltaic systems. The geometry of the optical cavity and reflective elements can be tuned to control the degree of photon recycling, the emitter temperature, the emitter-to-PV cell effective view factor and separation distance as well as the emission losses. Numerical analysis shows that a thermal emitter-to-electric power conversion efficiency of 38.6% and a power density of 22.5 W/cm^2 can be achieved using a single prolate spheroid optical cavity equipped with an optical filter at its semi-major axis. Furthermore, results show that an optical cavity in the form of an integrated oblate- and prolate-spheroid can be used to achieve a system efficiency of 42.5% and power density of 25.5 W/cm^2 when the solar concentration factor is 1500X. These spheroid-based optical cavities can be integrated into the design of advanced STPV systems to bring their performance closer to the high efficiencies they are capable of.

7.2 Introduction

Solar thermophotovoltaic (STPV) systems, first reported by Swanson over four decades ago [1,2], operate by concentrating solar energy onto an absorber to raise its temperature to $\sim 1000 \text{ K}$ or higher. Heat from the absorber is transferred to an emitter which radiates with a spectrum that is well-matched with the spectral response of a PV cell. From a theoretical standpoint, STPV systems can achieve high efficiencies of 85.4% [3-5]. Furthermore, high STPV operating temperatures provides an opportunity to integrate these technologies with thermal energy storage systems [6-10]. Other advantages of STPV systems are that they have no moving parts and their quiet operation. However, the design and fabrication of STPV systems that exhibit high efficiencies has proven to be a challenging task.

Various STPV systems have been fabricated, tested, and reported in the literature. Shimizu et. al. [11] fabricated an absorber/emitter on both sides of a planar tungsten substrate in the form of a multilayered

coating consisting of a thin-film tungsten layer sandwiched between yttria-stabilized zirconia layers. In this study a total system efficiency of 8% was measured when the emitter temperature was 1640. Kohiyama et. al. [12] demonstrated a STPV system with a spectrally selective absorber/emitter made of a multilayered structure with hafnium oxide (HfO_2) and molybdenum. Conversion efficiencies of 5.1% were achieved at an absorber/emitter temperature of 1640 K and an irradiance of 102 W/cm^2 . Ungaro et. al. [13] reported a power conversion efficiency of 6.2% for a STPV system with a tungsten absorber/emitter that had a laser-microtextured absorbing surface coated with an anti-reflection film. Lenert et. al. [14] integrated a multi-wall carbon nanotube absorber and a one-dimensional Si/SiO_2 photonic crystal emitter into a TPV device that reached a conversion efficiency of 3.2% under a solar concentration of 750X. Rinnerbauer et. al. [15] demonstrated a conversion efficiency of 3.74% at an irradiance of 130 kW/m^2 in an STPV system with a selective photonic crystal absorber/emitter fabricated on either sides of a tantalum substrate. Bhatt et. al. [16] achieved an overall power conversion efficiency of 8.4% with a STPV system comprising a micro-textured absorber and a nanostructure multilayer metal-dielectric coated selective emitter fabricated on a tungsten substrate. The effective solar concentration factor and emitter temperature was 2100x and 1676 K, respectively.

To further improve STPV system efficiencies, researchers have focused on the major loss mechanisms inherent to TPV technologies, which can be categorized as spectral or directional losses of radiant energy from the emitter. Spectral losses are due to the miss-match between the spectral distribution of the radiation emitted from the emitter and the bandgap of the PV cell. In most TPV applications, unless a selective emitter is used, the majority of emitted photons have energy lower than that of the bandgap of the PV cell, and are not able to generate current in the PV cell. These lower energy photons are referred to as out-of-band photons. Only photons with energy above the bandgap of the semiconductor in the PV cell, referred to as in-band photons, can be converted to electric power. Directional losses are due to a non-unity view factor between the emitter surface and the PV cell; as not all of the radiant energy from the emitter is incident onto the PV cell.

A key design objective for reducing spectral losses in a TPV device is to minimize the fraction of out-of-band photons the emitter radiates. The radiation spectrum of the emitter can be tailored by engineering its photonic density of states through compositional design, such as emitters made from rare-earth materials, or by structuring it in the form of a metamaterial or photonic crystal [17]. However, there are limitations on the design of the emitter because it must be thermally stable, shock resistant, and maintain its structure and composition through high-temperature cycling. Another strategy is to reflect out-of-band photons back to the emitter. This reflective spectral control scheme is achieved either by using an optical filter between the emitter and PV cell [18, 19], or a back surface reflector (BSR) coated on the rear surface of the PV cell, which reflects the photons transmitted through the PV cell [20, 21].

Design strategies for decreasing directional losses and achieving a high emitter-to-PV cell view factor include using angular selective emitters [22-24], and employing a cage-type configuration wherein the emitter is completely surrounded by an array of PV cells [25-27]. Other technologies to significantly enhance the transfer of thermal energy from the emitter to the PV cell include near-field (micron-gap), light-pipe TPV systems [28-32]. In micron-gap TPVs, energy transfer between the emitter and PV cell occurs via evanescent fields and exceeds that given by Planck's radiation law because the gap between them is decreased to a fraction of the characteristic radiation wavelength [33]. In light-pipe based TPVs the photonic density of states available for radiation transfer to the PV cell is increased from σT^4 to $n^2 \sigma T^4$, where n is the refractive index of the waveguide material between the emitter and PV cell (σ is the Stephen-Boltzmann constant and T is the temperature of the emitter in Kelvin). Note that the applied waveguide should have a very low thermal conductivity (k_c) and extinction coefficient (k) to avoid absorption and attenuation of thermal radiation.

To date, most research on improving TPV systems has focused on the design of selective emitters and absorbers [34-38], PV cells [39-45], and optical filters to reflect out-of-band photons [20]. However, the design of optical cavities for STPV systems has rarely been studied, despite the fact that optical cavities can be used to increase the system efficiency, photon recycling and emitter-to-cell effective view factor [46-49].

Optical cavities can be made from robust and relatively low-cost mirror-polished surfaces that direct radiation from the emitter towards the PV cell [50-52]. In previous work, we performed numerical analysis to show the potential of using ellipsoidal structures as an optical cavity in STPV systems [53]. Results showed a solar-to-electric power conversion efficiency of 15.5% could be achieved in a STPV system comprising an optical cavity under sunlight at a solar concentration factor of 1400x without using selective absorbers, emitters, or filters. In this work we show that optical cavity designs in the form of prolate and oblate spheroids with optical filters can greatly improve the performance of STPV systems. Results from our numerical analysis show that solar-to-electric conversion efficiencies greater than 50% can be achieved at a solar concentration factor of 1500x.

7.3 Description of the optical cavity

A STPV system comprising a prolate spheroid optical cavity is shown in Fig. 7-1. This structure is referred to as a Radiant Energy Spectrum Converter (RESC) because it absorbs sunlight and emits radiation with a spectrum that is well matched with the spectral response of the PV cell. As shown in Fig. 7-1a, all thermal radiation emitted from the focal point f_1 that are specularly reflected from the internal surface of the spheroid converges onto f_2 . As shown in Fig. 7-1b, a disc-shaped blackbody (BB) emitter (i.e., graphite) can be placed at f_1 to receive the concentrated solar irradiance that enters through a port at the top of the RESC, and the thermal radiation reflected from the internal surface of the RESC structure is reflected to f_2 where a PV cell is located. The internal surface of the RESC structure is highly reflective for radiation in the IR spectra (e.g. an aluminium, gold or silver coating). The angle between the line connecting the edges of the emitter and entrance port is referred to as the acceptance angle (θ). The acceptance angle determines the maximum solar concentration onto the emitter that can be achieved. Increasing the acceptance angle allows for a higher solar concentration factor, which increases the temperature of the BB absorber/emitter. However, increasing θ also results in higher emission losses through the entrance port.

The geometrical parameters of the RESC-based TPV system can be tailored to control the probable fate of photons emitted from the BB, such as the fraction of photons that return to the emitter and are recycled, and the portion of photons that are incident onto the PV cell. By controlling the probable fate of photons emitted from the BB it is possible to increase the temperature of the BB and the conversion efficiency of the STPV system. The geometrical design parameters for the STPV system shown in Fig 7-1b are the semi-minor axis (a and b), semi-major axis (c), and the semi-latus rectum (p) which is the radius of the ellipse at its vertices. The radius of the emitter (r_{BB}) and PV cell (r_{PV}) can also be designed to optimize system performance.

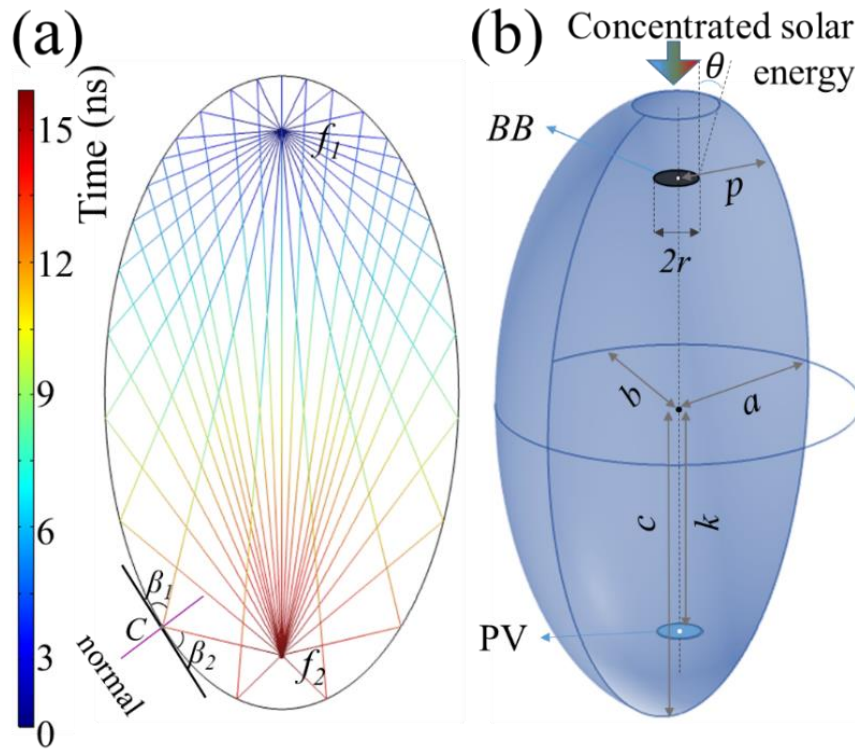


Figure 7-1 Schematic of an ellipse showing the optical refocusing of light emitted from f_1 onto f_2 . b) Prolate spheroid used as an optical cavity to convert concentrated solar radiation for STPV applications.

Reflective components can also be added at the minor-axis of the STPV system shown in Fig. 7-1b to increase performance. Fig. 7-2a and 7-2b show the prolate RESC structure with an annular specular reflector added at its minor-axis. The annular reflector can increase the emitter temperature by reflecting and recycling photons back to the emitter. When the emitter temperature is increased it emits a higher fraction

of in-band photons (photons that have enough energy to generate current in the PV cell). As shown in Fig 7-2c an optical filter can be situated at the minor axis of the prolate RESC structure to selectively transmit in-band photons while reflecting out-of-band photons (which do not have enough energy to generate current in the PV cell) back to the emitter. That is, the optical filter can be designed to achieve a high emitter-to-PV cell effective view factor for in-band photons and a high level of photon recycling for out-of-band photons.

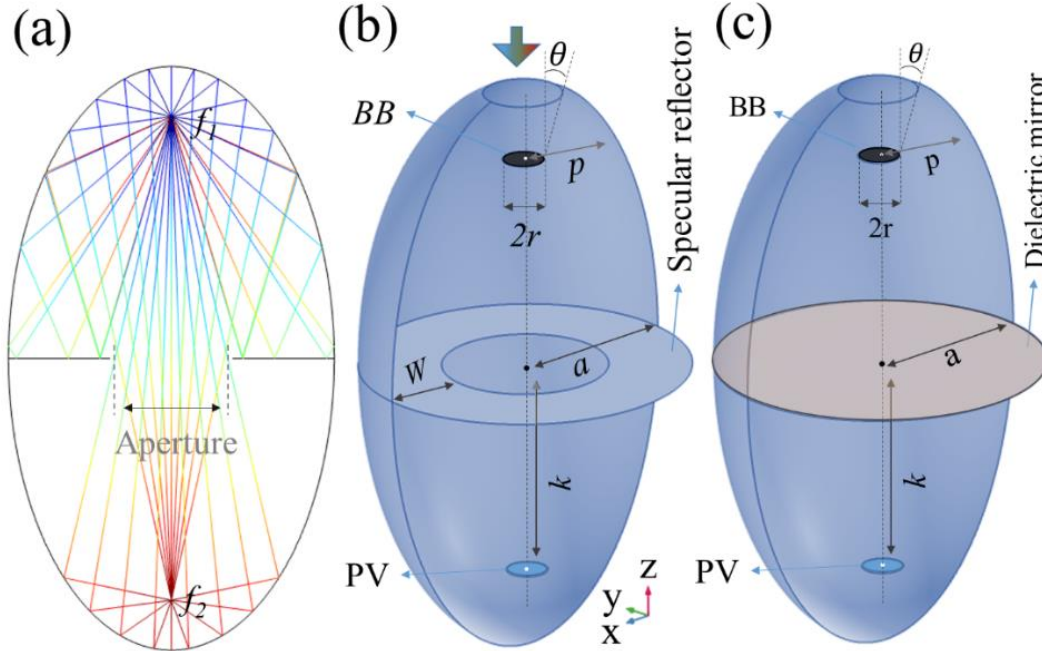


Figure 7-2 An ellipse with the addition of an annular specular reflector at its minor axis, which can be used to recycle photons back to the emitter at f_1 . b) A RESC-based STPV system which shows the width of the annular reflector, w , and the radius of the aperture, $a - w$. c) A RESC-based STPV system with a dielectric mirror at its minor axis, which can be used to reflect out-of-band photons.

An efficient optical cavity requires a very high specular reflectivity for the internal surface (e.g. 95% using a polished aluminum surface, or 99% using a gold coating) and a geometry which is able to reflect the thermal emission from the emitter with a minimum number of reflections (to minimize absorption losses within the cavity walls). For the RESC structures shown in Fig. 7-1, if the emitter was an infinitesimal point situated at the focal point then emitted rays would converge onto the PV cell after a maximum of one reflection from the internal walls of the cavity. For the RESC structure shown in Fig. 7-2, if the emitter is an infinitesimal point at f_1 then emitted rays will either converge onto the PV cell or be recycled (returned

to the emitter) after a maximum of two reflections, which includes the possibility of reflection from the annular ring or middle aperture. However, the emitter and PV cell have some finite width and the emitted rays may be reflected multiple times before being recycled or incident onto the PV cell.

The average number of times emitted rays are reflected can be reduced by adding an oblate spheroid structure at the top of the prolate spheroid, as shown in Fig. 7-3a. This structure makes use of the fact that rays emitted from a point along the foci of an ellipsoid (the foci spans the distance between the focal points of the ellipsoid shown as the red one in Fig. 7-3a) will return to the foci after being reflected once from the internal walls of the ellipsoid [54]. In the RESC structure shown in Fig. 7-3a the center of the foci of the oblate spheroid coincides with the upper focal point of the prolate spheroid. In this structure. Rays that are emitted in the upwards direction from any point on the emitter (not just the infinitesimal point at the center of the emitter) are recycled after being reflected once from the internal surface of the oblate spheroid. Thus, losses for the rays emitted in the upwards direction are limited to the photons that exit the cavity through the entrance port and the average absorption that occurs when photons are incident onto the cavity walls.

As shown in Fig. 7-3b and 7-3c, the upper oblate spheroid can be extended, as defined by the angle ω (ω), which we refer to as the recycling angle. The recycling angle can be used to tune the trade-off between the emitter-to-PV cell effective view factor and the number of recycled photons. The recycling angle, ω , can be positive or negative, which increases or decreases the volume of the oblate hemispheroid at the top of the RESC structure, respectively. As ω increases, the view factor between the emitter and the PV cell decreases, and less photons are incident onto the PV cell. However, the benefit of increasing ω is that more photons are recycled back to the emitter, thereby increasing its temperature. Ultimately there will be an optimum value of ω that maximizes the number of in-band photons incident onto the PV cell. As shown in Fig. 7-3d, an optical filter can be placed at the semi-minor axis of the oblate-prolate RESC structure. This filter can selectively reflect out-of-band photons back to the emitter while transmitting in-band photons to the PV cell.

to reach a reasonable efficiency [14, 55, 56]. A large emitter-to-absorber area ratio can be used to reduce emission losses. However, a high solar concentration factor is needed when the emitter surface area is large to maintain high emitter temperatures. Furthermore, when the surface area of the emitter is high the surface area of the PV cells must also be high in order to collect the emitted radiation, which increases costs.

7.4 Material and methods

COMSOL Multiphysics is used for ray tracing analysis and MATLAB software for numerical computations to determine the probable fate of photons emitted from the emitter. The probability of occurrence for four different photon fates are simulated for each RESC-based STPV system considered: photons absorbed by the PV cell (F_{PV} , which is the effective view factor), photons returned to and absorbed by the BB emitter (F_{BB} , which is the photon recycling factor), photons that escape through the top entrance port (F_{esc}), and photons lost due to absorption by the cavity walls (F_{cav}). The photon fate probabilities are used to calculate the effective emissivity, ε^* , for the emitter within the RESC-based STPV systems considered in this work. The effective emissivity is a key parameter to measure the efficiency of an optical cavity. The effective emissivity is the emittance an emitter would have in the absence of a cavity that results in the same radiative losses that occur when the cavity is present [47, 54].

Ray tracing analysis are performed to determine the dependency of the emitted photon fate and ε^* on the geometrical parameters of the RESC structures. The following assumptions are made: a) The emitter is assumed to be a blackbody with a constant temperature at all points on its surface. b) Thermal emission from the BB emitter is diffusive and Lambertian. In the simulations a total of one million rays are emitted with a Lambertian profile from points that are distributed in a hexapolar grid. c) Two values of the reflectivity of the internal surface of the cavity are assumed: 95% (representing an aluminium coating) and 99% (representing a gold coating). d) the acceptance angle, θ , which determines the size of the entrance port, is constant at 10.4° , which allows for a maximum solar concentration of 1500X. Three different solar concentration factors of 500X, 1000X and 1500X are assumed in the simulations. e) The cavity is under

vacuum and the pressure is low enough such that conduction and convection can be neglected. f) The PV cell is assumed to be sufficiently cooled and its temperature is maintained at 300 K. g) The absorptivity of the PV cell is one ($\alpha_{cell} = 1$), and the Internal Quantum Efficiency of a GaSb PV cell (IQE_{GaSb}) is used to calculate the electrical power generated by the PV cell. Furthermore, the mesh sizes used in the simulations are normalized to the radius of the emitter and do not exceed 0.01. The maximum relative tolerance for convergence is 10^{-5} .

The directional emittance, ε' , is integrated across the emitters surface to calculate the effective emissivity according to Equation 7.1 [47]:

$$\varepsilon^* = \frac{2}{A_{emt}} \int_{A_{emt}} \int_0^{\pi/2} \varepsilon'(\phi, x, y) \cos \phi \sin \phi \, d\phi \, dA \quad (7.1)$$

where, A_{emt} is the surface area of the emitter and ϕ is the polar angle. In this work, the effective spherical emissivity, ε^* , is calculated by using the ray tracing methods to solve Equation 7.2 [54]:

$$\varepsilon^* = \varepsilon_{emt} \left(1 - \frac{N_{abs}}{N_{tot}}\right) \quad (7.2)$$

where, N_{abs} and N_{tot} are the total number of rays reabsorbed and emitted by the BB emitter, respectively and ε_{emt} is the emissivity of the BB emitter ($\varepsilon_{emt} = 1$).

The temperature of an emitter, T^* , functioning within an optical cavity is determined by performing an energy balance using the probable fate of the emitted photons as shown in Equations 7.3 to 7.5:

$$C \cdot G \cdot A_{abs} \cdot \alpha_{abs} = P_{PV} + P_{cav} + P_{esc} = A_{emt} \cdot \int_0^\infty \varepsilon^*(\lambda) \cdot E_{bb}(\lambda, T^*) \, d\lambda \quad (7.3)$$

$$E(\lambda, T^*) = \frac{2\pi hc^2}{\lambda^5 \left[\exp\left(\frac{hc}{\lambda k_0 T^*}\right) - 1 \right]} \quad (7.4)$$

$$F_{PV} + F_{cav.} + F_{esc.} + F_{BB} = 1 \quad (7.5)$$

where $G = 800 \text{ W/m}^2$ is the direct solar irradiance, C is the solar concentration factor, A_{abs} is the BB absorber area, it is assumed $\alpha_{abs} = \varepsilon_{abs} = 1$, P_{PV} is the power received by the PV cell, P_{cav} is the radiant power absorbed by the optical cavity, P_{esc} is the radiant power that escapes the cavity through the entrance port, A_{emt} is the BB emission area, $E(\lambda, T^*)$ is the spectral emissive power of the BB, h is Planck's constant, c is the speed of light and k_0 is the Boltzmann constant. In this study $A_{emt} = 2 \cdot A_{abs}$. Also, in determining the emitter temperature, T^* , radiation received from the environment surrounding the emitter (e.g. the cavity walls) has been neglected. As shown in previous work [53], the temperature of the cavity walls increases by just a few degrees even when the emitter temperature is raised to $\sim 2000 \text{ K}$ because the cavity is assumed to be at low pressure during the operation of a TPV system, the absorption in the cavity walls is relatively small, and the outer surface of the cavity is in contact with air and can dissipate heat effectively. Furthermore, the contribution of the radiative heat transferred from the optical cavity to the PV cell ($T_0 = 300 \text{ K}$) as compared to the heat transferred from the emitter at T^* is less than 0.01% and is omitted from the calculations.

Noting that the ray tracing simulations are independent of wavelength, Equation 7.3 can be expressed as follows to simulate RESC structures that have an optical filter (e.g. Figs. 7-2c and 7-3d), wherein the photon fate is different for in-band and out-of-band photons:

$$C \cdot G \cdot A_{abs} \cdot \alpha_{abs} = P_{PV} + P_{cav} + P_{esc} = A_{emt} \cdot \left(\varepsilon_{inband}^* \cdot \int_0^{\lambda_g} E_{bb}(\lambda, T^*) d\lambda + \varepsilon_{outband}^* \cdot \int_{\lambda_g}^{\infty} E_{bb}(\lambda, T^*) d\lambda \right) \quad (7.6)$$

$$\varepsilon^*(\lambda) = \begin{cases} \varepsilon_{inband}^* = \varepsilon_{emt} (1 - F_{BB-inband}) & 0 < \lambda < \lambda_g \\ \varepsilon_{outband}^* = \varepsilon_{emt} (1 - F_{BB-outband}) & \lambda_g < \lambda < \infty \end{cases} \quad (7.7)$$

where λ_g is the cut-off wavelength for the optical filter which is designed to match the band-gap energy of the GaSb PV cell ($\lambda_g = 1.72$). For RESC structures that do not have an optical filter, Equation 7.3 can be simplified to:

$$G \cdot C \cdot A_{abs} \cdot \alpha_{abs} = P_{PV} + P_{cav} + P_{esc} = A_{emt} \cdot \varepsilon^* \cdot \sigma \cdot T^{*4} \quad (7.8)$$

where, σ is the Stefan–Boltzmann constant.

The power delivered to the PV cell (P_{pv-in}) is given by Equation 7.9. The fraction of energy incident onto the GaSb PV cell that are in-band is given by Equation 7.10. The power density generated by the PV cell is calculated by Equation 7.11.

$$P_{pv-in} = A_{emt} \cdot \int_0^\infty F_{pv}(\lambda) \cdot E_{bb}(\lambda, T^*) d\lambda \quad (7.9)$$

$$\eta_{inband} = \frac{\int_0^{\lambda_g} F_{PV}(\lambda) \cdot E(\lambda, T^*) d\lambda}{\int_0^\infty F_{PV}(\lambda) \cdot E(\lambda, T^*) d\lambda} \times 100\% \quad (7.10)$$

$$Power\ Density \left(\frac{W}{cm^2} \right) = \frac{P_{conversion}}{A_{PV}} \quad (7.11)$$

The solar-to-electric system efficiency (η_{TPV}) is provided by Equations 5.18 through 5.23.

7.5 Results and discussion

7.5.1 Photon fate determination and optical cavity characterization

The probable fate of photons emitted from the BB located at the focal point of the RESC-based TPV system in Fig. 7-1 are plotted as a function of the ratio between the radii of the PV cell and the semi-latus rectum (the radius of the ellipse at its vertices), r_{pv}/p , for $k/p = 0.5, 1, 2$, and 4 in Fig. 7-4. In this study it is assumed that $r_{BB}/p = 0.1$ and the reflectivity of the optical cavity is 95%. If the BB emitter and PV cell were point sources, photon recycling would not occur because all radiation emitted from the BB would be incident onto the PV cell, where it is assumed to be absorbed. However, due to its finite size, some radiation emitted from the BB is not incident onto the PV cell, and returns to the BB after being reflected from the cavity walls. These photons that return to the BB emitter are assumed to be absorbed and recycled.

When the PV cell is small, the fraction of photons emitted from the BB that are incident onto the PV (F_{pv}) cell is low, and the fraction of photons that are recycled (F_{BB}) is high. As the size of the PV cell increases from $r_{pv}/p = 0.025$ to $r_{pv}/p = 0.4$, F_{pv} increases from about 5% to 86%, while F_{BB} decreases from about 65% to 2% for all RESC-based STPV systems considered in Fig. 7-4. Thus, setting the size of the PV cell is one method of controlling the trade-off between F_{pv} and F_{BB} . For cases when F_{pv} is large, but the fraction of in-band photons incident onto the PV cell is low, it may be desirable to increase F_{BB} (even at the cost of a decrease in F_{pv}). Increasing F_{BB} increases the temperature of the emitter, which increases the fraction of in-band photons that are incident onto the PV cell. For all RESC structures considered in Fig. 7-4, the losses (F_{esc} and F_{cav}) decrease as the size of the PV cell increases because emitted photons have less chance to strike the cavity walls multiple times or to escape through the entrance port. For smaller PV cell sizes, F_{BB} is larger, and the degree of photon recycling is higher. In looking at the progression from Fig. 7-4a to 7-4d, as k/p increases from 0.5 to 4, F_{cav} increases because the fraction of photons emitted from the BB that are directly incident onto the PV cell (without being reflected from the cavity walls) decreases. For example, when $r_{pv}/p = 0.1$ (the area of the emitter and the PV are same), F_{cav} increases from 10.7% at $k/p = 0.5$ to 14.4% at $k/p = 4$. Further, as k/p increases the distance between the BB emitter and the entrance port decreases, which causes F_{esc} to increase. For example, when $r_{pv}/p = 0.1$, F_{esc} increases from 5.7% at $k/p = 0.5$ to 8.2% at $k/p = 4$.

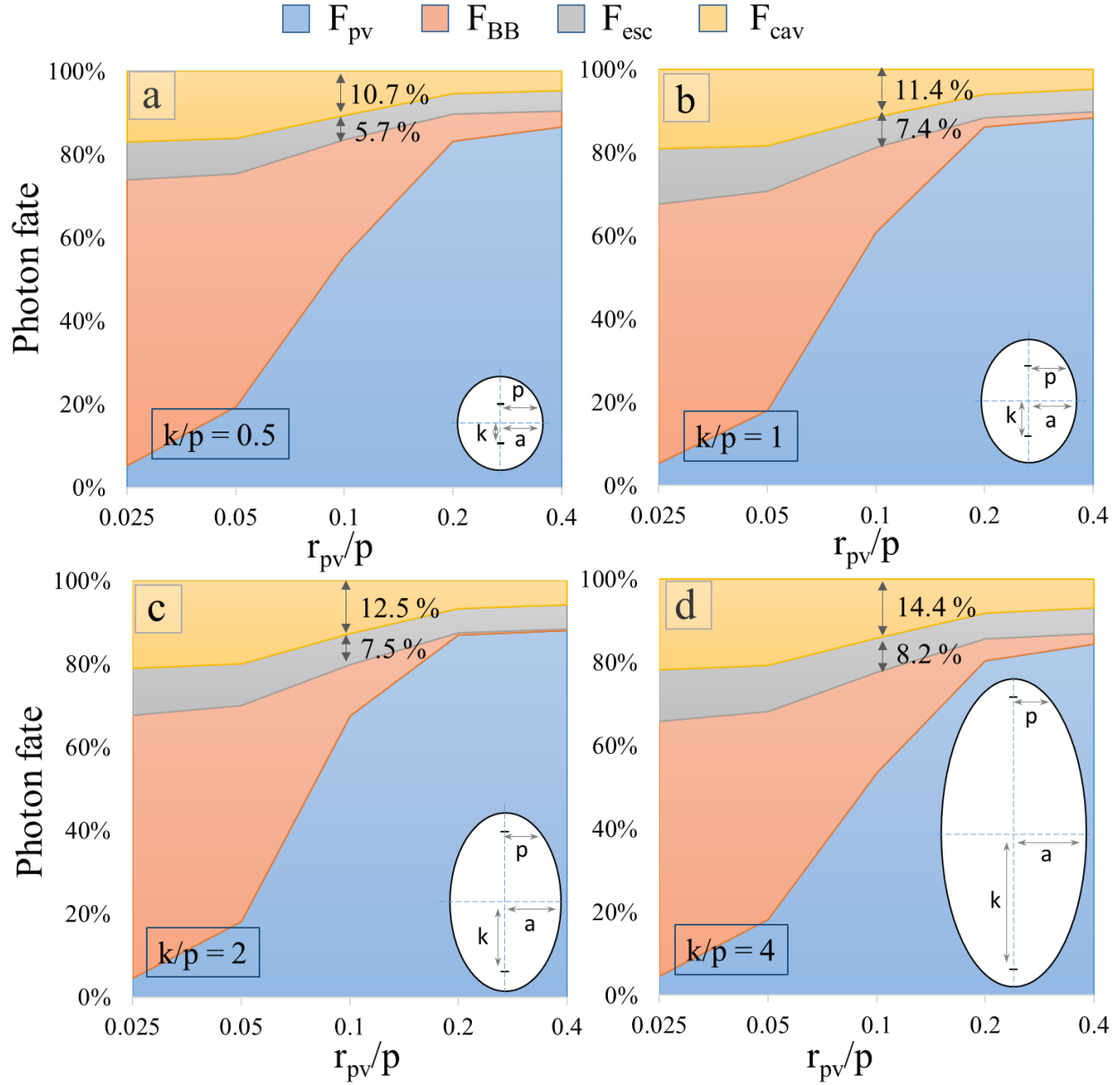


Figure 7-4 Photon fate analysis for the RESC structure shown in Fig. 1, plotted as a function of r_{pv}/p . Four values of a) $k/p = 0.5$, b) $k/p = 1$, c) $k/p = 2$, and d) $k/p = 4$, are considered and the relative lengths of k and p are shown in the inset for each sub-figure.

Fig. 7-5 shows the probable fate of photons emitted from the BB shown in Fig. 7-1, compared for the cases wherein the reflectivity of the optical cavity is 95% and 99%. Results are shown for $k/p = 0.5, 1$ or 2 and $r_{pv}/p = 0.2$ ($r_{BB}/r_{pv} = 0.5$), $r_{pv}/p = 0.1$ ($r_{BB}/r_{pv} = 1$) or $r_{pv}/p = 0.05$ ($r_{BB}/r_{pv} = 2$) and $r_{BB}/p = 0.1$ for all cases considered. As expected F_{cav} decreases significantly and F_{pv} increases as the reflectivity of the optical cavity

increases from 95% to 99% for all cases. Likewise, F_{BB} and F_{esc} also increase as the reflectivity of the optical cavity is increased for all cases considered in Fig. 7-5.

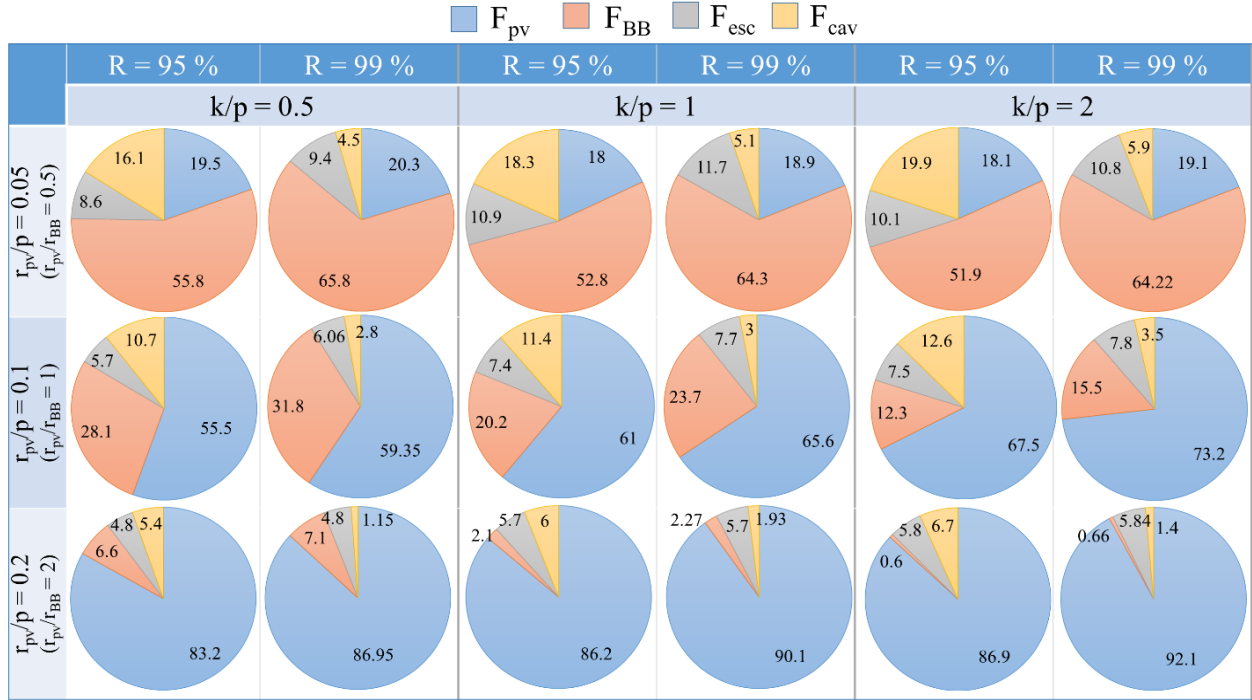


Figure 7-5 Photon fate analysis for the RESC structure shown in Fig. 1 for different values of surface reflectivity of the optical cavity, r_{pv}/p and k/p .

Fig. 7-6 shows the photon fate for the RESC structure with an annular aperture (Fig. 7-2b) as a function of the fraction of the width of the annular reflector to the semi-minor axis (w/a). For the results shown in Fig. 7-6 $R=0.95\%$, $r_{pv}/p = 0.1$ ($r_{BB}/r_{pv} = 1$) and $r_{BB}/p = 0.1$. As w/a increases from 0 to 0.9, F_{pv} decreases and F_{BB} increases. Tuning the width of the annular reflector provides a simple way to control the trade-off between F_{pv} and F_{BB} . As w/a increases F_{esc} increase. Furthermore, as w/a increases the average number of times that a photon emitted from the BB is reflected from the surfaces of the optical cavity increases, and F_{cav} also increases with increasing w/a . Therefore, the chances for the photons to escape or be absorbed by the cavity increases. For a constant value of w/a , F_{BB} is higher for $k/p = 1$ in comparison to when $k/p = 2$ because the annular reflector is closer to the emitter and reflects a greater portion of photons that can subsequently be recycled. For example, when k/p increases from 1 to 2, photon recycling decreases from $F_{BB} = 35.3\%$ to F_{BB}

= 23.6% for $w/a = 0.3$ and from $F_{BB} = 38.8\%$ to $F_{BB} = 32.8\%$ for $w/a = 0.6$. On the other hand, more photons are incident onto the PV cell when k/p increases from 1 to 2 and F_{PV} increases from 45.1% to 54.8% when $w/a = 0.3$ and from 40.2% to 43.6% when $w/a = 0.6$.

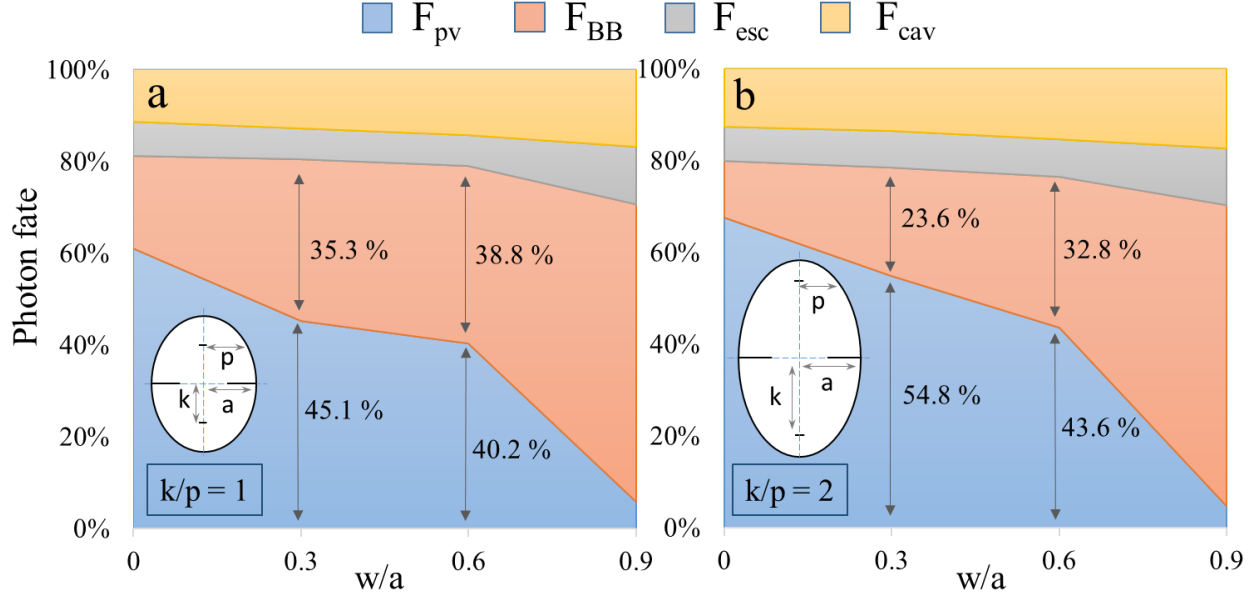


Figure 7-6 The photon fate for the RESC structure shown in Fig. 7-2b plotted as a function of w/a , for the cases when a) $k/p = 1$ and b) $k/p = 2$. The relative lengths of k and p are shown in the insets for each sub-figure.

The results from the photon fate analysis for the RESC-based TPV system with an optical filter on its minor axis, shown in Fig. 7-2c, are plotted in Fig. 7-7. Ideally, this optical filter reflects all out-of-band photons while transmitting all in-band photons. However, in practice optical filters will transmit some out-of-band photons while reflecting some portion of the incident in-band-photons. In this work we consider three cases for the transmission of in-band photons through the filter: $T_i = 100, 90$ and 80% , and three cases for the transmission of out-of-band photons through the filter: $T_o = 20, 10$ and 0% . The results from the photon fate analysis for transmission values of $T_i = 100, 90, 80\%$ and $T_o = 20, 10$ and 0% are shown in Fig. 7-7. For all cases shown in Fig. 7-7 $r_{pv}/p = 0.1$ ($r_{BB}/r_{pv} = 1$), and different cases of the RESC are considered; RESC structures with $k/p = 1$ or 2 , and $R = 95\%$ or 99% . As shown in Fig. 7-7, the filter increases F_{BB} for out-of-band photons while maintaining high values of F_{PV} for in-band photons. When the surface reflectivity

increases from $R = 95\%$ to $R = 99\%$, cavity losses decrease significantly and F_{BB} and F_{PV} increases for both in-band and out-band transmissions.

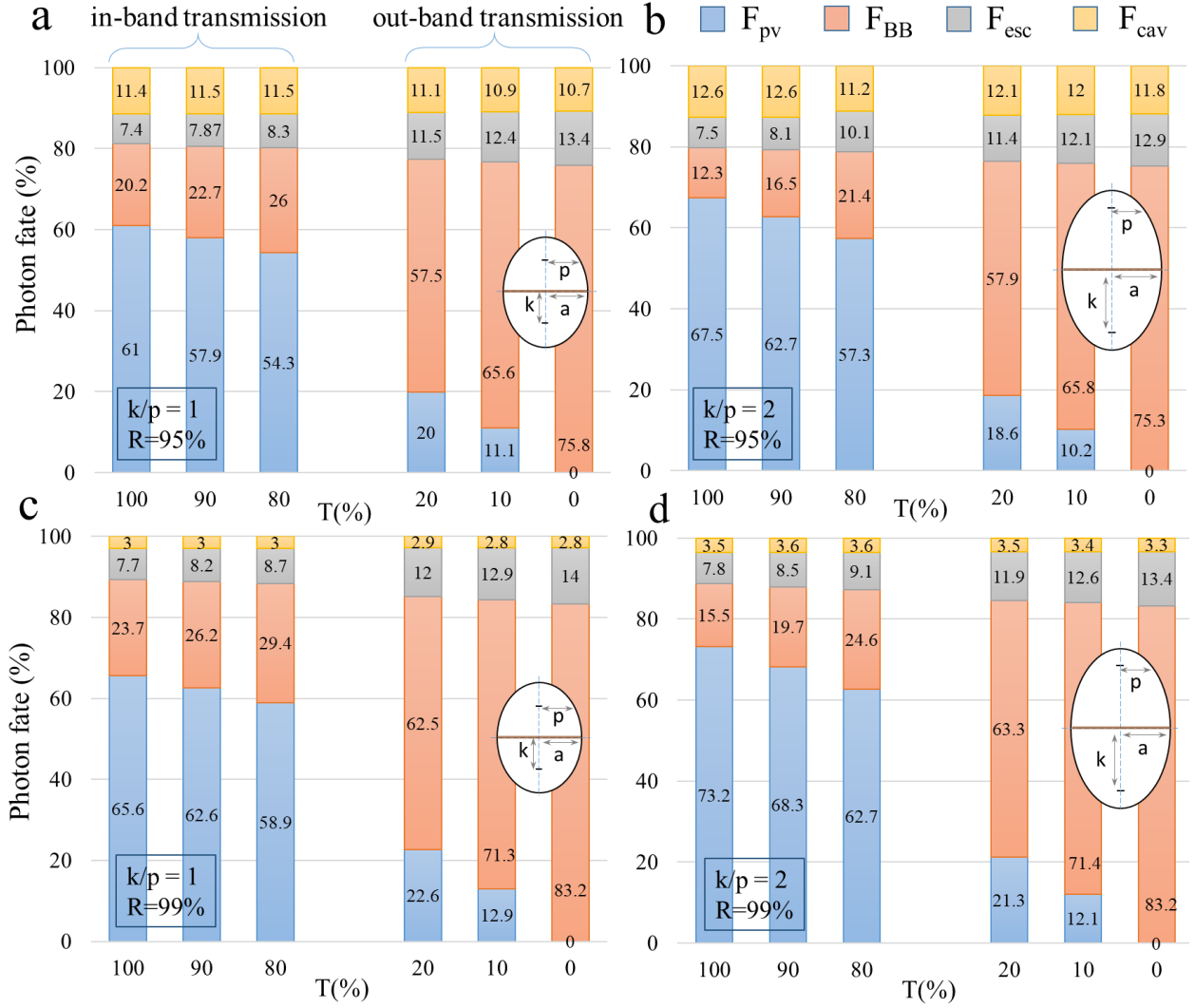


Figure 7-7 The photon fate for the RESC structure shown in Fig 7-2c when a dielectric mirror is placed at its minor axis. The photon fate is considered for RESC structures with a) $k/p = 1$, $R = 95\%$, b) $k/p = 2$, $R = 95\%$, c) $k/p = 1$, $R = 99\%$, and d) $k/p = 2$, $R = 99\%$. The schematic in each sub-figure shows the relative lengths of k and p . For each RESC structure the photon fates when the in-band transmission through the filter is $T_i = 100, 90$ and 80% are shown on the left side of the sub-figures. The photon fates when the out-of-band transmission through the filter is $T_o = 20, 10$ and 0% are shown on the right side of the sub-figures.

The results from the photon fate analysis for the RESC-based STPV system comprised of an oblate spheroid at the top half and a prolate spheroid at the bottom half are plotted in Fig. 7-8 as a function of ω for $k/p = 1$

and $r_{pv}/p = 0.1$ ($r_{BB}/r_{pv} = 1$). The photon fate is shown for four cases wherein $c_o/p = 1$ or 2 and the reflectivity of the cavity walls is either $R = 95\%$ or 99% (c_o is the semi-major axis of the oblate spheroid located on top of the emitter). For all cases, as ω increases, more photons are recycled, and the effective view factor decreases. The photons emitted from the BB that are incident onto the internal surface of the oblate spheroid at the upper half of the structure are recycled after being reflected from this surface once. At large negative values of ω F_{PV} is maximized, while at large positive values F_{BB} is maximized, and in between these extremes F_{esc} has a maximum value at $\sim 20^\circ$ for all cases considered. Furthermore, for a constant value of ω and reflectivity (R), when c_o/p increases from 1 to 2, the distance from the emitter to the entrance port at the top of the structure increases and F_{esc} decreases.

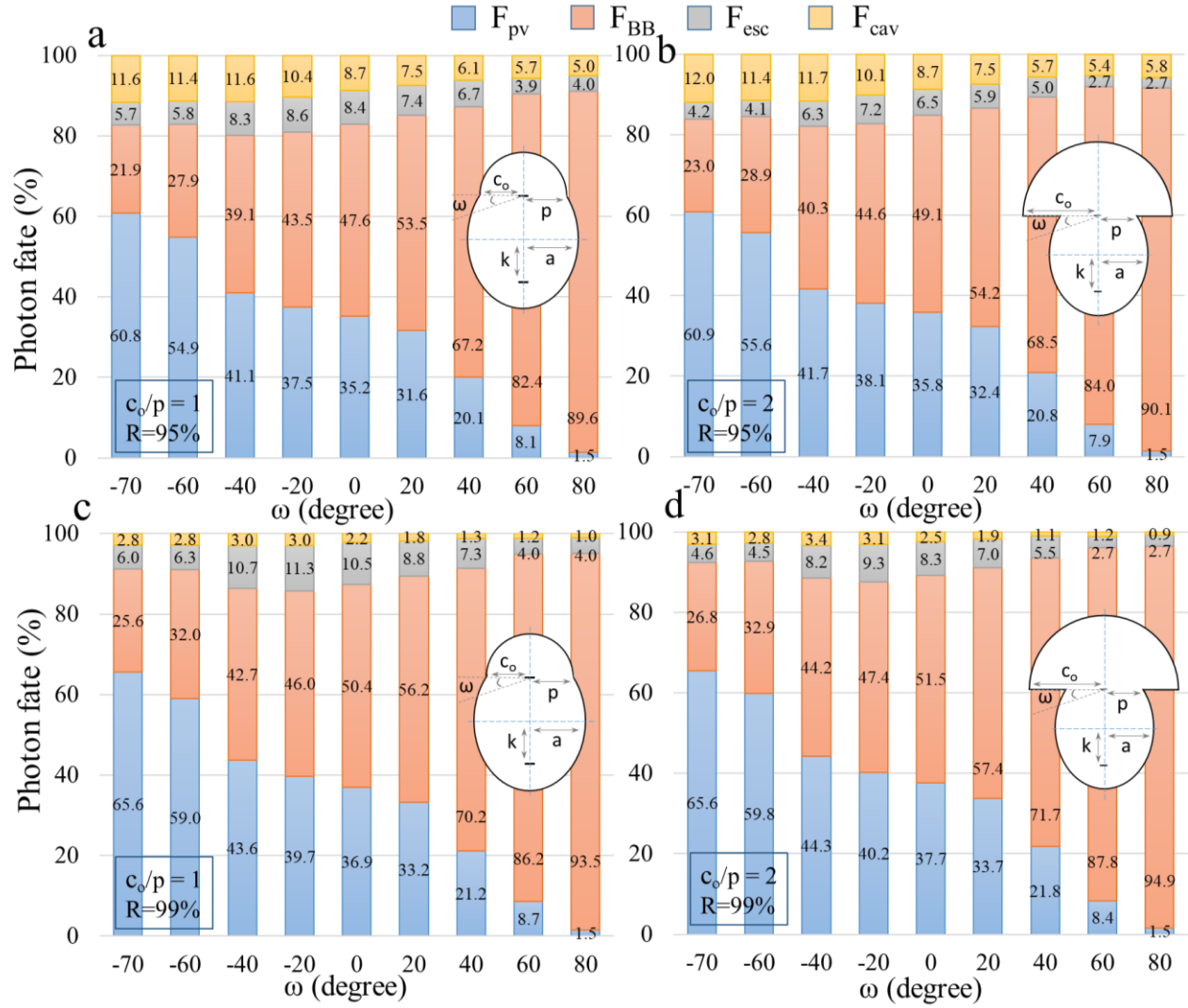


Figure 7-8 The photon fate for the RESC-based STPV structure shown in Fig. 7-3 as a function of the recycling angle (ω) when a) $c_o/p = 1$ and $R = 95\%$, b) $c_o/p = 2$ and $R = 95\%$, c) $c_o/p = 1$ and $R = 99\%$, and d) $c_o/p = 2$ and $R = 99\%$. The inset in each sub-figure shows the relative lengths of c_o , p and k .

Fig. 7-9 shows the result from the photon fate analysis for the RESC structure shown in Fig. 7-3d as a function of ω when $k/p = 1$, $c_o/p = 2$, $r_{pv}/p = 0.1$ and the surface reflectivity is $R = 99\%$. For the results shown in Fig. 7-9, the optical filter is assumed to be ideal with a transmission of $T_i = 100\%$ for in-band photons (Fig. 7-9a), and $T_o = 0\%$ for out-of-band photons (Fig. 7-9b). As shown in this figure, the view factor for in-band photons has a maximum value of $F_{pv} = 65.5\%$ when $\omega = -70^\circ$.

It should be noted that for recycling angles smaller than $\sim -75^\circ$, ω overlaps the opening angle (θ) and the structure becomes the prolate spheroid RESC structure shown in Fig. 7-1b. Moreover, as shown in Fig. 7-9b, for out-of-band photons F_{esc} is at a maximum when $\omega = 40^\circ$. When $\omega \sim 40^\circ$ the prolate spheroid at the bottom of the RESC structure shown in Fig 7-3d becomes a hemi-prolate spheroid, as the top half of the prolate spheroid is removed to make room for the oblate spheroid occupying the top half of the RESC structure. Emitted radiation that is reflected from the inner surfaces of the oblate spheroid is recycled back to the emitter. However, emitted radiation that is reflected from the optical filter may not return to the emitter. For lower values of ω , a large portion of emitted photons that are reflected from the filter undergo a second reflection from the inner surface of the top half of the prolate spheroid and are returned to the emitter. When the top half of the prolate spheroid is absent (e.g. when $\omega > \sim 40^\circ$) emitted photons that are reflected from the filter have a greater chance of exiting the RESC through the top entrance port, and thus F_{esc} is relatively large when $\omega = 40^\circ$. As ω continues to increase past 40° the inner surface area of the oblate spheroid increases while the surface area of the filter decreases, and consequently F_{esc} decreases.

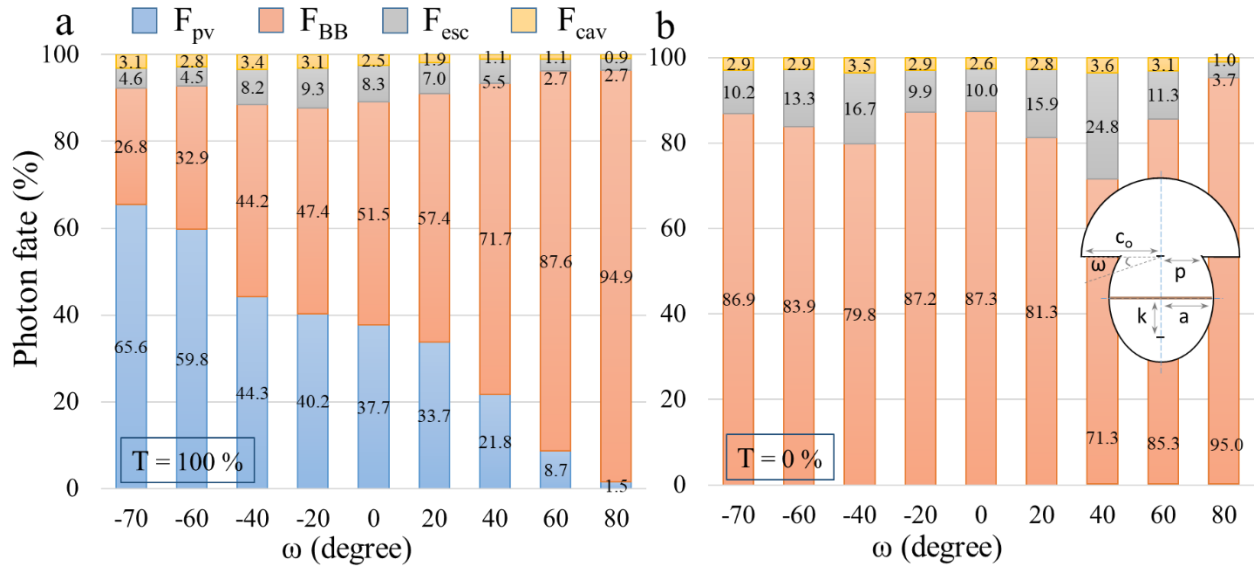


Figure 7-9 Photon fate in an oblate-prolate RESC structure with an optical filter at its minor axis as a function of the recycling angle, ω , for a) in-band photons when the transmission through the filter is $T_i = 100\%$ and b) out-of-band photons when the transmission through the filter is $T_o = 0\%$.

7.5.2 System efficiency assessment

The performance parameters for the RESC-based STPV system shown in Fig. 7-1 are plotted in Fig. 7-10. For all results shown in Fig. 7-10, $k/p = 1$ and $r_{BB}/p = 0.1$ and different cases of the STPV system are considered; the reflectivity of the cavity surface is either 95% or 99%, and the solar concentration factor is either 500, 1000, or 1500X. The effective emissivity (ε^*), plotted as a function of r_{pv}/p in Fig. 7-10a for the case of $R = 95\%$ (solid line) and $R = 99\%$ (dashed line), is the same for all solar concentration factors considered, as the geometry of the RESC structures is independent of the solar concentration factor. At relatively high values of r_{pv}/p the effective emissivity is close to 1, as a large fraction of photons are absorbed by the PV cell and the number of photons that are returned to and absorbed by the BB emitter (N_{abs} in Equation 7.2) is low. The size of the PV cells decreases as r_{pv}/p decreases, and the effective emissivity decreases as an increasing number of photons emitted from the BB are recycled. As expected from Equation 7.8, the temperature of the BB emitter (T^*), which is also plotted in Fig. 7-10a, decreases as r_{pv}/p increases (and ε^* increases). The power density generated in the PV cell is shown in Fig 7-10b; for all cases the power density increases as r_{pv}/p decreases (and r_{pv} decreases). The fraction of radiant energy emitted from the BB as in-band photons, $\eta_{in-band}$, is plotted in Fig 7-10c. For all cases, $\eta_{in-band}$ increases as r_{pv} decreases. As mentioned, a smaller PV cell results in a greater degree of photon recycling and a lower value of ε^* , which in turn causes an increase in the emitter temperature T^* . As the temperature of the emitter increases it emits a higher fraction of photons with energy greater than the cut-off value ($1.72 \mu\text{m}$) of the PV cell (in-band photons). The solar-to-electric system efficiency (η_{TPV}) is shown in Fig. 7-10d. For each case considered, there is an optimal value of r_{pv} that maximizes the conversion efficiency. When r_{pv} is small the emitter-to-PV cell effective view factor is comparatively small. On the other hand, when r_{pv} is relatively large the fraction of in-band photons incident onto the PV cell is small because the degree of photon recycling is low and the emitter is at a lower temperature.

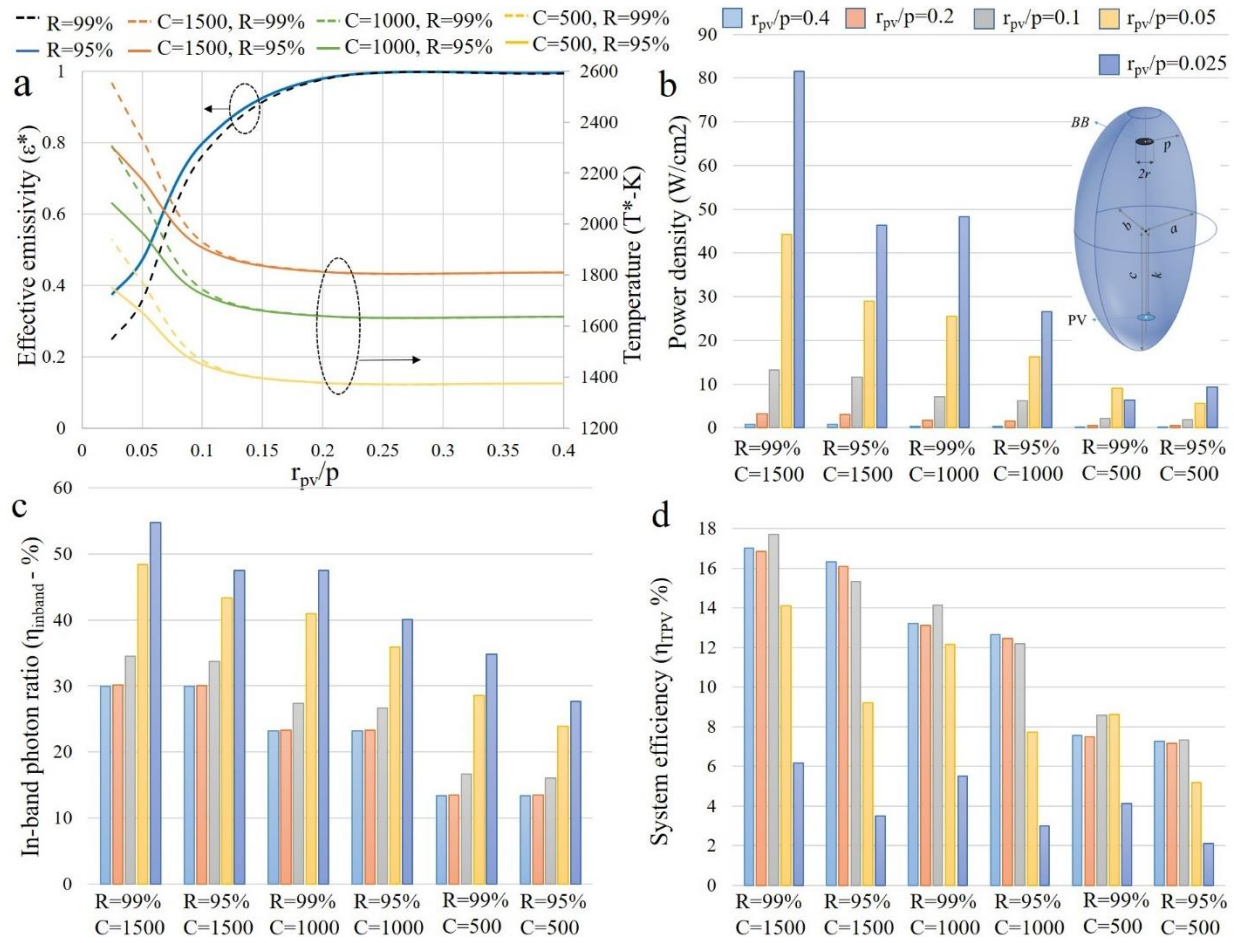


Figure 7-10 The results from the numerical analysis for the RESC-based STPV system shown in Fig. 7-1 (shown at the top right of this figure) when $k/p = 1$ and $r_{BB}/p = 0.1$. a) ϵ^* and T^* plotted as a function of r_{pv}/p . The b) power density c) fraction of photons incident onto the PV cell that are in-band, and d) system efficiency when $r_{pv}/p = 0.025, 0.05, 0.1, 0.2$ and 0.4 shown for the cases when $C = 500X, 1000X$, or $1500X$, and $R = 95\%$ or 99% .

The results from the photon fate analysis for the RESC-based STPV structure shown in Fig. 7-2b are shown in Fig. 7-11. In simulating the results shown in Fig. 7-11 it has been assumed that $k/p = 1$, $r_{BB}/p = 0.1$ and $r_{pv}/p = 0.1$. Also, different cases have been considered wherein the reflectivity of the optical cavity is 95% or 99%, and the solar concentration factor is 500, 1000, or 1500X. The effective emissivity and BB temperature are plotted as a function of the normalized width of the annular reflector (w/a). As w/a increases from 0 to 0.9 the degree of photon recycling increases because a larger fraction of photons is reflected back to the emitter, and the effective emissivity decreases. As shown in Fig. 7-11a the temperature of the BB

emitter increases as w/a increases from 0 to 0.9. As shown in Equation 7.8, the emitter temperature increases when photon recycling increases and the effective emissivity decreases. The fraction of radiant energy emitted as in-band photons from the BB ($\eta_{in-band}$) for different values of w/a are plotted in Fig. 7-11b. As w/a increases the emitter temperature increases, thereby shifting the radiation spectra of the emitter to higher energies and increasing $\eta_{in-band}$. The solar-to-electric system efficiency (η_{TPV}) is shown in Fig. 7-11c for different values of w/a . For each case considered there is an optimal value of w/a that maximizes η_{TPV} . For example, when $C = 1500X$, $R = 99\%$, and $w/a = 0.6$, $\eta_{TPV} = 18.7\%$. For $C = 1000X$, $R = 99\%$, and $w/a = 0.6$, $\eta_{TPV} = 15.6\%$ and when $C = 500X$, $R = 95\%$, and $w/a = 0.3$ $\eta_{TPV} = 7.83\%$.

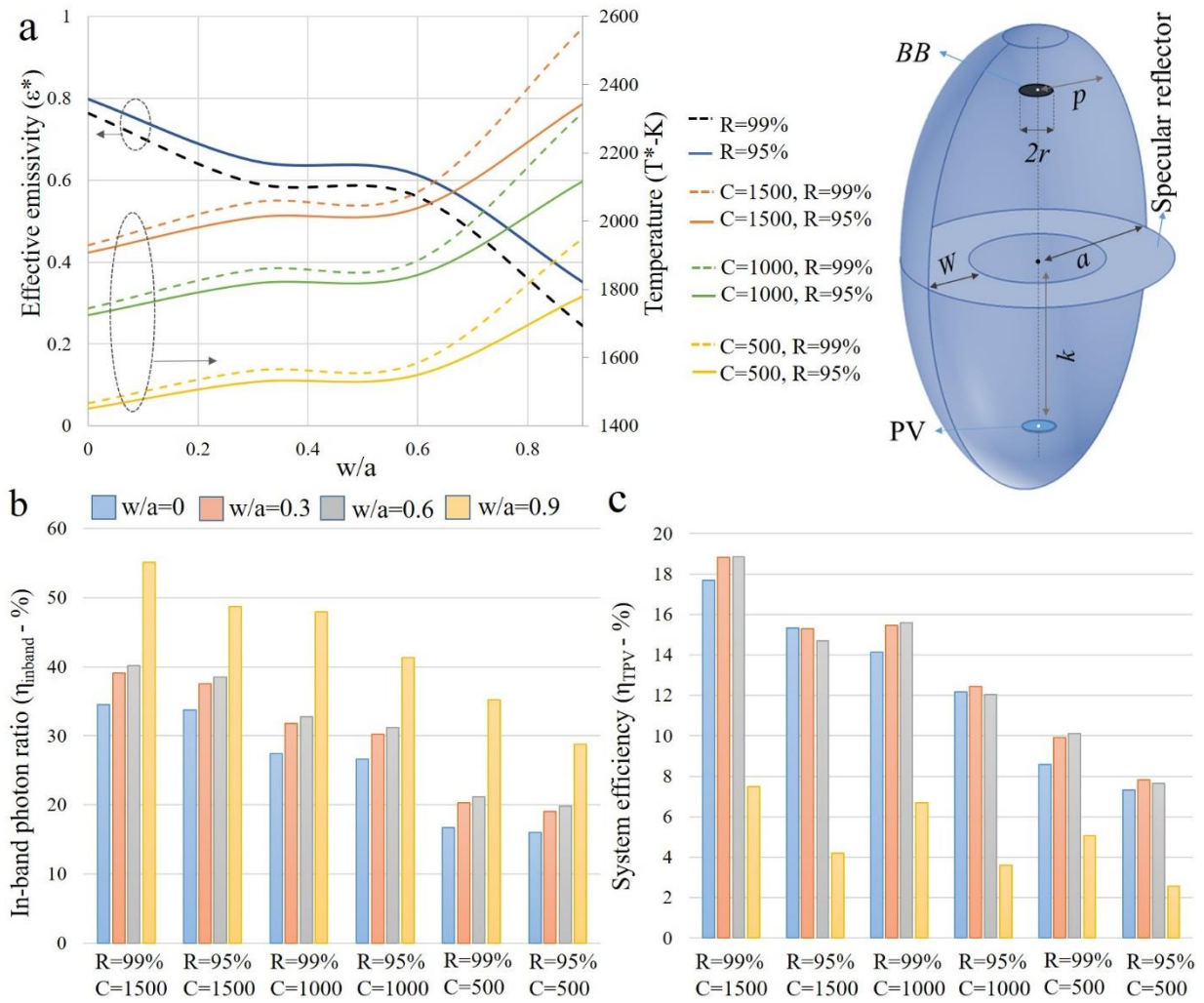


Figure 7-11 Results from the numerical analysis for the RESC-based STPV system shown in Fig. 7-2b (shown at the top right of this figure) when $k/p = 1$, $r_{BB}/r_{PV} = 1$ and $r_{BB}/p = 0.1$. a) ϵ^* and T^* plotted as a function of w/a . The b) fraction of photons incident

onto the PV cell that are in-band, and c) system efficiency when $w/a = 0, 0.3, 0.6$, and 0.9 shown for the cases when $C = 500X$, $1000X$, or $1500X$, and $R = 95\%$ or 99% .

The results from the RESC-based STPV system shown in Fig. 7-2c are presented in Fig. 7-12. For the results presented in Fig. 7-12 $k/p = 1$, $r_{pv}/p = 0.1$ ($r_{BB}/r_{PV} = 1$) and different cases of the RESC structure are considered wherein the reflectivity of the cavity is 95% or 99% and the solar concentration factor is 500 , 1000 , or $1500x$. Furthermore, two filters with different transmission spectra, which are shown in Fig. 7-12b, are considered: An ideal filter with $T_{in-band} = 100\%$ and $T_{out-band} = 0\%$, and a filter with $T_{in-band} = 90\%$ and $T_{out-band} = 10\%$. As shown in Fig. 7-12a, T^* reaches a maximum value of 2220 K when $C = 1500$, $R = 99\%$, $T_{inband} = 100\%$ and $T_{outband} = 0\%$. When $C = 1500$, $R = 99\%$, $T_{inband} = 90\%$ and $T_{outband} = 10\%$ the emitter temperature is $T^* = 2166\text{ K}$. In comparison, the temperature of the emitter under a solar concentration of 1500 would be 1803 K if it were not surrounded by a cavity. The temperature the emitter would be at (T) for three solar concentration values of $C = 1500, 1000$ and 500 in absence of the optical cavity ($\varepsilon^* = \varepsilon = 1$) are plotted in dashed horizontal lines in Fig. 7-12a. The in-band photon ratio, $\eta_{in-band}$, is plotted for the different RESC-based STPV systems considered in Fig. 7-12c, and $\eta_{in-band} = 1$ when $T_{outband} = 0\%$ because all photons incident onto the PV cell are in-band for these cases. When $T_{in-band} = 90\%$ and $T_{out-band} = 10\%$, $\eta_{in-band}$ has a maximum value of 79% which occurs when $C=1500$ and $R=99\%$ or 95% . Although T^* and $F_{PV-inband}$ are higher when $R = 99\%$ rather than 95% , $F_{PV-outband}$ is also higher, and consequently $\eta_{in-band}$ is independent of the reflectivity of the cavity walls for this case. For the cases shown in Fig. 7-12c wherein $T_{outband} = 10\%$, $\eta_{in-band}$ increases as the solar concentration factor increases. Generally, the emitter temperature is higher and its emission spectra is shifted to more energetic values when the solar concentration factor is higher. The solar-to-electric system efficiency is plotted in Fig. 7-12d. A maximum system efficiency of $\eta_{TPV} = 38.6\%$ is achieved when $C = 1500$, $R = 99\%$, $T_{inband} = 1$ and $T_{outband} = 0$. The maximum efficiency for the case when $T_{inband} = 90\%$ and $T_{outband} = 10\%$ is $\eta_{conv-eff} = 32.13\%$, and this value occurs when $C = 1500$ and $R = 99\%$.

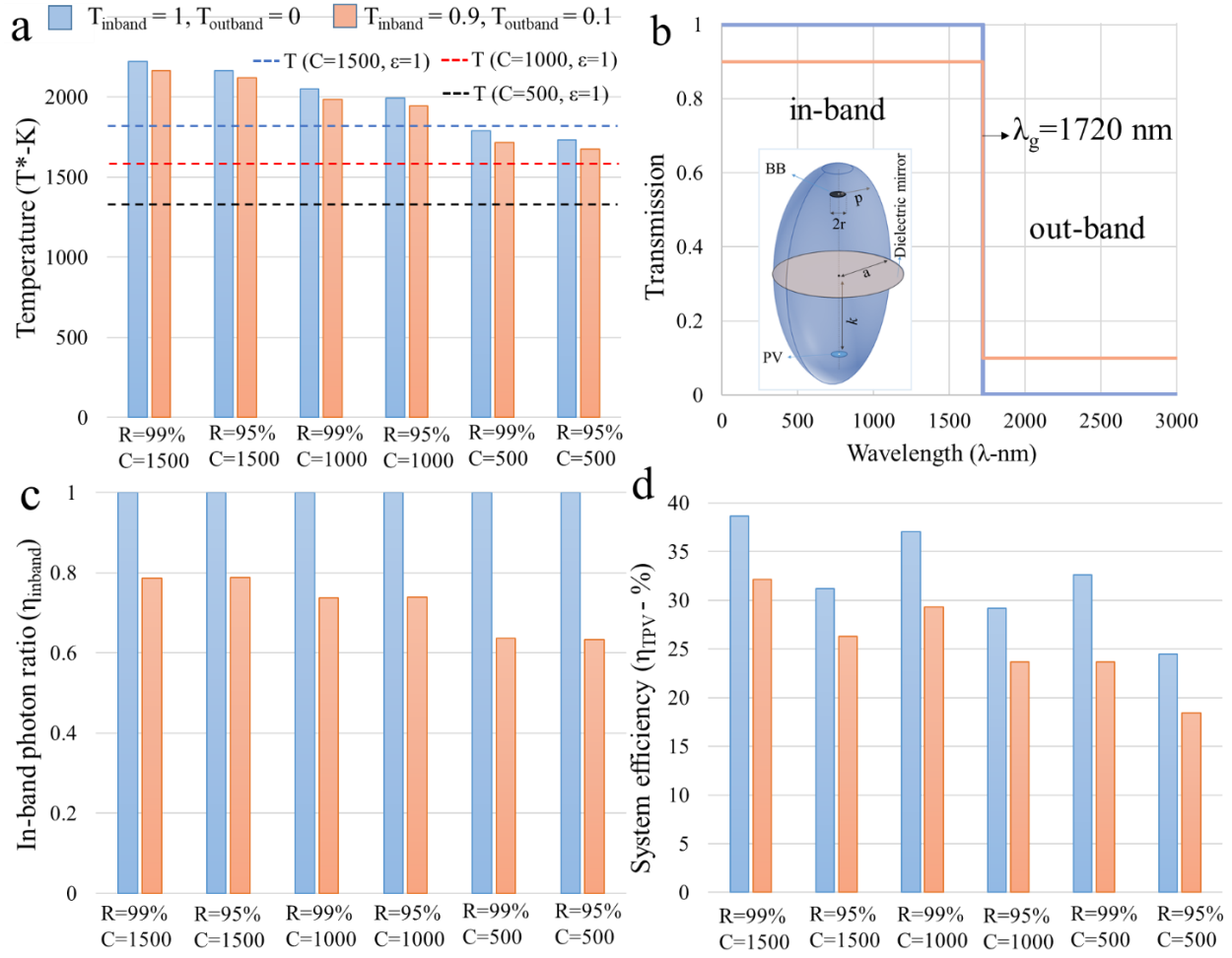


Figure 7-12 Results from the RESC-based STPV system shown in Fig. 7-2c (also shown as the inset in Fig. 7-12b in this figure) when $k/p = 1$, $r_{BB}/r_{PV} = 1$ and $r_{PV}/p = 0.1$. a) the emitter temperature, T^* , and the emitter temperature in the absence of a cavity ($\epsilon^* = \epsilon = 1$) for three solar concentration values of $C = 1500$, 1000 and 500 are plotted as dashed horizontal lines. b) two different optical filters are considered and their transmission spectra are $T_{\text{inband}} = 1, T_{\text{outband}} = 0$; and $T_{\text{inband}} = 0.9, T_{\text{outband}} = 0.1$. c) the fraction of photons incident onto the PV cell that are in-band, and d) the system efficiency for the cases when $C = 500X$, 1000X, or 1500X, and $R = 95\%$ or 99%.

The results from the numerical analysis for the RESC-based STPV system shown in Fig. 7-3c are shown in Fig. 7-13 for the case when $k/p = 1$, $c_o/p = 2$, $r_{PV}/p = 0.1$ and $r_{BB}/r_{PV} = 1$. Different cases are considered wherein the reflectivity of the cavity surface is 95% or 99% and the solar concentration factor is 500, 1000, or 1500. As shown in Fig 7-13a, the effective emissivity (ϵ^*) decreases while the emitter temperature (T^*)

increases as ω increases, and this occurs because an increasing number of photons are reflected back to the emitter.

As shown in Fig. 7-13b, the fraction of photons incident onto the PV cell that are in-band photons ($\eta_{in-band}$) increases as ω increases for all cases considered, which is consistent with the increase in T^* . The system efficiency for different values of ω is shown in Fig. 7-13c. There is an optimal value of the system efficiency which depends on the value of R and C. For example, when $C=1000X$ and $R=95\%$, a maximum value of $\eta_{TPV} = 16.55\%$ is obtained when $\omega = 40^\circ$. The highest system efficiency for the RESC structures considered in Fig. 7-13 is $\eta_{TPV} = 22\%$, and this occurs when $C = 1500X$, $R = 99\%$ and $\omega = 60^\circ$.

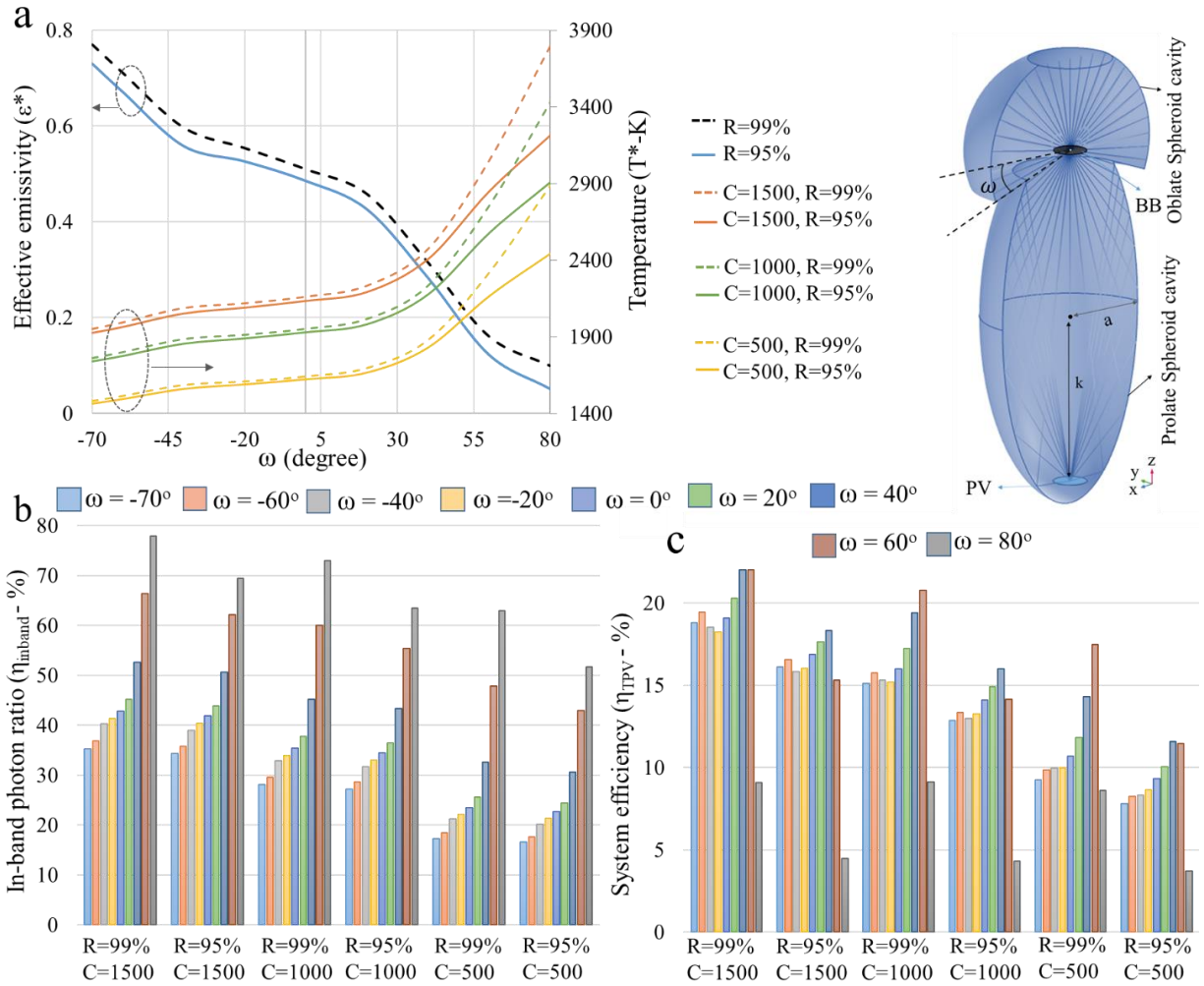


Figure 7-13 Results from the numerical analysis for the RESC-based STPV shown in Fig. 7-3c (shown at the top right in this figure) when $k/p = 1$, $c_o/p = 2$, $r_{BB}/r_{PV} = 1$ and $r_{pv}/p = 0.1$. a) ϵ^* and T^* plotted as a function of ω . The b) fraction of photons incident onto

the PV cell that are in-band, and c) system efficiency when $\omega = -60^\circ, -40^\circ, -20^\circ, 0^\circ, 20^\circ, 40^\circ, 60^\circ$, and 80° shown for the cases when $C = 500X, 1000X$, or $1500X$, and $R = 95\%$ or 99% .

Fig. 7-14 shows the results from the numerical analysis for the RESC-based STPV system shown in Fig. 7-3d when $R=99\%$, $k/p = 1$, $c_o/p = 2$, $r_{pv}/p = 0.1$ and the transmission of the filter at the minor axis is $T_i = 100\%$ and $T_o = 0\%$ for in-band and out-of-band photons, respectively. As shown in Fig. 7-14a, the emitter temperature, T^* , increases as ω increases, and a maximum temperature of $3800K$ is achieved when $C = 1500$ and $\omega = 80^\circ$. Although T^* increases with increasing ω , the system efficiency, η_{TPV} , decreases as ω increases from 0° to 80° because the optimum values of F_{PV} and F_{BB} do not occur in this range. On the other hand, η_{TPV} can be increased by setting ω to negative values. A maximum value of $\eta_{TPV} = 42.5\%$ is obtained when $\omega = -70^\circ$ and $C = 1500X$, which is the highest conversion efficiency in this study, and the power density for this case is 25.5 W/cm^2 . When ω is increased further to -76° the top part of the prolate spheroid is at the edge of the entrance port, and the structure becomes similar to the RESC structure shown in Fig. 7-2c (system efficiencies for the structure in Fig. 7-2c reached 38.6%). Furthermore, when $C=1000X$, a maximum value of $\eta_{TPV} = 41.3\%$ is obtained for $\omega = -70^\circ$, and when $C=500X$, a maximum value of $\eta_{TPV} = 37.6\%$ is obtained for $\omega = -70^\circ$.

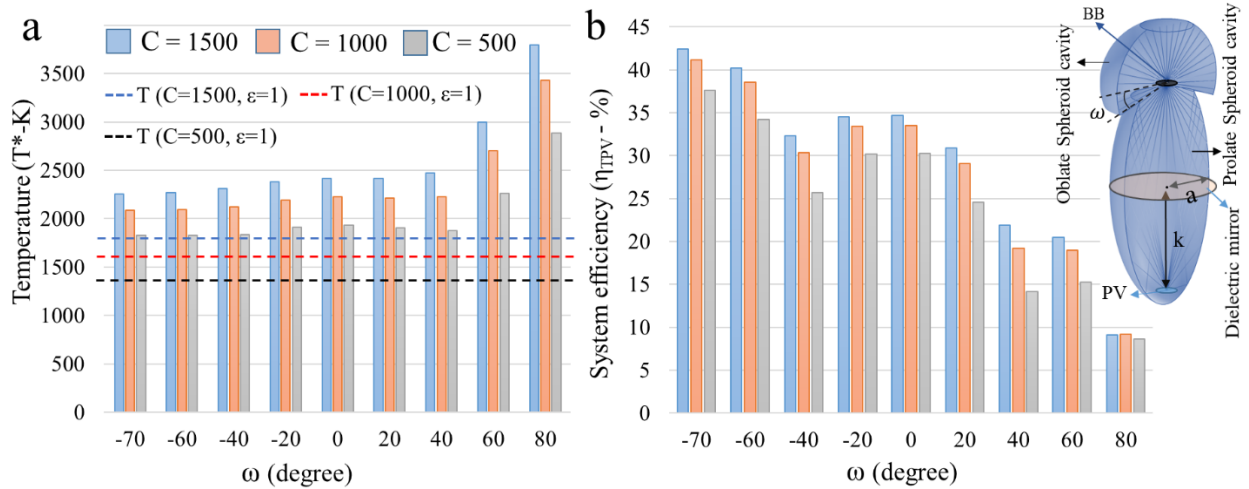


Figure 7-14 The emitter temperature and the emitter temperature in the absence of a cavity ($\epsilon^* = \epsilon = 1$) for three solar concentration values of $C = 1500, 1000$ and 500 are plotted as dashed horizontal lines. b) system efficiency for the oblate-prolate RESC structure

with an ideal optical filter ($T_i = 100\%$ and $T_o = 0\%$) when $R = 99\%$, $k/p = 1$, $c_o/p = 2$, and $r_{pv}/p = 0.1$. Results are shown for three different solar concentrations: $C = 1500$, $C = 1000$ and $C = 500$.

Our numerical analysis shows that efficiencies greater than 50% can be achieved using the RESC-based STPV systems presented in this work. Furthermore, these STPV systems can be made of durable components. For example, the emitter temperature for the STPV system with a simulated system efficiency of 42.5% (shown in Fig. 7-14) is over 2200 K, however, this emitter is assumed to be a blackbody and does not require nano- or micro-textured components that may not be able to withstand these elevated temperatures (instead a durable material that can withstand high temperatures such as graphite can be used as the emitter). Another advantage of the RESC-based STPV systems presented herein is that the optical elements or parts of the cavity walls could be made to operate dynamically to increase power output during different operating conditions. For example, the width of the annular reflector within the cavity shown in Fig. 7-2b (an annular reflector and an optical filter could be used simultaneously at the minor axis) could be made to increase at times when the solar irradiance is relatively low in order to maintain high emitter temperatures by increasing the degree of photon recycling.

7.6 Conclusion

This work presented STPV systems wherein the emitter and PV cell are located at the focal points within spheroid-based optical cavities. Results from numerical analysis show that these cavities can significantly enhance system efficiency by achieving a high emitter-to-PV cell effective view factor, a high degree of photon recycling, and high emitter temperatures. For example, considering a solar concentration factor of 1500x, the temperature of a bare black-body emitter (not surrounded by a cavity) can be increased from 1803 K to 2166 K by placing the emitter at the focal point of a prolate optical cavity equipped with an optical filter at its minor axis. Numerical analysis shows that a thermal emitter-to-electric system efficiency of 38.6% and a power density of 22.5 W/cm² can be achieved using a single prolate spheroid optical cavity equipped with an optical filter at its semi-major axis. Moreover, results show that an optical cavity in the

form of an integrated oblate- and prolate-spheroid can be used to achieve a system efficiency of 42.5% and power density of 25.4 W/cm^2 when the solar concentration factor is 1500X. Also, the spheroid cavities presented in this work reduce the PV cell area required to achieve high radiation-to-power system efficiencies, which is important for reducing the cost of TPV systems. Thus, the spheroid optical cavities presented herein can be integrated into the design of advanced STPV systems to bring their performance closer to the high efficiencies they are capable of.

7.7 References

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8 Conclusion and future work

8.1 Conclusions

The major outcomes of this work are the design and analysis of a novel class of optical configurations for solar energy harvesting devices, referred to herein as Radiant Energy Spectrum Converters (RESC). The energy harvesting devices and key performance indicators are listed as bellow:

- RESC structure for photobioreactors:
 - Optical efficiency and concentration factor of 73% and 29.2, respectively.
 - Non-PAR-to-electricity conversion efficiency of ~16%.
 - Enhancement of algae growth by 9.3%.
- RESC structure for elliptic array luminescent solar concentrator:
 - Optical efficiency and concentration factor up to 63% and 3, respectively.
 - Non-PAR-to-electricity conversion efficiency of ~17%.
- RESC structure for hybrid solar lighting:
 - Optical efficiency and concentration factor up to 55% and 60, respectively.
 - Non-visible-to-electricity conversion efficiency of 13.5%.
- RESC Structure for solar thermophotovoltaic:
 - System efficiency of 42.5%.
 - Power density of 25.5 W·cm⁻².

8.2 Future work

- The first important next step is to build a prototype of the optical cavities and to perform experiments in order to validate the results from the numerical analysis. Fabrication of the prototype has already been initiated. However, due to COVID-19 conditions it was not completed. Fig. 8-1a shows the bottom half of the fabricated TPV system. A ceramic-based thermal emitter is located at the bottom

focal point of the prolate-spheroid shaped cavity. In practice this emitter could be heated using solar energy or other forms of waste heat, while its temperature is controlled using a power supply for initial experiments. The surface of the ceramic heater is covered with a Pyromark high-temperature coating so it will behave like a high-emissivity blackbody-like thermal emitter. The cavity was designed, and 3D printed using a high resolution stereolithography 3D-printer (Formlabs). The inner surface of the cavity was highly smoothed using a polishing kit (Eastwood) and spray coated with Super Shield Nickle to provide a conductive coating such that Copper/Aluminium could be electroplated using a CASWELL electroplating kit in order to create a coating with a very low emissivity (highly reflective in IR). The reflection quality (specular and diffraction) was measured using a UV-VIS spectrophotometer (SHIMADZU/UV-2600). Subsequently, the top-half of the optical cavity was installed using alignment posts to concentrate thermal radiation from the ceramic heat source to the second focal point within the top half of the prolate spheroid. To complete the prototype, the upper half of the optical cavity will be fabricated similarly to the way the bottom half was fabricated as described above. Also, to finalize the prototype, the optical cavity will be attached to a high precision 3-axis translation stage which will allow the heat source and PV cell to be located at its focal points. The inset in Fig. 8-1a shows a quarter of the bottom section of the RESC structure after electroplating with copper.

After completing the first prototype of the prolate optical cavity initial experiments will be performed. Either an optical power meter console (Thorlabs) or a thermal camera can be positioned at the focal point within the top half of the optical cavity to measure the temperature distribution/changes of the emitter and the intensity of the thermal radiation that could be harvested by PV cells. Due to the broadband and high absorptivity of the optical power meter console over the wavelength range from 300 nm to 15 μm , it provides a good estimation to the density of power absorbed by the PV cell (W/cm^2). A thermal camera with an operation range of 50 $^{\circ}\text{C}$ to 900 $^{\circ}\text{C}$ illustrates the emissivity changes of the emitter and consequently the level of recovered thermal energy in the form of a

temperate distribution profile over the emitter surface. Fig. 8-1b shows a schematic diagram of the experimental set-up. The set-up is placed in a vacuum chamber to eliminate conduction and convection loss mechanisms ($\sim 10^{-2}$ Torr). The vacuum chamber has some electrical feedthroughs for electric connections through the vacuum chamber. A data acquisition system (Agilent 34970A) is utilized to collect the signals coming from the electric feedthroughs. The heat source is isolated from the optical cavity by ensuring a 1 mm circular gap exists between the ceramic heat source and the optical cavity. The characterisation of the system will be carried out for the four degrees of freedom (k/p , k/r , k_1/p , and k_2/r) shown in Fig. 6-1b. The effective emissivity of each RESC structure tested will be determined by comparing the temperature of the emitter when the cavity is present to the temperature of the emitter under similar conditions, but without the cavity being present.

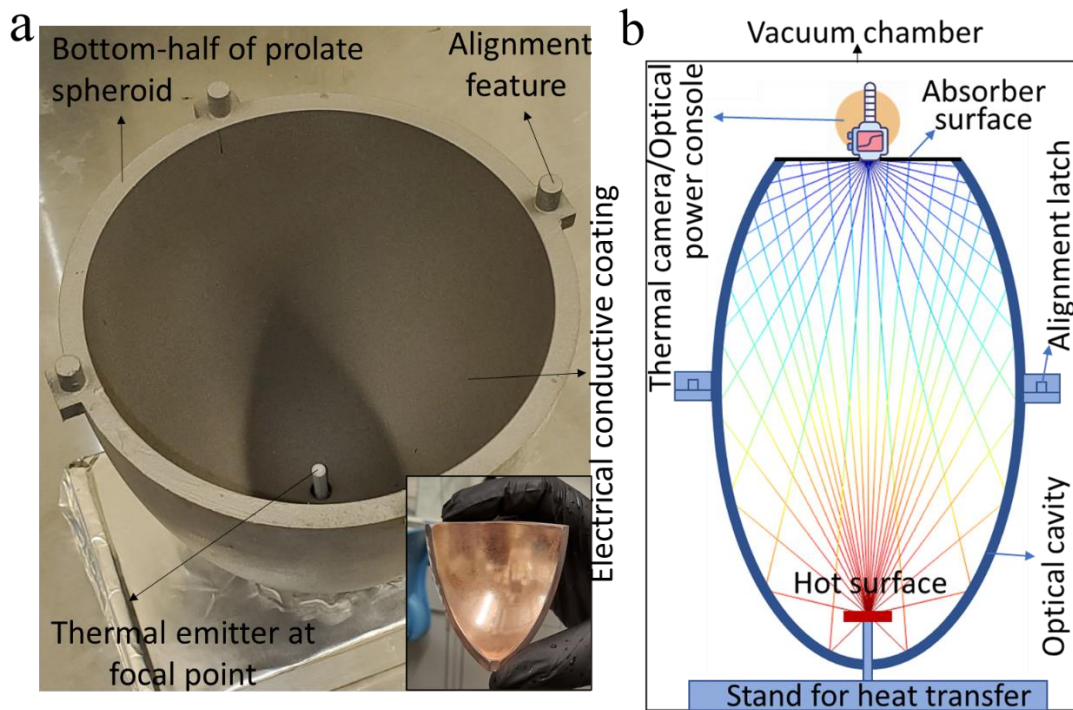


Figure 8-1 a) Bottom half of the fabricated. In set shows the quarter of the bottom half electroplated by Copper b) Experimental setup to measure the fate of emitted photon.

To fabricate the optical cavity configuration shown in Fig. 6-1d, an annular reflector will be fabricated using a CO₂ laser cutter on a 1 mm-thick aluminium sheet. Alignment posts situated on the bottom half of the prolate spheroid optical cavity will be used when installing the annular specular reflector.

- Fabrication of a transparent heat mirror for the entrance port of the RESC structure can be considered for the future work. Using this optical filter minimizes the escape losses.
- Fabrication of an optical filter for the minor axis of the RESC structure (Fig. 7-2c) to reflect and recycle the out-of-band photons and transmit the in-band photons.
- Completing the parametric analysis (Chapter 5) to investigate the effect of varying the photon fates for a TPV system in an optical cavity when: 1. There is a back-surface reflector (rear mirror) under the PV cell to reflect and recycle the photons not absorbed by the PV cell and transmitted through the PV cell (Fig. 8-2a). 2. There is an optical filter coated on the PV cell to reflect the out-of-band photons to the emitter (Fig. 8.2b). 3. The emitter/absorber is a spectrally selective surface (Fig. 8.2c), and 4. Different types of PV cells with different EQEs such as c-Si ($E_g = 1.1$ eV), Ge ($E_g = 0.66$ eV), and InGaAs ($E_g = 0.74$ eV).

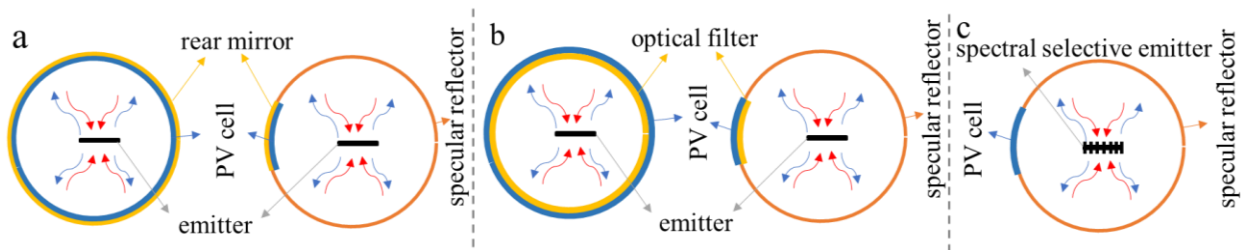


Figure 8-2 Future work is to conduct a parametric analysis for a TPV system comprising an optical cavity and a) a back-surface reflector coated on the rear side of the PV cell, b) an optical filter coated on the front surface of the PV cell, and c) a spectrally selective emitter.

- Combining the RESC structures with other heat-based energy harvesting elements such as Thermoelectric generators (TEG) for combined heat and power applications. For example, the PV

cell on a TEG element can be placed on the focal point of RESC structure to convert the non-useful photons absorbed by the PV cell into electricity.

- Expand the application of the RESC structures in different areas such as combined heat and power, lightweight portable power generator, smart net zero buildings, waste heat recovery, spacecrafts and aerospace, and radiative heat cooling.

In the last part of the future work, three important points are discussed that can be considered in future studies and experimental analysis:

1. The effect of non-homogeneous illumination on the PV cell within the TPV system: The PV cells used along with the optical cavities proposed in this study experience non-homogeneous illumination. It should be noted that spatial non-homogeneous light distribution on a PV cell affects the series resistance of the cell (increases the series resistance losses) and therefore, decreases the fill factor. At very high currents, the non-uniformity decreases the short circuit current density as well. Eventually, at very high current density, losses due to the series resistance become the dominant factor for the cell efficiency [1-3]. There are some general approaches in order to reduce the series resistance including: increasing the density of wiring contact grids on the front/bottom surface, or increasing the conductivity of the top layer of the semiconductor by increasing its thickness or dopant concentration [1-3]. For the structures presented in this thesis, a slight offset (displacement) of either the PV cell or the emitting material can be induced to adjust and control the light distribution on the PV cell. For example, referring to Fig. 2-5, by slightly moving the emitter material located at the shared focal point, light distribution on the PV is changed. A small diffuser can also be used to control the light distribution incident onto the PV cell.

As another example, for the configurations including the ellipsoidal structures, as the rays emitted from the emitter converge on the second focal point, where the PV cell is located, the PV cell can be slightly moved up or down to have a more uniform distribution of incident photons. As another example referring to Fig. 4-3, the PV cell on the overlapped semi-ellipsoids can be reshaped to match the highly concentrated area.

In this case, the area occupied by the PV cell decreases, and also the illumination distribution on the PV cell will become more homogeneous with high intensity. Therefore, the efficiency of the PV cell increases [3-5].

Furthermore, all design parameters defined for the structures in this thesis, can be used to control the distribution of incident light onto the PV cell to some degree.

2. Thermal management for the PV cells: The PV cells used in this study experience a high intensity level of light irradiation. Therefore, it is essential to provide a cooling system in order to keep the PV cell at low temperatures. For the RESC structures with solid transparent material presented in Chapters Two and Three (for the applications of self-powered photobioreactors and microalgae cultivation systems), three main approaches can be considered: 1. As the system is not under vacuum conditions, efficient passive and active cooling systems (heat exchanger) can be integrated on the PV cell to dissipate the heat away from the PV cell. For example, a pin-fin heat sink can be attached to the PV cells to increase the surface area in contact with the cooler medium surrounding it (air). 2. By appropriately choosing the index matching layers in the interface layer of the PV cell and the PMMA/glass RESC structure to create a thermal insulation as well as index matching medium for the photons reaching the PV cells through the host matrix (PMMA or glass). That is, this index matching layer will be highly transmissive to allow light to pass from the host matrix to the PV cell, but would also provide thermal resistance to prevent heat from conducting from the host matrix to the PV cell. 3. Using different techniques to decrease the attenuation coefficient of the host matrix (PMMA or glass in this study) to decrease the absorption level and therefore, alleviate the thermal effects on the PV cell. These techniques are: fluorination, perfluorination, or adding copolymers or fluoroacrylate. Furthermore, different types of transparent solid host materials such as N-BK7 glass and low-OH fused silica optical fibers can be used to decrease the attenuation coefficient (this method is discussed in section 2.7.2).

For the RESC structure proposed in Chapter Four (for hybrid solar lighting systems for power generation in buildings), heat sinks can be integrated on the side walls of the PV cells; or heat pipes with working fluids

can be built between two back-to-back PV cells to actively dissipate the heat away from the PV cell. The aforementioned techniques for decreasing the attenuation coefficient of the host matrix can be applied to the RESC structures shown in Chapter Four.

For the RESC structures proposed in Chapters Six and Seven (For solar TPV applications), as the TPV system is under vacuum condition, it is possible to build small fluidic channels within the two back-to-back PV cells and dissipate the heat to the outside of the vacuum using a working fluid inside the channels. Furthermore, due to the ellipsoidal configuration of the STPV system and a large gap between the PV cell and the emitter, it is possible to bring the PV cell out of the vacuum system and use natural or forced convective cooling methods to cool the PV cell more efficiently.

3. Effect of thermal expansion: For the optical cavities defined in Chapter Two to Four and referring to Fig. 2-6, the heat distribution in the RESC structures is introduced non-uniformly. Therefore, the thermal expansion will be non-uniform as well. When the structure is expanded or deformed due to heating the focal point is displaced causing emission losses to increase.

For the structures used for the TPV systems, thermal expansion changes the focal points and therefore decreases system efficiency. However, as described in the thesis, the temperature of the optical cavities does not increase more than 3 degrees.

Finally, it should be noted that, for the RESC structures made of solid materials that reflect optical rays using TIR, the mechanical elements supporting the body of the structure should not be in direct contact with the surfaces on which TIR occurs. The reason is, the mechanical supports are mainly metal or polymer with refractive index equal or higher than PMMA/glass. Therefore, on the interface surface between the mechanical support and the optical cavity the TIR may no longer be satisfied and therefore emission losses and overall surface scattering increases. For these structures, the mechanical support can be integrated on the bottom and/or top surfaces where the PV cell or specular mirror is attached.

For the TPV systems, absorber/emitters and PV cells can be situated at the focal points of the RESC structures using thermally and electrically insulated beams such as glass.

8.3 References

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