Appropriate Solar Spectrum Usage: The Novel Design of a Photovoltaic Thermal System

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ABSTRACT

The path towards zero energy buildings is fraught with many challenges, the onsite renewable energy production to drive consumer appliances that are not low or zero energy is an important challenge. Therefore, developing the energy production such that the production mode is matched to the usage mode is the simplest manner to improve efficiency. As such, energy consumption for lighting could be significantly reduced by optimizing the building`s design to maximize direct daylight usage, similarly cooking using solar stoves, or water heating using solar geysers eliminates the need for PV cells to generate electricity. The most important energy consumption in most buildings is HVAC (accounting for approximately 40% of a building`s energy consumption) which can be addressed with the use of a solar power absorption chiller. This article introduces the design of a novel solar concentrated photovoltaic thermal (CPVT) system that produces electricity and thermal energy simultaneously from the same surface area. The goal of the proposed system is to provide sufficient heat for an absorption cooling system, water heating as well as to produce electricity in a cost effective way.

The CPVT system is designed to operate over a wide spectrum (400nm upward contains around 90% of the incident solar radiation spectrum). In the proposed system, solar irradiation is highly concentrated (to the equivalent intensity of approximately 100 suns) onto a single point, using a dual axis sun tracking concentrator with a Fresnel lens. A filter then separates the infrared (IR) from the visible light (VL) components using an imaging lens (viz. a hot mirror which has approximately a 98% filter efficiency). The IR is then utilized for heating while the VL components power the PV cell.

The efficiency of the electricity generation in the PV cell improves when the IR component is removed from the incident solar irradiance. High-temperature high pressure water, at approximately 95-120°C (203–248°F), is generated by the IR and serves as a heat source for the absorption cooling system (lithium bromide water / ammonia-water). The proposed system is expected to deliver electricity at the rate of 0.08 W/cm² (0.2032 W/in²) of PV cell area, and around 0.04W/cm² (0.1.016 W/in²) collector area. Given that the ratio of collector area to PV cell area is ±9:1 this allows us to design the relative size to suit the building requirements.

INTRODUCTION

"Net Zero Energy Building" (NZEB) is an ambitious title that is unlikely to be obtained without scrupulous attention to every aspect of the design of a building. A typical building's path towards being a NZEB starts with achieving significant energy load reductions by means of building design optimization and the usage of low or zero energy consumption systems, plus meeting the remaining loads with on-site clean energy generation. Traditionally the onsite renewable energy has been produced in one of two forms: thermal energy using solar thermal collectors or electricity generation using PV cells which are used for different applications. Transforming the energy from the produced form (thermal/electricity) into the form required often results in a significant loss.

The best and most efficient technique for renewable energy production in buildings is the one that is developed to directly drive the consumer appliances. For example, energy consumption for lighting could be significantly reduced by optimizing the building's design to maximize direct daylight usage, similarly cooking using direct collection solar stoves, or water heating using solar geysers, all these eliminate the need for PV cells. The most important energy consumption in many buildings is HVAC systems which can be addressed by means of a solar power driven

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absorption chiller.

Since HVAC and water heating contribute significantly to the energy consumption in both commercial and residential buildings (around 27-40%) (C2ES 2014), treating these while still supplying electricity for other uses can be seen as a key to achieving the NZEB. Thermally driven absorption chillers are considered as one of the greenest HVAC systems primarily because they can be powered directly by solar thermal energy. Most of the absorption chiller types provide an opportunity to produce almost free space heating and cooling if a suitable solar thermal source is available. For example, a 17.585 kW (5 TR) absorption chiller provides chilled water at inlet of 12°C (53.6°F) and outlet of 7°C (44.6°F) when the hot medium ranged from 70-95°C (158-203°F) supplied at the generator.

From a production perspective, PV cells present a clean renewable energy that should be used widely. One of the main limiting factors which has slowed the acceptance and more extensive use of PV cells in applications is the relatively low conversion efficiency of PV cells (Saad and Masud 2009). The main reason behind low PV cell efficiency is: the heat buildup under the PV cells as well as the PV cell's solar spectrum operating range. Commercial single layer PV cells are predominantly designed to operate in the VL range of 400-700 nm as illustrated in figure 1. Both the above mentioned reasons are the result of the solar spectrum IR component.

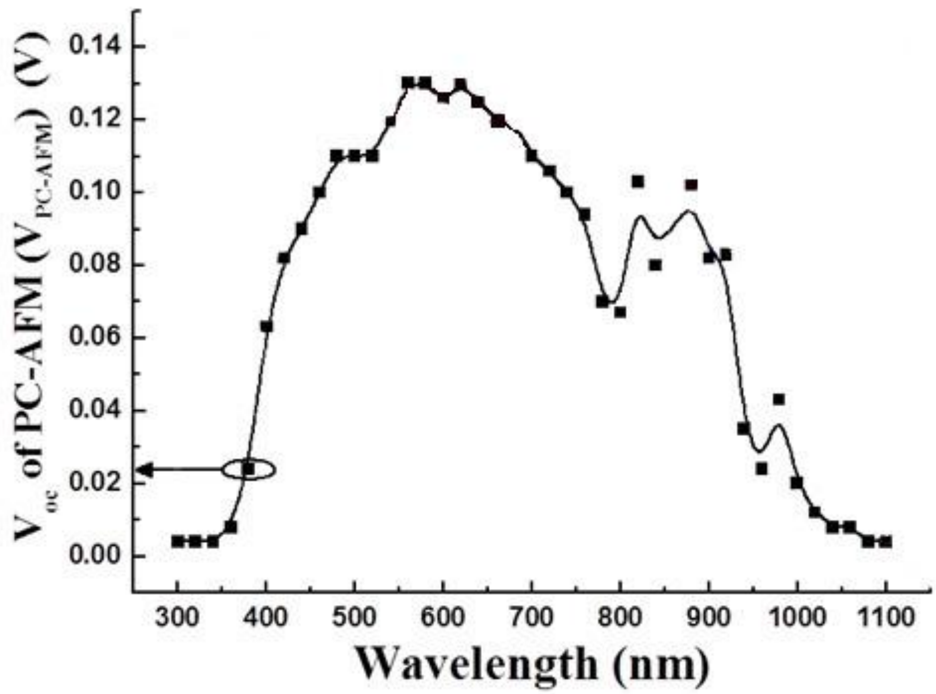


Figure 1 VPC-AFM value with light wavelength of poly-Si solar cell devices (Heo 2013)

The new development of the multi-layer PV cell which is designed to operate over a wider solar spectrum has overcome the low conversion efficiency of the traditional PV cells. These newer PV cells achieve efficiencies approaching 40% in the laboratory. This new trend still faces many challenges, one of which is the high cost of the fabricated material compare to the retail price of the single layer commercial PV cell (McGehee 2012). Another challenge is related to the undesired heat build up under the PV cell surface. One of the leading manufacturers of a sophisticated multi-layer PV cell states that as much as 39% of the solar spectrum which strikes their PV cell surface is transformed into heat (Kribus et al. 2006).

Although, the PVT and CPVT concept of removing the undesired heat of the incident radiation from the PV cells and turning it into a useful energy has gained more attention, harvesting this energy is still quite limited. An increase of only 1°C in the PV cell temperature results in a 1% decrease of the PV efficiency (Hollick 2011). Moreover, the PV structure is only capable of tolerating temperatures up to 100°C (212°F) (in the case of the most recent multi-layer PV cells (Mittelman et al. 2007)). In response to this dilemma, this project seeks to develop a novel PVT design that uses an inline filtering element.

PRINCIPLES

Solar Spectrum Utilization

The solar irradiance striking the earth's surface is divided based on wavelength and energy contents into three ranges:

- ultraviolet (UV) 5-10% energy content (below 400 nm),
- visible light (VL) around 40% energy content (400 to 700 nm)
- and infrared (IR) 50% of the energy content (above 700 nm).

The target of the proposed system is to get the most out of the sun light energy, mainly by using various components of the solar spectrum in a more appropriate way. Mostly the proposed system focuses on the IR and the VL which counts for more than 90% of the total spectrum. The IR range is considered as the only source of heat in the solar spectrum and it is most useful for the thermal energy collection. While, VL range shows the highest electricity production from the commercial single layer PV cells. To this end, the appropriate utilization of solar irradiance should be governed by the ability to collect the energy across the total spectrum by means of utilizing the VL for electricity production and the IR for thermal energy collection as illustrated in figure2:

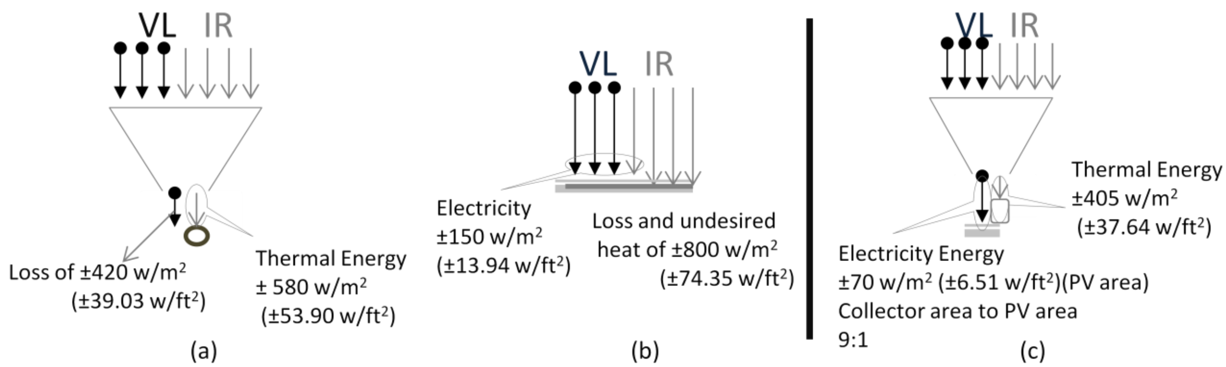


Figure 2 (a) Concentrated solar collector concept
2 (b) PV cell electricity production concepts
2 (c) Proposed concentrated PVT concept

Figure 2 explanations:

- Figure 2 (a): Solar thermal collector concentrates sun light in order to increase thermal density – results in the production of thermal energy mainly using IR component
- Figure 2 (b): PV cell operates mostly on the VL range with a reduction in performance due to the incident IR component.
- Figure 2 (c): The proposed system aims to concentrate the sun light while separating the IR and the VL. The IR component is used for heating and the VL light for electricity production. Reducing the incident IR component from the surface of PV cell may even increase the overall PV cell efficiency.

Water Sun Light Absorption

Water properties have been extensively studied in the past century; several studies have been performed to investigate the absorption of solar irradiance by water in different fields (space, ocean, swimming pool, etc.). Most studies agreed that water predominantly absorbs the IR spectral components and very little of the VL components (Chaplin 2015; Prahl 1998; Geek 2007). Figure 3 demonstrates this phenomenon as it shows that the water's lowest absorption coefficient occurs in the VL range; in other words it is very transparent toward the VL light, while still heated up by the IR portion.

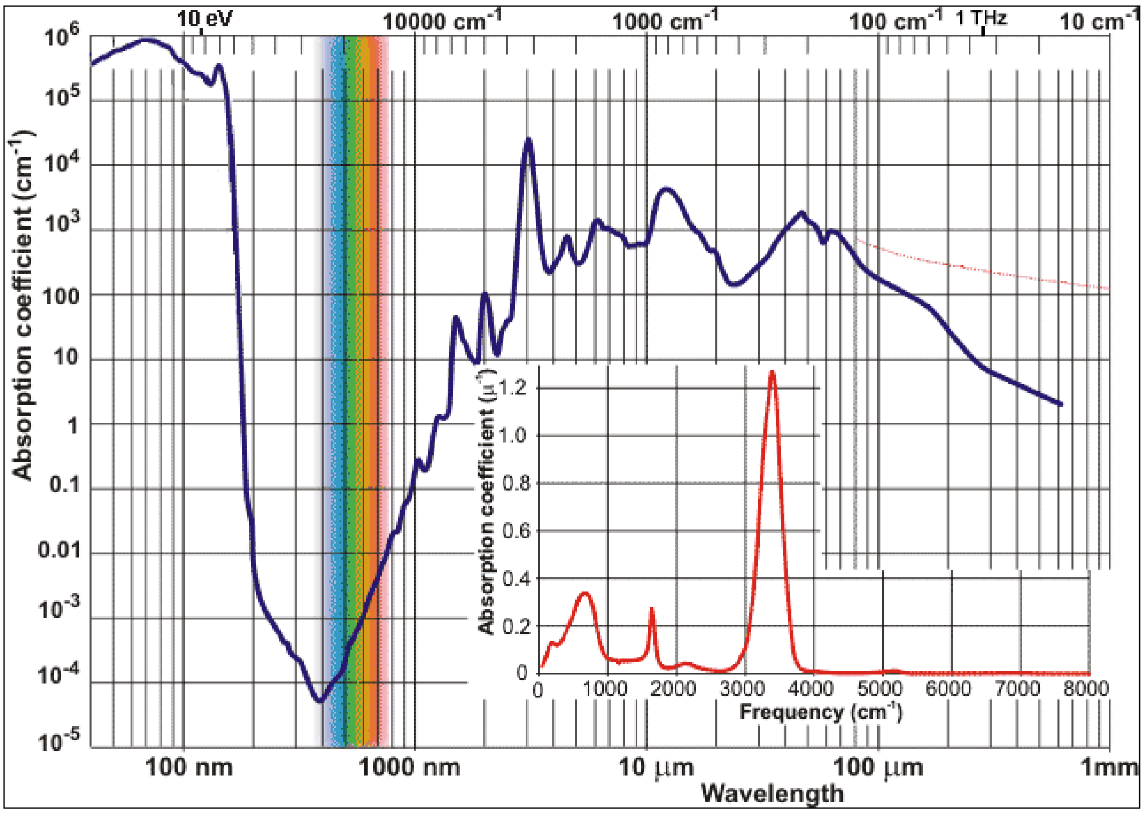
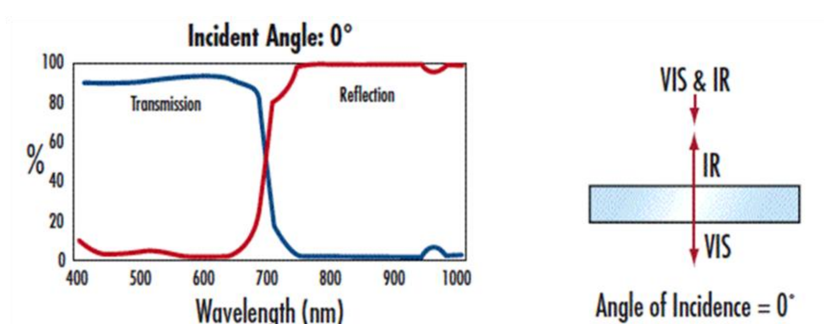


Figure 3 Water absorption coefficient across sun spectrum (Chaplin 2015)

IR/VL Light Filtration

Imaging theory has confirmed the possibility to easily separate solar spectrum components (UV, VL and IR). Whereby, several mirrors and lenses are highly sensitive to specific range of light wavelength has been commercially produced. For instance, "hot mirror" and the "cold mirror" shows a very high efficiency up to 98% to reflect the IR and VL lights respectively as illustrated in figure 4.



(a)

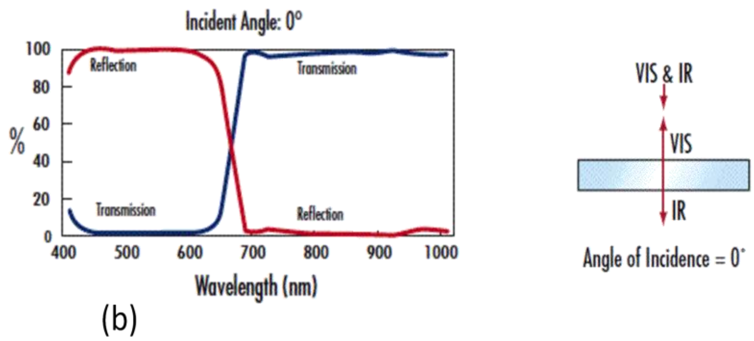


Figure 4 (a) hot mirror trasmission and reflection and incident angle
4 (b) cold mirror trasmission and reflection and incident angle

DESIGN AND LAYOUT

Figure 5 illustrates the proposed system layout which consists of 4 major elements:

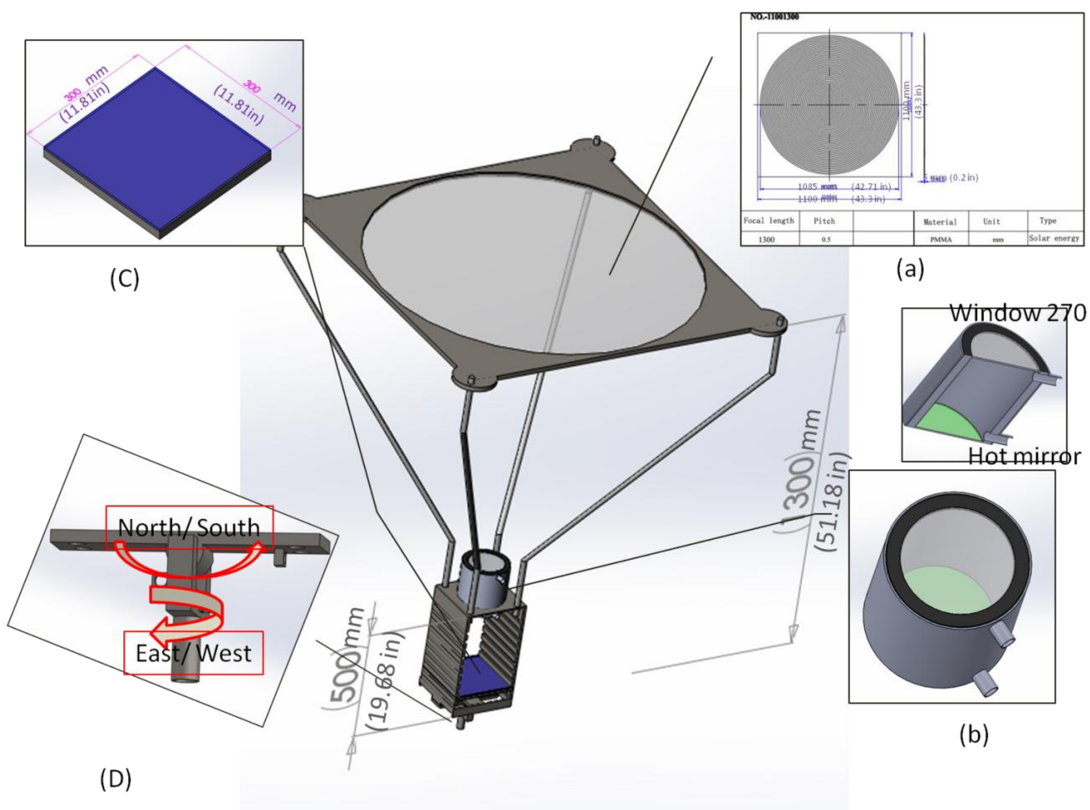


Figure 5 system layout (a) Fresnel lens specification (b) water container (c) PV cell (d) solar tracker holder

1. Concentrator (detailed specification and layout illustrated in figure 5 (a))

To maximize the harvested thermal energy it is mandatory to increase the total heat density by concentrating sun light. There are different types of concentrated solar collector (CSC) mostly differ based on several parameters but most importantly driven by the required output temperature. The selection of this concentrator was based on two parameters:

a) Single point collectors (dishes, Fresnel lens collectors and helio towers) have the highest output temperature ever achieved (Stine et al. 2001). Even though the Fresnel lens is considered among the highest CSC temperature achievers, it is also one of the cheapest, simplest and lightest concentrators.
b) The feature of the buildings, namely the building's foot print, occasionally limits the option of which concentrator can be used. The fact that it is a PVT system leads to a preference for the Fresnel lens over the dish concentrator.

2. Water Container

Water was selected as the thermal energy collection medium due to its:

- high thermal conductivity;
- high absorption of the IR spectrum;
- high transmission of the VL spectrum.

Water light absorption and transmission are best described by Beer's law using the following equations (Chaplin 2015):

$$A = -\log10(I/I_o) = \alpha l. \quad (1)$$
$$I/I_o = 10^{-\alpha L} \quad (2)$$

3. Sun Light Filtration

As illustrated in figure 5 (b) the water container has a top glass and a bottom glass:

Top glass: a very clear and highly light transmitted glass cover is used. It allows most of the concentrated light to penetrate to the water. The selected cover glass has a transmission efficiency of 90% across the solar spectrum from 300 to 2000nm.

Bottom glass: a hot mirror was selected to reflect the unabsorbed IR component back into the water. This process will allow as much of the IR component to be absorbed as possible while still using thin layer of water, which in turn minimize the amount of the VL absorbed by the water.

4. Electricity Generation PV

Since a standard PV cell reaches its highest efficiency with incident radiation in the VL range and shows a negative response to IR (responsible for the undesired heat buildup in the PV cell) the removal of the IR component is essential for optimal performance. Thus removing the IR component and its associated heat from the surface of the PV cell allows the usage of the single layer commercial PV illustrated in figure 5 (c).

The aim of developing the reduced area concentrator is that this suits many buildings' footprints and allows us to use a limited lens size of only ±1000 mm (±39.37 in) diameter. To retain the correct incident VL at the PV cell surface the concentration ratio of the Fresnel lens (based on incident area) to the PV cell area must be ±9:1 area ratio, therefore the cell area is ± 300 x 300 mm (11.81 x 11.81 in).

Electricity output could be calculated using below equation:

$$P_{EL} = I_o \times \eta_{lens} \times \eta_{top\ Glass} \times 10^{-\alpha L(water\ hight)} \times \eta_{hot\ mirror} \times \eta_{pv} \quad (3)$$

5. Solar Tracker

In order to achieve the highest possible concentration (+100 sun) it is important to use a dual axis solar tracker. The selected tracker consists of 3 major parts as illustrated in figure 6:

1. sun sensors on the four directions,
2. control which receives the sensor signal and transfers it to the actuators
3. two actuators 1500N (337.21 lb_f) each, one for north- south and one for East- West

Figure 6 Solar tracker kit

SYSTEM OPERATION

The proposed system was designed to operate in the following manner:

1. Light strikes the lens surface at a 0° incident angle (due to the usage of a dual axis solar tracker).
2. The lens concentrates 90% of the sun light at a distance of 1300 mm (51.18 in) away from the lens surface into a focal point of 70 mm (2.76 in) diameter.
3. 90% of the concentrated light penetrates through the cover glass into the water.
4. Water with a thickness of 100 mm (3.94 in) absorbs most of the IR component and a small portion (38%) of the VL.
5. The remaining light strikes the hot mirror, 98% of the IR component is reflected back into the water and the VL portion continues to the PV cell.
6. The water is circulated from the cold water tank into the heating container and back to the hot water tank. By monitoring the container inlet and outlet temperatures by means of thermocouples the circulation tempo of the pump is managed. For this design the stored water temperature was set at 95°C (203°F) to suit the operation requirement of the common 17.585 kW (5 TR) absorbtion chiller.
7. VL light passes through the water and the top and bottom glass cover to impinge onto the PV cell.
8. The PV cell receives the net of a 10 times solar concentration which is available for electricity generation.

DISCUSSION AND CONCLUSION

The design of an innovative, small scale CPVT system is presented based on an analysis of the solar spectrum and the manner in which the various components can best be used in conjunction with standard elements. One of the main governing factors was the common operation requirement of the 5TR absorbtion chiller heating requirements of 95°C inlet temperature. The design is based on the concept of using a simple concentrator and mirror type splitter to more efficiently drive parallel PV cell and thermal collection units. The proposed system is expected to deliver the following outputs:

- Hot water at over 95°C (203°F) and 405 W (0.5431 hp)
- Approximately ±69 W (0.0925 hp) of electrical energy from a 300 x 300 mm single layer PV cell.

This design is likely to be more cost effective than more expensive concentrator designs due to the use of standard solar energy elements and the improved utilization of the solar spectrum. The system has also been designed to be smaller than many solar concentrator systems so that it may be applied in areas with limited space for solar system implementation.

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NOMENCLATURE

A	=	absorbance of an optical medium
I	=	density of light transmitted through the substance W/m^2
Io	=	density of light striking a substance W/m^2
α	=	absorption coefficient of the substance
L	=	is the distance the light travels through the substance
η_{lens}	=	Lens light remission efficacy
$\eta_{top\ Glass}$	=	top glass light remission efficacy
$\eta_{hot\ mirror}$	=	Hot mirror light remission efficacy
η_{pv}	=	PV cell efficacy

REFERENCES

C2ES Center for claimte and energy solutions. 2014. Residential and commercial electricity consumption by end user. http://www.c2es.org/technology/overview/electricity

Chaplin, M. 2015. Water Structure and Science, http://www1.lsbu.ac.uk/water/water_vibrational_spectrum.html.

Edmund optics a. 2014. Hot mirrior marketing material. http://www.edmundoptics.com/optics/optical-mirrors/hot-cold-mirrors/hot-mirrors/43843/

Edmund optics b. 2014. Cold mirrior http://www.edmundoptics.com/optics/optical-mirrors/hot-cold-mirrors/cold-mirrors/62633/

Geek, R.C. 2007. Water Absorption and Heating from Sunlight. http://www.troublefreepool.com/threads/9205-Water-Absorption-and-Heating-from-Sunlight

Heo, J. 2013. Characterization of Wavelength Effect on Photovoltaic Property of Poly-Si Solar Cell Using Photoconductive Atomic Force Microscopy (PC-AFM), Materials Characterization and Measurement Group, Korea Institute of Materials Science, Changwon 641-831, Korea

Hollick, J. 2011. PV thermal systems – capturing the untapped energy, Conserval Engineering Inc, 200 Wildcat Road Toronto Ontario

Intl-Trading. Complete Dual Axis Solar Tracking System -DC 12V 6"&12" Linear Actuator and Electronic Controller-Solar Panel Sunlight Tracker. http://www.aliexpress.com/store/product/Complete-Dual-Axis-solar-tracking-system-DC-12V-6-12-Linear-Actuator-Electronic-Controller-Solar-Panel/1279440_32268540225.html.

Kribus, A., G. Kaftori, G. Mittelman, A. Hirschfeld, A. Flitsanov and A. Dayan. 2006. A miniature concentration photovoltaic and thermal system. Energy Conversion and Management Volume 47 Issue 1: 3582–3590

McGehee, M. 2012. An Overview of Solar Cell Technology. Materials Science and Engineering, Precourt Institute Stanford University. https://gcep.stanford.edu/pdfs/2wh9Q1Alh3q2zMOQRKD4MQ/MikeMcGehee_SolarEnergy101.pdf

Mittelman G, A Kribus, A Dayan. 2007. Solar cooling with concentrating photovoltaic/thermal (CPVT) systems. Energy Conversion and Management Volume 48 Issue 9: 2481–2490

Prahl, S. 1998. Optical absorption of water. Available at http://omlc.ogi.edu/spectra/water/index.html

Saad, O., and B. Masud. 2009, Improving photovoltaic module efficiency using water cooling, Heat Transfer Engineering; 30(6):499e505

Solar cell central. 2011. The Shockley Queisser Efficiency Limit. http://solarcellcentral.com/limits_page.html

Stine, W.B. and M. Geyer. 2001. Power from the Sun, http://www.powerfromthesun.net/book.html.

Yazaki. 2007. WFC-SC5 Water Fired Chiller absorption type with H2O/LiBr. http://www.yazaki-airconditioning.com/fileadmin/templates/pdf_airconditioning/data_sheets/FT_WFC_SC_5_en.pdf