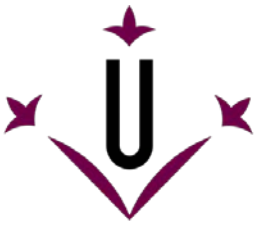

Universitat de Lleida

Fluid-based spectrally selective filters for direct immersed PVT solar systems in building applications

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Abstract

Liquid filters applied in hybrid photovoltaic-thermal (PVT) solar systems report potential benefits as they allow for selecting the wavelengths at which the solar cell operates with higher efficiency. Among the rest, low frequency photons are absorbed by the liquid, therefore not warming the cell up. In addition, direct immersion of photovoltaic cells in liquids enhances temperature control by cooling the cells under almost negligible contact resistance between the liquid and the cell. The characteristics of the liquids for direct immersed PVT application are described, defining an indicator (ideal filter window) to select the best liquid depending on the PV technology and the incident irradiance. Several liquids are assessed based on the required properties for the present application. As a conclusion, regarding optical, thermal, electrical and operational aspects, a mixture of deionized water and isopropyl alcohol results as proper candidate satisfying well all of them.

Keywords: Fluid-based filters; Direct immersion; Hybrid photovoltaic-thermal (PVT); Spectral selection; Dielectric liquids.

List of symbols and abbreviations

AM	air mass [-]
AOD (or τ)	aerosol optical thickness [-]
c-Si	crystalline silicon
C_e	specific heat [J g^{-1} K^{-1}]
CIGS	copper indium gallium diselenide
D	inner tube diameter [m]
DIW	deionized water
DMSO	dimethyl sulfoxide
d_s	total thickness of the cuvette [mm]
GaAs	gallium arsenide
GLY	glycerol
I_0	diode saturation current [A]
I_F	diode forward current [A]
I_R	diode reverse current [A]
IBA	isobutyl alcohol
IFW	ideal filter window
IPA	isopropyl alcohol
Jsc(λ)	spectral short-circuit current density [A m^{-2} nm^{-1}]
Jsc	short-circuit current density [A m^{-2}]
k	extinction coefficient [-]
L	pipe length [m]
n_D^{20} (or n)	refractive index at 20ºC and 589 nm (sodium yellow doublet D-line) [-]
n*	complex refractive index [-]
v	fluid velocity [m/s]
V	potential [V]
PW	precipitable water [cm]
Q	flow rate per collector aperture area [l $h^{-1}m^{-2}$]
Re	Reynolds number [-]
SR	spectral response [A W^{-1}]
T	temperature [K or ºC]

Greek symbols

α	absorption coefficient [cm^{-1}], $\alpha = 4\pi k\lambda^{-1}$
ε_r	dielectric constant [-]
λ	wavelength [nm]
μ	dynamic viscosity [Pa s]
ρ	density [kg m^{-3}]

1 Introduction

Hybrid photovoltaic-thermal (PVT) solar collectors can be a high-efficient technology able to cogenerate heat and electricity with global efficiencies around 70%, with electrical efficiencies near 20% and thermal efficiencies higher than 50% [1]. One of the main applications of such technologies is the building sector where both heat and electricity are needed and 40% of the total energy consumption in Europe is registered [2]. The on-site renewable energy production is the only solution to achieve buildings with nearly-zero or zero energy consumption, and therefore, space limitations lead to the necessity of efficient and space saving technologies such as PVT collectors. In this regard, it has been demonstrated that 60% additional area is required for a separate solar thermal collector and PV module to produce the same yield as a PVT liquid system [3]. On the other hand, direct immersed PVs have proved to enhance efficiency attending to a reduction of the Fresnel losses with respect to a bare PV, a reduction of the surface recombination losses [4] and a better temperature control by the reduction or elimination of the thermal contact resistance at the interface between PVs and dissipater [5]. Despite these notable benefits, direct immersed PVTs have to be further investigated to completely understand their performances and key design parameters to leverage their potential.

In order fill the gap in direct-immersed PVT collectors characteristics and to address the goal of designing high-efficient PVT systems for applications in buildings, the present research focuses on the investigation of several fluid-based optical filters for direct immersion of the solar cells which aim at covering a double objective: (1) the filter should adapt the incident spectrum to transmit photons at the photovoltaic cell maximum spectral response bandwidth and absorb photons out of this zone; (2) the fluid should remove the infrared photons emitted by the solar cell to prevent from problems

associated with overheating as efficiency reduction, thermal stress or dilatation of materials, etc. First, the optical, electrical and thermal characteristics that a liquid filter for PVT generation should achieve are discussed and stated. Later, a series of experiments and calculations are conducted to categorize a set of candidate liquids based on the requirements previously defined.

2. Key characteristics of a liquid filter for direct immersed PVT collectors

In the following subsections, the optical, electrical and thermal properties that a fluid-based filter should meet are analyzed.

2.1 Optical properties

The optical properties studied are directly related to the optical constants involved in the complex refractive index ($n^* = n + ik$). The refractive index, n, (real part), should balance the refractive indexes of the module components in order to minimize Fresnel losses. The imaginary part (the extinction coefficient, k) is analyzed, instead of the directly related absorption coefficient (α), in terms of the spectral transmittance since this is the most widely referred parameter.

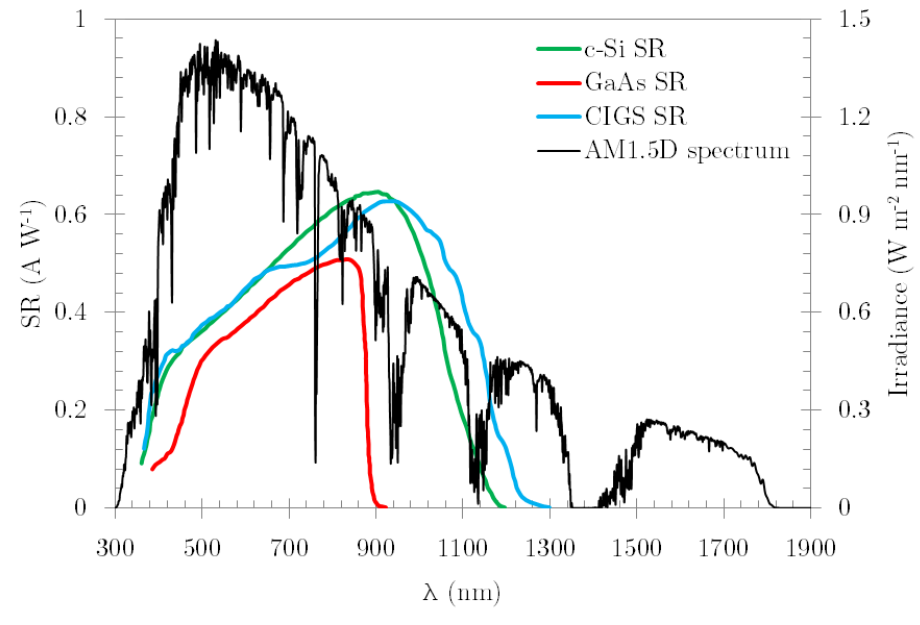
The spectral transmittance requirements for the liquid filters should be in agreement with two factors, namely: a) to transmit the maximum for optimizing the PV electrical output and b) to absorb the maximum for optimizing the heat dissipation and production.

Regarding the electrical generation, some researchers define an ideal filter bandwidth selection criterion based on the spectral response (SR) of the cell [6, 7]. For instance, in [6] the criterion is to select the bandwidth at which the spectral response of the cell (c-Si) is greater than 0.5 A/W. This criterion could be considered as a good first approach

when studying the zone where the liquid filter should transmit the maximum to optimize the generation of the semiconductor device. However, it does not consider the solar spectrum shape and its impact as a function of the specific SR of the device. A second strategy is to define the appropriateness and behavior of the liquid filter relying on the solar characteristics of the AM1.5 direct (D) reference spectrum [8]. Finally, some authors analyze the performance of liquids considering both the SR and the solar AM1.5D spectrum [9, 10]. Nevertheless, there is no study in the literature defining explicitly the transmittance window the filter should match depending on the PV technology and the particular incident solar spectrum. Concerning solar spectrum, only the AM1.5D is referred as the most general while in the majority of the locations the annual mean spectra differ considerably from the AM1.5D as the atmospheric parameters are far from those included in the AM1.5D standard spectrum definition [11].

A proper parameter to cope with the definition of the ideal filter for enhancing the PV performance is the spectral short-circuit current density, Jsc(λ), which is obtained by the product of the SR of the PV technology and the spectral incident solar irradiance. Figure 1(a) shows the spectral responses of three characteristic PV cell technologies jointly with the AM1.5D solar spectrum. From these data, the spectral short-circuit current densities are calculated and plotted in Figure 1(b).

(a)



(b)

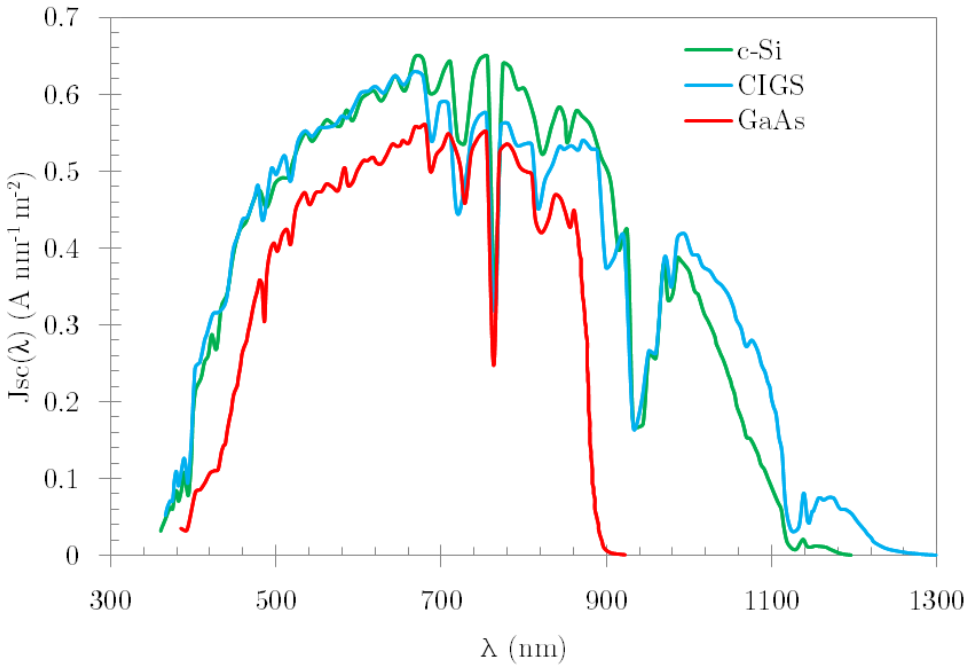


Figure 1. (a) AM1.5D standard spectrum and c-Si, CIGS and GaAs spectral responses; (b) Spectral short-circuit current density of the three PV technologies.

From the spectral short-circuit current, it is defined the range of an ideal filter as the minimum bandwidth which comprises at least the 75% of the short-circuit current

generated by the PV cell. The 75% value is selected as a compromise between the increase of short-circuit current density generation and the additional bandwidth needed to obtain such increment. The spectral short-circuit current density curves (Fig. 1(b)) show a clear decrease in the generation at the tails, where the gain of generation per wavelength increment becomes very low. This condition could vary for different PV technologies and/or incident illumination conditions that would produce, for instance, a more constant spectral short-circuit current generation.

The criteria for the ideal liquid filter are indicated in Eq. (1). Subscripts *i* and *f* indicate the initial and final wavelengths where the PV cell generates current and subscripts *a* and *b* refer to the interval limits of the ideal filter window.

$$Ideal\ filter\ window\ (IFW) criteria \begin{cases} \dfrac{\int_{\lambda a}^{\lambda b} J_{SC}(\lambda) d\lambda}{\int_{\lambda i}^{\lambda f} J_{SC}(\lambda) d\lambda} \geq 0.75 \\ \min[\lambda_b - \lambda_a] \end{cases} \quad (1)$$

For the three photovoltaic technologies depicted in Figure 1, the spectral ranges fulfilling the stated conditions under AM1.5D spectrum are included in Table 1.

Table 1**.** Ideal filter window intervals and bandwidths for three PV technologies and under AM1.5D spectrum.

PV technology	$IFW_{AM1.5}$ **(nm)**	$\Delta\lambda$ **(nm)**
c-Si	422.4-893.3	470.9
CIGS	407.9-920.9	513.0
GaAs	477.5- 850.3	372.8

In the following paragraphs the ideal filter window wavelength interval is assessed for annual mean spectra different from the AM1.5D standard reference spectrum. The calculated spectra aim at covering all the possible casuistic by considering the atmospheric parameter values that produce bigger changes in the spectrum. Also, since one of the main potential applications of liquid-based filters is for PVT concentrating

modules [5, 6, 8, 9], the direct irradiance spectra are only considered. Moreover, under direct beam conditions, spectral changes due to atmospheric parameters variations are more sensitive because diffuse irradiance does not interfere.

The atmospheric variables that mostly affect the solar spectrum characteristics are the air mass (AM), aerosol optical depth (AOD or τ) and precipitable water (PW). AM is defined as the distance, relative to the shortest (vertical) path length, that the sunrays traverse through the atmosphere before impacting the Earth's surface. AOD characterizes the radiative strength of aerosols (urban haze, smoke particles, desert dust, sea salt, etc.) in the vertical direction. Finally, PW is the amount of condensed water (expressed in cm) corresponding to the total water vapor contained in a vertical atmospheric column above any location. The water vapor has strong absorption bands in the near infrared, which directly impacts the spectrum. The explicit influence of these atmospheric parameters on the spectrum is described in previous works for both the direct and global spectral irradiance [12, 13]. As it was previously commented, the most important atmospheric parameters that influence the spectrum shape are AM and AOD, which lead to noteworthy attenuation effects on the Ultraviolet-Visible waveband, while PW only modifies slightly the infrared portion. Figure 2 illustrates the spectral content variation for the combination of parameters for which the spectrum is more sensitive. The air mass annual mean of 3 represents a representative high value and the aerosol optical depth of 0.7 indicates highly turbid conditions [12]. The reference AM1.5D spectrum parameters are: AM = 1.5, AOD (at 500 nm) = 0.084 and PW = 1.416 cm. The spectra are generated using the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS 2.9.5) [14]. The spectra are normalized to the same irradiance (the AM1.5D one) in order to focus the discussion on the wavelengths effect on the PV cell

generation for the IFW definition and to better illustrate how the spectrum changes as a function of the atmospheric parameters.

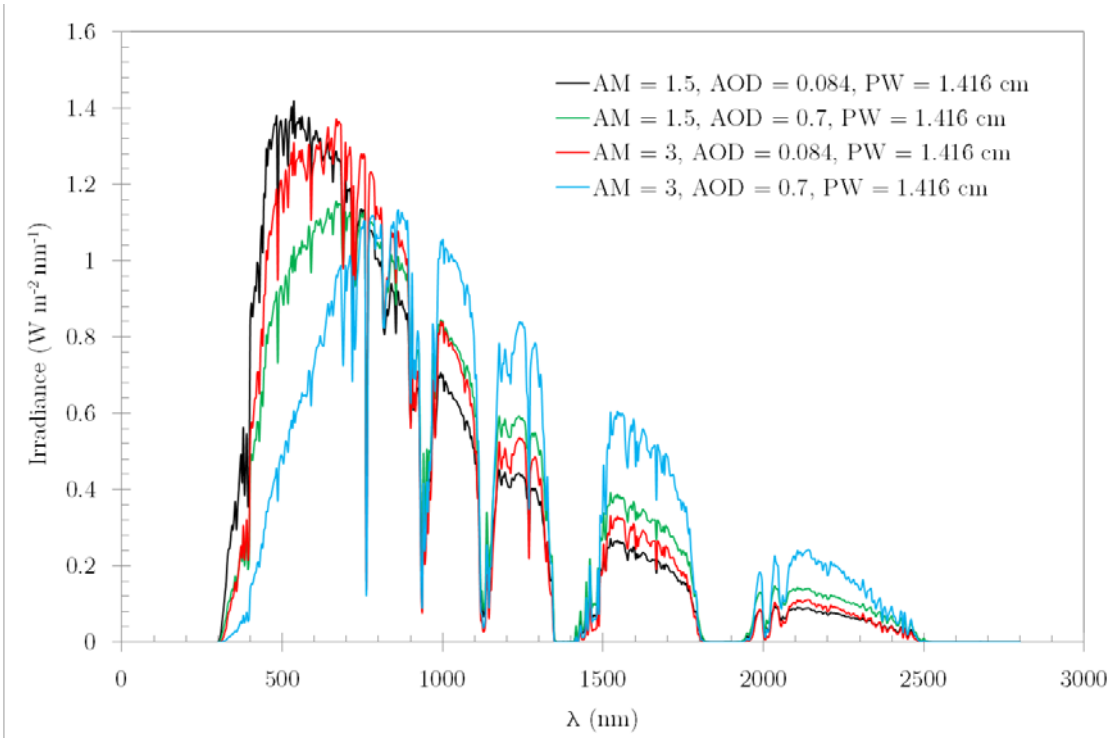
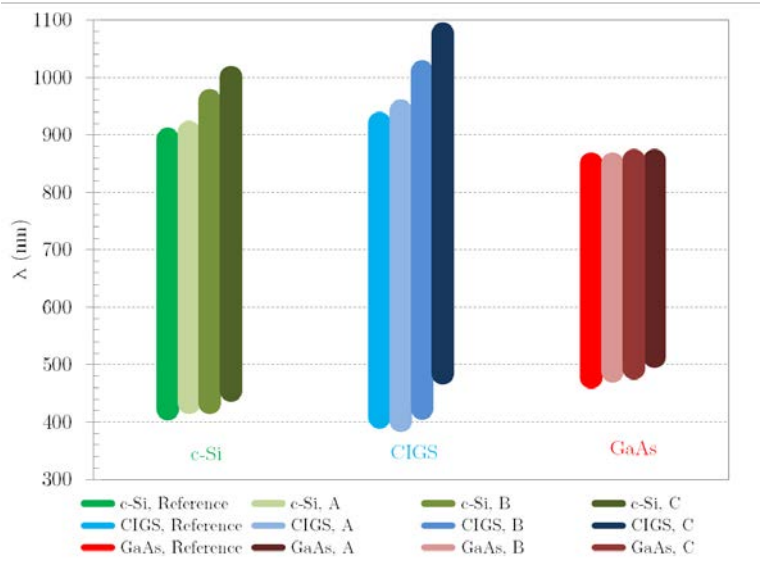


Figure 2. Generated spectra for several atmospheric parameters combinations.

Figure 3 plots the IFW interval limits for the spectra combinations. Looking at the c-Si cell, the movement of the spectrum maximum to longer wavelengths due to the increase of AM does not affect the IFW because even though the cell is more efficient for those wavelengths the intensity of the spectrum is lower due to atmospheric absorption around 700nm (case A). However, the more pronounced red-shift that occurs in the cases B and C influences the widening of the IFW bandwidth and, specifically in the case C there is a displacement of the IFW intervals to longer wavelengths. This performance is analogous for the CIGS technology. On the contrary, the ideal filter maximum transmittance bandwidth for GaAs cells is practically not sensitive to spectral variations. This is associated to the narrower bandwidth where the cell is efficient. For this reason the upper interval of the IFW does not move from around 850 nm and the

lower interval moves to slightly higher wavelengths caused by the red-shift mentioned above. Therefore, the IFW intervals should be defined depending on the location and its associated spectrum. It is worth mentioning that the analysis conducted here aims at demonstrating the variability of the IFW in terms of annual mean spectra, but for the exact calculation of the IFW for a specific location it should be determined considering the annual spectral variations and selecting the interval which maximizes power output.



Case	AM	AOD	PW (cm)
Ref	1.5	0.084	1.416
A	3	0.084	1.416
B	1.5	0.7	1.416
C	3	0.7	1.416

c-Si	IFW (nm)	Δλ (nm)
Ref	422.4-893.3	470.9
A	433.9-904.9	471.0
B	433.9-960.0	526.1
C	455.6-1000.7	545.1
CIGS		
Ref	407.9-920.9	513.0
A	402.2-942.6	540.4
B	423.8-1010.7	586.9
C	484.5-1076.1	591.6
GaAs		
Ref	477.5-850.3	372.8
A	489.0-850.3	361.3
B	493.3-856.1	362.8
C	513.5-856.1	342.6

Figure 3. IFW intervals for different PV technologies and incident spectra.

On the other hand, the transmittance of the filter should be minimal from the thermal point of view for the rest of the wavelengths which are not appropriate for electrical generation. Certainly, this is hardly achievable since two clear areas are identified: irradiances of photons with shorter wavelengths than the minimum of the IFW and irradiances of longer wavelengths than the maximum of the IFW. Concerning the short wavelengths, these are not problematic at all as in most of the cases the glazing element utilized in the PVT modules is soda lime glass which, depending on the silica content, does not transmit wavelengths shorter than 300-350 nm. In addition, even with less

efficiency and warming the solar cell up by thermalization effect those more energetic photons contribute in pumping electrons. Finally, this bandwidth around 400 nm fits very well the absorption wavelengths of several luminescent dyes which re-emit at wavelengths included in the IFW interval [15, 16]. From the above mentioned, the liquid filters should present minimum transmittances for bandwidths above the upper limit of the IFWs.

2.2 Electrical properties

The main electrical property that a liquid for direct immersion has to fulfill is to be dielectric. In addition, some authors associate the dielectric to an electrical performance increase of the PV cell due to a positive effect originated by the adhesion of the liquid dipole to the cell:

a) Ugumory and Ikeya [17] found that the photocurrent of solar cells operated in liquid increases with the increase in the permanent dielectric moment (rather than the dielectric constant) of liquid molecules. This increase in photocurrent was attributed to a possible adsorption of the polarizable molecules which can reduce the surface recombination current. In addition to the reduction of surface recombination effect, they speculated that band bending at the surface could cause an increase in the photoconductance, but they indicated that it was not possible to propose the definitive mechanism for that.

b) Abrahamyan *et al.* [4] reported that a dielectric liquid thin-film can increase the efficiency of common silicon solar cells by 40-60%, considering that the adhesion of the liquid dipoles to the cell surface can result in lower surface recombination velocity and lower light reflection. From the studied liquids, those experimenting higher increase in short-circuit current and open-circuit voltage were acetone and glycerin. They

analyzed the electric effect in absence of light to eliminate reflection issues with and without glycerin. The increase of short-circuit current, open-circuit potential and efficiency was attributed to several factors: an increase in the barrier height of pn junction, a decrease in the velocity of the surface recombination followed by an increase in the factor of separation of charge carriers generated by light as well as a decrease in a part of the reflected radiation. Moreover, they noticed that the increase of the thickness of the liquid layer over the cells promotes the wetting and the adsorption phenomena, but on the contrary the higher the thickness the higher the absorption. As a conclusion, there should be an optimum thickness depending on the dielectric utilized.

c) Wang *et al*. [18] performed some tests and described a possible mechanism for cell performance increase when immersed in a liquid. The adhered dipoles at the cell surfaces, both front and back, originate electric fields with identical directions to the built-in electric field in the cell. These electric fields at both surfaces can suppress the surface recombination. However, the electric fields could also cause electric leakage, which could result in a decrease of the shunt resistance. They differentiated between non-polar and polar liquids, that present different permanent electric moment and in consequence the electric fields formed vary their intensities depending on the liquid molecule type. From the liquids tested (tap water, ethanol and silicone oil), they selected the non-dipolar one as the best candidate (silicone oil).

d) Han *et al.* [4, 19] reported that the increase in the concentration of electrons in the n-layer that is moistened with a liquid leads to a decrease in the saturation current (proportional to the surface recombination reduction). They observed that the dark current decreases more for polar liquids such as deionized water or isopropyl alcohol, and less for non-polar liquids (dimethyl silicon oil and ethyl acetate).

2.3 Thermal properties

The thermal properties that make a liquid adequate for PVT modules are high specific heat and high thermal conductivity to maximize thermal exchange and low coefficient of expansion to prevent the increase of pressure inside the hydraulic circuit when temperature increases. Also, the liquid should present an appropriate range of temperatures between melting and boiling points so that real operational conditions are well covered.

Direct liquid-immersion active cooling eliminates the thermal contact resistance at the interface between PVs and dissipater. The contact thermal resistance is moved to the boundary layer between the bulk liquid and the cell. In addition, it provides the opportunity to cool the cells at both surfaces, top and rear, and not to be limited to the back one as in the conventional coolers [5]. The thermal advantage of liquid immersion cooling is more important than the increase in the electrical performance with the dielectric. With the same flow rate (1.1 l/s) and inlet temperature (298K), deionized water as coolant can make the operating temperature of the module 20ºC lower than that of isopropyl alcohol [5].

A very important aspect in an active PVT system is related to the power needed for cooling-fluid pumping. In this direction, it is essential to maximize the liquid density and to minimize the viscosity, so as the system can maximize the heat removal with low pressure losses [20].

3. Analysis of possible dielectric liquids candidates for spectral selection in PVT collectors

A set of dielectric liquids have been selected to study their performances based on the optical, thermal and electrical characteristics described in section 2. The candidates are:

deionized water (DIW), isopropyl alcohol (IPA), isobutyl alcohol (IBA), dimethyl sulfoxide (DMSO), Glycerol (GLY) and some mixtures under different volumetric fractions (IPA / GLY, IPA / DIW, DMSO / DIW and DMSO / IPA). DIW is chosen because, even it may oxidize the metallic components under direct contact, it presents the best properties concerning the thermal and electrical desired characteristics (highest specific heat, thermal conductivity and the lowest electrical conductivity). IPA and IBA register a good range of operating temperatures between melting and boiling points, not only to work as pure substances but also to be a good mixture molecule to prevent the PVT module from freezing. GLY is the liquid for which the best electrical performance increase has been reported in the literature [4]. DMSO is the molecule with the second highest dielectric constant (48.9), it also presents high density, low viscosity and medium specific heat coefficient that make it appropriate from the thermal point of view. In Table 2 the different properties of the pure substances are shown. An additional column has been included regarding health toxicity in agreement with NFPA 704 standard health code [21]. This ranges from 0 (no health hazard) to 4 (could cause death or major residual injury).

Table 2. Characteristics of the dielectric liquids. Physical properties are at 20ºC except those indicating a specific temperature.

Liquid	**ε_r**	**n_D^{20}**	**C_e (J g^{-1} K^{-1})**	**ρ (kg m^{-3})**	**μ (mPa s^{-1})**	**[$T_{melting}$-$T_{boiling}$](ºC)**	**Health code**
DIW	80.2	1.330	4.18	1000	1.0	[0-100]	0
IPA	18.6	1.376	2.60	785	2.4	[-89-82.6]	1
IBA	15.8 (25ºC)	1.396	2.30	802.5	3.9	[-108-107.9]	1
GLY	42.5	1.475	2.20	1100	1553	[17.8-290]	0
DMSO	48.9	1.478	1.96	1260	2.7	[19-189]	1

3.1 Optical performance

In the case of a direct immersed PVT system, the module configuration over the PV cells presents two layers: the dielectric liquid and the transparent top casing that allows transmitting the incident light and confines the liquid in the cavity. Attending to this structure, the optical performance will be better when the refractive indexes of the materials of the slab will be the most similar possible regarding Fresnel losses. Considering that the most usual antireflection single layer is made of silicon nitride with a refractive index around 2 and the transparent top layer could be either of polymeric materials or glass with refractive indexes surrounding 1.5, the best liquids are those achieving refractive indexes closer to the range (1.5-2). Based on this fact, the best candidate would be DMSO and the worst DIW. Table 3 describes the Fresnel losses in terms of the power loss at the PV cell level for the liquid candidates and under the slab scheme mentioned (considering silicon nitride refractive index) at normal incidence. It is assumed that at the n_D wavelength (589 nm) the extinction coefficient of the liquids is negligible. It can be appreciated that the power loss is almost three times lower in the case of DMSO than in the empty cavity, but at the same time the maximum difference between liquids is small (around 2%).

Table 3. Fresnel power losses of the different liquids.

Dielectric liquid	**Power loss (%)**
No liquid in the cavity	18.1
DIW	8.22
IPA	7.46
IBA	7.16
GLY	6.20
DMSO	6.17

Concerning the transmittance of the liquids, it has been measured with an Ocean Optics UV-VIS-NIR spectrometer utilizing a 10 mm light path optical glass cuvettes. The range of the spectrometer (350-2500 nm) encompasses the 98.2% of the energy comprised in the AM1.5D spectrum. It is assumed that no interference is produced as the bandwidth ($\Delta\lambda$) used is 0.5 nm and the thickness of the three-slab system for the 10 mm cuvette (walls of 1 mm thick) is 12 mm (d_s). Therefore, for the worst case (n = 1.33 and λ=2500 nm), the incoherent superposition condition is met [22]:

$$d_s > \frac{\lambda^2}{2\pi n \Delta\lambda} \tag{2}$$

In Figure 4, the pure substances transmittances measured along with the IFW intervals are included. The IFWs indicated correspond to the reference AM1.5D case and to case C (AM = 3 and AOD = 0.7) for c-Si (for the other two PV technologies the analysis would be analogous). In terms of the PV receiver, under the reference spectrum it can be seen that all the substances behave adequately at maximum transmittances; however, in the case C spectrum, the upper interval of the IFW moves to higher wavelengths into a lower transmittance zone for the DIW and GLY. The rest of the liquids keep high their transmittances. On the other hand, regarding the thermal performance of the PVT collector, the transmittance should be minimal for longer wavelengths than the upper limit of the IFW. GLY and DIW are the two liquids that clearly best suit this condition for both IFWs. Since there is no coincidence under the most demanding IFW conditions in the thermal and electrical requirements for the set of liquids, a series of mixtures were prepared to try to decrease the transmittance above the upper IFW limits and to try to increase the transmittance of GLY and DIW so that case C conditions are met. It should be highlighted that the case C spectrum considered presents high values of AOD and AM, but concerning the AM much higher values are observed during a day at the first

and last hours. Therefore, similar spectra to the one considered here with the red-shift observed occur in all the places at certain moments of the day.

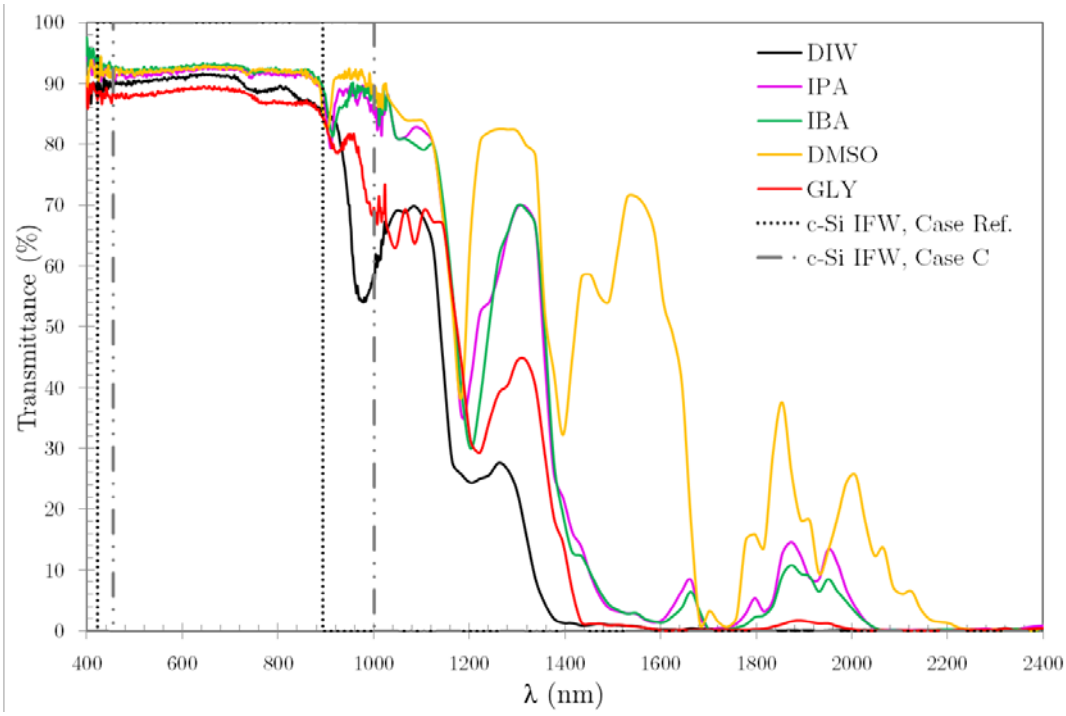


Figure 4. Spectral transmittances and IFW ranges for c-Si.

Figure 5 depicts the liquid mixtures transmittance spectra of those liquids selected based on the previous transmittances obtained and conditioned to miscibility between them. The criterion of mixing was to obtain the maximum transmittance in the IFW range and the minimum transmittance above it. The two mixtures that best match the criterion are DIW + DMSO and DIW + IPA as they balance the maximum and minimum transmittance levels required for the PVT generation (%V indicates volumetric proportions).

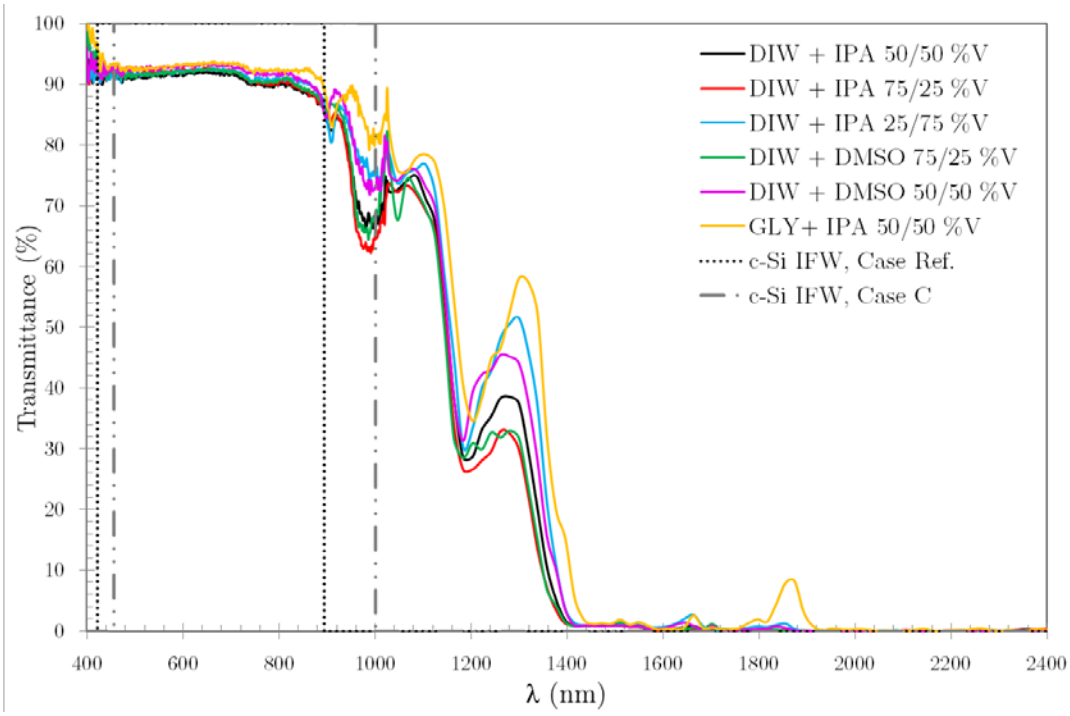


Figure 5. Liquid mixtures spectral transmittances and IFW ranges for c-Si.

3.2 Electrical performance

The dielectric liquids effect on the PV cell performance is analyzed by testing a batch of 2x2 cm^2 solar cells immersed in 10 mm of the different liquids assessed inside a series of cuvettes with a Keithley 2460 sourcemeter. In Figure 6, the experimental set-up scheme is depicted.

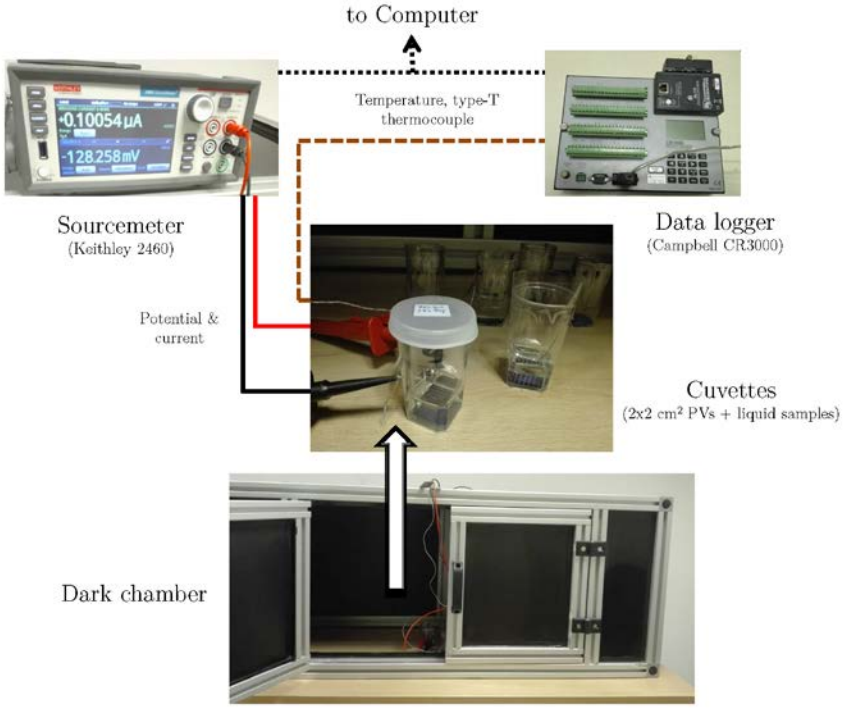


Figure 6. Scheme of the electrical characterization experimental set-up.

Dark IV curves measurements before and after the cell immersion are conducted under dark conditions to eliminate Fresnel losses and to directly identify if the dielectric liquids affect the cell performance through the diode current. In the diode equation, the saturation current (I_0) is referred as a direct indicator of the recombination phenomena, but it shows a strong dependence on the temperature effects [23]. Therefore, no temperature variations should be ensured to attribute the possible variations to changes in the recombination rates associated to I_0. A T-type high accuracy thermocouple is attached at the back of the cells to perform the IV curve measurements at the same temperature and few sampling points are applied to acquire the curve the fastest possible. A small error is assumed since the measured temperature does not correspond to the pn junction, even though the thermocouples are accurate, an error of 0.4 % is associated and the IV tracing is performed fast but around 2 seconds are needed. In Figure 7, some of the measurements for the pure liquids are plotted, indicating that the

diode reverse current (I_R) decreases slightly when the cells are immersed in the different dielectric liquids. The shift of the diode current for a forward voltage bias (I_F) is very small for DIW and IPA and negligible for IBA and DMSO. This effect is in agreement with what has been reported by other authors [3, 4, 17-19], but it is necessary to point out that the positive effect observed is marginal in comparison with the performance increase due to Fresnel losses reduction or temperature control from the cells by the direct contact with the liquid. Since PV cells have experienced a continuous evolution to enhance performance, the passivation layers and techniques, among others, have been considerable improved. For this reason, the electrical performance increase produced by the dielectric liquids effect is small in comparison with that reported in 2002 by Abrahamyan *et al.* [4].

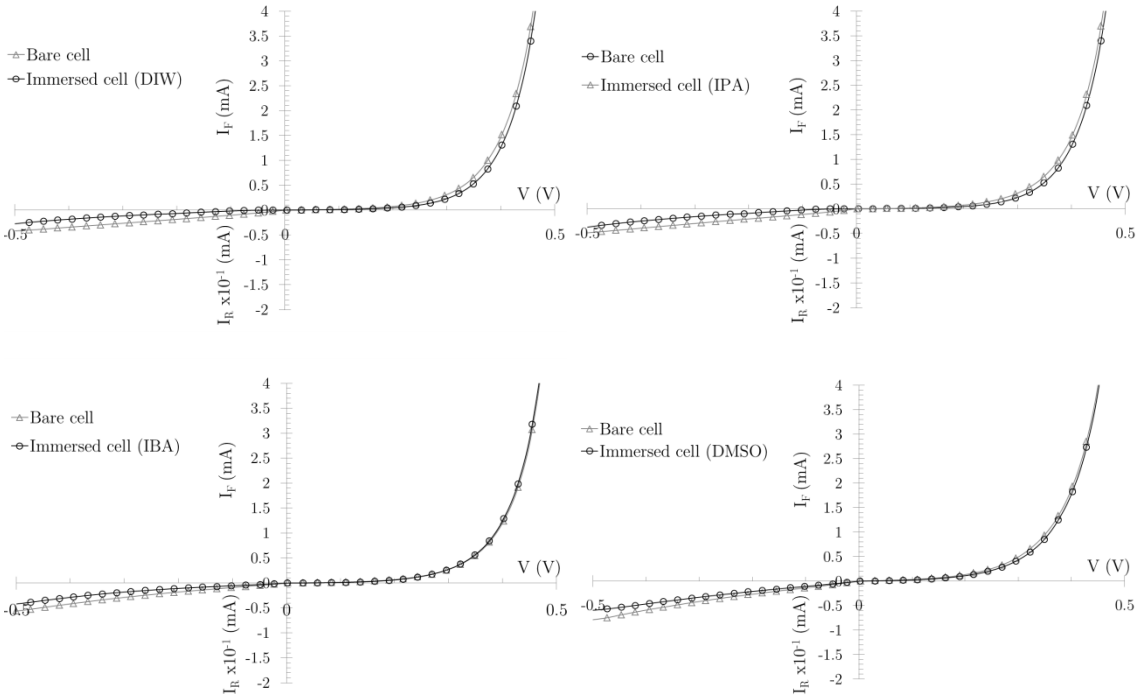


Figure 7. Characteristic dark IV curves. Temperatures of the measurements: DIW = 22.45ºC, IPA = 22.77ºC, IBA = 23.07ºC, DMSO = 20.47ºC.

3.3 Thermal performance

The heat extraction capacity of the dielectric liquid in a PVT collector not only depends on the liquid properties but also on the geometry and characteristics of the dissipation scheme. Regarding the fraction of the incident irradiance that the liquid filter directly absorbs, it can be derived from the irradiance fraction that is transmitted with respect to the incident one. Considering the interval from 1000nm to 2500 nm, the percentages transmitted by the pure substances calculated by the Fresnel equations and for unpolarized light are included in Table 4. DMSO transmits an important percentage of 25% of the incident irradiance that only warms the PV cell up, which positions it as a not good candidate from the thermal point of view. The rest of liquids achieve a quite reasonable values ranging from 1 to 5%.

Table 4. Percentage of irradiance in the range (1000-2500) nm that is not absorbed by the dielectric liquids.

Dielectric liquid	**Irradiance transmitted (%), range (1000-2500) nm**
DIW	1.15
IPA	5.01
IBA	4.43
DMSO	25.7
GLY	2.07

In concern to the rest of properties of the liquid as heat transfer fluid, a simple analysis to estimate the pumping power necessary for a 1 m^2 aperture area flat-plate collector is conducted based on the fluid properties of Table 2 and by considering the assumptions defined in Table 5. Only primary pressure losses in the hydraulic circuit are included in the calculations as the objective is to qualify the liquids independently of the collector geometry.

Table 5. Assumptions for the pumping power calculation. Re is the Reynolds number.

Inner pipe diameter , D (m)	0.01
Pipe length, L (m)	11
Flow rate, Q (l/h/m^2)	70
Velocity, v (m/s)	0.25
Primary pressure losses, ΔP (Pa)	$\Delta P = \frac{64Lv^2}{2ReD}$
Pumping power, (W)	Power $= Q\Delta P$

In Figure 8, two sensitivity analyses are included: the first (Figure 8, left) shows the power necessary to pump the liquid keeping the temperature difference between the inlet and outlet at 7ºC and for different dissipated powers; the second (Figure 8, right) maintains the removed power level at 500 W/m^2 while temperature raise varies from 1 to 10ºC. From both graphs it can be appreciated a clear change in the pumping requirements depending on the liquid. The most demanding is GLY, attending to its very high viscosity (even to be non-Newtonian liquid the viscosity value is considered not to vary). Conversely, the best liquid is DIW. In the middle region, DMSO, IPA and IBA appear. From these three, DMSO is the one achieving less pressure losses.

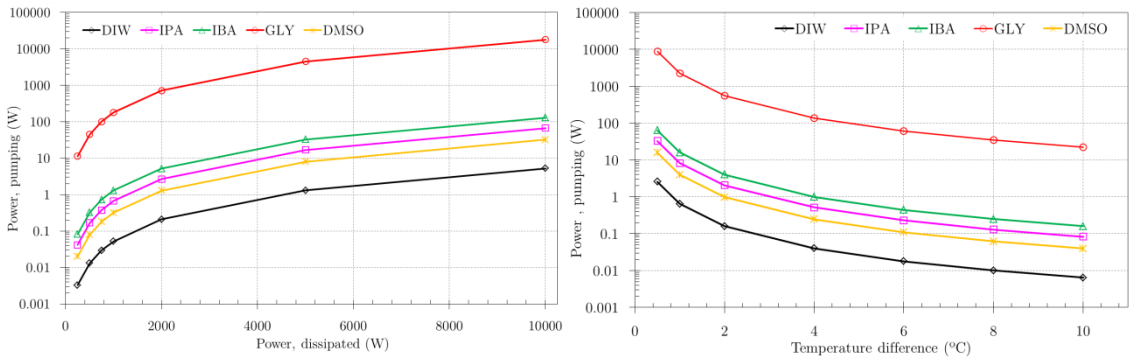


Figure 8. Pumping power (logarithmic scale) vs. dissipated power (left) and temperature difference (right).

3.4 Operational properties

In general, the changes in the spectral properties with time are only marginal for all the dielectric liquids if they are not operating at temperatures above 80ºC [6]. Nevertheless, some affectations are reported in the literature. GLY become yellowish with time [24]. Deionized water, and polar liquids in general, could oxidize metallic components (tin, silver and copper mainly in the electrical contacts and soldering), but the emitter is not affected [5]. IPA is very stable for immersion [5, 7]. Alcohols in general may degrade polymeric materials, including many types of sealants. The assessed alcohols do not present problems with the working temperatures as they boil above 80ºC. Nonetheless, the rest of liquids melting points are at temperatures equal or greater than 0ºC which may cause freezing depending on the ambient temperatures of the location. For European climates, in all the cases, it would be recommended to mix them with alcohols in different fractions in order to reduce the freezing temperature depending on the minimum temperatures at each specific the place. Finally, it is important to mention that all the tested liquids are not dangerous from the health point of view.

4 Summary and conclusions

The use of liquid-based filters to spectrally select the incident irradiance in a direct immersed photovoltaic-thermal module reports several benefits. These are based on the possibility of selecting the photons that are most efficiently converted into electricity by the PV cell to be transmitted and the photons out of this range to be absorbed by the liquid to prevent from overheating.

Optical, electrical and thermal characteristics of the dielectric liquids have been analyzed based on the state-of-the-art. The most important issues are:

- The liquids have to be highly transparent at the region where the solar cells are more efficient.
- The refractive index of the liquids should be higher than the one of the air since this produces a reduction in the Fresnel losses.
- The adsorption of the liquid dipoles at the front and rear surface of the cell may improve the cell performance.
- The direct thermal contact between the cell and the liquid enhances heat dissipation.

An ideal filter window indicator has been defined to identify the bandwidth at which the filter should transmit the maximum and out of it should absorb the maximum. The parameter takes into account the spectral response of the photovoltaic technology and the incident spectrum as both are quite irregular in shape. In the case of the spectrum, possible variations of its morphology due to atmospheric parameters variability throughout the day and depending on the placement have also been discussed. The ideal filter window and therefore, the requirements for the liquid filter to be used vary considerably depending on atmospheric parameters variation (air mass index and aerosol optical thickness are the parameters which most influence the spectrum).

A series of dielectric liquids candidates have been selected based on their optical, thermal and electrical adequateness for the present application. The liquids have been studied optically, thermally and electrically to state their advantages and disadvantages for a PVT direct immersed solar module. Moreover, operational features have been considered as freezing temperatures, stability, degradation of components, etc. Table 6 sums up the obtained results regarding the different aspects analyzed. The electrical characteristics are not included as all the liquids respond satisfactory and not substantially different.

Table 6. Summary of the results.

Liquid	Optical characteristics	Thermal characteristics	Operational characteristics
DIW	-high transparency at VIS bandwidth -refractive index low in comparison to the glass and ARC ones (Fresnel losses) -regarding PV performance, absorbs from 900nm on diminishing photons available.	-the best performance as heat extraction liquid	-possible oxidation of metallic components -need of mixing to avoid freezing
IPA	- high transparency at VIS bandwidth -refractive index close to those of glass and ARC but lower than the GLY and DMSO ones	-good heat extraction liquid	-may degrade polymers
IBA	-high transparency at VIS bandwidth -refractive index close to those of glass and ARC but lower than the GLY and DMSO ones	-good heat extraction liquid	-not miscible with DIW, GLY -may degrade polymers
GLY	- high transparency at VIS bandwidth -refractive index close to the glass, few Fresnel losses	-the worst performance as heat extraction liquid	-need of mixing to avoid freezing -need of mixing to reduce viscosity -possible yellowing
DMSO	-high transparency at VIS bandwidth -refractive index close to the glass, few Fresnel losses	-good heat extraction liquid -does not absorb an important part of the infrared photons that are not converted by the PV cell (25%)	-need of mixing to avoid freezing

From the obtained results, it can be concluded that proper candidates for PVT direct immersed modules would be some mixtures achieving: adequate melting points to avoid freezing, high transmittance for the bandwidth fixed based on the IFW criteria, high absorbance for photons above the upper interval of the IFW and good thermal characteristics to remove heat with the highest efficiency and lowest pumping power necessary. As a result, two liquids have been identified as optimal: a mixture of deionized water with isopropyl alcohol and a mixture of deionized water with dimethyl sulfoxide. The last may not properly work in cold climates as the freezing temperature is above 0ºC.

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